



LEXNET

Low EMF Exposure Future Networks

D5.1 Smart low-EMF architectures: novel technologies overview

Contractual delivery date: M23
Actual delivery date: M24

Document Information

Version	V6.1	Dissemination level	PU
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Abstract	This document focuses on EMF exposure reduction in existing and emerging network deployments, addressing both 3GPP and non-3GPP wireless networks and exposure originated from both user equipment and various base stations and access points. Targeting Exposure Index reduction, as defined by WP2, different network management techniques, topologies and new algorithms are studied. General strategies for population EMF exposure reduction are proposed, with special attention paid to proxy metrics for assessing the exposure, available parameters and policies that help in exposure reduction, and the impact of user mobility, user profiles and preferences. Scenarios are defined for validation through experiments including simulations and measurements in a real network, and preliminary results are shown. Further, specific topics are studied in more detail, such as EMF reduction with small cells, EMF/QoE trade-offs, routing for multi-hop networks, EMF-aware optimization of WiFi settings. Each proposed technique is being evaluated through simulations and measurements, and is to be further developed in the course of LEXNET project in a manner outlined in this deliverable.
Key words	low-EMF networking, Exposure Index reduction, network densification, access network selection, handover, EMF proxy metrics, user context, small cells, EMF and QoE, RBRP, EMF optimization

Project Information

Grant Agreement n°	318273
Dates	1 st November 2012 – 31th October 2015

Document approval

Name	Position in project	Organisation	Date	Visa
Joe Wiart	Coordinator	Orange	3/11/2014	OK

Document history

Version	Date	Modifications	Authors
V1.0	25.07.2014.	Individual chapters	All
V2.0	04.08.2014.	Individual chapters reviewed	All
V2.1	18.08.2014.	Individual chapters corrected	All
V3.0	20.08.2014.	Integral version	TKS

V4.0	12.09.2014.	Integral version reviewed	FLE, UC
V4.1	22.09.2014.	Integral version corrected	All
V5.0	22.09.2014.	Edited version for internal review	TKS
V5.1	7.10.2014	Internal Review	IMINDS
V5.2	29.10.2014.	Internal Review	CEA
V6.0	31.10.2014.	Internal review remarks corrected	All
V6.1	31.10.2014.	Edited final version	TKS

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Executive Summary

This deliverable presents the main results of research on novel network techniques, algorithms and procedures for reducing EMF exposure index (EI), i.e. the cumulative, total (uplink plus downlink) exposure of the population in subject areas induced by wireless user equipment, base stations, access points and backhaul links of various radio access technologies (RATs), existing and emerging ones.

The impact of different topologies is assessed, along with network management techniques that could contribute to EMF exposure reduction. These considerations are incorporated into strategies for reducing EMF exposure, in combined 3GPP and non-3GPP networks. Ways for assessing the exposure using available network and field measurements are studied, and the proxy metrics is introduced. Means for exposure reduction are analysed through the aspects of planning and optimization, from general network management techniques to lower-layer adaptations. Basics of the future EMF-optimizing self-organizing network are given. The impact of user behaviour and the handovers on EMF exposure, and consequently on strategies for its reduction is covered in more detail. Assumptions made are being validated by field and network measurements in a real network, through simulations and experimental measurements. Part of the results is presented in this deliverable, and the methodology for the analysis of measurement results obtained for different technologies and services is proposed, to be further developed.

Following the outline of global strategies, particular topics and techniques are studied in more detail. EMF exposure reduction using small cells is analysed through three topics: access network selection, autonomic networking with the new optimization goal and small cell densification. EMF/QoE trade-offs in cellular networks are studied through the case of a video application, showing that the adjustment of Layer 2 and Layer 3 algorithms and protocols may lead to EMF exposure reduction without compromising the QoE. A new algorithm for routing in multihop networks is proposed and its impact on EMF reduction evaluated. EMF-aware optimization of WiFi settings is studied through the implementation in the wireless network problem optimiser and evaluation in the wireless testbed.

List of Acronyms

Acronym	Meaning
2G	2nd generation
3G	3rd generation
3GPP	3rd Generation Partnership Project
4G	4th generation
ABS	Almost Blank Sub-frame
ACP	Auto Configuration Planning
AFI	Autonomic network engineering for the self-managing Future Internet
ANDSF	Access Network Discovery and Selection Function
AODV	Ad hoc On-Demand Distance Vector
AP	Access Point
ARFCN	Absolute Radio Frequency Channel Number
AS	Active set
AuC	Authentication Centre
BLER	Block Error Rate
BSC	Base Station Controller
BTS	Base Transceiver Station
CAPEX	Capital expenditures
CDMA	Code Division Multiple Access
CDR	Call detail record
CIO	Cell Individual Offset
CMA-ES	Covariance Matrix Adaptation Evolution Strategy
CoMP	Coordinated Multi-Point transmission and reception
CPC	Continuous Packet Conectivity
CPICH	Common Pilot Channel
CRE	Cell Range Extension
CRRM	Common radio resources management
CS	Circuit switched
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CT	Video Content
DAS	Distributed Antenna System
DCH	Dedicated channel
DCS	Digital Cellular Service
DE	Decision making element
DL	Downlink
DRX	Discontinuous Reception
DTX	Discontinuous Transmission
Ec/No	Energy per chip/Noise spectral density
EDGE	Enhanced Data rates for GSM Evolution
EGO	Efficient Global Optimization
EI	Exposure Index
eICIC	enhanced ICIC
EMF	Electro-magnetic field

eNB	eNodeB
eNodeB	Evolved Node B, 4G base station
EPS	Evolved Packet System
FACH	Forward Access Channel
FDD	Frequency Division Duplexing
FFR	Fractional Frequency Reuse
FR	Frame Rate
FTP	File Transfer Protocol
GMLC	Gateway Mobile Location Centre
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HetNet	Heterogeneous Network
HLR	Home Location Register
HO	Handover
HSS	Home Subscriber Server
HSS	Hammersley Sequence Sampling
HTTP	Hypertext Transfer Protocol
ICIC	Inter-Cell Interference Coordination
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IFOM	IP Flow Mobility
IMS	IP Multimedia Subsystem
IMSI	International Mobile Subscriber Identity
IP	Internet Protocol
ISD	Inter-site Distance
ISM	Industrial, scientific and medical radio bands
IUT	Inter-User Transfer
KP	Knowledge plane
KPI	Key Performance Indicators
LBAR	Load Balance Ad-hoc Routing
LHS	Latin Hypercube Sampling
LTE	Long Term Evolution
LTE-A	LTE-Advanced
M2M	Machine to Machine
MAC	Media access control
MANET	Mobile Ad hoc Networks
MAPCON	Multi Access PDN Connectivity
MBR	Mean Burst Length
MeNB	Macro eNodeB
MIMO	Multiple-Input Multiple-Output
MO	Management Object
MOS	Mean Opinion Score
NMS	Network Management System
No	Noise Spectral Density
Node B	3G base station

OFl	Objective Function Improvement
OLPC	Open-Loop Power Control
OMA	Open Mobile Alliance
OPEX	Operational expenditures
OSI	Open Systems Interconnection model
OSS-RC	Operations Support System, Radio and Core
OTT	Over-The-Top
P2P	Peer-to-Peer
PDCP	Packet Data Convergence Protocol
PDN	Packet data network
PESQ	Perceptual Evaluation of Speech Quality
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio-Access Technology
RBRP	Reward Based Routing Protocol
RF	Radio-Frequency
RNC	Radio Network Controller
RRC	Radio Resource Control
RSCP	Received Signal Code Power
RSSI	Received Signal Strength Indicator
RTSP	Real time streaming protocol
Rx	Receiver
SAR	Specific Absorption Rate
SBR	Sender Bit Rate
SC	Small-Cell
SCC AS	Service Centralization and Continuity Application Server
SGSN	Serving GPRS Support Node
SHO	Soft handover
SINR	Signal to Interference and Noise Ratio
SIR	Signal to Interference Ratio
SLP DA	Service Location Protocol Directory Agent
SLP SA	Service Location Protocol Service Agents
SLP UA	Service Location Protocol User Agent
SMS	Short Message Service
SON	Self-organising network
SPR	Subscription Profile Repository
STD-THLD	STandard Deviation THreshoLD
STD-WIDTH	STandard Deviation WIDTH
SUMO	SURrogate MOdeling
SUT	System Under Test
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TS	Time Slot
TSA	Traffic Size Aware
Tx	Transmitter
UE	User Equipment

UL	Uplink
UMTS	Universal Mobile Telecommunications System
URL	Uniform Resource Locators
USRP	Universal Software Radio Platform
UWB	Ultra Wideband
VAF	Voice activity factor
VLR	Visitor Location Register
VNI	Visual Networking Index
VoIP	Voice over Internet Protocol
WARP	Wireless open Access Research Platform
WCDMA	Wideband Code Division Multiple Access
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WP	Work Package

1 INTRODUCTION

Investigating and designing novel network architectures and management techniques which reduce human exposure to electromagnetic field (EMF) without compromising the quality of service (QoS) is the key objective of LEXNET.

This objective will be achieved by contributions from the different WPs, culminating in the development of demonstrators of proposed techniques. In this process, WP5 is a linchpin activity, bringing together expertise in analysis, modelling, simulation and standardisation of wireless communication systems. More specifically, WP5 has a key role in linking the exposure metrics developed in WP2 and measurement techniques to calculate said metrics designed in WP3, as well as the radio-link technologies from WP4, with the WP5-developed EMF-aware network architectures and management principles. Additionally, key WP5 findings will be evaluated in WP6 using the EMF exposure index, bringing to life technologies for its measurement and quantification.

