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D2.3

The BeFEMTO System Concept and its Performance

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Abstract:
This final deliverable summarizes the most promising set of innovations from WP3-6 and synthesises them to demonstrate how they contribute towards the BeFEMTO System Concept. Several topics in each deployment scenario are comprehensively covered by showcasing various contributions from the BeFEMTO partners. The most promising of these are then selected and it is shown how they achieve the key performance targets of the BeFEMTO System Concept. Furthermore, this deliverable also highlights the results of the system-level simulator calibration campaign carried out by all the partners of the project.

Keyword list:

Bandwidth (BW), Component Carrier (CC), Carrier Aggregation (CA), Hardware, Interference Management, OFDMA, RF scenarios, Spectrum Sharing, Standalone Femtocell, Mobile Relay, Power Control, Frequency Partitioning, Graph Colouring, Radio Resource Management, SON, Multi-cell RRM techniques, Synchronization, Geo-location, Coverage, Game theory, Q-learning, Power control, Antenna array, Codebook, Precoding, Access control, Authentication, Traffic Forwarding, Offloading, Routing,

Resource Sharing, Mobility Management, Network Management, Offloading, LIPA, SIPTO, Fault Diagnosis, Energy Management

Executive Summary

This final deliverable summarizes the most promising set of innovations from WP3-6 and synthesises them to demonstrate how they contribute towards the BeFEMTO System Concept. The predecessor report to this one (IR2.4) grouped the contributions according to the layer to which they were applicable. In this deliverable, we have deviated from this distinction and instead we group the contributions according to the deployment scenario that they satisfy. This document thus consists of four main sections:

Section 1 provides an illustrative picture of contributions summarized in this deliverable and introduces subsequent sections.

Section 2 gives a brief overview of the BeFEMTO System Architecture as detailed exhaustively in the BeFEMTO deliverable D2.2.

Section 3 then covers the system-level simulation calibration campaign to which all the BeFEMTO partners have contributed. This is done so that a meaningful comparison can be made between the results obtained by the different partners. The system-level simulator is LTE compliant with the simulation parameters aligned with 3GPP recommendations. The results indicate that there is a very good match between the simulators of the various partners.

Section 4 focuses on the deployment of standalone femtocells. Section 4.1 major contributions on the design of RF front to comply with the constraint of 10mW maximum transmit power in BeFEMTO. This section covers various aspects such as the definition of RF specifications for LTE-A and its architecture analysis, the impact of carrier aggregation on this architecture and some RF frontend designs. Next, in Section 4.2, a number of interference management techniques to mitigate interference on control and data channels are presented. Here, topics such as opportunistic spectrum reuse, static interference avoidance schemes, TDD underlay in an FDD network and interference cancellation techniques are discussed. Radio resource management, the topic of sub-section 4.3, finds an important place in the study of heterogeneous networks. Here, soft frequency use in heterogeneous networks is analysed.

Section 5 then covers the deployment of networked femtocells. Enablers are contained in Section 5.1, where topics such as automatic location determination and coverage estimation, SON taxonomy and reinforcement and learning algorithms are discussed. Section 5.2 then presents techniques dealing with power and coverage control where topics such as access policies are presented. The important topic of interference mitigation in the context of networked femtocells is exhaustively discussed in Section 5.3. Here topics such as interference issues in the presence of open and closed access femtocells, cell association, spatial domain interference cancellation, distributed interference mitigation, eICIC techniques, etc. are presented and discussed. RRM and scheduling fall under the purview of Section 5.4. Section 5.5 covers SON aspects such as docitive femtocells and self-optimization of antenna tilt are portrayed. Security issues are discussed in Section 5.6, whereas traffic management is covered by Section 5.7. Mobility and network management are covered by Sections 5.8 and 5.9 respectively.

Section 6 is dedicated to the deployment of fixed relays and mobile femtocells. Topics such as downlink CoMP for femtocells, femto assisted macro relaying and mobile/moving femtocells are presented in Section 6.2. Finally mobility management in the context of mobile femtocells and relays is covered by Section 6.3. Here topics such as backhaul issues for mobile femtocells and multi-homing femtocells are discussed.

Section 7 consolidates all the work presented in Sections 4 through 6 and fits them into the framework of the BeFEMTO System Concept. The BeFEMTO System Concept consists of four foreseen femtocellular deployments. This section aims to show how the work done in the BeFEMTO project fits these broad deployment categories.

Finally, the deliverable is closed in Section 8 which contains concluding remarks and a brief discussion of the material presented in Sections 2 through 6.

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Table of Contents

Table of Abbreviations

Acronym	Meaning
3G	3rd Generation
3GPP	3rd Generation Partnership Project
4G	4th Generation
ABS	Almost Blank Subframe
ACLR	Adjacent Channel Leakage Ratio
ACI	Adjacent Channel Interference
ACS	Adjacent Channel selectivity
A/D	Analogue to Digital
ADC	Analogue to Digital Converter
AKA	Authentication and Key Agreement
AM	Amplitude Modulation
AMMP	Active Macro Mobile Protection
AP	Access Point
API	Application Programming Interface
B7	Band 7
B20	Band 20
BB	Base Band
BeFEMTO	Broadband Evolved Femtocells
BER	Bit Error Rate
BS	Base Station
BW	Bandwidth
CA	Carrier Aggregation
CC	Component Carrier
CCE	Control Channel Element
CCI	Co-Channel Interference
CDF	Cumulative Distribution Function
CN	Core network
CQI	Channel Quality indicator
CRS	Common Reference Symbol
CSG	Closed Subscriber Group
DAC	Digital-Analogue Converter
dB	Decibel
dBm	Decibel with respect to milliwatt
dBc	Decibel with respect to carrier
DCI	Downlink Control Information

DCR	Direct Conversion Receiver
DL	Downlink
DoS	Denial of Service
EER	Envelope Elimination and Restoration
eNB	evolved Node B
EPC	Evolved Packet Core
E-UTRA	Evolved-Universal Terrestrial Radio Access
EVM	Error Vector Magnitude
FAP	Femto Access Point
FDD	Frequency Division Duplex
FFR	Fractional Frequency Reuse
FR	Frequency Reuse
FUE	Femtocell User Equipment
GHz	Gigahertz
GW	Gateway
GNSS	Global Navigation Satellite System
HeNB	Home evolved Node B
HO	Hand Over
HPA	High Power Amplifier
HSDPA	High-Speed Downlink Packet Access
ICI	Inter Carrier Interference
ICIC	Inter-Cell Interference Coordination
ICS	In channel Selectivity
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IFFT	Inverse Fast Fourier Transform
IMT	International Mobile Telecommunications
IP	Internet Protocol
ITU-R	International Telecommunication Union-Radiocommunication Sector
KHz	Kilohertz
LGW	Local Gateway
LFGW	Local Femtocell Gateway
LIPA	Local IP Access
LNA	Low Noise Amplifier
LO	Local Oscillator
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution Advanced
MART	Mobile Assisted Range Tuning

MBS	Macro Base Station
MBSFN	Multimedia Broadcast Single Frequency Network
MHz	Megahertz
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
ms	millisecond
MUE	Macrocell User Equipment
mW	milliwatt
NL	Network Listen
NLM	Network Listen Mode
PM	Phase Modulation
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OFP	Orthogonal Frequency Pattern
OTA	Over-The-Air
P_A	Power consumption of PA
PA	Power Amplifier
PC	power control
PCFICH	Physical Control Format Indicator CHannel
PCI	Physical Cell Identity
PDCCH	Physical Downlink Control CHannel
PDF	Probability Distribution Function
PDN	Packet Data Network
PFAP	Power of the Femto Access Point
P-GW	PDN Gateway
PHY	Physical (Layer)
PHICH	Physical Hybrid-ARQ Indicator CHannel
P_L	Power consumption of LNA
PLL	Phase Locked Loop
P_R	Total power consumption for transmitting
P_{RB}	Power consumption in base band circuit for receiving
P_{RRF}	Power consumption in front-end circuit for receiving
P_T	Total power consumption for transmitting
P_{TB}	Power consumption in base band circuit for transmitting
P_{TRF}	Power consumption in front-end circuit for transmitting
QoE	Quality of Experience
QoS	Quality of Service
RB	Resource Block

REM	Radio Environment Measurement
RF	Radio Frequency
RLF	Radio Link Failure
RRC	Radio Resource Control
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
Rx	Receiver
SEM	Spectrum Emission Mask
SINR	Signal to Interference-plus-Noise Ratio
SIPTO	Selective IP Traffic Offload
SNR	Signal to Noise Ratio
SISO	Single Input Single Output
SON	Self-Organizing Networks
TDD	Time Division Duplex
TTI	Time Transmit Interval
Tx	Transmitter
UAA	Uplink Adaptive Attenuation
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunication System
VLAN	Virtual LAN
VLR	Visitor Location Register
VPN	Virtual Private Network
WiMAX	Worldwide interoperability for Microwave Access
WP	Work Package

1. Introduction

This final deliverable summarizes the most promising set of technical innovations from WP3-6 and condenses them to depict a high-level overview of the BeFEMTO System Concept. About the System Concept itself, there can be two viewpoints as illustrated below:

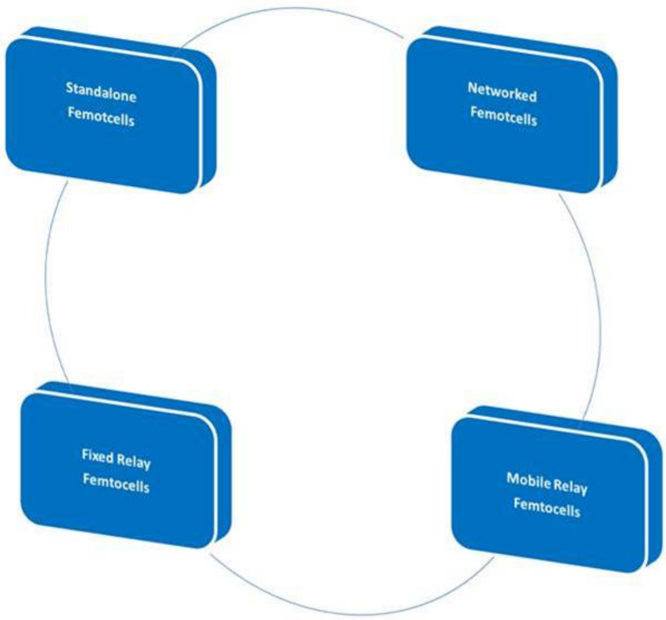


Figure 1: The BeFEMTO System Concept: Viewpoint from Themes perspective

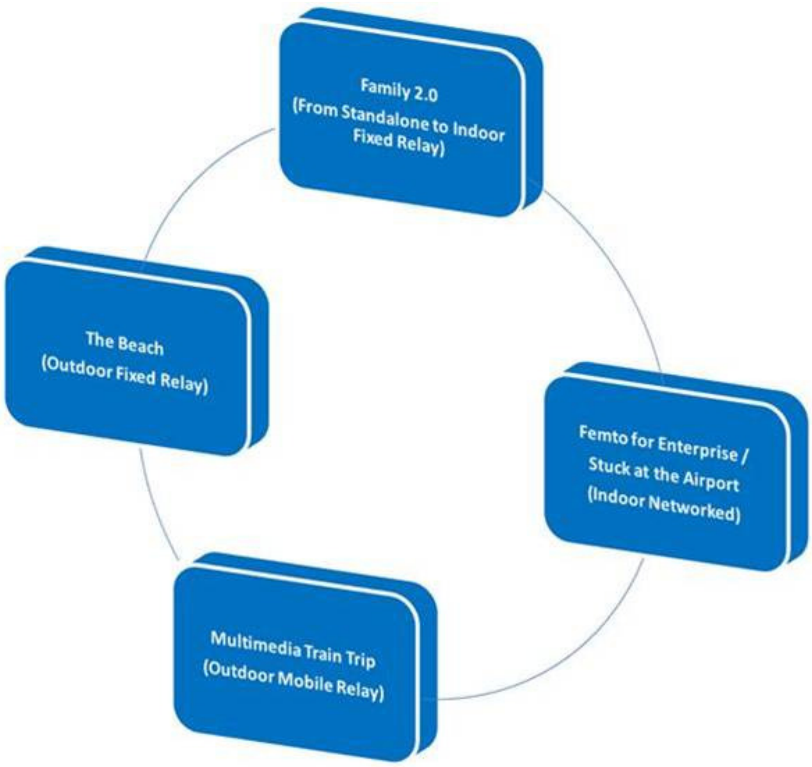


Figure 2: The BeFEMTO System Concept: Viewpoint from Use-cases perspective

Figure 1 illustrates the BeFEMTO system concept from the perspective of four themes:

- Standalone Femtocells

- Networked Femtocells
- Fixed Relay Femtocells
- Mobile Femtocells

and infact this viewpoint was the one that was promoted right from the beginning of the project. The second viewpoint of BeFEMTO system concept as illustrated in Figure 2 is the one that was developed when BeFEMTO in year-1 developed use-cases from business and market perspective. These use-cases were captured in deliverable D2.1 [1] and each describes a practical deployment scenario. These are:

- Family 2.0 [Standalone femtocell with advanced features such as indoor relays]
- Femto for Enterprise [Indoor networked with closed access]
- Stuck At the Airport [Indoor network with open access]
- Multimedia Train Trip [Outdoor mobile relay]
- The Beach [Outdoor fixed relay]

Further details about these use-cases can be seen in D2.1 [1], however it is clear from the very titles and short description in square brackets that there is one-to-one relationship between the two viewoints, i.e. the system concept viewpoint from themes' perspective and system concept viewpoint from use-cases perspective (Note that Femto for Enterprise and Stuck At the Airport both refer to indoor networked femtocells but differ only in access policy). Infact, this deliverable is structured to take into account both viewpoints as can be seen in the structure of deliverable which will be explained shortly. Before that, it should be noted that due to enormous complexity of the system, the evaluation of BeFEMTO system concept can be done in stages, i.e. from the perspectives of:

- Higher Layer Protocols (L3 and above)
- Architecture
- Radio Access Techniques (L1 and above)
- Proof of Concepts

The above mentioned stages also correspond very closely to the work package structure adopted in BeFEMTO and will be used throughout this document in explaining the BeFEMTO innovations.

This document is structured so that the reader is first introduced to the BeFEMTO System Architecture. This is then followed by covering the system-level simulator campaign which all the partners have taken part in and which is the basis for all the simulation work shown in the remainder of this document. As per the BeFEMTO description from, the scope of this deliverable covers contributions from WP3-6. Therefore, the next sections are structured as follows:

- Standalone femtocell deployment
- Networked femtocell deployment
- Fixed relays and mobile femtocell deployment
- BeFEMTO System Concept (from Use-cases perspective)

The chapter on System Concept also presents summary tables that captures the essence of work done across different work packages targeting different themes and use-cases and also harmonizes the effort into a unified and holistic viewpoint. Finally, the document ends with a conclusion. The overall structure of this document is pictorially described in Figure 3.

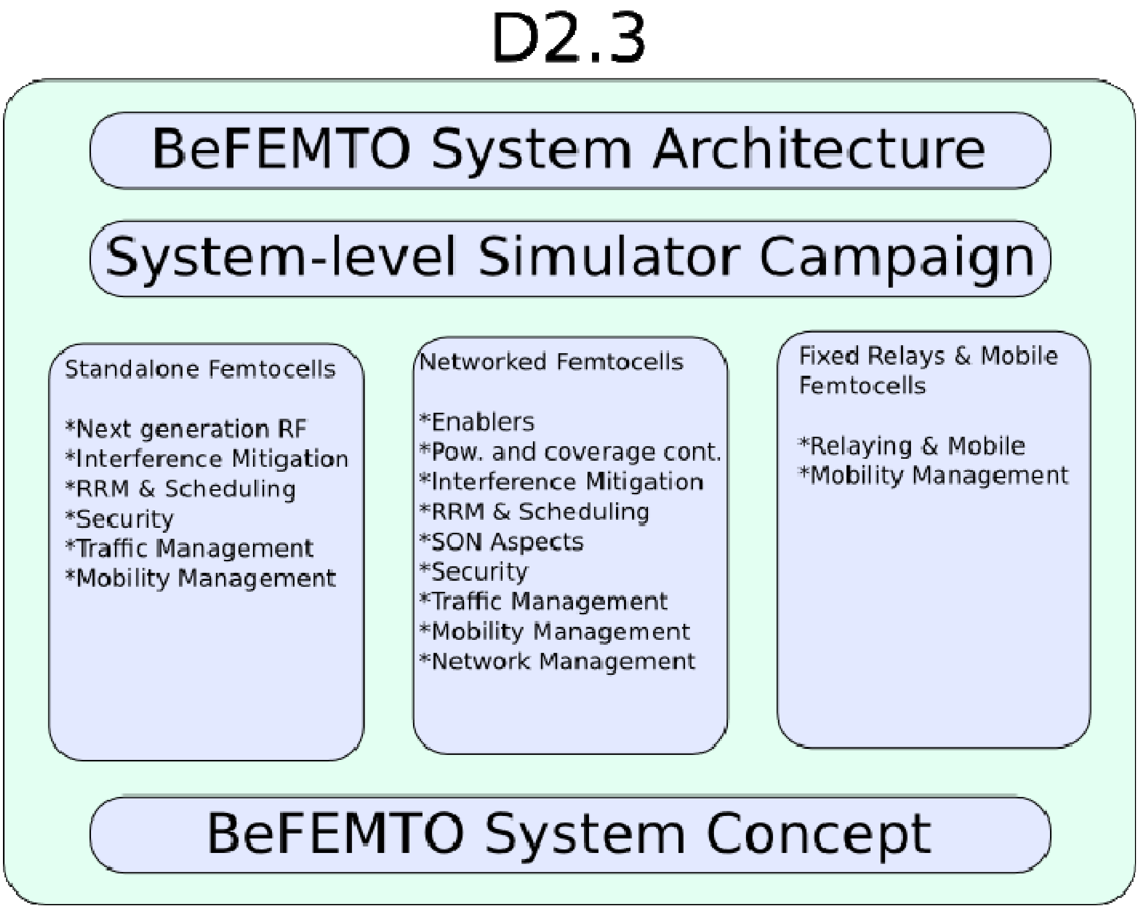


Figure 3: The layout of BeFEMTO deliverable D2.3.

References

[1] BeFEMTO D2.1, "Description of baseline reference systems, use cases, requirements, evaluation and impact on business model", ICT 248523 FP7 BeFEMTO project, December 2010.

2. Overview of the BeFEMTO System Architecture

2.1 The BeFEMTO System Architecture and its Sub-System Architectures

2.1.1 BeFEMTO System Architecture

The BeFEMTO System Architecture captures the technical innovations developed within the BeFEMTO project and how they relate to each other as well as to current mobile and fixed network architectures. These innovations focus on improving performance and functional aspects of standalone femtocells based on LTE-Advanced, but also extend the use cases of femtocells in three directions: towards outdoor, relay femtocells, towards mobile femtocells and towards femtocell networks.

The BeFEMTO System Architecture is composed of the following sub-system architectures (Figure 4):

- the BeFEMTO Evolved Packet System (EPS) Architecture that extends 3GPP's EPS architecture and encompasses the mobile network layer (core network and radio access network, including the femtocell sub-system),
- the BeFEMTO Transport Network Architecture, which describes the communication networks that transport the data between the elements of the BeFEMTO EPS Architecture, e.g. the local area network connecting a network of femtocells and the fixed broadband access network,
- the BeFEMTO HeNB and the LFGW Node Architectures, which provide the internal architecture of the two functional entities that are vastly extended and newly introduced by the project, respectively.

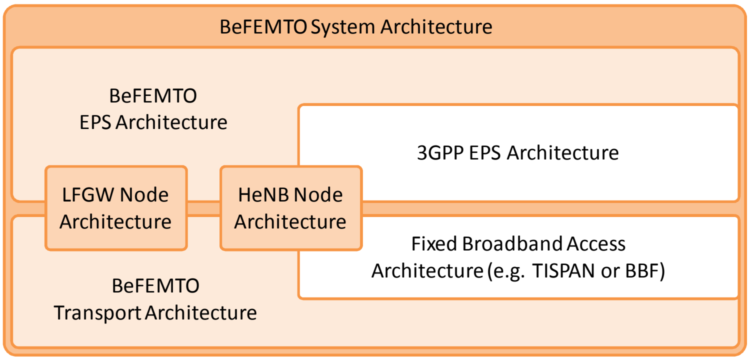


Figure 4: The BeFEMTO System Architecture and its Sub-system Architectures.

In the following, we provide a birds-eye view of the different sub-system architectures and how BeFEMTO innovations relate to them. More details on the architecture itself can be found in BeFEMTO Deliverable D2.2 [2] as well as in the following sections.

2.1.2 BeFEMTO Evolved Packet System (EPS) Architecture

The BeFEMTO Evolved Packet System (EPS) Architecture builds upon the 3GPP's Rel-10 EPS architecture and extends it in several aspects. Figure 5 provides a graphical overview of the functional entities of this sub-system architecture as well as the interfaces between them. For the sake of clarity, this overview only contains the most important entities of the Evolved Packet Core (EPC) and the Evolved UTRAN (E-UTRAN). Functional entities and interfaces that are enhanced or newly introduced by

BeFEMTO are highlighted.

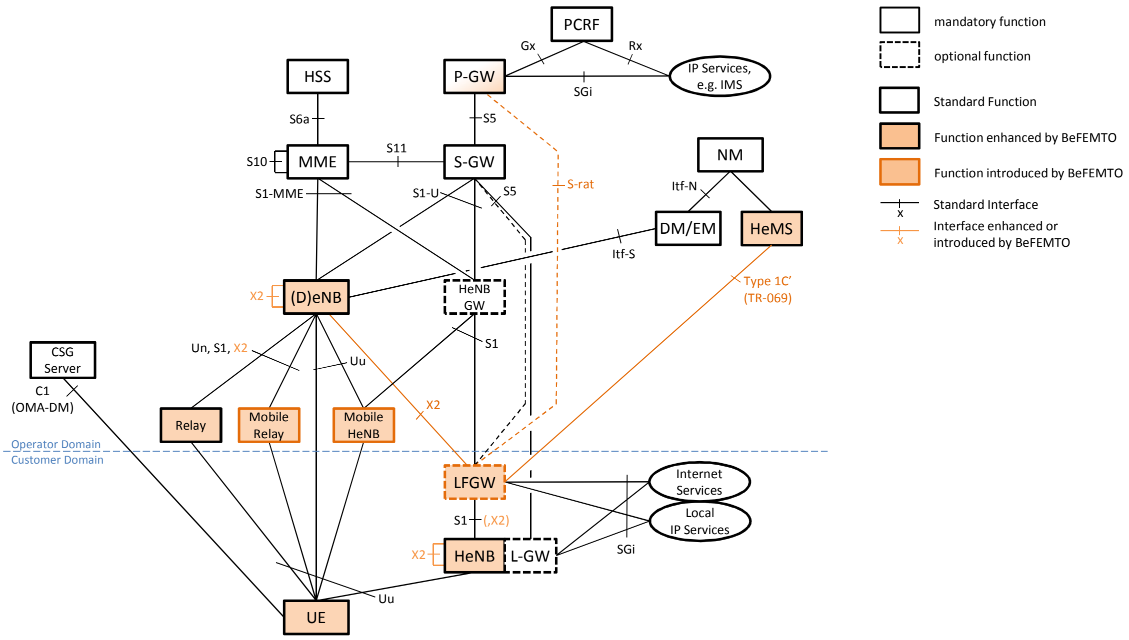


Figure 5: The BeFEMTO EPS Architecture.

A large number of BeFEMTO innovations address new RF techniques for LTE-A HeNBs, radio resource and interference management between HeNBs and between HeNBs and the eNBs on the macro layer, as well as novel SON techniques. Several of these innovations improve the system efficiency by exchanging additional information between these network elements, either over the X2 interface or over-the-air (e.g. snooping on other (H)eNBs' transmissions). An X2 interface between HeNBs has been introduced by 3GPP in Rel-11 during the runtime of BeFEMTO, an X2 interface between eNBs and HeNBs is still under discussion at the writing of this document.

Innovations on the fixed outdoor relay theme include coverage estimation and antenna tilt optimization as well as full-duplexing schemes and HetNet backhauls for fixed relays. Apart from the relays themselves, these schemes impact also the DeNBs and in part require support by the UEs.

In the theme on networked femtocells, a new, optional network entity has been introduced: the Local Femtocell GateWay (LFGW). Its basis is a small scale version of the (optional) HeNB GW that is located on customer premises instead of within the EPC. It hosts several functions that enable local mobility, local routing, local traffic breakout, local network management or local SON coordination. This element is inserted into the S1 and X2 interfaces between EPC and HeNBs. For this, it requires support from the HeMS, which also provides the operator policies for the local functions. For enhanced traffic breakout functionality, it either needs an S5 interface or the newly introduced S-rat interface to the EPC (see also Section 2.2).

On the mobile relay/femtocell theme, two architecture enhancements have been studied. The main approach is to build upon 3GPP's fixed relay architecture and to study how to make those fixed relays mobile. Architecture options for this have been studied in 3GPP supported by and with contributions from BeFEMTO partners (see Section 2.3). An alternative approach is to build on 3GPP's HeNB sub-system and make femtocells mobile by using one or more mobile network accesses as femtocell backhaul (see

Section 6.3.2).

2.1.3 BeFEMTO Transport Network Architecture

The BeFEMTO Transport Network Architecture defines the underlying transport layer below the mobile network layer of the BeFEMTO EPS Architecture. It extends existing fixed broadband access architectures, e.g. by TISPAN or BroadBand Forum, into the customer premises to provide a true end-to-end solution. Figure 6 exemplarily shows this extension for the case of the TISPAN's NGN Rel-2 architecture and a femtocell network scenario. Again, functional entities and interfaces that are enhanced or newly introduced by BeFEMTO are highlighted.

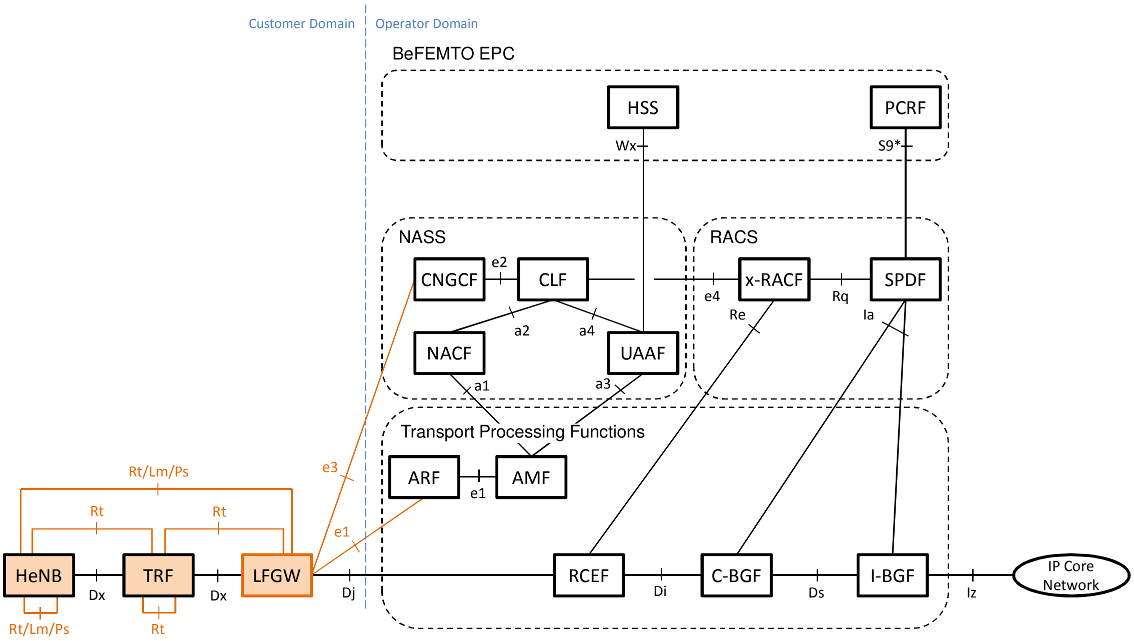


Figure 6: The BeFEMTO Transport Architecture.

BeFEMTO innovations on the transport network include security mechanisms and traffic management mechanisms. With respect to security, BeFEMTO innovations enable the customer network gateway (the HeNB in case of standalone femtocells or the LFGW in case of networked femtocells) to authenticate towards the fixed broadband access in addition to the authentication towards the mobile network it has to do anyway. Another innovation on the LFGW allows the local network operator to control access to the local network and services for breakout traffic. With respect to traffic management, the BeFEMTO Transport Network Architecture contains mechanisms for routing and load balancing femtocell traffic within the local network, for which it needs interfaces between HeNBs, LFGWs and Traffic Routing Functions (switches or routers) within the network.

2.1.4 BeFEMTO HeNB Node Architecture

While the HeNBs are typically implemented in a vendor-proprietary manner, they normally include similar functional blocks. The BeFEMTO HeNB Node Architecture shown in Figure 7 describes those functional blocks that would typically be found inside a BeFEMTO-enhanced HeNB.

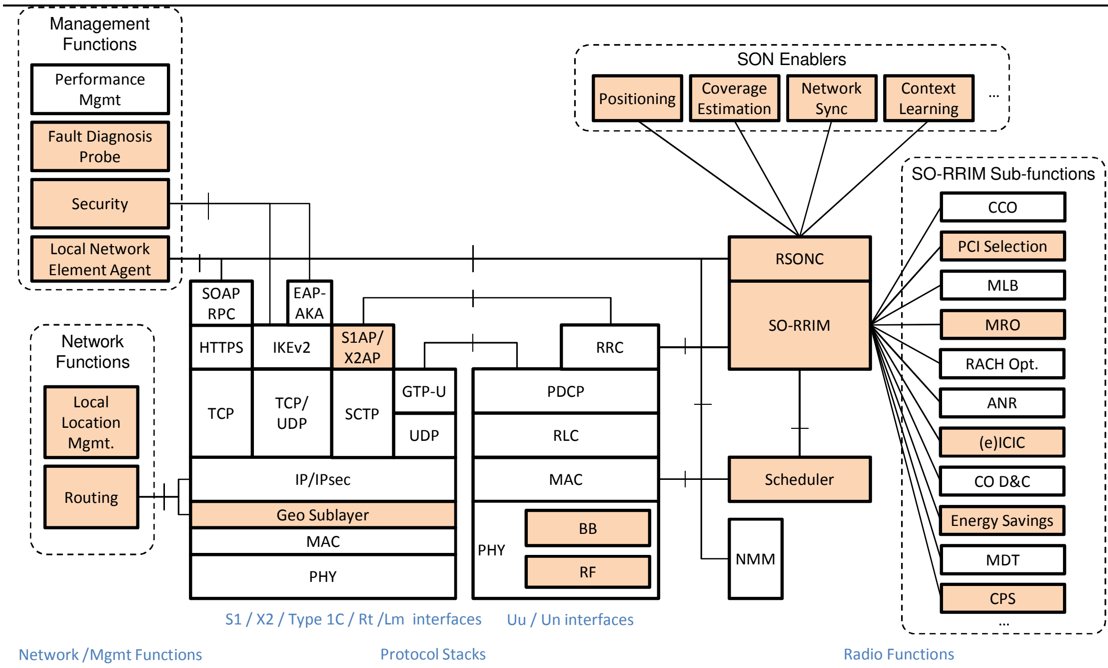


Figure 7: The BeFEMTO HeNB Node Architecture.

Again, BeFEMTO has contributed to several of those functional blocks. This includes the enhancements to the RF and baseband processing for LTE-A, e.g. for carrier-aggregation. The Radio SON Coordinator (RSONC) plays a central role in self-configuration and -optimization, as it combines the information provided by the SON enabling functions, together with parameters and operator policies received from OA&M, to coordinate and control the self-optimisation of system parameters to achieve a given performance goal. These parameters are related to the Self-Optimising Radio Resource and Interference Management (SO-RRIM) functional block that optimizes the radio resource usage within and between (H)eNBs with the help of different SO-RRIM strategies. The lower level scheduler in turn performs resource allocation between radio bearers at the subframe level under the constraints imposed by the SO-RRIM, potentially also giving feedback to the SO-RRIM when needed. Apart from the radio-related functions, BeFEMTO also contributed to the network management functions, adding a fault diagnosis and power management support, traffic management and mobility management.

2.1.5 BeFEMTO LFGW Node Architecture

A new network element introduced by BeFEMTO is the Local Femtocell GateWay (LFGW). Different from HeNB GW that is deployed by mobile operators in the core networks to act as a concentrator/distributor for control/user plane interfaces, LFGWs are deployed at users' premises such as in an enterprise building to act as a local controller/coordinator. This allows accessing to and integrating with local network services, exploiting local knowledge to improve mobile network functionality such as routing, radio resource and interference management, energy management and fault diagnosis. It further serves to reduce the signalling and user plane load on the mobile core network and broadband access link by handling functions autonomously and in a decentralized manner as well as by keeping local communication local.

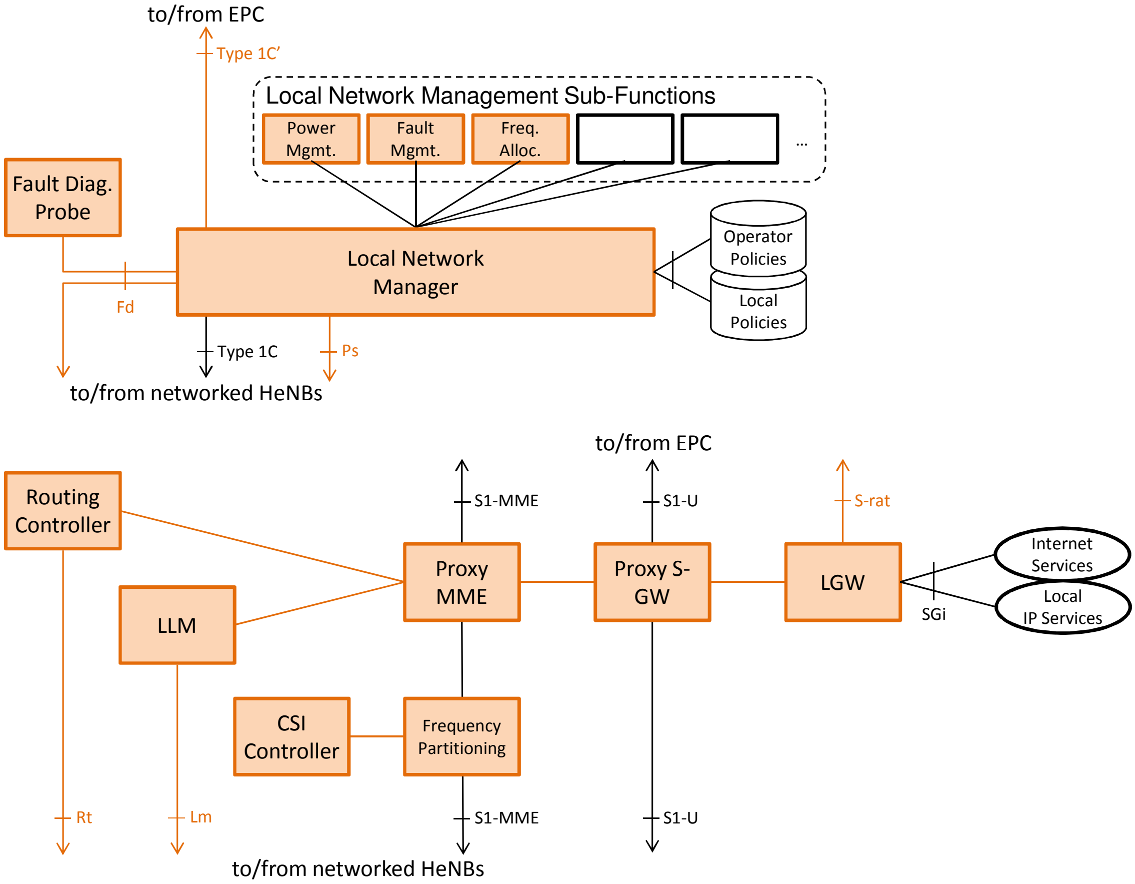


Figure 8: BeFEMTO LFGW Node Architecture.

Figure 8 shows the most relevant functional blocks of a BeFEMTO LFGW node. Generally speaking, they can be divided into those that are network management related, like for fault management, performance management, and energy management, (top) and those that are related to operational aspects like local mobility and location management, local routing, traffic offload, and radio resource and interference management coordination for the femtocell radio accesses (bottom).

2.2 Architectural Considerations for Femtocell Networks

2.2.1 Introduction

Femtocell networks are groups of femtocells connected via a local network and typically belonging to one administrative domain. They perform some of the mobile network's operation and management functions cooperatively and locally, minimizing the involvement of the mobile core network. This makes them different from collections of geographically close standalone femtocells that are not coordinated or get coordinated by the mobile core network.

There are several advantages to handling part of the mobile core network's functionality locally within the femtocell network.

- The most obvious is scalability: The signalling load on the mobile core network is positively correlated with the number of femtocells deployed on a given site (e.g. more mobility management and more network management related signalling). Also, one can expect a significant share of femtocell network traffic to be between local devices, whether UE to UE or UE to/from local network service. Any reduction in signalling or user plane traffic by handling mobile network functionality locally directly translates into savings of capital and operational expenses.

- Another advantage is the possibility to exploit local knowledge to improve femtocell services. This includes knowledge about the location and type (hallway, meeting room, etc.) of femtocell installation site, typical user mobility pattern, radio propagation characteristics and more. Such kind of information would typically not be exported to the mobile network for information privacy and traffic load reasons. It can be used to improve, e.g., radio resources and interference management, mobility robustness optimization, and energy management, though.
- Apart from these non-functional aspects, another advantage of delegating functionality to the local femtocell network is the possibility to integrate with local network services to create value-add services, e.g. integrating femtocell presence and data and video/voice with unified communication, facility (energy) management or security solutions.

There are also some challenges that need to be addressed. In particular, there need to be ways for the operator to keep a certain degree of control the local femtocell network and to keep the ability to monitor the state and performance of the femtocell network. This pertains to facilities that allow the operator to offer value-add services through service differentiation, to meet service level agreements with customers with respect to uptime and performance, and to fulfil legal obligations like lawful intercept that most regulatory domains require for telecommunication services in licensed spectrum.

2.2.2 Key Requirements

The following list presents some key requirements from the list of requirements identified by BeFEMTO in D2.1 [3] that pertain to architectural decisions.

- Business-Level Requirements
  - The femtocell network solution shall minimize control plane signalling and user plane traffic via the core to the extent possible with reasonable complexity and effort.
  - It shall provide the mobile operator with the capabilities for control and monitoring of the femtocell network and services running over it necessary to fulfil market requirements and legal obligations, e.g. lawful interception.
  - It shall provide the local network operator with the capability of controlling and monitoring the femtocell network and services running over it necessary to ensure the security and operation of the local network and its services.
  - It should be compatible with 3GPP standards and in particular be backward compatible to Rel-8 capable UEs.
- Functional-level Requirements:
  - Femtocells shall be able to communicate with each other locally, i.e. without involvement of the mobile core network, the Internet or the broadband access link to either mobile core network or Internet.

- Connectivity between femtocells should be possible both using wired and wireless networking technologies.
- It shall be possible to utilize the full radio access capacity for local (UE⇔UE or UE⇔local network) communication, irrespective of resource constrains on the backhaul.

2.2.3 Architectural Aspects

When federating or delegating functionality from the mobile core network to the local femtocell network, there are two main options in principle: the functionality could be distributed over all femtocells or be centralized in one or more additional network entities; a femtocell gateway/controller. There is also the possibility to centralize functionality in one or more "master femtocells" that have more capabilities than normal femtocells, of course, but in this case these "master femtocells" should for the reason of argument be logically separated into a "normal femtocell" part and a femtocell gateway/controller part.

The advantages of distributing femtocell network functionality over femtocells are that this saves the cost of an additional network element, potentially results in a solution that is more scalable, resource-efficient and robust to failure and that can also more quickly react to events like changes in the backhaul connectivity, e.g. in the case of all-wireless networks of femtocells.

On the other hand, the advantages of centralizing functionality on a central local femtocell gateway are the lower complexity, the potential of implementing functionality in a way that works in a non-proprietary manner, i.e. with femtocells from different vendors, and the reduced management complexity and higher security that result from being able to centrally administer policies and security measures. For similar reasons, centralized controllers are popular in Enterprise WiFi deployments.

In the BeFEMTO System Architecture, the preferred solution is to centralize some of the functionality like local traffic offload, access control and energy management, while other functionality is distributed like routing and load balancing of femtocell traffic.

2.2.4 Architectural Alternatives for the Example of LIPA/SIPTO Support

The previous section has shown that the most suitable approach to handling mobile network functions locally within the femtocell network depends on the specific function. But even if one approach, say, a centralized approach, seems more suitable, there are typically several architecture alternatives. This section cannot provide an exhaustive discussion of architecture alternatives for every function. Instead, the example of LIPA and SIPTO, i.e. traffic breakout from the 3GPP domain to the local network and Internet, respectively, will be briefly discussed.

3GPP Rel-10 studied and specified the use of an L-GW co-located with the femtocell (HeNB) to provide Local IP Access to the local network and its services. The L-GW is essentially a local, small-scale P-GW, which maximizes the reuse of existing specifications. As a consequence, however, the L-GW on the HeNB needs to be connected over an S5 interface to an S-GW in the EPC, which the corresponding security and scalability implications. This choice also means that pre-Rel-10 UEs, which cannot establish concurrent PDN connections, cannot access local network services (via the L-GW) and operator services / the Internet (via a P-GW in the EPC) concurrently.

It is easy to see that the approach of co-locating an L-GW on each HeNB is somewhat suitable for standalone femtocells, but not appropriate for networks with multiple femtocells. The reason is not only the scalability and security implications of exposing the S5 interface, but also because mobility for breakout sessions cannot be elegantly solved: When a UE with an on-going LIPA session hands over to another standalone femtocell, it would have to continue using the previous femtocell's L-GW (= mobility anchor!). With only standard-compatible mechanisms, this would mean sending traffic via an S-GW in the EPC back to the currently serving femtocell. Short-cutting traffic instead would require a proprietary new interface and protocol.

As this issue has been identified early on in BeFEMTO, a solution has been proposed and presented ([3]) in Femto Forum (now Small Cell Forum) in which the HeNBs of the femtocell network all use a common L-GW that is not co-located on a HeNB but centralized on the new LFGW network entity. BeFEMTO has also helped initiate the 3GPP Rel-11 work item on LIPA Mobility and SIPTO at the Local Network (LIMONET) whose objectives includes studying architectures with centralized L-GW. BeFEMTO has contributed one of the two architecture alternatives studied in 3GPP TR 23.859 [5], which uses an L-GW that is on-path of the S1 interface (see Figure 9). Compared to the architecture alternative that foresees an off-path L-GW (see Figure 10), it has the advantage of not requiring a new interface between HeNBs and L-GW and to be able to combine L-GW-based traffic breakout with a different technique (Traffic Offload Function) for transparent breakout that is also working with pre-Rel-10 UEs.

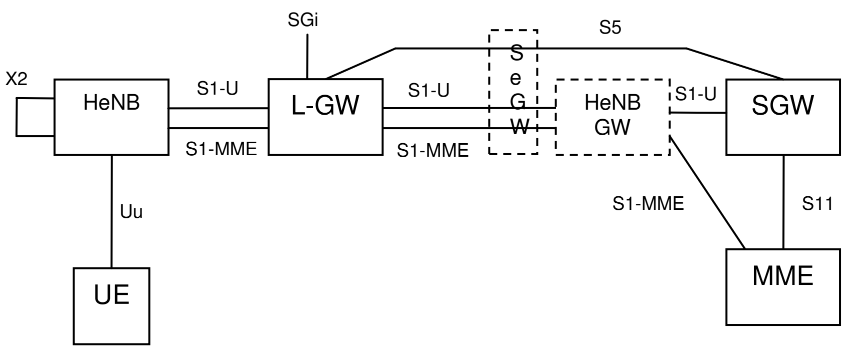


Figure 9: Standalone L-GW on the S1 path (EPS diagram for HeNB subsystem) [5].

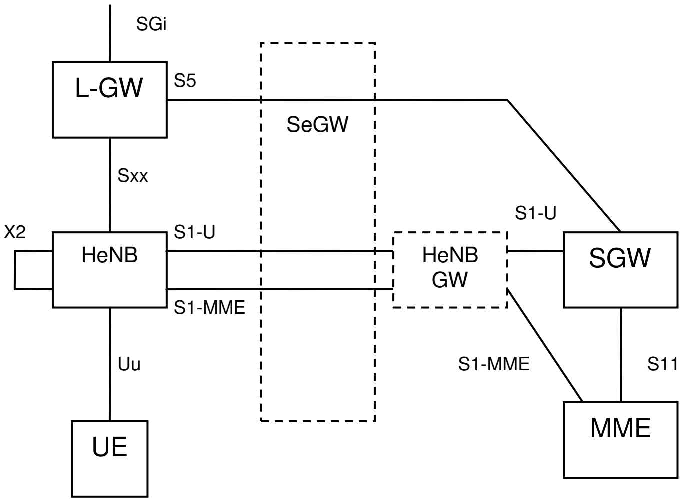


Figure 10: Stand-alone L-GW architecture (EPS diagram for HeNB subsystem) [5].

2.3 Architectural Considerations for Mobile Relays

2.3.1 Introduction

After the introduction of relay functionality in Rel-10, recent work is focusing on the introduction of mobility function for relay nodes as enabler for further deployment scenarios. The first relay feature is focusing on fixed relays introduced for coverage purposes, whereby the coverage of an eNB is extended by the introduction of a relay node, which consists in an eNB with wireless backhaul [5]. Such a device supports a very basic form of mobility, whereby the relay can be turned off and reconnected in another location of the network (so called nomadic mobility), under careful planning. In this regard, procedures have been defined for the relay start-up to handle that with minimal operational costs [6], but no handover is possible for the relay backhaul link.

Afterwards, other scenarios in which relay could be used have been considered, where also mobility of the relay node is playing a more significant role. The most relevant of such scenario, which gives good motivation for the introduction of mobility relay, is coverage extension to moving vehicles like high speed trains. In this case mobile relays can be installed on the train wagons to provide in-car coverage as (low power) wireless access point and this overcoming the high penetration loss an indoor UE would suffer otherwise.

2.3.2 Key Requirements

Different requirements have been derived for the mobile relay [8], here below the key ones are briefly summarized:

- Focus on scenarios in which both backhaul link spectrum and access link spectrum belong to the same operator, but support for other models shall not be precluded (different operators for access/backhaul links).
- Both in-band (when applicable) and out-band mobile relay can be considered, as defined in [9].

- Multi-RAT support is considered for mobile relays, with LTE backhaul but different air interface technologies (e.g. LTE/3G/2G) on the access link

2.3.3 Architectural Aspects

One of the main aspects requiring careful selection is the architecture of the mobile relay, as fixed relay architecture was selected without considering mobility aspects and may be unsuitable when mobility function is introduced.

One important principle for the architecture of the mobile relay is the selection of the mobility anchor point for the relay and for the UE [10]. To support relay mobility and trying to maximize the reuse of the existing procedures without incurring significant complexity, it seems beneficial to consider the PGW/SGW functions of the mobile relay as logically separated from the DeNB and reuse the S1 interface towards the DeNB. This way the mobile relay SGW can serve as mobility anchor point for mobile relay inter-DeNB handovers [8]. In case of the UE, the PGW/SGW reside in the core network and a full reuse of existing procedures can be taken as baseline solution, at expense of reduced routing efficiency the UE traffic traverses two sets of GWs on the core network before arriving at the relay). To further optimize the traffic routing for UEs connected via mobile relays, the PGW/SGW could be logically collocated with the mobile relay and reuse the SIPTO/LIPA principles.

2.3.4 Architecture Alternatives

Following the principles highlighted above, different architectures can be considered for mobile relays [11].

A first option (Alt.1 – see e.g. [12]) is shown in Figure 11 both S1 user and control plane for the UE are terminated at relay and EPC and packets of a UE served by the mobile relay are transported by the relay user plane EPS bearers. Existing handover procedures defined for UE can be reused for the relay itself with some enhancement/modification in case needed, and both UE and relay PDN connections are preserved during mobile relay handover. The baseline mobility procedure is therefore identical to inter-eNB handover defined in [7], with no additional signalling for UE handovers, i.e. the relay handover is transparent to the UE in both radio access and core network.

Another option worth considering is to reuse the fixed relay architecture (Alt.2 in [12]): in this case the mobile relay GW/PGW/SGW are located in the initial DeNB where the mobile relay attaches for normal operation and kept upon handover. Both S1 user and control plane as well as packet transport now involves also the relay GW in the initial DeNB. Existing handover procedures defined for UE can still be reused, and both UE and relay PDN connections are preserved during mobile relay handover. The mobility procedure is therefore identical to Alt.1 case, except the relay PGW/SGW is always located in the initial DeNB, with no additional signalling for UE handovers, i.e. the relay handover is transparent to the UE in both radio access and core network

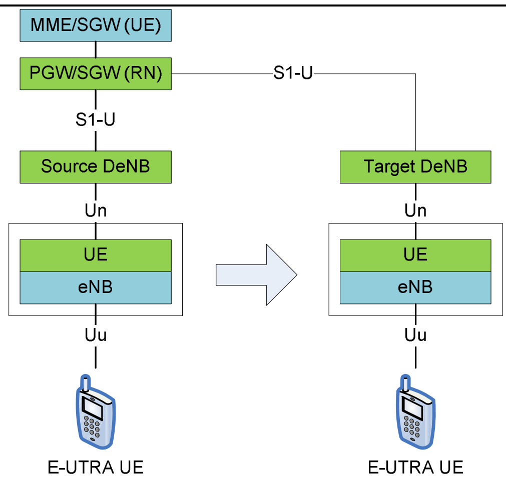


Figure 11: Alt. 1 relay architecture [11].

While Alt. 1 calls for simplicity and good reuse of existing procedures to support mobile relays, Alt.2 was optimized for fixed relay and further enhancements may be necessary to deal with mobility. One simple option, is to separate relay GW and PGW/SGW from initial DeNB and put them into a separate mobility anchor while still keeps the S1/X2 functionality. Another possible alternative proposed to enhance alt. 2, is to use two Rel-10 relays entities in the mobile relay device that attach to two neighbouring DeNBs, and can provide a similar function as RN handover [11] (the relay handover is realized without a relay mobility procedure and each UE performs the same inter-DeNB handover defined for fixed relays). Finally, another possible enhancement to Alt. 2 is the addition of mobile IP (PMIP) function, whereby user plane transmission of a UE under the mobile relay can be accomplished via IP forwarding (in the form of PMIP tunnelling).

Both Alt.1 and 2 support relay mobility reusing the existing Rel-8 handover principle. However the value of the relay GW in Alt. 2, which was introduce to terminate the S1 and X2 interfaces and to perform better QoS on the backhaul, seems vanishing when the relay moves far way.

For an extended discussion of both architecture alternatives see Section 6.3.1 and the references therein.

2.3.5 Interfaces and Procedural Aspects

Key scope of the X2 interface is to provide optimized mobility and to enable additional functionalities like support for SON and ICIC enhancements with neighbouring eNBs, mainly beneficial in case of stable deployments. Given added complexity, it seems therefore more recommendable to not consider X2 interface for mobile relay and focus only on basic mobility provided by the S1 interface. Among the possible alternatives, it is preferred to simply terminate the S1 interface directly at the MME, with the reuse of the S1 procedures [13]. This way the mobile relay can be assigned a tracking area independent of the DeNB, so that relay mobility does not require the relay to change tracking area when moving, which makes the relay mobility transparent to UEs connected to the relay node.

As far as the air interfaces are concerned, in fixed relays both access and backhaul links are LTE-based, and the backhaul is handled by a new interface called Un, which terminates at an upgraded eNB acting as donor for the relay (also named donor eNB - DeNB). However, in case of mobile relay, as the main scope is to provide realisable and high quality services on-board high-speed train carriages, 3GPP felt the need to not preclude support for additional or different RATs in the access link, like GSM or UMTS. By using LTE as sole backhaul, limits the standardization effort and ease the deployment and optimization effort for high-speed train coverage.

References

[2] BeFEMTO D2.2, “The BeFEMTO System Architecture,” ICT 248523 FP7 BeFEMTO project, December 2011.

[3] BeFEMTO D2.1, “Description of baseline reference systems, use cases, requirements, evaluation and impact on business model”, ICT 248523 FP7 BeFEMTO project, December 2010.

[4] Frank Zdarsky, Gottfried Punz and Stefan Schmid, “Enterprise Femtocell Networks – Architecture Proposal”, presented at Femto Forum #14, San Francisco, September 2010.

[5] 3GPP TR 23.859, “LIPA Mobility and SIPTO at the Local Network (Release 11)”.

[6] 3GPP TR 36.806, "Relay architectures for EUTRA (LTE-Advanced)”.

[7] 3GPP TS 36.300, “Overall E-UTRAN Description”.

[8] 3GPP TR 36.416, “Mobile Relay for E-UTRA”.

[9] 3GPP TR 36.814, “Further advancements for E-UTRA physical layer aspects”.

[10] R3-113020, “The location of the mobility anchor for Mobile Relays”, Qualcomm Incorporated.

[11] R3-120486, “Report email#10: Mobile architecture options”, CATT (rapporteur).

[12] R3-120296, “Impact of mobility support for the candidate mobile relay architectures” , Qualcomm Incorporated.

[13] R3-120297, “The termination of the X2 and S1 interfaces for Mobile Relays”, Qualcomm Incorporated.

3. System-level Simulator Calibration Campaign

3.1 Introduction

In order to facilitate the comparison between the partners' contributions, Work Package 3 (WP3) decided to trigger a calibration of the downlink system level simulators used by each partner, thus enforcing the consistency and coherency of BeFEMTO outputs. The results of the static macrocell-only calibration were given in BeFEMTO D2.1 [14]. This section extends them by adding static calibration results of the classical femtocell models as well as updated results of one dynamic calibration in a macrocell-only environment (initial results could be found in BeFEMTO IR 3.3 [15]). In addition, system-level simulation results for various antenna configurations are provided by Sagemcom Energy & Telecom for the partners in order for them to derive the expected performance when using MIMO if their tools only support SISO transmission mode.

3.2 System-Level Simulator Calibration

The main assumptions and equations used by the partners for the static and dynamic calibration of their Monte-Carlo-based downlink system-level simulators can be found in BeFEMTO IR3.3 [15]. These are fully compliant with 3GPP TR 25.814 [16] and TR 36.814 (Model 1) [17], while the femtocell transmission power has been lowered to meet the BeFEMTO target of 10dBm. For each set-up scenario, these assumptions are recalled as well as the metric of interest.

3.2.1 Static Calibration

Two models are commonly used when evaluating femtocell in an urban environment [17]: the Dual-Stripes model and the 5x5 Grid. The former takes into consideration the exact number of walls separating one femtocell from one user equipment when computing the pathloss, while the latter simplifies the computation by dropping this number but increasing the shadowing standard deviation. Dual-Stripes model is usually used when investigating macro-femto scenarios whereas the 5x5 grid adds a strong femto-femto interference component [18].

3.2.1.1 Main Simulation Parameters

One common macrocell layout has been used which parameters are given in Table 1. On top of this layout, Closed Subscriber Group (CSG) femtocells have been dropped according to one of the classical model under a co-channel deployment. Macrocell and femtocell user equipments have the same parameters, which are given in Table 2.

System Parameters	Value
Carrier Frequency	2GHz
Bandwidth	10MHz

Macrocell Layout			Value
Inter-Site Distance			500m
Number of Sites			7
Number of Sectors per Site			3
Transmission Power (Sector)			46dBm
Antenna	Boresight Gain		14dBi
	Front to Back Ratio		25dB
	Angle Spread at -3dB		70°
	Gain		See [15], (6.1)
Pathloss			See [15], Table 6-8
Shadowing	Standard Deviation		8dB
	Correlation	Inter-Site	0.5
		Intra-Site	1
Number of UEs per Sector			10 (uniform drop)

Table 1: System-Level Simulation Assumptions (Static, Macrocell).

For the static calibration, the statistics of the geometrical factor (G-Factor) associated to the macrocell users and the femtocell users have been computed as the metric of interest. The G-Factor represents the Signal to Interference-plus-Noise Ratio (SINR) experienced by one user when only long term parameters, namely pathloss, shadowing and antenna gains, are considered in the budget link affecting the transmission power of a serving/interfering cell.

User Equipment	Value
Antenna Gain (omni)	0dBi
Noise Figure	9dB
Thermal Noise Density	-174dBm/Hz

Table 2: System-Level Simulation Assumptions (Static, User Equipment).

3.2.1.2 5x5 Grid Results

The parameters associated to the 5x5 Grid model are given in Table 3. One drop example of such macro-femto heterogeneous network (HetNet) deployment is depicted in Figure 12.

Femtocell Layout		Value
Cluster Model		5x5 Grid
Number of Clusters		21 (uniform drop)
Number of Floors per Cluster		1
Number of Blocks per Floor		25 (5 x 5)
Block size		10m x 10m
Femtocell Deployment Ratio per Block		20% (uniform drop)
External Wall Attenuation		20dB
Femtocell Transmission Power		10dBm
Antenna Gain (omni)		0dBi
Pathloss		See [15], Table 6-9
Shadowing	Standard Deviation	10dB
	Correlation	0
Number of UEs per Femtocell		1 (uniform drop within one block containing one femtocell)

Table 3: System-Level Simulation Assumptions (Static, 5x5 Grid).

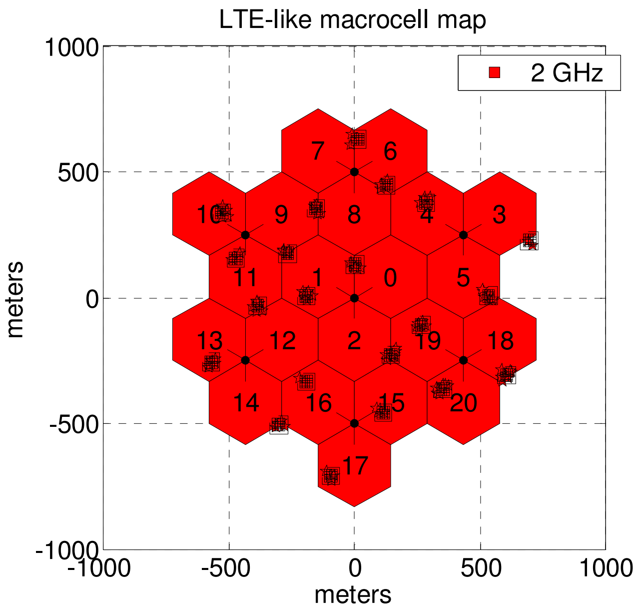


Figure 12: 5x5 Grid HetNet Deployment.

Average, median, 5-percentile and the Cumulative Distributed Function (CDF) of the G-Factor for both macrocell and femtocell users are given in the following.

System-Level Simulator Femtocell Calibration

Layout	Hexagonal 7 3-sector sites with wrap-around - 21 5x5 Grids (20% deployment)
Bandwidth	10MHz
Transmit power	46dBm (Macro)
	10dBm (Femto)

Macrocell G-factor (dB)

	CEA	DOCOMO	Sagemcom	UOLU	UniS	AVERAGE
Average	5,88	5,29	4,54	4,44	5,31	5,09
Median	5,17	4,01	3,63	3,21	5,02	4,21
5-percentile	-4,17	-2,44	-3,48	-4,04	-3,99	-3,63

Femtocell G-factor (dB)

	CEA	DOCOMO	Sagemcom	UOLU	UniS	AVERAGE
Average	3,85	4,59	4,02	3,46	3,46	3,88
Median	3,38	3,54	3,81	3,07	2,53	3,26
5-percentile	-17,32	-18,56	-20,27	-20,07	-17,67	-18,78

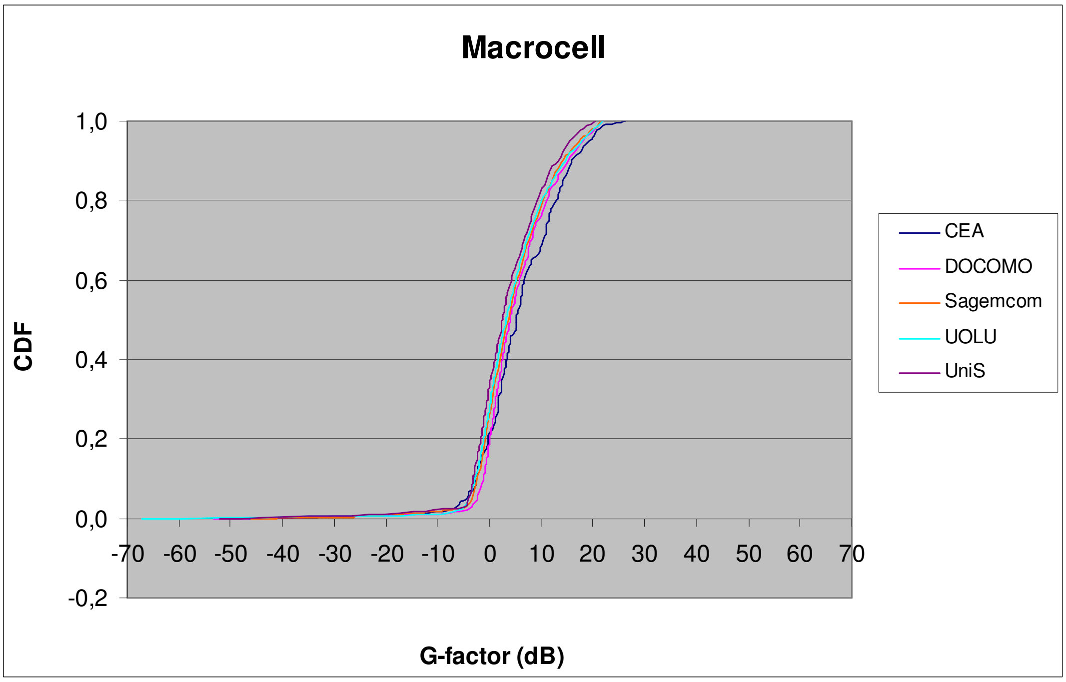


Figure 13: CDF comparison of the macrocell G-Factor among WP3 partners.

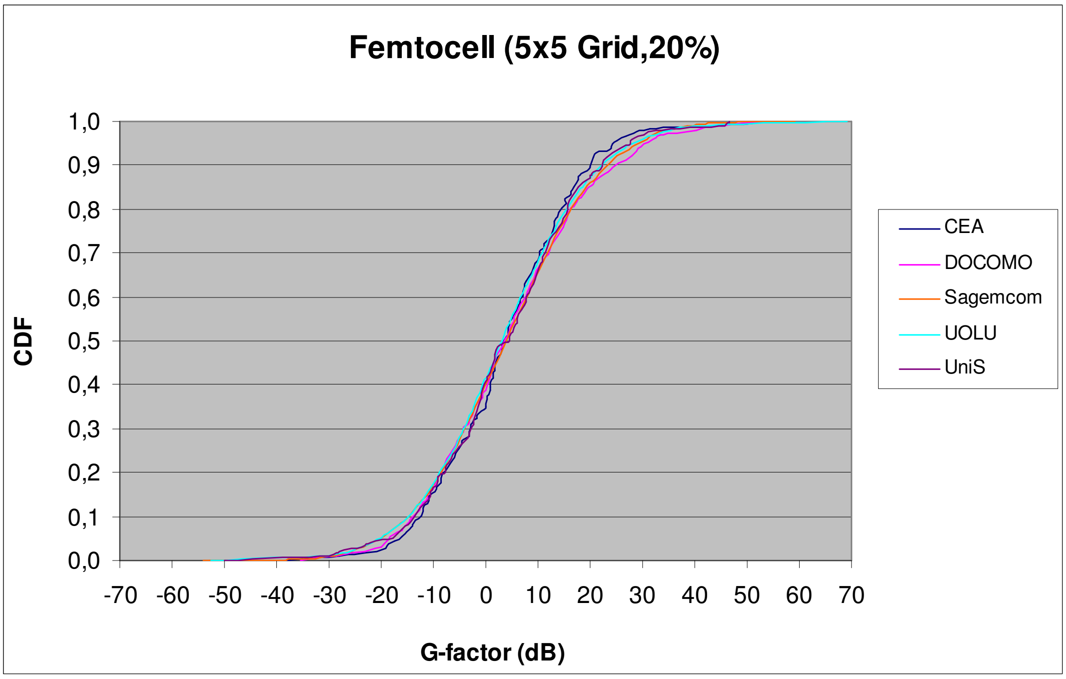


Figure 14: CDF comparison of the femtocell G-Factor among WP3 partners.

3.2.1.3 Dual-Stripes Results

The parameters associated to the Dual-Stripes model are given in Table 4. One drop example of such macro-femto HetNet deployment is depicted in Figure 15.

Femtocell Layout		Value
Cluster Model		Dual-Stripes
Number of Clusters		21 (uniform drop)
Number of Floors per Cluster		6
Number of Blocks per Floor		40 (2 stripes of 2 x 10)
Block size		10m x 10m
Femtocell Deployment Ratio per Block		10% (uniform drop)
External Wall Attenuation		20dB
Internal Wall Attenuation		5dB
Femtocell Transmission Power		10dBm
Antenna Gain (omni)		0dBi
Pathloss		See [15], Table 6-10
Shadowing	Standard Deviation	4dB

Correlation	0
Number of UEs per Femtocell	1 (uniform drop within one block containing one femtocell)

Table 4: System-Level Simulation Assumptions (Static, Dual-Stripes).

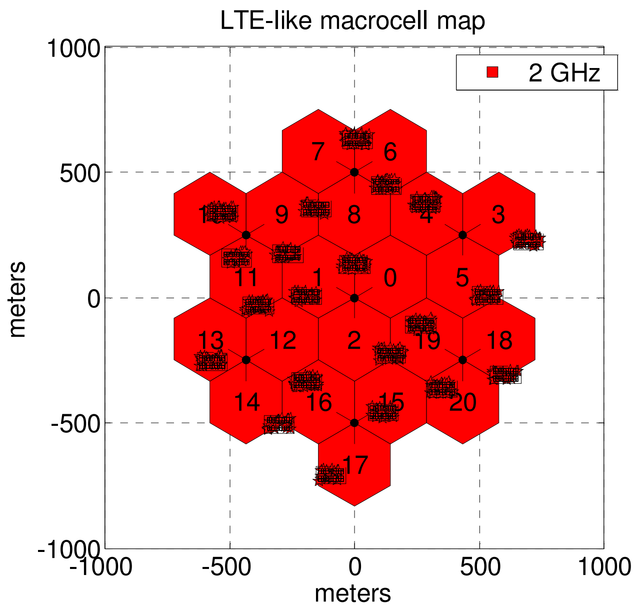


Figure 15: Dual-Stripes HetNet Deployment.

Average, median, 5-percentile and the CDF of the G-Factor for both macrocell and femtocell users are given in the following.

System-Level Simulator Femtocell Calibration

Layout	Hexagonal 7 3-sector sites with wrap-around - 21 Dual-Stripes (10% deployment)
Bandwidth	10MHz
Transmit power	46dBm (Macro)
	10dBm (Femto)

Macrocell G-factor (dB)

	CEA	DOCOMO	Sagemcom	UOLU	UniS	AVERAGE
Average		5,52	4,64	4,37		4,84
Median		4,57	3,37	3,16		3,70
5-percentile		-2,83	-3,09	-3,99		-3,30

Femtocell G-factor (dB)

	CEA	DOCOMO	Sagemcom	UOLU	UniS	AVERAGE
Average		12,28	12,23	11,38		11,96
Median		12,21	12,05	11,16		11,80
5-percentile		-6,18	-5,50	-5,19		-5,62

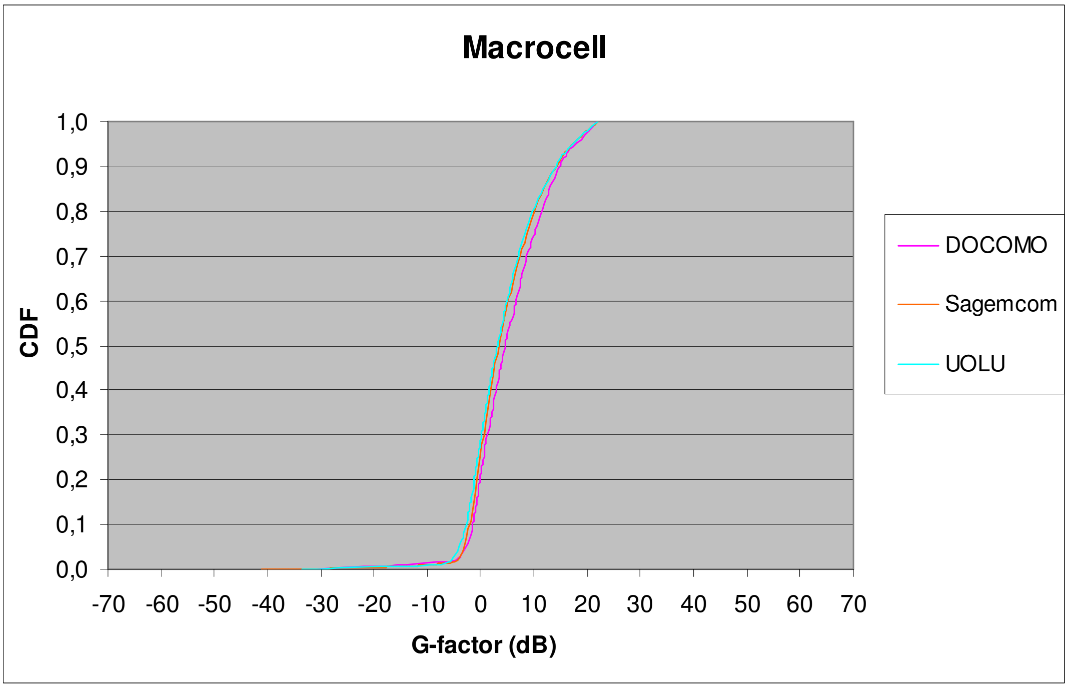


Figure 16: CDF comparison of the macrocell G-factor among WP3 partners.

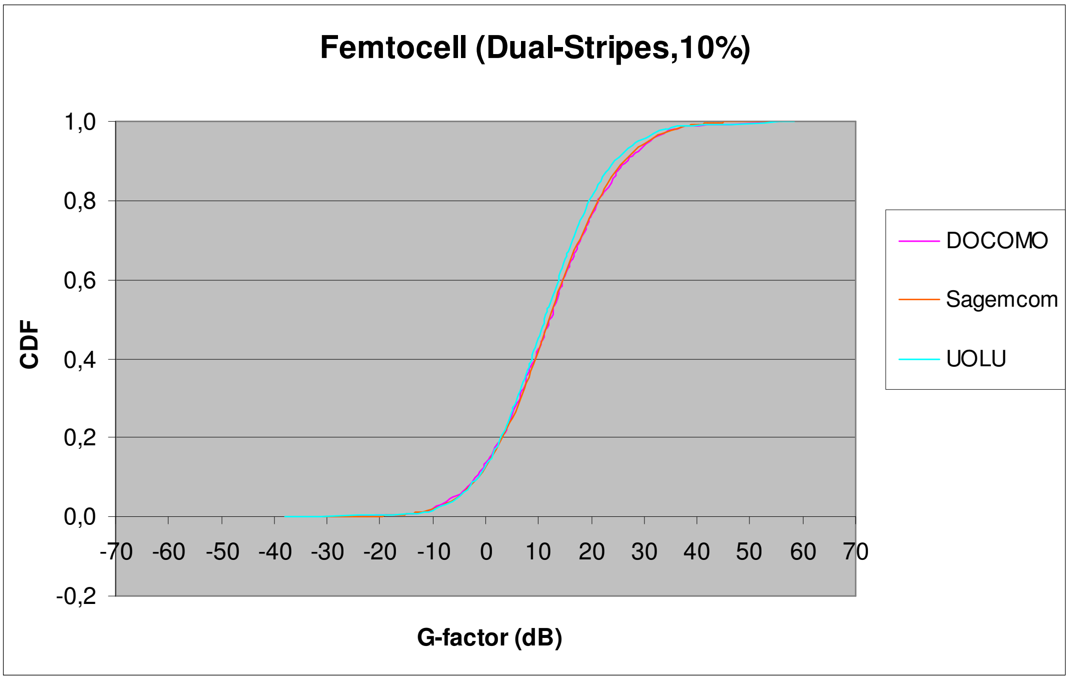


Figure 17: CDF comparison of the femtocell G-factor among WP3 partners.

3.2.1.4 Conclusion

The results seem to be inline among the partners, validating the layout and deployment assumptions as well as the pathloss equations for the various femtocell models: 5x5 Grids presents a high level of femto-to-femto interference, while the Dual-Stripes attenuates this effect due to the explicit modelling of the exact number of walls separating two HeNBs.

3.2.2 Dynamic Calibration

3.2.2.1 Main Simulation Parameters

For dynamic system-level simulation, the fast fading over the time and the scheduling at each Time Transmit Interval (TTI) are considered which allow the testing and performance assessment of radio resource management algorithms. As the femtocell models were calibrated thanks to the static calibration effort (see previous subsection), it was decided to perform a macrocell only dynamic calibration. For the fast fading, the SCM model [19] was used as a common model despite it being valid only up to 5MHz channel bandwidth.

The same macrocell network configuration parameters as the ones used in the static case apply here. The only differences are that 19 sites were considered instead of 7 and that wrap-around can be turned-off to speed simulations. In such case, only the 3 sectors of the central cell will be of interest, while the other sectors will be assumed to be fully loaded (maximum transmit power, no mobile dropped).

System Parameters	**Value**
Carrier Frequency	2GHz
Bandwidth	10MHz
Time Transmit Interval	1ms

Macrocell Layout			**Value**
Inter-Site Distance			500m
Number of Sites			19
Number of Sectors per Site			3
Transmission Power (Sector)			46dBm
Number of Transmit Antennas			1
Antenna	Boresight Gain		14dBi
	Front to Back Ratio		25dB
	Angle Spread at -3dB		70°
	Gain		See [15], (6.1)
Pathloss			See [15], Table 6-8
Shadowing	Standard Deviation		8dB
	Correlation	Inter-Site	0.5
		Intra-Site	1

Number of UEs per Sector	10 (uniform drop)
Scheduler	Round Robin
Resource Allocation per TTI	whole bandwidth

User Equipment		**Value**
Number of Receive Antennas		2
Antenna	Gain (omni)	0dBi
	Spacing (wavelength)	0.5λ
Noise Figure		9dB
Thermal Noise Density		-174dBm/Hz
Speed		3km/h
Receiver		MRC/MMSE

Fast Fading	**Value**
Channel Profile	SCM UMa
Line of Sight (Macro only)	Not considered

Table 5: System-Level Simulation Assumptions (Dynamic).

To ease the calibration phase, a simple 1x2 SIMO context has been adopted with Maximum Ratio Combining (MRC) or Minimum Mean Square Error (MMSE) receiver (both offers equivalent performance in 1x2). Full buffer traffic model, truncated Shannon bound and Round-Robin scheduling (in a TDMA fashion, no need of feedback) have been preferred in order to limit the possible causes of misalignment among the partners. All the bandwidth is allocated to one user at each TTI. Table 5 summarizes the major assumptions followed by WP3 partners.

Mobile and cell throughputs statistics are gathered. These quantities are computed relying on the truncated Shannon bound.

3.2.2.2 Truncated Shannon bound & Compression

Based on the SINR obtained through compression at the TTI t, the spectral efficiency (b/s/Hz) of a scheduled user can be obtained using the truncated Shannon bound given by:

$$\eta_t = \begin{cases} \min(\eta_{\max}, \alpha \log_2(1+SINR) & SINR_t > SINR_{\min} \\ 0 & SINR_t \le SINR_{\min} \end{cases} \quad (1)$$

where $\alpha = 0.6$, $\eta_{\max} = 4.4$ and $SINR_{\min}(dB) = -10$ for the downlink.

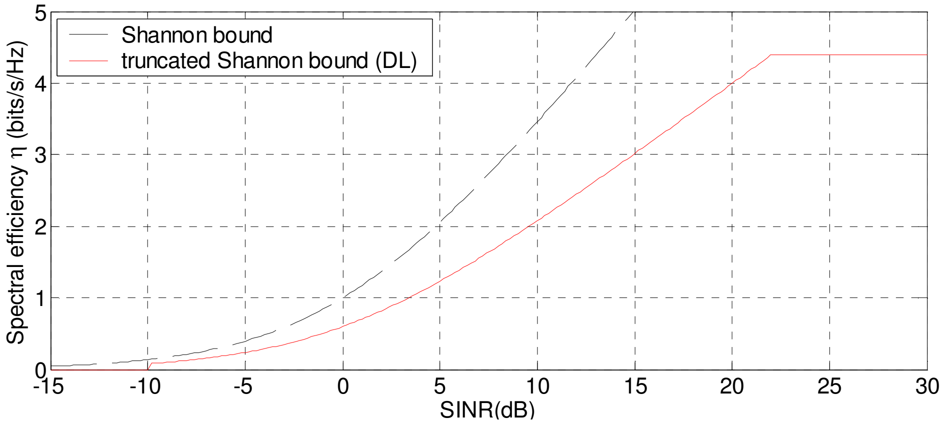


Figure 18: Truncated Shannon bound in downlink

The mobile throughput in b/s is easily derived by multiplying the spectral efficiency by the allocated bandwidth B (in Hz).

$$mthpt_t = \eta_t B \tag{2}$$

Regarding compression, the Shannon capacity was used to ease the computation. If $SINR(n)$ denotes the SINR computed on the subcarrier n (using MRC or MMSE receiver) then the compressed SINR is given by:

$$SINR = I^{-1}\left(\frac{1}{N}\sum_{n=1}^{N} I\left(SINR(n)\right)\right) \tag{3}$$

with the following compression function:

$$I(x) = \log_2(1+x) \tag{4}$$

3.2.2.3 Results

The following tables depicts the calibration results among WP3 partners for macrocell network only based on an hexagonal 19 3-sector layout with wrap-around and a 10 MHz bandwidth.

System-Level Simulator Dynamic Macrocell Calibration

Layout	Hexagonal 19 3-sector sites with wrap-around
Bandwidth	10MHz
Transmit power	46dBm (Macro)
Channel Model	SCM
UEs per cell	10
Scheduler	Round Robin, 1UE per TTI

Macrocell Throughput (Mbps)

	CEA	DOCOMO	Sagemcom	UOULU	UniS	AVERAGE
Average	13,81		13,84	14,66	12,87	13,79
5-percentile	9,01		9,58	9,31	8,65	9,14

Mobile Throughput (Mbps)

	CEA	DOCOMO	Sagemcom	UOULU	UniS	AVERAGE
Average	1,33		1,38	1,47	1,29	1,37
5-percentile	0,41		0,42	0,35	0,39	0,39

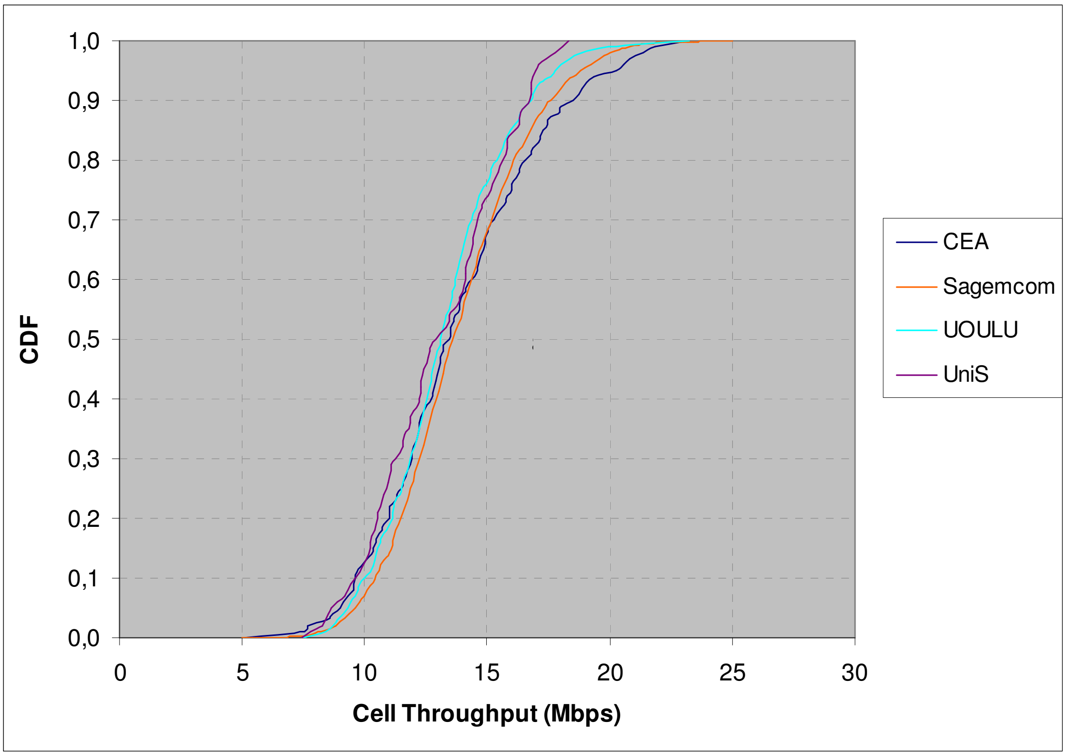


Figure 19: CDF comparison of the cell throughput among WP3 partners.

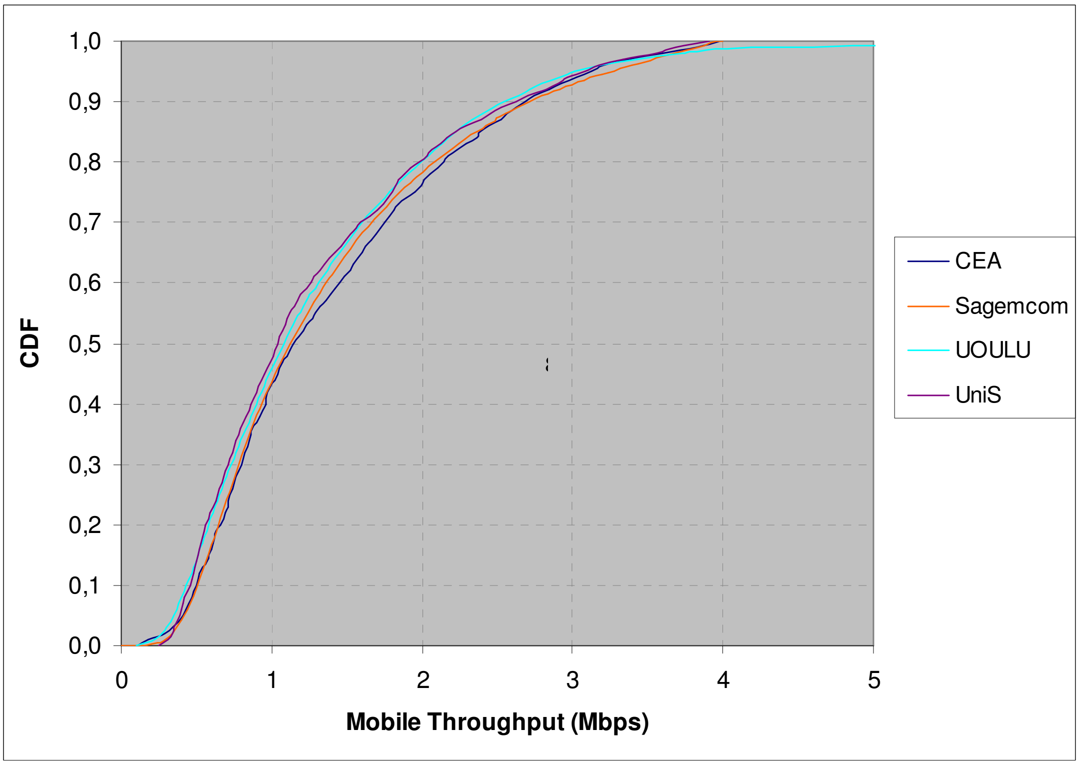


Figure 20: CDF comparison of the mobile throughput among WP3 partners.

3.2.2.4 Conclusion

Alignment in the CDF of the dynamic results is not as clear as for the static ones for the cell throughput, while the mobile throughput results seem to be more inline. Regarding the average values, they do not present a big deviation on both statistics among the partners.

3.3 SISO to MIMO Scaling Factor

This subsection provides LTE HetNet system-level simulation results for SISO and various MIMO configurations obtained by Sagemcom Energy & Telecom for WP4. Indeed, this collection of results may help partners in deriving expected performance when using MIMO if their tools only support SISO transmission mode.

Average spectral efficiencies at the mobile side and average cell throughputs are given in suburban and urban environment for macrocell and femtocell. The House model was used for suburban deployment [20]. This model is a simple 1 floor 12m x 12m block encompassing one femtocell and having the same parameters (pathloss, shadowing) as the Dual-Stripes without (obviously) internal walls to consider. The House model is particularly useful to derive the femtocell performance with very limited interference coming from the macrocell. Dual-Stripes model adds intermediate level of femto-femto interference while the 5x5 grid model adds strong level of femto-femto interference.

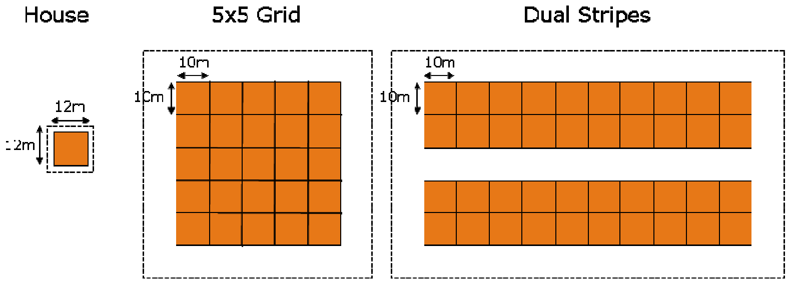


Figure 21: Classical femtocell model.

The SCME model [21] was used for the fast fading, as this model supports bandwidth higher than 5MHz. At each TTI, the whole bandwidth was allocated to one mobile based on a proportional fair scheduler. Downlink transmissions were performed using Release 9 transmission mode 1 (Single Antenna port) in SISO configuration and Release 9 transmission mode 4 (Closed Loop Spatial Multiplexing) in MIMO configuration.

In addition three types of receiver were investigated at the mobile side: the classical MMSE, the MMSE with Interference Rejection Combining (IRC) of the most dominant interferer and the MMSE with perfect cancellation of the spatial streams (only for MIMO configuration).

3.3.1 Main Simulation Parameters

The following tables summarize the main system-level simulation assumptions.

3.3.1.1 Suburban deployment

System Parameters	Value
Carrier Frequency	2GHz
Bandwidth	10MHz
Time Transmit Interval	1ms

Macrocell Layout			Value
Inter-Site Distance			1732m
Number of Sites			7
Number of Sectors per Site			3
Transmission Power (Sector)			46dBm
Antenna	Boresight Gain		14dBi
	Front to Back Ratio		25dB
	Angle Spread at -3dB		70°
	Gain		See [15], (6.1)
	Spacing (wavelength)		10λ
Pathloss			See [15], Table 6-8
Shadowing	Standard Deviation		8dB
	Correlation	Inter-Site	0.5
		Intra-Site	1
Channel Profile			SCME SMa
Line of Sight			Not considered
Number of UEs per Sector			10 (uniform drop)
Scheduler			Proportional Fair
Resource Allocation per TTI			whole bandwidth
RI/CQI/PMI Reporting Period in TTI			5TTI
RI/CQI/PMI Processing Delay in TTI			1 (report issued at TTI by the mobile is available at TTI+1 at the cell)

Table 6: Suburban Macrocell Assumptions.

Femtocell Layout	Value
Cluster Model	House
Number of Clusters	21 (uniform drop)
Number of Floors per Cluster	1

Number of Blocks per Floor		1
Block size		12m x 12m
Femtocell Deployment Ratio per Block		100% (uniform drop)
External Wall Attenuation		20dB
Femtocell Transmission Power		10dBm
Antenna Gain (omni)		0dBi
Pathloss		See [15], Table 6-10
Shadowing	Standard Deviation	4dB
	Correlation	0
Number of UEs per Femtocell		1 (uniform drop within one block containing one femtocell)

Table 7: Suburban Femtocell Assumptions.

3.3.1.2 Urban deployment

System Parameters		**Value**
Carrier Frequency		2GHz
Bandwidth		10MHz
Time Transmit Interval		1ms
Macrocell Layout		**Value**
Inter-Site Distance		500m
Number of Sites		7
Number of Sectors per Site		3
Transmission Power (Sector)		46dBm
Antenna	Boresight Gain	14dBi
	Front to Back Ratio	25dB
	Angle Spread at -3dB	70°
	Gain	See [15], (6.1)
	Spacing (wavelength)	10λ
Pathloss		See [15], Table 6-8
Shadowing	Standard Deviation	8dB

Correlation	Inter-Site	0.5
	Intra-Site	1
Channel Profile		SCME UMa
Line of Sight		Not considered
Number of UEs per Sector		10 (uniform drop)
Scheduler		Proportional Fair
Resource Allocation per TTI		whole bandwidth
RI/CQI/PMI Reporting Period in TTI		5TTI
RI/CQI/PMI Processing Delay in TTI		1 (report issued at TTI by the mobile is available at TTI+1 at the cell)

Table 8: Urban Macrocell Assumptions.

Femtocell Layout		**Value**
Cluster Model		Dual-Stripes
Number of Clusters		21 (uniform drop)
Number of Floors per Cluster		6
Number of Blocks per Floor		40 (2 stripes of 2 x 10)
Block size		10m x 10m
Femtocell Deployment Ratio per Block		10% (uniform drop)
External Wall Attenuation		20dB
Internal Wall Attenuation		5dB
Femtocell Transmission Power		10dBm
Antenna Gain (omni)		0dBi
Pathloss		See [15], Table 6-10
Shadowing	Standard Deviation	4dB
	Correlation	0
Number of UEs per Femtocell		1 (uniform drop within one block containing one femtocell)

Table 9: Urban Dual-Stripes Femtocell Assumptions.

Femtocell Layout		Value
Cluster Model		5x5 Grid
Number of Clusters		21 (uniform drop)
Number of Floors per Cluster		1
Number of Blocks per Floor		25 (5 x 5)
Block size		10m x 10m
Femtocell Deployment Ratio per Block		10% (uniform drop)
External Wall Attenuation		20dB
Femtocell Transmission Power		10dBm
Antenna Gain (omni)		0dBi
Pathloss		See [15], Table 6-9
Shadowing	Standard Deviation	10dB
	Correlation	0
Number of UEs per Femtocell		1 (uniform drop within one block containing one femtocell)

Table 10: Urban 5x5 Grid Femtocell Assumptions.

3.3.1.3 User Equipment

In all scenarios, the user equipments have the same parameters given as follows.

User Equipment		Value
Antenna	Gain (omni)	0dBi
	Spacing (wavelength)	0.5λ
Noise Figure		9dB
Thermal Noise Density		-174dBm/Hz
Speed		3km/h

Table 11: User Equipment Assumptions.

3.3.2 MMSE Results

Antenna configuration		1x1	2x2	4x2	4x4
Mobile	Macro Spectral Efficiency (b/s/Hz)	1.30	2.10	2.47	3.79
	Femto Spectral Efficiency (b/s/Hz)	3.95	5.14	6.58	8.18

Cell	Macro Throughput (Mb/s)	12.06	20.20	21.41	32.93
	Femto Throughput (Mb/s)	35.58	46.22	59.27	73.58

Table 12: Suburban House (MMSE).

Antenna configuration		1x1	2x2	4x2	4x4
Mobile	Macro Spectral Efficiency (b/s/Hz)	1.24	2.01	2.30	3.59
	Femto Spectral Efficiency (b/s/Hz)	2.23	3.22	3.87	4.95
Cell	Macro Throughput (Mb/s)	11.73	19.88	20.39	30.84
	Femto Throughput (Mb/s)	20.00	28.95	34.82	44.57

Table 13: Urban Dual-Stripes (MMSE).

Antenna configuration		1x1	2x2	4x2	4x4
Mobile	Macro Spectral Efficiency (b/s/Hz)	1.22	1.98	2.27	3.55
	Femto Spectral Efficiency (b/s/Hz)	1.84	2.73	3.31	4.31
Cell	Macro Throughput (Mb/s)	11.73	19.55	19.87	29.39
	Femto Throughput (Mb/s)	16.52	24.55	29.75	38.83

Table 14: Urban 5x5 Grid (MMSE).

3.3.3 MMSE-IRC Results

Antenna configuration		1x1	2x2	4x2	4x4
Mobile	Macro Spectral Efficiency (b/s/Hz)	1.39	2.35	2.69	4.23
	Femto Spectral Efficiency (b/s/Hz)	4.00	5.24	6.58	8.50
Cell	Macro Throughput (Mb/s)	12.51	21.61	23.00	36.97
	Femto Throughput (Mb/s)	35.97	47.17	59.25	76.46

Table 15: Suburban House (MMSE-IRC).

Antenna configuration		1x1	2x2	4x2	4x4
Mobile	Macro Spectral Efficiency (b/s/Hz)	1.29	2.21	2.48	3.96
	Femto Spectral Efficiency (b/s/Hz)	2.37	3.64	4.27	5.66
Cell	Macro Throughput (Mb/s)	11.96	20.18	21.88	33.86
	Femto Throughput (Mb/s)	21.28	32.79	38.40	50.90

Table 16: Urban Dual-Stripes (MMSE-IRC).

Antenna configuration		1x1	2x2	4x2	4x4
Mobile	Macro Spectral Efficiency (b/s/Hz)	1.28	2.20	2.47	3.95
	Femto Spectral Efficiency (b/s/Hz)	1.85	2.99	3.56	4.82
Cell	Macro Throughput (Mb/s)	12.06	20.51	21.51	34.70
	Femto Throughput (Mb/s)	16.59	26.91	31.98	43.40

Table 17: Urban 5x5 Grid (MMSE-IRC).

3.3.4 MMSE-Perfect Spatial Interference Cancellation Results

Antenna configuration		2x2	4x2	4x4
Mobile	Macro Spectral Efficiency (b/s/Hz)	2.61	3.04	5.40
	Femto Spectral Efficiency (b/s/Hz)	7.24	8.23	16.09
Cell	Macro Throughput (Mb/s)	23.27	24.72	40.10
	Femto Throughput (Mb/s)	65.17	74.10	144.83

Table 18: Suburban House (MMSE-Perfect Spatial Interference Cancellation).

Antenna configuration		2x2	4x2	4x4
Mobile	Macro Spectral Efficiency (b/s/Hz)	2.52	2.88	5.19
	Femto Spectral Efficiency (b/s/Hz)	4.12	5.28	9.46
Cell	Macro Throughput (Mb/s)	22.78	23.37	37.19
	Femto Throughput (Mb/s)	37.08	47.55	85.11

Table 19: Urban Dual-Stripes (MMSE-Perfect Spatial Interference Cancellation).

Antenna configuration		2x2	4x2	4x4
Mobile	Macro Spectral Efficiency (b/s/Hz)	2.48	2.85	5.13
	Femto Spectral Efficiency (b/s/Hz)	3.44	4.30	7.68
Cell	Macro Throughput (Mb/s)	22.30	22.48	37.17
	Femto Throughput (Mb/s)	30.95	38.65	69.08

Table 20: Urban 5x5 Grid (MMSE-Perfect Spatial Interference Cancellation).

3.3.5 Conclusion

As expected, femtocell users really benefits from the high SINR they experienced enabling higher rank MIMO transmission mode to be used. If femto-femto interference is avoided (or greatly reduced) at the bandwidth or subband level, the femtocell suburban results should be used for SISO to MIMO extrapolation results. Otherwise, urban results can be used as well but they are subject to higher femto-femto interference that neither the IRC nor the perfect spatial cancellation process can mitigate when the whole bandwidth is allocated to one user.

References

[14] BeFEMTO D2.1, "Description of baseline reference systems, use cases, requirements, evaluation and impact on business model", ICT 248523 FP7 BeFEMTO project, December 2010.

[15] BeFEMTO IR3.3, "Promising Interference and Radio Management Techniques for Indoor Standalone Femtocells", ICT 248523 FP7 BeFEMTO project, December 2010.

[16] 3GPP TR 25.814, "Physical Layer Aspects for Evolved UTRA (Release 7)," v7.1.0, September 2006.

[17] 3GPP TR 36.814, "Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects (Release 9)", v9.0.0, March 2010.

[18] M. Maqbool, M. Lalam, and T. Lestable, "Comparison of femto cell deployment models for an interference avoidance technique," in *Proc. of Future Network & Mobile Summit (FUNEMS'11)*, June 2011.

[19] 3GPP TR 25.996, "Spatial channel model for Multiple Input Multiple Output (MIMO) simulations (Release 9)", v9.0.0, December 2009.

[20] Femto Forum, "Interference management in OFDMA femtocells," White Paper, Feb. 2010. Available online: www.femtoforum.org.

[21] D. S. Baum, J. Hansen, G. D. Galdo, M. Milojevic, J. Salo, and P. Kysti, "An Interim Channel Model for Beyond-3G Systems Extending the 3GPP Spatial Channel Model (SCM)," in *Proc. of IEEE VTC Spring*, May 2005.

4. Standalone Femtocells

4.1 Next Generation RF techniques

4.1.1 Definition of LTE-Advanced RF specifications

4.1.1.1 Description of the Scheme

The identification of the RF technical requirements represents the first step to follow in the RF front-end research. The technical RF requirements for LTE-A femtocell hardware are not defined in 3GPP [22] but several LTE (Rel. 8) parameters could be taken into account due to the fact that LTE-A must be LTE backward compatible. In [23], it is recommended that whenever appropriate, LTE-A RF requirements shall be based on the re-use of existing LTE Rel. 8 structure in a "building block" manner. However some others have to be carefully deduced.

Table 21 summarizes the main technical requirements for the RF front-end, which are product of the research done in BeFEMTO. These are grouped in three categories, depending on the RF part affected: the component carrier aggregation, the transmitter and the receiver ones. More detailed information can be found in [24].

RF technical requirements	Requirement	Value
Component carrier aggregation	**Channel raster**	100KHz
	Channel Bandwidth (MHz)	1.4, 3, 5, 10, 15, 20
	Additional Transmission Bandwidth configurations	102, 104, 106, 108, 110RBs
	Carrier spacing between contiguously aggregated CCs	Integer multiple of 300KHz
Transmitter characteristics	**Frequency error**	±0.25ppm
	Maximum Output Power	+10dBm
	Transmitter OFF power (TDD)	< -85dBm/MHz
	Error Vector Magnitude (EVM)	@ 64QAM → EVM < 8%
	Adjacent Carrier Leakage Ratio (ACLR)	Less stringent of -50dBm/MHz or 45dBc
	Operating band unwanted emissions (Spectrum Emission Mask)	See [24]
	Transmitter spurious emissions	See [24]

RF technical requirements	Requirement	Value
Receiver characteristics	**Reference sensitivity level**	See [24]
	In channel selectivity (ICS)	See [24]
	Adjacent Channel Selectivity (ACS) and narrow-band blocking	See [24]
	Blocking	See [24]
Transmitter/Receiver characteristics	**Local oscillator phase noise**	< 1ºrms (15KHz to 20MHz)
	Local oscillator step size	300KHz

Table 21: Summary of LTE-A RF front-end specifications.

4.1.1.2 Contribution to BeFEMTO System Concept and Objectives

The identification of the RF technical requirements is the first step on the research on new RF hardware solutions on BeFEMTO. Due to LTE-A requirements have not been yet defined on 3GPP, some of these requirements have been defined on the basis of LTE, while some other ones have been deduced, which represents the step further given in BeFEMTO.

References

[22] 3GPP TR 36.912 V9.3.0 (2010-06), "Feasibility study for Further Advancements for E-UTRA (LTE-Advanced) (Release 9)".

[23] 3GPP TR 36.815 V9.1.0 (2010-06), "Further advancements for E-UTRA; LTE-Advanced feasibility studies in RAN WG4 (Release 9)".

[24] BeFEMTO D3.1, "RF Front-end solutions".

4.1.2 LTE-A femtocell RF front-end architecture analysis

4.1.2.1 Description of the Scheme

Today's RF transceivers have to face several challenging requirements [25]. They should cover wider frequency ranges, be able to handle system bandwidths from below 10MHz up to 100MHz and signal bandwidths from 1.25 to 20MHz. Besides, wider input and output power dynamic ranges must be supported and a multitude of modulation schemes must be handled, with very different peak to peak average ratios. Apart of these functionality demands, it is also required significant improvements in size and integration, while power efficiency and cost must be optimized. For this reason, the selection of an optimal architecture is a key parameter for the development of wireless devices.

Taking all of these points into account, several RF front-end architectures for BeFEMTO standalone femtocells were analysed, being selected the direct conversion as the most appropriate one. Originally developed as a replacement to superheterodyne receivers [26], direct conversion receiver directly demodulates an RF modulated carrier to baseband (BB) frequencies where the conveyed information is recovered. On the other side, a direct conversion transmitter modulates a RF carrier directly from BB. The reduced number of components (which results from eliminating intermediate frequency (IF) stages) make of it an attractive choice. In addition, this kind of architecture offers more freedom in addressing multiple bands of operation using a single hardware solution, which promises to be more cost effective for enabling high performance multi-standard/multi-band radio designs. For these reasons, direct conversion appears as the most cost effective and integrated solution

Figure 22 illustrates a typical configuration of a Direct Conversion Receiver (DCR).

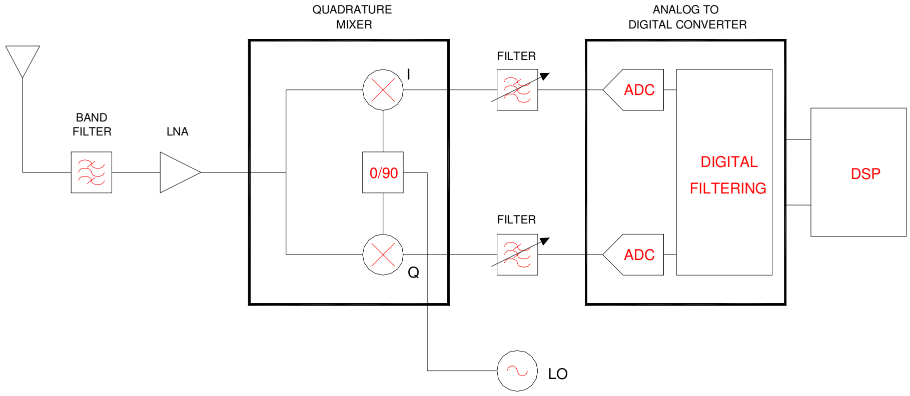


Figure 22: Direct conversion Receiver basic scheme.

The first two blocks are the band selection filter and the LNA. After amplification, the signal is directly down converted with a quadrature mixer to baseband I and Q signals. Subsequently, I/Q signals can be amplified to a suitable level for the A/D converters. Low pass filters perform the channel selection. Along with this, DCR eliminates a second frequency synthesizer, which reduces spurious mixer products.

Figure 23 shows direct conversion transmitter architecture, which is favored for its simplicity and low cost [27].

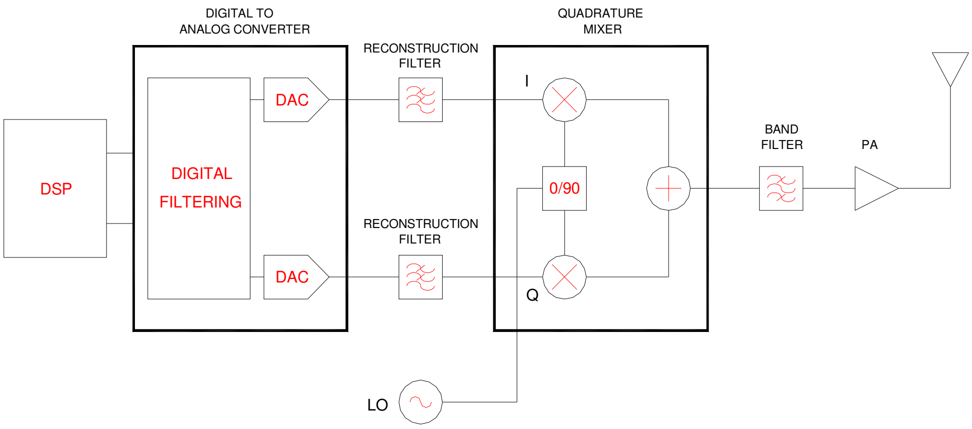


Figure 23: Direct conversion transmitter basic scheme.

The DAC outputs generate in-phase and quadrature (I/Q) components of a complex BB signal resulting from modulation mapping, pulse shaping, and upsampling (via interpolation filters) to the DAC sample clock frequency. The DAC reconstruction filters are usually implemented with inexpensive discrete inductors and capacitors. The filtered baseband I/Q signals along with the LO signal drive the corresponding I/Q and LO inputs of an analogue quadrature modulator which produces a modulated RF waveform at a carrier frequency that is equal to the LO frequency. This modulated output signal is band filtered (to remove out of band spurs) and amplified by the Power Amplifier (PA) circuitry.

Table 22 shows the main advantages and challenges of the direct conversion architecture [28].

	Receiver	**Transmitter**
Advantages	Not required any external IF filters for channel selection It does not have the image frequency problem Reduced Bill of Materials, cost and consumption High integrated solution	Reduced Bill of Materials Reduced cost High integrated solution
Challenges	Current and time varying offset voltage in the BB LO radiation through antenna 'Self mixing' in the quadrature modulator, High linearity required	LO leakage I/Q imbalance LO injection pulling by the output of the Power Amplifier

Table 22: Advantages and challenges in Direct Conversion Architecture.

On this activity, several kinds of architecture were explored for the LTE-A Femtocell RF front-end hardware. On this research, several important aspects (from a terminal development point of view) were taken into account, like cost, consumption, integration and current available technology. In this way, the solution proposed by BeFEMTO, direct conversion architecture, appears as the most adequate one for addressing the LTE-A requirements and contributing to the BeFEMTO objective of research on new RF hardware solutions.

References

[25] "RF transceiver Architecture for Cognitive Radio User Equipment", End to End Reconfigurability II (E2R II) White Paper, June 2007.

[26] Rakesh Soni and Eric Newman, "Direct conversion receiver designs enable multi-standard/multi-band operation", Analog Devices, Inc., 2/16/2009.

[27] David Brandon, David, Crook, and Ken Gentile, "The advantages of using a quadrature digital upconverter (QDUC) in Point-to-Point Microwave Transmit Systems", Analog Devices, Application Note AN-0996.

[28] BeFEMTO D3.1, "RF Front-end solutions".

4.1.3 Impact of Carrier aggregation on femtocell RF architecture

4.1.3.1 Description of the Scheme

Carrier aggregation is one of the key features for IMT-Advanced. Achieving the challenging peak data rate of 1Gb/s will require wider channel bandwidths than currently specified in LTE Release 8 [29]. At the moment, LTE supports channel bandwidths up to 20MHz. The only way to achieve significantly higher data rates is to increase the channel bandwidth. In this way, IMT-Advanced sets the upper limit at

100MHz, with 40MHz the expectation for minimum performance.

Because most spectrum is occupied and 100MHz of spectrum is needed, the ITU has allowed the creation of wider bandwidths through the aggregation of contiguous and non contiguous component carriers (CC). Thus, spectrum from one band can be added to spectrum from another band in an UE that supports multiple transceivers. In order to support legacy LTE Release 8 terminals, it is required that each of the CCs can be configured to be an LTE Release 8 carrier (however not all CCs are necessarily LTE release 8 compatible). This is in order to ensure backward compatibility with LTE, which means that an LTE terminal can work in an LTE-A network and an LTE-A terminal can work in an LTE network.

In this way, the 100MHz bandwidth can be achieved by aggregating up to five LTE carriers of 20MHz each. To an LTE terminal, each component carrier will appear as an LTE carrier, while an LTE-A terminal can exploit the total aggregated bandwidth [30]. To meet ITU requirements, LTE-A will support three component carrier aggregation scenarios: intra band contiguous, intra band non contiguous and inter band non contiguous aggregation.

Carrier aggregation will undoubtedly pose major difficulties for femtocell architecture, which must handle multiple simultaneous transceivers. The addition of simultaneous non contiguous transmitters creates a highly challenging radio environment in terms of spurious management and self blocking. There exist various options for implementing carrier aggregation in the transmitter architecture depending primarily upon the deployment scenario (contiguous or non contiguous band), which heavily influences where the component carriers are combined. Thus, the CCs can be combined:

- At digital Baseband
- In analogue waveforms before the RF mixer
- After the RF mixer

The carrier combination at digital baseband is mainly intended for contiguous scenarios, while the second and third options are mainly thought for non-contiguous scenarios. In this way, while the combination in analogue waveforms before the RF mixer is more indicated for intra band, the combination after the RF mixer is more adequate for inter band scenarios. In the last kind of combination, depending on the frequency band separation, the combination could be made after the power amplifier (due to the limited bandwidth of this kind of circuits). In the following figures a general transmitter scheme for each type of carrier combination is shown.

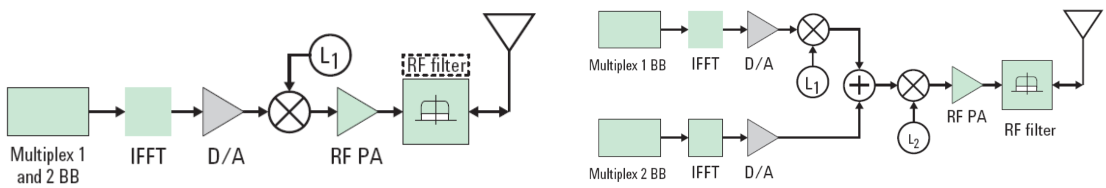


Figure 24: Baseband CCs combination scheme (left), in analogue waveform before RF mixer (right).

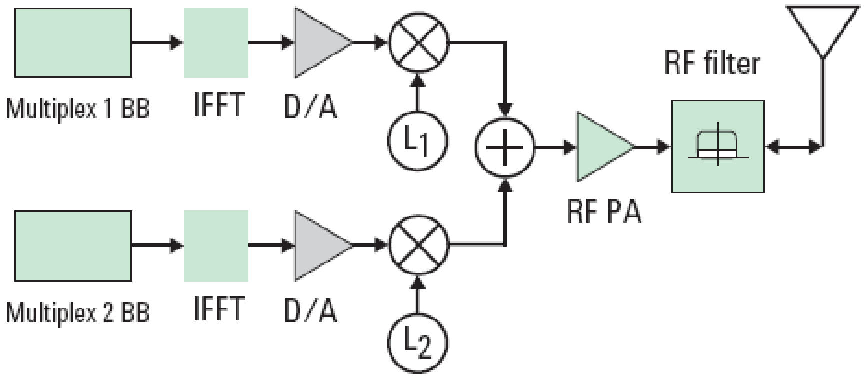


Figure 25: CCs combination after the RF mixer.

In conclusion, carrier aggregation will have a strong impact in the RF front end architecture. LTE-A terminals will have to include capabilities of simultaneously transmitting and/or receiving multiple carriers. Thus, RF front-end will have to deal with multiple transceivers integration issues.

4.1.3.2 Contribution to BeFEMTO System Concept and Objectives

Carrier aggregation is one of the most important features of LTE-A and key for achieving the 100MHz Bandwidth target in BeFEMTO. The RF Front-end hardware is an enabler of this target, and the impact of carrier aggregation on this hardware was analysed in order to propose the optimum RF architecture depending on the deployment scenario. In this way, different architectures are proposed depending if contiguous, non contiguous inter-band or non contiguous intra-band carrier aggregation scenarios are deployed.

References

[29] Agilent Technologies, “Introducing LTE-Advanced”, Application note 5990-6706EN, March 2011.

[30] Rhode and Schwarz, “LTE-Advanced Signal Generation and Analysis”, Application Note 1MA166, February 2010.

4.1.4 RF front-end design for 2.3-2.4GHz (TDD) scenario

4.1.4.1 Description of the Scheme

In this activity is presented the results obtained for the proposed femtocell RF front-end design [31] for the 2.3-2.4GHz scenario (which is proposed as a deployment scenario for ITU-R submission by 3GPP). This is a TDD scenario, which allows contiguous aggregation of up to 5CC’s of 20MHz Bandwidth each in order to reach the 100MHz Bandwidth.

In order to allow any possible combination of component carriers, that is, from 1 to 5 CCs in any band inside 2.3-2.4GHz, it has been proposed to use 5 independent LTE transceivers, one per CC. These transceivers will share common elements, like switch, RF filter, LNA and HPA, in order to optimize the bill of materials and consumption of the whole terminal. In this way, the combination (in the case of transmitter) is made after I/Q modulator, while the split (in case of receiver chain) is made before I/Q demodulator. Each independent transceiver will be able to handle up to 20MHz of bandwidth. Figure 26 shows the proposed general scheme.

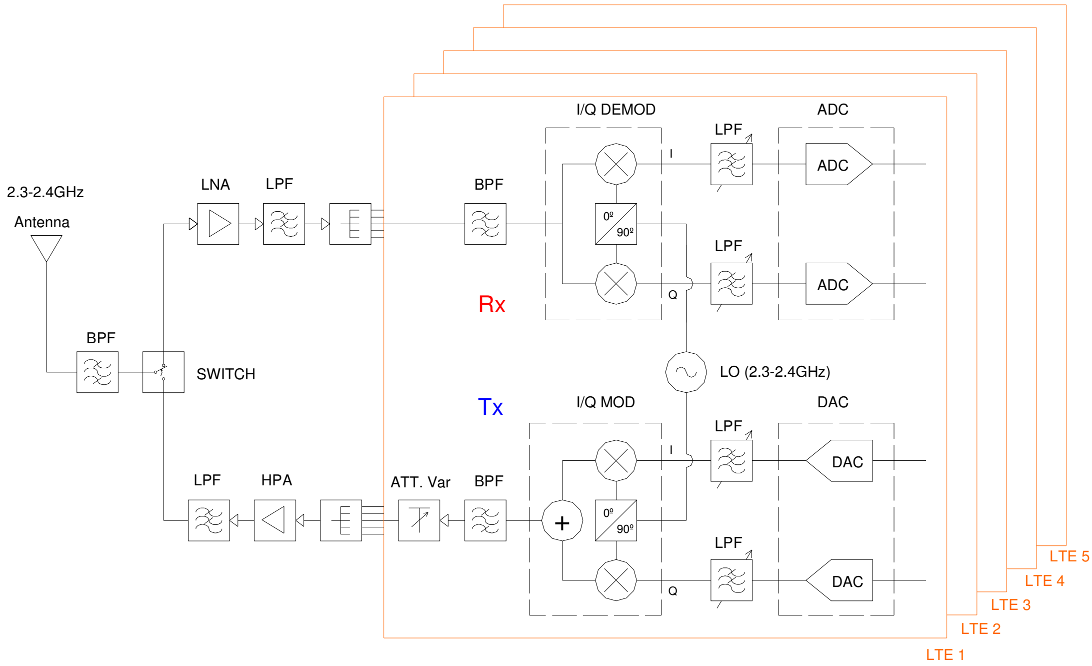


Figure 26: 2.3-2.4GHz RF Front-end proposed architecture.

In Figure 27 is shown the block diagram for a single transceiver. The transceiver is composed by one transmitter and by one receiver, which share the same local oscillator, since both work in the same frequency. Transmitter and receiver chains are connected to the antenna by means of a 2 to 1 switch (TDD operation). The five transceivers share LNA, HPA and switch (apart from some filtering stages) and are combined just before and after these components. On the transceiver design it was taken into account the available technology and minimum cost, size and consumption criteria were followed on the selection of the individual components.

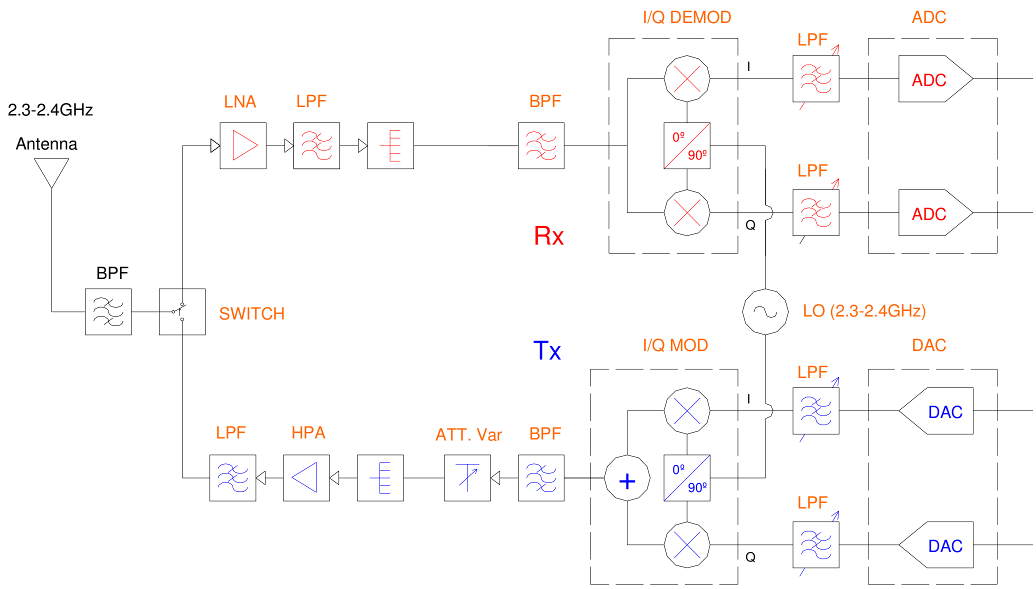


Figure 27: Individual transceiver proposed architecture.

Finally, Table 23 shows a summary of the results obtained for the proposed RF front-end solution for this scenario. As it can be seen, all the requirements were fulfiled.

Parameter	Required Value	Expected Value
Bandwidth	100MHz	100MHz
LO step size	300KHz	300KHz
LO Phase Noise (Tx/Rx)	<1º rms (15KHz-20MHz)	0.04º rms (15KHz-1MHz)
Maximum Output Power	10dBm	10dBm (5CC of 3dBm each)
EVM	<8%	<8%
ACLR	>45dB	>46.83dB
Spectrum Emmision Mask (SEM)	Limits defined in [31]	Below limits
Transmitter spurious emissions	Limits defined in [31]	Below limits
Power adjustment Capability	Yes	>30dB
Transmitter Transient Period (TDD)	<17us	<100ns

Table 23: Performance expected for proposed RF front-end

4.1.4.2 Contribution to BeFEMTO System Concept and Objectives

It was presented the RF front-end design for 2.3-24GHz TDD scenario which was one of the proposed by 3GPP. The proposed front-end design covers the 100MHz Bandwidth and 10mW of maximum output power, both targets of BeFEMTO, fulfiling the LTE-A requirements.

References

[31] BeFEMTO D3.1, “RF Front-end solutions”.

4.1.5 RF front-end design for B20 (800MHz) + B7 (2.6GHz) scenario (FDD)

4.1.5.1 Description of the Scheme

In this activity is presented the results obtained for the proposed femtocell RF front-end design [32] for the B20(800MHz) + B7 (2.6GHz) scenario. This scenario is based on current LTE deployments: an FDD non contiguous carrier aggregation scenario with 30MHz bandwidth in B20 and 70MHz bandwidth in B7, covering the 100MHz bandwidth target. This scenario considers two CCs aggregated in B20 (one of 20MHz and one of 10MHz) and up to four CCs aggregated in B7 (3 CCs of 20MHz and another one of 10MHz).

The proposed architecture is composed of 2 transceivers for B20 (one of 20MHz of BW and one of 10MHz of BW) and of 4 transceivers for B7 (three of 20MHz and one of 10MHz). Each B20 transceiver share a single LNA, HPA, duplexer and antenna and each B7 transceiver also share a single HPA, LNA, duplexer and antenna, in order to minimize as much as possible the overall bill of materials. Figure 28 depicts an overall overview of the RF front-end architecture proposed for this scenario.

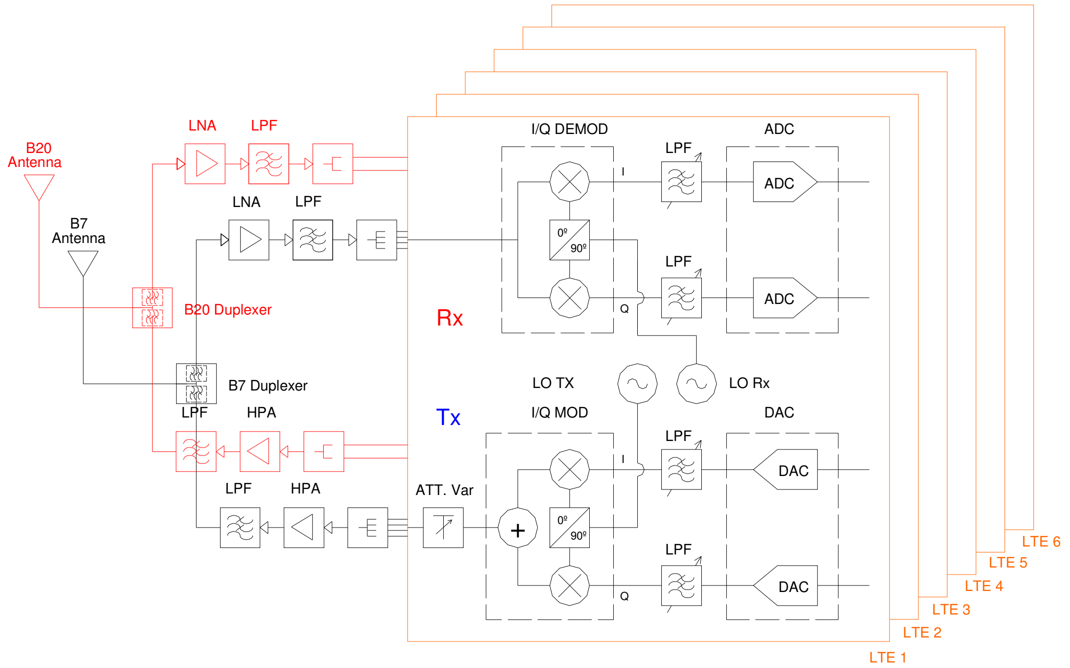


Figure 28: Proposed Femtocell RF front-end architecture for B7+B20 scenario.

Figure 29 shows the block diagram of the individual transceivers for B20 and B7, respectively. Each transceiver is composed by one transmitter and by one receiver, which uses different local oscillator (they operate in different bands) and joint by a duplexer filter, due to the FDD operation. On each transceiver design it was taken into account the available technology and minimum cost, size and consumption criteria were followed on the selection of the individual components.

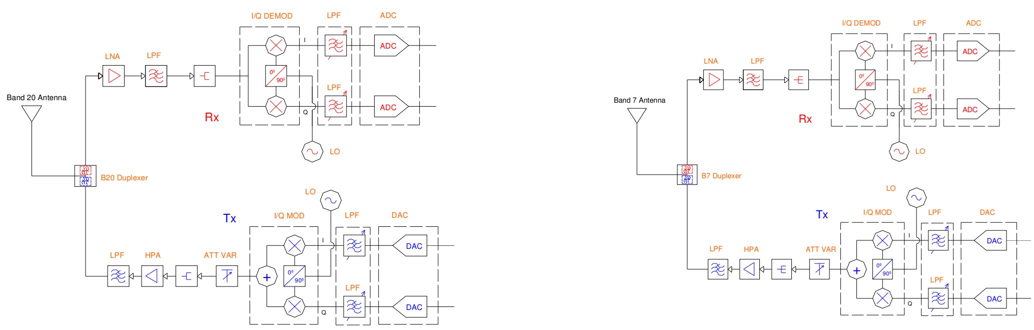


Figure 29: Proposed Transceiver architecture for B20 (left) and for B7 (right).

Finally, Table 24 shows a summary of the results obtained by means of simulations for the proposed RF front-end solution for this scenario. As it can be seen, all the requirements were fulfiled.

	Band 20		**Band 7**	
Parameter	**Required Value**	**Expected Value**	**Required Value**	**Expected Value**
Bandwidth	30MHz	30MHz (B20)	70MHz	70MHz (B7)
LO step size	300KHz	300KHz	300KHz	300KHz
LO Phase	<1º rms (15KHz-	0.13º rms	<1º rms (15KHz-	0.38ºrms (15KHz-

	Band 20		Band 7	
Parameter	**Required Value**	**Expected Value**	**Required Value**	**Expected Value**
Noise (Tx/Rx)	20MHz)	(15KHz-1MHz)	20MHz)	1MHz)
Maximum Output Power	4.7dBm	4.7dBm	8.45dBm	8.45dBm
EVM	<8%	<8%	<8%	<8%
ACLR	>45dB	>63.28dB	>45dB	>53.47dB
SEM	Limits defined in [32]	Below limits	Limits defined in [32]	Below limits
Transmitter spurious emissions	Limits defined in [32]	Below limits	Limits defined in [32]	Below limits
Power adjustment	Yes	>30dB	Yes	>30dB

Table 24: Expected Performance for Band20 and Band7 proposed RF front-end.

4.1.5.2 Contribution to BeFEMTO System Concept and Objectives

It was presented the RF front-end design for B20+B7 FDD scenario, which was one proposed by BeFEMTO, taking into account current LTE deployments in Europe. The proposed front-end design covers the 100MHz Bandwidth and 10mW of maximum output power, both targets of BeFEMTO, fulfiling the LTE-A requirements.

References

[32] BeFEMTO D3.1, "RF Front-end solutions".

4.1.6 Synthesis

Next Generation RF techniques activity focused on the research of novel architectures for Femtocell RF front-end for BeFEMTO, which has to be LTE-A compliant. In this way, the first logical part of the activity was to identify, and in some cases to deduce (because they have not yet been defined by 3GPP), the requirements to be fulfilled by this hardware. Once these were identified, the next step was to choose the most suitable front-end architecture, taking into account the previously defined requirements and the available technology. In this way, direct conversion architecture was chosen as the most appropriate one in cost, size and performance terms. Next step was to analyse the impact on the RF architecture of one of the most characteristic features of LTE-A, which is the Carrier Aggregation. The aggregation of the bandwidth, up to 100MHz, and how it is aggregated (in a contiguous or no-contiguous way) impacts directly in the RF architecture and in the number of transceivers to be employed (depending on the frequency deployments). Finally, the proposed design for the femtocell RF front-end was analysed in two different scenarios. The first one was a TDD scenario (2.3-2.4GHz), proposed by 3GPP, while the second one was a FDD scenario in B20 and B7 frequency bands, taking into account current LTE deployments.

For both cases, it was demonstrated that LTE-A requirements were fulfilled.

4.2 Interference Mitigation

4.2.1 Static Interference Avoidance Schemes

4.2.1.1 Description of the Scheme

In order to successfully deploy the femtocell architecture, several challenges need to be addressed. Cross-tier Interference is one of these major issues, i.e. femtocells which operate in the same spectrum as macrocell users produce a cross-tier interference which degrades the latter users' Quality of Service (QoS). In order to avoid cross-tier interference operators may (statically or dynamically) allocate different parts of the available spectral resource to macrocell and femtocell users. In this section, the problem of cross-tier interference is mainly addressed with a static combination of flexible frequency and power reuse.

Different static schemes are considered in this scenario including: Soft Frequency Reuse (SFR), Fractional Frequency Reuse (FFR) and Inverse Frequency Reuse (IFR). The aforementioned static schemes are compared with Frequency Reuse 1 (FR1) and Frequency Reuse 3 (FR3) as the main benchmarking schemes.

We investigate the performance of different static interference avoidance schemes in a heterogeneous network comprising macro and femtocells. In particular, we evaluate the effect of system parameters like the activation ratio (AR) of the femtocells on the overall performance of the system.