The deliverable D5.1 presents main results of ongoing research activities in WP5, addressing both network topologies and management, being inextricably linked. For a variety of commonly used radio access technologies (RATs), 3GPP and non-3GPP, strategies for reducing EMF exposure are studied and new techniques and algorithms proposed. EMF exposure is seen through the Exposure Index (EI), defined in WP2, as a combined exposure originating from base stations or access points on one hand (DL exposure) and user equipment (UE) on the other (UL exposure), as a daily average dose (measured as specific absorption rate in time) received by population in an area. EI thusly defined is complex to evaluate, suitable for long-term planning, but does not lend itself easily to (near) real-time network management. In order to estimate exposure reduction through directly available quantities (field measurements, network reports) that can be further related to the EI, proxy metrics are proposed. These proxy metrics are considered for averaging on a smaller time scale, for possible near-real-time estimations. The document captures general strategies for reducing EMF exposure and further elaborates specific topics on various levels, from topology and management issues to algorithms pertaining to different layers of the Open System Interconnection (OSI) model. Preliminary evaluation results are also presented.

Chapter 2 provides an overview of strategies for reducing the EMF exposure in combined 3GPP and non-3GPP networks. It outlines main directions of research, resulting in specific scenarios that are studied in more detail in the remainder of the deliverable. Different topologies and network management techniques are analysed, and a special focus is given on access network selection, user mobility and handover, device selection and service continuity. Long-term and short-term EMF-optimization is considered, and proxy metrics proposed, to be further mapped to the EI. The impact of user context, profiles and preferences is also outlined. In the end, main scenarios resulting from the analysis are given, along with results of preliminary measurements.

Chapter 3 extends Chapter 2 considerations by focusing on EMF exposure reduction using small cells. Three topics of interest are analysed: access network selection

algorithm, autonomic networking with the new optimization objective and small cell densification. For the cell selection in heterogeneous networks a new algorithm is proposed and evaluated, with the aim of reducing the user UL exposure while maximizing the number of UEs that meet their DL data rate targets. The implementation of a new objective, reducing EMF, in the autonomic network architecture is studied focusing on two optimization strategies: derivation of dimensioning rules for EMF efficient Small-Cells deployment in HetNets with self-optimization capabilities, and self-optimization of UL metrics trading-off exposure with DL throughput. Both strategies are evaluated through simulations. The impact of small cell densification in LTE-A on EMF exposure reduction, also considering traditional objectives, the user QoS and energy consumption, is studied using a network coverage and analysis tool with user traffic modelling, assessing the UL and DL exposure using proxy metrics. Optimal strategies for moderate user traffic are analysed, as well as the impact of future traffic growth.

Exposure reduction as an optimization goal may conflict with existing network policies and targets, including the user quality of experience (QoE). Chapter 4 deals with EMF/QoE trade-offs in cellular networks. Problem definition is given, along with QoE models and metrics. Further, a scenario of interest is described and analysed, video transmission over LTE, showing that the adaptation of techniques belonging to the link and transport layers may reduce the EMF exposure whilst retaining the required QoE. To this aim, modification of current 3GPP architecture is proposed and further studies to evaluate the impact of these modifications are proposed.

In Chapter 5, a reward-based routing protocol is proposed for EMF reduction in multi-hop networks. Evaluation scenario is provided and the results from two simulation campaigns are presented, exposing the benefits of proposed algorithm. The chapter is concluded with main research directions of the ongoing work.

Chapter 6 deals with non-3GPP-centric network optimization, specifically in WiFi networks. The multi-parameter optimization in wireless networks is addressed, including performance optimization and EMF exposure minimization goals. The optimization problem is analysed using the wireless network problem optimiser, and its performance validated through integration in the wireless testbed, using a wireless conferencing scenario. Further, the impact of a number of configurable parameters on the efficiency of the optimiser is analysed.

Finally, Chapter 7 concludes this deliverable with the summary of achievements made so far, and the directions of the ongoing work.

2 GLOBAL STRATEGIES FOR REDUCING THE EMF EXPOSURE IN CELLULAR NETWORKS

2.1 Overview

In this Chapter we will focus on cellular networks and explore various representative EMF exposure scenarios, identify resources for EMF assessment and techniques for its reduction, and pave the way for future validation of proposed techniques. Preliminary measurement and simulation results will be presented in this Chapter, together with an initial assessment of the impact on cellular communications standards of our proposed approach.

Cellular networks, while not the sole focus of LEXNET, are of key importance for this project, being the main enabler of wideband wireless connectivity, and due to their all-pervasive nature. The importance of EMF reduction for cellular operators (which will help remove encountered impedance to network roll-out [Orange_1, 2014]) underpins the project, and so do the potential business models which operators, manufacturers, and service providers could use, in order to develop new services built around low-EMF networking. These new services could include:

- Providing EMF-optimised network solutions with supporting metrics;
- Optimising operation based on EMF data and diversifying device usage;
- Monitoring network EMF metrics (the Exposure Index -- EI);
- Providing more accurate / trustworthy / all-encompassing information on EMF than what is currently available to general public;
- Providing guidelines (and supporting metrics) to network planners on low-EMF network deployment.

The current networking trend is towards smaller base stations located closer to the users. This reduces uplink (UL) power, but moves access points (APs) closer to the user and increases inter-cell / cross-tier interference. Recent surveys have shown that public underestimate near-field exposure and overestimate far-field exposure [Tesanovic, 2014]. People are more concerned about base stations than about all other RF-EMF sources, and this has ramifications on roll-out times for existing and emerging network deployments, not least in light of the highlighted need for increased densification. Speed of network roll-out could be significantly compromised, as already explained. We are therefore trying to future-proof wireless networks against any concerns, and also minimise any potential (objective) increase in EMF levels.

In many countries, severe constraints have been put on addition of new cell sites. This overlooks some important issues. Personal devices and network transmitters are at present commonly represented as two separate issues when dealing with exposure; this leads to problems since e.g. focusing only on the downlink (DL) can unexpectedly lead to a rise in the UL emissions and therefore potentially increase the exposure. Furthermore, some novel network technologies and architectures may be dismissed even if these innovations can reduce the global exposure. Therefore, there is a need to effectively manage EMF levels and people's concerns, so as not to impact network rollout, or the quality of user experience. The global exposure in this

sense refers to combined UL and DL exposure of a population in an area, as embodied in LEXNET's EI.

In this Chapter we describe different strategies for reducing user EMF exposure originated from cellular networks. In Section 2.2, available means and possible new strategies for reducing EMF exposure of the population in current and emerging cellular networks are summarized. This section will demonstrate that available cellular technologies in an area, current traffic conditions and user context, including services used, are key points to be taken into account. Section 2.3 differentiates between long-term optimization (planning and optimizing the network accordingly based on the EI) and short-term optimization (periodic or based on triggers, probably involving proxy metrics, with time of reaction depending on measurement period for averaging and processing time). The EI is suitable for long-term planning, but does not lend itself easily to (near) real-time network management and the Section 2.3 provides an outline that can help alleviate some of the underlying issues.

Section 2.4 focuses on user mobility, studying the impact of handover procedure on EMF exposure and ways of reducing it. Real-network data on handover is provided in the same section. Section 2.5 looks at specific applications, with special focus on the very important case of video transmission over cellular networks. The use-case in question describes how IP Multimedia Subsystem (IMS) can be used for device selection and service continuity, while maintaining low EMF.

Given the importance of user satisfaction for the operators, Section 2.6 looks at introducing EMF into user profiles and preferences and at the impact of user behaviour on network strategies. And lastly, Section 2.7 describes main scenarios/assumptions pertaining to the work of this Chapter, which are to be validated in future work. Preliminary results from measurements performed in a live network are provided with discussion on EMF assessment methodology for comparison of different technologies and services, necessary for the selection of adequate strategy.

2.2 General network management techniques

Based on state-of-the-art and preliminary measurements, we define assumptions and steps an operator could undertake in order to reduce the average global exposure. In order to quantify the exposure and assess the impact of different strategies, the Exposure Index has been defined [Tesanovic, 2014] [Conil, 2014], capturing both UL and DL exposure, different technologies used, environments, user behaviour, user profiles etc. In this section we try to determine which topologies lower the user exposure and which management techniques, existing and emerging, can be used to reduce exposure for a given topology. This is then supported by preliminary results from a live network, presented in Section 2.7.2, highlighting the impact of Radio Access Technologies (RAT) selection, layer type and service used on EMF exposure. In the present section, an assessment of standards impact of our proposed approach is additionally presented.

2.2.1 RF-EMF exposure metrics: from individual to global exposure

In order to evaluate the exposure of users and the gain of proposed strategies, LEXNET defines an Exposure Index (EI). EI is defined as an average cumulative exposure of the population in an area, over a longer period of time (e.g. 24 hours), taking into account exposure from different technologies and layers, and considering the usage of different types of applications and their durations. EI also captures the effect of the posture of the user and type of device and application used, since these affect the EMF energy absorption. Simply put, EI is the cumulative sum of relevant SAR values, weighted by the usage time (thereby giving us the total dose) across all types of device usage, for all the various RATs and user profiles in an area. The EI merges the exposure incurred by personal devices with that attributable to base stations and access points, thus becoming a new parameter to be reduced as part of network optimization; for more details and a mathematical description please see [Conil, 2014].

EI calculation combines the statistical data from different operators' databases with the Specific Absorption Rate (SAR) obtained from simulation results. The EMF exposure is strongly linked to user behaviour as well. For example, mobility of the user increases the exposure, since the user experiences frequent handovers. Handover increases the EMF severely in 2G technologies, but in 3G or 4G this is less prominent [Wiar, 2012]. User profile, types of services used and their duration also influence the exposure.