To evaluate the performance of different static algorithms, we initially model a system level simulation of 2-tier hexagonal layout for macrocells comprising tri-Sectorized eNodeBs with 500m inter site distance (ISD). The statistics are collected for a total of 100 snapshots assuming full buffer scenario where in each snapshot, a total of 10 UEs are uniformly dropped per cell. The femto blocks are deployed based on 5x5 grid model where different activation ratios are considered per grid at this stage.

Figure 30 and Figure 31 depict the performance of macrocell and femtocell, respectively in presence of static avoidance schemes as the AR (for femtocells) gradually increases from 20% to 60%.

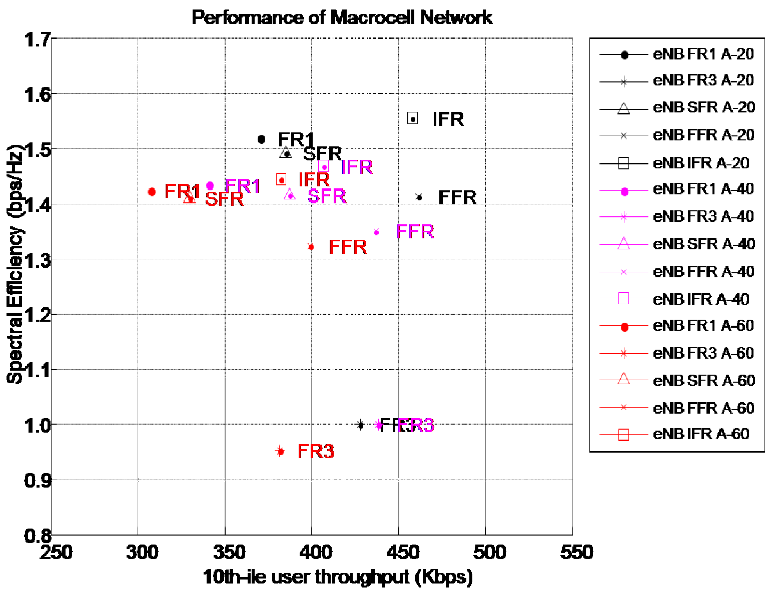


Figure 30: Performance of macrocell network in different ARs for femtocell.

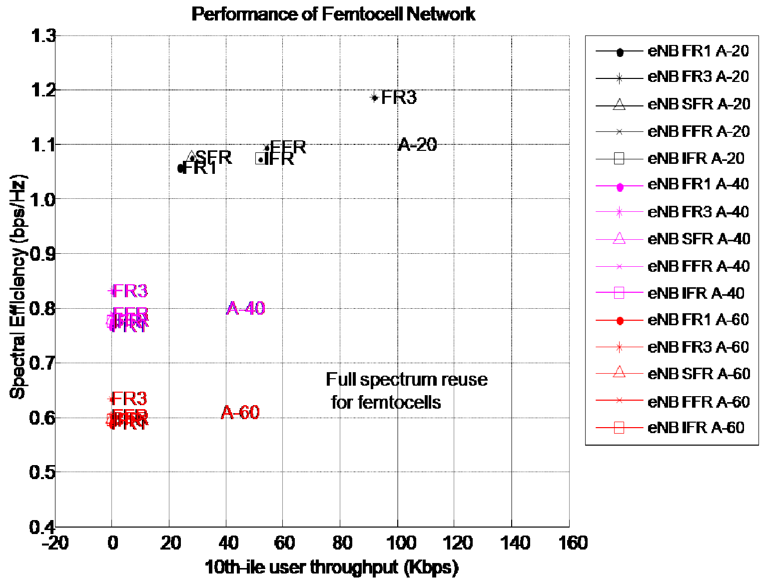


Figure 31: Performance of femtocell network in different ARs of itself.

As can be seen, in case of femto network, the total spectral efficieny as well as 10th percentile user throughput is severely reduced due to the significant increase in co-tier interference where the 10th percentile user throughput reaches zero for ARs beyond 60%. However, the macrocell performance is not affected as much due to little impact of AR on cross-tier interference. It is worth noting that the number of femto grids per each cell is fixed (equal to one) across all ARs in this scenario.

Comparing different schemes in low AR regime, the IFR performs better in macrocell due to a better utilization of radio resources in this hybrid scheme whereas the FR3 scheme outperforms the rest for femtocell network. The superior performance of FR3 for femtocells is attributed to suppression of strong cross-tier interference from other neighbouring macro cells on part of spectrum per cell. However, this scheme would severely penalize the macro performance by full partitioning of spectrum as evident by the results. On the other hand, in high levels of AR, all schemes perform similarly for the femtocell network and can not mitigate the impact of co-tier interference. As a result, more dynamic schemes are to be used along static schemes to mitigate the effect of co-tier interference in dense femto scenarios.

4.2.1.2 Contribution to BeFEMTO System Concept and Objectives

In this section, we evaluated the impact of some system parameters on the overall performance of different static interference avoidance schemes where IFR and FR3 outperformed the other schemes for macro and femto networks in different cases, respectively. IFR achieves more than 1.5 b/s/Hz in this SISO scenario for macrocell in low AR regime while keeping high 10th percentile performance. IFR performance is similar to FFR performance on the femtocell side where FR3 takes the lead by achieving spectral efficiency of 1.2 b/s/Hz. However, FR3 performance is severely penalized at macrocell side due to the full partitioning of resources.

4.2.2 Femto-to-macro control channel interference issues

4.2.2.1 Description of the Scheme

A co-channel and random deployment of femto-cells can cause heavy downlink (DL) interference to user equipment (UE) in the vicinity of one or more femto-cells and not belonging to their closed subscriber groups (CSGs). In this section, we focus on protection of the LTE DL control channels. Failure to decode these channels correctly results in the loss of the subsequent subframe. This section is dedicated to introducing some of the oft-mentioned standards-compliant control channel interference avoidance techniques in 3GPP and analysing their performance [33].

Figure 32 shows the various interference mitigation techniques compared against the uncoordinated case which is shown in Figure 32 (a). Without going into intricate details, this figure only depicts the part of the LTE subframe associated with control information transmission. As can be seen, this involves up to three OFDM subframes. Since macrocells are expected to serve a higher number of users than femtocells, their control regions are expected to always be fully occupied as can be observed in the top half of the figure for all cases (a) through (d). Focusing now on case (a), we see that the femtocell occupies only the first OFDM symbol after which data transmission begins. It is obvious that such a configuration causes high interference to all three OFDM symbols of a macro UE that may be trapped close to the aggressor femtocell. This is therefore known as the uncoordinated case. In (b), we relax the constraint that the femtocell may only use the first OFDM symbol to carry control information [34]. This has the result that the control information is smeared over the three OFDM symbols, thus resulting in a sparse arrangement of control information. The effect of this is that the trapped macro UE will experience lower control region interference than case (a). In case (c), the femtocell is only allowed to use the first two OFDM symbols to carry control information. This arrangement exists in the standards and is known as the multicast broadcast single frequency network (MBSFN) arrangement [35]. Finally, in (d), the femtocell is not allowed to transmit anything in the subframe other than pilot symbols [36]. This arrangement is known as the almost blank subframe (ABS) case. Clearly this case results in the least interference to trapped macro UEs.

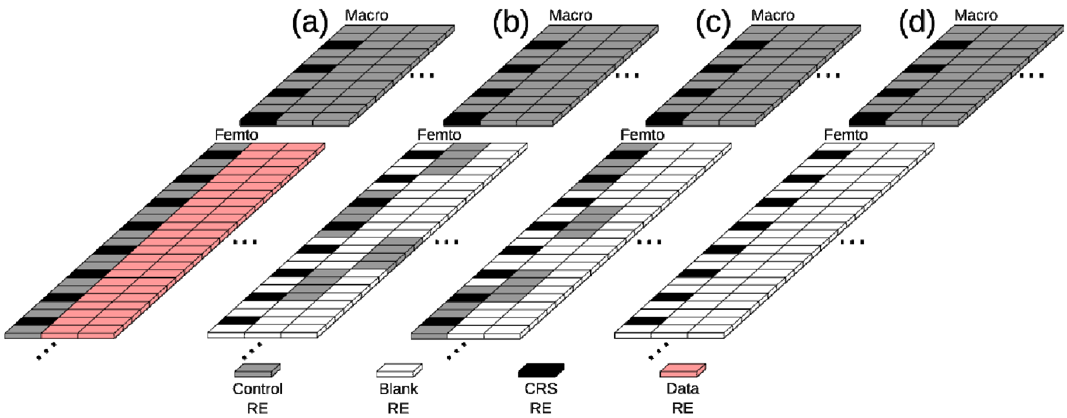


Figure 32: State-of-the-art femto-to-macro interference avoidance techniques. The system with no coordination is shown in (a), control channel sparseness is depicted in (b), the MBSFN configuration (with the control region spanning two OFDM symbols) is shown in (c) and the ABS configuration is shown in (d).

Figure 33 shows the results of a system-level simulation where the four techniques described above are compared against one another. The cumulative distribution function (CDF) of the effective signal-to-interference-plus-noise-ratio is exhibited in this figure. For the sake of completeness, it bears mentioning that the performance of one of the three LTE control channels known as the physical downlink control channel (PCFICH) is shown in this figure. From the three control channels used in LTE, this one is the most crucial one because it indicates to the UE how many OFDM symbols are dedicated for carrying control information in any given subframe. Incorrect decoding of the PCFICH instantly results in the total loss of the subframe. The results are compared against the benchmark where femtocells (and therefore the interference they cause) do not exist. It is seen that the uncoordinated case performs the worst as expected. The best performance is achieved by the ABS case, while the MBSFN and sparse cases have intermediate performance. The disadvantage of the ABS case is that since the subframe does not contain control information, it also does not carry any data. Therefore, even though the interference is highly reduced, the capacity on the femto layer is also greatly diminished. The next section addresses this issue and proposes a novel way to circumvent it.

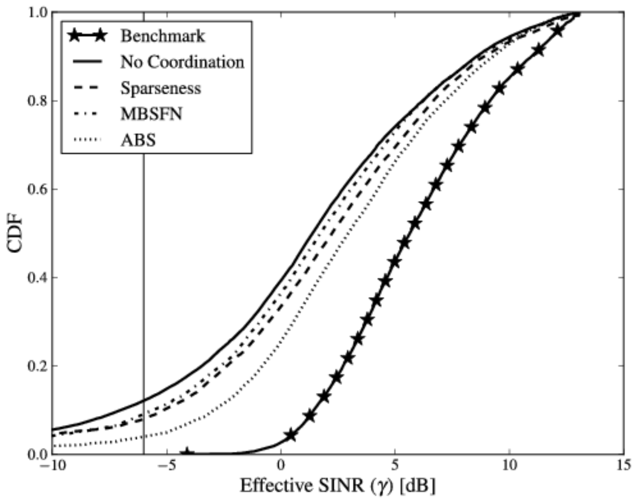


Figure 33: Performance of all MUEs in the system without power control.

4.2.2.2 Contribution to BeFEMTO System Concept and Objectives

It is not straightforward to quantify spectral efficiency gains when considering only the control channel performance. However, it is well known that if the control channel is incorrectly decoded, the rest of the subframe is lost. Since the schemes depicted in this section improves control channel performance, clearly, it reduces the probability of incorrect decoding of the control channel resulting in less subframes being lost, which finally results in a higher achievable capacity. Therefore, the schemes depicted in this section indirectly adhere to the BeFEMTO System Concept objectives in terms of spectral efficiency due to the above reason and the fact that no additional signalling overhead is required.

References

[33] Z. Bharucha, G. Auer, and T. Abe, "Downlink Femto-to-Macro Control Channel Interference for LTE", in *Proc. of the IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1259-1264, Mar. 2011.

[34] Kyocera, "Range Expansion Performance and Interference Management for Control Channels in

Outdoor Hotzone Scenario", 3GPP TSG RAN WG1 Meeting #60b R1-102363, Apr. 2010.

[35] E. Dahlman, S. Parkvall and Johan Sköld, *4G LTE/LTE-Advanced for Mobile Broadband*. Academic Press, 1st Ed., 2011.

[36] CATT, "Analysis of Time-Partitioning Solution for Control Channel", 3GPP TSG RAN WG1 Meeting #61b R1-103494, Jun. 2010.

4.2.3 Femto-to-macro interference mitigation for PCFICH

4.2.3.1 Description of the Scheme

In Section 4.2.2, it is seen that the interference management technique depicted in Figure 32(d) reduces interference on the control channel via the loss of all the information in the subframe (ABS). This causes a very significant loss in femto data capacity. Furthermore, the other techniques depicted in the same figure cannot attain the same advantage as the ABS technique, however, they do not result in a loss of data capacity. The aim of the work shown in this subsection is to achieve the same improvement in performance as that achieved by the ABS method *without* resulting in the same loss of capacity. In order to make a fair comparison, we focus once again on the PCFICH control channel. Again, it must be mentioned that the PCFICH is the most important of the LTE control channels and its incorrect decoding directly results in the loss of the subsequent subframe.

The aim of this technique is to rearrange the elements of the control region of the aggressor femtocells such that they do not destructively interfere with the PCFICH of the vulnerable macro UEs that may lie close to those femtocells [37]. This is shown in Figure 34.

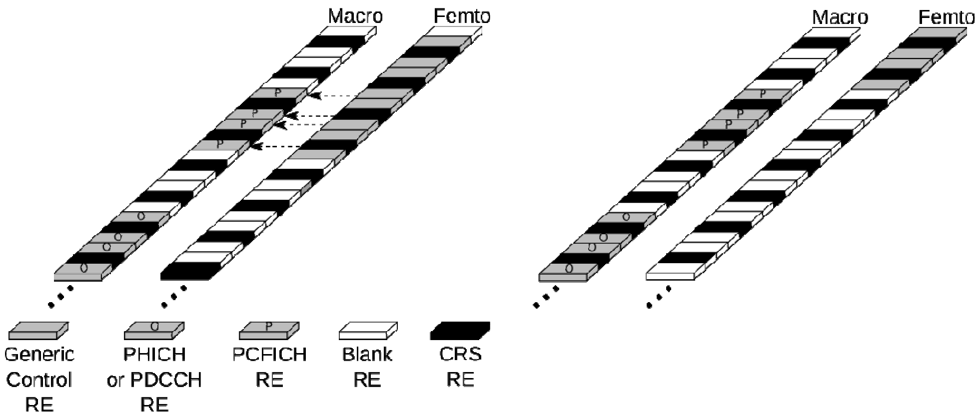


Figure 34: An example of how the PCFICH can be protected via PCI manipulation. The left-hand figure shows an uncoordinated system with high interference to the macro layer PCFICH. By carefully manipulating the PCI on the femto layer, such collisions can be avoided as is shown on the right-hand figure.

Clearly, it helps if the control region of the femto layer contains free space to successfully manoeuvre the control elements around. Therefore, this scheme is most effective if it is used in conjunction with the sparse control channel technique as described in Section 4.2.2. An important property of LTE networks is exploited in order to ensure the functioning of this technique. Every LTE BS is associated with a cell identity. Every unique cell also broadcasts its own reference (pilot) symbols to aid the UEs in channel estimation, etc. These are shown in black in Figure 34. In order to avoid collisions between the control channels and reference symbols of neighboring cells, a cell-specific cyclic shift is employed such that any two neighboring cells should ideally distribute their control channels and reference symbols in non-colliding positions. When a femtocell is deployed, it usually chooses its cell identity at random during the startup procedure, without taking into account the cell identity of the macrocell within which it lies. This is the cause of undue interference to the control channels of a macro UE lying in the vicinity of the femtocell in question. In contrast to this, at startup, the femtocell first decodes the cell identity of the strongest macrocell and then adjusts its own cell identity so as to minimize PCFICH interference to UEs belonging to this macrocell. This simple method can be employed to protect any of the other control channels or even the reference symbols. In this work, we try to minimize collisions of any sort. It must also be noted that this technique is completely backwards-compatible, *i.e.*, it works with LTE or LTE-A and therefore can be used with legacy UEs without any loss of efficiency. Furthermore, it is important to note that this technique requires no changes to current standards, does not require any additional infrastructure to be installed and does not require any additional signals to be transmitted. All femtocells are expected to be equipped with downlink receivers, therefore identifying the most dominant macro BS is not problematic. Finally, it is also noted that in comparison to the ABS scheme where data capacity is significantly compromised, this is not the case here, where femtocells continue to transmit data unimpaired.

Figure 35 shows the performance of this technique compared against the ABS solution described in Section 4.2.2 and the benchmark system where femtocells (and therefore the interference they cause) do not exist. First it is noted that both ABS and the technique discussed here perform worse than the benchmark system as expected. However, it is noteworthy to see that at the lower SINR percentiles, our scheme outperforms even ABS. This is because even the reference symbols of the aggressor femtocells are rearranged to minimize collisions. Therefore, this scheme successfully demonstrates that acceptable macrocell performance can be maintained without a loss of capacity on the femto layer.

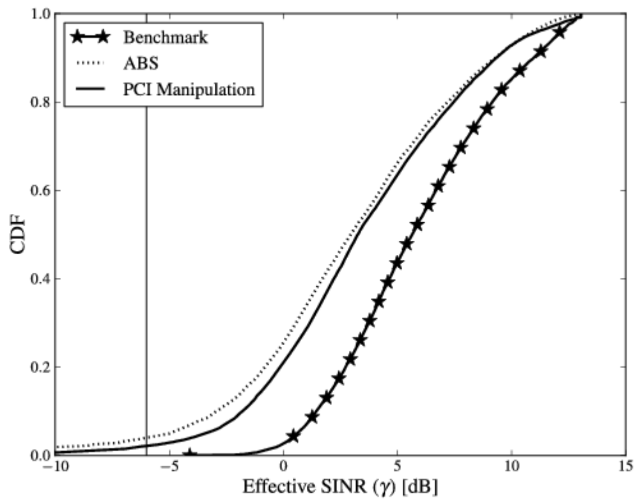


Figure 35: Performance of all MUEs in the system without power control.

4.2.3.2 Contribution to BeFEMTO System Concept and Objectives

It is not straightforward to quantify spectral efficiency gains when considering only the control channel performance. However, it is well known that if the control channel is incorrectly decoded, the rest of the subframe is lost. In comparison to the ABS scheme shown in Section 4.2.2, the technique described here does not come at the cost of a loss of data capacity. Therefore, this technique goes further towards achieving the spectral efficiency targets of BeFEMTO.

References

[37] Z. Bharucha, G. Auer, T. Abe and N. Miki, "Femto-to-Macro Control Channel Interference Mitigation via Cell ID Manipulation in LTE", in *Proc. of the 74th IEEE Vehicular Technology Conference (VTC)*, pp. 1-5, Sep. 2011.

4.2.4 TDD underlay at UL FDD

4.2.4.1 Description of the Scheme

In this proposed scheme, the macrocell network operates in an FDD mode, while the underlaid femtocells operate in a TDD mode. Indeed, augmenting the paired FDD spectrum with smaller unpaired TDD bands is seen as a key enabler for a mass roll-out of dense heterogeneous networks. This is of particular interest for indoor communications.

The concept can be described as follows: if femtocells are far enough from the macrocell base station, the same spectrum can be reused leveraging on spatial reuse [38]. In this case, the detrimental factor is the femto-to-femto interference due to the aggressive resource reuse among neighboring femtocells. To remedy to this, coordination mechanisms take central stage to alleviate the co-tier interference by means of busy burst (or busy tones), thereby relying on minimal signalling. In the proposed coordination mechanisms (CM), potential interferers coordinate their transmissions based on the received signal strength from the tagged receiver (*coined* **CM1**) or when potential interferers use the received beacon to estimate their channel gain to the tagged receiver, and adjust their transmit power accordingly (*coined* **CM2**). Note that levering on channel reciprocity, the coordination mechanisms do not need to require any information exchange over the X2 interface. Finally, in the uncoordinated scenario, communication links are subject to strong interference with no coordination whatsoever.

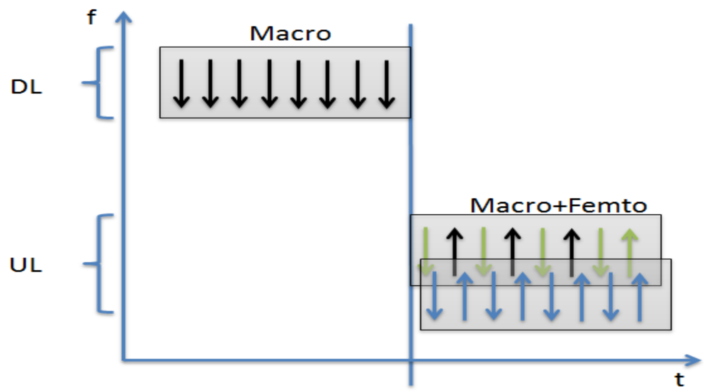


Figure 36: Femtocells reuse the uplink macrocell transmission, and transmit in a TDD underlay fashion.

Figure 36 illustrates the frame spectrum partition for the macro and femtocell transmissions, with the TDD underlay at UL FDD. A performance evaluation in terms of spectral efficiency for the femtocell tier as a function of the network density is shown in Figure 37. It can be seen that the baseline non-coordinated approach (i.e., FDD) exhib low performance compared to when coordination is leveraged.

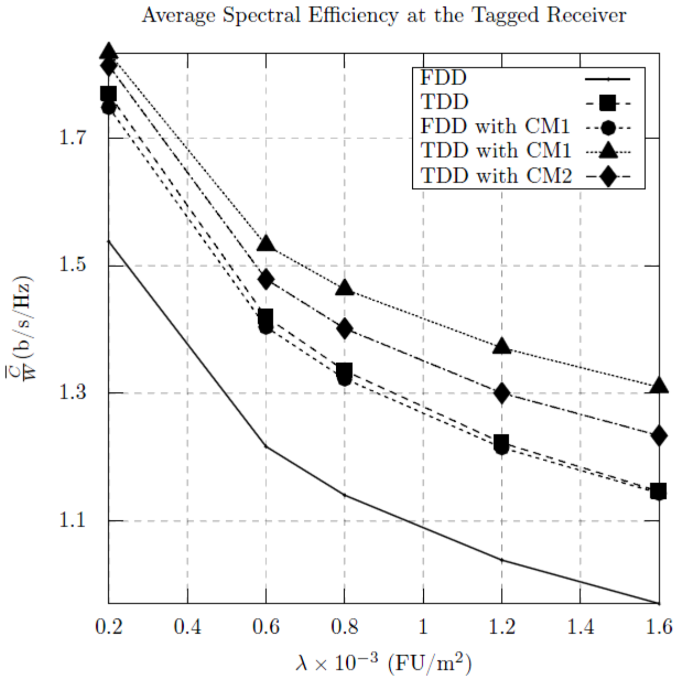


Figure 37: Average spectral efficiency of the femtocell networks, for different coordination mechanisms.

4.2.4.2 Contribution to BeFEMTO System Concept and Objectives

The proposed TDD underlay at UL FDD is seen as an enabling solution for addressing the capacity crunch and foreseen BeFEMTO objectives. When compared to the uncoordinated deployment, the outage probability is reduced by nearly 80%, while the average spectral efficiency increases by approximately 90% at high loads. While the TDD underlay at UL FDD is in its infancy, it is also expected that it will take central stage in upcoming LTE releases

References

[38] C.H. Lima, M Bennis, and M Latva-aho, "On the stochastic analysis of coordinated TDD underlay for self-organizing femtocells in two-tier coexistence scenarios," *(submitted) to EURASIP special issue on 4G femtocell networks*.

4.2.5 Statistical modelling of HetNets

4.2.5.1 Description of the Scheme

HetNets and small cell networks constitute a paradigm shift in cellular network deployment where current cellular networks are drifting away from traditional macrocell base stations towards heterogeneous elements, with a mix of low power nodes, distinguished by their DL transmit powers/coverage areas, backhaul, and propagation characteristics. This shift presents an enormous opportunity for capacity improvement, and solving other challenges in terms of co-existence and network management. In view of this, new theoretical models for understanding the next generation of heterogeneous cellular networks are deemed necessary, and the practical constraints and challenges those operators must tackle in order for these networks to reach their potential are of utmost importance. Here, we use tools from Stochastic Geometry (SG) in order to model the spatial and random deployment of small cell networks. SG allows network designers to obtain closed-form expressions of network utility metrics such as transmission rate, area spectral efficiency, outage probability etc. These in turn allow operators to save dramatic time and OPEX/CAPEX when running complex Monte Carlo simulations. For sake of illustration, let us consider Figure 38 in which a spectrum partition deployment is considered. Roughly speaking, through SG every femtocell is able to characterize the aggregate interference being function of a number of network parameters (channels, density, etc) which is used to calculate various network-wide metrics. As an example, we considered herein one possible spectrum partition with a dedicated band for macrocell deployment, as well as one shared part among both tiers.

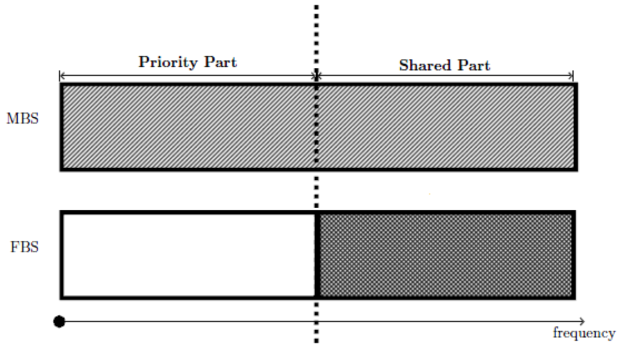


Figure 38: Considered spectrum partitioning.

In this particular setting, the victim/aggressor is the macro/femtocell tier. Therefore, femtocells need to self-organize with minimum overhead so as to control their interference towards the MUEs as well as friendly coexist with other neighboring femtocells. For sake of illustration, Figure 39 depicts the transmission rate for the femtocell tier in the downlink, as a function of the femtocell networks. It can be shown how the ASE varies with increasing values of density of femtocells. When the serving femtocell of the tagged FUE remains in the priority part, the FUE performance strongly depends on the distance to the serving MBS which dominates the CCI; conversely, femtocells in the shared part use orthogonal spectrum allocation and are not affected by that serving eNodeB. It is also possible to identify a crossing point where the capacity in the shared part becomes worse than in the priority part. And if the tagged FUE is far from the MBS, 50 meters for instance, it can take better advantage of the coordination performed by the MUE.

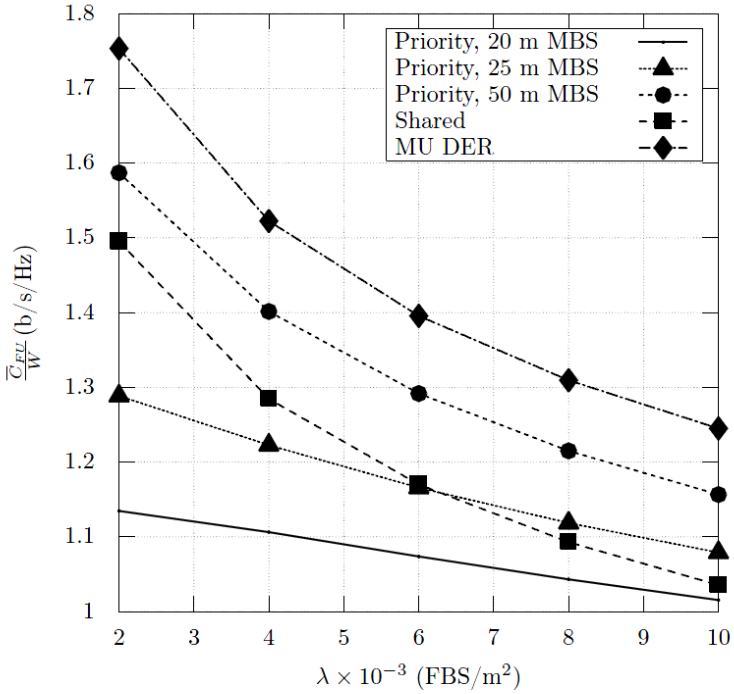


Figure 39: Area spectral efficiency (ASE) experienced by the FUEs of interest for an increasing density of interfering femtocells.

4.2.5.2 Contribution to BeFEMTO System Concept and Objectives

The essence of this contribution is to showcase the powerful tool of Stochastic Geometry which allows operators to obtain network-wide view of an eventual femtocell deployment, either operator or user controlled. Although SG does not account for all the intricacies of a system level simulator, it is still instrumental into getting a good overview of what is happening. Applications of SG are set to gain more momentum with the advent of dense small cell networks, with time-domain, frequency-domain and spatial domain ICIC schemes. In addition, and quite notably, SG is an enabler for RRM algorithms, especially when it comes to self-organization.

References

[39] C. H. Lima, M. Bennis and M. Latva-aho," Coordination Mechanisms for Self-Organizing Femtocells in Two-Tier Coexistence Scenarios," *IEEE Transaction in Wireless Communications*, June 2012.

[40] C. H. Lima, M. Bennis, and M. Latva-aho, "'Coordination Mechanisms for Stand-Alone Femtocells in Self-Organizing Deployments," in *Proc. IEEE GLOBECOM*, Houston, USA 2011.

4.2.6 Interference cancellation for femtocells

4.2.6.1 Description of the Scheme

In this proposal, successive interference cancellation (SIC) is used to allow macrocell UEs and femto UEs to share a common resource block in the UL. This boils down to a multiple access channel where both MUEs and FUEs communicate with the HeNB. SIC has been shown as a feasible technique in OFDM networks for both uncoded and coded systems. Here, we intend the macrocell user to be the primary user and the femto user to be the interfering user. The FUE is located very close the HeNB and is often slow moving or stationary. After decoding the FUE's signal, the femtocell access point can then decode the macro user's signal. Using this strategy, we are able to achieve the joint decoding and both the MUE and FUE can achieve their desired SINR threshold while sharing a single channel, see Figure 40.

In addition, as macrocell users lower their transmit power to connect to a nearby FAP, the amount of interference they cause to other femtocells also decreases. This will in turn increase the likelihood of FUs in those other femtocells being able to establish a link. In Figure 41, the average at the required SINR with their corresponding FAP is shown. We show curves for both the power control scheme without the handover process and the SIC scheme that allows the handover to occur. We clearly see that the SIC scheme outperforms the PC scheme and at high values of femtocell density, large gains in the number of users served are realized.

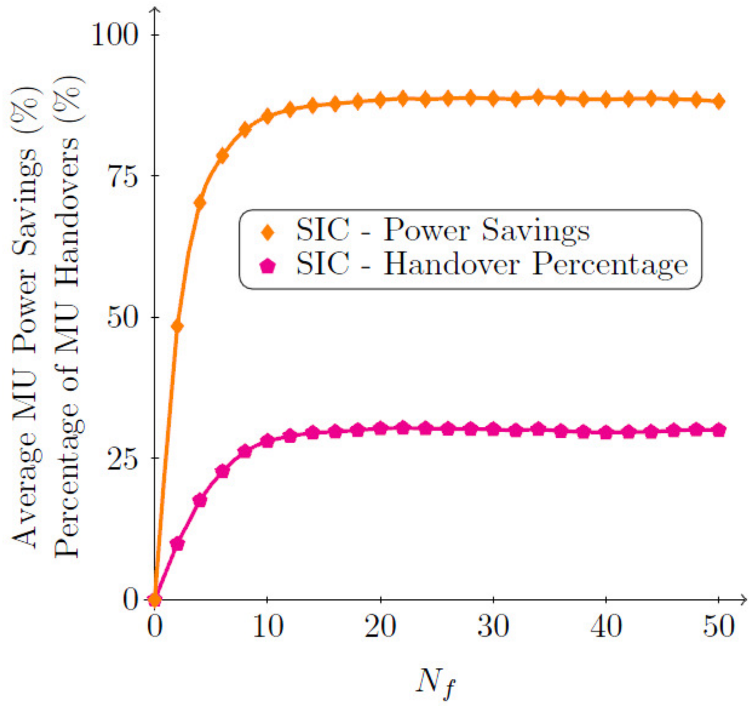


Figure 40: Average number of MUEs handover and their power savings versus the average number of femtocells per macrocell. SIC is used to allow a MUE and a FUE to share a common channel in the uplink.

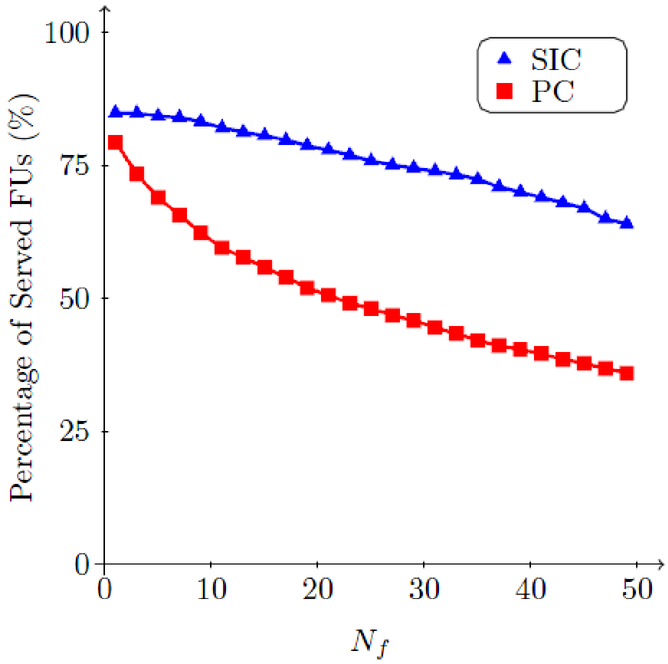


Figure 41: Average number of femtocell users who are served by their corresponding femtocell access points versus the number of average number of femtocells per macrocell.

4.2.6.2 Contribution to BeFEMTO System Concept and Objectives

By adding this mechanism to the power control and channel assignment schemes, we show gains over 200% in sum rate and power savings up to 90% for macro cell users.

References

[41] B. Kauffman, E. Erkip, J. Lilleberg, and B. Aazhang, "Femtocell Interference Mitigation Through Successive Interference Cancellation and Cellular Handover," accepted to *the 2011 IEEE International Conference on Communications: Workshop on Heterogeneous Networks (ICC)*, Kyoto, Japan, June 2011."

4.2.7 Synthesis

In any communication system, interference management is of vital importance – particularly in the case when different communication links share the same resources in a given network. This is the case for LTE-based heterogeneous networks such as those discussed throughout this document. In such hierarchical systems where several low-power, small-coverage femtocells are embedded within the coverage of one or more macrocells, priority is assumed to lie with the macrocell. Here, it is important that users connected to the macrocells do not undergo a severe degradation in performance due to the presence of active femtocells in the vicinity. In fact, in such networks, the macro users should undergo *no* degradation in performance compared to a system where femtocells are simply not deployed, *i.e.* a flat network architecture.

The research detailed in this section deals with the problem described above. This section begins by detailing the application of a static combination of frequency reuse and power allocation to a hierarchical network. It is shown that IFR performs better from the perspective of macrocells, but FR3 performs best in the case of femtocells. However, this would come at the cost of degraded macrocellular performance. Therefore, the study recommends using more dynamic schemes in conjunction with the static ones described in this report in order to cope with the problem of cross-tier interference. The following two studies divert attention to mitigating cross-tier interference on the control channels of a heterogeneous network based on LTE. The first of these studies presents the performance comparisons of widely used state-of-the art interference mitigation techniques as discussed in 3GPP. It is seen that despite the use of these techniques, one of the control channels still remains largely degraded. What is more, the best performing technique comes at the cost of severe capacity degradation at the femto layer. To combat this issue, the next study presents a novel interference mitigation technique that outperforms the best of the techniques from the preceding study, while at the same time not causing the high capacity degradation. Another study proposes that the macrocell operate in the FDD mode while the femto layer operates in the TDD mode overlapping with one of the FDD bands. Co-tier interference can then be mitigated by using techniques such as busy burst scheduling, etc. It is shown that using this FDD-TDD coordination can result in an outage reduction of approximately 80% and a spectral efficiency improvement of up to 90% at high loads. The next study proposes the use of SG to model heterogeneous network deployment. The study is conducted such that a certain portion of the frequency spectrum is shared between macro and femto layers and the remaining portion is prioritized for use by the macrocell. The study shows that in the prioritized region, the performance of the femtocell largely depends on its proximity to the macro BS. On the other hand, femtocells in the shared part are not affected by the macrocell due to the use of orthogonal resources. Finally, the last study in this section deals with SIC such that the femto and macro layers both use a common resource without undergoing high performance degradation. By decoding the macro transmission, the femtocell is able to suppress interference. This allows macrocells to lower their transmission power, which, in turn, further drives down the interference they cause. It is shown that incorporating this scheme can result in a gain of over 200% in terms of sum rate and a 90% power saving for macrocell users.

This synthesis therefore shows that all of the studies described above contribute towards the BeFEMTO system concept and its objectives.

4.3 RRM and Scheduling

4.3.1 Soft Frequency Reuse in Macro/Femto HetNet

4.3.1.1 Description of the Scheme

Co-channel deployment of macro/femto heterogeneous networks (HetNets) is very attractive from spatial frequency reuse point of view. However, assuming closed subscriber group (CSG) femto base station (called HeNB), the co-channel deployment may lead to some highly undesirable interference limited scenarios. An extensive research is going on at the moment to resolve the cross-tier interference problems in macro/femto HetNets. Solutions based on power control, fractional frequency reuse (FFR) and soft frequency reuse (SFR) have been discussed in the literature. In this section, a dynamic mechanism is presented to mitigate the interference caused by an aggressor FBS to its nearby macro user equipment (MUE) which does not belong to its CSG. This is one of the critical scenarios in the downlink of a co-channel macro/femto deployment [42].

In order to describe our dynamic interference mitigation algorithm, we first introduce the relative scenario. We consider an HeNB in the coverage area of a macro base station (eNB). Both macro and femto transmit on same set of subbands **S**. An MUE u_k^m finds itself close to the HeNB nominated as an aggressor HeNB. This MUE is declared as a victim. Let u_n^f be an HUE served by an HeNB, $\boldsymbol{\delta}_k^{\mathbf{m}}$ be the set of SINR values of all the subbands of **S** reported by an MUE to its serving eNB, $\mathbf{p}_k^{\mathbf{m}}$ be the set of power received (accounting both the pathloss and shadowing) from neighbouring cell by an MUE, $\mathbf{u}_{victim}$ be the set of MUEs which are victim of HeNBs and $\mathbf{B}_k^{(l)}$ be the matrix in which every row includes subband index of $|\mathbf{l}_k|$ best subbands in terms of SINR for a victim macro user *k*. The pseudo code for proposed algorithm is given hereafter:

Algorithm

eNB:

Initialization:

$\mathbf{u}_{victim} = \phi$,

$\mathbf{B}_k^{(l)} = \phi$

Action Phase:

Every macro user u_k^m sends periodically the vector $\mathbf{p}_k^{\mathbf{m}}$ to its serving eNB. Whenever, eNB receives the periodic report from a user u_k^m , it performs the following steps:

if the strongest interferer in the vector $\mathbf{p}_k^{\mathbf{m}}$ is a femto base station

  $\mathbf{u}_{victim} \leftarrow u_k^m$

  find $\mathbf{l}_k$ best subbands in terms of SINR from $\boldsymbol{\delta}_k^{\mathbf{m}}$

  if $\mathbf{l}_k \notin \mathbf{B}_k^{(l)}$

    $\mathbf{B}_k^{(l)} \leftarrow \mathbf{l}_k$

    ask the aggressor HeNB to reduce the power on $\mathbf{l}_k$ these subbands through X2 interface.

  else

    If $u_k^m \in \mathbf{u}_{victim}$

      ask the aggressor HeNB that it could restore the power on $\mathbf{B}_k^{(l)}$ these subbands through X2 interface.

      $\mathbf{u}_{victim} = \mathbf{u}_{victim} - u_k^m$

    end if

  end if

end if

HeNB:

Initialization:

Distribute total cell power equally among all subbands of set **S.**

Transmit all the subbands with equal power.

Action Phase:

HeNB receives message from eNB to reduce or restore the power on $\mathbf{l}_k$ subbands.

HeNB reduces or increases the power on $\mathbf{l}_k$ subbands and redistributes the power on other subbands by keeping the power budget as was in initialization phase.

The Monte-Carlo simulation results for the proposed algorithm are given in Table 25. We assume proportional fair scheduler per subband in both the eNB and the HeNB with 10 MHz of system bandwidth. Every eNB serves exactly 10 UEs while every HeNB serves 2 UEs each. We compare three scenarios in terms of victim MUE and HUE throughputs: no mitigating action in aggressor HeNB, full muting of two subbands in aggressor HeNB and reducing power by 50% on two subbands in the aggressor HeNB. As shown in Table 25, the proposed algorithm (as compared to complete muting and no mitigation action) improves the throughput for both the victim MUE and the HUE.

Parameter	**No mitigation in aggressor HeNB**	**Power reduction factor in aggressor HeNB over 2 subbands**	
		0	**0.5**
HUE Throughput (Mbps)	13.92	13.71	14.2
Victim MUE Throughput (Mbps)	0.8823	5.32	5.28

Table 25: Simulation Results.

4.3.1.2 Contribution to BeFEMTO System Concept and Objectives

The proposed algorithm exploits the X2 interface present between macro and femto base stations as given in BeFEMTO EPS System Architecture [43]. In absence of X2 interface it is not possible that HeNB could change its power dynamically on certain subbands in accordance with channel conditions of victim macro user. It is because the latency of messages on X2 is quite better as compared to the alternate interface S1. From the point of femtocell throughput, the proposed solution avoids the complete muting of subbands by reducing only the power on certain subbands. Hence improved bandwidth utilization will lead to improved per cell spectral efficiency for a given system bandwidth.

References

[42] Femto Forum, "Interference Management in OFDMA Femtocells", White paper of Femto Forum, March 2010.

[43] BeFEMTO D2.2, "The BeFEMTO System Architecture," ICT 248523 FP7 BeFEMTO project, December 2011.

4.3.2 Opportunistic spectrum reuse for stand alone femtocells

4.3.2.1 Description of the Scheme

Considering a cellular environment, there are several levels of diversity that can be exploited based on the dynamics of channel and environment. Multi-user diversity and Route diversity are quite well-known in radio resource scheduling where independence across channel quality experienced by different users is employed to more efficiently utilize scarce resources. However, in a multinode-multiuser environment, another level of opportunity arises based on the isolation factor among different pairs of transmitting node-user to do concurrent transmission, i.e. to reuse the spectrum. This isolation factor is highly dependent to the channel quality gap of a transmitting node to its own users compared to the links to users served by other transmitting nodes. The higher the gap, the better will be the resulting isolation factor. To better picture the new opportunity leading to higher reuse, here an illustrative example is in Figure 42.

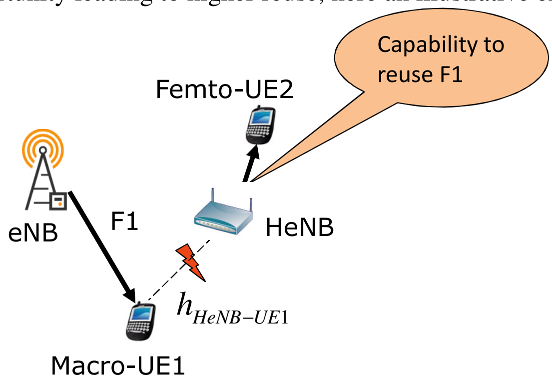


Figure 42: The concept of opportunistic reuse.

In this scenario, we try to exploit the isolation factor from a transmitting node to the users served by another node to do concurrent transmission. As shown, the deep fading condition between a macro user (UE1) and Home eNB (HeNB) provides an opportunity to reuse the same resource for concurrent transmission from HeNB to its corresponding user (UE2) as it does not cause any significant interference to the primary transmission. This method effectively provides some low-cost resources (in terms of interference) in frequency to be scheduled by HeNB to its own users.

Based on the above concept, here we propose a decentralized algorithm to incorporate opportunistic reuse in radio resource allocation for standalone femtocells:

- *Listening to primary channel assignments*, reuse opportunities are quite dependent on the isolation factor among different pairs. So, at the first stage, it is important to categorize channel assignment of primary users based on primary scheduling at the serving node. In this case, the eNB acts as the primary serving node where it supports corresponding macro users.
- *Reuse identification*, at this stage, the reuse opportunities are identified by estimating the channel between secondary serving node (HeNB) and the primary users (Macro). This estimation is done for each primary user based on the channels that has been assigned to it in previous phase. The reusable resources are the one with faded channel condition on HeNB-primary user links. The fading threshold can be tuned adaptively based on the target level of service for primary macro users.
- *Secondary scheduling*, the identified reusable resources are scheduled according to the adopted scheduling policy in secondary node (HeNB) to the corresponding femto users

4.3.2.2 Contribution to BeFEMTO System Concept and Objectives

The proposed solution provides a simple and low cost resource allocation procedure to facilitate integration of femtocells in existing cellular systems without consuming any additional frequency resources.

To evaluate the efficiency of proposed scheme, a set of simulation studies is carried out on the downlink of an OFDMA-based cellular environment comprising seven wraparound cells. The interference is calculated from the first-tier of neighbouring cells as well as serving eNB, HeNB for femto (4) and macro users (8), respectively. For the benchmarking purpose, a plain macro case is additionally considered where the resource allocation is exclusively done for macro users while HeNB is not active. The rest of the simulation parameters are consistent with LTE-Advanced assumption (HeNB power is set to 10 mW). In this scenario, a single femtocell is located at the central block of a 5x5 grid of blocks (each 10m x 10m) whereas the macro users are located indoor in all the other blocks where no femtocell exists.

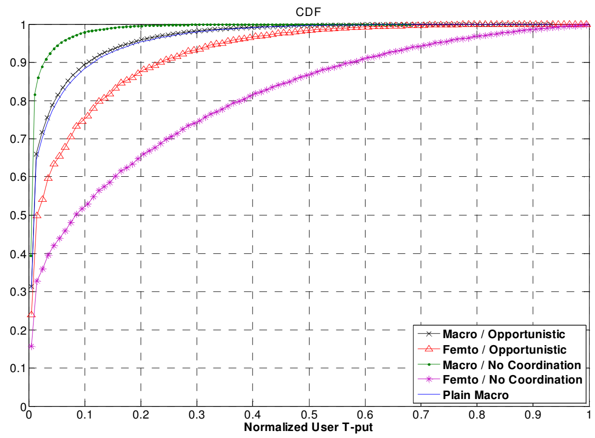


Figure 43: Fully indoor results, exterior penetration loss=10 dB

Figure 43 shows the simulation result for penetration loss value of 10 dB. Here, the throughput values are normalized with respect to the maximum achievable throughput. As shown, the proposed opportunistic reuse solution has minimal impact on the performance of primary macro users whereas it provides substantial gain in the total throughput compared with plain macro scenario. Assuming 50% signalling overhead for the system (either femto or macro), the plain macro spectral efficiency (0.88 b/s/Hz- SISO) slightly decreases to 0.81 b/s/Hz by employing the proposed scheme while the femto cell achieves the spectral efficiency of 0.9 b/s/Hz. It is worth to note that due to eliminating the exterior wall loss between macro users and femto access point, the considered scenario represents a worst case where the performance of macro users could be seriously affected without any coordination as it is evident in the Figure. In no coordination case, spectral efficiency of 2.33 b/s/Hz could be achieved by the femtocell at the cost of drastic reduction in macro throughput (0.24 b/s/Hz). In high penetration loss (20dB), similar trend is observable. However, due to sever reduction in reuse opportunities, the average throughput gain is limited to 5% over the legacy plain macro case.

4.3.3 Synthesis

Femtocells are envisioned to coexist and cooperate with umbrella macro-cells in the same licensed band. This operation, in particular, for closed subscriber group (CGS) femto base stations can lead to undesirable cross-tier interference. In this section, dynamic RRM and scheduling algorithms are proposed to alleviate the undesirable effect (in particular on the macro side) in presence of standalone femtocells.

In general, two specific dimensions can be identified to address this issue: power allocation and resource allocations. In the first algorithm, the macro UE, periodically updates its serving Macro eNB (eNB) on the received power from neighbouring cells. In case a strong interferer (aggressor) is identified as a femtocell, the serving eNB notifies the corresponding femto base station to reduce its power. As the total power budget of each femto station is fixed, the power per resource (sub-channel) is tuned accordingly after each stage of power update. This process will result in a lower level of cross-tier interference leading to better bandwidth utilization and higher spectral efficiency. In the second part, another complementary scheme is proposed that tries to opportunistically exploit the fading condition between a femto base station (aggressor) and the counterpart macro UE (victim). In case the fading condition holds based on a predefined threshold, the femto base station is authorized to reuse the spectrum on the identified faded resources in a dynamic manner as it has insignificant effect on normal macro transmission. This algorithm effectively provides low-cost resources (in terms of interference) for femto transmission resulting in promising performance for femto UEs while controlling the undesirable effect on the macro side. The performance of Femto UE can be dynamically adapted in this scenario based on the tolerable level of interference for Macro UEs via tuning the fading threshold parameter.

4.4 Security

4.4.1 Secure, loose coupled authentication of femtocell subscriber

4.4.1.1 Description of the Scheme

A new procedure is defined in the Home Network in order to perform the authentication for the Femtocell Subscriber. The solution proposed retrieves the subscriber credentials stored in an UICC card inserted in the Broadband Access Router/Femtocell and triggers the authentication procedure that identifies the Femtocell subscriber towards the xDSL or FTTx backhaul.

It is been selected UICC supporting EAP-AKA authentication as the storage point for the subscriber credentials. As currently there is neither a Broadband Access Router nor Femtocell equipment supporting UICC cards insertion and management, an external pluggable USB Smart Card Reader will be used. This device will be plugged into the Multiradio Femtonode attached to the Broadband Access Router (since the Broadband Access Router does not offer either USB connections or UICC cards).

EAP-AKA over 802.1X is the selected algorithm to authenticate the subscriber to the fixed backhaul and configure it in real time. The procedures developed cover the possible scenarios that may take place:

- Initial attachment: The user inserts the UICC card for first time.
- Full Re-authentication: IMSI is used and fresh authentication vectors are generated to avoid security threads.

- Fast Re-authentication: TIMSI is used to avoid overloading the network and detect whether or not the UICC card is removed.

The solution leans on ETSI TISPAN NGN Release 2 specifications for the definition of the access network architecture to support this authentication and real-time configuration solution. Specifically we will rely on [44] specification for subscriber authentication in the fixed access network, and [45] for the dynamic configuration of the access network to deliver the services subscribed.

The following figure depicts the overall architecture employed in the access network.

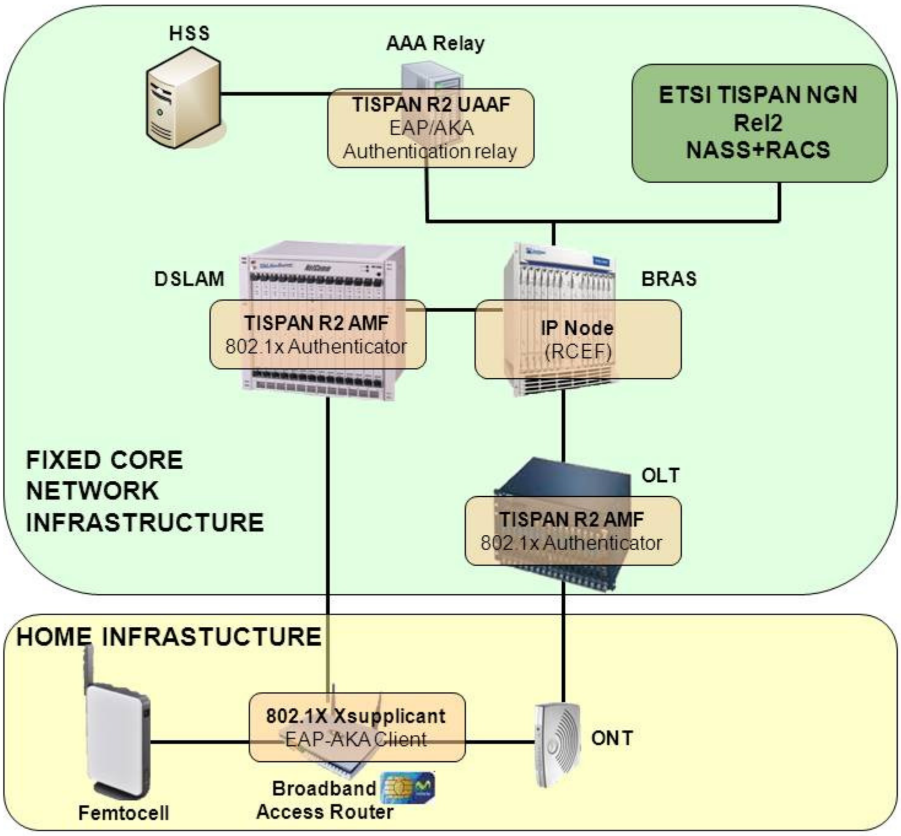


Figure 44: Architecture.

4.4.1.2 Contribution to BeFEMTO System Concept and Objectives

The benefits of this solution is to decouple the authentication procedure from the configuration of the physical elements located in the access network enabling a real time configuration and speeding up the delivery of new services to the user. This solution also allows the service mobility to the user. This means that inserting the UICC card in other Broadband Access Router/Femtocell, it triggers the authentication procedure configuring the Access Network identically as if the subscriber were at home.

References

[44] ETSI ES 282 004 V1.3.0 “Network Attachment Subsystem (NASS)”.

[45] ETSI ES 282 003 V3.4.1 “Resource and Admission Control Sub-System (RACS); Functional Architecture”.

4.4.2 Architecture and IP Security

4.4.2.1 Security aspects of the architecture

Femotcell security is not the primary focus of the project and as a result there is no extensive development but rather a concise review of proposed or general aspects and a selective highlight of security issues worth exploring. Security of the architecture and of individual FAPs has been covered by documents [46] and [47] produced under 3GPP/3GPP2 umbrella. These documents provide sufficient basis for developing secure architecture for femto environment; however, security measures implicated there may need a review once the actual architecture of a system is completed. The reason for such caution is quite simple: a new vulnerabilities and new angles of attack are constantly being developed and applied. Cost of the equipment used to interfere is also much lower than in the past. There is also a valid expectation that such attacks would be carried out as the type of communication passing via mobile networks is often of a high value: financial information, access credentials to banking services, and confidential correspondence. While architecting a femto solution various aspects must be considered. Much effort and attention has been devoted to security of individual femtocell devices. One thing we can be sure of is that for most intensive purposes femto devices are or would be deployed in environment that is out of control of the telecommunication company. At least in theory many of the measures implemented to secure femto device were shown as insufficient or ineffective. Following sections will take a bit deeper look at these aspects and provide a general recommendation for system architects.

3GPP2 Femtocell Security Framework utilizes reference model that provides a simplified view of the architecture. Framework document delivers overview of the features expected from a system. As indicated above we will focus on select set of aspects: communication via public network, security of the Femto Access Point (FAP), and security of communication via FAP.

Highlights of exploitation angles

Majority of the attacks shall be expected from locations on a public network; however, the fact that physical device may end up in the wrong hands is also a major threat. Below are some ways attackers may attempt to get around security measures of our solution:

- Root and flashing the femtocell utilizing rogue device.
- Remote root access with remote root exploit.
- Information collecting once the device is controlled. Information may include some details of subscribers connecting via the device, including the telephone number and the location of the device.
- Security Gateway access or interference with operator network.
- Subscriber denial of service (DoS) / Owner DoS / Operator DoS.
- IMSI-Catching.
- Interception of communication due to misconfigured or compromised devices
- Modification of communication details

The above list is just an example of what has been attempted in the past and what would most likely be attempted before any new exploits were devised. While some of these seem impossible to perform it has been shown in the past that attackers would go to many lengths if the prize was worthwhile the effort.

4.4.2.2 Countermeasures

Various measures have been recommended in the aforementioned documents. We will highlight three areas.

IP security (communication over the public network)

The recommendation for communication over the public network is to utilize IPSec in order to secure IP protocol communication. All communication would pass via encrypted tunnel and would be safe from eavesdropping. This may be the strongest measure in securing the Femtocell deployments. Thus far IPSec has been considered a strong element in the security toolset. Nevertheless, each implementation should have detailed guidelines for IPSec reflected in proper configuration policies and instructions.

FAP device security

Security of the device may be the most difficult since physical access to the device gives skillful attacker an enormous advantage. Most of the security measures should be considered as deterrents rather than complete security measures. Obviously, every effort should be made to establish measures so effective that breaching the security may be too complex or too expensive. This said, while architecting the solution it would be a good advice to treat FAP device as an element that comes without security warranty – it may not be ours for all the intensive purposes. Remaining components of the system must be architected in a way that follows such line of thought: no information stored/cached in the device, limited or no information about operator network, and no way to interfere with communication between subscriber and the operator.

Security of communication via FAP is a major issue if the operator assumes that the device is secure. No such assumption should be made and a proper security review should take this under consideration.

References

[46] 3GPP2 S.S0132-0 ,"Femtocell Security Framework", V1.0, January 28 2010.

[47] 3GPP ,"Security of Home Node B (HNB) / Home evolved NodeB (HeNB)", TS 33.320, V10.4.0, January 2012.

4.4.3 Synthesis

Security of the Femto architecture has been only highlighted in the above two sections. First section provides a strong point on benefits of the solution where the authentication procedure is decoupled from the configuration of the physical elements located in the access network. Such approach enables a real time configuration and speedier delivery of new services to the user. This solution also allows the service mobility to the user. This means that inserting the UICC card in other Broadband Access Router/Femtocell triggers the authentication procedure configuring the Access Network identically as if the subscriber was at home.

The second section highlights some aspects of the Femto architecture security. Initial analysis of potential ways to breach devised security measures some general recommendations are presented. These include:

following a strict policies and instructions when configuring IPSec for securing IP protocol, treating FAP device as an element that is owned (and thus fully accessible) by a third party, and finally, to take measures that would secure communication between subscriber and the operator.

4.5 Traffic Management

4.5.1 Analytical framework for the analysis of traffic offloading

4.5.1.1 Description of the Scheme

The increasing demand of mobile data traffic is starting to stress the networks of mobile network operators (MNOs). Techniques for offloading traffic (partially or totally) from the network of the MNO are currently being designed and deployed at various points of the network, which depend on the goal of each MNO. Such techniques divert traffic to offloading networks, e.g. a femtocell network, or directly to the Internet. An eventual analytical framework is expected to help in taking network design decisions when deploying offloading techniques. Within the BeFEMTO project we propose a generic analytical approach for the analysis of the impact that offloading techniques might have on the networks of MNOs. The model is generic in the sense that it is independent of the specific offloading technology used and may be of use to provide bounds on network dimensioning.

The proposed theoretical framework is based on traffic models found in the literature. In this sense, and based on previous measurements [48], we characterize the duration of offloading periods as heavy-tailed. On the other hand, [49] and references therein present well-known models of the behaviour of single flow traffic, which describe traffic burstiness in terms of long-range dependence and heavy-tails. In the same way, we characterize user activity according to these models.

Thus, it assumes that user activity periods Y(t) and periods characterizing offloading X(t) are heavy-tailed. We model them as strictly alternating independent ON/OFF processes. Therefore, the non-offloaded traffic Z(t) (i.e., that traffic still being served by the MNO on a regular basis) is modeled as the product of these two processes Z(t) = X(t)Y (t) as shown in Figure 45.

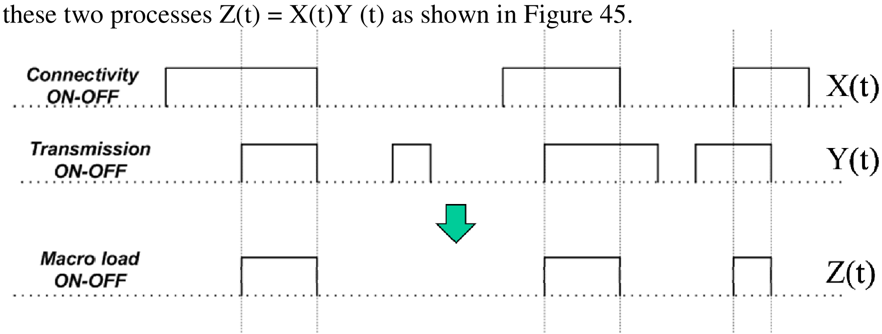


Figure 45: Non-offloaded traffic from a single source.

By studying asymptotic behaviour of the non-offloaded traffic, we have proved that the ON/OFF process Z(t) has ON and OFF periods with durations that follow a heavy-tailed distribution, hence making it long-range dependent. We derived the tail-indices describing the heaviness of the ON and OFF periods of Z(t) as a function of tail-indices of the two original processes.

The analytical results were validated by means of simulations and the results of the simulations matches well with the analytical result.

That is, when applying offloading to a heavy-tailed ON/OFF source, the distribution of the resulting sequence of ON/OFF durations may still keep heavy-tail behaviour but with a different behaviour of the tail. At large scale, when aggregating a large number of sources, the result is that the burstiness of the arrival flow has changed.

In particular, if to denote as Hz and Hy, the Hurst parameters of the aggregate arrival process to a system when we apply an offloading strategy (Hz) and when it is not applied (Hy) we obtained the following observations:

$$\begin{cases} H_z > H_y, & if\ \alpha^z_{min} = \alpha^z_{off} \text{ and } \alpha^x_{off} < \alpha^y_{min} \\ H_z \leq H_y, & otherwise \end{cases},$$

where α is the parameter characterizing the heavy-tails of the ON and OFF periods of processes Z(t), X(t), Y (t), correspondingly.

From a network dimensioning perspective this relation has a high relevance. Specifically, the expression states that special care should be taken to control the distribution of the duration of offloading periods. In particular, when disconnection (offloading) durations present higher heavy-tailness than the original system (i.e., αoffx < αminy), the net result is that the offered load to the Mobile Network will present a higher degree of burstiness (i.e., Hz > Hy).

That is, taking into account the expression a worst case scenario is when αoffx →1, a best case scenario when both αoffx and αonx do not have a heavy-tailed distribution (i.e., αonx=2 and αoffx=2).

To calculate the network capacity needed to guaranty the certain level of QoS under bursty traffic we used the methodology proposed by Norros in [50], [51].

Hence, performance bounds of the resource consumption in the network of the mobile operator can be defined for arriving traffic with a different degree of burstiness (Hz or Hy) and can be used when dimensioning the network.

It is possible also to evaluate the benefits of offloading by comparing the required resources before and after deploying offloading for providing a given quality of service.

As an illustration of this fact, let us consider Figure 46, which plots the relation Cz/Cy between the resources needed after and before offloading with respect to the tail index of offloading periods (αoffx). The figure shows the influence of the different design parameters on the dimensioning of the network after applying offloading. In particular, the figure focuses on illustrating the strong dependence of the effectiveness of offloading on the actual distribution of offloading periods. Taking as a reference the dashed line in the figure indicating the amount of traffic offloaded (i.e., P(X(t) is in ON state), it can be seen that when the distribution of offloading periods exhib large tails (i.e., αoffx is low) there is a high probability that the network operator needs to increase resources to maintain QoS. Another interesting observation is that the reduction on the number of resources is best (and cannot do better than) when $\alpha^x_{off} \geq min(\alpha^y_{off}, \alpha^z_{on})$.

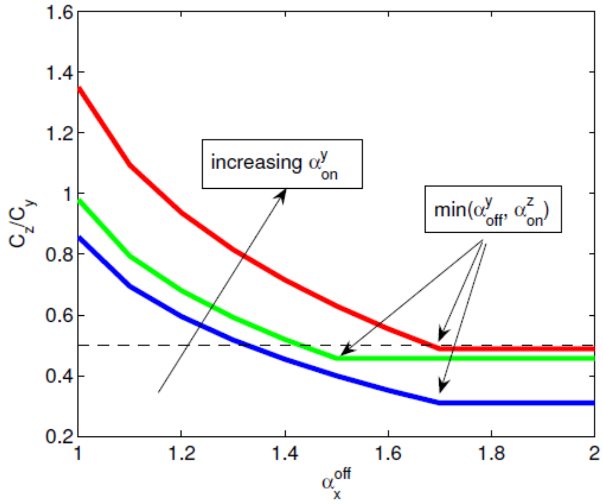


Figure 46: Illustration of the relation between the parameters of the system and the required capacity before and after implementing offloading.