2.2.2 High-level strategies for exposure reduction

High-level strategies that can be applied by an operator include technology, topology and user-context considerations. User context, in its broad sense, comprises user profile, service used, its current mobility, type of User Equipment (UE) and user preferences, set in the UE, which the operator has no control of (for instance, GSM-only option etc.). EMF optimization of the network involves data collection, exposure assessment and performing the necessary actions to reduce exposure. Available means for exposure reduction involve topology changes, network management techniques and implementing low-EMF radio components. EMF optimization must take into account coverage and capacity issues, and might, in some cases, have to be balanced against usual network policies on QoS.

2.2.2.1 General and enhanced strategies

The broadest strategy concerns the choice of the access technology to be used. This decision involves considerations not only on EMF properties of different technologies, but also on capacity issues, UE type and velocity, services used and their QoS requirements.

The Access Network Discovery and Selection Function (ANDSF) [3GPP TS 24.312] could be used for identifying the available access technologies in the vicinity of the UE. ANDSF could be modified to incorporate the choice of the best policy access rule, from the EMF reduction point of view, choosing between 3GPP access and non-3GPP access, based on user context (e.g. velocity). ANDSF is preferred because it is standardized in 3GPP. It could provide policies for access selection between different technologies (3GPP and non-3GPP) (e.g. prioritize the access to a WiFi access point vs. 3GPP connectivity for a local area, during a period of time for a type of service). On the other hand, 802.11u or 802.16e, which are instantiations of 802.21, provide

information to a mobility application of the UE only connected with WiFi or WiMAX technologies, respectively.

An intuitive, initial list of priority per type of 3GPP RAT would be 4G, 3G, 2G, reasoning behind it being that the newer technology generates less EMF exposure [Wiar, 2012]. Such order of priorities might be overridden by existing operator policies in some situations (e.g. mobility, inter-RAT handover):

- Do not change the type of RAT during active session (best Quality of Experience, or QoE);
- If change of RAT is needed, then hand over to the last RAT technology used, or to a 2G macro cell, as a fall-back.

This brings us to the question of QoE/EMF trade-off. From the operator's point of view, QoE is the priority, and retaining the service (no call drops) is undisputable. Use cases may be defined where the offered strategy for EMF reduction might be in conflict with regular network policies. Network capacity issues might occasionally conflict EMF reduction policies. One should also have in mind that not all customers have 4G capable devices (currently, 6% of global connections are 4G [GSMA, 2014]), or even 3G capable phones. And also, the UE might decide on its connectivity, i.e. the policy sent by the ANDSF to the UE is not mandatory. Within the 4G network, Self-Organising Network (SON) principles [Sesia, 2011] might additionally be applied with the objective of EI reduction.

Moreover, general strategy could involve offload to smaller cells: femto/micro or non-3GPP networks (WiFi). Offload to femto/micro might be activated for UEs at the macro cell border, e.g. by adjusting handover margins. The order of preference of different types of access might depend on different conditions, including cell traffic load, services used, user velocity, and is to be proven by measurements. If the order is femto, then WiFi (for UEs that are almost static), and 4G, 3G, 2G (if mobile) – the network nowadays has no means to perform such an action, i.e. to give such a command, which may lead to the need for standardizing new network commands. Strategy considerations should include the concepts of IP Flow Mobility (IFOM) [3GPP TS 23.261] and Multi Access PDN Connectivity (MAPCON) [3GPP TS 23.402].

The described general strategy refers to choosing the right configuration/topology. Other, complementary strategies might include more sophisticated methods that involve traffic manipulation:

- Delayed transmission: transmit when channel conditions get better (application synchronization messages, other) – this might reduce QoE in terms of higher latency for some applications
- Traffic adaptation: Select the best protocol (UL streaming, Real time streaming protocol (RTSP) [Schulzrinne, 1998] vs. HTTP streaming [Pantos IETF, 2013]) – network cannot change the protocol used; Compress data (e.g. SPDY [Google, 2013])
- Speech compression: Adaptive Multi-Rate (AMR), Half Rate (HR), Full Rate (FR) vs. Voice over IP (VoIP)

The traffic adaptation should be focused on the UL, as upload generally has more effect on the exposure. This adaptation could be done only by the UE, which should

select e.g. the best protocol (e.g. RTSP vs HTTP streaming). For instance, observations (by operational probes on Gi interfaces) of the whole mobile traffic that crosses Orange mobile core network have produced the following figures for one month of observations (October 2012):

- HTTP streaming: Ratio between uplink/downlink volume=2.81%,
- RTSP (Audio/Video streaming): ratio between uplink/downlink volume= 0.03%.

These observations suggest that HTTP streaming downloading contents requires several times more upload requests than RTSP. These ratios therefore suggest that RTSP should be preferred to reduce uplink exposure, or compress data before it is sent. As this adaptation is linked to the device and service used, it would be difficult to impose this type of adaptation on Over-The-Top (OTT) providers, UE vendors, or users. Speech compression coding schemes in legacy networks (AMR, HR, FR) and VoIP could also be evaluated from the point of view of the impact on EI. If a significant impact is identified, ways for enforcing a specific voice codec by the network side are to be explored.

Each defined strategy should be mapped to a subset of network parameters/techniques to be used for reducing EMF exposure.

2.2.2.2 Slow-loop and fast-loop EMF control

As explained in the introductory section of this chapter, in general EMF optimization of the network could be performed in two ways:

- Long-term optimization would involve data collection in a longer period, assessing the exposure and planning and optimizing the network accordingly. Slow optimization, non-real-time control, should be performed according to statistics gathered on a period-of-a-day, or daily basis (taking into account time of the year etc, network statistics, learning, reasoning on performance measurements).
- Short-term optimization could be periodic, or based on triggers, and would involve real time decision, based on real-time measurements from the network, with time of reaction depending on real time measurement and period for averaging and processing time (e.g. user profiles, context, cell load measurements).

Proxy metrics to be used for fast-loop (short-term) control involve data that may be collected from the network and include:

- Measurements (e.g. UL Transmissions power (Tx), Received Signal Strength Indication (RSSI), received signal code power (RSCP))
- User context: velocity, services used, user profile.
- Statistics: cell statistics (traffic load) etc.

This will be further elaborated in Section 2.3.

2.2.2.3 User segmentation

Different strategies might be applied depending on user segmentation and offered access technologies. User segmentation in general may be done based on user profiles (subscription), past behaviour (statistics on voice calls, packet data sessions,

amount of transferred data), current context (velocity, services used) and user preferences (set in the UE).

The UE connectivity manager, which also holds the mobility manager, would select one of the policies set by network optimisation management, according to the behaviour of the UE with local and real time information. 4G access with SON mechanisms could also self-optimize the network with a new objective to “reduce EMF exposure”, but should also take into account legacy objectives (e.g. energy saving, cost reduction, maximizing coverage and capacity). The impact of user context on strategies is elaborated in more detail in Section 2.6.

2.2.2.4 Network measurements and policies available for EMF exposure assessment and reduction

For network operation and management, there are different measurements available that can be used to assess EMF exposure. Some of these measurements are taken on regular basis, while for other measurements special reports need to be triggered. Some of the measurements are done by network elements, while others are performed by probes, sensors, robots (e.g. UE apps, drive test), thus the measurements may be gathered from them. The quantities that may be used to assess EMF exposure include UL Tx power (per UE, per cell), RSSI, RSCP, Base Station / AP transmissions power etc. Besides network measurements and cell statistics (traffic etc), the autonomic network (or the operator) will use all available data concerning user context in an area. For autonomy, new information exchange needs to be standardized.

Multiple functionalities are to be addressed in the design of network mechanisms to reduce EMF. Different functionalities can monitor and set different parameters. These include mobility load balancing (handover margin, cell individual offset), off-loading, admission control (RAT/Frequency Selection Priority (RFSP)), inter-system load balancing (vertical handover trigger parameters), cell outage compensation, coverage capacity optimization, uplink CoMP, multiple transmission concept (HSPA+, 3GPP TR 25.872), advanced schedulers etc. The Auto Configuration Planning (ACP) tools could be used to identify the best configuration that should reduce exposure in a dedicated area. According to different times of the day, load, strategies or priorities, different policies could be applied in the network, via the Network Management Systems (NMSs), down to the managed network equipment.

2.2.2.5 SON principles

Depending on the mapping between different strategies and sets of network parameters and techniques, an autonomic (self-organizing) network could perform self optimal network management concerning network performance, QoS, and EMF exposure of its customers. By introducing CEM (Customer Experience Management), even the QoE could be introduced to this concept.

The very principle of autonomic is to self-manage the network and reduce the network management complexity. Autonomic network should be governed with high level objectives to steer control loops. Control-loops are used to dynamically adapt network resources and parameters or services upon events reported by managed elements. As the different objectives might become conflicted (e.g. load balancing,

energy saving), the control loop conflicts arising between different network policies should be foreseen. Introducing EMF exposure minimisation objectives as an integral part would require entities (or split functionalities) responsible for EMF reduction and resolving conflicts with existing policies, which take into account other objectives (cost reduction, energy saving, security and resilience ...).

In the current network management, the network is sized according to the market forecast. The new built network is then defined according to the network coverage and capacity that should be deployed. In this construction phase configuration planning tools are used. In the running phase the network will be optimised to reduce the cost of increasing the network capacity and increasing QoS. The location of the different antennas will be then static. The only way to optimise the radio access network after it is deployed is to define the best configuration of the different network elements (some configuration will need manual intervention (e.g. mechanical tilt management) or with automated tool which changes the parameters of managed entities without any manual or human intervention). There are different types of radio access technologies (2G, 3G, 4G, WiFi ...), different types of base stations (femto, micro, macro) that should be managed. A more global radio resources optimization should be performed, taking into account the available 3GPP and non-3GPP resources (e.g. WiFi, WiMAX, CDMA 2000 - in Lexnet we should take into account only WiFi, as WiFi networks are widely available in European households). This management should identify the distribution of the traffic between all these accesses. Other optimisations will be then applied per 3GPP technologies (2G, 3G, 4G) between the different types of base stations (femto, micro, macro). These optimisations will take into account the market (capacity, coverage, planning information), the customer care (QoS), etc. The defined optimisation will be then used to manage user connections/flows in real time. Different types of user connection management will be used in this optimised network. Connection management policy will be selected depending on user contexts retrieved in real time. The user context describes the user, network and services behaviour.