4.5.1.2 Contribution to BeFEMTO System Concept and Objectives

The proposed analytical framework contributes to BeFEMTO System Concept by estimating the impact that offloading technique might have on the network resources. In particular, based on the characteristics of the aggregated non-offloaded traffic, it provides performance bounds of resource consumption in the network of the MNO when deploying offloading strategies. Furthermore, it illustrates the influence of the different design parameters on the dimensioning of the network before and after applying offloading.

One of the main conclusions of our study is that offloading does not necessarily entail less resource consumption in the network of the operator. Under certain conditions, and due to an increase of the burstiness of the non-offloaded traffic, the amount of network resources to offer a given level of QoS is increased. In this context, the tail-index of offloading periods is the most important design parameter to make non-offloaded traffic less heavy-tailed, hence reducing the resources needed in the network of the operator. Thus, the appropriate design of offloading periods is key in network dimensioning.

Since the analytical framework for modelling traffic in networks implementing offloading is agnostic of both the point of the network in which it is applied and the specific offloading technique and it agrees well with the BeFEMTO System Concept. For instance, a HeNB or a LFGW can be considered as offloading points and offloading technique based on LIPA/SIPTO can be applied.

References

[48] K. Lee, Y. Yi, J. Lee, I. Rhee, S. Chong, ”Mobile Data Offloading: How Much Can WiFi Deliver?”, in *Proc. of ACM CoNEXT 2010*, USA, December, 2010.

[49] S. Stoev, G. Michailidis, and J. Vaughan,”On Global Modeling of Network Traffic”, *the 29th Conference on Computer Communications INFOCOM 2010*, San Diego, California, March 2010.

[50] I. Norros, ”On the use of fractional Brownian motion in the theory of connectionless networks”, *IEEE J. Select. Areas Commun. 13, 6*, 953-962, 1995.

[51] I. Norros, ”A storage model with self-similar input”, *Queueing Systems Volume 16*, Numbers 3-4, pp. 387-396, 1994.

4.5.2 A QoS-based Call Admission Control and Resource Allocation Mechanism for LTE Femtocell Deployment

4.5.2.1 Description of the Scheme

This study addresses the problem of congestion that can occur when a large number of femtocells utilise DSL as a backhaul link. Traditionally, fixed broadband access providers provision dedicated network resources to land-line calls, meaning that there would be little or no degradation in call quality due to limited network resources. In the case of most femtocell deployments, however, voice calls are transported together with data traffic over residential Internet connections.

Femto voice traffic is tagged by the femtocell with a DiffServ Code Point (DSCP) in the IP header that allows the DSL Access Multiplexer (DSLAM) to identify it as voice and forward it through the Expedited Forwarding (EF) queue. The EF queue provides the highest service level and is utilised for low latency and low bandwidth intensive services such as voice; however in typical deployments it has a fixed and relatively limited bandwidth. As the number of FAP deployments increases, the EF queues on DSLAMs will become increasingly congested, which will lead to increased packet delays, jitter and loss with a corresponding impact on the voice call quality. Therefore, the quality of the call depends on both the radio link from the customer's mobile device to their HeNB *and* the level of congestion on the backhaul link [52].

This work has developed and studied a method to enable both Quality of Service (QoS) aware Call Admission Control (CAC) and bandwidth negotiation in the backhaul links [53]. It assumes that MNOs would have Service Level Agreements (SLA) in place with the fixed broadband access provider that ensure maximum and minimum bandwidths at each DSLAM dedicated for their femtocell VoIP traffic, but that these bandwidths would be dynamically re-negotiable to allow control of cost for bandwidth reserved at the DSLAM while maintaining high voice call quality for their customers.

The proposed scheme is based upon the quality of ongoing voice calls passing through the HeNB-GW. A voice monitor application residing in the HeNB-GW maintains a list of ongoing calls, measures the real time voice call quality, determines when problems occur and employs the admission control and dynamic resource allocation mechanisms to restore/maintain the quality.

It uses the Committed Information Rate (CIR) value from the SLA to calculate a nominal number of calls, i.e. the maximum number of calls that can be supported with the default bandwidth allocation provided by the ISP to the MNO. It is computed as the ratio between the CIR [bps] and the call bit rate plus tunnelling overhead (using AMR’s highest mode).

For each call, it then monitors the incoming packets and calculates the call’s delay, jitter and packet loss. With the formula provided by the E-model [53] the transmission factor R and the average MOS is calculated. The monitor uses the individual average MOS values of each call to compute an average MOS value across all calls passing through the HeNB-GW. As some calls may have a significantly lower MOS value due to quality issues in the Home Area Network, the average MOS value is corrected by filtering out these outliers.

If the corrected average MOS value is less than 3.8 then no new calls will be accepted until the resource allocation in the DSLAM can be increased and the backlog of packets in the queue is cleared. If the current bandwidth used in the EF queue is lower than the committed burst then the VoIP monitor will request more bandwidth. If the average MOS is higher than 3.9 then new call requests will be accepted. If it is higher than 4.0 and the number of simultaneous calls has decreased then the level of bandwidth in the EF queue is decreased, but no lower than the committed information rate (CIR). The average MOS thresholds were decided considering Figure 2.65 obtained from [54]. The proposed mechanism attempts to maintain all calls in the Medium to Best quality range.

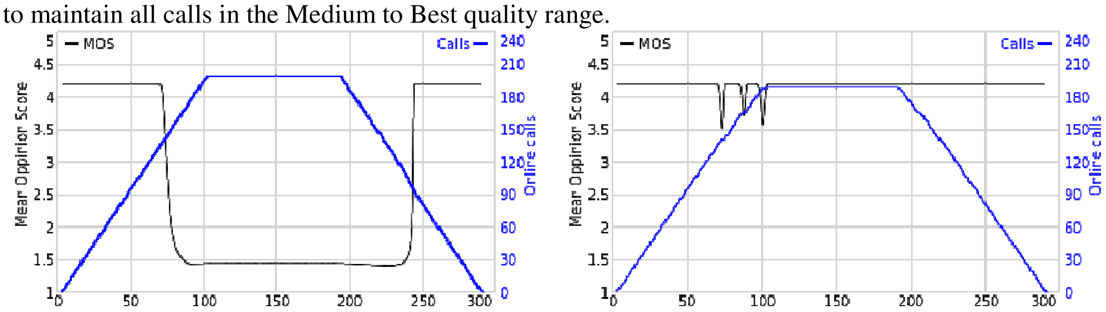


Figure 47: Overall MOS and number of online sessions versus time without (left) and with (right) proposed scheme.

Figure 47 exemplarily shows the average MOS and the number of ongoing calls over time without (left) and with (right) the proposed QoS and CAC mechanisms in place. Without the scheme (left), all calls are accepted and voice packets are forwarded from the EF queue as soon as they arrive; this is unless the imposed bandwidth limitation has been reached in which case the packet is queued. This queuing means introducing extra delay and this delay increases until the buffer is full at which point the buffer will overflow resulting in dropped/lost packets. At this point the MOS of all ongoing calls degrades rapidly.

With the proposed scheme (right), when the overall MOS drops, the feedback mechanism rejects any new call requests and the overall MOS for all calls is restored to a high level. Figure 48 then shows a plot of the bandwidth requests made by the algorithm in the FGW and granted by the DSLAM. It can be seen that for each moment when the average MOS is below the threshold (3.8) the requested bandwidth on the DSLAM is increased up to the maximum committed burst. This extra bandwidth is released only when the average MOS has returned to a high value and the number of simultaneous calls has decreased.

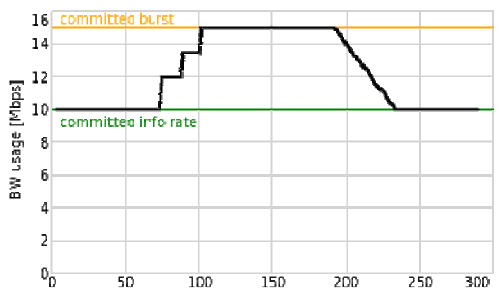


Figure 48: DSLAM's EF queue bandwidth usage versus time.

4.5.2.2 Contribution to BeFEMTO System Concept and Objectives

The proposed QoS-based call admission control and resource allocation scheme addresses the case that femto voice call quality is degraded not as result of resource limitations on the access but on the femtocell backhaul. It is applicable both to the BeFEMTO themes of (large numbers of) standalone femtocells as well as femtocell networks.

References

[52] C. Olariu, M. O. Foghlu, P. Perry, and L. Murphy, "VoIP quality monitoring in LTE femtocells," in *Proc. of the IFIP/IEEE International Symposium on Integrated Network Management (IM)* , pp. 501-508, Dublin, 2011.

[53] C. Olariu, J. Fitzpatrick, P. A. Perry, and L. Murphy, “A QoS based call admission control and resource allocation mechanism for LTE femtocell deployment,” in *the 9th Annual IEEE Consumer Communications and Networking Conference (CCNC’2012)*, Las Vegas, NV, USA, Jan. 2012.

[54] ITU-T. G.107, "The E-Model, A Computational Model For Use In Transmission Planning," 2005.

4.5.3 Voice Call Capacity Analysis of Long Range WiFi as a Femto Backhaul Solution

4.5.3.1 Description of the Scheme

This work studied the use of long range WiFi as alternative to current copper, optical fibre or microwave based technologies for backhauling outdoor smallcell traffic. A frequent challenge in smallcell deployments is that wired backhaul connectivity is not readily available at the most suitable smallcell installation site and that installing wired connectivity or resorting to microwave-based wireless solutions is neither practical nor cost-efficient. This has motivated many operators to begin looking for alternative lower cost wireless backhauling solutions like Wireless Fidelity (WiFi) [55]. Although WiFi was originally designed as a short range best effort wireless technology, studies and deployments have shown its ability to achieve much longer distances [56], and in developing nations it is already used to provide long-range Internet and telecommunications connectivity.

Specifically, this study analysed the number of high quality circuit switched AMR voice and packet switched AMR VoIP calls that can be supported via femtocells using long range WiFi backhauling. For this, the WiFi implementation of the ns-3 network simulator used for the study had to be adapted to the requirements of long range WiFi point-to-point links (optimized ACK timeout, DIFS and slot times, etc.) and support for RTP and AMR had to be added. The implemented AMR application supports all eight codec modes and includes codec adaptation, DTX and voice activity generation functionality.

Codec adaptation is normally done based on a combination of quality metrics of the radio access channel only, i.e. it cannot adapt to changes in the performance of the backhaul connectivity. In this work we developed a QoS based adaptation mechanism. The QoS metric used is the MOS and is computed using a real time implementation of ITU-T’s E-Model, a standardised computational model for subjective call quality assessment [57]. Each VoIP application continually monitors its downlink QoS in real time based on delay, jitter, loss and the AMR codec mode. When the MOS score falls below a predefined threshold the application sends a CMR request using the AMR header of outgoing packets to the source application, on reception of this the source application will change the source coding rate to the requested mode. Correspondingly, if the computed MOS value is above a predefined threshold then the receiving application sends a CMR request to increase the coding rate to the next highest rate. To prevent rapid and continual changes in the codec modes due to the small network fluctuations, a time constraint is placed on the period between codec changes; in the results presented in this paper a time constraint of 1 second is used. This constraint is not used when changing from a silent period to a voice active period.

Figure 49 shows that this mechanism effectively adapts to changes of the backhaul connection's performance. It plots the achieved MOS and AMR mode of a single voice call over time. The voice call traverses a 2Mb/s backhaul link that is loaded with an additional background voice call every 5 seconds, reaching a peak of 32 background calls at 200s, from which point on one background call terminates every 5 seconds. Plots on the left and right show the results without and with codec adaptation, respectively.

As can be seen the link begins to become congested after approximately 160s at which point the call quality begins to degrade. In the case were no adaptation is performed, the call quality of the ongoing voice calls drops to a very low MOS value of approximately 1.5. However, in the case were all calls utilise the proposed adaptation mechanism, much higher call quality was maintained due to each endpoint dynamically adapting encoding rates to match network conditions. It can also be observed that with the proposed adaptation the call quality recovers much faster as calls begin to end and link capacity becomes available.

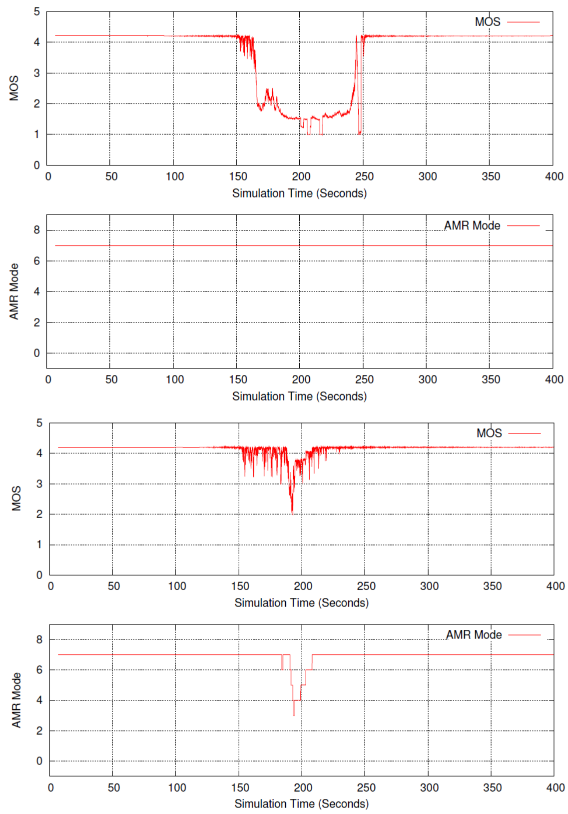


Figure 49: Call quality over 2Mbps link with background voice calls without (left) and with (right) adaptation.

Data Rate	Analytical upper bound)	Analytical (with collisions)	Simulation
6 Mbps	22	21	19
9 Mbps	27	26	25
12 Mbps	30	29	28
18 Mbps	34	32	33
24 Mbps	37	35	35
36 Mbps	40	38	38
48 Mbps	41	39	40
54 Mbps	42	40	41

Table 26: AMR over Iuh voice capacity for 5km 802.11a link (PS mode).

This work has studied both CS and PS voice call capacity over different WiFi backhaul link configurations both using analytical and simulation models. Table 26 exemplarily shows the AMR over Iuh voice capacity for a 5km 802.11a backhaul link at different link data rates for PS calls. It can be seen that there is a very good correlation between both analytical and simulations results. The CS mode results are similar, but more calls can be supported due to lower protocol overhead of the CS calls.

4.5.3.2 Contribution to BeFEMTO System Concept and Objectives

The proposed scheme constitutes a second solution for smallcell backhauling investigated by BeFEMTO, next to the relay-based backhauling to a macrocell. The advantage of this solution relative to the relay-based one is that it uses a different spectrum than the radio access and therefore does not impair the spectral efficiency of the access. On the other hand, as it utilizes license-exempt spectrum, it is more susceptible to interference from other networks.

References

[55] O. Tipmongkolsilp, S. Zaghloul, and A. Jukan, “The evolution of cellular backhaul technologies: Current issues and future trends,” *Communications Surveys Tutorials*, IEEE, vol. 13, no. 1, pp. 97 –113, 2011.

[56] P. Bhagwat, B. Raman, and D. Sanghi, “Turning 802.11 inside-out,” *SIGCOMM Comput. Commun. Rev.*, vol. 34, pp. 33–38, January 2004.

[57] ITU-T, The E-model, a computational model for use in transmission planning, International Telecommunication Union Recommendation G.107, May 2000.

4.5.4 Deployment, Handover and Performance of Networked Femtocells in an Enterprise LAN

4.5.4.1 Description of the Scheme

The pilot was deployed in the ground floor of a Telefónica I+D building in C/Don Ramón de la Cruz 82-84, in Madrid. Femtonodes from two manufacturers that will be referred as manufacturer A and manufacturer B were installed in the same locations in order to allow a consistent performance comparison. Also two femtonodes subsystems (A and B) were used in this pilot to provide service to the corresponding femtonodes

The femtonodes were connected to TID’s LAN, and connected through a IPSEC tunnel to each respective femtocell subsystem located in Telefónica’s radio labs in Pozuelo (Madrid). It must be noted that the enterprise femtonodes pilot was not connected to the general mobile core network that provides service to

Spain's customers, but to an evaluation core network used for testing purposes and used a different frequency and PLMN ID that the commercial mobile network, to avoid uncontrolled interactions with real customers.

Two femtocell subsystems were used; one for each manufacturer, and as it is not possible to disclose some vendor-specific details, the next figure shows the generic architecture of a femtocell subsystem and the network architecture used in this pilot. The generic elements that compose a femtonode subsystem are:

Security GW (IPSec Gateway).

IP Clock Server, that provides a reference clock for femto synchronization.

Configuration Server (Femtocell Manager), which configures the femtonodes radio parameters.

Femto Manager (Femtocell Home Register).

Femto subnetwork manager, controller of the femtonode subsystem network.

AAA Server (Authentication, Accounting and Authorization Server).

Femto Gateway (Access Gateway).

Figure 50 depicts the network architecture of the enterprise femtocell pilot. In this picture the Femto Manager includes the AAA Server

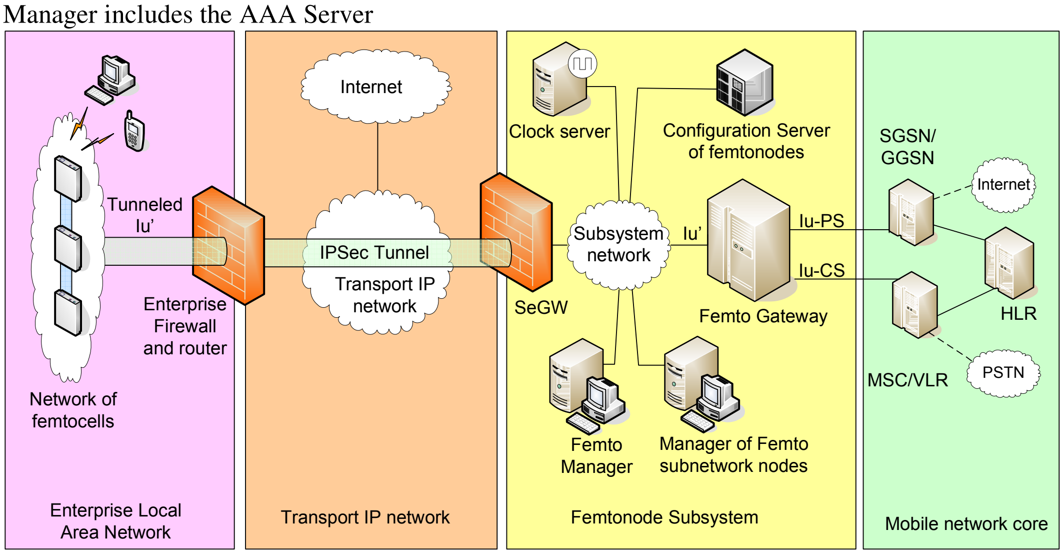


Figure 50: Network architecture of the enterprise femtocell pilot.

The total area to cover has been 1,900 m2, and the femtonodes were installed in the upper side of three pillars, close to the ceiling and beside the enterprise Wi-Fi access points. In order to avoid any interference with the macro layer, it was decided to make use of the UMTS carrier assigned in Telefónica Spain for indoor coverage, i.e. UARFCN 10788..

In order to evaluate handover between femtonodes the first step was to configure the femtonode cluster, using the femtocell configuration server, configured with the frequency and the list of the possible scrambling codes that the femtonodes choose in the initial scanning. Figure 51 shows the Wireshark traces corresponding to handover failure when the mobile was moving between F_2, F_3 and F_1.

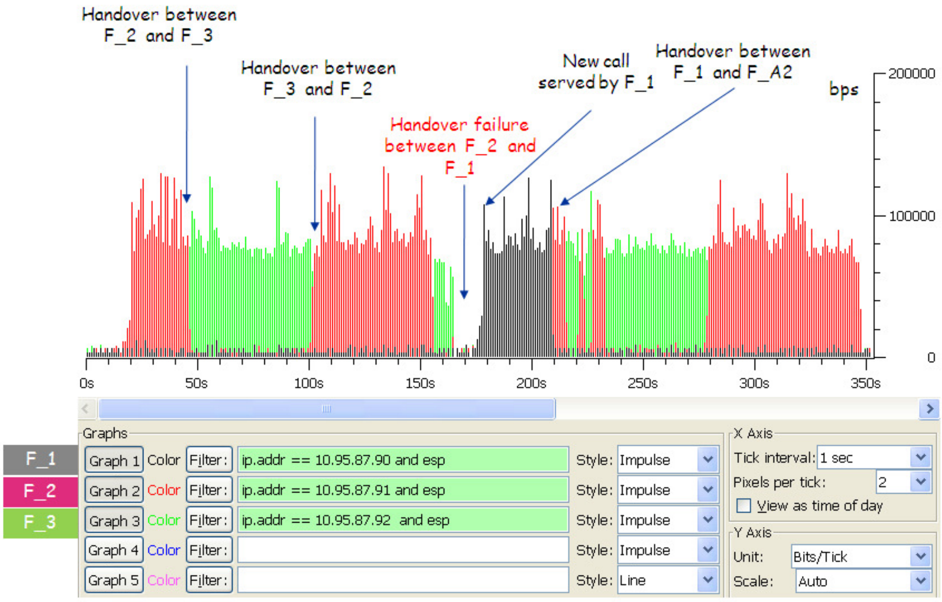


Figure 51: Wireshark traces.

The figure shows the call drop during a handover among F_2 and F_1 using self-scanning of the femtonode to create the femtonode neighbouring list and hard handover. We can extract the conclusion that the creation of a group of networked femtonodes, based on scanning of neighbours is a highly adaptive technique that can automatically add or remove neighbour femtocells, but present the inconvenience that in the moment to proceed the scanning of a neighbour femtocell, its signal is temporally hidden or interfered, it will be not included in the neighbour list, and therefore handover to this femtocell will be not possible.

Regarding the femtocells IP connectivity, two options were considered to connect the group of femtonodes to the Internet. a) Sharing the Public IP Address. With this approach it was created the IPSeC tunnel without problems, but there were packet losses when the IPSeC tunnel closed in the direction SeGW-to-femtonode when the firewall timer “UDP Virtual Session Timeout" expired and there were not traffic from the femtonode to the SeGW. B) Dedicated Public IP Address. With a dedicated Public IP Address there were not packet losses between the femtonodes and the SeGW.

4.5.4.2 Contribution to BeFEMTO System Concept and Objectives

The proposed schemes contribute to BeFEMTO System Concept by significantly reducing the cost of the femtocell backhauling in an enterprise scenario, and at the same time improving its reliability, thanks to the reuse of the enterprise’s wired infrastructure. The proposed scheme makes its possible to use current Ethernet-based Local Area Networks and the enterprise access link for providing connectivity to the core network to the femtocells installed in the enterprise’s premises.

4.5.5 Synthesis

Besides enhanced indoor coverage, a main driver for femtocell deployments is that they can be used to offload the macrocellular network and enhance mobile access capacity in hot-spot areas in a highly cost-efficient manner. Cost-efficiency of femtocell deployment and operations is also a common theme for the traffic management schemes presented in this section.

The first work presented an analytical framework for studying the effect of offloading network traffic at standalone outdoor femtocells and in particular on the traffic that still remains to be handled by the mobile core network. A key finding from an application of this framework is that when heavy-tailed traffic is offloaded with offloading periods that are themselves heavy-tailed, the burstiness of the non-offloaded traffic can actually increase. This result is important for operators to plan the cost-impact of and dimension their mobile networks for traffic offloading.

The second work presented a method for performing call admission control and dynamic backhaul resources allocation for LTE(-A) femtocells. It addresses the issue that in LTE, voice calls are transported as VoIP and typically DiffServ marked for the EF queue to receive preferential treatment on resource limited backhaul links, but that these EF queues' capacity is finite. The proposed method measures the Quality of Experience of ongoing voice calls to determine whether new calls can be admitted without adversely affecting ongoing calls and to potentially increase the backhaul's EF queue capacity if needed. This results in conservative backhaul resource allocation instead of costly static overprovisioning.

The next work studied the use of commercial off-the-shelf IEEE 802.11 technology as a more cost-efficient solution for long-range wireless backhauling of femtocell traffic than traditional microwave-based backhauling. In particular, it studied the backhaul's capacity of transporting VoIP calls both without rate adaptation and with rate adaptation using a novel algorithm that considers Quality of Experience targets for the voice calls. It is shown that the new rate adaptation algorithm effectively maintains high QoE values as the backhaul link quality or the link's utilization change.

Finally, the section reports on a pilot study in which several enterprise femtocells were deployed in an office environment. One of the goals was to determine whether they can be deployed over a LAN shared with enterprise services instead of a costly dedicated infrastructure. Other goals included testing of the auto-configuration features that reduce deployment and operational costs. The pilot has revealed weaknesses in current femtocell systems with respect to automatic neighbour list creation and handovers.

4.6 Mobility Management

4.6.1 Fast Handover Failure Recovery

4.6.1.1 Description of the Scheme

In the 3GPP LTE system, a UE-assisted hard handover procedure is used [58]. For inbound handover from macrocell to femtocell and outbound handover from femtocell to macrocell, the HO signalling has to go through the Internet backhaul, the latency of which may be considerably large and uncertain. Furthermore, the femto base stations are normally deployed indoors. The radio signal strength may suffer an abrupt degradation when the UE is crossing the doorway due to the wall penetration loss. Finally, the interference from the neighbouring cells under the co-channel deployment may reduce the decoding probability of the HO signalling messages. The above factors together may cause frequent Radio Link Failures (RLFs) occurring during a HO procedure, i.e. the UE may lose the connection to the current serving cell before a HO is completed. In the current specification, when the UE detects a RLF, it starts the RLF timer (T310). Upon expiration of the RLF timer, the UE will search for a suitable target cell to perform the Radio Resource Control (RRC) connection re-establishment. If the target cell has been prepared by the source cell (i.e. RLF occurs after the source cell sends the HO request but before the HO command is sent out to the UE), the re-establishment is successful and the session communication will resume. Otherwise, the UE transitions from RRC_CONNECTED state to RRC_IDLE state and attempts to establish a new connection from the scratch. This will incur a long service interruption time, extra signalling load to the core network and buffered data loss at the source cell. In order to avoid the UE entering RRC_IDLE state, the RLF timer is normally set to be conservatively long to allow enough time for the target cell preparation. Thus, the service interruption time due to RLFs may be relatively long even when the RRC connection re-establishment is successful.

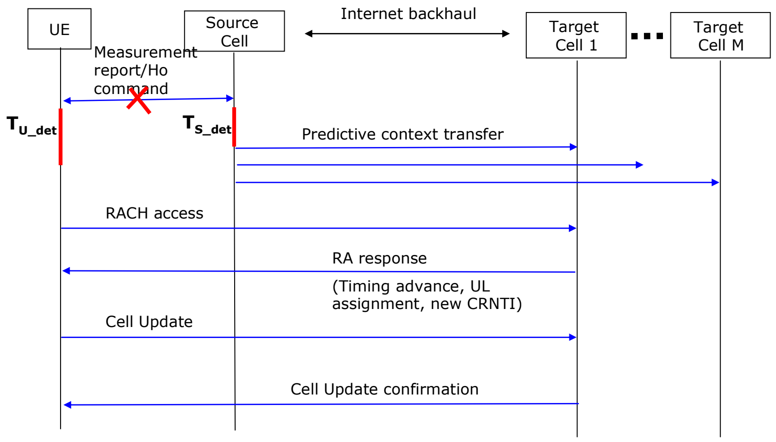


Figure 52: MSCs of the forward handover with predictive context transfer in case of a RLF.

We propose a UE-based *Forward Handover procedure with Predictive Context Transfer* (*FH_PCT*) for fast RLF recovery. Figure 52 shows the message sequence chart of this scheme. In case of a RLF occurring before the HO command is successfully decoded by the UE, the UE can identify the latest measurement report successfully received by the source cell by examining the ARQ information. The UE will start a timer (T_{U_det}) to eliminate the effect of the channel fluctuation. We can reuse the RLF timer (T310) defined in 3GPP for this purpose, but the duration of this timer can be set to be relatively short. If the connection with the source cell is recovered before this timer expires, the normal transmission resumes. Otherwise, the UE will initiate the RRC connection re-establishment procedure upon the expiration of this timer. The UE will autonomously select a target cell and contact it via RACH access. From the source cell's side, a similar timer (T_{S_det}) is started on detection of the RLF for the UE. The detailed implementation for RLF detection at base station is left to operators' discretion. Upon the expiration of this timer, the source cell will select N potential target cells based on the latest received measurement report to send the UE's context (downlink data buffered at the source cell can be sent as well depending on the requirements of the services). Meanwhile, a copy of the UE's context is kept at the source cell in case that the target cell selected by the UE does not match the potential target cells predicted by the source cell. After the RRC connection re-establishment is completed at the UE, if its context is already available at the target cell, the data transmission will be resumed immediately. Otherwise, a context fetch request will be sent from the target cell to the source cell to get the UE's context.

The U-plane interruption latency is analysed for two cases: (1) A RLF happens before a measurement report is sent to the source cell; (2) A RLF happens after the measurement report is sent to the source cell but before the HO command is received by the UE. The T310 timer used in 3GPP should be given a relatively high value compared to the HO preparation delay. This can enable that the target cell has been prepared when the UE tries to connect with the target cell. For comparison purpose, we assume that $T_{310} = 2 \times T_{backhaul}$, where $T_{backhaul}$ is the expected backhaul latency from the source cell to the target cell. Figure 53 shows that the proposed scheme can significantly reduce the service interruption latency in case of a RLF, especially when the backhaul latency is long. In addition, the interruption latency of the proposed scheme is same for both cases, i.e. no matter whether the failure happens due to missing measurement report or HO command.

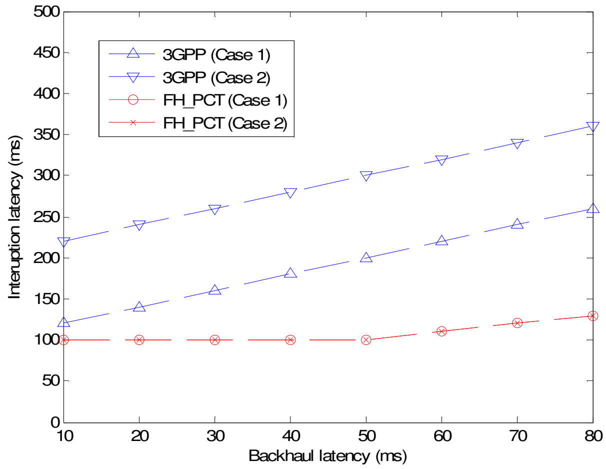


Figure 53: Interruption latency in case of a RLF.

4.6.1.2 Contribution to BeFEMTO System Concept and Objectives

The RLFs may frequently occur when the UEs move between macrocell and femtocell. To reduce the service interruption time when a RLF occurs, a UE-based forward handover procedure with predictive context transfer is proposed. The proposed scheme contributes to BeFEMTO System Concept by optimizing the handover procedure.

References

[58] Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (EUTRAN); Overall description; Stage 2 (Release 10), 3GPP Std. TS 36.300 v10.5.0, Sep. 2011.

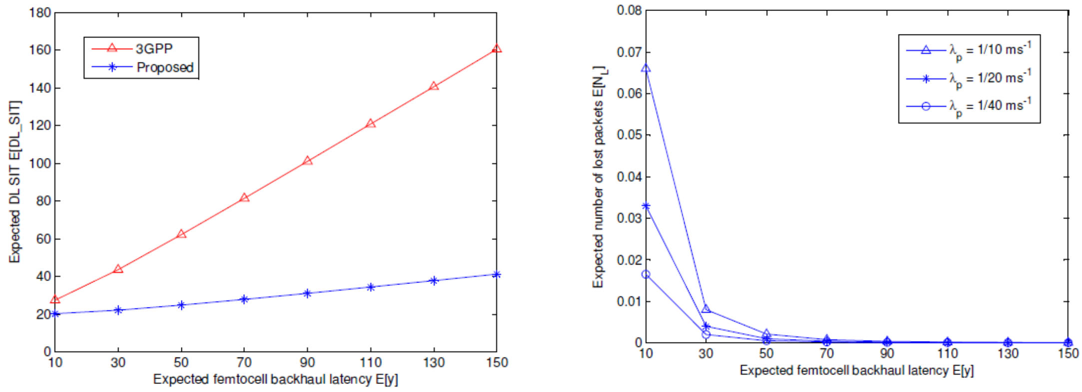
4.6.2 Seamless Handover Based on Reactive Data Bicasting

4.6.2.1 Description of the Scheme

When a user moves from a macrocell to a femtocell or vice versa, seamless mobility should be supported by the employed handover procedure such that the handover is not perceptible to the users. Two main Key Performance Indicators (KPIs) during handover are Service Interruption Time (SIT) and packet loss. In current 3GPP standard, the same hard handover procedure as for inter-macro mobility is used for macro-femto mobility [59] . A data forwarding procedure is used to forward the Downlink (DL) packets from the source cell to the target cell during handover to enable lossless packet delivery. Whereas this procedure works well for the handover between macrocells, it may be inappropriate for the handover between macrocells and femtocells. In most deployment cases, the fixed broadband operators will have no contractual agreements with the mobile network operators to provide guaranteed backhaul performance. Thus, remarkable DL SIT up to several hundreds of milliseconds may be perceived by the users in handover due to the data forwarding latency along the delay-prone residential backhaul.

A simple but effective modification based on the standard 3GPP HO procedure is proposed to tackle this problem. When the MME receives the *HO Required message* from the source cell, the MME will determine the target cell by checking this message and send a *Data Bicasting Request* to the S-GW. When the S-GW receives this request, it will duplicate the downlink data packets and bicast them to both the source and the target. The target cell maintains a receiving buffer for the bicasted data. Data bicasting is activated after the HO is initiated, thus called reactive data bicasting. Since there is no data forwarding process from the source cell to the target cell during the HO, the data packets that arrive at the source after the UE is detached and are also not buffered at the target will be lost. It has been shown that the number of lost packets is very small. Actually, this loss can be simply ignored for the real-time traffic such as VoIP. However, if lossless handover is required, an optional drop-head buffer can be adaptively activated at the S-GW to keep the latest N packets. When the S-GW receives the *Data Bicasting Request*, it will first empty the drop-head buffer and send the packets in the buffer to the target cell.

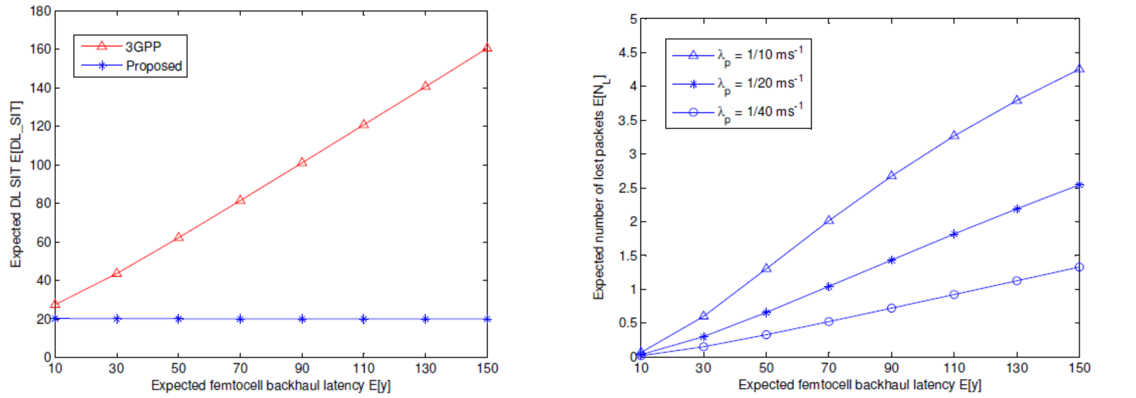
Figure 54 and Figure 55 show that the proposed scheme can significantly reduce the downlink service interruption time compared to the standard 3GPP procedure. The expected number of lost packets when using the proposed scheme is negligible for the handover from macrocell to femtocell. For the handover from femtocell to macrocell, it will increase as the femtocell backhaul latency increases but still under 5 packets even when the femtocells backhaul latency is up to 150 ms. This implies that additional S-GW buffering mechanism is actually not necessary for the real-time traffic such as VoIP where a small amount of lost packets are acceptable. In case that a lossless handover is required, a small drop-head buffer at the S-GW will be enough to avoid the packet loss.



(a) Expected downlink service interruption time

(b) Expected number of lost packets without S-GW buffering

Figure 54: Handover from macrocell to femtocell.



(a) Expected downlink service interruption time

(b) Expected number of lost packets without S-GW buffering

Figure 55: Handover from femtocell to macrocell.

4.6.2.2 Contribution to BeFEMTO System Concept and Objectives

The standard 3GPP handover procedure may cause large downlink service interruption due to the delay-prone Internet backhaul of the femtocells. To tackle this problem, an effective modification based on the 3GPP procedure is proposed by employing reactive data bicasting. The proposed scheme can significantly reduce the downlink service interruption time compared to the standard 3GPP scheme while still avoiding the packet loss with the help of a small drop-head buffer at the S-GW.

References

[59] Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (EUTRAN); Overall description; Stage 2 (Release 10), 3GPP Std. TS 36.300 v10.5.0, Sep. 2011.

4.6.3 Synthesis

The indoor usage, co-channel deployment and residential backhaul provide new challenges for mobility management when users move from a macrocell to a femtocell or vice versa. Frequent RLFs may happen during macro-femto mobility due to the large handover preparation delay and the wall penetration loss. A UE-based forward handover procedure with predictive context transfer is proposed to enable fast RLF recovery. Depending on the backhaul latency, the proposed scheme can recover a session from a RLF up to 3 times faster than the standard 3GPP procedure. The delay-prone Internet backhaul may also cause large downlink service interruption time due to the data forwarding operation during the handover procedure. A novel modification on the basis of the standard 3GPP handover procedure is proposed to reactively bicast the downlink data to the source and the target cell when the handover is initiated. The proposed modification can significantly reduce the downlink service interruption time while still avoiding packet loss with the help of a small drop-head buffer at the S-GW. Therefore, the proposed scheme can enable seamless handover for macro-femto mobility while requiring only light modification to the current standard.

5. Networked Femtocells

5.1 SON Enablers

5.1.1 Automatic Location Determination

Unlike macro base stations that are deployed by network operators at known locations after careful cell planning, femtocells are deployed by users in their home or office premises. Determining the location of user-deployed femtocells is important due to the following main reasons:

1. Network management

Disjoint or non-overlapping allocation of resources in the time and/or frequency domains among femtocells operating close to each other should be done in way to reduce interference at user terminals. Information about femtocell locations may help in clustering neighbouring femtos together and allocating resources appropriately among them.

- Position information may be used as an input to self-organizing network (SON) algorithms to properly initialize and update network/base station parameters.
- Operators may need to identify the geographic region where a femto is being used for functions like billing, network monitoring, statistics gathering, etc.

2. Regulatory requirement

In some countries, operators need to roughly determine the location of a femtocell before it is put into operation to satisfy regulatory requirements.

3. Emergency positioning

Enhanced emergency response services require that the location of a user terminal that initiates an emergency call is reported within a certain time window to a nearby Public-Safety Answering Point (PSAP). If no estimate of the exact location of the user terminal is available, the location of the serving cell is reported as a rough guess of the user terminal's location. In this context, the location of a serving femtocell needs to determine. As femtocells have small coverage areas, a femtocell's location serves as a reasonably guess of the locations of the users it is serving.

5.1.1.1 Description of scheme

A standalone Femto with a built-in GNSS module can be located using assisted Global Navigation Satellite System (GNSS), where the assistance data is calculated based on its rough position estimate, e.g., the location of the macro base station in whose coverage area the femtocell is located. Assisted-GNSS may not work when the femtocell is located deep indoors because the satellite signals are very weak and enough satellites are not visible to compute a position solution.

In a cluster of femtocells located, e.g., in an office building in an enterprise deployment, relative positioning is proposed as a viable positioning method. Femtocells that are placed close to windows can be located using, e.g., Assisted-GNSS or macrocell signals. These 'reference' femtocells then have known positions and are synchronized to common base time. Other femtocells, which are located deep indoors or see strong interference from nearby neighbours, may not be positioned using weak satellite or macrocell signals. These femtocells that have unknown positions and asynchronous transmit times are termed as 'blind' femtocells. In relative positioning method, each blind femtocell makes measurements (e.g., round-trip time (RTT), time of arrival (TOA) or time difference of arrival (TDOA)) with respect to not only the reference femtocells but also the other blind femtocells. Macro base stations whose signals are received indoors by one or more blind femtocells also serve as reference base stations and considered a part of the cluster for relative positioning.

Measurement of RTT between a pair of femtocells requires implementation of a trigger-response mechanism, where a packet is sent by one femtocell to the other which then responds by sending a packet back. The first femtocell then measures the time that elapsed between the transmission of the outgoing trigger packet and reception of the incoming response packet. The estimated range between the two is directly related to one half of the measured RTT. Measuring TOA of a packet transmitted by a neighbour femtocell requires perfect synchronization between all femtocells/macro base stations. It is not possible to measure either RTT or TOA using the existing radio interface defined for 3GPP cellular communication systems, e.g., LTE. It is, therefore, proposed to make TDOA measurement at blind femtocells with respect to pairs of neighbour femtocells. TDOA measurements may be made using signals broadcast by neighbour femtocells, e.g., cell-specific reference signal (CRS) or positioning reference signal (PRS) in LTE Rel. 9. Measuring TDOAs at a femtocell requires some limited user terminal functionality to be built-in the device, as the femtocell needs to process downlink broadcast signals that are meant for user terminals. Such functionality may be added to an already existing module like the one for radio environment monitoring.

The task of determining positions of blind femtocells can be formulated in the form of a least-squares joint estimator. This estimation problem can be solved by different methods, e.g., gradient search or genetic algorithm. Note that the transmit times of the blind femtocells need to be estimated in addition to positions as an LTE network is inherently asynchronous.

5.1.1.2 Performance

System level simulations are conducted to determine positioning performance of RTDOA estimation. The system simulator models a heterogeneous network with femtocells deployed within the coverage area of a hexagonal macrocell layout. For femtocell deployment the dual-stripe model [60] is adopted, and each dual-stripe layout constitutes a femtocell cluster. TDOA measurements are generated at each blind femtocell, based on received Positioning Reference Signals (PRS) [61]. RTDOA estimation is done for two different channel models; One Peak and Pedestrian A [62]. The One Peak channel exhib a single non-fading line of sight (LOS) path, whereas Pedestrian A is a multipath channel with one LOS and 3 non-LOS paths. The RTDOA estimates collected at all blind femtocells in a cluster are fed into the position/transmit time calculation function to compute positions (and possibly transmit times) of all blind femtocells.

The CDFs of the position errors are depicted in Figure 56 for two deployment ratios in an asynchronous femtocell cluster. The deployment ratio is the probability that an apartment in a dual-stripe layout contains a femtocell. This ratio controls the density of femtocell deployment.

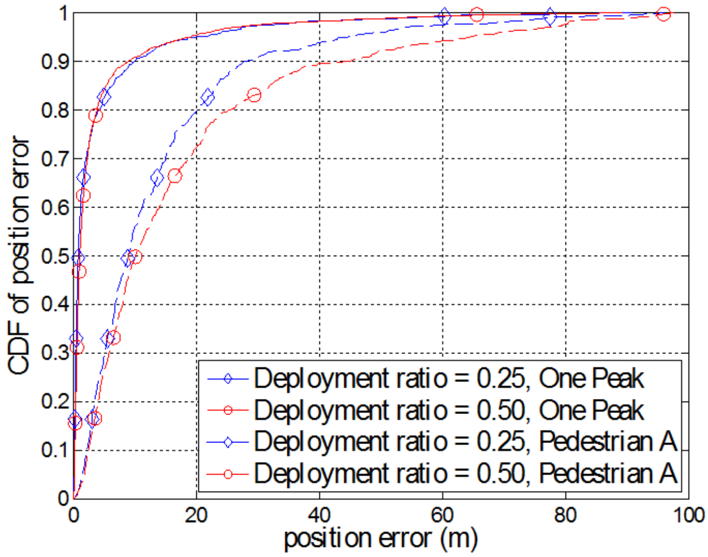


Figure 56: CDF of position errors.

The position error at 67-percentile is below 2 m in case One Peak channel model is assumed. As the multipath profile of Pedestrian A channel results in larger errors in TDOA estimates, position error at 67-percentile is around 15 m.

References

[60] 3GPP TR 36.814, "Further Advancements for E-UTRA; Physical Layer Aspects," V9.0.0, Mar. 2010.

[61] 3GPP TS 36.211, "Physical Channels and Modulations," V10.2.0, Jun. 2011.

[62] "Guidelines for the evaluation of radio transmission technologies for IMT-2000," Recommendation ITU-R M.1225, 1997.

5.1.2 Automatic coverage estimation

5.1.2.1 Description of the Scheme

In order to enable self-organisation, cellular systems need to have a framework to estimate their performance and diagnose specific performance related problems to trigger appropriate self-organising mechanisms. While much work is ongoing on self-organization in cellular networks, work on *enabling self-organization* is still scarce. To this end, we propose a novel algorithm for autonomous coverage estimation of an access point, which could subsequently be used for triggering various self-organising functions and hence acts as an enabler for self-optimisation and self-healing. The algorithm is named as RSRP (Received Signal Received Power) based Autonomous Coverage Estimation (RACE). RACE can be used to estimate the coverage of a node based on the user RSRP reports and their position information in an autonomously manner. This coverage estimation is carried out by dividing the coverage area into virtual bins and estimating expected coverage in each bin by averaging the RSRP reports of users associated with that bin. The steps that need to be executed at each access point in order to obtain the coverage map autonomously are explained below:

- Entire coverage area is divided in virtual bins.
- Each UE's location is determined at the access point and based on its location, it is allocated to the respective bin. It should be noted that location estimation is not part of coverage estimation algorithm; rather it is assumed that knowledge of UE location (with some inaccuracy) is available at the access point by any of the existing technologies like GPS, or other methods available in literature.
- Each UE reports its RSRP to the access point, which in turn logs these RSRP measurements together with the bin in which UE lies.
- These reports are collected over a long period such that all the bins in the potential coverage area have been reported from by at least one UE.

The access point determines whether or not a given bin is covered by comparing the average RSRP reported from that bin with a threshold RSRP that indicates minimum level of coverage, e.g. -124 dBm in 3GPP LTE [63]. Figure 57 shows the coverage map obtained through the RACE algorithm. Bin size of 50m × 50m is used. Total 80000 users are dropped in the whole cellular network of 19 cells with total area of around $\pi\,(1200\times2.5)^2$ m^2. It can be seen in the figure that other than the overall characterization of coverage, the coverage map can be used to identify the location and intensity of covered dead zones as well.

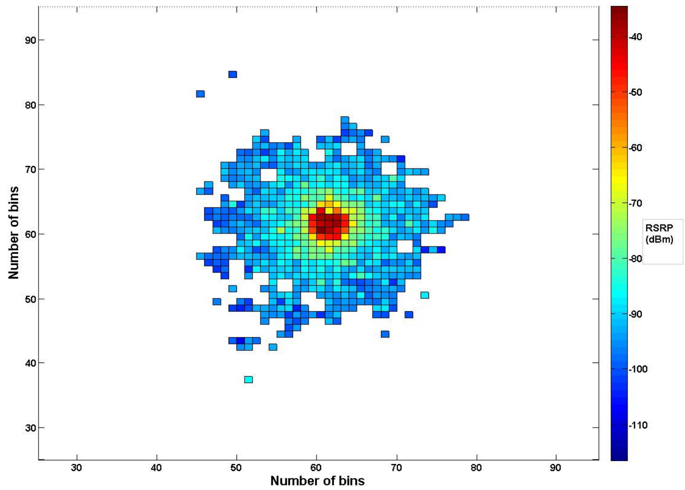


Figure 57: Autonomously generated coverage map at central eNB.

Although RACE is a very useful mechanism in identifying the location of coverage dead zones, for some SON algorithms, e.g. handover parameter optimization, knowing the definitive boundary of the coverage area autonomously at the access point is vital. Automatic Boundary Estimation (ABE) algorithm proposed here provides a simple method to estimate the boundary of coverage area autonomously and is inspired by a boundary estimation suggested method in [64] and used for estimation of geographical spread of population of various species in the field of ecology. The procedure for algorithm is explained as follows.

The coverage map obtained through RACE is divided into M virtual angular strips. For a given strip, an arbitrary temporary value of radius is assumed that represents the temporary boundary of that strip. The bins in that strip are then petitioned into *rightly classified* and *misclassified bins*, for that temporary boundary. Misclassified bins are the bins outside the boundary that have required level of coverage, or bins inside the boundary that do not have required level of coverage. The temporary boundary is then optimised to minimise the number of misclassified bins in that strip. Using this procedure for each strip, the optimal radius is obtained for the each strip. The boundary of the coverage area of each access point can be obtained by joining the radii of all strips as shown in Figure 58.

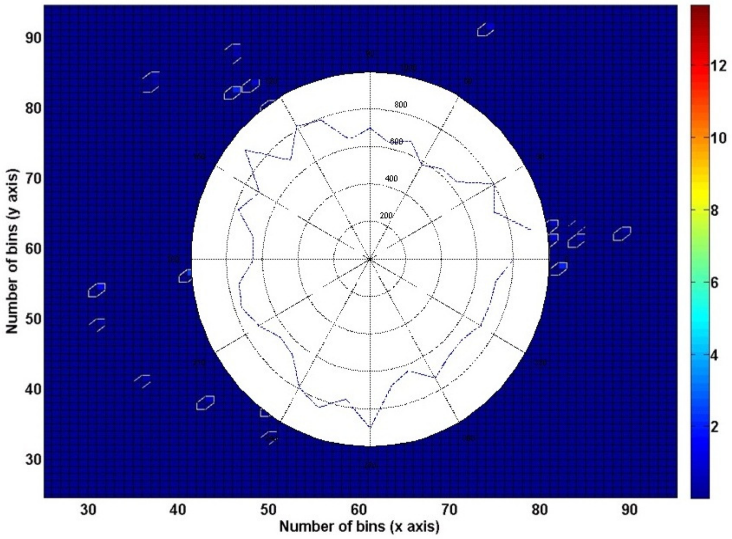


Figure 58: Automatically predicted coverage boundary for central eNB.

5.1.2.2 Contribution to BeFEMTO System Concept and Objectives

The spectral efficiency metric is not directly applicable to RACE and ABE algorithms. However, the RACE algorithm can used to determine the dead zones autonomously. Thus, RACE can be used to trigger SO techniques and thus boost system performance in terms of spectral efficiency. Similarly, the autonomously estimated boundaries of coverage area determined through the proposed ABE algorithm can also be used to trigger a number of SO techniques that aim at capacity, fairness and coverage optimization such as handover parameters optimization, etc. All these can substantially increase system spectral efficiency.

References

[63] 3GPP TS36.133, “Evolved Universal Terrestrial Radio Access (EUTRA); Requirements for support of radio resource management (Release 9),” v9.3.0, Mar. 2010.

[64] A. A. Sharov, E.A. Roberts, A. M. Liebhold, and F.W. Ravlin, “Gypsy moth (Lepidoptera: Lymantriidae) spread in the Central Appalachians: Three methods for species boundary estimation,”*Environ. Entomol. 24*, 1529-1538, 1995.

5.1.3 Distributed Reinforcement Learning Algorithms (SON)

5.1.3.1 Description of the Scheme

In this proposal, we propose a distributed reinforcement learning based interference management algorithm (coined SON-RL), in which femtocell networks self-organize in a totally autonomous manner, without information exchange. The only information required by every single HeNB is a feedback from their respective femto UEs, in a form of SINR. Based on this feedback, femtocells optimally learn their long-term performance by accumulating a knowledge of playing certain strategies, after which decisions are made as to which power level and frequency are taken at every time instant. Figure 59 depicts the convergence behaviour of the proposed algorithm and its benchmark (best response) whereby femtocells maximize their instantaneous performance without accumulating any knowledge about their played strategies in the past. Figure 60 shows that the proposed reinforcement learning algorithm is scalable with the network densification. Since the proposed algorithm relies on local information, the final outcome of the overall performance is sub-optimal in the sense that better performance can be further obtained. However, more overhead in the form of information exchange should be considered.

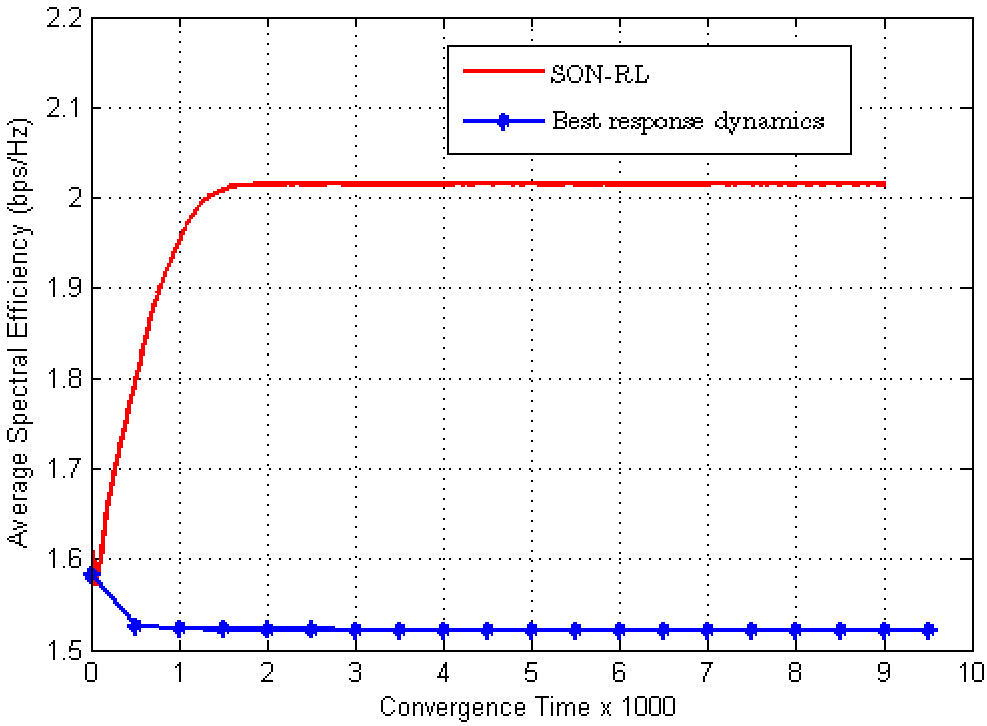


Figure 59: Average femtocell spectral efficiency versus time, for both SON-RL and best response dynamics.

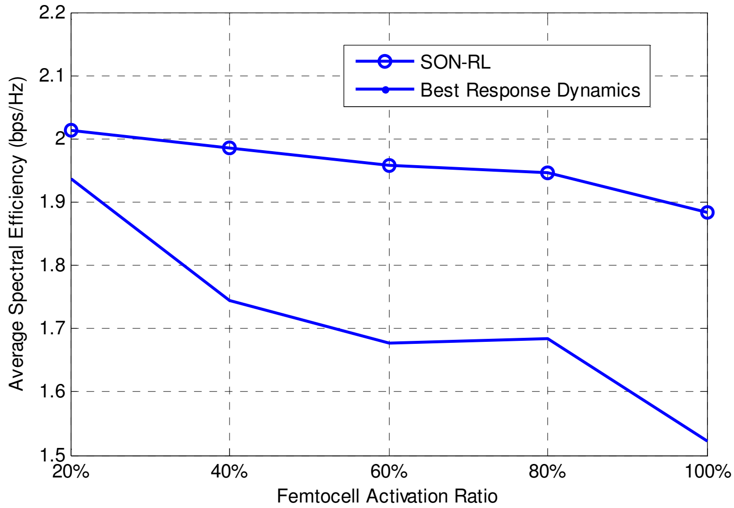


Figure 60: Average femtocell spectral efficiency as a function of the femtocell density.

5.1.3.2 Contribution to BeFEMTO System Concept and Objectives

An average femtocell spectral efficiency of around 2bps/Hz is obtained in a dense small cell deployment. In order to obtain higher performance, information exchange among femtocells should be considered, preliminary results alongside this direction can be found in Figure 60.

References

[65] M. Bennis et al., "Decentralized Cross-Tier Interference Mitigation in Cognitive Femtocell Networks," in *Proc. IEEE ICC 2011*, Kyoto, Japan.

[66] M. Bennis et al., "Learning coarse-correlated equilibria in two-tier networks," in *Proc. IEEE ICC 2012*, Ottawa, Canada.

5.1.4 Synthesis

Often taken for granted in self-organizing network (SON) approaches, the network needs suitable preparation and support to be able to execute the SON algorithms. This is achieved by a set of approaches, referred to as SON-enabling techniques. Key enablers considered in this section pertain to location determination and coverage estimation.

Accurate real-time geographic location determination of femtocells, as well as their associated mobile terminals is a key enabler and an essential requirement for many applications: to meet regulatory constraints, like verification of licensed spectrum operation, or emergency caller location identification, as well as accurate user/module location. Moreover, location awareness is an important input for SON algorithms to properly initialize and update system parameters. As signal reception from satellite navigation (e.g. GPS) is generally limited indoors, alternative approaches need to be identified. In a cluster of networked femtocells, where a fraction of all nodes have access to satellite navigation, the objective is to determine the relative position of all nodes towards those reference nodes. In relative positioning a node needs to estimate its distance to its neighbors, which is facilitated by relative time difference of arrival (RTDOA) measurements.

Targeting the automatic estimation of a femtocell's radio coverage is particularly relevant in the design of admission control and interference management schemes, since it will support the handover procedure to and from the macrocell. By utilizing the measurement capabilities implemented by LTE equipment the coverage area of femtocells can be autonomously controlled. These methods enable e.g. the protection of macro mobiles that are trapped within the femtocell coverage area. An coverage estimation algorithm was investigated, where coverage estimates are generated based on RSRP (Reference Signal Received Power) measurements.

By interpreting SON as the capability of drawing intelligent decisions by self-adapting to the dynamics of the environment and to the decisions made by neighboring nodes, learning approaches may enable self-organization in networks of femtocells. Recent advances in the area of reinforcement learning tackle close the gap between fundamental research and practical implementation: (i) speeding up the learning process by allowing nodes to teach other nodes; and (ii) reduce the signalling overhead by enabling nodes to operate in a scenario with partial observation, so that decisions are taken in an autonomous fashion.

5.2 Power and Coverage Control

5.2.1 Power control and sniffing capability

5.2.1.1 Power control

5.2.1.1.1 Description of the Scheme

The High Power amplifier (HPA) is the element that feeds the antenna in the transmitter part and provides the desired levels of the output signal. Femtocell requirements include both absolute and relative accuracy for transmit power requirements [67]. The absolute requirements define a lower and an upper transmit power limit relative to a nominal transmit power. The relative requirements define a minimum and maximum transmit power difference between two transmitted slots, not necessarily adjacent time slots, as well as an aggregated transmit power difference over several time slots. There are two types of loops to implement the power control: closed-loop and open-loop.

Closed-loop power control represents one method for controlling the transmit power within the wireless communication device to comply with the relative and absolute transmit power requirements. Using a sample of the transmitted power, an error signal with respect to a reference is calculated and with this signal, the transmitted power signal is corrected. This type of control loop has the limitation of the power detector dynamic range. Another type of power control loop is the open-loop power control. It adjusts the transmitted power in response to power control commands produced by operational parameters and/or environmental conditions. These commands can be described as power commands produced by the Network Management, the own unit detection of low traffic load (introducing an ECO-mode or dormant state) or user pushing a save energy mode. The combination of open-loop with closed-loop avoids [68] the transmit power to drift away from the desired transmit power.

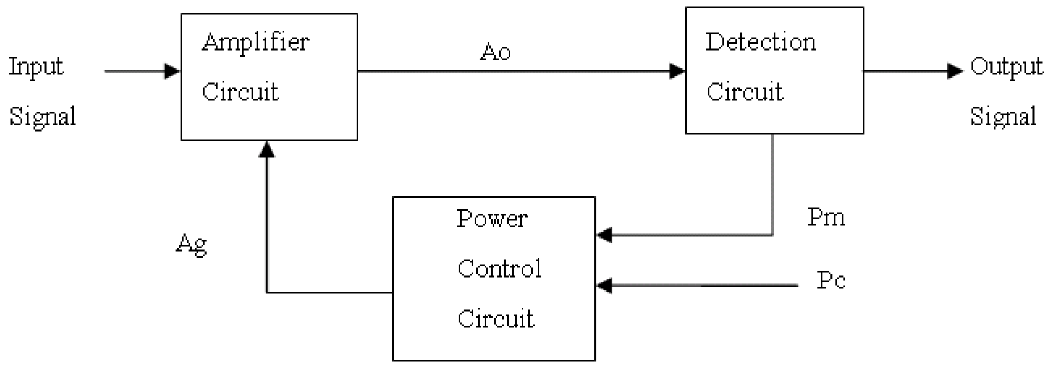


Figure 61: Power Control.

5.2.1.1.2 Contribution to BeFEMTO System Concept and Objectives

The power control circuit in transmitter described above allows to achieve the 10 mW and also follows the power up /down commands in power control techniques in SON. Implementation of power control is an important issue in Networked femtocells when the FAPs are required to transmit with variable and accurate power in order to follow interference strategies.

5.2.1.2 Sniffing capability

5.2.1.2.1 Description of the Scheme

Definition of Sniffer Module: Sniffer module is a real-time system, it continuously captures/monitors data or signals passing through the network.

The sniffer capability is also called Network Listen Mode (NLM), Radio Environment Measurement (REM) or "HeNB Sniffer" in [69] and [70]. With it, the HeNB incorporates functionalities of user receiver, that is, a DownLink Receiver with a special possibility of performing Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ) measurements in order to obtain the power received from other femtocells and macrocells at FAP. With these measurements the femtocell can calculate the best working point taking into account coverage and interference to both close co-channel macrocell users and co-channel FAP. Other type of measurements described in [71] are performed in order to minimize interference to adjacent MUEs and macrocells, detection of victim UEs, obtain other cell ID, etc.

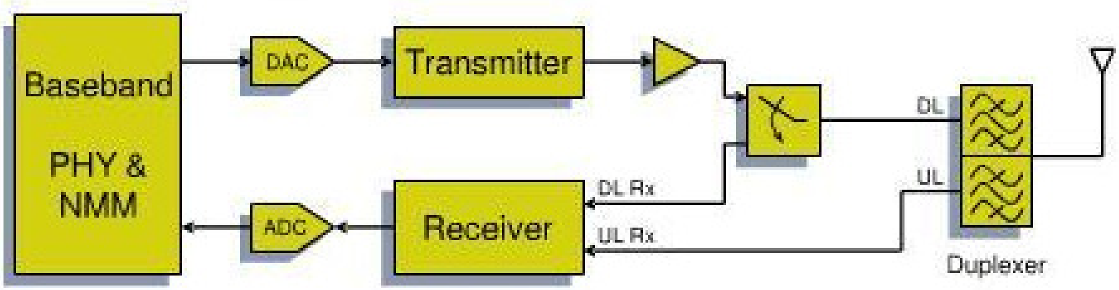


Figure 62: Sniffer module description.

Measurement type	Purpose
Co-channel RSRP	Setting femto TX power for desired coverage and protection of co-Channel MUEs
Co-channel RSRQ	
Adjacent-channel carrier RSRP	Setting femto TX power for protection of adjacent-channel MUEs
Adjacent channel ref signal Rx power	
Uplink Ref Signal Detection	Detection of Victim UEs
Read system info	Tx power (for pathloss calculations) CSG status…

Table 27: Sniffer measurement and their use.

Standalone femtocells can use the sniffer capabilities to obtain information about its environment and take decisions in accordance. Measurements performed by the sniffer module are also used by SON techniques implemented in Networked femtocell. To implement this sniffer capability, the femtocell needs to incorporate a DownLink receiver with UE receiver characteristic described in [72] if transmit and receive frequencies are different. This sniffing capability is used in networked femtocells to minimize interferences between femtocells and macrocell deployments. For standalone femtocells it can also be useful to calculate interference from macrocell and to obtain input to optimize transmitting power to minimize interference to macrocell.