One solution depicted in Figure 1 consists of orchestrating the different control loops (management tools). The highest hierarchical control loop should provide the objectives for the next control loop. The slow control loop will identify the behaviour of fast control loops and the interactions (coordination, orchestration, between fast control loops) in order to avoid conflicted solutions. The green fast control loop reacts in real time and the red slow control loop reacts with planning information within a long period. Planning information is retrieved thanks to the knowledge plane (KP), which analyses, reasons, learns on monitoring information with cognitive modules. As cognitive module might not provide the entire information, administrator could also provide some input such as planned intervention (e.g. football game event, deployment of new networks (e.g. 4G), constraints (e.g. Cost, reconfiguration costs...)). With such a solution we could avoid conflicted situations between control loops. However our orchestration should follow the generic autonomic network architecture defined in Autonomic network engineering for the self-managing Future Internet (AFI) [ETSI GS AFI, 2013], which defines the hierarchical control loops.

Each control loop could resolve optimisation objectives problems. An orchestration of the list of objectives in the optimisation problem should also be defined by the provider (e.g. prioritise the cost reduction, then EMF reduction). It is easier for an

operator to identify priorities of objectives than the weight of each objective, because it is not easy to weight e.g. EMF and QoE objectives as they can't be linked. Each input and output of control loops could also identify some constraints (e.g. rate of 2G only capable phones, 3G/2G phones and 4G phones, as well the rate of non-3GPP, 3GPP phones which could apply provider policies, UL/DL data rate ...).

The highest red slow control loop should identify, according to the different provider objectives, the behaviour that should be applied in the fast green control loop. The result of the slow control loop could provide the distribution of resources between 3GPP and non-3GPP networks. As well the slow control loop (shown in red in the diagram) should provide how to orchestrate different conflicting algorithms (e.g. sections 3.1 and 3.2 (by disabling one of those solutions or identifying how they could work together)). The result of the slow control loop should provide the value of the deviation of the EI and its evolution. As the EI is defined by averaging over an area, self optimization per-cluster of users would not be possible using EI as a measure, but other related parameters i.e. measurements that can be collected from the network on "per-user" or "per-cluster" basis. As well, as the EI is defined by averaging in a long period of time, close-to-real-time actions will not be possible based on EI, but again, based on measurements that can be obtained from the network, per-user in real-time.

The Figure 1 below describes the autonomic network architecture which could be used to self-reduce the EI. The highest control loop could be the ACP with a decision making element (DE) and reference point with the knowledge plane and the other control loops (e.g. solution described in sections 3.1, 3.2). This ACP tool should identify the usage of the different networks, 3GPP and non 3GPP, with planning information and according to the common objective of reducing the EMF level. One result of the ACP could be the location of each AP (e.g. solution described in Section 6), and the distribution of traffic between the different RATs (e.g. solution described in Section 3). The ACP will provide input for the "common radio resources management" (CRRM) loops used to self-manage the 3GPP network. As other optimisations could be done in each RAT as well, input from the ACP and CRRM could be used to self-optimize the network like the 4G HetNet.

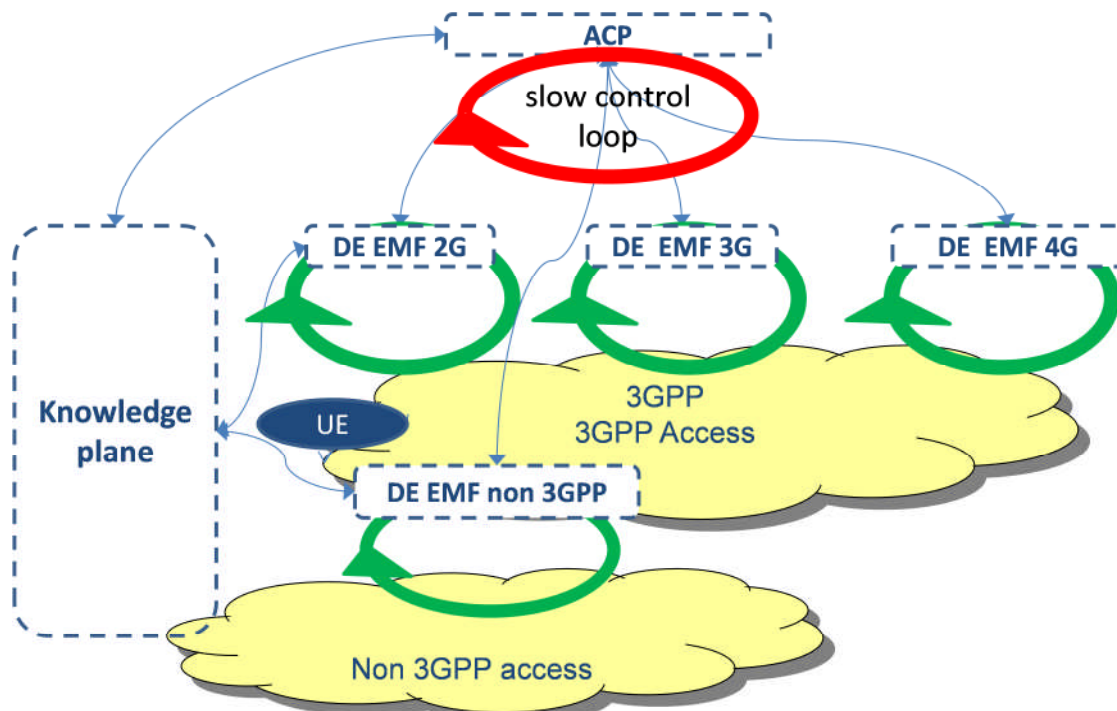


Figure 1: Autonomic network

The KP will retrieve knowledge from monitoring, inventory and fault management information. The knowledge plane will share knowledge that should be used to self-manage the network. The KP will also be used to retrieve the information needed to calculate the EI and identify its deviation using the proxy metric presented in Section 2.3. Then a network decision entity like an ACP should identify the best optimised topology solution according to different provider objectives (cost reduction, QoE improvement, EI reduction, energy saving...), different types of constraints, and define the network objectives that could be applied in the network. The self-optimised network should minimise EI for the planned upload and download traffic in different types of areas, for different times of day, different types of population, different types of location, different types of networks and different types of usages. For instance, the self-optimised Hetnet (Section 3.2) algorithm will retrieve from the knowledge plane the uplink load of the macro cell to decide the best configuration of the parameter Cell information offset of the small cell. If both of these algorithms (self-optimised network and self-optimised HetNet) are applied in the network then the distribution of the traffic between 3GPP and non-3GPP network will decrease the load of the macro cell. The performance of the self-optimised Hetnet is proportional to the load of the macro cell. This performance should be reduced because the self-optimised network should reduce the load of the macro cell. However if both of these algorithms (self-optimised network and self-optimised HetNet) are applied together then the global performance of the EI reduction should increase.

2.2.3 Possible impact on standards

Many of the (cellular) technologies LEXNET is developing, some of which were highlighted in Section 2.2.2, would most likely fall within the remit of 3GPP SA2. We provide here a list of standards and corresponding technologies this work could be captured in:

- 3GPP TS 23.401: This is the Stage 2 service description for the Evolved Packet System (EPS). Aspects where our work may have an impact include Inter-RAT handover, the UE-specific “RAT/Frequency Selection Priority” (RFSP Index), mobility, and so on.
- 3GPP TS 23.261: This document specifies the Stage 2 system description for IP flow mobility between 3GPP and a WLAN. The solutions therein allow the operator to indicate how the IP flows are routed through the available access systems and to selectively offload some traffic. EMF could be brought into this, meaning we may need to standardise new network commands.
- 3GPP TS 23.402: This is the Stage 2 service description for providing IP connectivity, using non-3GPP accesses to the EPS. The criteria specified therein, pertaining to the selection of a WLAN, could be modified to e.g. include awareness of EMF exposure. Additionally, the UE behaviour based on the ANDSF information could be modified.
- 3GPP TS 24.312: Management Object (MO) could be redefined to take into account the specific WiFi technology (a/b/g/n/ac/...), the type of 3GPP antenna (macro, femto, ...)

Our work may, in addition, impact some Open Mobile Alliance (OMA) specifications (which are network-agnostic), most notably the OMA Device Management protocol. Another standardization outlet for various connectivity manager features residing in gateways (e.g. Femtocell, WiFi AP) is the Broadband Forum’s TR-069 [TR-069, 2004]. This is where various EMF/QoS trade-offs (user preferences) could be introduced / implemented.

2.3 Proxy metrics and EI

Proxy metric will be used to retrieve all the information that will be needed from the network to calculate the EI, all the information which will be used to decide on the strategies which will be applied in the networks, and other information which will be used to decide in real time on the configuration of managed entities to minimise the EI.