5.2.1.2.2 Contribution to BeFEMTO System Concept and Objectives

Sniffer is a helping module to obtain info of the neighbour FAP and macrocells to calculate interference with a more accurate way. The sniffer block is useful tool whose measurements can be used in SON techniques to adapt the transmitting power taking into account interferences to other users and systems.

References:

[67] 3GPP TS 36.104 "Evolved Universal Terrestrial Radio Access (E-UTRA); Base station (BS) radio transmission and reception", V10.0.0, Dec. 2010.

[68] Gustavson et al., "Continuous alternating closed-open loop power control", www.freepatentsonline.com

[69] 3GPP TR 36.921, "Evolved universal terrestrial radio access network (E-UTRAN); FDD Home eNode B (HeNB) Radio Frequency (RF) requirements analysis (release 9)," vol. 9.0.0., Mar. 2010.

[70] Patel et all, "Femtocell and Beacon Transmit Power Self-Calibration", www.qualcom.com.

[71] 3GPP TS 36.214, "Evolved universal terrestrial radio access network (E-UTRAN); Physical layer; Measurements (release 10)", vol. 10.1.0., Mar. 2011.

[72] 3GPP TS 36.101, "Evolved universal terrestrial radio access network (E-UTRAN); User Equipment (UE) radio transmission and reception (release 10)", vol. 10.1.1., Jan. 2011.

5.2.2 Coverage Control

5.2.2.1 Description of the Scheme

Literature investigation provides different methods to have control over uplink and downlink coverage based on measurements of real deployments, with them automatic coverage estimation can be performed.

This automatic estimation can mismatch from a desired coverage because it takes into account the presence of alien mobiles and other events that produce interference and can reduce the coverage. **Downlink Coverage:** Using the transmitter with fixed power is not really the most optimal option when there are co-channel deployments in the neighborhood. Three main methods based on the control of the transmitted power transmitted by the femtocell are presented, which are Network Listen, Mobile Assisted Range Tuning and Active Macro Mobile Protection.

- Network Listen (NL): This type of Downlink Tx power configuration is described in [74][73] . In this method, the femtocell's transmitted power is configured using the measurement of the received power from the macrocell and doing some corrections. There must be some constraints criteria to set power to the femtocell transmitter that are Macro Mobile Protection Constraint and Home Mobile Coverage Constraint.. The femtocell power is configured to produce a minimum received power for a potential user at a distance r placed between the macrocell and femtocell. This potential FUE will receive the transmitted power from the femtocell reduced by the propagation losses. The initial femtocell power can be calculated in decibels as Pfemto, = min(PRx-macro + Lfemto(r), Pt,max). The path-loss Lfemto(r) from the femtocell to a FUE at the target femtocell radius r can be modeled as L(d) = L1 + L2×10 log10(d).

- Mobile Assisted Range Tuning (MART): This method is described in [73] and gives a more accurate estimation of coverage radius and improved tx power adjustment. Moreover, this method achieves a balance between coverage and interference minimization.

  Adequate coverage for home users can be ensured by using channel quality reports from home mobiles. A femtocell can request a home mobile to periodically measure and report back DL channel quality metrics. By using these reports, the femtocell can estimate the path- loss between itself and a home mobile at different locations in the home, and also learn the macro signal. Unlike Network Listen, reports from home mobiles allow the femtocell to sample RF environment at different locations in the home. Thus, a femtocell can learn the desired coverage range and also handle the measurement mismatch issue that fills Network Listen. As a result, by combining information from alien user registration statistics and home mobile reports, a femtocell can determine the optimal power.

- Active Macro Mobile Protection (AMMP): MART method [73] helps to reduce femtocell interference to macro users, but it cannot completely eliminate this interference. For example, guest users visiting a femtocell home and receiving service from a macrocell can still face significant interference. AMMP method gives better results than always transmitting with low power because it only sacrifices femtocell coverage when a macro user is detected. An active macro mobile is in femtocell vicinity and therefore is being interfered on the DL by the femtocell (macro and femtocell are co-channel. The femtocell detects the presence of a macro user in its vicinity by continuously measuring out-of-cell interference on the Uplink channel. Out-of-cell interference level above a certain threshold serves as an indication of the presence of an active macro user in the femtocell vicinity. When out-of-cell interference greater than a certain threshold is observed, the femtocell "throttles" its DL transmission, i.e., it reduces Tx power on its DL or completely shutdowns DL temporarily to protect the active macro mobile. The new Tx power level can be determined as a function of the out-of-cell interference level. Normal DL transmission is resumed by discontinuing throttling after a time out or when the out-of-cell interference level falls below a certain threshold.

Uplink Coverage: The main problem that concerns the uplink operation is high level received signals. A FUE can get arbitrarily close to the femtocell and it cannot obey the power control (PC) down commands due to reaching its minimum transmit power capability because the dynamic range has a limit. Such transmitting higher than the required power may desensitize the femtocell receiver.

- Uplink Adaptive Attenuation (UAA): One simple solution to deal with the high input power problem is to raise the input threshold. A better solution is to desensitize the interference by attenuating the signal at the receiver. As a result, interference operation is more comparable to thermal noise. Another advantage is that the attenuation pulls nearby FUEs to a power controllable range and solves the saturation problem, using attenuation only when high out-of-cell interference or receiver desensitization is detected at the femtocell. The UL signal to be attenuated only when the total received signal level is saturating the receiver or the UL is being jammed by a nearby non-associated cell.

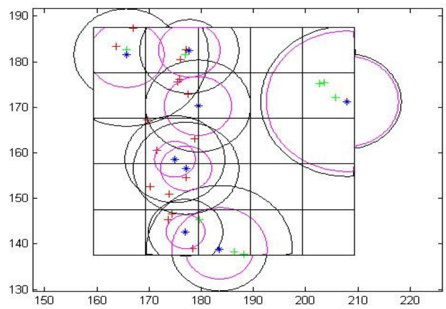


Figure 63: Example of coverage with PFAP=10 dBm and interference from macrocells, other FAPs MUEs and other FUEs

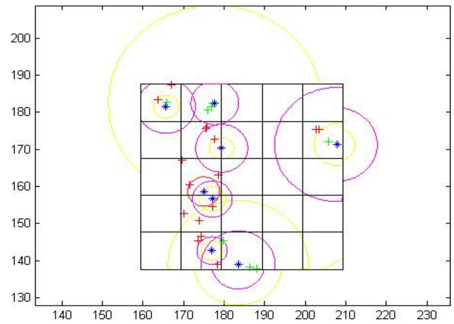


Figure 64: Example of coverage with PFAP=opt dBm and interference from macrocells, other FAPs MUEs and other FUEs.

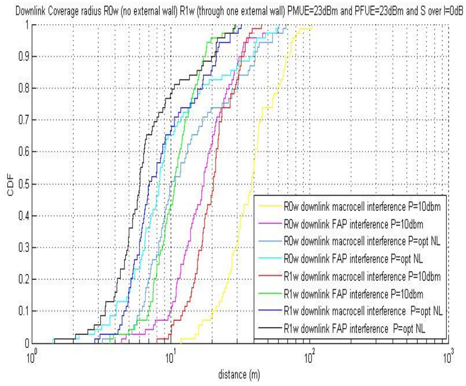


Figure 65: Downlink coverage radius.

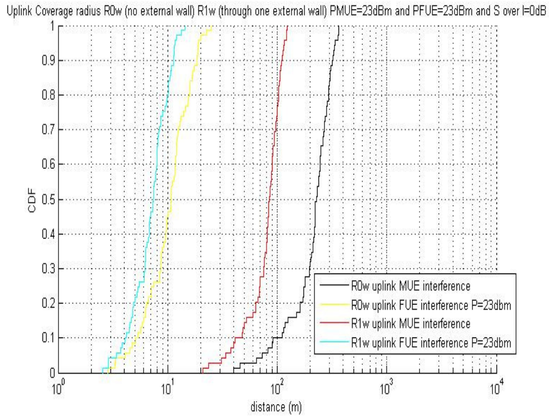


Figure 66: Uplink coverage radius.

In Figure 63 to Figure 64 an example of combination of downlink and uplink coverage is shown. In this case SINR is 0 dB. The blue stars represent the FAP active inside the apartment block and the crosses are FUEs. If the FUE receives signal from above SINR and its FAP also receives signal above SINR it is green cross. If in one or both cases received signal is not above SINR its color is red. Downlink coverage with PFAP=10 dBm are black lines in Figure 63. Downlink coverage with PFAP=Popt dBm from NL method are yellow lines in Figure 64. Uplink coverages in the two figures are represented by pink lines.

In Figure 65 the CDF of the different coverage radius are shown for SINR=0 dB and all the FUE inside their apartments. In Figure 66 the CDF of the different coverage radius are shown for SINR=0 dB and all the FUE inside their apartments.

5.2.2.2 Contribution to BeFEMTO System Concept and Objectives

With coverage control a first rough estimation of the coverage area of a FAP can be obtained.

Bibliography

[73] Patel, et al., "Femtocell and Beacon Transmit Power Self-Calibration", Qualcomm, Feb. 2010.

[74] Claussen, Ho, and Samuel, "Self-optimization of Coverage for Femtocell Deployments," Wireless Telecommunications Symposium, Apr. 2008.

5.2.3 Power Control in a Femtocell Network and Access Policy

5.2.3.1 Description of the Scheme

Heterogeneous Network (HetNet) co-channel deployment with femtocells in closed access urges the need of efficient interference mitigation mechanisms, especially when considering downlink. Indeed, the core network will deny the access to all users that do not belong to the femtocell Closed Subscriber Group (GSG). Therefore, a User Equipment (UE) coming close to a femtocell but not listed in the femtocell CSG can be highly interfered and lose its network connection. Though frequency partitioning strategies could alleviate the interference affecting data channels in OFDMA-based systems like LTE (at the cost of the overall system throughput), control channels are more difficult to protect as they span over the whole bandwidth. Classical femtocell power setting approaches try to address this issue of macrocell UE outage. This section presents a power setting algorithm for clusters of femtocells in an HetNet deployment. When the same CSG is used among all the femtocells of a cluster, the method can also switch-off the most disrupting femtocells enabling an autonomous organisation of the cluster. Such approach leads to an overall enhanced HetNet performance as well as a massive energy saving in the case of a dense femtocell deployment.

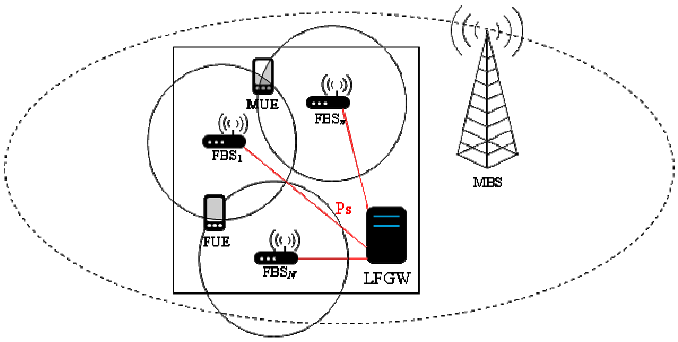


Figure 67: HetNet deployment

A cluster is made of *N* co-located Femtocell Base Stations (FBSs), all using the same carrier as the Macro Base Stations (MBSs). An FBS *n* can adjust its transmission power P_t^n in the range [$P_{\min}^n, P_{\max}^n$] and can broadcast either an independent CSG or a common one within the cluster. The set of femtocells is connected to a BeFEMTO Local Femto GateWay (LFGW) as shown in Figure 67. The LFGW temporally coordinates the measurements made by the femtocells through the Ps interface [75]. These measurements will feed a linear programming framework, thus enabling a simple resolution from which will be derived the transmission powers of the femtocells. Those measurements are possible thanks to an embedded Network Listen Module (NLM) in each femtocell making it comparable to a virtual UE in terms of sniffing capabilities. In order to deduce the set of transmission powers, the following optimisation problem (OP) is formed:

$$\max_{P_t^n} \quad c = \sum_{n=1}^{N} c_n P_t^n$$
$$\text{w.r.t} \quad \forall n \in \{1, N\}, P_t^n + \sum_{m \neq n} \frac{1}{\rho^2} \alpha_{n,m} P_t^m \leq \frac{1}{\rho^2} \frac{P_r^{n,macro}}{\gamma_{\text{MUE}}^{\text{target}}}, \quad (5)$$

where c_n are weighting factors allowing femtocell discrimination if required, $P_r^{n,macro}$ is the power measured by the FBS n NLM coming from the strongest MBS and $\alpha_{m,n}$ represents the long-term channel attenuation between the FBS m and the FBS n deduced using FBS n NLM. The cost function c to maximise carries the femtocell network performance in a linear fashion while the constraints are built around the macrocell network protection. A virtual zone is defined around each FBS, outside which a Macrocell UE (MUE) should experience an SINR greater than the predefined target $\gamma_{\text{MUE}}^{\text{target}}$. This zone is deduced from the measurements made at the FBS location taking into account the parameter ρ which represents power attenuation.

Transmission powers being the positive values to find, the OP can be easily solved using linear programming in a centralised way by the LFGW once it acquires through the Ps interface all the measurements (backhaul consuming), e.g. with the simplex algorithm [76]. An iterative distributed resolution at the femtocell level is also possible based on the first order Jacobian, Gauss-Seidel or Successive Over-Relaxation (SOR) approach [77] (with coordination messages being the only backhaul overhead through the Ps interface).

Table 28 shows the system-level simulation results of the proposed centralised (simplex) and iterative distributed (Gauss-Seidel) solutions when using the aggressive [78] 5x5 grid urban model for the femtocells with high femtocell deployment ratio (60%). All femtocells deployed within a 5x5 grid form a cluster with a common broadcasted CSG and the minimum and maximum transmit powers of -10dBm and 10dBm, respectively. For comparison purpose, results without Power Setting (PS) and with classical distributed PS based on macro sniffing [79] are displayed. The switch-off property is enabled here when the resolution leads to a femtocell transmission power lower than the minimum authorised. The numbers reveal a clear advantage of using the proposed power setting algorithm in terms of outage and average transmit power (computed only on the active FBSs).

Average	**No PS**	**Distributed PS**	**Simplex**	**SOR (ω=0.5)**
MUE's outage @ -6dB	32.46%	18.06%	**3.93%**	**6.99%**
FUE's outage @ -6dB	0.28%	0.52%	**0.055%**	**0.069%**
FBS Tx power	10dBm	0.17dBm	**-0.96dBm**	**0.26dBm**
FBS switch-off ratio	0%	15.67%	**62.5%**	**58.4%**

Table 28: UE outage and FBS avg. Tx power comparison (60% deployment, common CSG).

5.2.3.2 Contribution to BeFEMTO System Concept and Objectives

The proposed solution exploits the BeFEMTO LFGW architecture introduced for networked femtocells to coordinate femtocells measurements. Based on these measurements, the femtocell transmission powers within a cluster are derived using a linear programming framework either in a centralised way (at the

LFGW level) or in an iterative distributed way (at the femtocell level, thus reducing the need of signalling only to the coordination mechanism). In terms of outage, the proposed solution outperforms classical approaches in all simulated scenarios while using on average less transmission power in the centralised case (energy saving). In addition, the ability to autonomously switch-off the most disruptive femtocells is particularly efficient in high deployment scenarios where the radio planning will be automatically handled.

References

[75] BeFEMTO D2.2, "The BeFEMTO system architecture," ICT 248523 FP7 BeFEMTO project, December 2011.

[76] G. B. Dantzig, *Linear Programming and Extensions*. Princeton University Press, 1963.

[77] D. Bertsekas and J. Tsitsiklis, *Parallel and distributed computation: numerical methods*. Prentice Hall, NJ, 1989.

[78] M. Maqbool, M. Lalam, and T. Lestable, "Comparison of femto cell deployment models for an interference avoidance technique," in *Proc. of IEEE Future Network & Mobile Summit (FUNEMS'11)*, Jun. 2011.

[79] 3GPP TR 25.967, "Home Node B (HNB) Radio Frequency (RF) requirements (FDD) (Release 10)," 3rd Generation Partnership Project.

5.2.4 Synthesis

Power and coverage control are some of the key enablers for self organising network to be a reality, especially regarding co-channel heterogeneous deployment. In the BeFEMTO System Concept, a femtocell is equipped with a power control circuit allowing it to dynamically and accurately adjust its transmission power up, thus its coverage. This coverage could be dynamically adapted either based on the femtocell's own measurements or using user equipment's measurement feedbacks or relying on a victim detection mechanism (uplink monitoring from the femtocell or a combination of all these approaches. This power flexibility is crucial in order to protect the macrocell user equipments in a HetNet deployment where femtocells are deployed in a closed subscriber group (CSG) access policy, despite the low maximum power targeted within BeFEMTO (10dBm).

Since an authorised user equipment is not always connected to the femtocell, the BeFEMTO femtocell should be equipped with its own sniffing capability, i.e. all the necessary circuitry, namely a Network Listen Module (NLM), to perform the same measurements as a traditional user equipment would do in the downlink. Within the BeFEMTO System Concept, the NLM's outputs are of particular interest for deriving an adequate transmission power either locally or in a centralised fashion when a network of co-located femtocells is considered. Indeed, such femtocell network can be connected to the BeFEMTO Local Femto Gateway (LFGW) and benefit from the joint transmission power optimisation algorithm developed in BeFEMTO (and supported by the BeFEMTO architecture through the Ps interface). Compared to the classical non-joint baseline approach described in the 3GPP, the joint optimisation proposed in BeFEMTO reduces significantly the outage experienced by both macro (from 18.06% down to 3.93%) and femto users (from 0.52% down to 0.055%) in heavy femtocell deployment, leading to an overall HetNet performance increase. The method defined within BeFEMTO also allows the switch-off of the most disturbing femtocells (option which makes more sense when the CSG is shared among the femtocells) enabling energy saving and paving the way to autonomous network femtocell deployment.

5.3 Interference Mitigation

5.3.1 Interference analysis between femtocells and macrocells in open access mode in real scenarios

5.3.1.1 Description of the Scheme

The objective is to study through simulations the interferences that might happen between the femto and macro layer over a real network scenario, i.e., a scenario extracted from a real network deployment. Thanks to this, the conceptual study will take into account the peculiarities and heterogeneity inherent to real deployments.

The aim is to assess performance in a real network scenario with a massive femto deployment. For that purpose, different alternative scenarios have been evaluated, varying the femto density per macro, starting from 10 to 40, which means increasing the number of femtos from 660 to 2640 in the whole scenario.

As considering open access mode the UEs will connect to the best server anyway, i.e., there is no restriction for the connection to any femtocell. According to FemtoForum Interference Management Whitepaper [80], the Open Access is not that harmful when dealing with co-channel interference between macrocells and femtos. The results try to figure out whether these conclusions were also valid for a massive deployment in a real network scenario.

Following tables show a summary of the obtained results:

Scenario	SINR_DL (dB)	Throughput_DL (Mbps)	SINR_UL (dB)	Throughput_UL (Mbps)
Macros	1,82	20,37	-5,38	8,78
Macros_660Femtos	1,76	20,21	-5,77	8,51
Macros_1320Femtos	1,71	20,04	-5,98	8,29
Macros_1980Femtos	1,66	19,87	-6,27	8,1
Macros_2640Femtos	1,6	19,71	-6,46	7,92

Table 29: Average SINR and Throughput values for Macro served UEs

Scenario	SINR_DL (dB)	Throughput_DL (Mbps)	SINR_UL (dB)	Throughput_UL (Mbps)
660Femtos	14,11	45,73	16,24	26,76
1320Femtos	13,58	45,28	13,53	24,63
1980Femtos	13,24	44,99	11,62	23,09
2640Femtos	12,91	44,63	10,2	21,85

Table 30: Average SINR and Throughput values for Femto served UEs

5.3.1.2 Contribution to BeFEMTO System Concept and Objectives

The main conclusion that can be extracted from the previous analysis is that interference does not seem to be very harmful when access to femtocells is not restricted, i.e., when working in open access. This statement already concluded for canonical scenarios is extended to a real deployment since it has been observed that there is no significant degradation even when increasing density of femtos per macrocell. Although the global capacity increases when adding more femtos in the scenario, degradation can be detected when analysing statistics for macros and femtos separately. Femtos seem to be more affected, overall in the uplink, where there is a degradation of 6 dB on average.

References

[80] Femto Forum, "Interference Management in OFDMA Femtocells", White Paper, Mar. 2010.

5.3.2 Interference analysis between femtocells and macrocells in close access mode in real scenarios

5.3.2.1 Description of the Scheme

A performance analysis considering UE connectivity restriction to femtocells is presented. This analysis aims to assess the impact of dominant interference conditions in downlink when macro UEs are in close proximity of femtocells.

When dealing with Close Subscriber Group (CSG) femtocells, radio conditions for macro UEs in close vicinity of a femto could be highly unfavorable. To assess the CSG restrictions, a parameter that represents the probability for the users located in the femto best server area to be connected to this femto is defined (CSG probability). A value of 25% for CSG probability means that just 25% of the users in the femto best server area are connected to this femto. The remaining 75% would be connected to their best macro server and hence, these 75% of users would experience a high degree of interference due to the former femto best server. Next figure shows how average throughput is degraded as the percentage of UEs connected to their best server femto decreases. The extreme cases have been also analysed. The 100% means that all UEs would be able to connect to the femto if this is the best server for them, so this means no restriction at all and is equivalent to open access. On the contrary, 0% simulates the worst case when no UEs could be connected to the desired femto.

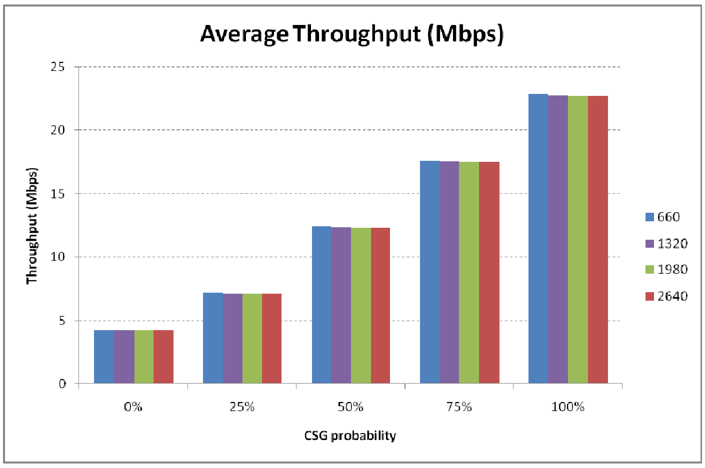


Figure 68: Average throughput in increasing femtos density scenarios, femto best server areas, CSG access.

These throughput values average experienced throughput in zones where femtos are best server. However the following figure considers the whole simulation area. In such case, the degradation becomes softer, since zones where macros are best server are considered too, and in DL these points are not affected by the CSG condition (what are affected are macro UEs served in a femto best server area).

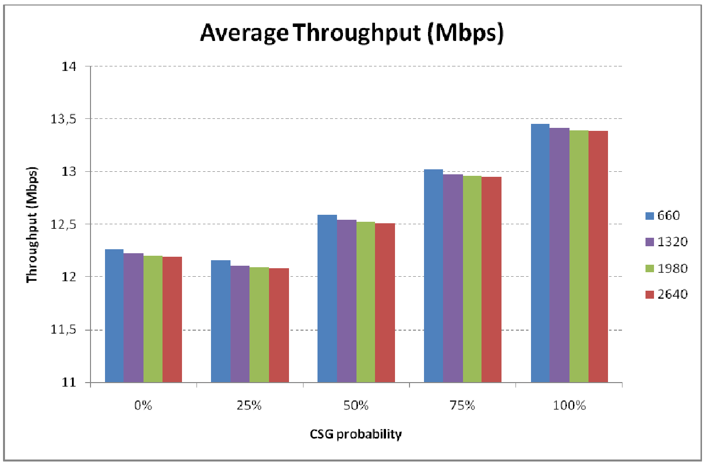


Figure 69: Average throughput in increasing femtos density scenarios, CSG access.

For completing the analysis, figures with sum throughput and spectral efficiency are provided too.

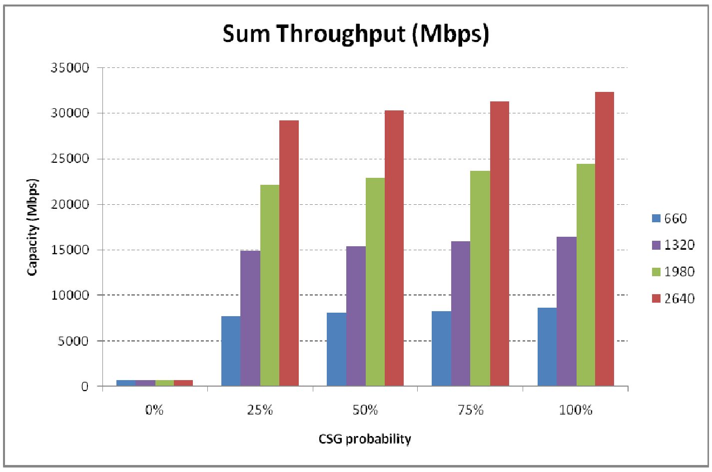


Figure 70: Sum throughput in increasing femtos density scenarios, CSG access.

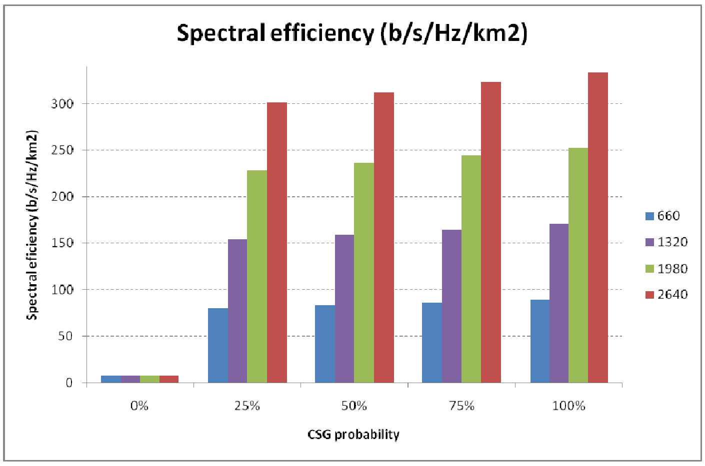


Figure 71: Spectral efficiency per km2 in increasing femtos density scenarios, CSG access.

5.3.2.2 Contribution to BeFEMTO System Concept and Objectives

The simulation results confirm the impact of dominant interference conditions in downlink when macro

UEs are in close proximity of femtocells. Results conclude that average throughput is degraded as the percentage of UEs connected to their femto best server decreases. It means that more macro UEs will experience a higher level of interference and hence will worse their throughput. This degradation is confirmed for any of the simulated scenarios, no matter if the number of femtos is higher of lower. The CSG probability could be a candidate parameter to be monitored in order to trigger a SON mechanism to deal with such harmful interference situation. Regarding spectral efficiency results, if we translate bps/Hz/Km2 to bps/Hz/cell we can see that there is still room until reaching the 8bps/Hz/cell Befemto target. It is important to remark that these results have been achieved in a scenario where no SON technique, that might have increased spectral efficiency, have been applied.

References

[81] Femto Forum, "Interference Management in OFDMA Femtocells", White Paper, Mar. 2010.

5.3.3 Spatial Domain based Interference Coordination

5.3.3.1 Description of the Scheme

Base Station Coordinated Beam Selection (BSCBS) has been introduced in [82]. The general idea of beamforming for transmitting data to mobile users in a wireless network with sectorized base station antennas is to radiate most of the power into the desired direction. A beam directed towards a cell-edge user may cause significant interference to a nearby user in an adjacent cell when both users are served at the same time-frequency resources. Performance gains can be expected when the selection of beams can be coordinated in neighbour cells in such a way that beam collisions between nearby cell-edge users can be avoided. An example situation is shown in Figure 72. Beam collisions can be avoided by coordinating the selection of precoding matrices in different cells. The coordination is based on feedback from UEs including not only CQI, Rank Indicator (RI) and Precoding Matrix Indicator (PMI), but also different types of additional messages to support the cooperation. For example, a RESTRICTION REQUEST (RR) feedback message from the UE contains information about unwanted precoding matrices. The users request in advance the restriction of the usage of certain precoding matrices in neighbour cells over the resources that could be used for data transmission at a later time instant. More details of the message design are provided in [82] and [83].

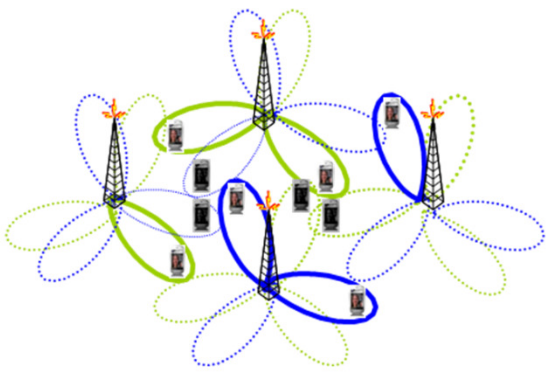


Figure 72: Avoidance of Beam Collisions.

The overall goal of the coordination approach is then to maximize a network (cluster) wide utility metric over all the combinations of precoding matrices considering the restriction request from received from users. This requires the exchange of messages between base stations over the X2 interface that logically connects base stations with each other in LTE. In order to keep the information exchange acceptable both in delay and complexity, a scheduling design was chosen that can be added on top of the Rel. 8 scheduling functionality. More details can be found in [82] and [83].

In the following we show simulation results for a 4x2 antenna configuration for a scenario with CSG femtos and macro cells. In such a scenario the only UEs belonging to the CSG of the femto cell can connect to it. UEs not belonging to the CSG cannot connect to the femto cell and must connect to a macro cell even if they are in the coverage area of the femto cell. Those macro UEs suffer from strong interference from the femto cell and can benefit from sending RESTRICTION REQUEST messages.

Detailed simulation assumptions can be found in [82]. In the simulations it is assumed that each RESTRICTION REQUEST message sent by the UE covers a frequency subband of 5 PRB (called frequency validity of 5 PRB in the following). Only macro UEs with a geometry below -3 dB are allowed to send RESTRICTION REQUEST messages. Figure 73 shows the mean relative gain in throughput for the macro and femto UEs compared to the reference system without codebook restrictions when a different percentage of codebook entries is restricted. It is seen in Figure 73 that the macro UEs that are allowed to send RR messages benefit significantly from the reduction in interference by avoiding unfavorable beams in the femto cell. It is further seen that the gains become the larger the more codebook entries are restricted. Figure 73 shows that even macro UEs in better RF conditions (i.e. whose geometry is larger than -3 dB) benefit slightly from restricting beams in the femto cell. Gains are again largest, if the femto restricts all beams in the current subframe since then the femto does not generate interference at all.

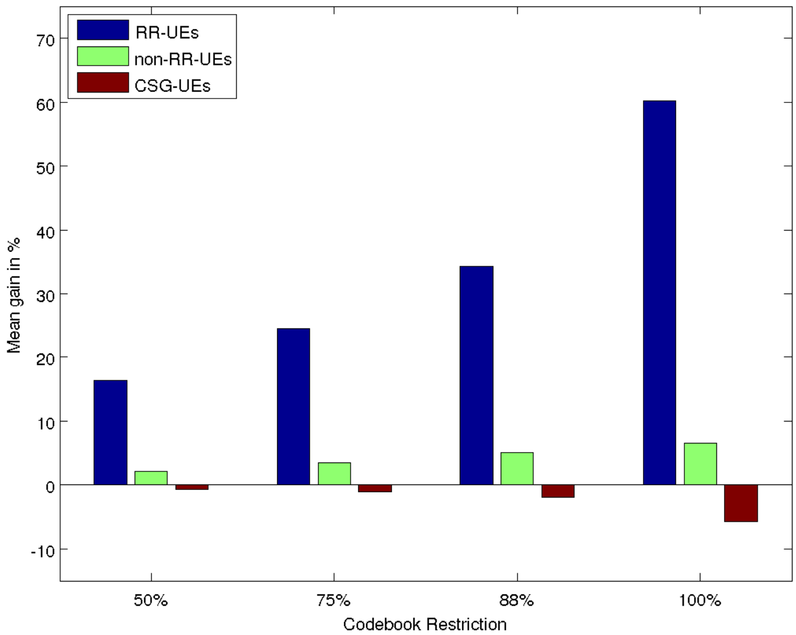


Figure 73: Relative Gain of Macro and Femto UEs.

Figure 73 shows that in average 5% throughput reduction for femto users needs to be taken into account by improving the throughput for macro users that suffer from strong interference by the femto cell. However, this loss seems tolerable since the load in a femto cell is low and the user throughput in bps/Hz is very large.

5.3.3.2 Contribution to BeFEMTO System Concept and Objectives

BSCBS is an interference coordination scheme in spatial domain by restricting precoding matrices that aims to improve the user throughput of UEs in a victim cell suffering from strong interference by an aggressor cell and, therefore, fits to the BeFemto system concept and objectives. The largest gains are achieved if the entire codebook is restricted for a specific frequency subband. In this case the spatial domain coordination converges to a time domain interference management. In [82], it has been shown that BSCBS can then be seen as an extension of eICIC in LTE Rel-10 since it applies time-domain restrictions in a frequency-domain subband and not for the entire bandwidth as eICIC does.

References

[82] EU FP7-ICT BeFEMTO project, "Preliminary SON enabling & multi-cell RRM techniques for networked femtocells", D4.1, Dec. 2010.

[83] J. Giese, A. Amin, and S. Brueck, "Application of Coordinated Beam Selection in Heterogeneous LTE-Advanced Networks", in *Proc. of the IEEE International Symposium on Wireless Communication Systems (ISWCS)*, Nov. 2011.

5.3.4 CoMP for femtocells in the DL

5.3.4.1 Description of the Scheme

A decentralized downlink beamformer design using coordinated HeNBs is proposed for minimizing the total transmitted power of coordinated HeNBs subject to fixed cross-tier interference constraints and femto-UE specific SINR constraints. The proposed minimum power beamformer design relies on limited backhaul information exchange between coordinated HeNBs. Instead of exchanging full CSI between coordinated HeNBs, *real valued* HeNB specific co-tier interference terms are exchanged. Therefore, a centralized controlling unit is not required, and the minimum power beamformers are obtained locally at each HeNB. Coordination between HeNBs can be handled, for example, using X2 interface.

Our decentralized beamforming approach is TDD based, thus, it is fair to assume that each HeNB can measure at least the channels of all cell-edge users, independent of which HeNB they are connected to. In order to turn the centralized problem into a decentralized one, the problem should be reformulated into a proper form for applying a dual decomposition method. The dual decomposition approach is appropriate when the optimization problem has a coupled constraint, and when relaxed the problem decouples into several sub-problems. Consequently, the original one level optimization problem can be divided into two levels of optimizations, i.e., a master dual problem and several sub-problems. Sub-problems are solved for fixed dual variables whereas the master problem is in charge of updating the dual variables. In other words, the amount of resources used in each sub-problem depends on the resources' prices set by the master problem.

Figure 75 illustrates the average sum power of HeNBs as a function of path-loss difference α between Macro-UE and a group of cell-edge femto-UEs, with 0 dB SINR constraints requirement. Cross-tier interference constraint from HeNB to Macro-UE is set to 10 dB below the noise power level. Note that eNB employs optimal minimum power beamforming for serving its Macro-UE, and is not concerned about the caused interference to femto-UEs. Therefore, the transmit power of eNB remains constant when path-loss difference α is varied. Consequently, eNB power is omitted from the simulation results. Low user specific SINR constraints can be interpreted as a user being far from its serving BS (cell edge UE). Therefore, Figure 74 models the case where femtocells are located far away from eNB. Results show that the proposed optimal decentralized coordinated beamforming yields significant performance gain over Zero-Forcing beamforming. Thus, it can be concluded that HeNB coordination is highly beneficial when the SINR constraints are low for Macro-UE and femto-UEs. Furthermore, it can be seen from the lower bound curve that non-controlled interference from eNB to femto-UEs causes significant performance loss for femtocells. Obviously, this is due to the fact that eNB pays no attention on the caused interference to femto-UEs.

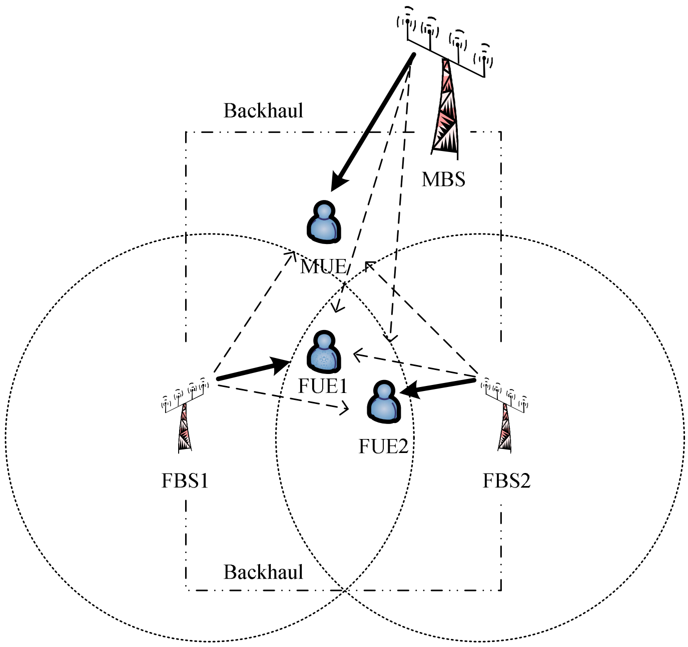


Figure 74: Simulation scenario.

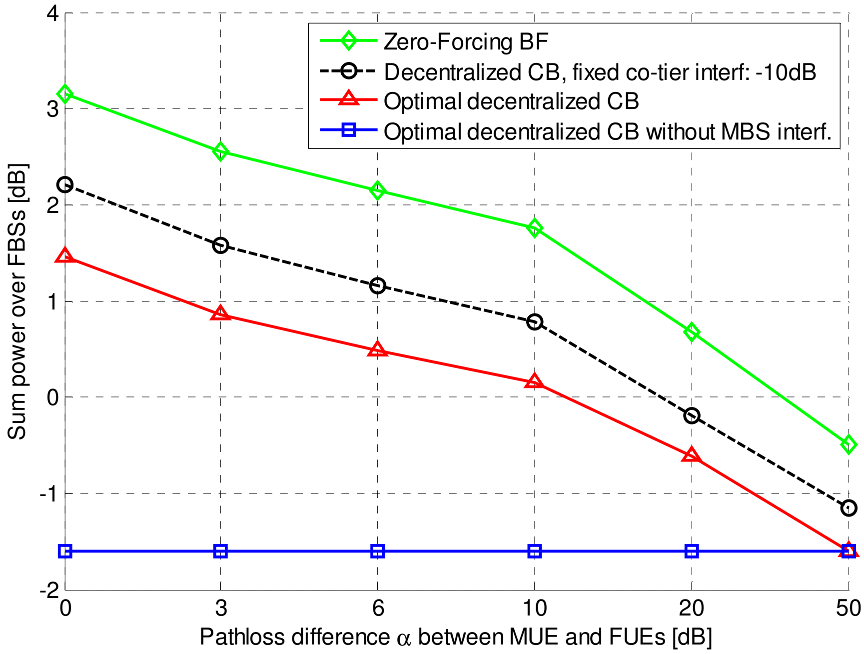


Figure 75: Average sum power of HeNBs for 0 dB femto-UE and 0 dB Macro-UE SINR targets.

5.3.4.2 Contribution to BeFEMTO System Concept and Objectives

Through Coordinated multi-point transmission, the objective of 8bps/Hz can be satisfied, within a typical scenario as it depends on the QoS required at the macrocell tiers, as well as among femtocell tiers. Moreover, that depends on whether we are looking at energy efficiency or rate enhancements.

References

[84] H. Pennanen, A. Tölli, M. Latva-aho, "Decentralized coordinated downlink beamforming for cognitive radio networks, " in *Proc. of the IEEE PIMRC 2011*, Toronto, Canada.

5.3.5 Central Interference mitigation between femtocells

5.3.5.1 Description of the Scheme

Large-scale femtocell deployment comes with some challenges. Among these challenges, interference between base stations (BSs) requires more attention, especially in networks where BSs are densely deployed, such as within enterprises or residential complexes. Frequency reuse, where interfering neighbors transmit data on different frequency resources (subbands), is used to enhance the throughput of cell edge users. Access to the remaining subbands (secondary subbands) is restricted, so as not to interfere with neighboring BSs. Thus, user equipments (UEs) located in the vicinity of two or more BSs face less interference and enjoy better service quality. On the other hand, frequency reuse decreases the network's overall resource efficiency. Unlike macrocell networks, femtocells are installed by the end user, so that the operator cannot determine the locations of the neighboring base stations *a priori*. This may result in vast variations of the interference conditions experienced by BSs. This implies that BSs having a lower number of interfering neighbors can use more subbands than BSs that are in close vicinity to one another. Consequently, in order to increase the resource usage efficiency, BSs should use as many subbands as possible depending on their geographic distribution. In this report, a novel graph-based dynamic frequency reuse (GB-DFR) approach is presented. The main objective of GB-DFR is to dynamically assign subbands to BSs, so as to improve the throughput of cell-edge UEs, without causing a sharp decrease in the overall network throughput.

In GB-DFR, a central controller collects the cell identities (IDs) of the interfering neighbors from all BSs and maps this information onto an interference graph. Interfering neighbors are identified based on a pre-defined signal-to-interference-and-noise ratio (SINR) threshold, γ_{th}, which specifies the minimum desired SINR for each UE. Then, the central controller assigns subbands to BSs by applying a modified graph coloring algorithm that takes into account the usage efficiency of subbands. Conventional graph coloring algorithms, such as the one given in [85], color the nodes of a graph with the minimum number of colors such that no two connected nodes have the same color. By assuming that each color represents a different subband, graph coloring facilitates subband assignment, where two BSs connected via an edge in the interference graph cannot use the same subband. The drawback of conventional graph coloring is the inefficient usage of the subbands since each BS is assigned only one subband. In order to increase the spatial reuse of subbands, a BS in a less interfering environment should be able to use more subbands without causing high interference to its neighbors. Shortcomings of conventional graph coloring are addressed with the proposed GB-DFR scheme, where the subbands are assigned to BSs in three steps and a cost function is introduced to maximize the spatial reuse of subbands. Additionally, in order to increase the fairness for situations where the number of subbands is high, a parameter s_{min} is introduced. It indicates the minimum number of subbands that should be assigned to each BS.

The novelty of GB-DFR comes from the flexibility in the number of assigned subbands which depends on the interference conditions of each BS. Those BSs facing low interference are assigned more subbands. Another advantage of GB-DFR is its low complexity and modest signalling overhead. The central controller only needs the cell-IDs of the interfering neighbors and determines the subband assignment by graph coloring and search algorithms which have low complexity. For more details, the reader may refer to [86].

For simulations, a downlink transmission in a femtocell network based on 3GPP Long Term Evolution (LTE) is considered. The deployment of femtocells is modeled by a 5×5 grid, where a single floor building with 25 apartments is used. BS activation probability is set as 0.2 meaning 1/5th of the apartments, on average, have one active BS. Each active femto-BS serves only one UE. For the sake of simplicity, interference from the macrocell network is neglected, which may be accomplished by allocating different frequency bands to macro and femtocells. The frequency band is divided into S=4 subbands. For GB-DFR, the SINR threshold for constructing the interference graph, γ_{th}, is set to 5 dB and the minimum number of subbands assigned to each BS, s_{min}, is set to 1. Detailed explanation of the simulation parameters can be found in [86].

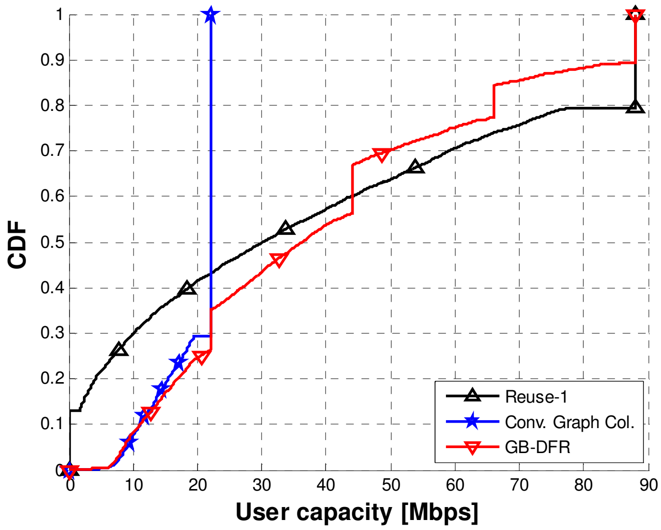


Figure 76: CDF of user capacity.

Figure 76 compares the capacities of the three approaches where all BSs use all available subbands (Reuse 1), BSs are assigned one subband based on the conventional graph coloring algorithm and subbands are assigned to BSs using GB-DFR. For the reuse-1 case, nearly 15% of the UEs have diminishing capacity as they experience an SINR less than the minimum SINR used by the available modulation and coding schemes. It is seen from Figure 76 that by implementing conventional graph coloring and GB-DFR, the performance of cell edge UEs is significantly improved, which results in a shift of the CDF at low capacities. As the minimum SINR experienced by a UE is approximately 5 dB, minimum capacity achieved by a user increases to around 6 Mbps. However, for the conventional graph coloring, the increased SINR cannot compensate the reduced resources utilization of the UEs facing less interference, thus causing their capacity to decrease. The positive impact of GB-DFR at this point is clearly seen; as more subbands are assigned to the BSs that are exposed to low interference, GB-DFR greatly outperforms conventional graph coloring at high capacities. These results indicate that the GB-DFR combines the benefits of traditional coloring and full reuse.

5.3.5.2 Contribution to BeFEMTO System Concept and Objectives

The main objective of this work is to adaptively match the frequency reuse in femtocell networks depending on varying interference conditions. Simulation results show that GB-DFR attains a significant improvement for cell-edge users, at the expense of a modest decrease for cell-center users. The scheme depicted in this section also compatible with the BeFEMTO System Architecture. According to the given deployment parameters, the average spectral efficiency achieved is 2 bps/Hz for single antenna transmission. Additionally, by using the multi-antenna techniques, we can get higher spectral efficiencies.

References

[85] D. Brélaz, “New Methods to Color the Vertices of A Graph,” *Communications of the ACM*, vol. 22, no. 4, pp. 251–256, Apr. 1979.

[86] S. Uygungelen, G. Auer, and Z. Bharucha, “Graph-Based Dynamic Frequency Reuse in Femtocell Networks,” in *Proc. of the 73rd IEEE Vehicular Technology Conference (VTC)*, Budapest,

Hungary, May 15–18 2011.

5.3.6 Distributed interference mitigation between femtocells

5.3.6.1 Description of the Scheme

In this report, we present a dynamic and autonomous subband assignment (DASA) method that is better suited to serve multi-user scenarios with the objective of increasing the cell-edge capacity whilst maintaining high subband utilization. In order to enable this, we define two classes of subbands depending on their foreseen usage by a base station (BS): primary subbands (PSs) and secondary subbands (SSs). The PSs are used to protect cell-edge user equipments (UEs) facing high interference. The PSs belonging to a particular BS cannot be used by their interfering neighboring BSs because such neighbors can cause high interference to UEs of the BS in question. For identifying the interfering neighbors, a global, pre-defined signal-to-interference-plus-noise ratio (SINR) threshold, γ_{th}, is defined which represents the minimum tolerated SINR for each UE. In order to ban/block subbands at the interfering BSs, BSs send a PS indicator to their interfering neighbors. When a BS receives such an indicator, it cannot use the indicated subband and this way cell-edge UEs allocated resources from within the set of PSs experience low interference. The SSs, belonging to the set of all unblocked (in other words, non-PS) subbands can be used by a BS depending on the prevailing interference conditions; but, enjoying no privileges, these subbands cannot be blocked at interfering neighboring BSs. Resources of SSs can therefore be allocated to cell-center UEs facing less interference as long as they do not cause high interference to neighboring BSs. Consequently, the usage of the PSs boosts cell-edge capacity, whereas the SSs increase the spatial reuse of resources especially for multi-user deployments.

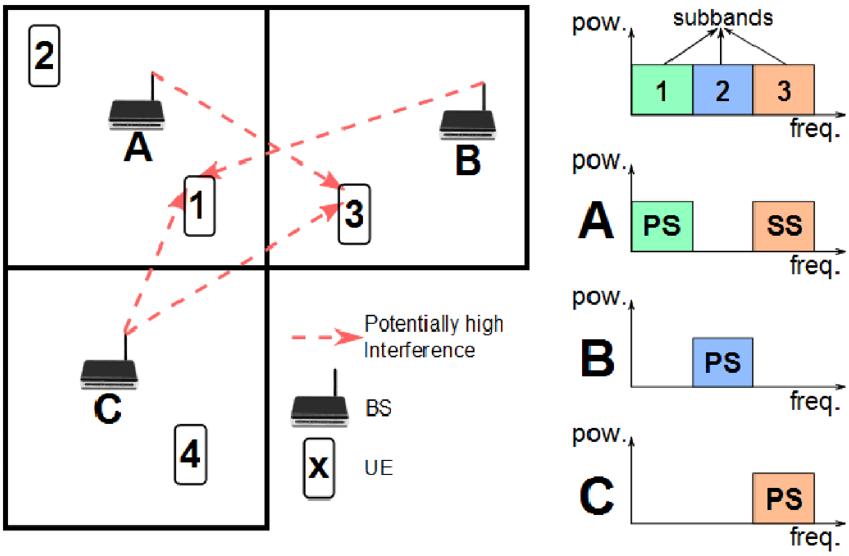


Figure 77: An example of subband assignment where the system bandwidth consists of 3 subbands.

A toy example of the allocation of subbands to the various users of various BSs is depicted in Figure 77. According to this figure, BS_C causes high interference to *some* UEs served by BS_A and BS_B. Since these UEs are allocated RBs from subbands 1 and 2, respectively, these subbands are blocked at BS_C. Likewise, BS_A cannot use subband 2 and BS_B cannot use 1. Therefore, subband 1 is declared the PS for cell A, subband 2 the PS for cell B and subband 3 for cell C. On the other hand, UE_2 served by BS_A does not face high interference from BS_B and BS_C, therefore BS_A may allocate subband 3 RBs to UE_2 without causing high interference to UE_4 served by BS_C. In DASA, subband assignment is done on an event triggered basis which means subbands are updated only if there is a change in the interference environment. Additionally, all BSs are synchronized with a time duration equal to that of a so-called *time slot*. Between the starting instances of two time slots, the subband configuration remains undisturbed, *i.e.*, changes in the subband assignment are only made at the start of the time slots. For more details, the reader may refer to [87].

For simulations, a downlink transmission in a femtocell network is considered. The deployment of femtocells is modeled by a 5×5 grid, where a single floor building with 25 apartments is used. BS activation probability is set as 0.2 and each active femto-BS served 4 UEs. For the sake of simplicity, interference from the macrocell network is neglected, which may be accomplished by allocating different frequency bands to macro and femtocells. The total 20MHz frequency band is divided into 4 subbands. For DASA, the SINR threshold for constructing the interference graph, γ_{th}, is set to 5 dB and the number of PS per BS is set as 1. The performance of DASA is compared to fixed frequency reuse (FFR) methods. We use two FFR schemes: FFR 1/4 and FFR 2/4 where each BS is centrally assigned one and two subbands out of four available subbands respectively. Detailed explanation of the simulation parameters can be found in [88].

Method	Cell-edge Capacity [Mbps]	Average Cell Capacity [Mbps]
FFR 1/4	1.54	19.83
FFR 2/4	0.32	30.14
DASA	1.60	35.26

Table 31: Performances of the Compared Methods.

The improvements in overall performance are summarized in Table 31, which compares the cell-edge capacity (defined as the 5% of the CDF of user capacity) and the average cell capacity. The results demonstrate that DASA significantly outperforms FFR in terms of cell-edge and average cell capacity. Since SSs are not blocked, more subbands are utilized with DASA, and hence, cell-center UEs can be allocated more resources. Therefore, DASA boosts cell-edge capacity without compromising the system capacity.

5.3.6.2 Contribution to BeFEMTO System Concept and Objectives

The main contribution of this work is to autonomously assign resources in femtocell networks that are characterized by varying interference conditions. The method offers the BS an autonomous resource allocation limited by its interference environment. The scheme depicted in this section also compatible with the BeFEMTO System Architecture. Simulation results demonstrate that DASA attains a significant improvement for both cell-edge user as well as system capacities, compared to conventional centralized frequency reuse methods. The average cell spectrum efficiency is around 1.75 bps/Hz for single antenna systems. By adapting the system parameters (such as SINR threshold) and using multi-antenna techniques, higher gains can be achieved.

References

[87] S. Uygungelen, Z. Bharucha, and G. Auer, "Decentralized Interference Coordination via Autonomous Component Carrier Assignment," *in Proc. of the 54th IEEE Global Telecommunications Conference (GLOBECOM)*, Houston, USA, Dec. 5–9 2011.

[88] S. Uygungelen, G. Auer and Z. Bharucha, "Graph-Based Dynamic Frequency Reuse in Femtocell Networks," *in Proc. of the 73rd IEEE Vehicular Technology Conference (VTC),* Budapest, Hungary, May 15–18 2011.

5.3.7 eICIC (Interference Management with ABS (Almost Blank Subframes))

5.3.7.1 Description of the Scheme

3GPP work on interference management covers work in Release 8 for macro cell homogeneous networks and the work items "Enhanced ICIC for non-CA based deployments of heterogeneous networks for LTE" and "LTE TDD/FDD Home eNodeB RF Requirements" which provide the current status for LTE femtocells. The focus of these work items is the study if unplanned deployment of standalone femtocells with focus on MUE protection, so the results and solution proposal discussed in the following can not be directly applied to networked femtocells and to the femto to femto interference case.

In order to avoid the dominant interference conditions in downlink when a MUE is in close proximity a femtocell it was concluded in the studies that the Release 8 and 9 mechanisms defined so far are not enough to reduce downlink control channel interference to an acceptable level. For uplink interference management the Release 8 and 9 mechanisms, mainly uplink power control, are deemed sufficient for heterogeneous networks.

Possible solutions evaluated in the work items can be categorised into

- power control,
- time domain and
- frequency domain solutions.

Time domain solutions use different types of subframe. A regular subframe is transmitting data and control channels normally, with the option of not utilising the PDCCH completely. Non-regular subframes can be MBSFN, almost blank (AB) or fake uplink (TDD only) subframes.

Non-regular subframes have to take into account some restrictions in order not to disturb normal Rel8/9 operation. These restrictions are that PSS/SSS are transmitted every 5ms and the PBCH is transmitted every 10ms, furthermore PCFICH, PDCCH and PDSCH transmissions are scheduled for SI-RNTI every 20ms and for P-RNTI when paging is scheduled. All of these need to be transmitted irrespective of the subframe type. In addition the non-regular subframes have different properties of how cell-specific reference signals (CRS) are transmitted and therefore how much interference due to CRS is created. The MBSFN and fake uplink subframes do not transmit any CRS in the control and data channel part of the subframe, while the almost blank subframe includes CRS in the control and data region.

Additional time-domain solutions, mainly for FDD only, are shifting of OFDM symbols in order to avoid interference from CRS and control channel to victim control channels and subframe shifting in order to avoid interference on subframes 0 and 5 (PSS/SSS and PBCH).

An example time-domain solution using two AB+MBSFN subframes plus and subframe shift of 1 is shown in Figure 78.

5.3.7.2 Contribution to BeFEMTO System Concept and Objectives

In this work we investigated the concept of a resource partition between macro eNBs and HeNBs in the time domain. In considered scenarios, macro eNB is allowed to use all subframes while HeNBs can use a part that is ABS was configured at HeNBs. It allowed macro UEs to maintain reliable communication with its serving macro eNB at cost of a throughput reduction for HeNBs due to the reduced available resources.

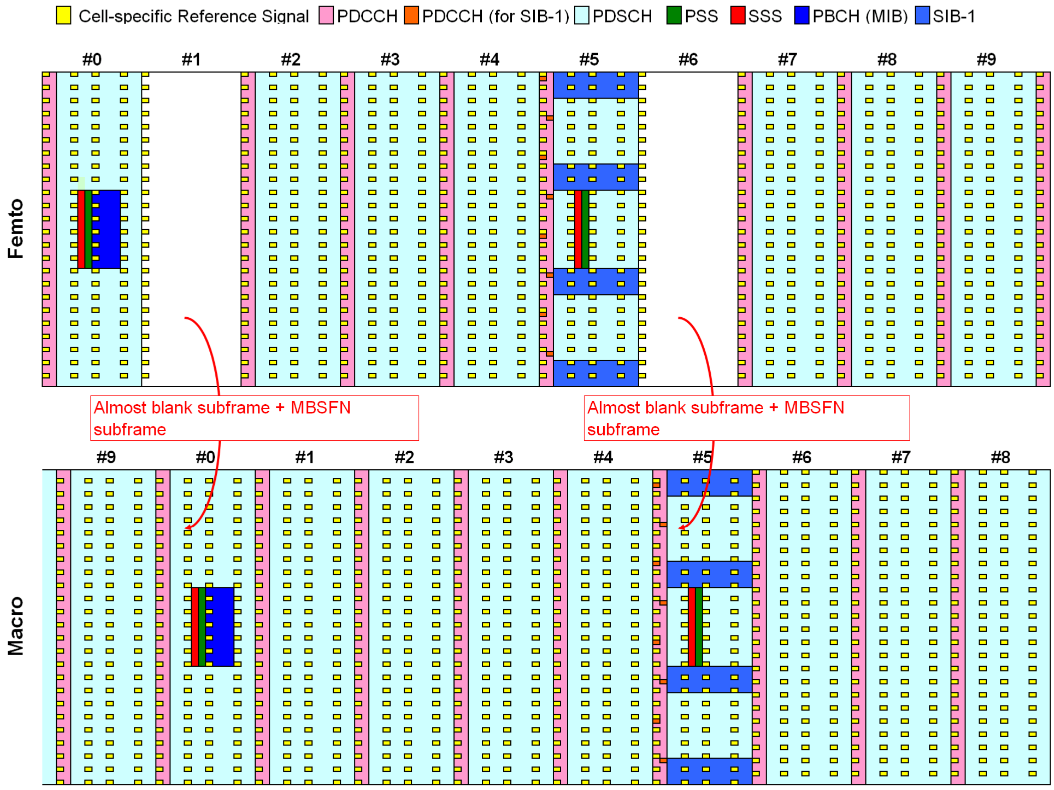


Figure 78: Overview of subframe types [89].

References

[89] R1-105442, "Views on eICIC Schemes for Rel-10," NTT Docomo, RAN1 #62bis, October 2010.

5.3.8 MIMO and interference mitigation for achieving spectral efficiency of 8bps/Hz/cell

5.3.8.1 Description of the Scheme

Spatial multiplexing is a prominent feature of Multiple Input Multiple Output (MIMO) systems in 3GPP LTE networks. Higher Signal to Interference-plus-Noise Ratio (SINR) values are required in order to achieve higher number of spatial layers (for a given antenna configuration). With reuse 1 in the network, interference may become more significant and hence could reduce the SINR values. In this section, we study the performance of femto/macro Heterogeneous Network (HetNet) characterized by a MIMO spatial multiplexing. We show how the objective of 8 b/s/Hz spectral efficiency could be achieved in femto network by exploiting MIMO spatial multiplexing and employing a self-organized bandwidth allocation scheme for interference management. The interference management scheme is briefly presented in the following text.

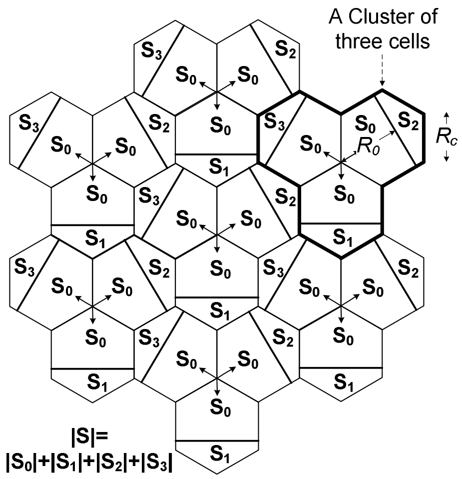


Figure 79: Fractional Frequency Reuse (FFR) case.

In our proposed interference mitigation scheme, fractional frequency reuse (FFR) is employed in the macro network (Figure 79). As shown in the figure, $\mathbf{S_0}$ subbands are used in the inner region and $\mathbf{S_m}$ (where $m \in \{1,2,3\}$) are used in the outer region. If **S** represents the total subbands associated with system bandwidth *W*, then in every macro cell there will be $|\mathbf{S}| - |\mathbf{S_0}| - |\mathbf{S_m}|$ orthogonal subbands that could be exploited by the underlay femto cells. In our simulations, these least interfered subbands are found by a femto base station (HeNB) through sniffing process.

Among the multiple spatial multiplexing modes specified in LTE (Rel. 8, 9), we focus on transmission mode 4 Close Loop Spatial Multiplexing (CLSM). In this transmission mode, independent data streams could be transmitted. The maximum number of spatial streams is defined by $\min(N_t, N_r)$ where N_t and N_r are the number of transmit and receive antennas respectively.

In order to evaluate the proposed solution, we have carried out Monte Carlo system level simulations with a significant number of runs, each run lasting several transmit time intervals (TTIs). The macro network is composed of 7 sites with 3 sectors per site. Deployment of femto cells is carried out with the help of dual-stripes model. The dual stripes clusters are dropped randomly at the start of a run with average one cluster per macro sector. A femto cell is hosted by a 10 m x 10 m block inside the cluster. The presence of HeNB in a block is governed by the probability of femto cell deployment (0.1 in our simulations). The position of HeNBs inside a block follows uniform random distribution. On each floor there are 40 blocks and a total of 6 floors have been considered in the simulation. User equipments (UEs) are also dropped with uniform random distribution across macro/femto network at the start of each run. We have considered a total networked bandwidth of 10 MHz. With this bandwidth, we have 9 subbands. For the FFR scheme in macro network, 6 subbands are assigned to the inner region while 1 to the outer region of each sector. The UEs are scheduled by applying a policy of resource fairness.

Parameter	Antenna configuration	Reuse 1 in macro		FFR in macro	
		Macro cell	Femto cell	Macro cell	Femto cell
Average cell throughput (Mbps)	1x1	16.1	6.7	14	8
	2x2	25.1	11.6	22	14.1
	4x2	29.8	13.2	26.1	15.7
	4x4	43	21	38.9	26
Average spectral efficiency (b/s/Hz)	1x1	1.4	3.3	1.7	3.7
	2x2	2.4	5.8	2.9	6.6
	4x2	2.8	6.6	3.4	7.3
	4x4	4.2	10.5	5.2	12.1

Table 32: Comparison of Average Values of Different Key Performance Indicators (KPIs)

The simulation results are given in Table 32. The results with reuse 1 and FFR in the macro network are compared. Two subbands are chosen by each HeNB through sniffing process in all cases. It can be observed that partial subband usage by femto network and CLSM with 4x4 MIMO results into an average spectral efficiency of more than 8 b/s/Hz. The main drawback of this approach is the use of lesser resources in the femto and the macro network and hence the reduced average cell throughput. Furthermore, 4x4 antenna configuration will results in higher cost of HeNB and UE.

5.3.8.2 Contribution to BeFEMTO System Concept and Objectives

We have shown the performance of a macro/femto network equipped with MIMO spatial multiplexing mode. We have shown that by combining spatial multiplexing characterized by 4x4 antenna configuration and interference mitigation, a target of 8 b/s/Hz is attainable. However, as compared to reuse 1, the average cell throughput is lesser. In future, we intend to work upon interference mitigation techniques that could further increase the value of average cell throughput while maintaining average spectral efficiency.

5.3.9 Co-tier Interference alignment

5.3.9.1 Description of the Scheme

Interference alignment (IA) among femtocells is proposed to address the interference problem in dense small cell networks, by allowing FBSs to cooperatively perform interference alignment in the downlink to reduce their mutual interference, and consequently improve their overall performance. The problem is looked at from a game theoretic perspective, in which cooperative femtocells self-organize into coalitions or cluster, within which IA is carried out. The cooperative femtocells are referred to as *players* that decide when to cooperate so as to maximize their *utility metric*. In addition, a cooperation cost is taken into account upon forming coalitions in a form of pilot signal transmission power. Unlike most works, inter-coalition interference is accounted for, and hence the game is said to be in partition form due to externalities. No cross-tier interference is considered. The proposed approach is composed of three steps: first, the femtocells sense their environment in order to identify potential strong interferers, which are essentially cooperation candidates; second, femtocells start their cooperation phase by optimizing their best coalition partners while at the same time incurring costs for cooperation. After the network is partitioned into disjoint coalitions of femtocells, interference alignment is carried out per cluster. Using the proposed algorithm, femtocells can self-organize into a stable network partition composed of disjoint coalitions, which constitute the *recursive core* [1]of the cooperative game. In detail, inside every coalition, cooperative femtocells use advanced IA techniques to improve their downlink transmission rate. An average femtocell gain reaching up to 30% as compared to the non-cooperative approach is obtained with 300 femtocells.

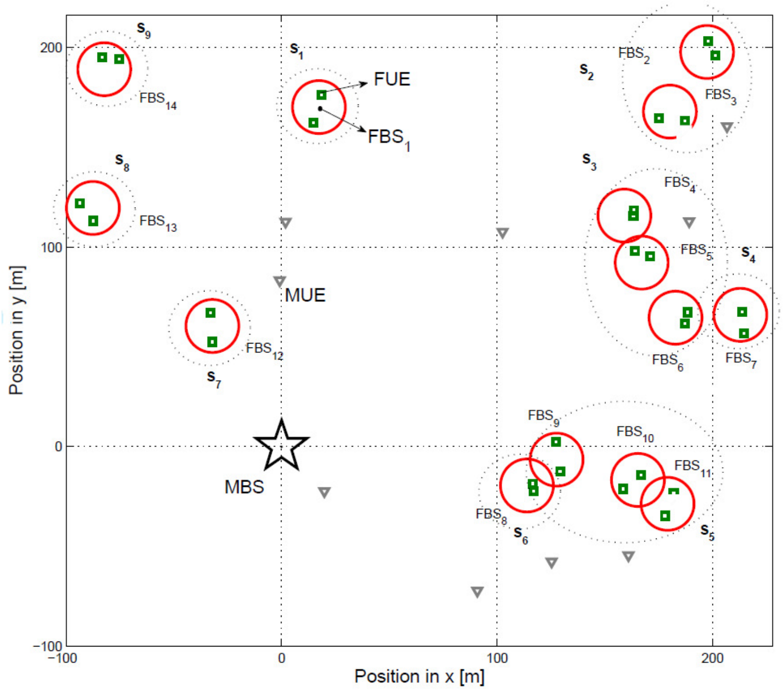


Figure 80: A close-up of the network resulting from the proposed algorithm with 250 femtocells, 2 FUEs per femtocell and 100 MUEs.

[1] The recursive core is a game theoretic solution that enables to find efficient partitions in the network such that no femtocells have any incentive to break away.

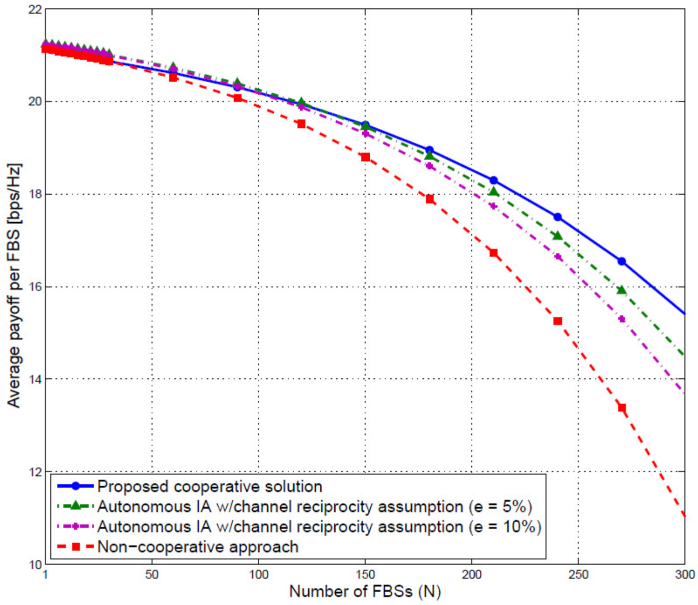


Figure 81: Cooperation gains in terms of the average payoff per FBS achieved by the proposed scheme compared to the non-cooperative setting, for different network sizes.

5.3.9.2 Contribution to BeFEMTO System Concept and Objectives

Leveraging on cooperation and MIMO capabilities, the proposed approach is a step towards fulfiling the 8 bps/Hz.

References

[90] F. Pantisano, M. Bennis, W. Saad, and M. Debbah, "Cooperative interference alignment in femtocell networks," in *Proc. of IEEE GLOBECOM 2011*, Houston, USA.

5.3.10 Interference control based on decentralized online learning

5.3.10.1 Description of the Scheme

In the situation where femto-cells work in closed access and co-channel operation with the macrocell system, the interference management task becomes a challenging problem. Since femto-cells are placed by end consumers, their number and position is unknown to the network operator, so that the interference cannot be handled by means of a centralized frequency planning. Therefore, in this section, femto-cells are modeled as a decentralized system able to autonomously select their Downlink (DL) transmission power per Resource Block (RB) in order to manage the aggregated interference they may generate at macro-users. The interpretation we give to autonomous decisions relies on the self-organization theory, where each femto-cell is an agent able to evolve coherent behaviours in accordance with the environment [91]. When multi-agent systems have to deal with interdependent and dynamic problems, (i.e. agents can not have an environment representation) the agents conforming the system are called reactive agents and have to act using stimulus-response type of behaviour [92]. As a form to implement reactive agents, Machine Learning (ML) introduces the concept of Reinforcement Learning (RL), which works based on learning from interactions with the environment, and on the observed consequences when a given action is executed. From the RL methods we focus on the Q-learning Time Difference (TD) algorithm, since in the considered problem it is required an incremental learning method, able to adapt to the environment online and without environmental models [93].

It is assumed that the environment is a finite-state, discrete time stochastic dynamical system, as shown in Figure 82. The interactions between the multi-agent system and the environment at each time instant corresponding to RB *r* consist of the following sequence: 1) The agent *i* senses the state of the environment; 2) Based on the perceived state, agent *i* selects an action (i.e. a transmission power level); 3) As a result, the environment makes a transition to the new state; 4) The transition to the new state generates a return for agent *i*; 5) The return is fed back to the agent and the process is repeated. The objective of each agent is to find an optimal policy for each state, to maximize some cumulative measure of the return received over time.

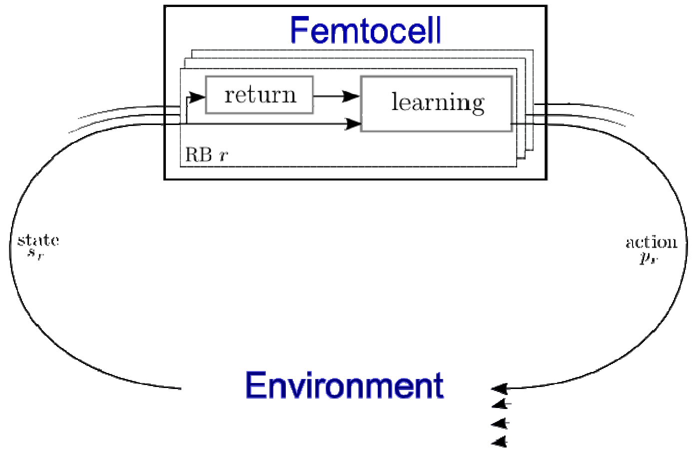


Figure 82: Learner-environment interaction.

In our system the multiple agents with learning capabilities are the femto BSs, so that for each RB they are in charge of identifying the current environment state, select the action based on the Q-learning methodology and execute it. The state perceived by the femto-cells is represented through two components: 1) an indicator to specify whether the femto-cell system contributes to generate an aggregated interference above or below the threshold selected for the macro-users. This measurement is based on the Signal to Interference Noise Ratio (SINR) value computed at the macro-user allocated at RB *r*. 2) A total transmission power indicator. The designed Q-learning algorithm aims to maintain the total transmission power of each femtocell below an allowed threshold, and the SINR at the macro-user below the selected SINR threshold [94]. Figure 83 presents system level simulation results for the proposed learning approach obtained for the scenario described in D 2.1. Figure 83 shows the convergence curves for different values of desired SINR at the macro-user allocated in RB r, for a femto-cell occupation ratio of 40%. It can be observed how the Q-learning is able to maintain at different desired values (e.g., 17, 20, 23 dB) the SINR at the macro-user. Similar results can be obtained for different values of occupation ratio ranging from 10 to 50%.

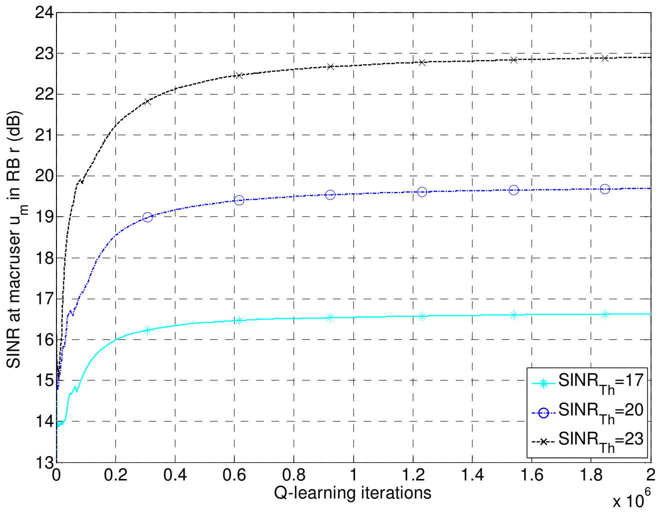


Figure 83: Convergence of SINR at macro-user to three desired values (i.e. 17, 20 and 23 dB).

5.3.10.2 Contribution to BeFEMTO System Concept and Objectives

We have proposed a decentralized Q-learning algorithm based on the theory of multi-agent learning to deal with the problem of interference generated by multiple femto-cells at macro-users. Through the proposed learning algorithm, the multi-agent system is able to automatically learn an optimal policy to maintain the interference in the macro-users under a desired value. Simulation results have shown that constraints in terms of maximum femto transmission power and SINR at macro users can be fulfiled by introducing learning capabilities in the scenario. Therefore, the learning technique allows the coexistence between femto-cells and macrocells in such a way that femto-cells do not jeopardize the macrocell capacity, maintaining it at a desired level (above the BeFEMTO target of 8bps/hz/cell), independently of the number of femto-cells. However, the implementation of the learning approach requires some information exchange among macrocells and femto-cells regarding the interference perceived by the macro-users. This information is proposed to be conveyed through the X2' interface.

References

[91] C. Prehofer and C. Bettstetter, "Self-organization in communication networks: principles and design paradigms," *IEEE Communications Magazine*, vol. 43, no. 7, pp. 78–85, July 2005

[92] K. P. Sycara, "Multiagent systems," *AI Magazine*, vol. 19, no. 2, pp. 79–92, 1998.

[93] R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction*. The MIT Press, 1998.

[94] A. Galindo-Serrano and L. Giupponi, "Distributed Q-learning for Interference Control in OFDMA-based Femtocell Networks", in *Proceedings of IEEE 71st Vehicular Technology Conference (VTC2010-Spring)*, 16-19 May 2010, Taipei, Taiwan.

5.3.11 Interference study for integrated multi-cell scheduling

5.3.11.1 Description of the Scheme

A major challenge in femtocell networks originates from the downlink interference among different femtocells in the system. The resulting interference in femtocells can have different origins. Co-tier interference refers to the inter-cell interference between femtocells (or HeNBs) whereas cross-tier interference is the interference between femtocell and macro-cells [95] assuming that femtocells are located under a macro-cell "umbrella". In [96], a semi-analytical model to study the effect of interference has been introduced for femtocells where marginal effect of co-tier interference has been observed due to high natural isolation between the femtocells in addition to low nominal transmission powers. However, this study was mainly based on symmetric assumptions on the deployment of femtocells. Unlike the macro-cells, femtocells do not follow predefined deployments based on the cell-planning strategies of operators and more investigation is required to capture the effect of this random deployment on the resulting interference in the system. The aforementioned issues motivated us to revisit the problem of co-tier interference in femtocells with more detailed analysis and evaluation studies. The Femtocell deployment used in this study is in accordance with 3GPP dual stripe model [97] as can be seen in Figure 84.

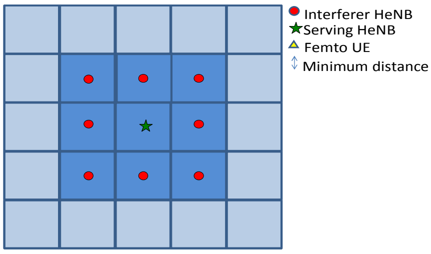


Figure 84: 5x5 grid layout.

Using this deployment, the effect of radio access parameters and deployment configurations were examined:

- **Effect of Path Loss Model**

The path loss model used in our study is based on the 3GPP dual stripe model [97] for the current 5x5 grid layout to better capture some contributing factors including the effect of internal penetration loss of the walls. In the path loss model used in [97], the path loss exponent (a=3.68) is much higher than the dual stripe model (a=2). This denotes a larger attenuation of inter-cell interference as the user is approaching the serving HeNB.

- **Effect of Wall Penetration Loss**

Another parameter that potentially can decrease the inter-cell interference in a femtocell network is the wall that separates each apartment. In this work, the UE location-independent CDF of the downlink SINR was compared for a symmetric deployment of HeNBs using different wall penetration levels

- **Effect of Lognormal Shadowing**

Another key radio access parameter is the Lognormal Shadowing effect. The Shadowing effect can be approximated as a lognormal random variable where it estimates the random variations of the received power around a mean value. Our results show that by adjusting the standard deviations of lognormal shadowing, the low tail of the CDF gets higher. However, in the high SINR region the CDF shows a decrease.

- **Location of Femtocells and User Distribution**

Here, some new asymmetric scenarios and case studies are introduced to evaluate the effect of topology, density and formation of femtocells on resulting interference. This can be further categorized in location-based and location-independent scenarios. In location-based scenarios, the statistics are averaged over different snapshots as UE approaches Serving HeNB (Scenario 1) or vice versa (Scenario 2). On the other hand, in location-independent scenarios (Scenarios 3a, 3b) the UE and depicted Interferer HeNBs (4 out of 8) gradually move jointly on worst-case potential locations but other interferers are kept fixed. We consider, 36 potential UE locations (uniformly distributed) and the final PDF function is the numerical average of all the PDFs.

Figure 85 shows the performance of scenarios 3a (serving HeNB at the center) and 3b (serving HeNB at the edge) compared with a reference scenario (UE location-independent symmetric deployment). The results highlight the impact of topology and formation on severity of interference compared with the symmetric reference scenario.

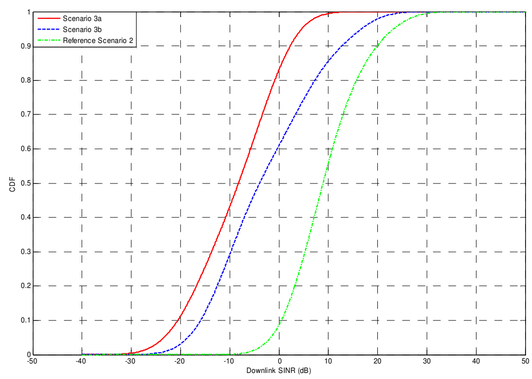


Figure 85: CDF of SINR in scenarios 3a, 3b and reference.

5.3.11.2 Contribution to BeFEMTO System Concept and Objectives

This study quantifies the impact of co-tier interference in femtocells through a semi-analytical approach concluding that without interference mitigation techniques, QoS in the form of acceptable outage probability was not achievable in scenarios representing medium to worst cases of interference. Results obtained from semi-analytical approach were also compared against Monte Carlo simulations for evaluation purposes. Subsequently, some important radio access parameters and deployment configurations, such as path loss model, shadowing, wall penetration loss, location of femtocells and user distribution were further examined as key elements that can potentially affect the femtocell-to-femtocell interference in a multi-femtocell deployment.

References

[95] Jie Zhang and Guillaume de la Roche, *Femtocells: Technologies and Deployment.* Wiley Publishing 2010.

[96] Ki Won Sung, Harald Haas, Stephen McLaughlin, “A Semianalytical PDF of Downlink SINR for Femtocell Networks” , *EURASIP Journal on Wireless Communications and Networking*, vol. 2010 (2010), Article ID 256370.

[97] 3GPP TS 36.300: "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved UniversalTerrestrial Radio Access Network (E-UTRAN),Overall Description".

5.3.12 Synthesis

In order to come to grips with the capacity crunch, HetNets can rely on a multi-disciplinary approach whereby a variety of tools can be applied to reap the benefits of such network deployments. In view of this, open access femtocells constitute one solution for mitigating cross-tier interference in a real HetNet scenario deployment. Although the overall capacity increases with an increasing femtocell density, that degradation can be detected when analysing statistics for macros and femtos separately. In contrast, with closed access femtocells, the average throughput is degraded as the percentage of UEs connected to their best femto decreases. Also, more macro UEs experience a higher level of interference which decreases their throughput.

When self-organization is at stake, a number of interference mitigation techniques can be applied such as adaptively match the frequency reuse in femtocell networks depending on varying interference conditions (GB-DFR) shown to attain a significant improvement for cell-edge users, at the expense of a modest decrease for cell-center users. In addition, when an autonomous implementation is sought after, a decentralized version (DASA) can reach a significant improvement for both cell-edge user as well as system capacities, compared to conventional centralized frequency reuse methods. On the other hand, time-domain ICIC techniques have been proposed to improve the cell edge spectral efficiency and make use of picocells. time domain ICIC includes cell range expansion and the concept of almost blank subframe where the macro eNB is allowed to use all subframes while HeNBs can only use one part following periodic patterns exchanged through the X2 interface. Yet another ICIC technique is the spatial domain based interference coordination in which femtocells are able to jointly maximize their performance, where interestingly, the spatial domain coordination is seen to converge to a time domain interference management

SON is a cornerstone for self-aware and self-adaptive femtocell networks, which is gaining a significant momentum. One of the timely and useful tools that enable operators to save OPEX and CAPEX is machine learning. In this respect, interference control based on decentralized online learning has been show to yield very promising results, in both decentralized and semi-centralized approaches. The interest in these tools is set to ramp up in the upcoming years.

The BeFEMTO 8 bps/Hz target is achieved by combining spatial multiplexing characterized by 4x4 antenna configuration and interference mitigation. However, as compared to reuse 1, the average cell throughput is lesser. Other MIMO techniques that are able to reach the same target include interference alignment among femtocells leveraging on cooperation.

5.4 RRM and Scheduling

5.4.1 Energy-aware RRM for co-channel femtocells

5.4.1.1 Description of the Scheme

This scheme is applicable to the following BeFEMTO theme: standalone femtocells. In this context, one prime concern, as a result of an extensive femtocells deployment in the near future, is the resulting substantial energy usage at either the user or the base station sides, or both. From the energy usage perspective, only very few preliminary results on energy efficiency are available [98],[99], and concern on the energy usage at femtocell users is rarely addressed.

5.4.1.1.1 System model and problem formulation

We focus on the uplink of the co-channel femtocell network consisting of multiple FUEs. Each FUE has a single antenna and intends to communicate with the FAP having *d* receiving antennas via orthogonal channels in the frequency domain.

Specifically, we now propose following admission control and radio resource scheduling (RRS) scheme in a distributed manner. To this end, it is worth pointing out the fact that in the context of resource scheduling, there exist two inherent phases: control signalling phase; and data phase:

i) Control signalling energy phase (denoted by Phase 0) in which signalling information is exchanged,

ii) Data-transmission energy phase (denoted by Phase 1) in which data transmission occurs.

Unlike conventional approaches emphasizing mainly the energy usage at Phase 1, we take into account the *sum energy usage by all FUEs* at both the above *control and data phases (i.e., Phase 0 and Phase 1).* During the two phases, exchange of both signalling and data between the transmitters and the receivers occurs at every time slot. Particularly, we propose the following:

- Control phase: By properly selecting a value for the size of admitted FUEs, the FAP randomly activates *n* among *N* FUEs at every time slot according to the Uniform distribution. This random selection at each time slot is used in order to achieve fairness among users in terms of equal probability of accessing the channel. Once the above *n* active FUEs are selected, a subset of only *n*v* active sub-channels is self-organized and the size of the subset is set to *n*v*. Here, notice that the corresponding entries of the subset are random according to the Uniform distribution such that all the sub-channels have equal likelihood of activation. Also, once active sub-channels are given, the average power level for control signalling is selected for the mutual co-existence with the macrocell.
- Data phase: In a given subset of active sub-channels from the control plane, the opportunistic data transmission is performed [100]. That is, among the subset of active sub-channels, only the best is scheduled for the data transmission at each time slot. The selection criterion for the best is to find the sub-channel whose SINR is the best among others.

We study a self-organizing problem that influences not only the average sum rate but also the energy efficiency of the femtocell, while limiting the sum energy usage by FUEs and the corresponding interference strength below the maximum energy allowance and the tolerated interference threshold, respectively.

5.4.1.1.2 Summary of key results

When using the proposed energy-aware SON RRM scheme [101], the achievable ergodic sum capacity has been illustrated in Figure 86. Particularly, in the case when there are 8 FUEs available, the achievable ergodic sum rate monotonically increases with average SINR. For comparison, this figure also illustrates the conventional case when all FUEs are admitted with a fixed power allocation per FUE, where no self-organization manner is used. As per this figure, autonomously self-organizing both the power allocation and the active FUEs is superior to the conventional case with respect to the ergodic sum rate.

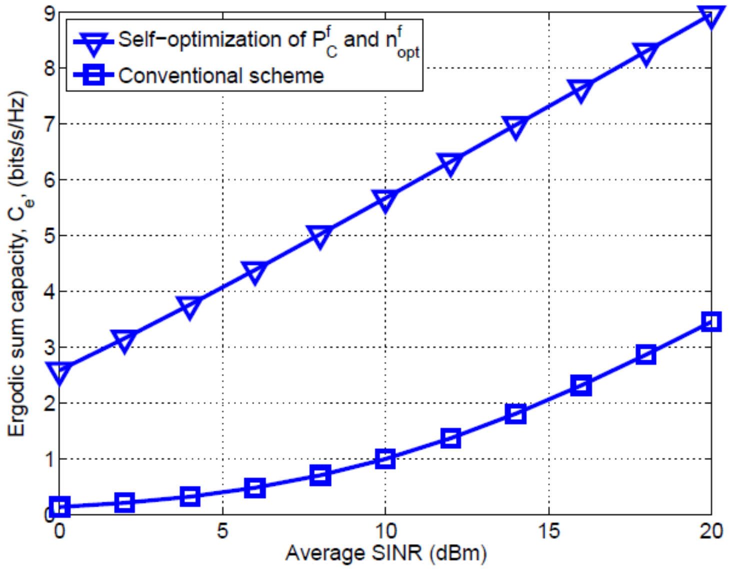


Figure 86: Comparison of the self-organizing cases to the conventional case has been depicted with respect to the ergodic sum capacity versus the average SINR.

5.4.1.2 Contribution to BeFEMTO System Concept and Objectives

Based on the above energy-aware SON femtocell techniques, it is clearly observed that the energy-aware SON enabled femtocell benefits from enhancing system data rate in a given sum energy usage by femtocell UEs. Particularly, when properly selecting the power allocation and the number of active FUEs, it has been shown that the ergodic sum capacity of co-channel femtocell can be achieved at, for example, 8 b/s/Hz/cell at 17 dBm while maintaining the interference towards the MBS below the threshold. These contributions are useful to BeFEMTO System Concept and objectives.

References

[98] I. Ashraf, L. T. W. Ho, and H. Claussen, "Improving energy efficiency of femtocell base stations via user activity detection," *IEEE Wireless Communications and Networking Conference (WCNC)*, 2010, pp. 1-5.

[99] Y. Ko, S. A. Vorobyov, and M. Ardakani, "How much multiuser diversity is required in energy limited multiuser systems?", *IEEE Trans. on Signal Processing*, vol. 58, no. 8, pp. 4367-4378, Aug. 2010.

[100] D. Tse and P. Viswanath, *Fundamentals of wireless communication*. Cambridge University Press, 1st edition, 2005.

[101] Y. Ko, A. Quddus, and R. Tafazolli, "On distributed optimum energy usage in a two–tier co-channel femtocells network", *IEEE Trans. on Wireless Communications*, submitted Apr. 2012.

5.4.2 Graph-based Multi-cell scheduling for femtocell networks

5.4.2.1 Description of the Scheme

This section proposes a novel dynamic graph-based locally centralized solution that targets the ICI mitigation and capacity maximization in network of femtocells. This wok was inspired from framework of [102] to deal with the multi-cell OFDMA resource allocation problem in macro-cellular networks. Here, we adapt this to femtocell networks and therein we propose novel algorithms to efficiently solve the multi-cell OFDMA downlink resource allocation problem in presence of co-tier interference. This framework incorporates adaptive graph-partitioning and utility optimization concepts to address inter-cell interference in dense small cell deployments.

Inter-cell interference is initially managed by an adaptive graph-based ICIC scheme which combines graph-partitioning with local searching to provide near-optimal interference isolation between users of different clusters. Subsequently, the adaptive clustering of users based on their mutual interference levels simplifies the problem to SNR maximization across the clusters. The proposed graph-based framework comprises of three parts in similar manner as in [102] and is presented on Figure 87.

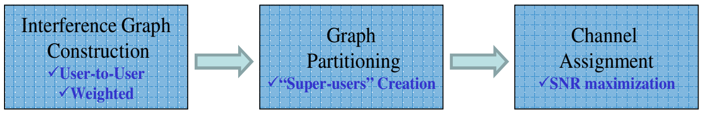


Figure 87: Solution Framework.

- **Graph-Construction:** An interference graph *G (V, E)* is created, that consists of *V* vertices that correspond to the users in the system and *E* edges that show the downlink interference conditions between users. An edge between them logically shows the level of signal degradation to both users assuming they utilize the same resource. This graph is a weighted un-directional graph that connects all the users in the system. The interference graph is constructed in a central entity which is locally deployed. The weights are updated based on the users' relative locations and the corresponding channel losses. The weights are discrete in 4 states that reflect the interference conditions for pairs of users (Low, Potential, Critical and Intra-cell Interference).
- **Graph-partitioning:** Thereafter, a novel adaptive graph-partitioning algorithm is implemented to group the users of the entire network into clusters. The objective is to deliver dynamically a variable number of clusters with lowest possible intra-cluster sum weight which reflects the best ICI isolation throughout the network. In particular, starting from a node with the best neighbourhood (minimum degree), we traverse iteratively in the graph by gradually adding the nodes that minimize the sum weight towards the already chosen nodes. When the target interference threshold (bound) is reached, a cluster is finalized and the algorithm continues from start to form other clusters, removing the traces of the pre-selected nodes. At the end, we achieve a variable number of clusters *K* with a variable number of users therein depending on the target threshold as well as relative channel conditions.
- **Channel Assignment:** The clustering of the users is similar to creating new "super-users" consisting of multiple users of different cells in each cluster. The proposed algorithm iteratively assigns the clusters to sub-channels to find the cluster with the maximum weighted sum-capacity at each stage. Note here that utility-maximization is used instead of capacity maximization to ensure proportional fairness between clusters of users.

5.4.2.2 Contribution to BeFEMTO System Concept and Objectives

The system consists of a dense femtocell deployment and a local Femto-GW. The Femto-GW is defined as an optional solution for management purposes mainly for enterprise femtocell networks [103] and subsequently acts as a medium between small cells and the internet backhaul. The 5x5 path loss model is used to evaluate our model in a dense deployment of femtocells derived from 3GPP [104]. For evaluation purposes our proposal is compared with two cases where interference management is only available via Intra-cell Scheduling (Proportional Fairness) in Reuse-1 and Reuse-3 scenarios. Furthermore, we compare our proposal with the Dynamic ICIC approach introduced in [102]. The following figures show the gains of our proposal in CDF of Downlink SINR (Figure 88-left) and the CDF of user throughput (Figure 88-right) as a performance metric for the achievable per user throughput.

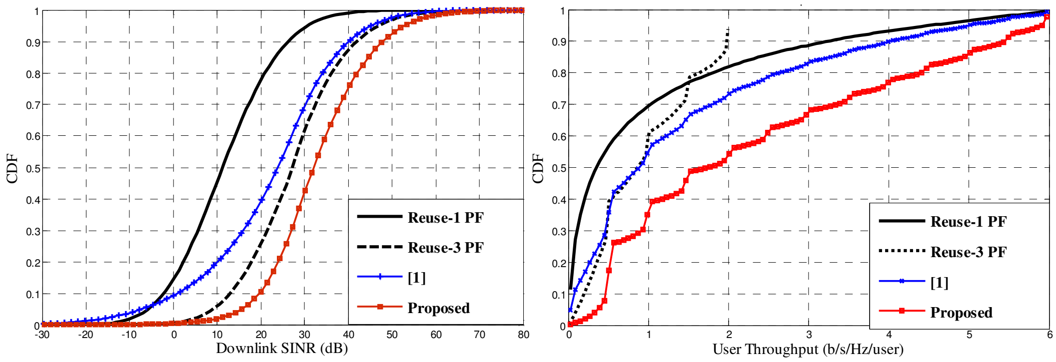


Figure 88: CDF of Downlink SINR (left) and CDF of User Throughput (right).

Here, the improvement of our proposal is impressive over the benchmarks. Targeting the 5thpercentile of the CDF curves, we observe a significant improvement of 70% over the Reuse-3 PF and [102]. Additionally, our algorithm shows 91% enhancement over Reuse-1 PF. At the 90thpercentile the improvement is also noteworthy (26%, 40% and 63% over [102], Reuse-3 PF and Reuse-1 PF, respectively).

References

[102] R. Y. Chang, T. Zhifeng, J. Zhang and C. C-J Kuo, "Multicell OFDMA Downlink Resource Allocation Using a Graphic Framework," *IEEE Transactions on Vehicular Technology*, vol.58, no.7, pp.3494-3507, Sept. 2009.

[103] F.A. Zdarsky, A. Maeder, S. Al-Sabea and S. Schmid, "Localization of Data and Control Plane Traffic in Enterprise Femtocell Networks," *Vehicular Technology Conference (VTC Spring)*, 2011 IEEE 73rd , vol., no., pp.1-5, 15-18 May 2011.

[104] 3GPP TS 36.300: "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN),Overall Description".

5.4.3 Carrier Aggregation/Multi-cell capable HeNBs

Carrier aggregation (CA) is not supported for Rel-10 HeNB and Rel-9 HeNB can serve only a single cell. At 3GPP RAN #51 meeting, work item (WI) on carrier-based HetNet ICIC was agreed, where enhancement on HeNB with CA is also considered. The support of only one cell was sufficient in typical use cases in Rel-9, however, higher peak throughput provided in Rel-10 and beyond can be achieved for home usage and for enterprise deployment scenarios only by enabling CA for HeNB. Additionally, CA could also be used for ICIC advanced mechanisms between macro cell and femto cells. Thus, HeNBs with CA (both for coordinated and uncoordinated deployments) has been proposed to be investigated in Rel-11.

5.4.3.1 Benefits of Carrier Aggregation at HeNBs

- Increase throughput: The deployment of fiber connections down to the home will provide high capacity backhaul link solutions for femto cells in the near future. Highest mobile data activity takes place within the user's home and new high-rate demanding multi-media applications have been appearing. As femto cells need to not be bottleneck they must provide datarates not less as backhaul link (broadband local network access link). Carrier Aggregation is one of the most important features (besides of enhanced MIMO scheme support) to meet the peak data rate requirements of International Telecommunication Union (ITU) for the IMT-Advanced .
- Similar user experience for indoor and outdoor users: A large change of total available bandwidth caused by a handover from a CA-capable macrocell to a non-CA-capable femtocell can cause an abrupt change of throughput in case if the femotocell will not be able to compensate throughput loss by the short distance.
- The CA-capable femtocell will be able to provide a similar user experience for indoor and outdoor users.
- Interference management: Carrier aggregation in HeNBs could facilitate interference mitigation between HeNBs and pico cell/macro cells. Interference management based on dynamic carrier selection, assignment of primary and secondary component carriers (PCC and SCC correspondingly) can be used for interference mitigation of control and data channels between different base station types. CA can be also used for ICIC in macro-femto scenarios. An example of handling the interference scenarios with cross-carrier scheduling with 2 component carriers is specified in [105] and illustrated in Figure 89. Downlink interference for control signalling is handled by partitioning component carriers in each cell layer into two sets, one set used for data and control and one set used mainly for data and possibly control signalling with reduced transmission power. For the data part, downlink interference coordination techniques can be used.

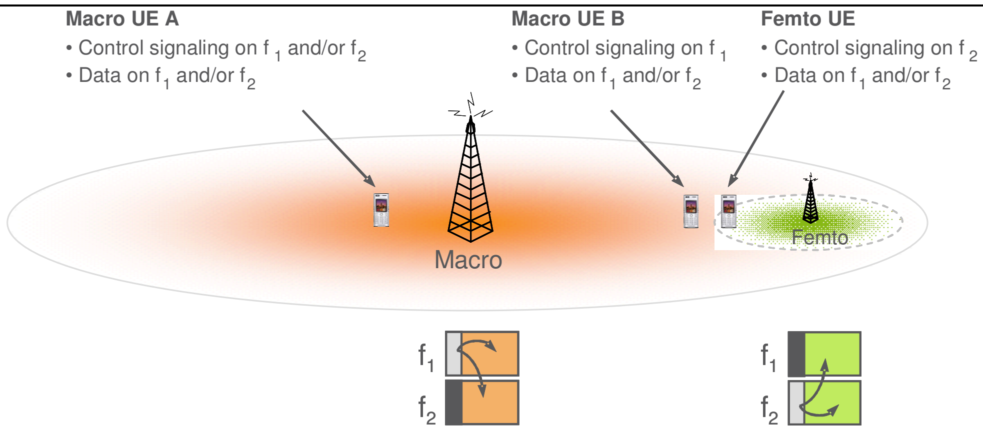


Figure 89: Example of interference management with carrier aggregation.

- Energy saving: Energy consumption of home user becomes an important issue. Carrier Aggregation is one of mechanisms to increase the flexibility for energy saving. HeNBs may switch off secondary carriers when high capacity is not used and switching them on only when additional throughput is required. UE power consumption may also be reduced when switching off non-required secondary carriers.

5.4.3.2 Scenarios with Carrier Aggregation/Multi-cell capable HeNBs

5.4.3.2.1 Macro UE Protection

Assuming both eNB and/or HeNB support multiple carriers one of the carriers of HeNB interferes to Macro UE. Then, the HeNB recognizes which carrier interferes to the Macro UE and changes traffic load and/or power setting on this carrier.

As alternative, when eNB (also multiple cells capable) detects interference from HeNB for a macro UE, it can handover Macro UE to other carrier which is not interfered from the HeNB.

5.4.3.2.2 Initial Carrier Selection

At power up, HeNB monitors eNBs around by obtaining related information via network listening module or HeNB exchanges information with eNB using X2 interface. Based on it, HeNB selects appropriate carrier(s) which will introduce less interference to eNB around HeNB. The idea of the initial carrier selection is itself not new and is also applied for R8/R9 HeNBs, but with CA-capable HeNBs the scenario is extended for case of multiple carriers/cells selection.

In case of un-coordinated HeNBs, it is very challenging to predict how dynamic selection of any available cell carriers at HeNBs will impact robust and stable network function. Mobile operators avoid problems by limiting multiple carrier selection within a subset of carriers under O&M supervision.

5.4.3.3 CA-based ICIC Scenarios

5.4.3.3.1 CA-ICIC for Control Signaling Protection

PCCs and SCCs selection are managed by HeNBs and could be flexibly selected to mitigate interference. Despite of the fact that it is allowed in the standard that different UE may have different carriers as their PCC, eNB and HeNBs can use a single carrier as PCC for all its served UEs in challenging radio conditions in this scenario. SCC are, assigned per UE as needed. HeNBs choose their PCC on a component carrier different from the carrier chosen for UEs in challenging radio conditions by the strongest eNB in the neighbourhood. In this case, control signalling of macro UEs in challenging radio conditions will be protected. The investigation should be performed how HeNB can determine the carrier reserved for control signalling protection of macro UEs.

5.4.3.3.2 Carrier Partitioning

Neighbouring HeNBs and the strongest eNB coordinate carrier usage to avoid overlapping. The overlapping can be avoided for PCC or for both PCC and SCC. eNB can reserve some carriers for the exclusive usage thus performing static carrier partitioning between macro and femto networks. Dynamic carrier partitioning is better suited between neighbouring HeNBs. It could be performed by a distributed algorithm to identify the carriers that are minimal from the surrounding interference. For enterprise femto cells, where the X2 support is supported, the dynamic partitioning may be done through X2 exchanging.

Carrier partitioning will significantly reduce interference but may result in lower spectral efficiency (especially when overlapping of both PCC and SCC is to be avoided). Here it is also assumed again the PCC is configured per node.

5.4.3.3.3 PCC/SCC Selection or Reselection for UE

PCC/SCC selection is done in generally per UE. This method could use report UE measurement configurations based on event-triggered reporting criteria (for possible events see [106]) which cause the UE to send a measurement report when ‘entry condition’ is met. Additionally, the statistical information about carrier usage and selected PCC/SCC for served UEs in the considered and the neighbouring cells could be taken into account.

5.4.3.4 Contribution to BeFEMTO System Concept and Objectives

The main contribution of this work was to identify benefits and scenarios of Carrier Aggregation usage for HeNBs(both for coordinated and uncoordinated deployments) that represents the first step on the research of these topics on BeFEMTO. Higher peak throughput provided in Rel-10 and beyond can be achieved for home usage and for enterprise deployment scenarios only by enabling CA for HeNB. Additionally, CA could also be used for ICIC advanced mechanisms between macro cell and femtocells.

References

[105] 3GPP TR 36.814, “Further advancements for E-UTRA physical layer aspects”, V9.0.0, March. 2010.

[106] 3GPP TS 36.300 – E-UTRAN Overall description.

5.4.4 Ghost femto cells

5.4.4.1 Description of the Scheme

We concentrate on femto-to-femto and femto-to-macro interference in LTE downlink scenarios. Our goal here is to achieve effective spectral reuse between macrocells and femtocells while guaranteeing the QoS of users served by both macro and femto base stations. We propose a novel resource management scheme that limits for each Resource Block (RB) the interference generated outside the coverage range of a femtocell while reducing its transmission power. This method does not involve any message exchange between Femto and Macro BSs.

In our vision, femtocells should be invisible in terms of interference generated to neighbouring cellular users. Nevertheless, femtocells deployment presents a very challenging issue: while femto BSs power consumption and interference range should be small, their coverage where UEs can meet their QoS constraints should be maintained. Based on this observation, we propose a novel RRM algorithm designed to strongly lower femto BSs downlink transmission power. In our proposal, we take advantage of the unusual communication context of femtocells for which locally few UEs compete for a large amount of resources. We come out with a 9 step RRM algorithm, the Ghost Femtocells (RRM_{ghost}) [107] that reduces transmission energy by using available frequency resources. The detailed description of the proposed algorithm is as follows:

Step 1: [Classification of Interferers] Femto UEs overhear the broadcast channel and estimate which neighbouring femto BSs are currently strong interferers. An interferer is strong, if its sensed power level is larger than a predefined threshold.

Step 2: [Feedback to femto BS] Femto UE feedbacks to its serving femto BS its QoS constraints, the momentary Channel State Indicator (CSI) measurements, and the cell-IDs of the femto BSs perceived as strong interferers.

Step 3: [Feedback to Femtocell Control Server] Each femto BS within the femtocell network (i.e., the group of femtocells placed in a block of apartments) reports this information to the Femtocell Control Server (FCS).

Step 4: [Computing Scheduling Matrices] According to the CSI measurements and the selected scheduler algorithm, the FCS computes the related scheduling metric,

Step 5: [Scheduling] For each user to serve, the FCS selects the minimum number of RBs that meets QoS and power constraints. The FCS manages the resource allocation for neighbouring F-UEs and decides on a frequency reuse scheme amongst femtocells for which the estimated interference does not harm. In this way, the controller avoids peaks of interference while improving the spectrum reuse with respect to the orthogonal frequency resource allocation schemes,

Step 6: [MCS Scaling] The FCS associates to each transmission the Modulation and Coding scheme of minimum order such that QoS constraints are satisfied

Step 7: [Repetition] The FCS allocates unused RBs to repeat the original message and improve the transmission robustness.

Step 8: [Power Scaling] The algorithm estimates the SINR perceived at each served user and reduces the allocated transmission power to meet the SINR threshold given by the target packet error rate (PER) and the selected MCS . We trade-off transmission energy for frequency resources: such an approach allows reducing the downlink transmission power to obtain a given target bit rate in femtocells and it also limits the aggregate generated interference.

Step 9: [Message Reception] Finally, each user collects the information received in each of its allotted RBs and combines these RBs using the Chase combining scheme [108].

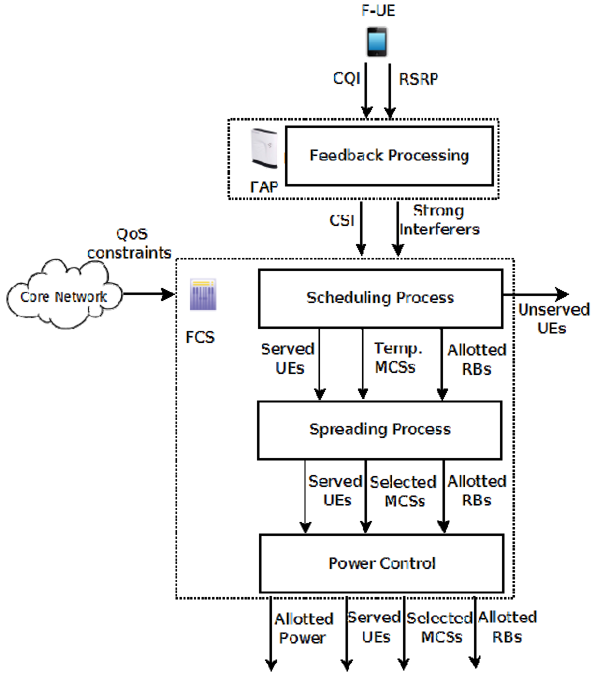


Figure 90. Ghost Femtocell Scheme.

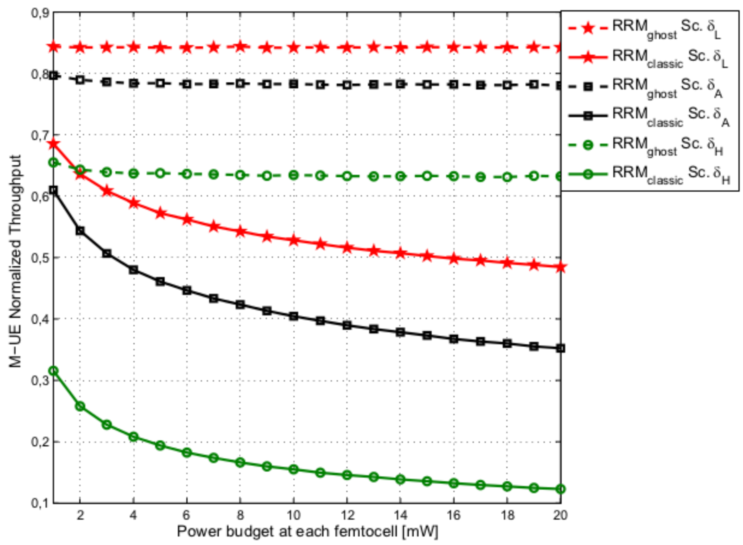


Figure 91: M-UE normalized Throughput.

Here, we assess the effectiveness of the proposed scheme by comparing its performance with a reference algorithm (RRMclassic). In RRMclassic, there is no coordination within the femtocell network, so femto BSs are not aware of the allocation strategy of neighbouring femto BSs. Moreover, RRMclassic algorithm does not implement MCS and Power scaling (Steps 6 and 8 in RRMghost algorithm). Figure 91 shows the indoor M-UE performance as the normalized throughput versus the power budget at each femtocell. In the co-channel femtocell deployment, indoor M-UE performance is limited by femto-to-macro interference. M-BS scheduler is not aware of the RBs exploited by the interfering Femto BSs. When the M-BS assigns to an indoor user a RB that is used by a neighbour femto BS, this M-UE can be exposed to a high level of interference. To compare RRMghost and RRMclassic algorithms, we have set the M-UE throughput target (Ttg) equal to 600 kbit/s and considered three different femtocell deployment scenarios:

Scenario δL : low density of femtocell, star marked curves.

Scenario δM : medium density of femtocell square marked curves.

Scenario δH : high density of femtocell = 0.8, circle marked curves.

Dashed and solid lines, respectively, correspond to the throughput of RRMghost and RRMclassic schemes. The results show how RRMghost strongly limits the impact of the femto-to-macro interference in all scenarios.

Contribution to BeFEMTO System Concept and Objectives

The main objective of this work is to mitigate femto-to-macro and femto-to-femto interference by trading off frequency resources for transmission power. Simulation results show that RRMghost achieves a significant improvement for M-UEs. The scheme depicted in the previous section is compatible with the BeFEMTO System Architecture. However, the same algorithm can be implemented in a distributed fashion by exploiting the X2 interface available in networking femtocell scenarios.

References

[107] E. Calvanese Strinati, A. De Domenico, and A. Duda, “Ghost Femtocells: a Novel Radio Resource Management Scheme for OFDMA Based Networks,” in *Proc. of the IEEE Wireless Communications and Networking Conference (WCNC 2011)*, Cancun, Mexico, March 2011.

[108] D. Chase, “Code Combining–A Maximum-Likelihood Decoding Approach for Combining an Arbitrary Number of Noisy Packets,” *IEEE Transactions on Communications*, vol. 33, no. 5, pp. 385–393, May 1985.

5.4.5 Synthesis

One prime technical challenge in the networked femtocells is to properly design the RRM and scheduling which is not only to manage the interference requirements, but also to improve the system performance of femtocells. To meet this challenge, BeFEMTO has proposed several approaches. Firstly, as a result of an extensive femtocells deployment in the near future, an energy-aware RRM has been proposed to manage the resulting substantial energy usage at either the user or the base station sides, or both. Unlike conventional approaches emphasizing mainly the energy usage for the data transmission, this proposal has taken into account the balance of the energy usage between the control signalling and the data transmission. It has been clearly observed that the energy-aware SON enabled femtocell benefits from enhancing system data rate in a given sum energy usage by FUEs, while guaranteeing the interference requirement. Secondly, BeFEMTO has proposed a novel dynamic graph-based locally centralized solution. This work targeted the ICI mitigation and capacity maximization in network of femtocells. This wok was inspired from framework dealing with the multi-cell OFDMA resource allocation problem in macro-cellular networks. This approach has been extended to femtocell networks and therein novel algorithms were proposed to efficiently solve the multi-cell OFDMA downlink resource allocation problem in presence of co-tier interference. This framework incorporates adaptive graph-partitioning and utility optimization concepts to address inter-cell interference in dense small cell deployments. Using this proposal, it has been observed that targeting the 5^{th}percentile of the CDF curves results in a significant improvement of 70% over the Reuse-3 PF. Additionally, our algorithm shows 91% enhancement over Reuse-1 PF. Thirdly, as per the CA, HeNBs with the CA (both for coordinated and uncoordinated deployments) has been proposed to be investigated in Rel-11. The main contribution of this work was to identify benefits and several scenarios of CA usage for HeNBs (both for coordinated and uncoordinated deployments). It was observed that higher peak throughput provided in Rel-10 and beyond can be achieved for home usage and for enterprise deployment scenarios only by enabling CA for HeNB. Additionally, CA can be used for ICIC advanced mechanisms between macro cell and femtocells. Finally, a new method for achieving effective spectral reuse between macrocells and femtocells has been proposed. The main objective of this work is to mitigate femto-to-macro and femto-to-femto interference by trading off frequency resources for transmission power. In the context of LTE downlink scenarios, it has been shown that the proposed RRM achieves a significant improvement for M-UEs by mitigating femto-to-femto and femto-to-macro interference.

5.5 SON Aspects

5.5.1 Docitive femtocells: A cooperative paradigm

5.5.1.1 Description of the Scheme

In the context of decentralized multiagent systems presented in Section 5.3.10, the environment perceived by a given agent is no longer stationary, since it consists of other nodes who are similarly adapting. The dynamics of learning may thus be long and complex in terms of required operations and memory, with complexity increasing with an increasing observation space. A possible solution to mitigate this problem, to speed up the learning process and to create rules for unseen situations, is to facilitate expert knowledge exchange among learners. To this end, the novel concept referred to as docitive radio was introduced in [109]. Whilst the emphasis in cognitive radios is to learn (“cognoscere” in Latin), the focus of docitive radios is on teaching (“docere” in Latin). It capitalizes on the fact that some nodes have naturally acquired a more pertinent knowledge for solving a specific system problem and are thus able to teach other nodes on how to cope under the same or similar situations. The high-level cognitive radios operational cycle, consists in acquisition, decision and actuation processes. We extend this cycle by the introduction of the docitive functionalities, given by the docitive entity, as shown in Figure 92. The acquisition unit provides quintessential information of the surrounding environment. The core of a cognitive radio is without doubt the environmental state dependent intelligent decision engine, which typically learns from past experiences. With the decision taken, an important aspect of the cognitive radio is to ensure that the intelligent decisions are being carried out, which is handled by the action unit. The docition unit has two main tasks, the knowledge relation and the knowledge dissemination and propagation among agents. Those tasks have to be realized under the non-trivial aim of improving the own or other agent’s learning process and performance. As shown in Figure 92, the docition unit is linked to the intelligent decision unit and communicates with the other agents’ docition units. By these means, each docition unit builds its relationships with the other agents in the system and decides on the key docitive parameters.

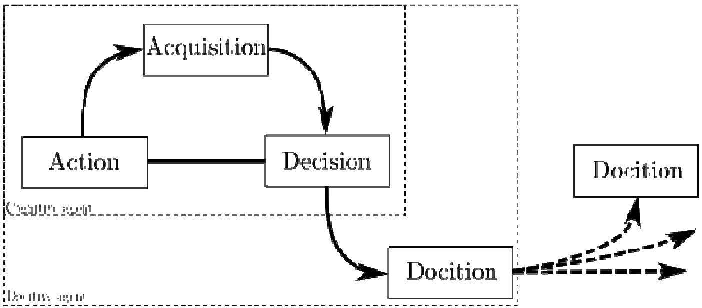


Figure 92: Docitive cycle which extends the cognitive cycle by cooperative teaching.

In our scenario, a femto BS which has recently been switched on can advantageously exchange information via a (backhaul) network, through a X2 interface between femtos, with other expert femto BSs in the neighborhood, the so-called docitive femto-cells. The agents select the most appropriate femto BS from which to learn, based on the level of expertness and the similarity of the impact that their actions may have on the environment, which is captured by a gradient which measures how the agents actions affect the Signal to Interference Noise Ratio (SINR) at macro-users. The rationale behind the definition of this gradient is that nodes should learn from nodes in similar situations. Depending on the degree of docition among nodes, we consider the following cases, 1) Startup Docition where docitive femto BSs teach their policies to any newcomers joining the network. In this case, each node learns independently; however, when a new femtocell joins the network, instead of learning from scratch how to act in the surrounding environment, it learns the policies already acquired by more expert neighbors. Policies are shared by Q-table exchanges between femto BSs with similar gradients. 2) IQ-Driven Docition, where docitive radios periodically share part of their policies with less expert nodes with a similar gradient, based on the reliability of their expert knowledge. More expert nodes share their expert knowledge periodically, by exchanging rows of the Q-table, corresponding to states that have been previously visited. Figure 93 shows performances in terms of precision, i.e. oscillations around the target SINR. In particular, it represents the Complementary Cumulative Distribution Function (CCDF) of the variance of the average SINR at macro-users with respect to the set target SINR. It can be observed that due to the distribution of intelligence among interactive learners the docition stabilizes the oscillations by reducing the variance of the SINR with respect to the specified target. More precisely, at a target outage of 1%, we observe that the IQ driven docition outperforms the startup docition by a factor of two, and the independent learning algorithm by at about an order of magnitude. Figure 93 shows the probability that the total power at a femto-cell is higher than power threshold as a function of the learning time. It can be observed that the docitive approaches better satisfy the constraint in terms of total transmission power, and significantly speeds up the learning process. The degree of cooperation, and thus the overhead, augments with an increasing degree of docition. The optimum operating point hence depends on the system architecture, performance requirements, etc.

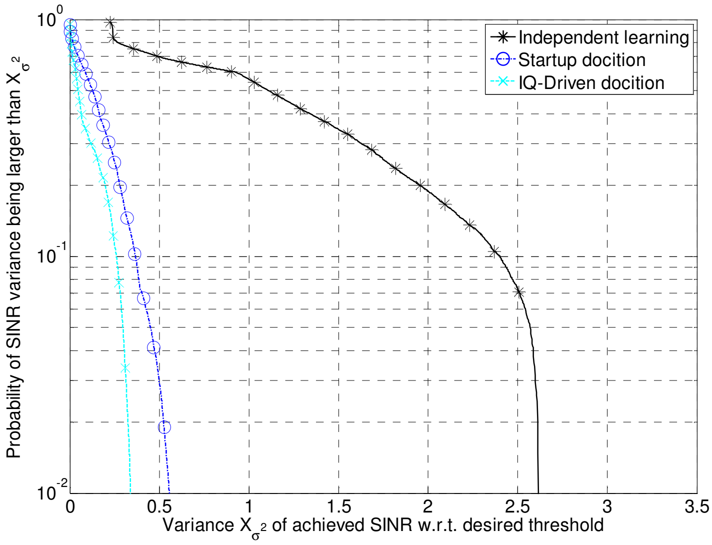


Figure 93: CCDF of the average SINR at macrouser.

5.5.1.2 Contribution to BeFEMTO System Concept and Objectives

The main drawback of the decentralized Q-learning approach presented in Section 5.3.10 is the length of the learning process. As a result, we have focused on the novel paradigm of docition, with which a femto BS can learn the interference control policy already acquired by a neighboring femtocell which has been active during a longer time, and thus saving significant energy during the startup and learning process. Notably, we have shown that, with respect to decentralized Q-learning, docition applied at startup as well as continuously on the run yields significant gains in terms of convergence speed and precision. We have also shown that BeFEMTO target of 8b/s/Hz/cell can be achieved by applying the proposed learning approaches, even when the density of femto-cells in the scenario is increasing.

References

[109] L. Giupponi, A. Galindo-Serrano, P. Blasco and M. Dohler, "Docitive Networks – An Emerging Paradigm for Dynamic Spectrum Management," *IEEE Wireless Communications Magazine*, vol. 17, no. 4, pp. 47 - 54, Aug. 2010.

5.5.2 Energy saving aspects of RF design for HeNB

5.5.2.1 Description of the Scheme

There are various factors impacting on the development of RF components and systems that are being researched and investigated. For general communication systems, for example, there is the continuous movement towards smaller, secure systems that have increased functionality and reduced power consumption.

The receiver or the transmitter has to switch to the standard or to the operator featuring the more efficient characteristics. There are also similar requirements concerning battery and performance management. In fact, relating to the electromagnetic environment, the performance of the receiver/transmitter can be more or less relaxed in order to save energy, which is a key issue in the case of portable communications. In this case the system has to be smart enough to choose the best configuration by trading off the electrical performance (that is, linearity and noise figure) and the power consumption

The simplest way to describe a wireless communication module [110] could be defined as described in next figure. This scheme is applicable to the following BeFEMTO themes: standalone femtocells and networked femtocells.

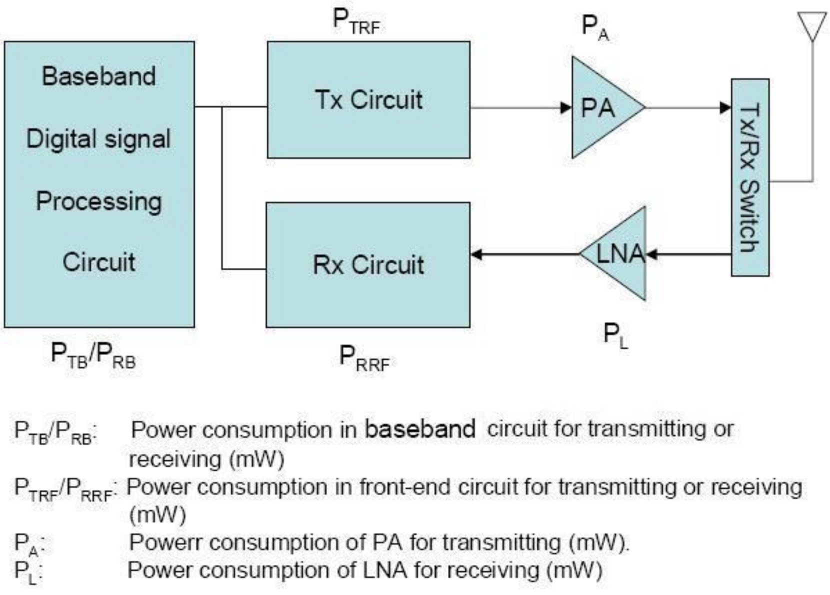


Figure 94: Femtocell block diagram

Based on the structure and power consumption of each component, the total power consumption for transmitting and for receiving, denoted by *PT* and *PR,* are specifically given by:

$$P_T(d) = P_{TB} + P_{TRF} + P_A(d) = P_{T0} + P_A(d) \qquad (6)$$

$$P_R = P_{RB} + P_{RRF} + P_L = P_{R0} \qquad (7)$$

where *PA(d)* is the power consumption of the power amplifier which is a function of the transmission range, *d,* that is the desired coverage and interference level. Since P_{TB} and P_{TRF} do not depend on the transmission range, the two components can be modelled as a constant, P_{T0}. Similarly, the power consumption of the receiving circuitry can be modelled as a constant, P_{RO}, since P_{RB} and P_{RRF} are clearly not dependent on transmission range, and P_L is also a constant while assuming that the LNA is properly designed and biased to provide the necessary sensitivity to reliably receive, demodulate and decode a minimum power signal, $P_{Rx\text{-}min}$.

While there are many types of RF power amplifiers, the total power consumption of a power amplifier, $P_A(d)$, will depend on many factors including the specific hardware implementation, DC bias condition, load characteristics, operating frequency and P_A output power.

The power amplifier delivers RF output power, P_{Tx}, to the antenna. In general, the required RF output power, $P_{Tx}(d)$ for reliable transmission will depend on the transmission range, *d,* this is the desired coverage and interference to other cells and foreign users.

The total power consumption of the P_A is given by P_{DC} and is the same as P_A defined above. The ratio of RF output power to DC input power is called the drain efficiency (denoted as η) and is given by:

$$\eta = P_{Tx} / P_{DC} \qquad (8)$$

By definition, the drain efficiency of a P_A will be less than 100%. For example, simple class A power amplifiers have a maximum drain efficiency of 50% as equal amounts of power are dissipated in the bias circuitry and in the load. The drain efficiency will typically vary when the output power delivered to the load changes. In particular, for most types of power amplifiers, the drain efficiency increases while P_{Tx} is increasing and reaches its maximum value when P_{Tx} reaches the maximum output power, P_{max}.

By combining the concept of drain efficiency with the formula described in the previous part of this section, the power consumption of the communication module can be modelled as:

$$P_{T(d)} = P_{T0} + P_{Tx}(d)/\eta \quad (9)$$

$$P_R = P_{R0} \quad (10)$$

During dormant or Eco modes the total consumption is:

$$P_{total} = P_T(d) + P_R = P_{T0} + P_{R0} \quad (11)$$

if the P_A is completely switched-off.

Some RF components that can be used to implement FAP transmitter and receiver have Enabling Entries that can be used to implement power saving periods when the FAP enters a no user load period. During these periods transmitter can be shunted down and only receiver operates in order to detect user load.

Using current available devices to amplify signals I/Q to enter in modulator, consume 1 W in normal operation mode and they reduce its consume to less than 10 mW [111] using shunt-down option. I/Q modulators, also part of Tx circuit, with shunt down mode can pass from 250 mW normal operation mode to less than 1mW in sleep mode [112]. Current power amplifiers used in LTE handsets even incorporate internal coupler to use in the power control loop. These devices also have saving operation modes that reduce consume.

5.5.2.2 Contribution to BeFEMTO System Concept and Objectives

When entourage conditions allow the FAP to shunt down part of the transmitter, essentially the HPA, the consumption is reduced. The saving capability described before can be useful to improve FAP battery live and reduction of interferences when the maximum transmitting power is not required.

References

[110] Qin Wang, Mark Hempstead and Woodward Yang, "A Realistic Power Consumption Model for Wireless Sensor Networks Devices", *IEEE SECON 2006 proceedings*, pp 286-295.

[111] http://www.analog.com/en/specialty-amplifiers/variable-gain-amplifiers/ad8372/products/product.html

[112] http://www.rfmd.com/CS/Documents/2483DS.pdf

5.5.3 Synthesis

Next Generation communications require smart approaches to efficiently fulfil current and future network performance requirements. SON systems appear as promising solutions since they allow to develop flexible and adaptive systems, as claimed by 3GPP standardization body and NGMN. BeFEMTO has focused on the development of SON techniques to solve different network issues in an efficient and autonomous way. Specifically, proposed SON enablers focus on smart solutions from an energy efficient point of view. First, docitive techniques are introduced to diminish the learning period, which besides the logical improvements of the network performance since early learning stages, also diminish the energy expenses of the network during the startup and learning process. Second, with the introduction of the smart RF configuration for FAP transmitters and receivers, considering the trade-off between electrical performance and power consumption, allows more efficient systems in terms of energy consumption. This solution also optimizes the LTE RF components utilization and introduces saving operational modes.

5.6 Security

5.6.1 Access control to local network and services

5.6.1.1 Description of the Scheme

The scheme presented provides a solution to the problem of access control to local services in the NoF (e.g., those offered to users visiting some company premises). The standard mechanism used by BeFEMTO to share control between the MNO and the LNO is the CSG [113]. In fact, both operators can control what UEs are allowed attaching to a given closed subscriber group by appropriately managing the lists stored in core network servers in charge of managing CSGs. All the HeNB connected to the same LFGW may broadcast the same CSG-ID, so this CSG-ID will be shared by all these HeNB. The membership of a CSG is managed by the Hosting Party of the LFGW together with the MNO and under ultimate control of the operator as the membership status needs to be reflected in various core network nodes and also updated on the USIM of the subscriber (e.g., via OMA-DM). The problem and also the solution are divided into two different aspects: the access control part under the control of the mobile network operator (MNO), and the access control to local services of the network of femtocells, which is under the control of the local network operator (LNO). The former is about allowing UEs attaching to a femtocell that operates in the licensed spectrum of the MNO. The latter is about providing a fine-granular control on what local services offered by the LNO can be accessed by what UE and during what period of time.

5.6.1.2 CSG provisioning

Next figure shows the CSG provisioning for roaming UEs involving the CSS.