The cumulative sum of exposure of all individual users in a given area is difficult to calculate in practice due to unavailability of EMF levels at every single user and the processing complexity. The EI is therefore defined by LEXNET, as the weighted sum of SAR values for different “classes”, “categories”, or “types”, of users; the weights are determined by the distribution of users across different classes, and the (average) time of exposure to EMF within each of the class (this determines the dose). The classes will be characterized by the following information:

- Reference SAR values;
- Average transmit power values on the UL; per technologies; per velocity, per network load
- Average observed DL power density; per technologies; per velocity, per network load
- Duration of exposure.
- Inventory of the network (e.g. Location of base station/type of technology/transmit power/) type of area (urban/rural/sub urban)

- Service utilization (UL/DL per type of traffic (elastic vs. non elastic)/ per time/ per area, per device, per age, per user type, per device type, ...)
- Population profile: e.g. genre, age, working day, user subscription profile

General strategy could be classified as slow-loop EMF control, as we apply it and then eventually check the outcomes on a larger-scale time basis. This strategy would take into account long-term network statistics, distributions of user profiles and habits (services used etc), times of day, period of year etc. The impact may be assessed on hourly, period-of-day, or daily basis (we could also take into account the time of year etc), and the strategy would affect network planning.

Fast-loop (event-based) EMF control would be a response to a temporary change of conditions. This kind of control requires triggers, i.e. thresholds that can be assessed on near-real-time scale – this time scale would not be as granular as for power control, but rather in minutes, hours, etc. For fast-loop control, offload techniques may be used as for general strategy, but also other strategies as changing codecs, delayed transmission etc. Fast-loop control without using triggers would be periodic optimization on a smaller time-scale.

Proxy metrics to be used for fast-loop control involve data that may be collected from the network and include:

- Measurements (UL Tx power, RSSI, RSCP...);
- User context: velocity, services used, profile;
- Statistics: cell statistics (traffic load) etc.

The proxy metrics for fast-loop EMF control need to be linked to the long-term exposure, as embodied by the EI. If we try to reduce EMF by applying correct general policies, and additionally control it on a smaller time-scale (minutes) with fast-loop control, then the overall exposure and the EI (defined on daily level) will decrease.

2.4 User mobility and handover

Basic principles of handover in different cellular technologies are given in the Appendix 1. The following subsections focus on EMF aspects of handover due to mobility.

2.4.1 Intra-RAT and inter-RAT handover

In order to maintain service continuity during mobility in multi-layer network (see Figure 2), UE must continuously monitor neighboring cells. Typically, network efforts are directed towards providing service continuity on a preferred RAT, so while a UE has service with its preferred access network, it will be requested to perform intra-RAT handover. Intra-RAT handover may be within the same carrier frequency (intra-frequency) or with the change of carrier frequency (inter-frequency). Inter-RAT handover is performed in cases when the serving technology has limited coverage (usually a technology on higher frequency band, implemented on existing sites, designed for technology on lower frequency band).

Handover procedures and messaging flow depend on current serving RAT and RATs being monitored, but we can identify common principles, which are basically the

same regardless of the RAT involved. In the connected state, the UE performs periodic measurements of serving cell and neighboring cells, and reports measured values: periodically (in GSM, and in some cases also in LTE and UMTS) or event-based (in UMTS and LTE). Reporting criterion for event-based reporting are sent to the UE through *Measurement Control* message. The *Measurement Report* message sent from UE is first step in the handover procedure. Based on this report, the handover decision is done by the network (Base Station Controller (BSC), Radio Network Controller (RNC) or Evolved Node B (eNodeB)). After the network has checked and prepared new resources for call continuation on a different base station, the UE receives a *Handover Command* message. The UE performs synchronization on the physical layer (if needed), accesses the target cell and sends a *Handover Complete* message. Handover process introduces additional signaling on the air interface. Having in mind that high-speed users can pass through the coverage area of cell within matter of a second, increase in signaling could have a possible impact on EMF.

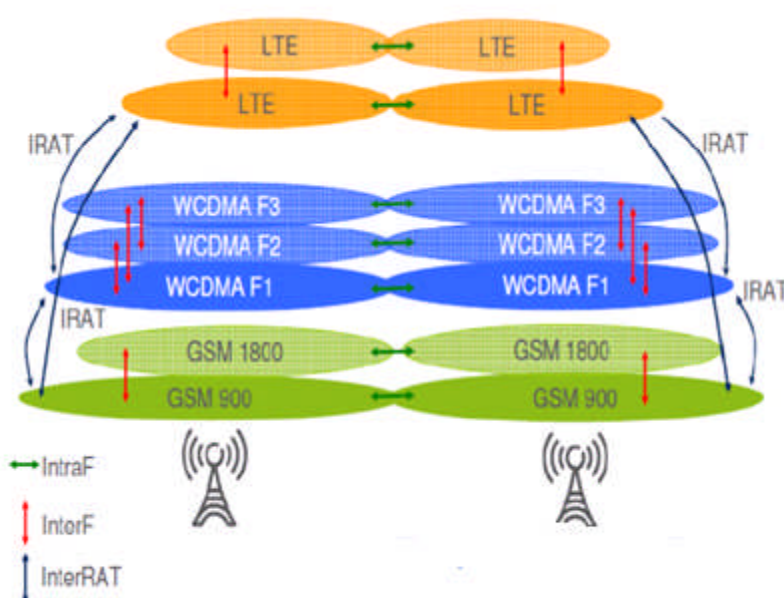


Figure 2: Example of a cellular network, with indicated directions of intra-frequency (IntraF), inter-frequency (InterF) and inter-technology (InterRAT) handovers

Handover decision is based on the DL received signal strength (or quality) from the serving base station and neighboring base stations. Signal is averaged over time, using an averaging window to remove influence of fading. When the DL signal strength (or quality) of a serving cell, as measured by the UE, drops below a certain threshold, and/or DL signal quality of a neighboring cell, relative to the serving cell, exceeds a defined hysteresis, after a predefined period of time, handover is triggered. In a UMTS system, intra-frequency and inter-RAT handover can be triggered when the UE uplink power reaches the threshold value. Different values of thresholds, of hysteresis and of time to trigger are used for optimization of handover process and handover performance (for example, to prevent the ping-pong effect, etc.), with possible usage in the future in EMF optimization processes.

In most existing networks, the handover is triggered based on a drop in DL channel quality. Focusing on the power control commands related to the UL, [Yavuz, 2012] suggests: essentially, the handover is performed based on comparing various parameters related to the UL transmit power against some threshold values. Addition of this kind of approach to handover decision algorithms could give more possibilities for EMF exposure reduction.

2.4.2 EMF exposure considerations

Handovers in GSM technology are expected to have a significant influence on EMF exposure, because of transient UE power levels, which reach their maximum during a handover event. In the LTE technology, handovers are expected to have rather less influence, because transient transmitting power is estimated based on DL. Soft/softer handovers in UMTS are expected to be EMF friendly, but, influence of inter-frequency and inter-RAT handovers should be considered.

On the next graph (Figure 3), UL power measurements of a fast-moving UE are presented. The UE was connected to the GSM network with 900MHz and 1800MHz layers, with collocated base stations. 1800MHz layer is designed as a capacity layer and preferred for users in good radio conditions, i.e. cell centre (1800MHz cells have a smaller cell range compared to collocated 900MHz cells). Handover events are marked with numbers.

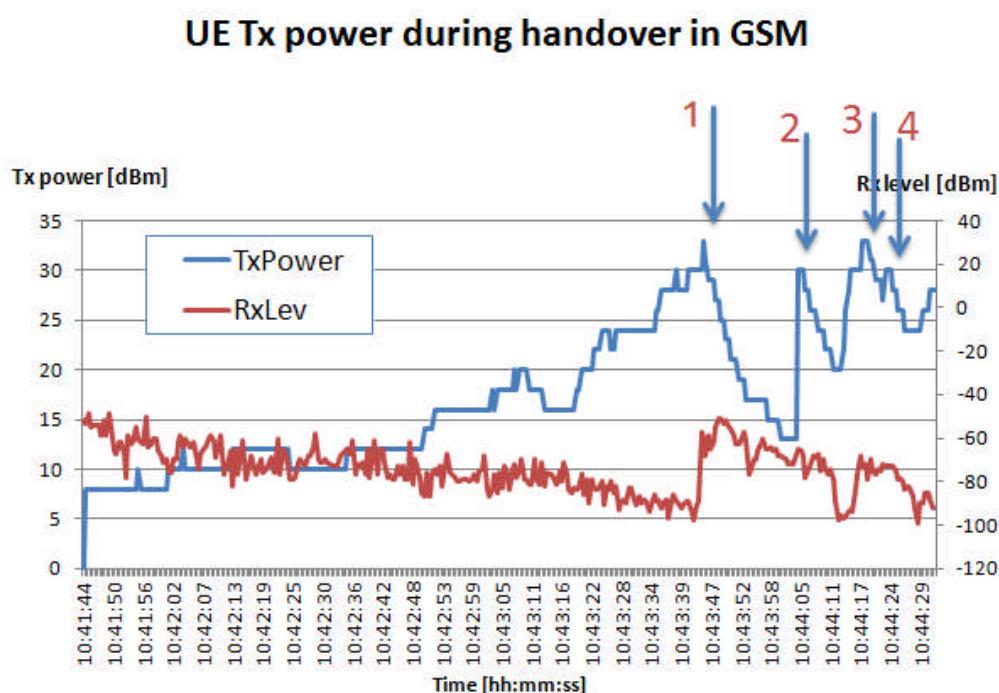


Figure 3: UE TX Power during handover in GSM

We can see the power level jump to maximum values during handover (maximum UE uplink power in GSM900 and GSM1800 are 33dBm and 30dBm, respectively).

In the first part of graph, the UE was connected to 1800MHz, speeding up from 60 to 120km/h and moving towards the cell edge. Reaching the cell edge at point 1 on the graph, it performed a handover to 900MHz cell. At this point, the handover had to be done, due to coverage reasons, and the UL power level had already reached its

maximum value (before the handover). From point 1, the UE was connected to the 900MHz cell, moving towards the cell center and, at a defined DL signal level threshold, it was handed to the 1800MHz cell, due to multi-layer traffic management strategy (point 2). This handover introduced a high “unnecessary” peak in the UE’s transmitted power, from the EMF perspective. From point 2, during 18 seconds (still with 120km/h speed), the UE repeated exactly the same behavior, with handover due to coverage in point 3 and handover due to multi-layer traffic management at point 4.