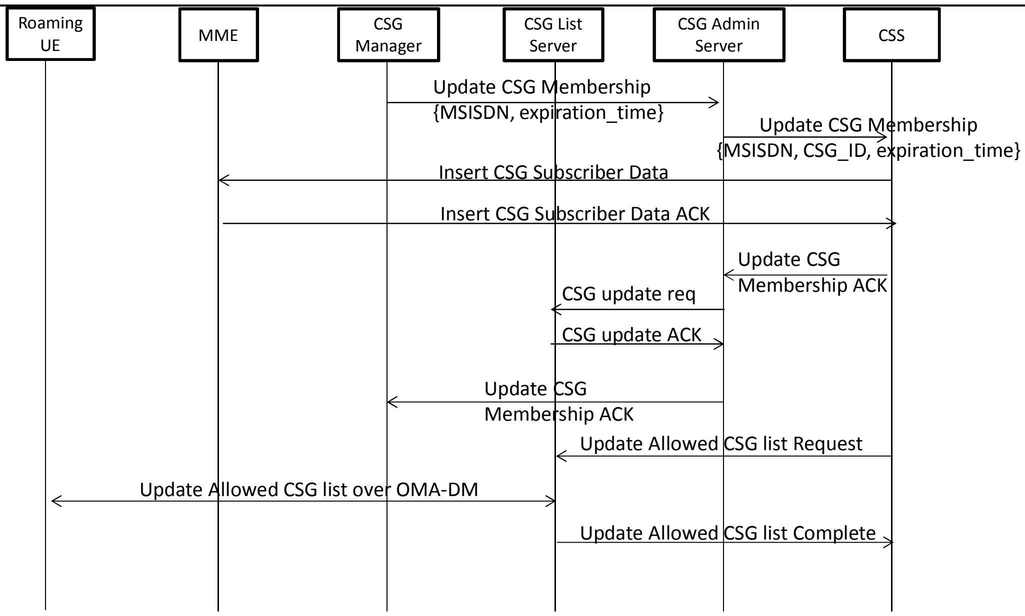


Figure 95: CSG provisioning for roaming UEs involving the CSS.

When accessing CSGs, there are two scenarios to consider. In the first one the UE and the femtocells in the NoF belong to the same HPLMN. The regular servers for CSG management (i.e., CSG Lists Server and CSG Admin Server) can be used in this case. In the second one, when a roaming agreement is in place, the UE may access femtocells belonging to a VPLMN [113]. In this case, VPLMN Autonomous CSG Roaming has been chosen instead of HPLMN CSG Roaming because of its flexibility due to reduced administrative exchanges with the HPLMN. It is important to emphasize the role the CSG Subscriber Server (CSS) [114] plays in the multioperator scenario: it performs the same function as the HSS but only for handling CSG subscription data and procedures. The CSS stores CSG subscription data for roaming subscribers and provides VPLMN specific CSG subscription information to the MME.

5.6.1.3 Local Access Control List Provisioning

Next figure shows the procedure for establishing a PDN connection for a local APN (or “home APN”) through a CSG provisioned in a VPLMN.

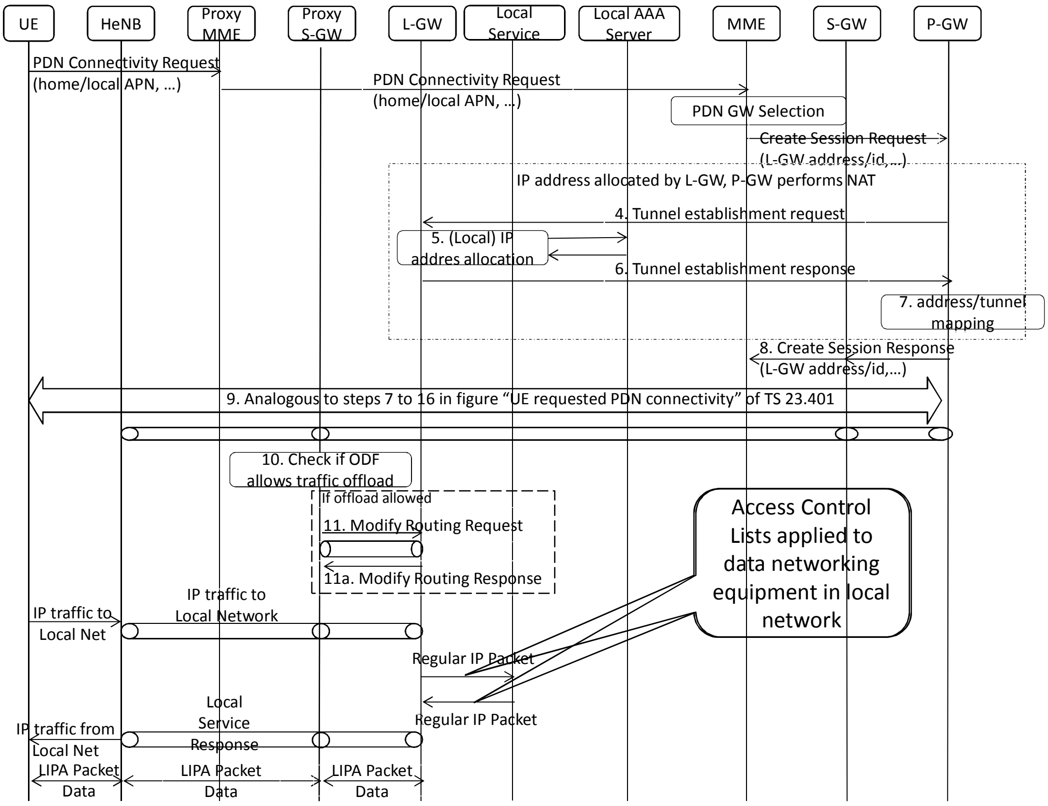


Figure 96: MSC for establishing PDN connectivity with LIPA/SIPTO support and local access control.

Once a UE is allowed to attach to femtocells in the visited network it is necessary to grant the access to the allowed local services. In order to provide different local services to different UEs, a local access control in the NoF is implemented by applying regular data networking access control policies.

The main idea is that the LNO manager maintains a local AAA server with information on each roaming UE indexed with its MSISDN. The allocated IP address for each UE is also stored in each record. Therefore, the LGW will ask this server for the IP address to be assigned to the UE when it establishes the PDN connection to the "home APN" [115]. As for access control lists, they could be manually configured in the networking equipment of the company. Alternatively, there are schemes in which Access Control Lists (ACLs) could also be stored for each UE in the local AAA in the form of downloadable ACLs. In this case, when there is the first attempt from the UE to access a local service, the firewall would contact the local AAA server for user authentication and for downloading the associated ACL if not already enforced.

5.6.1.4 Contribution to BeFEMTO System Concept and Objectives

The main contribution of this task is:

-Access control of visiting UEs to local network services (of the network of femtocells) that allows shared control between the MNO (access to CSG) and the operator of the local network (fine-granular access to local services). Regular data networking access control policies can still be used in the local network.

References

[113] 3GPP technical specification TS22.220. "Service requirements for Home Node B (HNB) and Home eNode B (HeNB)," version 11.4.0, December 2011.

[114] 3GPP technical specification TS23.401. "General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access (Release 11)," version 11.1.0, March 2012.

[115] 3GPP technical specification TS 29.061, "Interworking between the Public Land Mobile Network (PLMN) supporting packet based services and Packet Data Networks (PDN) (Release 11)," version 11.0.0, March 2012.

5.7 Traffic Management

5.7.1 Centralized Traffic Management for Cooperative Femtocell Networks

5.7.1.1 Description of the Scheme

Cooperative femtocells will be deployed in enterprises or public spaces where a large number of femtocells would be connected via a common LAN to the broadband access link. In many practical deployment scenarios, it is not feasible or economical to deploy an additional dedicated physical network and backhaul for connecting networked femtocells. Instead, they need to be connected over the existing network infrastructure and to share the communication resources with existing services and applications of the LAN operator.

A frequent approach for logically separating the femtocell user and control traffic from other traffic would be to use a separate VLAN within the local network. The problem that needs to be answered then is whether to allocate a certain fraction of resources to each VLAN, at the risk of not fully utilizing resources, or whether to prioritize traffic from one VLAN over the other one at the danger of starving other potential traffic. Also, signalling effort and latency for resource management needs to be considered. Furthermore, if local network resources are not highly over-provisioned, it may be necessary to add admission control and policing at the network edge. Ideally, the admission control and resource management for the local network should integrate well with their respective 3GPP counterparts.

Of course, both the mobile operator(s) and the provider(s) of local network services do not want to see the Quality of Experience of their services affected by the other stakeholders. Additionally, it would be desirable to monitor the performance of the respective networks remotely to ensure service level agreements are met.

To ensure that local network resources are used efficiently and fairly, to maintain a satisfactory QoS of both femtocell and non-femtocell traffic flows, and to allow network performance to be monitored, it is necessary to perform some form of traffic management within the LAN. The function or entity performing the routing for flows needs to be aware of a) the capacity on each link of the topology and b) the traffic within the network which includes the femto and non-femto traffic. Under these requirements a distributed approach for traffic engineering and routing would require a large signalling overhead to disseminate this information to all routing functions and would be more complex and thus more error-prone to implement. It therefore seems logical to take a centralized approach, in which traffic engineering and routing is performed within a single "routing controller" function that then installs paths with the forwarding entities in the network.

Under this scope, in this work, we implement and evaluate the need for centralized routing based on load-balancing architecture using an Openflow switches which are connected to a controller.

5.7.1.2 Contribution to BeFEMTO System Concept and Objectives

To evaluate and understand the effects of co-existing traffic in a cooperative femto network a hypercube network consisting of Openflow switches was designed in NS-3 network simulator. The key issues the analysis addresses are:

- Investigation of femto and non-femto traffic management within cooperative femto networks.
- Analysis the issues which arise due to sharing of network between the two traffic stakeholders and how it can be resolved using Openflow switches.
- How can resources be guaranteed for the femto and non-femto traffic
- How can the operator validate that such resources or SLA are being met.

To analysis the effect four basic scenarios were designed, which are:

1) **Baseline:** femto and non-femto traffic and real-time and best-effort traffic are mixed and the flow tables installed on the switches are simple based on the MAC addresses of source and destination. The forwarding decisions in the flow entries are based on the shortest path between the source and the destination. This scenario assisted in understanding the effects on the co-existing traffic.
2) **Scenario 1:** In the second scenario we segregate the traffic using the priority tags and femto and non-femto traffic is separated with VLANs. But the paths are still based on shortest path algorithms and possible with a simple Priority queuing between VLANs. This scenario can help in understanding the overheads involved in such cases and if traffic management can be achieved through a simple approach.
3) **Scenario 2:** In this scenario the traffic management is based on Valiant load balancing method [116]. This analysis facilitates to study the performance enhancement which can be achieved for different stakeholders in a networked femto cell scenario.

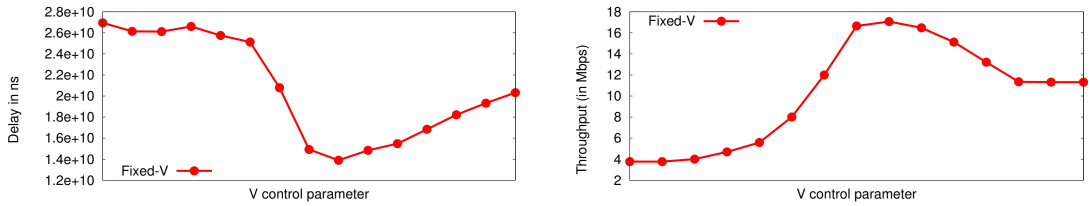
References

[116] Rui Zhang-Shen and Nick McKeown "Designing a Predictable Internet Backbone with Valiant Load-Balancing" , in *Proceedings of Quality of Service—IWQoS* , Spinger Publications, 2005.

5.7.2 Dynamic Backpressure Routing Algorithm for an All-Wireless Network of Femtocells

5.7.2.1 Description of the Scheme

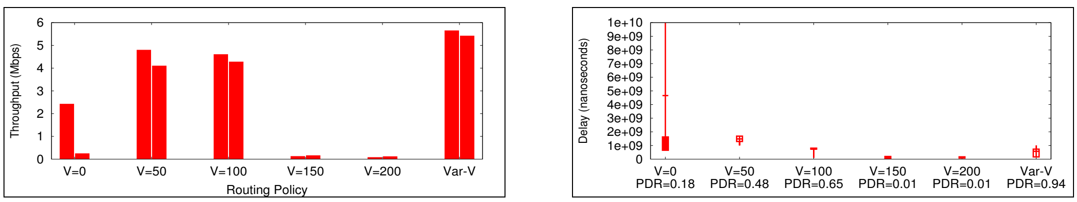
Theoretical backpressure routing, on which the proposed solution is based, is throughput optimal [117]. However, important modifications are needed to roll-out these schemes in a practical all-wireless NoF. In fact, it must be adapted from centralized to distributed operation, from one queue per destination at each HeNB to a single queue per HeNB, and from infinite to finite queue sizes. Bearing these constraints in mind, we propose a combined distributed plus geographic backpressure routing strategy [118] that has its theoretical foundations on the Lyapunov drift-plus-penalty framework. Additionally, it neither builds nor maintains end-to-end routes, and takes per-packet routing decisions. Under this framework, routing decisions are taken as a trade-off between 1) maintaining the stability in the all-wireless NoF (i.e., finite queue backlogs), and 2) ensuring that the packet gets closer to the intended destination. The drift takes care of the former, whilst the penalty function takes care of the latter. Furthermore, there is a non-negative weighting parameter of the penalty function (V) that allows determining its relative importance compared to the drift when taking routing decisions. To compute the Lyapunov drift, we exploit 1-hop queue backlog information of neighboring nodes, which is mainly used to perform queue load-balancing in the NoF, hence reducing queue drops. To compute the penalty function, we exploit 1-hop geographic information. Geographic information provides a sense of proximity to the intended destination. Therefore, we assume that local geographic coordinates (GPS or virtual) are available at each HeNB. Furthermore, coordinates of an intended destination (i.e., LFGW or HeNB) are provided by the LLM entity (Section 5.8.2). On the other hand, our scheme works at the transport network level, hence being transparent to 3GPP procedures, and is used to handle data through the S1-MME, S1-U, and X2 interfaces of the NoF.



(a) **(b)**

Figure 97: The impact of V on NoF performance metrics: (a) Delay and (b) Throughput

The resulting distributed routing algorithm, as well as an extensive performance evaluation, is presented in [118]. The main issue under study is the impact of a fixed-V value assigned to each HeNB on the target NoF performance metrics. Figure 97 shows the evolution of delay and throughput as a function of the V parameter. We observe throughput and delay degradation for low V values since decisions are only taken based on queue backlogs (i.e., packets are not steered towards the destination). We also observe a range of values with the best possible performance metrics when increasing V (i.e., low end-to-end delay and high throughput). In fact, increasing V means that the minimization of distance to the destination is prioritized when taking routing decisions. However, once a certain value of V is exceeded, performance metrics start experiencing degradation again due to high queuing backlogs, which introduce high queuing delays. Furthermore, and as observed in [118], curves in Figure 1 vary depending on traffic conditions, but in a realistic setup, they are hardly known a priori. To be able to adapt to traffic conditions, we propose to calculate a distributed and adaptive penalty weight (i.e., variable-V) at each HeNB. In this way, dynamic and uneven traffic demands and wireless network variations can be met.



(a) **(b)**

Figure 98: Comparison of different distributed routing variants: a) Throughput and b) Delay

The potential of this variable-V algorithm becomes more evident when symmetric and bidirectional traffic is evaluated, as this is one of the main challenges for a single-queue distributed backpressure routing strategy. Figure 98 presents an evaluation carried out in an all-wireless NoF deployed in a grid layout. It shows that none of the values used in the fixed-V strategy is able to achieve the 12Mbps being injected (i.e., 6Mbps flows in each direction). On the other hand, the variable-V algorithm outperforms the best fixed-V variant by 40% in terms of throughput by distributing traffic (i.e., decreasing V) in loaded HeNBs, while increasing V in not-so-loaded HeNBs. In terms of delay, the variable-V policy also outperforms the best fixed-V variant (i.e., V=50 for this specific setup), despite delivering almost twice more packets, as shown by packet delivery ratio (PDR) values.

The main properties of the proposed algorithm are also evaluated in an indoor proof-of-concept NoF testbed (in WP6). In particular, the testbed is composed by a network of 3G Femtocells connected to the EPC through a WiFi backhaul. We focus on the different degrees of load balancing capabilities provided by the adjustment of the V parameter in the WiFi backhaul. Thus, we validate the concepts and simulations results obtained in WP5.

5.7.2.2 Contribution to BeFEMTO System Concept and Objectives

In such a constrained environment the solution shows throughput and delay gains with respect to topology-based routing solutions. The throughput gains are significant, especially when the offered load injected to the NoF requires data traffic distribution in order to be efficiently served. Roughly, the solution proposed can improve up to close to 100% classical topology-based routing approaches in terms of throughput. Regarding end-to-end delay, it is difficult to quantify the gains since the proposed solution usually experiences much higher Packet Delivery Ratios compared with classical topology-based routing solutions. Therefore, a fair comparison of end-to-end delay without taking into account the Packet Delivery Ratio is unfeasible. Nevertheless, we can qualitatively state that the proposed solution is able to experience similar or even lower end-to-end delays experiencing lower packets losses and so handling more data packets compared with topology-based routing protocols. The above results, jointly with the main features of the protocol, make us conclude that distributed backpresure routing is a key enabler of the BeFEMTO System Concept, as far as the transport network layer of all-wireless networks of femtocells is concerned.

References

[117] M.J Neely, "Stochastic Network Optimization with Application to Communication and Queueing Systems," *Synthesis Lectures on Communication Networks*, Morgan & Claypool Publishers, 2010.

[118] J. Núñez, J. Mangues, M. Portolés, "Studying Practical Any-to-any Backpressure Routing in WiFi Mesh from a Lyapunov Optimization Perspective," in *Proceedings of the 8th International Conference on Mobile Ad-hoc and Sensor Systems (IEEE MASS)*, 2011, Valencia (Spain).

5.7.3 Local Breakout for Networked Femtocells

5.7.3.1 Description of the Scheme

Local IP Access (LIPA) is a 3GPP architecture enhancement enabling femtocell users to access services in the IP network in which the femtocell is located directly, rather than by routing traffic via the mobile network and the public IP network back into the local network. This requires traffic to be "broken out" of the 3GPP domain at or near the femtocell. A related concept is the Selective IP Traffic Offload (SIPTO) that allows mobile operators to specify the subset of traffic flows between femtocell users and Internet services that is to be broken out at or near the femtocell in order to bypass (and thus offload) the mobile network.

BeFEMTO's local breakout scheme, developed during the time of 3GPP's initial studies on this topic [119], provides the same features as the now standardized solution, but extends it in two aspects:

1) It uses a single, centralized breakout point on the LFGW, rather than one on each femtocell, which allows local mobility for breakout sessions, facilitates management and control of these sessions and provides consistent breakout with legacy femtocells.
2) It allows breakout sessions to be handed-out/in to/from the macro network as well as to (re-)establish LIPA sessions from the macro network.

The latter is important because in 3GPP's current solution, when a mobile user has an on-going LIPA session, leaves the femtocell coverage and experiences a connection loss, there is no way to re-establish the session other than to defaulting to a different mechanism (e.g. the "Remote IP Access (RIPA)"), which results in an inconsistent and often frustrating user experience.

In the proposed solution, a new network element called Local Femtocell GateWay (LFGW) is introduced within the local femtocell network. The LFGW is transparently inserted into the S1 interface between the HeNBs and the EPC such that neither HeNBs nor EPC have to be changed. The LFGW provides functionality for local mobility management (see related section) and, to support traffic breakout as defined above, is extended with a local P-GW (≈L-GW) functionality and a new, optional interface (the "Remote Access Tunnel" S-RAT) between the L-GW and the P-GW of the EPC that enables the seamless service continuity in the macro-network and only carries data in case the user continues a session in the macro network.

Centralizing the breakout point in the LFGW instead of having one breakout point on each femtocell has the advantage that breakout policies are simpler to configure and security can be more easily enforced. For L-GW-based traffic breakout, it also means fewer entities connecting back to the core network, i.e. the number of L-GWs scales with the number of enterprise customers, not with the number of their installed femtocells. Centralizing also means that breakout mobility can be supported using standard mobility management procedures, i.e. can be readily implemented with non-proprietary femtocell solutions as well.

The proposed scheme supports Traffic Offload Function (TOF) based breakout with mobility, too. This is because the LFGW is *on-path* of the S1 interface and is thus able to dynamically redirect traffic from a bearer to the offload function and vice versa. Implementing the LFGW and the local breakout on-path also means that no proprietary interfaces are necessary between femtocells and the off-path breakout point. There is still an on-going discussion within 3GPP on whether L-GWs should be on- or off-path, and the experience gained from the design of the BeFEMTO solution is helpful in and being contributed to this discussion [120].

The impacts of the LFGW with local breakout on the backhaul and core network's capacity, on signalling latency and on the breakout traffic's QoS have been assessed using analytical modelling and numerical simulations. A flow-level model has been developed to reflect the interaction between elastic traffic like TCP-based file transfer or web-browsing and streaming traffic generated by applications with QoS requirements like voice over IP or video streaming. Effects on packet level are modelled with an M/D/1 approximation for streaming traffic and with the assumption of full buffer utilization for elastic traffic.

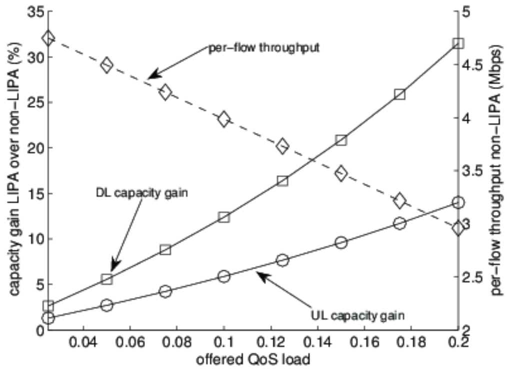


Figure 99: Capacity gains and per-flow throughput for local services.

Figure 99 shows as example result the capacity gain of a scenario with LIPA support over an equivalent system without LIPA. The solid lines with square markers denote the downlink capacity gain, while the solid line with circle markers denotes the uplink capacity gain. On the x-axis the offered QoS load is shown, which is in the case of the non-LIPA scenario the half of the total offered load according to the scenarios in the above sections. The results show that the capacity gain increases up to 30% in case of the downlink for an offered QoS load of ρ_{QoS}=0.2. The dashed line with diamond markers corresponds to the average per-flow throughput in the non-LIPA case. Due to the increasing number of best-effort flows and QoS flows it decreases from nearly the full uplink capacity to below 3Mbps. In the case of LIPA, the access to the local services would have the full capacity of the enterprise femtocell network, which is not shown in the above figure.

5.7.3.2 Contribution to BeFEMTO System Concept and Objectives

The proposed scheme has been developed with BeFEMTO's Femtocell Networks theme in mind and introduces local traffic breakout with mobility for breakout sessions in a way that improves the scalability of the HeNB sub-system for cases with many femtocells per local network. Apart from this functional enhancement, LIPA in general has the secondary effect that the spectral efficiency gained by BeFEMTO's improvements in the radio access can be realized for LIPA traffic even if the backhaul is resource-limited.

References

[119] 3GPP TR 23.829, 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Local IP Access and Selected IP Traffic Offload (Release 10), Version 1.0.1, March 2010.

[120] 3GPP TR 23.859, 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; LIPA Mobility and SIPTO at the Local Network (Release 11), Version 0.4.0, July 2011.

5.7.4 Synthesis

A dense deployment of networked femtocells automatically requires proper traffic management such that excessive signalling overhead is avoided, while at the same time ensuring that the additional amount of hardware required is minimized. The contributions detailed in this section have addressed these issues. The first contribution poses important questions regarding how cooperative femtocells should be connected using only existing network infrastructure, sharing communication resources with existing services and applications of the LAN operator. It is proposed that this be done by setting up virtual LANs within the local network. The rest of the contribution details how this can be achieved without either underutilizing the available resources nor starving other traffic. The next contribution proposes a combined distributed plus geographic backpressure routing strategy for a an all-wireless network comprised of femtocells. Routing decisions are taken bearing in mind that the network can contain only finite backlogs and that the packets always tend to get closer to their destinations. Drift factors and penalties are used to ensure that these two conditions are not violated. Geographical information as well as the queue backlogs of neighbors are used as parameters to assist in the computation of these factors. The proposed solution is able to experience similar or even lower end-to-end delays experiencing lower packets losses and so handling more data packets compared with topology-based routing protocols. Finally, the last contribution in this section deals with local IP access which enables femtocell users to access services in the IP network in which the femtocell is located directly, rather than by routing traffic via the mobile network and the public IP network back into the local network. This requires traffic to be "broken out" of the 3GPP domain at or near the femtocell. This scheme, compared to the already standardized Selective IP Traffic Offload (SIPTO) scheme is better because there is only one breakout point as opposed to many and breakout sessions can be handed. It is noted that with the existing standardized solution, when a user with an ongoing connection leaves the femtocell, the connection is dropped. This is not the case for the proposed solution. The proposed solution calls for a small addition to the S1 interface such that neither HeNBs nor EPC have to be changed. This centralized breakout point has the advantage that breakout policies are simpler to configure and security can be more easily enforced. There is still an on-going discussion within 3GPP on whether L-GWs should be on- or off-path, and the experience gained from the design of the BeFEMTO solution is helpful in and being contributed to this discussion. Simulations have shown a clear benefit in terms of capacity for networks implementing the proposed LIPA scheme.

5.8 Mobility Management

5.8.1 Local Mobility Management

5.8.2 Local, Distributed Location Management

5.8.2.1 Motivation and description

The aim of the Local Location Management function (LLM) is to solve the mapping between a UE identifier (e.g., IMSI, S-TMSI) and the physical/logical location of its current serving HeNB in the Network of Femtocells (NoF). In BeFEMTO, we propose a distributed LLM mechanism based on previous work on a scheme called VIMLOC (VIrtual home region Multi-hash LOCation service) [121], [122]. VIMLOC was initially conceived for large-scale wireless mesh networks, but it has been adapted in the context of BeFEMTO in order to operate in large-scale all-wireless networks of femtocells.

Our approach distributes location information over the LFGW as well as HeNBs within the Network of Femtocells in order to improve the scalability of the LLM function. Therefore, the scope of operation of this scheme is the NoF itself, and its goal is to reduce the impact of LLM signalling on the operation of the underlying all-wireless transport network without modifying any 3GPP procedure. It is deployed at layer 2.5, with VIMLOC messages being carried over geographic packets.

The approach is to detect relevant 3GPP location management messages and, in turn, trigger equivalent LLM procedures that have been designed to operate more efficiently over an all-wireless network. In this sense, there are enhancements that aim to reduce the overhead generated by the solution by restricting the messages sent through the wireless medium in broadcast-like operations, yet offering a good performance. The scheme is made reliable by replicating parts of the location database of the local network throughout the entire NoF. Furthermore, VIMLOC (and its adaptation to BeFEMTO) derives much of its scalability from appropriately exploiting geographic information. This work is described in detail in [121] and [122].

On top of this LLM scheme, we propose a 3GPP-compliant self-organized Tracking Area List mechanism in order to achieve an optimal Tracking Area Update vs. paging signalling ratio for each UE. This scheme is especially adequate for large-scale networks of femtocells, where handovers and cell reselections are more frequent than in macrocell deployments. In order to facilitate its implementation in commercial scenarios, the proposed mechanism is fully compliant with 3GPP Technical Specifications. This work is described in Section 5.8.3.

In addition, we also propose a distributed paging mechanism to reduce over-the-air (OTA) paging signalling traffic in large-scale, all-wireless NoFs. Our scheme leverages the standard 3GPP X2 interface between HeNBs to propagate paging messages efficiently throughout the wireless multihop backbone. In particular, this proposal reduces OTA location signalling traffic by sending a single unicast S1-AP Paging message from the MME to the closest femtocell in the destination Tracking Area (TA). Upon reception of this message, the receiving HeNB propagates the paging message to the neighbouring femtocells in the TA through the X2 interface.

5.8.2.2 Contribution to BeFEMTO System Concept and Objectives

The main contribution to the BeFEMTO System Concept is the reduction of broadcast-like location management signalling traffic over the underlying all-wireless network of femtocells, hence making the solution more scalable.

The limitations of this approach are that they require minor modifications to the HeNBs (insertion of layer 2.5), as well as the new Lm interface between the LFGW and the HeNBs. However, the rest of layers and procedures keep on working in the same way, since interfaces are respected.

5.8.2.3 Impact on Architecture

A new functional block (the LLM function) is introduced in all HeNBs of the network of femtocells. This new block is located in the transport network layer; hence regular 3GPP location management procedures operating at the radio network layer are not affected. Therefore, the EPS architecture is not modified.

Messages to maintain the distributed LLM information are sent over the Lm interface between the LFGW and the HeNBs as well as between HeNBs. Note that the Lm interface is defined in the Transport Network Layer (TNL).

X2-AP Paging messages have been defined in order to propagate paging requests over the X2 interface.

There are no additional requirements on the functionality or performance of the interfaces to other entities.

5.8.2.4 Impact on Standards

The Lm interface and the extensions to the HeNBs which could likely be implemented in a proprietary manner.

References

[121] A. Krendzel, J. Mangues-Bafalluy, M. Requena-Esteso, J. Núñez, "VIMLOC: Virtual Home Region multi-hash Location Service in wireless mesh networks," *1st IFIP Wireless Days*, 24-27 Nov. 2008.

[122] J. Mangues-Bafalluy, M. Requena-Esteso, J. Nuñez-Martínez, A. Krendzel, "VIMLOC Location Management in Wireless Meshes: Experimental Performance Evaluation and Comparison," *IEEE International Conference on Communications (ICC)*, 23-27 May 2010.

5.8.3 Dynamic Adaptation of Tracking Areas

5.8.3.1 Motivation and description

Local Location Management (LLM) solves the problem of mapping a UE identifier (e.g., the Serving Temporary Mobile Subscriber Identity, or S-TMSI) to its physical/logical location in the NoF. Knowing the location of a given UE is of critical importance, as this information is used by the underlying transport network to route packets towards the UE. Therefore, LLM is used to determine the endpoints of an eventual communication.

In a large-scale NoF, a substantial number of UEs will be reselecting and handing over from/to neighbouring femtocells in relatively short periods of time. Consequently, LLM must solve the scalability problem in terms of location signalling traffic towards the Mobility Management Entity at the EPC. Therefore, signalling traffic must be handled by P-MMEs whenever possible in order to keep it local to the NoF. Another scalability problem is caused by the large-scale, all-wireless backbone, in case all-wireless NoFs are considered. In this scenario, the goal is to minimize over-the-air signalling traffic.

In our architectural solution for a NoF, all LLM procedures are managed by the P-MME entity. In order to improve the efficiency of current 3GPP Location Management schemes and reduce the amount of over-the-air signalling traffic, we propose a self-organized Tracking Area List (TAL) mechanism. This proposal is discussed below.

The self-organized TAL mechanism aims at minimizing the amount of location signalling traffic needed to keep the location of the UE updated in the P-MME. This mechanism has been built on top of the standard 3GPP Tracking Area Update (TAU) procedure [123] in order to comply with 3GPP Technical Specifications. As opposed to the standard concept of global Tracking Areas, the P-MME assigns an individual TAL to each UE in the NoF. The size of the TAL varies as a function of the UE speed. Thus, static and semi-static UEs are assigned to small TALs, whilst fast UEs are assigned to large TALs. This is done in order to reduce the amount of signalling traffic generated by a UE during a TAU procedure.

A detailed description of the self-organized TAL mechanism, along with some analytical results, has been presented in [124].

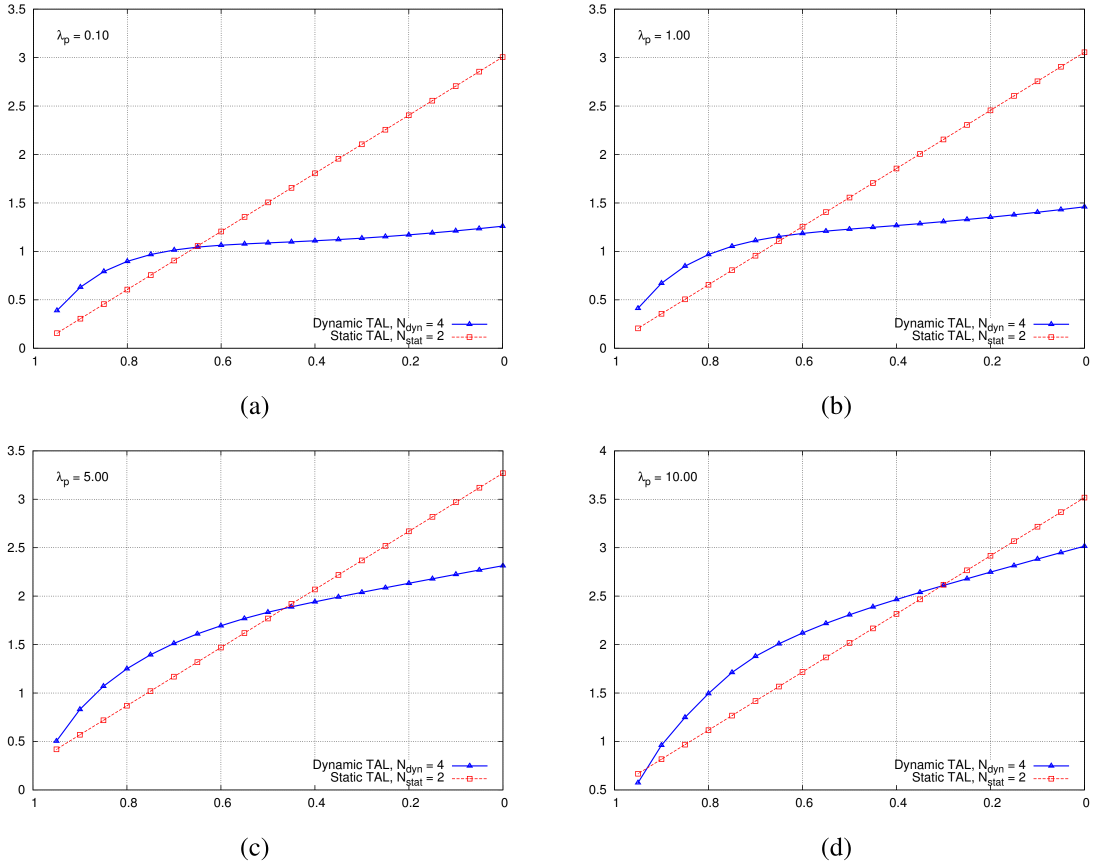


Figure 100: Impact of UE speed on location signalling traffic (static vs. dynamic TALs).

Figure 100 shows the impact of UE speed on the normalized signalling cost function for different paging arrival rates. The normalized signalling cost function is a metric that captures both TAU and paging signalling. In general, dynamic Tracking Area Lists generate less location signalling traffic than static TALs for medium- to high-speed UEs. This reduction is significantly higher when UEs are subject to moderate paging arrivals. Since the cost of a single TAU operation is tenfold that of a paging operation [125], the self-organized TAL mechanism aims at minimizing the normalized signalling cost function by reducing the probability of TAU arrival for each UE.

The intersections of the two curves in each figure determine the activation points of the self-organized mechanism. Thus, at speeds where static TALs generate less location signalling traffic than dynamic TALs, the self-organized mechanism keeps the TAL size constant. Once the activation point has been reached, the P-MME enables dynamic TAL management, hence reducing the overall location signalling traffic in the network. This switching strategy yields a significant reduction in location signalling traffic per UE, as shown in Table 33.

λ_p	**Location signalling traffic reduction**
0.1	39.45%
1	33.53%

5	13.21%
10	4.45%

Table 33: Reduction in location signalling traffic per UE.

5.8.3.2 Contribution to BeFEMTO System Concept and Objectives

The proposed self-organized Tracking Area List mechanism adapts the size of UE-specific TALs to the mobility state and the paging arrival rate of each terminal. This scheme is particularly suitable for large-scale Networks of Femtocells, where handovers and cell reselections happen more frequently than in macrocell scenarios. Furthermore, the self-organized TAL mechanism is fully compliant with 3GPP Technical Specifications in order to facilitate its implementation in commercial scenarios. The work carried out in [124] shows how the self-organized mechanism improves the performance of the conventional mechanism in terms of location signalling traffic for different paging arrival rates. Furthermore, analytical results show that the proposed mechanism can generate up to a 39% less location signalling traffic per UE than the conventional mechanism.

References

[123] 3GPP TS 23.401: "General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access, v.8.14.0 (Release 8)", June 2011.

[124] J. Ferragut, J. Mangues-Bafalluy, "A Self-Organized Tracking Area List Mechanism for Large-Scale Networks of Femtocells," in *Proceedings of IEEE International Conference on Communications (ICC 2012)*, 10-15 June 2012, Ottawa (Canada).

[125] A. Chandra, K. Mal, "Genetic Algorithm-Based Optimization for Location Update and Paging in Mobile Networks," in Proceedings *of Asian Applied Computing Conference (AACC)*, pp. 222-231, 2004.

5.8.4 Distributed Paging Mechanism Over the X2 Interface

5.8.4.1 Motivation and description

Standard 3GPP location management mechanisms comprise two main building blocks, namely the Tracking Area Update (TAU) and Paging procedures [126], [127]. The former refers to the ability of the Mobility Management Entity (MME) in the Evolved Packet Core (EPC) to track the location of a UE within the radio access network. The latter provides a mechanism to notify a UE of an incoming voice or data call. These procedures have been designed with macrocell scenarios in mind. Thus, their performance in large-scale, all-wireless NoFs is far from optimal due to (a) the overhead generated by frequent handovers/cell reselections and (b) the wireless multihop backbone in the Radio Access Network (RAN). Consequently, NoF scenarios require of specific Tracking Area Update and Paging procedures in order to track and page UEs efficiently whilst keeping over-the-air (OTA) location signalling traffic under control.

We propose a distributed paging mechanism to reduce OTA paging signalling traffic in large-scale, all-wireless NoFs. Our scheme leverages the standard 3GPP X2 interface between HeNBs to propagate paging messages efficiently throughout the wireless multihop backbone. In particular, our proposal reduces OTA location signalling traffic by sending a single unicast S1-AP Paging message from the

MME to the closest femtocell in the destination Tracking Area (TA). Upon reception of this message, the receiving HeNB propagates the paging message to the neighbouring femtocells in the TA through the X2 interface. Simulation results show that our proposal achieves up to an 85% reduction in the number of total signalling messages (S1-AP and X2-AP) per paging operation when compared to the standard 3GPP mechanism.

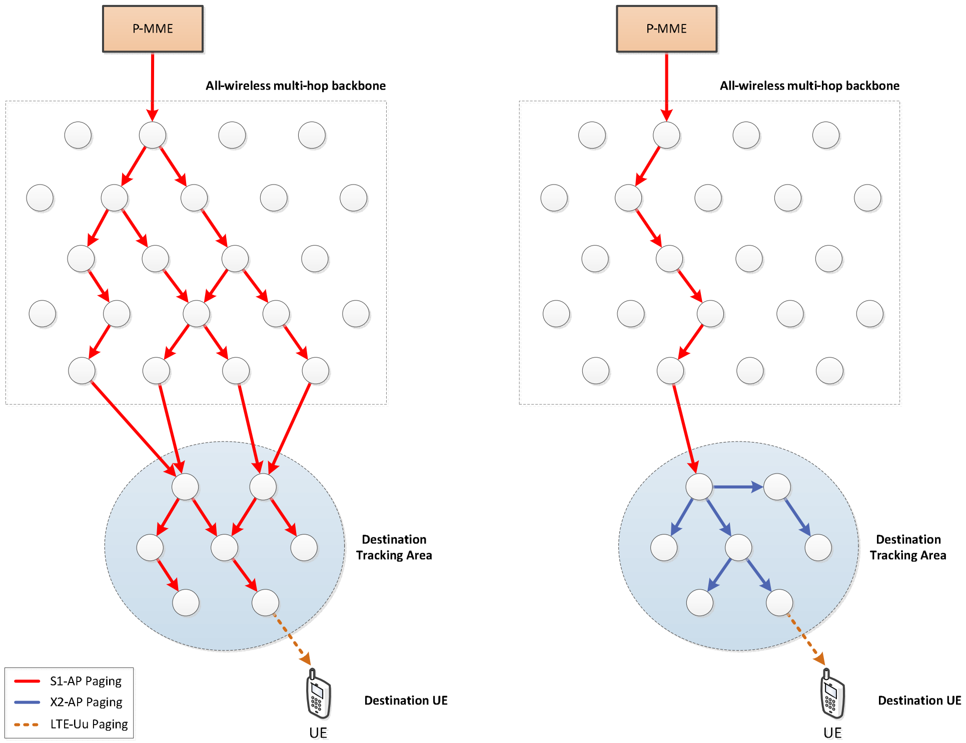


Figure 101: Operation of the Standard vs. Distributed Paging Mechanisms.

5.8.4.2 Contribution to BeFEMTO System Concept and Objectives

The proposed distributed paging scheme reduces the average number of over-the-air paging messages needed to locate a specific UE. This scheme is particularly suitable for large-scale, all-wireless Networks of Femtocells, where minimizing the amount of control-plane traffic over the wireless backhaul is a key requirement.

References

[126] P. Das and A. Chandra, "Location management in wireless networks: a survey", in *IEEE World Congress on Information and Communication Technologies*, pp. 576-580, 2011.

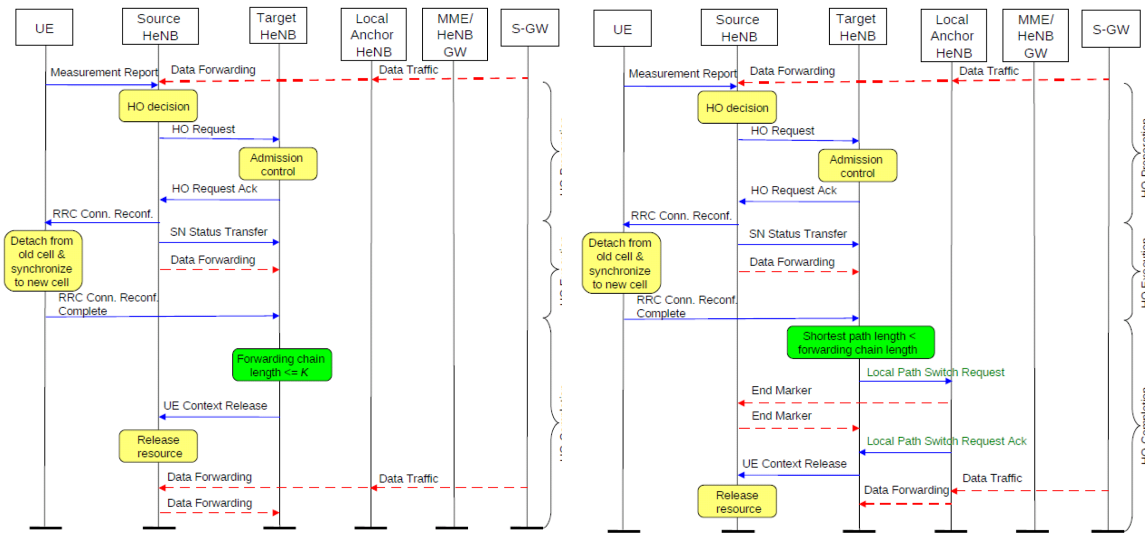
[127] S. Mishra and O.K. Tonguz, "Analysis of intelligent paging in personal communication systems", in *Electronic Letters*, vol.34, no.1, pp.12-13, 1998.

5.8.5 Mobility Management for Networked Femtocells Based on X2 Traffic Forwarding

5.8.5.1 Description of the Scheme

The small coverage and massive deployment of femtocells provide new challenges for mobility management, especially for inter-femto Handover (HO) in networked femtocells. Currently, 3GPP adopts a scheme for inter-femto HO similar to the scheme used for inter-macro HO [128]. After a UE establishes the radio connection with the target cell, the target cell will inform the core network entities to switch the data path. This scheme performs well for handover in conventional macrocell networks. Since the coverage of a macrocell is normally up to several kilometers, only few handovers will occur during one session. The data path switch after each handover can reduce the transmission latency over the data path. However, when a UE moves between femtocells, handovers will be much more frequent than macrocell scenarios due to the small coverage of each femtocell. Further considering the large scale deployment of femtocells, the frequent data path switch operations will cause significant signalling load to the core network entities.

Inspired by the idea of pointer forwarding scheme that is first introduced in [129] to reduce location management cost in cellular network, we propose two local mobility management schemes to reduce the inter-femto HO cost. Their Message Sequence Charts (MSCs) are shown in Figure 102.

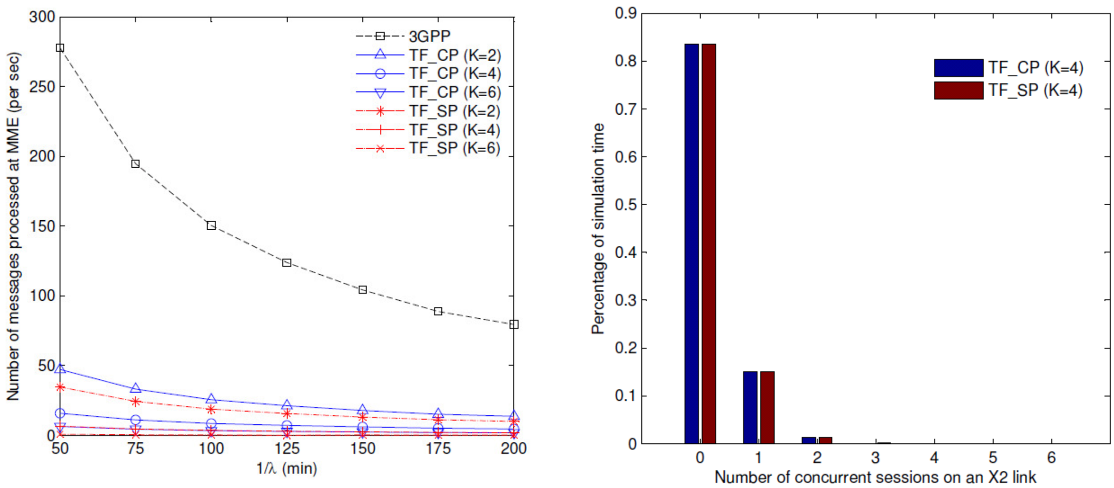


(a) **(b)**

Figure 102: MSCs of the proposed schemes: (a) TF_CP scheme; (b) TF_SP scheme.

The target HeNB will not send the *Path Switch Request* to the Evolved Packet Core (EPC) as long as the length of the forwarding chain does not exceed a predefined threshold *K*. A local X2 traffic forwarding chain will be established from the original local anchor femtocell to the current serving femtocell. In the first scheme, namely *Traffic Forwarding with Cascading Path* (*TF_CP*), the local path will be cascaded from the target femtocell to the previous source femtocell after a handover. In the second scheme, namely *Traffic Forwarding with Shortest Path* (*TF_SP*), the HeNB will advertise its neighbour list within the local network and thus, each HeNB will possess the network topology information and calculate the per-pair shortest path in advance. In HO completion phase, the target HeNB will compare the forwarding list with the shortest path to the local anchor point. If the length of the shortest path is less than the length of the forwarding chain, the target HeNB will initiate a local path switch operation.

We consider that 500 grid femtocell networks are deployed under the coverage area of an MME and each one is a 5×5 grid consisting of 25 femtocells. In each grid network, 50 UEs are randomly deployed and they move randomly within the local network from the current cell to one of its neighbours with equal probability. Figure 103 shows that both the TF_CP scheme and the TF_SP scheme can significantly reduce the number of signalling messages need to be processed at the MME even when the allowed maximum length of the forwarding chain is only 2 hops. The 3GPP scheme will incur heavy signalling load at the MME especially when the inter-session arrival interval $1/\lambda$ is small. In addition, more saving can be achieved by the TF_SP scheme compared to the TF_CP scheme since the local path optimization can reduce the chance that the forwarding chain reaches its threshold. On the other hand, the number of concurrent sessions traversing an X2 link is limited to two most of the simulation time. This implies that the traffic load incurred by the forwarding chain can be efficiently distributed over the local network. The bottleneck effect on an X2 link is negligible.



(a) **(b)**

Figure 103: Simulation results: (a) Signaling load at MME; (b) Local traffic load distribution.

5.8.5.2 Contribution to BeFEMTO System Concept and Objectives

The proposed schemes contribute to BeFEMTO System Concept by significantly reducing the inter-femto signalling load at the core network. Instead of implementing the path switch operation at the EPC for each HO, a local traffic forwarding chain is constructed to reuse the old Internet backhaul path. In this way, the processing load at the EPC can be significantly reduced at the cost of moderate distributed local traffic load. The proposed schemes are transparent to the EPC and the UEs and no upgrade is required from either side. Therefore, they can be easily incorporated into the current standard.

References

[128] Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (EUTRAN); Overall description; Stage 2 (Release 10), 3GPP Std. TS 36.300 v10.5.0, Sep. 2011

[129] R. Jain and Y.-B. Lin, "An auxiliary user location strategy employing forwarding pointers to reduce network impacts of PCS," *Wireless Networks*, vol. 1, no. 2, pp. 197–210, 1995.

5.8.6 Synthesis

Supporting smooth service continuity and efficient location management when users move among femtocells while requiring minimal support from the mobile core network is a key technical requirement towards the successful deployment of networked femtocells. To meet this requirement, BeFEMTO has developed various schemes: Firstly, a local mobility management scheme has been proposed to reduce handover latency and unnecessary signalling to the core network by introducing a Local Femto GateWay (LFGW). The LFGW can provide proxy MME and proxy S-GW functions such that the data and control plane traffic originally via S1 interface to the core network can be localized for inter-femto mobility. Secondly, a local and distributed location management approach is proposed to solve the mapping between a UE identifier and the physical/logical location of its current serving HeNB. This approach is deployed at layer 2.5 without modifying any 3GPP procedure and can reduce the broadcast-like location management signalling traffic over the underlying all-wireless network of femtocells. Thirdly, a self-organized Tracking Area List (TAL) mechanism is proposed to adapt the size of a TAL according to the UE mobility pattern. The proposed mechanism can reduce the total signalling cost of location update and paging operations. Fourthly, to reduce the paging signalling in all-wireless NoFs, a distributed paging mechanism is proposed by leveraging the standard 3GPP X2 interface between HeNBs to efficiently propagate paging messages. Up to an 85% reduction in terms of the number of total signalling messages (S1-AP and X2-AP) per paging operation can be achieved compared to the standard 3GPP mechanism. Finally, an X2-traffic-forwarding based method is proposed to reduce the signalling load to the core network due to the path switch operation during inter-femto handover. Instead of implementing the path switch operation at the EPC for each HO, a local traffic forwarding chain is constructed to reuse the old Internet backhaul path. In this way, the processing load at the EPC can be significantly reduced at the cost of moderate distributed local traffic load.

5.9 Network Management

5.9.1 Distributed Fault Diagnosis

5.9.1.1 Description of the Scheme

Fault Diagnosis in BeFEMTO focuses on the enterprise networked femtocells scenario and is designed as a distributed framework that allows local management capabilities inside the femtocell network. In order to implement this distributed framework, a multi-agent approach is followed. Fault diagnosis is therefore cooperatively conducted by a set of cooperation agents distributed in different domains which share their knowledge about network status. In particular, Fault Diagnosis targets the diagnosis of problems related to the use of video services while being under the coverage of an enterprise femtocell network. Diagnosis knowledge in BeFEMTO is modelled as a Bayesian Network (BN) which relates causes and symptoms by means of probabilities. This approach is well suited to deal with uncertainty and lack of full status information. Furthermore, diagnosis knowledge can be split up and appropriately distributed to the different domains involved.

In BeFEMTO there are different types of agents. A) Interface agents: These agents serve as the interface with other BeFEMTO components and external applications (such as a video client). Upon receipt of Service Error events, they request a diagnosis agent to start the corresponding diagnostic process. They are also in charge of propagating the resulting report to other BeFEMTO components, external applications and to a storage agent located in the LFGW. B) Diagnosis agents: They receive diagnosis requests, together with observations made for the diagnosis. A diagnosis agent will create its own BN and fill it with the evidences it has for a given request and the related evidences it may have in its cache. It will then infer the new probabilities and try to come up with the cause of the problem. If it needs further evidences to make a conclusion, it may request further observations/evidences to Observation Agents. In addition to observations, they may also request for beliefs on a particular Bayesian node state to a Belief Agent. C) Observation agents: They provide observations by performing specific tests upon request. Each Observation Agent will be specialised in a certain type of tests. D) Belief agents: They provide a belief on a certain node state. Like the diagnosis agents, they also have their own BN and make Bayesian inference to obtain the requested belief. The main difference with diagnosis agents is that they just provide the belief of the state of a particular node, rather than providing a whole diagnosis report. E) Knowledge agent: The knowledge agent is in charge of distributing diagnosis knowledge to all interested agents and performing Self Learning by processing the results of past diagnoses. Note Self Learning capabilities will be implemented in future iterations. F) Storage agent: This agent is in charge of storing diagnosis reports in a central repository to allow for self-learning.

In order to implement the multi-agent diagnosis system, the WADE/JADE multi-agent architecture is used. This agent platform can be distributed across machines (which not even need to share the same OS). In BeFEMTO, most JADE agents are located in the LFGW. Fault Diagnosis is designed as a recursive algorithm. BEFEMTO will iteratively perform Bayesian inference with available information until it reaches a given predefined confidence level. Otherwise, it tries to gather additional information by performing tests. From all the set of possible tests that can be performed, the one with the largest difference between value and cost is chosen first. Self-learning capabilities have been incorporated to the Fault Diagnosis functionality. For that purpose, diagnosis information is stored in a repository and is further processed in order to train the BN. This training requires diagnosis results to be validated, indicating whether they were right or wrong. Although the ideal solution would be to somehow automatically validate diagnosis results, manual validation is assumed.

The following figure depicts the relational diagram for the design of the database used to store and validate diagnosis operations.

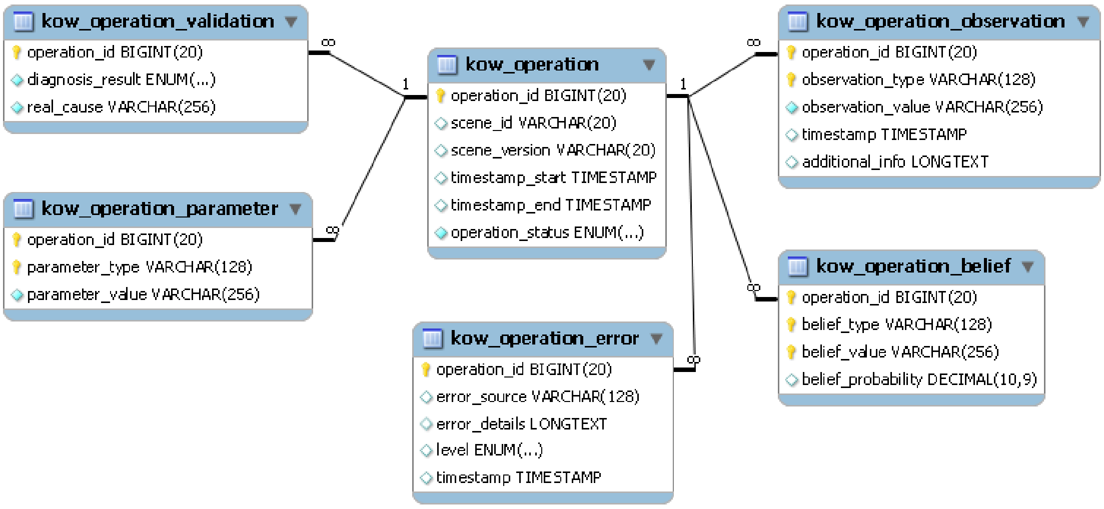


Figure 104: Fault diagnosis database tables.

Contribution to BeFEMTO System Concept and Objectives

The proposed fault diagnosis scheme is a procedure that helps to identify femtocells status in a networked environment, isolating the problems derived from the backbone network from those whose origin are the femtocells themselves. The scheme can operate in a scenario where the femtocells are provided by different vendors, and also ensures their supervision and fault management when the mobile operator has no control on the backbone network, usually an enterprise's local area network, they are connected to. The distributed nature of the algorithm and its self-learning capabilities minimizes also human intervention in a scenario where many femtocells can be installed in thousands enterprises.

5.9.2 Enhanced Power Management in Femtocell Networks

5.9.2.1 Description of the Scheme

The proposed scheme aims to reduce the amount of energy wasted in enterprise femtocell networks when femtocells are active during office hours at times and in locations when no user is present in the respective femtocell's coverage area [130]. It is based on the observation that individual users often follow a strict daily routine but that this routine can vary significantly amongst the employee base. It thus considers individual user activity and routine patters like the sequence of incoming and leaving users as well as electronic calendar entries for meeting appointments and absences, combined with user specific traffic demands, working locations and mobility patterns to only maintain the minimum set of femtocells powered-on to serve a particular group of users.

Four distinct energy management strategies and algorithms for operating an enterprise femtocell network have been considered by this study:

- **Schedule-based:** The simplest strategy simply switches on all femtocells in a given building during office hours and switches them off in the evening as the building opens and closes for business.
- **Location-based:** This strategy keeps certain femtocells powered-off until the associated user, i.e. the employee of a particular office, enters the building. In such a system, a dedicated cell, for instance in the reception, remains always powered-on. When detecting the presence and

connection state of a user, the system may determine that user's location/office, the path towards such location, and whether the corresponding femtocells need to be powered-on for ensuring a seamless service.

- **Location-Coverage Intelligence-based:** An enhancement of the previous strategy (i) takes the coverage and overlapping areas among neighboring femtocells into account and (ii) considers user activity, mobility and network resource availability. The primary objective is to accommodate incoming users on office femtocells already powered-on with adequate capacity. In case of resource shortage, another femtocell within the overlapping region is powered-on, preferably the one with minimum distance from the user location, breaking ties randomly. This strategy also considers context information like the type of area (corridor, common area, meeting rooms etc.) the femtocell is located in as well as user access permission rules and electronic calendar entries.
- **Information-Centric:** This strategy introduces further enhancements on the top of the location-coverage based one, considering (i) user statistics, i.e. history patterns, regarding entering and leaving the building and (ii) user movement within the network. Based on such user context, the management system performs an off-line operation to identify the optimal activation schedule to accommodate not only each individual user's coverage, but the future demands of all users. This activation schedule is then used as hint towards the location-coverage intelligence based strategy, such that not the femtocell that is closest to a user is powered on, but the one that is most beneficial also in terms of other users.

These four strategies were then evaluated using simulations of an office scenario with 20 femtocells (12 offices, 2 meeting rooms, and one community room with one femtocell each, 4 on the corridors and one at the entrance). Users would enter and leave the building during a certain time window following start of business hours and before end of business, respectively. It was assumed that users' meetings would be stored inside their electronic calendars. Figure 105 shows the relative savings of the location-based (Loc), location-coverage intelligence-based (Loc-Int) and information centric strategies, the latter without (Info-Cent) and with 20% prediction error (Info-Cent 20%) of individual femtocells in one simulated scenario, Figure 106 the minimum, average and maximum of 100 scenarios.

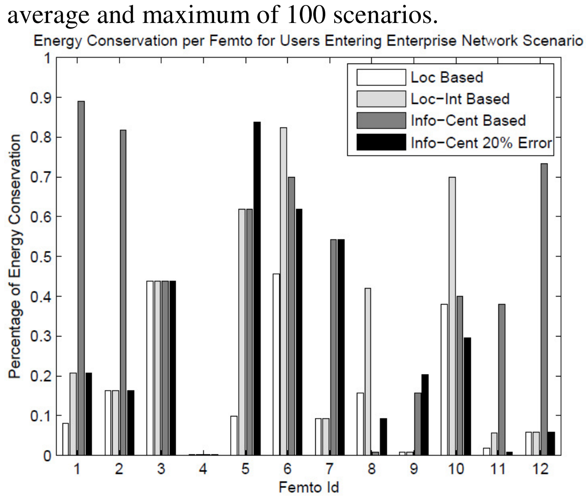


Figure 105: Femtocell energy conservation relative to schedule-based strategy.

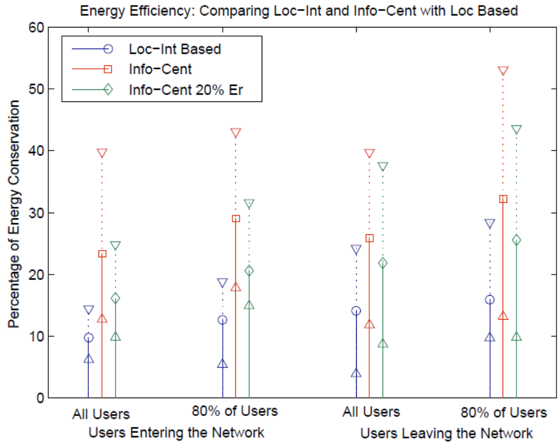


Figure 106: Average energy saving for entering/leaving scenarios.

The results show that context information like femtocell locations, typical user mobility and meeting + absence information can be effectively used to significantly reduce overall energy consumption by reducing the time individual femtocells are powered on. The Info-Cent strategy thereby showed 30% more energy efficiency than the Loc-Int strategy. The difference can even increase with the number of scheduled absences. It has also shown to be relatively robust to small errors in the predictions.

5.9.2.2 Contribution to BeFEMTO System Concept and Objectives

The proposed scheme would be implemented on BeFEMTO's Enterprise Femtocell Gateway, which allows it to integrate with Enterprise IT Systems and to access sensitive local information like employees calendar entries and office organization. Using this information, it is able to significantly lower the energy consumption of enterprise femtocell networks.

References

[130] A. P. Jardosh, et al, "Green WLANs: On-Demand WLAN Infrastructures", *ACM/Kluwer MONET*, Vol. 14, No. 6, Dec. 2009.

5.9.3 Synthesis

Fault Diagnosis focuses in enterprise networked femtocells and is designed as a distributed framework that allows local management capabilities inside the femtocell network. A multi-agent approach is followed, cooperatively conducted by a set of cooperation agents distributed in different domains which share their knowledge about network status. Diagnosis knowledge in BeFEMTO is modelled as a Bayesian Network (BN) which relates causes and symptoms by means of probabilities. This approach is well suited to deal with uncertainty and lack of full status information. In BeFEMTO there are different types of agents. A) Interface agents B) Diagnosis agents C) Observation agents. D) Belief agents E) Knowledge agent F) Storage agent. Fault Diagnosis is designed as a recursive algorithm, which iteratively performs Bayesian inference with available information until it reaches a given predefined confidence level. Otherwise, it tries to gather additional information by performing tests. From all the set of possible tests that can be performed, the one with the largest difference between value and cost is chosen first. Self-learning capabilities have been incorporated to the Fault Diagnosis functionality; information is stored in a repository and is further processed in order to train the BN.

6. Fixed Relays and Mobile Femtocells

6.1 Self-Optimization of Antenna tilt

6.1.1 Description of the Scheme

This scheme is applicable to the following BeFEMTO theme: fixed relay femtocells. The scope of this contribution is focused on Spectral Efficiency (SE) enhancement in the access link of Outdoor Fixed Relay femtocells (OFR) through SO of eNB antennas' tilts.

OFR are different from conventional femtocells as OFR generally have an over the air inband backhaul link called access link, to relay the traffic data to and from their donor eNB. This access link requires radio resource partitioning between the eNB and OFR to avoid mutual interference. Such additional partitioning of resources is bound to have negative impact on the spectrum reuse efficiency of the system and hence capacity. Therefore, it is very desirable to optimise the spectral efficiency of the access link so that less fraction of radio resources have to be allocated to OFR access link and more resources can be used to provide service to users than back hauling. In this contribution, we present a novel framework and the results of SE enhancement on the access link through SO of eNB antenna tilts.

In this framework, we formulate the system wide eNB tilt optimization problem for maximisation of spectral efficiency on the eNB-OFR links. The main idea of the proposed solution is that, by exploiting the symmetry of system model, the system wide spectral efficiency enhancement complex problem can be broken down to local, much less complex sub problems as suggested in [131],[132]. These sub-problems can then be solved locally among a cluster of cells. We propose this cluster to be a *triplet* of adjacent sectors that interfere the most as shown in Figure 107. The basic idea of decomposing the system wide problem into local sub-problems is inspired from case studies of self organisation in natural system and therefore the proposed framework is termed as TO-BSOF i.e. Tilt Optimization through Biomimmetic Self organisation Framework.

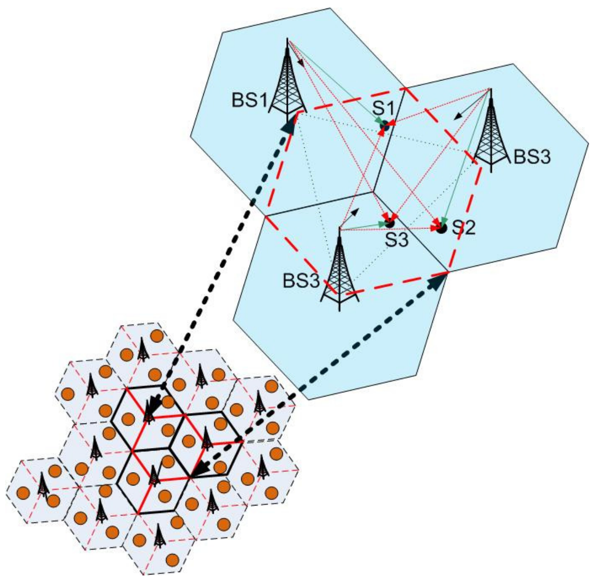


Figure 107: Illustration of the concept of triplet of most interfering sectors. Tilts are organized within each triplet independently leading to near optimal throughput at access links in distributed manner.

In order to assess the potential gain TO-BSOF can yield, numerical results for two different set of location of OFRs in triplet are obtained, as shown in Figure 108. It can be seen that depending on the location of OFRs, a gain in spectral efficiency from 1bps/Hz to 2bps/Hz can be achieved on average within each triplet, and hence system wide, through TO-BSOF. Thus, TO-BSOF can yield up to 3.6 b/s/Hz (SISO) spectral efficiency on the eNB-OFR access links. To investigate the impact of TO-BSOF on fairness, Jain's Fairness Index (JFI) is also plotted. It is interesting to note that optimal tilt angle for maximum fairness among access links throughput are different than the optimal tilt for maximum spectral efficiency.

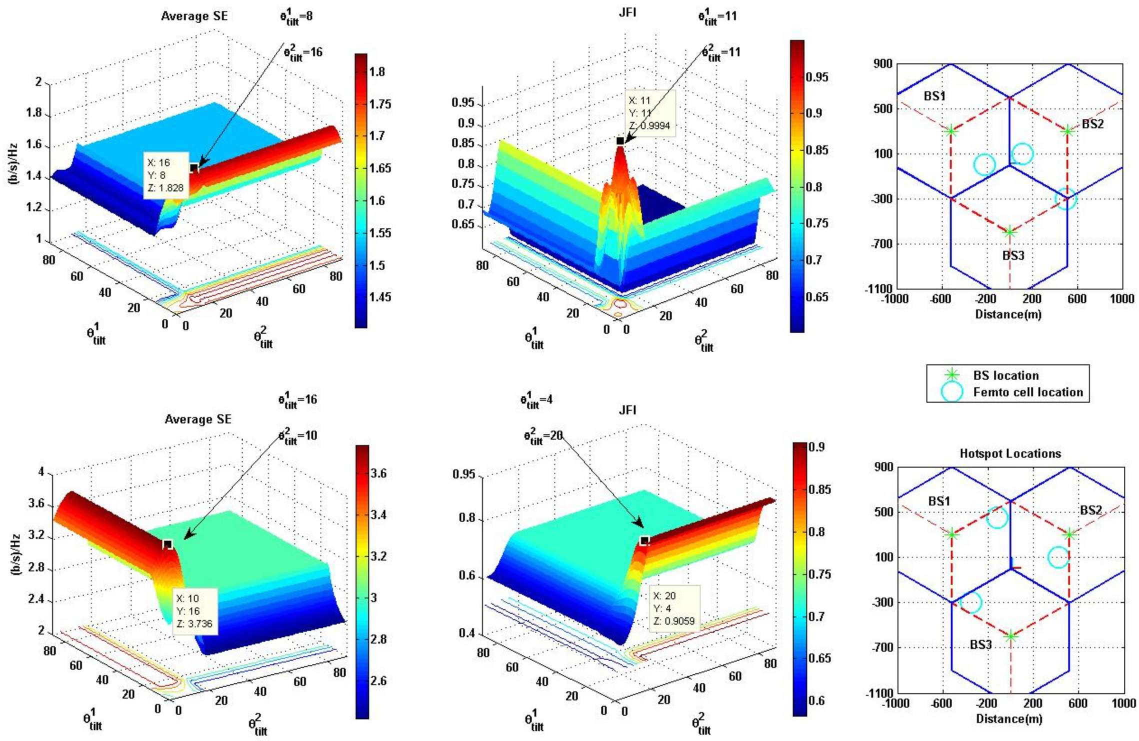


Figure 108: Average spectral efficiency per link and the Jain's fairness index among the access links within a triplet are plotted as function of tilt angle of two sectors while third is fixed at 13^0 degree.

6.1.2 Contribution to BeFEMTO System Concept and Objectives

The proposed scheme of antenna tilts adjustment of macro eNBs within each triplet in a distributed manner to optimize the spectral efficiency of outdoor fixed relays stations directly contributes to the BeFEMTO objective of maximizing spectral efficiency and as mentioned earlier can increase the average spectral efficiency from 1bps/Hz to 2bps/Hz which is quite significant. Furthermore, this increase is achieved in a distributed manner without relying on global coordination or central control. A negligible amount of signalling among the sectors within triplet is required to determine the location of OFRs. This signalling can be done through X2 interface and needs to be done only when location of OFR is changed.

References

[131] C. Prehofer and C. Bettstetter, "Self-organization in communication networks: principles and design paradigms," *IEEE Communications Magazine*, vol. 43, no. 7, pp. 78 – 85, Jul. 2005.

[132] A. Imran, M.A. Imran, R. Tafazolli, “Relay Station Access Link Spectral Efficiency Optimization through SO of Macro BS Tilts,” *IEEE Communcations Letters*, vol. 15, no. 12, pp. 1326 – 1328, Dec. 2011.

6.2 Distributed, Relaying and Mobile

6.2.1 Enabling relaying over HetNet backhauls in the UL

6.2.1.1 Description of the Scheme

Focus is on exploring cooperative strategies which aim at improving the data rate of the macrocell users with the aid of open access small cells. This is achieved by splitting the macro UE’s message into two parts: (i) coarse/private message which can only be decoded at the MBS and, (ii) *fine/common message* - which is broadcasted and can be decoded by any neighboring femtocell. Upon decoding the common signals of the MUEs, the femtocells forward them to the MBS via the backhaul (decode and forward relaying). It is assumed that the FBS-MBS backhaul link is shared among all femtocells and is assumed to be unreliable with finite capacity. It appears clear that it is not always the best strategy for MUEs to use femtocells as helping’s relays, since the reliability, densification of the network and the finite capacity of the backhaul should be taken into account. Therefore, we propose [133] a *novel* approach for interference management which leverages cooperation between the macro- and femto- cell tiers, while jointly optimizing the choice of an appropriate backhaul supporting this cooperation.

To benefit from rate-splitting in the UL, the MUEs must *appropriately* select the best serving FBSs for relaying their signals over the backhauls, and optimally split their rates between MBS and FBS. We show that these choices lead to a non-cooperative game between the MUEs in which each MUE needs to select its preferred relaying femtocell along with the associated power allocation so as to maximize its utility function which captures the tradeoff between the achieved data rate (due to relaying) and the expected transmission delay (due to the backhaul constraint). To solve this game, we propose a *best response*-based algorithm using which the MUEs can reach the equilibrium of the game. Figure 109 provides a depiction of the proposed approach.

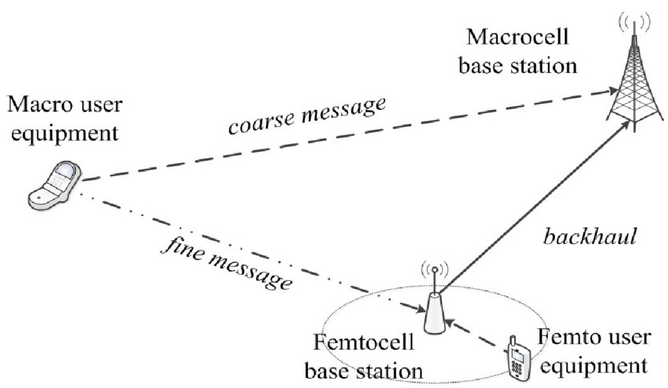


Figure 109: Illustration of the proposed relaying approach in which the MUEs use rate splitting in their UL transmission

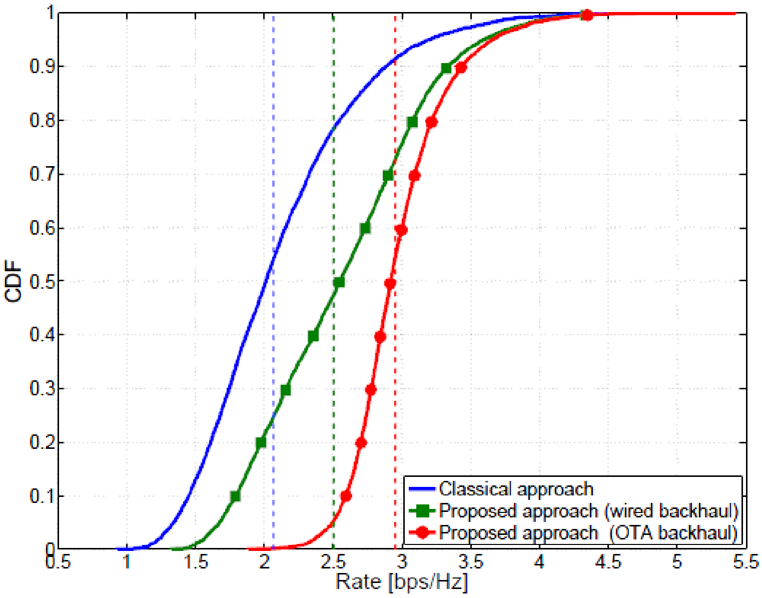


Figure 110: Cumulative distribution function (CDF) of the non-cooperative, and proposed scheme with heterogeneous OTA/Wired backhauls; 37.5 Mbps wired backhaul and 32 OTA backhaul channels are considered

6.2.1.2 Contribution to BeFEMTO System Concept and Objectives

Figure 110 plots the cumulative distribution function (CDF) of the proposed approach over two different backhauls (OTA and wired), in addition to the non-cooperative approach with no macro-femto cooperation/coordination. Clearly, through the concept of cooperation and rate splitting, larger gains can be obtained than the classical approach. In addition, backhaul-aware cell selection is shown to highly impact the performance. A natural trade-off emerges in which resource and delays are traded.

References

[133] S. Samarakoon, M. Bennis, W. Saad and M. Latva-aho, "Enabling Relaying over Heterogeneous backhauls in the Uplink of Femtocell Networks," in *Proc. IEEE Wiopt*, 2012.

6.2.2 Femto assisted macro relaying in the UL

6.2.2.1 Description of the Scheme

We propose a framework for macrocell-femtocell cooperation under a closed access policy, in which a FUE may act as a relay for MUEs. In return, each cooperative macrocell user grants the FUE a fraction of its super-frame. We formulate a coalitional game in which macrocell and femtocell users are the players, which can take individual and distributed decisions on whether to cooperate or not, while maximizing a utility function that captures the cooperative gains, in terms of throughput and delay. We show that the network can self-organize into a partition composed of disjoint coalitions which constitutes the *recursive core* of the game representing a key solution concept for coalition formation games in partition form. Figure 111 provides an illustration of the proposed approach.

It appears clear that MUEs and FUEs have a strong incentive to cooperate to improve their performance using advanced techniques such as relaying and spectrum leasing. Since MUEs and FUEs exhibit a tradeoff between the achievable throughput and the transmission delay, we use a suitable metric to quantify the benefit of cooperation defined as power of the network. We formulate a *coalitional game* among the FUEs and MUEs in a network adopting a CSG policy at each femtocell. Further we introduce a coalitional value function which accounts for the main utilities in a cellular network: transmission delay and achievable throughput. To form coalitions, we propose a distributed coalition formation algorithm that enables MUEs and FUEs to autonomously decide on whether to cooperate or not, based on the tradeoff between the cooperation gains, in form of increased throughput to delay ratio, and the costs in terms of leased spectrum and transmit power. It is shown that the proposed algorithm reaches a stable partition which lies in the recursive core of the studied game. The performance of MUEs and FUEs are respectively limited by delay and interference, therefore, the proposed cooperative strategy can provide significant gains, when compared to the non-cooperative case as well as to the closed access policy.

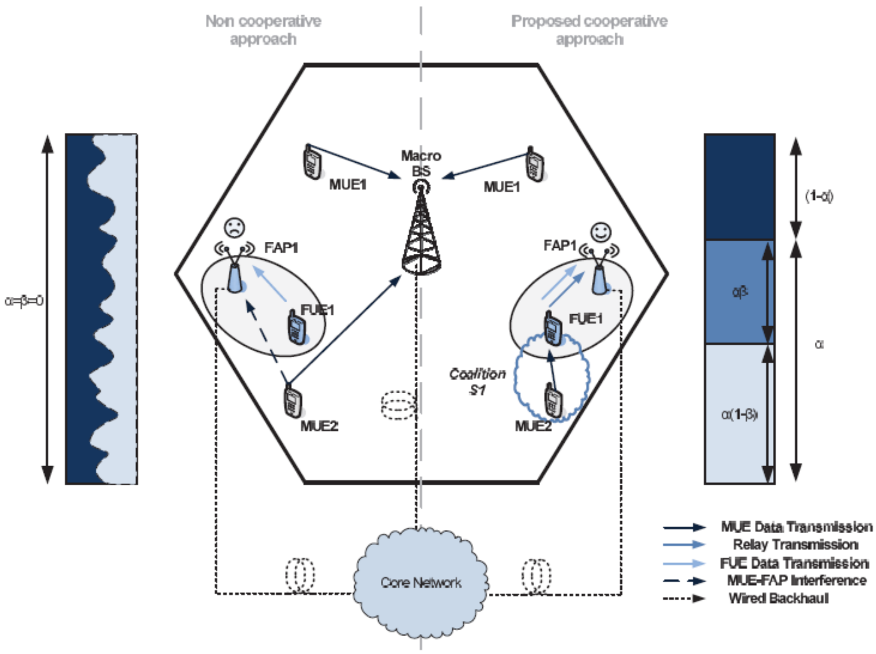


Figure 111: Illustration of the proposed solution compared to the traditional non-cooperative approach.

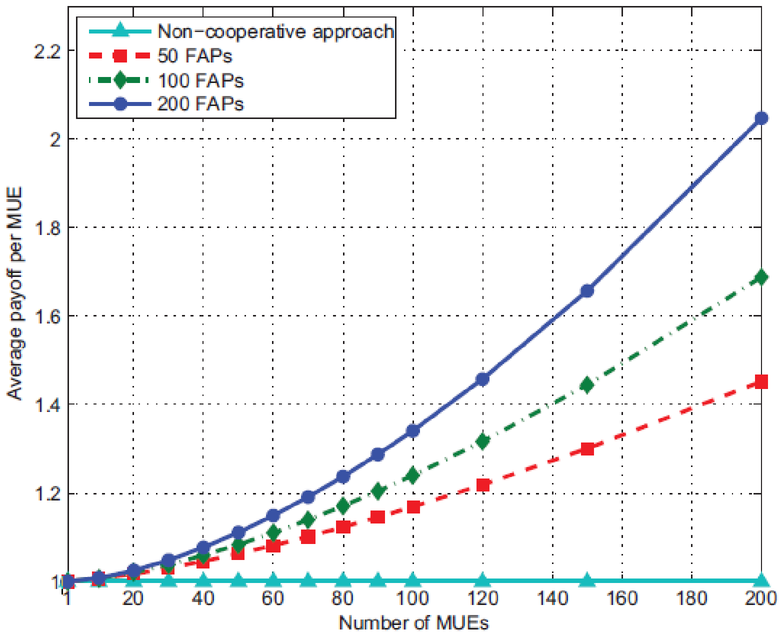


Figure 112: Average individual payoff per MUE, normalized to the average payoff in the non-cooperative approach, for a network with N = 50, 100, 200 FAPs

6.2.2.2 Contribution to BeFEMTO System Concept and Objectives

Figure 112 shows that cooperating MUE can gain up to 75% with respect than the non-cooperative case in a network with N = 200 FAPs and M = 160 MUEs. In fact, Figure 112 clearly shows that the average payoff per MUE increases in the cooperative case as the number of femtocells is large. It is also demonstrated that the proposed coalitional game model has a significant advantage over the non-cooperative case, which increases with the probability of having FUEs and MUEs in proximity, and resulting in an improvement of up to 205% for M = 200 MUEs.

References

[134] F. Pantisano, M. Bennis, W. Saad, and M. Debbah, "Spectrum Leasing as an Incentive towards Uplink Interference Mitigation in Two-tier Femtocell Networks," in *IEEE Journal on Selected Areas in Communications (JSAC)*, special issue on Femtocells, April 2012.

6.2.3 Mobile/Moving Femtocells

6.2.3.1 Description of the Scheme

Mobile femtocells are currently a very hot topic in the 3GPP community in which low-power nodes are mounted on public transportation such as high-speed trains and ferries. These deployments pose many challenges which are unique in their nature and different from conventional fixed relays and Wi-Fi hotspots. One of the limiting factors in the deployment of moving relays is the backhaul, and hence, smart backhauling strategies are of utmost importance. Different heterogeneous backhauls are envisaged, such as wired, wireless and a combination thereof. The former is among mobile femtocells, whereas the latter is between one or multiple mobile femtocells and one or many donor eNodeBs. Distributed antenna systems (DAS) in conjunction with MIMO techniques can also enable an efficient backhauling.

Coordinating these heterogeneous backhauls in an efficient manner in the case of load balancing, and mobility management is seen as instrumental.

We propose a coordinated and cooperative relay system (CCRS) made up of a group of moving relays (MRs), each of which is responsible for a local cell (within a carriage) and which may have a backhaul link established with an eNodeB. The CCRS may be connected to multiple eNodeBs at any given time, as well as multiple parallel backhaul links to the same eNodeB. The donor cellular system may control and coordinate these mobile backhaul links, together with smart cooperation between the MRs inside the CCRS. A new interface is defined (crX2) interconnecting the MRs, used for cooperation in duplexing operation, load-balancing and capacity sharing amongst the MRs and the local cells thereof, and connection and mobility management. The crX2 interface may be wired or wireless, and if wireless preferably out of band to avoid interference to cellular users. Figure 113 depicts the considered network topology with two donor eNodeBs and a mobile femtocell train. The primary assumption made for simulation of the CCRS is that the backhaul link (eNodeB to MR) is the capacity *bottleneck* of the whole system; therefore it is assumed that there is enough access link capacity for the MRNs to share the backhaul capacity in an efficient manner amongst the served users within the train. The access link is not modeled in the simulator, and the throughput of train users when served by a MRN is calculated by simply dividing the backhaul throughput of the MRN by the number of users of the MRN. It is also assumed that the crX2 interface connecting the MRNs has zero latency, and unlimited capacity. Simulations are carried out for both full-duplex and half-duplex backhaul link operation. Currently handover is not supported in the simulator, so simulations are carried out with all users inside the train connected directly to an eNodeB or through a MRN.

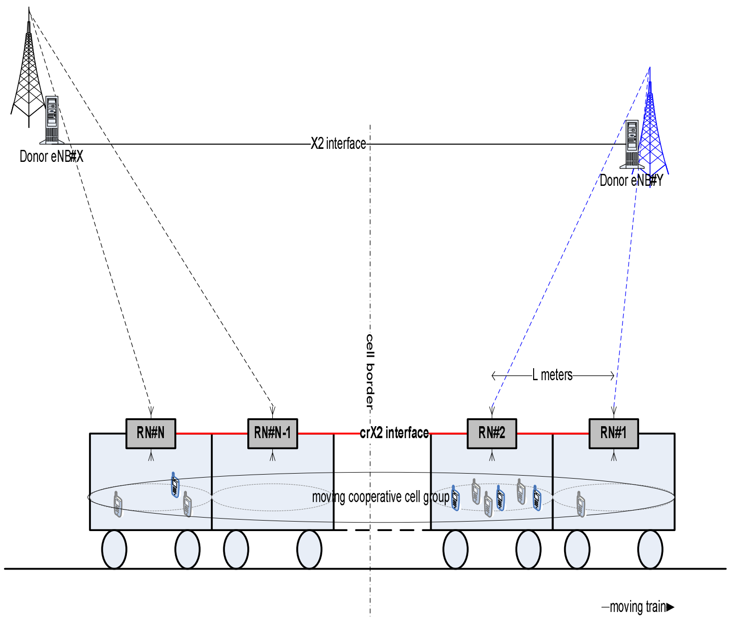


Figure 113: Considered network topology with two donor eNodeBs and a mobile femtocell train

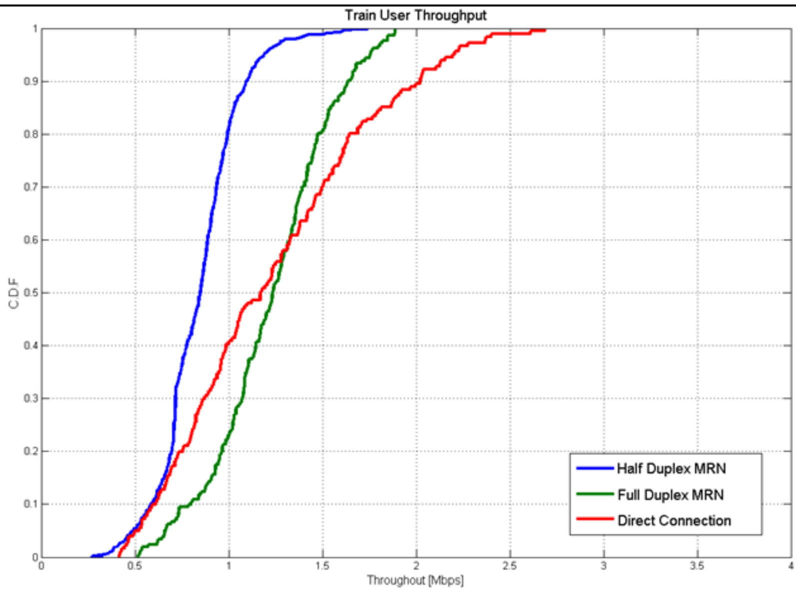


Figure 114: Cumulative distribution function (CDF) of the train user throughputs

6.2.3.2 Contribution to BeFEMTO System Concept and Objectives

Figure 114 shows the throughput of train users when connected to MRNs with full-duplex operation, MRNs with half-duplex operation, and the mean throughput of train users connected directly to an eNodeB. In the case of the chosen simulation parameters the use of half-duplex MRNs decreases the throughput of train users when compared to directly connecting to an eNodeB. The full-duplex case provides better throughput for more than half of the train users however in the case of direct connection the peak throughput is higher, at the expense of normal macro user throughput.

6.2.4 Synthesis

Coordinated multi-point transmission has been identified as an efficient means to boost the network capacity. The gains hinge on the backhaul which can be wireless or over-the-air. In the case of tight coordination among tiers, coordinated transmission among femtocells over high capacity backhauls and low delays exhibit sizeable gains in the downlink. In the uplink, several scenarios can be considered. For instance, in a cooperative setting and when femtocell users relay the uplink traffic of macrocell users, through a D2D communication, the performance of cell edge users can be dramatically improved, provided that a good backhaul exists. In other scenario, when the backhaul conditions do vary, macrocell users face a non-trivial problem which is how to split their transmission across the open access picocells and the macrocell, keeping in mind that the backhaul has a direct impact. This naturally calls for efficient backhaul-aware cell selection techniques, in which a natural trade-off emerges in which resource and delays are traded. Finally, when studying mobile femtocells or more generally moving relays, different solutions can be envisaged to remedy to the backhaul bottleneck. Indeed, it is shown that the use of half-duplex decreases the throughput of train users when compared to directly connecting to an eNodeB. In contrast, the full-duplex case provides better throughput for more than half of the train users however in the case of direct connection the peak throughput is higher, at the expense of normal macro user throughput.

6.3 Mobility Management

6.3.1 Backhaul for Mobile Femtocells/Mobile Relays

6.3.1.1 Description of the Scheme

In the technical report TR 36.806 3GPP [135] several alternatives of architecture for a case when relay becomes a part of the fixed access network are described. In such an architecture, the fixed relay is connected through a wireless backhaul to a Donor eNB (DeNB) by means of a modified version of the E-UTRA radio interface (the Un interface) and becomes a part of the fixed access network. It was concluded in the report that that the architecture Alternative 2 (proxy S1/X2) has more benefits in comparison with the other three alternatives and it is selected as the baseline architecture for the fixed relay node. But, taking into account that mobile relay node (MRN) has additional requirements (group mobility support, IP connectivity handling during handover, etc.), the other alternatives that were considered in [135] could bring more advantages.

For this reason, relay architectures presented in [135] were re-analysed keeping in mind relay mobility handling. As a result of this re-analysis, it was observed that the architecture Alternative 1 (a full L3 relay) that is transparent for Donor eNB (DeNB) is more appropriate than other architecture alternatives to provide mobile relay support. MRN handover process based on the Alternative 1 is illustrated in Figure 115.

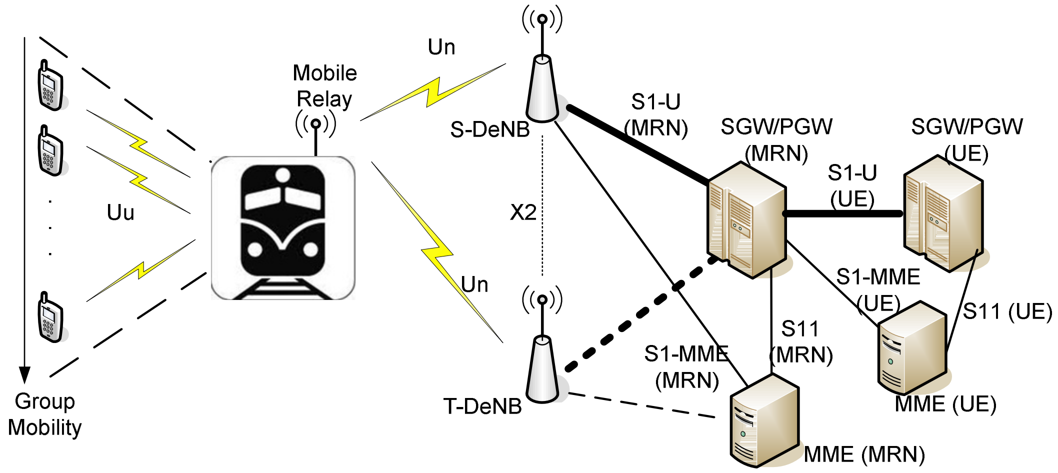


Figure 115: Mobile Relay handling based on the architecture Alternative 1

In the architecture Alternative 1 the S-GW/P-GW functionality serving relay is out of the DeNB in compare with other alternatives, i.e. traffic is delivered to/from a UE via two GWs, namely, the S-GW/P-GW serving relay and S-GW/P-GW serving the UE. In the context of mobility handling, the separation of the S-GW/P-GW serving MRN from the DeNB can brings some benefits since the S-GW/P-GW (MRN) can be considered as a stable “IP anchor point” to support the MRN mobility as shown in Figure 115. Moreover, taking into account that the specific feature of the architecture Alternative 1 is transparent to the DeNB for the full L3 relay, a GTP tunnel per UE bearer is entirely without any switching in the DeNB and goes from the SGW/PGW serving the UE directly to the MRN. From the signalling traffic point of view, the DeNB and the S-GW/P-GW of the MRN play the role of user plane transport nodes.

When the MRN moves from source DeNB (S-DeNB) to target DeNB (T-DeNB), IP connectivity is handled through the S-GW/P-GW (MRN) as the IP stable anchor in the network that enables not changing the IP address of the MRN at all. As a result, there is no need to perform the network re-entry at T-DeNB, i.e. to re-initiate the relay attach procedure. Besides, interworking between the MRN and its OAM is not interrupted that is crucial issue for normal operating conditions of the MRN. Moreover, the MRN handover procedure for this architecture does not require the downlink data path switches related to different S-GWs/MMEs serving UEs. In this sense, group mobility for UEs attached to the MRN is supported when the MRN moves from S-DeNB to T-DeNB.

As a sequence, mobile relay architecture based on the Alternative 1 should be less time-consuming than other alternatives where the S-GW/P-GW functionality serving the relay is embedded into the DeNB. Analysis of handover procedure duration fulfiled in D 5.2 confirms this supposition. It is based on latency values (taken from [136], [137], [138]) caused by different transmissions between network entities involved in the handover process. As an illustration, Table 34 presents estimated values of handover procedure latency when MRN handling is based on the Alternative 1 (Full-L3 relay) and the Alternative 2 (Proxy S1/X2) correspondingly. These handover scenarios were considered in detail in D5.2.

Mobile Relay Architecture	Handover duration, ms
Alternative 1 (Full-L3 relay)	88
Alternative 2 (Proxy S1/X2)	136

Table 34: Handover procedure duration for mobile relay architectures

As seen from Table 34, the latency to perform the full MRN handover procedure from S-DeNB to T-DeNB for the Alternative 1 is about 1.5 times faster than for the Alternative 2. This is because the relay mobility based on the Alternative 1 does not require the re-attach procedure at T-DeNB including OAM MRN configuration, MRN-initiated S1/X2 setup, S1/X2 T-DeNB configuration update. Moreover, note that in the case of the Alternative 2, it is supposed in Table that all UEs attached to the MRN are under the same S-GW/MME serving the UEs. If they are connected to different S-GWs/MMEs it can lead to more down link data path switching. That is, some operations related to the data path switching and taken approximately 41 ms should be repeated several times depending on the number of different S-GWs/MMEs (UEs). Definitely, it can increase additionally the duration of the handover procedure for relay mobility based on the Alternative 2. Thus, the architecture Alternative 1 shows better performance for the MRN.

6.3.1.2 Contribution to BeFEMTO System Concept and Objectives

It was concluded that for mobile relay changing its backhaul link (Un interface) from Source-DeNB to Target-DeNB the architecture Alternative 1 (a full L3 relay) [135] has more benefits than other architectures. The proposed scheme contributes to BeFEMTO System Concept by supporting IP connectivity for MRN during handover procedure by means of the stable IP anchor point (S-GW/P-GW serving mobile relay). As a consequence, mobile relay architecture based on the Alternative 1 do not require the time-consuming relay re-attach procedure when backhaul link is re-established to T-DeNB and it handles interworking between the MRN and OAM without connectivity interruption that are crucial issues for normal operating conditions of the MRN. Moreover, the MRN handover procedure for this architecture does not require the downlink data path switches related to different S-GWs/MMEs serving UEs. In this sense, group mobility for UEs attached to the MRN is supported when the MRN moves from S-DeNB to T-DeNB.

The latency analysis related to the MRN handover procedure confirms the analytical observations in accordance to which the architecture Alt 1 shows better performance in a mobile relay network.

In accordance with [135], the architecture Alternative 1 has low impact on standardization effort and complexity. It does not require new network elements in the BeFEMTO System Architecture. Just minor additional effort is needed from the viewpoint of extending functionality of network entities, e.g. P-GW of the relay needs to perform bearer mapping [135].

Bibliography

[135] 3GPP TR 36.806, Evolved Universal Terrestrial Radio Access (E-UTRA), Relay architecture for E-UTRA (LTE-Advanced), Release 9, V9.0.0 (2010-03).

[136] 3GPP TSG-RAN WG3 #66, R3-092738, “Architecture Options Comparison: UE Mobility Support”, Fujitsu, November, 2009.

[137] ARTIST4G (Advanced Radio InTerface TechnologIes for 4G SysTems), “D3.4 - Relay configurations”, July, 2011.

[138] S. Mohan, R. Kapoor, B. Mohanty, “Latency in HSPA Data Networks”, white paper of Qualcomm, February, 2011.

6.3.2 Mobile Femtocells based on Multi-homing Femtocells

6.3.2.1 Description of the Scheme

This work studied an alternative approach to Mobile Relays, which is to turn a normal femtocell into a Mobile Femtocell. The Mobile Femtocell works in an overlay manner by establishing the IP connectivity to its mobile operator’s Femtocell Gateway over a mobile cellular access. By extending such overlay solution to multiple IP backhaul links, i.e. by making the femtocell *multi-homing capable*, several mobile access links can be bundled for higher reliability, quality, and capacity. It is even possible to use mobile accesses of different vendors and to use any combination of radio access technologies. A further advantage of Mobile Femtocells compared to Mobile Relays is that they allow Local IP Access, e.g. for providing value-add services on the bus or train the Mobile Femtocell is installed in.

There are several ways to provide multi-homing support for such Mobile Femtocells. In this work, we studied replacing the existing protocol combination of GPRS Tunnelling Protocol User plane (GTP-U) over User Datagram Prototcol (UDP) to transport user flows between the femtocell and femtocell gateway with SCTP. SCTP has a number of key features which can be used to enhance femtocell functionality; these include transport layer multi-homing, multi-streaming, concurrent multi-path transfer and partial reliability. It is worth noting that every femtocell and femtocell gateway already utilises SCTP for transporting control plane data and as such it would not require any major modifications to existing femtocell protocol stacks.

Figure 116 shows the user plane stacks of a Mobile Femtocell connected via two backhaul connections of different radio access technologies to the HeNB-GW. In this example, one of the accesses is the MNO's own LTE network, the other one is a WiFi-based Internet access of a third-party, which is why the user plane traffic is transported with IPSec encryption and UDP encapsulation to provide security and Network Address Translation traversal (NAT-T) capability.

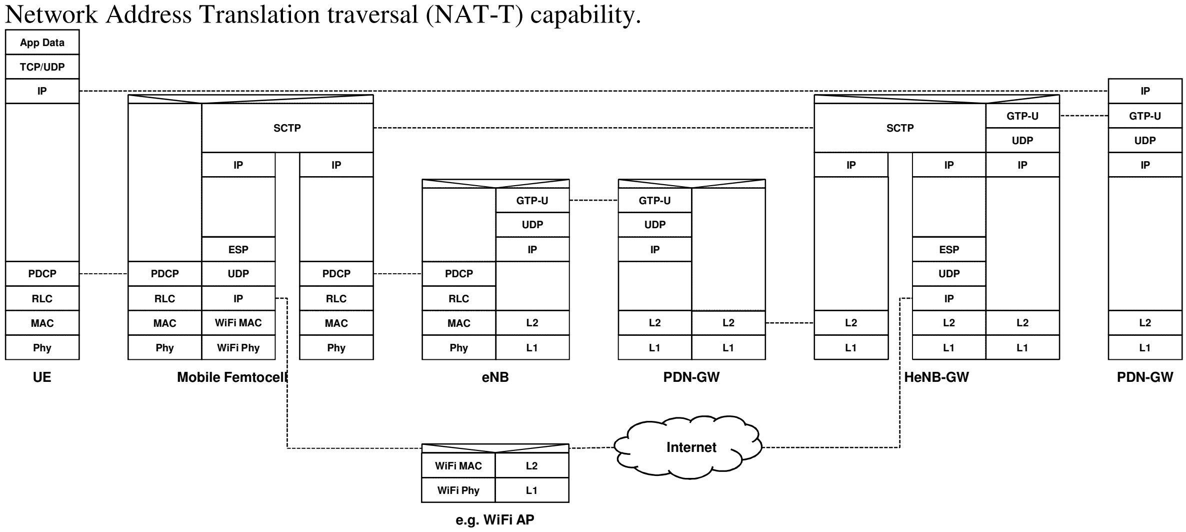


Figure 116: User-plane stacks of Mobile Femtocell with two backhaul connections of different radio access technologies.

In order to successfully utilise SCTP as a replacement for GTP-U over UDP, all required fields must be mapped to equivalent SCTP fields or at the very least provide the same functionality. The key functionality for GTP-U in a femtocell network is to separately tunnel individual user flows and bearers between the femtocell and femtocell gateway. To provide this functionality the two key parameters involved in a GTP-U tunnel are the Tunnel Endpoint Identifier (TEID) and the optional sequence number. These are mapped to the SCTP stream identifier and stream sequence number, respectively.

Using SCTP thus for both control and user plane, the Mobile Femtocell becomes multi-homing capable and can utilize SCTP's concurrent multi-path transfer and partial reliability extensions. A comparison between SCTP versus GTP/UDP header overheads shows that this is not even less efficient in most cases: SCTP's overhead is 12 bytes for the common header and 16 bytes for the data chunk header. In comparison, UDP and GTP add 8 and 12 bytes, respectively, so in the worst case the SCTP overhead is 8 bytes higher per packet. However, unlike UDP, each SCTP packet can contain multiple data chunks. Thus, the additional overhead can be amortized over the number of voice or data packets that can be bundled into one SCTP packet. SCTP can bundle as many data chunks as required to fill a message to the Maximum Transmission Unit (MTU). This is controlled by a user definable bundle time-out value which specifies the maximum amount of time that a data chunk is delayed while waiting on other data chunks with which it can be bundled. Figure 117 shows the transmitted data as a function of the number of packets that can be bundled for the standard GTP/UDP backhaul and the proposed SCTP backhaul.

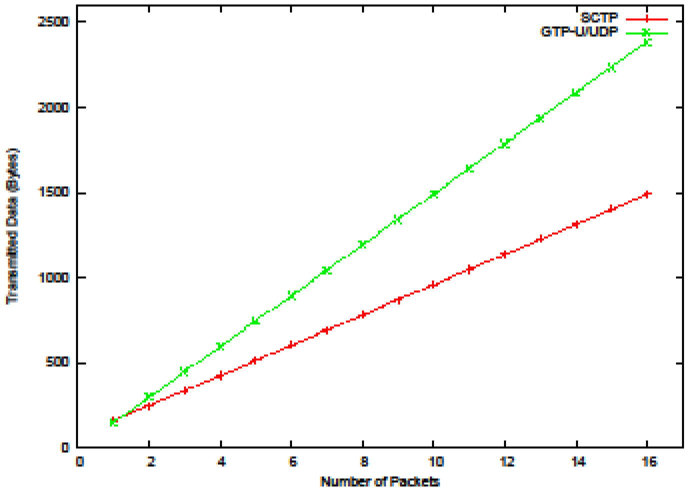


Figure 117: Overheads of GTP/UDP and SCTP-based backhaul as function of the number of bundle-able packets

6.3.2.2 Contribution to BeFEMTO System Concept and Objectives

This work proposes Mobile Femtocells as alternative to Mobile Relays and describes how to make those Mobile Femtocells multi-homing capable, supporting the aggregation of multiple backhaul links into a logical link of higher capacity.

6.3.3 Synthesis

As femtocells gain popularity, an obvious trend is to see them deployed in situations where the users are not stationary, but more importantly, where the entire deployment geography is also mobile, such as on buses, trains or even airplanes. In such a scenario, mobility management of the mobile femtocells becomes an important issue to be resolved from the network architecture point of view. In particular, it is important that latency, signalling overhead and outage are kept to a minimum. To this end, this section on mobility management contains two contributions. The first contribution compares two network architectures against one another from the perspective of handover latency. It was shown that one candidate architecture which does not require re-attachment procedures at the target donor eNB performs handovers up to 1.5 times faster than the other architecture. Furthermore, since the terminals attached to the relay node are under the same mobility management entity as the other terminals, the need for data path switching is removed, thus contributing to the quick handovers. Finally, in connection with this contribution, it must be mentioned that the impact to the overall network architecture and standardization is minimal. The second contribution in this section shows how a femtocell could be turned into a mobile femtocell. IP connectivity to the operator's femtocell gateway is maintained via the traditional cellular access. In fact, by doing so, it is even possible to use mobile accesses of different vendors and to use any combination of radio access technologies, thus rendering this technique very flexible. Local IP access can also be provided with this proposal.

7. BeFEMTO System Concept

As mentioned in Chapter 1, the BeFEMTO system concept can be depicted via four themes which have been the topic of previous chapters. It was also mentioned that the another equivalent viewpoint of system concept is centred around the use-cases (Family 2.0, Femto for Enterprise / Stuck at Airport, Multimedia Train Trip, The Beach) described in D2.1 [139] which is the focus topic of this chapter. It summarizes the key BeFEMTO innovations and their benefits to the corresponding use case essentially summarizing what BeFEMTO has achieved over its life to make the above use-cases a reality. The innovations considered below have been down-selected based on the higher level of compatibility with each other.

As pointed out briefly in Chapter 1 that evaluation of BeFEMTO's progress with respect to each use-case can be judged from the perspective of

- Architecture
- Radio Access Techniques (L1 and L2)
- Higher Layer Protocols (L3 and above)
- Hardware Proof of Concept

This is what we will do in the next sections, i.e. take up each use-case and illustrate the progress beyond the state of the art BeFEMTO has brought about from the perspectives of above mentioned categories. Before we embark on that, we also list those innovations and achievements of BeFEMTO that are not specific to a particular use-case, but that are general tools / methods and enablers that are valid across all the use-cases or themes and facilitate the analysis, so we list them first. After explaining the innovations related to use cases, we also list some forward looking and long-term visionary approaches that are likely be relevant to long term evolution of 3GPP standard, at present, due to innovations they bring about, they cannot be easily integrated into the standard. Finally, the chapter will close by summarising relevant BeFEMTO innovations (excluding the innovations related to Architecture) in a matrix form.

7.1 Methods and Tools

Innovation	BeFEMTO’s Progress Beyond SOTA
Statistical modelling of HetNets	• Showcase the powerful tool of Stochastic Geometry which allows operators to obtain network-wide view of an eventual femtocell deployment, either operator or user controlled. • Applications of SG are set to gain more momentum with the advent of dense small cell networks, with time-domain, frequency-domain and spatial domain ICIC schemes.
Analytical framework for the analysis of traffic offloading	• Propose a generic analytical approach to characterize user activity by modelling them as strictly alternating independent ON/OFF processes. • It can estimate the impact that offloading technique might have on the network resources and provide performance bounds of resource consumption in the network of the MNO when deploying offloading strategies.

7.2 Enablers

Innovation	BeFEMTO's Progress Beyond SOTA
Automatic network coverage estimation	• Design of a novel low complexity and scalable coverage estimation algorithms. • The first is the RACE algorithm which is based on RSRP power estimation and geographic location estimation. • The second is the ABE algorithm which is based on the smoothing of RACE bins and uses some best cell classification method.
Radio context aware learning mechanisms	• A truly wide range of context-aware learning mechanisms has either been adapted to networked femtocell settings, or explicitly designed for the problems at hand. • E.g., investigated was the applicability of evolutionary game (EG) theory, reinforcement learning (RL), among others. • Best solution depends on cost-benefit trade-offs. Better performance is obtained with more overhead.
Distributed fault diagnosis	• Design a distributed framework to help to identify femtocells status in a networked femtocell environment. • Isolate the problems derived from the backbone network from those whose origin are the femtocells themselves
QoS-based Call Admission Control and Resource Allocation Mechanism	• Proposes a mechanism and algorithm for call admission control considering resource limitations in the femtocells' backhaul connectivity and possibly adjusting the resource allocation. • The proposed solution effectively protects ongoing voice calls against congestion on the bottleneck by rejecting new calls and increasing backhaul capacity on demand, maintaining very good call quality (MOS > 4) while without the scheme call quality deteriorates (MOS down to 1.5) quickly.
Voice Call Capacity Analysis of Long Range WiFi as a Femto Backhaul Solution	• Studies the capacity achieved by using long-range WiFi radio links for femtocell backhauling instead of microwave and proposes a mechanism and algorithm to gracefully reduce codec rates in case of backhaul congestion. • Analytical and simulation results show, e.g., that a 54Mb/s link can support up to 40, a 18Mb/s link still up to 32 AMR voice calls. The proposed codec rate adaptation managed to maintain good call quality (MOS > 3) on a congested backhaul, while schemes that are not backhaul-aware showed poor voice quality (MOS down to 1.5).

After describing the innovations related to enablers / methodologies and tools, next, we take up each use case and summarise BeFEMTO innovations with respect to them.

7.3 Family 2.0 (from standalone to indoor fix relay)

In family 2.0 use case, standalone femtocells are deployed in the rooms to provide various services for the family. They are connected to the core network via wired residential backhaul or wireless backhaul via the macro base stations. In the latter case, the femtocells act as indoor fix relays. A number of technical requirements and challenges in this use case have been identified and investigated by BeFEMTO from architecture, L1 and L2 radio access techniques, to L3 higher layer protocols. In addition, the performance of interference management and authentication schemes have been evaluated via three testbeds.

7.3.1 Architecture

The main architectural impact of the innovations in this use case is on the HeNBs, in particular the RF and base band processing as well as the radio resource and interference management and scheduling. To enable some of the advanced solutions for macro⇔femto interference mitigation and soft frequency reuse, an X2 interface between eNBs and HeNBs is needed in addition to the X2 interface between eNBs that existed since Rel-8 and the X2 interface between HeNBs that was added in Rel-11. While there is an agreement in 3GPP on the introduction of this interface, discussions on how to solve issues with SCTP and X2AP scalability / backward-compatibility on the eNB side are still ongoing, and a device that performs SCTP concentration (like the LFGW) is likely needed.

With respect to the BeFEMTO innovations on the higher layers, the proposed approach for loosely-coupled authentication requires changes on the transport network, in particular allowing the HeNB to communicate with the fixed access networks authentication function (in case of a TISPAN architecture the AMF via the ARF). The handover mobility optimizations impact the eNBs, HeNBs and UEs, the data bicasting approach to implement seamless handover additionally impacts the MME and S-GW functionality.

7.3.2 Radio Access Techniques (L1 and L2)

Innovation	BeFEMTO's Progress Beyond SOTA
Definition of LTE-A RF specifications	• Identification and definition of the LTE-A RF technical requirements for femtocells, some of them not yet defined by 3GPP.
LTE-A femtocell RF front-end architecture analysis	• Analyse the different RF front-end architectures for the femtocells in order to select the most appropriate one in terms of cost, size and consumption while LTE-A requirements are fulfilled.
Impact of carrier aggregation on femtocell RF architecture	• Evaluation of the impact of carrier aggregation on the femtocell RF architecture to reach the 100MHz BeFEMTO's target. • Optimization of these architectures (taking into account the study made in the architecture analysis), by minimizing its cost, size and consumption depending on the carrier aggregation type (contiguous or non-contiguous), for the development of next generation LTE-A Femtocells. • For contiguous CA case, minimum size and cost is achieved by using wideband transceivers. In non-contiguous case, the reduction proposed is given by the use of wideband HPA's and LNA's.
RF front-end design for 2.3-2.4GHz scenario (TDD)	• Design of a femtocell RF front-end (taking into account available technology, size, consumption and cost) for 2.3-2.4GHz TDD scenario, proposed by 3GGP as deployment candidate scenario. • Fulfilment of the 100MHz bandwidth and 10dBm maximum output power BeFEMTO targets, being LTE-A compliant.
RF front-end design for B20 + B7 scenario (FDD)	• Design of a femtocell RF front-end (taking into account available technology, size, consumption and cost) for B7 and B20 FDD scenario, which is based on the current LTE deployments. • Fulfilment of the 100MHz bandwidth and 10dBm maximum output

	power BeFEMTO targets, being LTE-A compliant.
Data channel Interference Management	• Evaluating the impact of different static interference avoidance schemes on certain KPIs (key performance indicators). FFR in macro and sniffing based partial subband assignment in femtocells result in an average spectral efficiency equal to 3.7 bits/s/Hz/Cell for the SISO case in standalone femtocell deployments. It has been shown that spatial multiplexing in the same scenario exploits the good radio conditions of femtocells and increases this value to 12.1 bits/s/Hz/Cell with 4x4 antenna configuration
Control channel Interference Management	• Propose the mitigation cross-tier interference on the control channels of a heterogeneous network based on LTE. • It reduces the probability of incorrect decoding of the control channel resulting in less lost subframes and thus improved spectrum efficiency. • Present a novel interference mitigation technique that outperforms the best of the techniques from the preceding study, while at the same time not causing the high capacity degradation. • In comparison to the scheme shown above, the technique described here does not come at the cost of a loss of data capacity.
Opportunistic spectrum reuse	• Propose to opportunistically exploit the fading condition between a femto base station (aggressor) and the counterpart macro UE (victim). • This algorithm effectively provides low-cost resources (in terms of interference) for femto transmission resulting in promising performance for femto UEs (1.8 to 3 times improvement over legacy macro networks) while controlling the undesirable effect on the macro side.

7.3.3 Higher Layer Protocols (L3 and above)

Innovation	BeFEMTO's Progress Beyond SOTA
Secure, loose coupled authentication of femtocell subscriber	• Retrieve the subscriber credentials stored in an UICC card inserted in the Broadband Access Router/Femtocell and trigger the authentication procedure that identifies the Femtocell subscriber towards the xDSL/FTTx backhaul. • Decouple the authentication procedure from the configuration of the physical elements located in the access network enabling a real time configuration and speeding up the delivery of new services to the user.
Fast handover failure recovery	• Propose a UE-based forward handover procedure with predictive context transfer for fast radio link failure recovery during macro-femto mobility. • Reduce the interruption time by up to 3 times faster than 3GPP when the backhaul latency is above 50 ms.
Seamless handover based on reactive data bicasting	• Propose a modification to the standard 3GPP handover procedure by reactively bicasting the downlink data to both the source and the target cell after the handover is initiated. • Significantly reduce the downlink service interruption time from 160 ms (assuming 150 ms as femtocell backhaul latency) to around 20 ms while still avoiding the packet loss with the help of a small drop-head buffer at the S-GW.

7.3.4 Proof of Concept

Innovation	BeFEMTO's Progress Beyond SOTA
Femto / Femto interference management	• Testbed 1: Demonstrate the femtocell downlink scheduling agility in case of CSG interfering femtocell.
Macro / Femto interference management	• Testbed 6: Demonstrate the effect of X2 message passing from macrocell to femtocell.
Multi-radio femto node and authentication of femtocell subscriber	• Testbed 3: Demonstrate new services to be delivered to subscriber through a multi-radio femto node relying on secure loose coupled authentication (Home surveillance, automation, user identification …).

7.4 Femto for Enterprise (Indoor networked, closed access) / Stuck at the Airport (Indoor networked, open access)

In Femto for Enterprise and Stuck at the Airport use case, femtocells forms a local network to provide extended coverage, and high-speed and continuous services to employees/passengers. Specific problems such as inter-femto interference and mobility management have been investigated by BeFEMTO. Most BeFEMTO schemes can be applied to both use cases if they are not limited by the access control mode. We use asterisk (*) to indicate it if a scheme is only related/applied to Femto for Enterprise use case and use dagger (†) to indicate it if a scheme is only related/applied to Stuck at the Airport use case.

7.4.1 Architecture

The radio access techniques designed for this use case have a significant impact on the HeNB node architecture, in particular on the radio resource and interference management, the scheduler and the SON Controller with its SON Enabler functions and the different self-optimizing RRIM sub-functions. As coordination with the macro layer plays an important role in achieving high system performance, there is also an impact on the eNBs in the macro layer. The proposed techniques typically rely on coordination over X2, including an X2 interface between macro- and femtocells. There are also approaches with centralized coordination for SON and RRIM, in which case the LFGW (or alternatively the HeNB GW) can be used to host this centralized coordination function.

Many of the innovations on the higher layers require or are most suitably implemented on the LFGW as new network element inserted into the S1 interface between HeNBs and the EPC. For the case of local breakout, the HeNB should further be connected via S5 to the S-GW in the EPC for macro⇔femto mobility of LIPA sessions or even via the S-rat to the P-GW to additionally provide the option of re-establishing LIPA sessions from the macro-network using a common, uniform mechanism. BeFEMTo innovations also impact the transport network architecture, in particular for the dynamic backpressure routing for the all-wireless networks of femtocells, but also for the local location management. The HeNB architecture is affected by the latter two as well. The HeNB further require software upgrades to implement the X2 traffic forwarding scheme.

7.4.2 Radio Access Techniques (L1 and L2)

Innovation	BeFEMTO's Progress Beyond SOTA
Automatic location determination of femto BS & MS	• Development of distributed techniques which allow femtos and associated users alike to be located which is a requirement both legally as well as technically for various SON algorithms.
Biologically inspired network synchronization	• Derivation of a complete mathematical description by the theory of coupled oscillators, based on fire-flies. • This has been applied to the exchange of synchronization words between femto-cell entities. It exhibits low complexity and good scalability properties and allows for quick convergence, reaching an accuracy of 250ppb after 100 iterations.
Interference management in networked femtocells	• A detailed interference study from/to macrocells as well as between femtocells has been conducted. • Resource partitioning approaches have been put forward, where resources have been separated in frequency (band colouring), time (scheduling) or space (beamforming via codebooks)
Resource allocation for networked femtocells	• Several machine learning and game theoretical works tailored to networked femtocells have been conducted which learn optimal resource allocation strategies in terms of power, transmission slot, etc. • A notable contribution has been the decentralized Q-Learning approach which facilitates autonomous operation even in a dense network of femtos.
Energy management and optimization	• Several contributions to an energy-optimized protocol set have been made. • Join beamforming and duty cycling techniques have been put forward.

7.4.3 Higher Layer Protocols (L3 and above)

Innovation	BeFEMTO's Progress Beyond SOTA
Access control to local network and services *	• Shared access control between mobile network operator and the operator of the networked femtocell that allows a fine-granular control of which visiting UEs can access which local services in a visited network.
Dynamic backpressure routing algorithm for an all-wireless network of femtocells	• Propose a combined distributed plus geographic backpressure routing strategy. • Improve throughput up to close to 100% compared to classical topology-based routing approaches and. experience similar or even lower end-to-end delays and lower packets losses
Local Breakout for Networked Femtocells	• Proposes a centralized traffic breakout on the LFGW supporting femto⇔femto and femto⇔macro breakout session mobility. • Allows 100% of the radio access capacity to be used for accessing local services irrespective of resource limitations of the broadband backhaul connectivity.
Local Mobility Management	• Proposes a local mobility management by the LFGW and enables local UE⇔UE traffic routing. • Reduces mobility management related signalling traffic by hiding all inter-femtocell handovers from the mobile core network. This also reduces handover latencies from around 300ms to 52ms on average at a (low) offered load of ρ=0.1 on the backhaul.

	• Reduces the load on the backhaul and core networks by eliminating all UE⇔UE traffic from them. This also completely avoids the queuing delay and jitter caused by load (variations) on the backhaul link..
Local, distributed location management	• Propose a distributed Local Location Management (LLM) mechanism. • Reduce the broadcast-like location management signalling traffic over the underlying all-wireless network of femtocells.
Dynamic adaptation of tracking areas	• Propose a self-organized Tracking Area List (TAL) mechanism which adapts the size of UE-specific TALs to the mobility state and the paging arrival rate of each terminal. • Generate up to a 39% less location signalling traffic per UE than the conventional mechanism.
Distributed paging mechanism over the X2 interface	• Propose a distributed paging mechanism for large-scale, all-wireless NoFs by sending the paging messages over the X2 interface to neighbouring femtocells. • Achieve up to an 85% reduction in the number of total signalling messages (S1-AP and X2-AP) per paging operation when compared to the standard 3GPP mechanism.
Mobility management for networked femtocells based on X2 traffic forwarding	• Use a local traffic forwarding chain to avoid switching the path at the core network for each inter-femto handover where there is no LFGW available or not possible due to the network size. • Significantly reduce the processing load at the EPC to only around 1/5 of 3GPP at the cost of moderate distributed local traffic load.
Enhanced Power Management in Femtocell Networks	• Exploits local context-knowledge by the LFGW to control the power saving states of femtocells within the femtocell network. • Reduces energy consumption of the femtocell network by maximizing the time femtocells are switched off when unused.

7.4.4 Proof of Concept

Innovation	BeFEMTO's Progress Beyond SOTA
All wireless networked femtocell	• Testbed 2: Demonstrate the feasibility of an all-wireless femtocell network with dynamic backpressure algorithm applied to the femto/femto Wi-Fi links.
Local Femto Gateway (LFGW)	• Testbed 2: Demonstrate the Iuh message dissection available at the LFGW allowing for traffic rerouting, traffic breakout or traffic control.
Macro / Femto interference management and SON server	• Testbed 5: Demonstrate the use of a centralised SON server to act on the femtocell scheduler in order to reduce the interference toward the macrocell network.

7.5 Multimedia Train Trip (Outdoor mobile relay)

In multimedia train trip use case, the femtocells are installed in each rail car over which passengers can conveniently access both the train's local entertainment server as well as their mobile network operator's services. BeFEMTO has identified the unique technical requirements in this use case for the L1 and L2 radio access techniques and L3 and above higher layer protocols. And various innovations have been made to adapt to these unique technical challenges.

7.5.1 Architecture

The introduction of mobile relays impacts the relays themselves as well as the Donor eNBs. As the mobile relay itself needs a mobility anchor, i.e. an S-GW and a P-GW, which is chained with the UE's mobility anchors, there may be upgrades to existing S/P-GWs to optimize the internal user plane routing. The introduction of mobile relays is transparent to UEs, though. Two different architecture alternatives for mobile relays are being discussed within 3GPP and have been studied by BeFEMTO.

BeFEMTO has further studied the alternative of a mobile femtocell, which is enhanced by multi-homing capabilities. This approach would require changes to the mobile femtocells' and HeNB-GWs' network stacks to implement the multi-homing. Other than this, the approach works in an overlay manner, so no further changes to UEs or the mobile network(s) are required.

7.5.2 Radio Access Techniques (L1 and L2)

Innovation	BeFEMTO's Progress Beyond SOTA
Scheduling and resource allocation	• Based on various mobility and channel models, suitable scheduling and resource allocation models have been developed.
Selection of donor eNB	• A non-trivial task has been to design different possibilities of which entity could act as a suitable donor eNB (DeNB). • Two different architectural designs have been put forward and different issues traded.
Understanding mobility procedures	• Another important task when elaborating the selection of the DeNB has been the procedures of mobility, handoff, and involved interfaces .

7.5.3 Higher Layer Protocols (L3 and above)

Innovation	BeFEMTO's Progress Beyond SOTA
Wireless Backhaul for mobile femtocells/mobile relays	• Compare the 3GPP architecture alternatives for fixed relays when they are applied to mobile relays • Conclude that the architecture Alternative 1 (a full L3 relay) has more benefits than other architecture alternatives in terms of latency and complexity.

7.6 The Beach (Outdoor fixed relay)

In The Beach use case, outdoor fixed relay femtocells are deployed by the mobile network operators to augment their network capacity in hot-spot areas. The innovations made by BeFEMTO mainly focus on the architecture and the radio access side.

7.6.1 Architecture

The introduction of the proposed full duplex based fixed femtocell relay would require changes to the radio interfaces and their management and control on the eNBs, the relays as well as the UEs. The second novel approach that uses femtocells for relaying part of a UE's transmissions to the eNB, which recombines this transmission with the other part directly received from the UE, would require changes to

UEs, eNBs, HeNBs and the X2 interface between eNBs and HeNBs.

7.6.2 Radio Access Techniques (L1 and L2)

Innovation	BeFEMTO's Progress Beyond SOTA
Full duplex based transmission for fixed Femtocell Relays	• Development of full duplex transmission schemes for small cells, in which a femtocell base station serves as a fixed relay. • Definition of the rate regions and the outage probability of the schemes considering that the terminal is close to the femtocell. • The proposed solution is based on full duplexing, in which an intermediate helps the destination by cancelling interference coming from a nearby MUE in the uplink. This information is then relayed to the final destination.
Outdoors relay and backhaul architecture	• Development of an outdoor relay architecture presuming a fixed femto acting as a relay. • Application is thought for backhaul which is applicable not only to beach but smart cities, etc.
Self- Optimization of Antenna Tilt	• System-wide eNB tilt optimization to maximize spectral efficiency via breaking-down the problem to local triplets of adjacent sectors • Increase of spectral efficiency from 1b/s/Hz to 2 b/s/Hz

7.7 Forward-looking Innovations and Alternative Approaches

Innovation	BeFEMTO's Progress Beyond SOTA
TDD underlay at UL FDD	• Propose that the macrocell operate in the FDD mode while the femto layer operates in the TDD mode overlapping with one of the FDD bands. • When compared to the uncoordinated deployment, the outage probability is reduced by nearly 80%, while the average spectral efficiency increases by approximately 90% at high loads.
Interference cancellation for femtocells	• Deal with SIC such that the femto and macro layers both use a common resource without undergoing high performance degradation. • By adding this mechanism to the power control and channel assignment schemes, it is shown gains over 200% in sum rate and power savings up to 90% for macro cell users.

7.8 Summary of Innovations

The summary of BeFEMTO innovations as described in previous sections can be summarised in the following table.

Methods & Tools	Statistical Modeling of HetNets	Analytical framework for the analysis of traffic offloading		Family 2.0	Enterprise / Airport	Multimedia Train Trip	The Beach
			Use cases	*Standalone to Fixed Relay*	*Indoor Networked Femtos (Closed / Open)*	*Outdoor Mobile Relay*	*Outdoor Fixed Relay*
			L3 and Above		*Enhanced Power Management*		
			L3 and Above		*Dynamic paging mechanism over X2*		
			L3 and Above		*Dynamic adaptation of tracking areas*		
			L3 and Above		*Local, distributed location management*		
			L3 and Above		*Local Mobility Management*		
			L3 and Above	*Seamless handover based on reactive data bicasting*	*Local Breakout for Networked Femtocells*		
			L3 and Above	*Fast handover failure recovery*	*Dynamic backpressure routing algorithm for an all-wireless network of femtocells*		
			L3 and Above	*Secure, loose coupled authentication of femtocell subscriber*	*Access control to local network and services*	*Wireless Backhaul for mobile femtocells/mobile relays*	
			L1/L2		*Energy management and optimization*		
			L1/L2		*Resource allocation for networked femtocells*		
			L1/L2	*Opportunistic Spectrum reuse*	*Interference management in networked femtocells*	*Mobility procedures*	*Self- Optimization of Anntenna Tilt*
			L1/L2	*Data + Ctrl Channel Interference Management*	*Biologically inspired network synchronization*	*Selection of donor eNB*	*Outdoors relay and backhaul architecture*
			L1/L2	*Carrier Aggregation Architectures*	*Automatic location determination of femto BS & MS*	*Scheduling and resource allocation*	*Full duplex based transmission for fixed Femtocell Relays*
			Enablers	*Automatic network coverage estimation*			
			Enablers	*Radio context aware learning mechanisms*			
			Enablers	*Distributed fault diagnosis*			
			Enablers	*QoS-based Call Admission Control and Resource Allocation Mechanism*			
			Enablers	*Voice Call Capacity Analysis of Long Range WiFi as a Femto Backhaul Solution*			

Table 35: BeFEMTO Innovations

References

[139] BeFEMTO D2.1, "Description of baseline reference systems, use cases, requirements, evaluation and impact on business model", ICT 248523 FP7 BeFEMTO project, December 2010.

8. Conclusions

This final report about the BeFEMTO System Concept and its performance has showcased the most important technical contributions in the work packages 3 through 6. Each contribution has been purposely presented in a condensed format in order to highlight the work that has been done across the BeFEMTO research spectrum. Technical details for each contribution can then be found in the deliverables and reports submitted by the individual work packages.

This document, being the final deliverable, presents the entire collection of work done over the BeFEMTO timeframe. As a result, the document begins by presenting the BeFEMTO System Architecture, from the point of view of mobile femtocells as well as fixed femtocells. This is then followed by presenting results from the system-level simulator calibration campaign undertaken by all partners to ensure that their simulators were well-aligned. These simulators were then used by the individual partners to conduct their technical research.

The technical chapters are divided according to the deployment strategies for femtocells, namely, standalone, networked or mobile. Each chapter is divided into several subsections, with each subsection covering a research topic. Contributions related to each topic have been presented and the subsection is closed with a synthesis to give the reader and understanding of how the various contributions relate to each other, and, more importantly to the BeFEMTO requirements and objectives. Where possible, the achieved system spectral efficiency figures are reported, this being the main figure of merit at least for layer 1 and 2 contributions.

The technical chapters are terminated by a chapter on the BeFEMTO System Concept where the various contributions detailed above are categorized according to their envisaged deployment scenarios (family 2.0, femto for enterprise, multimedia train trip and outdoor beach). This is an important summary of the work done during the lifetime of the project and it shows how the various partners have contributed across the various research areas.