We can see that the correlation between the UE transmitted power and the DL received power is lost during handovers.

On the next graph (Figure 4), uplink power measurements of another UE located in the same vehicle as the previous one are presented. This UE was connected to the UMTS2100 network with two frequency channels. Load-based traffic management between the channels was implemented only for UEs in idle state, not for UEs in connected state. No obvious change in power level can be seen during the soft handover (SHO). SHO addition marks the addition of a new cell into the Active set (AS), meaning that the terminal enters the soft handover state and is connected to two (or more) cells. SHO removal marks the deletion of the cell from the AS, i.e. the exit from soft handover state. The UE transmitted power level is highly correlated with the DL received signal level.

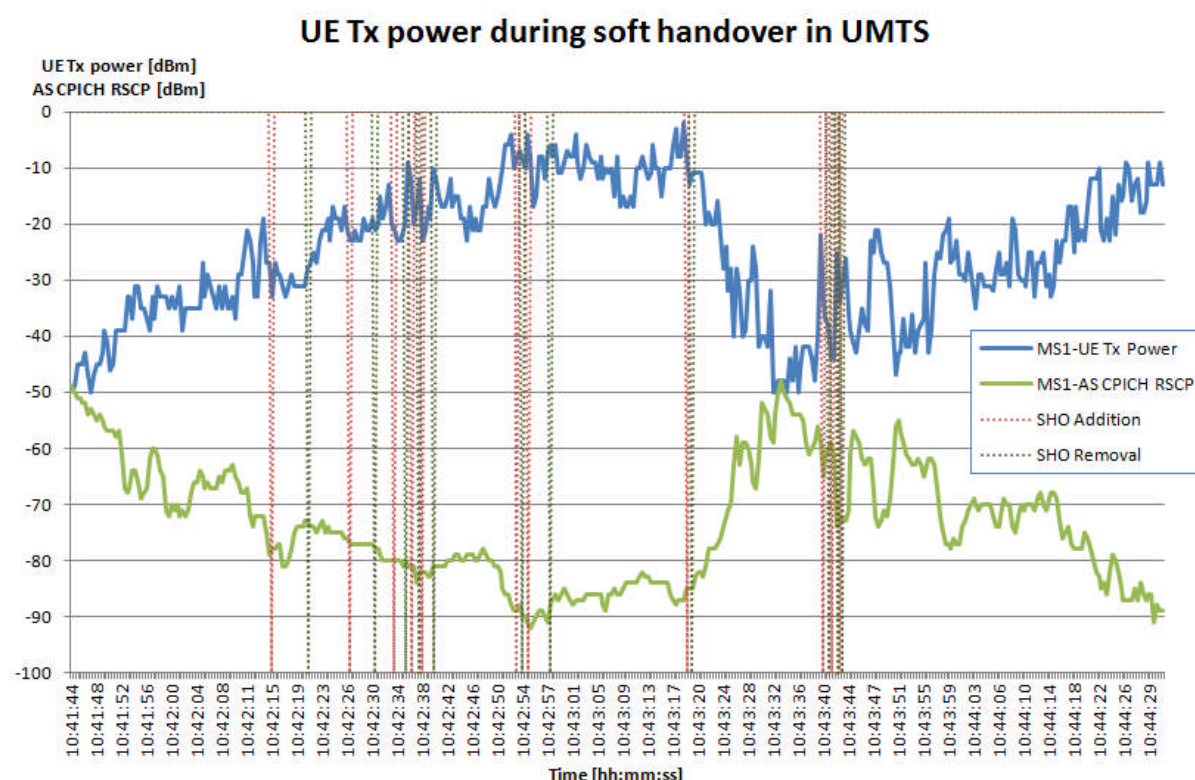


Figure 4: UE TX Power during soft handover in UMTS

On the next graph (Figure 5), UL power measurements of the UE in compress mode are presented. The reason for entering into the compress mode was the bad quality (poor E_c/N_0) of the serving UMTS channel. The first compress mode ended without

any handover, because the quality of the serving UMTS carrier rose above the defined threshold, the second one ending with handover to GSM. Even in the compress mode, no increase in the UL Tx power can be seen.

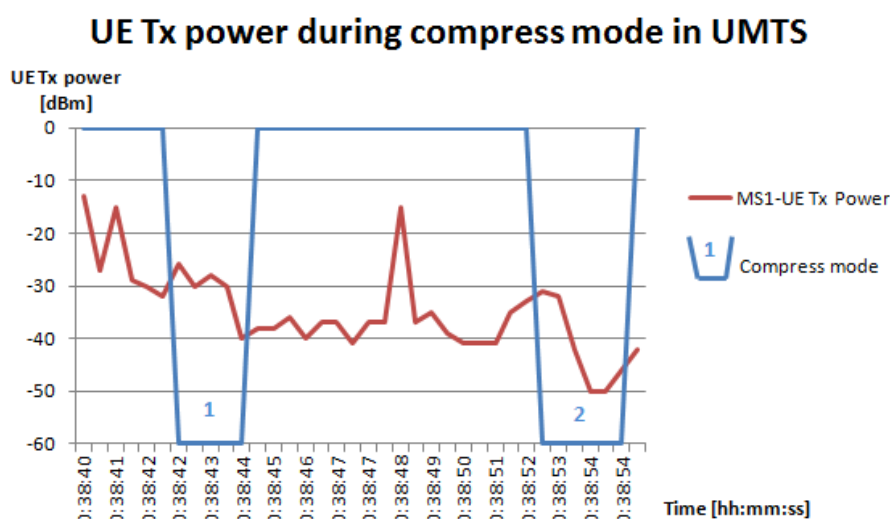


Figure 5: UE Tx Power during compress mode in UMTS

2.4.3 Strategies for EMF exposure reduction

The access selection procedure can be seen as the first step of handover events (mobility management procedures); the three following discovery mechanisms outstand amongst others:

- 3GPP cellular mobility management;
- heterogeneous mobility management, using a 3GPP solution between 3GPP and non 3GPP accesses;
- interworking solution with external networks, to be used for non 3GPP access (for instance, the solution fostered by IEEE 802.11u).

The information gathered by means of this discovery procedure is used by a mobility manager at the UE to select the best access point, among the available ones.

The second step comprises the selection of a radio access. This is based on the information gathered in the aforementioned discovery procedures, together with the user preferences and the provider policies. Although the integration of EMF levels might not be complicated to achieve, it is not currently considered, and most of the decisions are based on the user context and on the network load.

The third phase establishes the appropriate radio access configuration. This brings another possibility to reduce the EMF, since the corresponding transient levels might be also considered. For instance, in 2G technologies the transient levels reach their maximum values during a handover event (access configuration), while in 3G networks, where the UE can be simultaneously connected to various Nodes B, and the transmitting power is negotiated before the link setup, they are less relevant.

Besides, the management of those transient power levels in 4G, which is able to handle mobility faster, and in 2G, is similar.

One additional parameter which needs to be considered (also a means to reduce the EMF exposure) is the end-user speed. Traditionally, mobile users foster the connections to broader accesses (macro-cells), while the use of smaller cells is usually preferred by static nodes, or promoted so as to increase the QoE. Again, the integration of EMF in this particular aspect and the corresponding configuration parameters (handover margins and/or cell individual offset), might also bring clear benefits.

Finally, both the state of the user equipment (idle or active) and the particular requirements of the currently running services shall be considered in combination with the EMF level. The use of multi-RAT devices, which enables services to be handled by different technologies, poses new challenges, since the EMF levels of the various radio accesses in use shall be considered.

After the UE has made a decision, the admission control procedures of the network elements must decide whether the connection is allowed. This particular phase does not directly impact the EMF, but it is worth highlighting that in case the connection is not allowed, the UE should try another alternative, which would certainly increase the EMF exposure.

Another feature used quite extensively on mobile devices is location tracking. It can also be achieved through various methods, such as GPS, cellular network positioning, or WiFi location services, and also by some emerging technologies, like Ultra Wideband (UWB) [Porcino, 2003]; this capability might be used so as to reduce the EMF exposure during access selection and mobility processes.

Besides preliminary measurements, presented as an illustration, the impact of frequent handovers on EMF exposure will be studied through several scenarios with measurements in a real network, and the results will be presented in D5.2.

2.5 Reducing the EMF with device selection

In this section, the study focuses on the selection of the device with the lowest SAR when a user owns several devices. The study supposes that it is possible to rank devices according to their induced SAR values. An IP Multimedia Subsystem architecture, that is described thereafter, can help a user to use his device with the lowest SAR

The 3GPP work item called "IP Multimedia Subsystem Service Continuity - Inter Device Transfer enhancements" specifies an IP Multimedia Subsystem (IMS) architecture implementing device selection protocols. This architecture, called IMS Service Continuity [3GPP TS 23.237], relies on a server, called Service Centralization and Continuity Application Server (SCC AS), located in the IMS home network of a user. It enables adding, deleting and transferring one or more media of an IMS session through the implementation of Session Initiation Protocol (RFC 5631, 2009) that manages the IMS sessions between a user and a remote participant. The transfer of an IMS session can be done from an access network towards another

access network (inter-access network transfer) or from a device towards another device (inter-User Equipment transfer) without breaking the session continuity. An inter-access network transfer is managed by the SCC AS upon detection by a User Equipment (UE) of conditions requiring a transfer of one or more media from an access network, called the transferred-out access network, towards a new access network, called the transferred-in access network (Figure 6). For transferring a medium, the UE requests the SCC AS to establish a new signalling path over the transferred-in access network, called Target access leg, between itself and the SCC AS. If the request is accepted, the SCC AS creates a Target access leg and updates the Remote access leg, i.e. the signalling path between the remote device and the SCC AS. If no medium has to be sent over the transferred-out access network, the old signalling path, called Source access leg, is released; otherwise it is updated according to the media which have to be sent over the transferred-out access network.

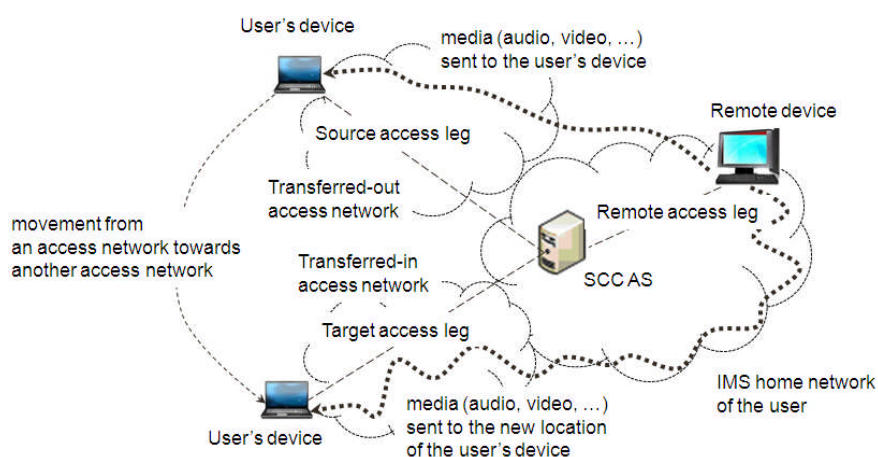


Figure 6: IMS inter-access network transfer architecture

An inter-User Equipment transfer, also managed by the SCC AS, is session continuity when transferring one or several media from a UE, called the controller UE, towards a set of target User Equipment, called the contolee UEs. The contolee UEs may belong to different IMS subscription profiles, i.e. they could belong to different users, unless the controller UE devolves the control of the Inter-User Transfer (IUT) procedures to another device, in which case the chosen device and the controller UE must share the same IMS subscription profile. The encoding parameters of a medium could be renegotiated between a contolee device and a remote device if the hardware characteristics of the contolee device are different from those of the controller device or if it is connected to an access network whose characteristics are different from the characteristics of the controller device access network. An example of an inter-UE transfer is shown in Figure 7: UE1 communicates with a remote device (UE2); then it requests the SCC AS to transfer the voice medium towards UE3, and the video medium towards UE4.

The controller UE may initiate the IUT procedures according to policies defined by the operator managing the networks and according to the information it gathers from

a location protocol like SLP (Service Location Protocol). OMA Device Management (OMA DM, 2006) is implemented between the controller UE and the SCC AS to supply the operator policies.

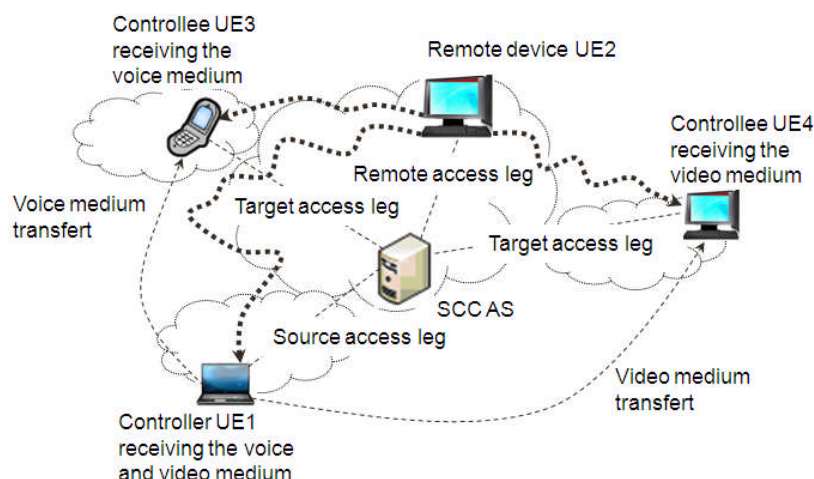


Figure 7: Media transfer among telecommunications devices

When a user transfers a medium from his mobile device towards one or several devices, he needs to be aware of his devices, their capabilities and their locations. Despite the myriad of the devices connected to the Internet, a global infrastructure gathering useful information for being aware of these devices is not currently standardized. Several solutions are analysed in (BETTSTETTER, 2000) and the IETF focuses on Service Location Protocol (RFC 2608, 1999). Briefly, when a device needs to find other devices, its Service Location Protocol User Agent (SLP UA) sends a Service Request message towards a SLP Directory Agent (SLP DA) listening on the UDP/TCP port 437. When it receives a Service Reply message containing a list of Uniform Resource Locators (URLs) matching the query, it sends an Attribute Request message towards the SLP DA for each URL to get the attributes of each device. An attribute is made up of information characterizing a device, such as its supported audio/video codecs or its radio interfaces characteristics, as well as its location, and is carried on an Attribute Reply message. The role of the SLP DA is to register the URLs of SLP Service Agents (SLP SA) and to respond to queries sent by SLP UAs (see Figure 8).

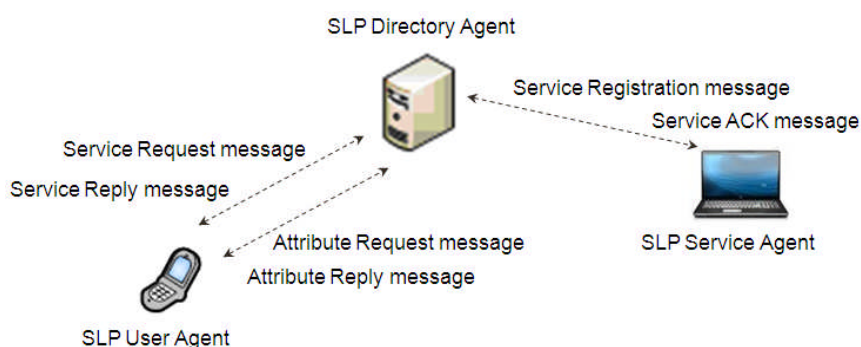


Figure 8: Overview of Service Location Protocol

2.6 User profiles and preferences – impact on strategies

The EMF exposure of a person during the day depends on many varying conditions and sources. For a network user, the exposure consists of his/her own UL and DL exposure originating from the network(s) he/she is connected to, downlink exposure from other networks and uplink exposure from surrounding persons (Figure 9).

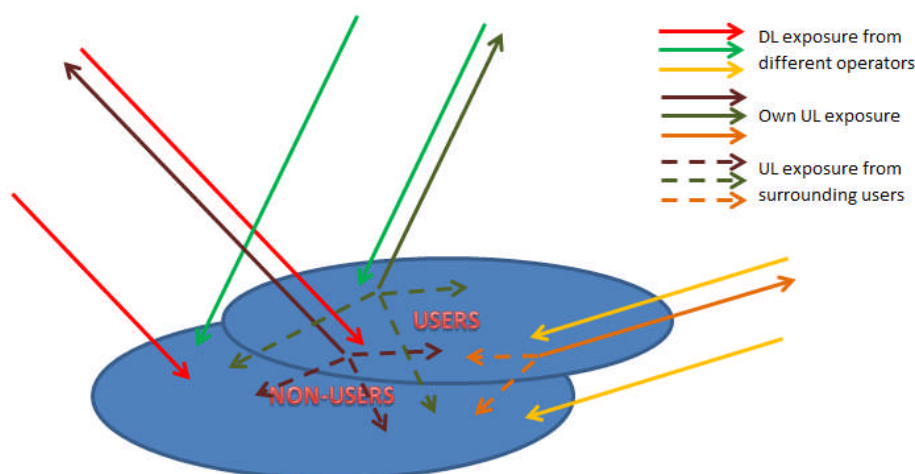


Figure 9: Different components of human exposure in an area

Considering different operator's strategies and network management mechanisms for reducing the exposure, the component an operator may influence is the exposure of its own connected users. Here, besides the network topology and enforced network policies, the important factor is user behavior – his/her profile, habits, current requests (applications used), occasion, preferences, device used, mobility, i.e. the overall user context. Considering that for the majority of users the UL component of the exposure is dominant, user behavior including services used and his/her mobility play, in fact, the key role. The user himself may contribute to exposure reduction by changing some habits, and to this aim, some indications from the network may be given, e.g. in form of pop-up messages, in situations when exposure might rise (e.g. frequent handovers etc.).

Different strategies for EMF exposure reduction might be applied depending on user segmentation and offered access technologies. Further, although the aim of the LEXNET project is reducing exposure without compromising the QoE, some users might be willing to sacrifice QoE to some extent in order to have lower exposure. Such requests may be fulfilled through setting the user preferences in the user equipment (UE), or through setting the preferences in the user profile stored in the network.

Strategies considered in the LEXNET project deal with reducing the exposure for the whole population in an area. Thus, it should be emphasized that the reduction is not subscription-based, and that user subscription as a part of his/her user profile is considered only to evaluate user behavior.

In the following subsections, main concepts that may concern user segmentation are given. As well, ways for retrieving this information from the network are explored, and the applicability is discussed.

2.6.1 User profile

User profiles are used to maintain subscription information such as service option subscribed (TV, P2P, VoIP...), QoS subscription, account status. In GSM and UMTS, user profiles are stored in the Home Location Register (HLR), along with the information on user's current location, in terms of the current Visitor Location Register (VLR) and Serving GPRS Support Node (SGSN). In the Evolved Packet Core, the Home Subscriber Server (HSS) combines the functions of a HLR and Authentication Centre (AuC). With the consolidation of subscriber data, user profiles are stored in the Service Profile Repository (SPR) and could be retrieved by the different authentication servers (e.g. HLR, HSS, ANDSF front end).

The user profile in a broader sense could be retrieved from the network as a part of the proxy metrics, to be used in the decision-making process. It would include the habits of a user, i.e. the statistics on user behaviour concerning number of calls, data sessions, their duration, transferred traffic volume. Network operators normally have customer analytics databases (non-real time analysis), and this data, along with network measurements and cell statistics on traffic load, could be used for decision making in EMF optimization.

2.6.2 User preference

User preferences are not managed nor controlled by the provider. The user can set them in the UE at any time. In smartphones, a connection manager is generally used to equip the UE with user connectivity preferences. It holds connectivity preferences, data scheduler, data download limits, threshold triggers to disable connectivity, gateway connection managers to switch off WiFi etc.

Examples of connectivity managers include:

- Home gateway connectivity manager: WiFi preference used to switch off AP [Orange_2, 2014]
- Dongle connectivity manager: connectivity preference, threshold triggers to disable connectivity [Orange_3, 2014]
- Mobile user connectivity manager: connectivity preference, scheduler, data consumptions [Google_1, 2014] [Google_2, 2014]

User preferences might override network policies concerning connectivity in some cases and might degrade the QoE. The example is the GSM-only option, which is in many cases not only the worst in terms of data traffic QoE, but also the worst from the EMF exposure point of view. Some user preferences concerning EMF exposure that might be applied in the future might include not having data connections during frequent handovers (e.g. in trains), switching off during the night (e.g. phone as alarm clock, near the head), avoiding multiple simultaneous connectivity paths with different types of access, scheduled connectivity for some types of services, per time of day or per radio conditions.

All these preferences are set manually by a user, according to his/her habits and previously obtained knowledge on situations when EMF exposure might rise. The network is not aware of user preferences, and might only deduce from measurements and statistics that, for instance, some users do not connect during the

night. Possibilities for network control include network instructions to the connectivity manager in the UE, where standardization is needed (OMA-DM, TR-069 – see Section 2.2.3).

2.6.3 User context

User context is related to the current state of the UE concerning mobility (static/moving), services used, etc. and in the most general sense includes the user profile and preferences. The user context also depends on occasion, time of day, time of year etc. It also includes the device used and its capabilities, which also has a significant impact on strategies. Not all phones are 4G, or even 3G-capable. According to [GSMA, 2014], 3% of global connections in 2014 were 4G, and this number will rise by 2020 to 25%; while 2G connections excluding M2M will decrease by 2020 to a third of the total connection base. The user device capabilities affect most strongly the offered strategies – concerning inter-RAT switching (including capacity issues), available preferences for the user and deployable network commands to the UE (e.g. policies sent by the ANDSF may not be applied for some types of UEs).

Different types of rules should be applied according to the velocity of the UE, as EMF exposure changes depending on whether the UE is in motion or static. The velocity vector may be obtained from the Gateway Mobile Location Centre (GMLC) [3GPP TS 29.172], or from the UE which could analyse the difference between different RATs measurements reports or the number of handovers during a period, or with a sensor such as a GPS. If the UE is in static state (with a vector estimated to 0), the strategy would suggest choosing policy for static UE which means priority for femto access, WLAN access, and other types of 3GPP access (4G, 3G, 2G); when the UE is in dynamic state, 3GPP access macro cell 4G/3G/2G would be chosen. Besides capacity issues, this strategy should take into account situations when the customer moves and stops often within an area, not to induce much switching between 3GPP and non-3GPP access, i.e. increased signaling, ping pong effect. Some offsets should be identified in order to stabilize the context of the UE, regarding the change of velocity and change of radio conditions in static state due to fast fading.

Services used also affect the EMF exposure of the user. Voice service, using different codecs, and different data services involve usage of different power levels, depending also on technology, and thus induce different exposure. This means that different strategies could be used to identify the best connectivity according to the service flow requested. Services which provide a huge amount of upstream activity and which are elastic enough to handle disruption connectivity between 3GPP and non-3GPP access (with no service disruption) could be offloaded to non-3GPP access. Otherwise the flow requested by the user cannot be connected to non-3GPP access. For instance, many users watch video on their mobile phones at home during the night between 20h and 23h. Video is one of the most consuming services in downstream and upstream due to the high service demands. As video is an elastic flow (thanks to the HTTP streaming protocol), video services could be offloaded to WiFi access during the night without any disruption. The ANDSF could therefore provide policies per type of application and prioritize to a type of access for a type of application. Further, strategies involving traffic adaptation or resource scheduling

could be deployed for services that do not require instantaneous connectivity, such as some M2M applications.

2.6.4 Applicability

User segmentation could be performed according to supposed QoE/EMF reduction priorities (business/private or similar), if any, and user context (type of service, velocity vector), occasion (mass-events). Proxy metrics to be used involves data that may be collected from the network and includes:

- Measurements (e.g. UL Transmit power (Tx), RSSI, RSCP)
- User context: velocity, services used, user profile.
- Statistics: cell statistics (traffic load) etc.

Some of these quantities are retrievable in real-time, or near-real-time, while some are not. Currently, in the live network (GSM, UMTS), data on user profiles may be retrieved from the HLR, data on specific users in a cell (user characteristics, voice call duration, data volume, number of sessions etc.) may be retrieved from the customer analytics database based on call records for the cell (International Mobile Subscriber Identities (IMSI) that made an active call in the observed period are retrieved from Call Detail Records (CDRs) and looked-up in the database with user data and call statistics; there is no feature to get all IMSIs attached to a cell, but some companies offer such a solution). Services used might be retrieved from probes on network interfaces, per IMSI, or at least some statistics (in time) for an area could be derived. Velocity of a user could be estimated based on UE measurement reports. Counters and key performance indicators (KPIs) concerning traffic load are retrievable e.g. on 15-minutes basis for Ericsson equipment and the same is with triggered network measurements (reports).

All network measurements may be done on the cell or the user basis, thus the target of EMF reduction in an area implies analysis of all data related to the cells covering the area. This is the basis for future SON mechanism, where the NMS would analyse all available data to decide on proper strategy, taking into account the legacy objectives as well (e.g. energy saving, cost reduction, maximize coverage and capacity).

User segmentation affects many proposed strategies – from access network selection, over offloading, to traffic adaptation. Based on available networks, their capacity and load, and for a given set of users in the area with different requirements and UE capabilities, the right “layout” of users per technology layers may be chosen, or offloading applied by changing, for instance, handover margins. Further, based on the service used, some traffic adaptation/resource scheduling (delayed transmission, forcing voice codecs, etc.) may be applied. Besides EMF optimization, EMF network planning should take into account long-term statistics on users in an area, like: profiles, traffic requirements, and most used services.

Network strategies/policies to be applied for reducing EMF exposure imply no QoS reduction, while user preferences might lead to eventual QoE reduction. It is important to identify possible user preferences and possible situations with EMF/QoE trade-offs, when user preferences might override network policies. This could impact the overall EMF profile in an area (e.g. target user layout per technologies). No connectivity as requested by user means more capacity, but also less income for the

operator. GSM-only option is least favorable from the EMF exposure point of view, but many users practice it. It implies lower QoS and also less income for the operator, so this is the situation where EMF reduction objective and QoE are in line, but opposed to user desire. The possibilities for network control, or network awareness of user preferences set in the UE are also being explored.

The possibilities of some pop-up messages that would warn the user in some situations that the EMF exposure is high (which would require the introduction of some new network signaling) is also considered. Yet, it is hard to define EMF levels for some red/orange/green warnings, and even harder to monitor every user on individual basis. Rather, right network planning and EMF optimization should be applied.

2.7 Main scenarios/assumptions to be validated

For the scenarios, we may have two distinct fields, namely: simulation scenarios and measurements made in live networks. Most LEXNET partners are focusing on simulations to access and study the strategies for reducing the EMF exposure in cellular networks, but operators are using directly the live networks' measurements results to do these studies as well.

2.7.1 Overarching simulation Scenarios

LEXNET's current effort on scenarios was presented in D2.3 [Vermeeren, 2014], where the main high-level scenarios were defined. The idea was to present five exposure scenarios representing typical exposure in an environment with one or more wireless communication networks. This project-wide work on scenarios is continuing with an ad-hoc working group on scenarios. Also, reference values for most of the systems parameters were considered.

These scenarios vary from indoor, to outdoor, considering just one or multiple cellular systems. An example is the "Outdoor scenario: macro cells", which is composed by multiple systems' macro cells and some WiFi hotspots, Table 1.

Table 1: Outdoor scenario with macro cells (extracted from [Vermeeren, 2014])

Parameter	Value
Time periods	Day, Night
Population	Adult, children
Load profile	Variable
Environment	Outdoor
RATs/Cell Types	
• Type	2G, 3G, 4G, WiFi
• Cell size	Variable

• Cell type	Macro
User	
• Usage	Voice, data
• Equipment	Smartphone, tablet, laptop
• Posture	Standing, sitting

The description of the scenarios is quite generic, so that each partner can implement it in the different simulation tools being used. It is worth noting that it may not be possible to consider all parameters needed to calculate the EI in a given simulator tool (e.g., the posture of the user), but the effect of these parameters may be added afterwards considering the results coming from the ongoing work around the exposure index.

An implementation example of the Outdoor scenario in a simulator tool, [Riverbed, 2014], is presented in Figure 10. In this example, 3 macro cells (2G, 3G and 4G) are placed in a center of a square, with 7 users in each of the systems. Also in the square are 7 WiFi Access Points (APs) with 2 users each. In the simulation tool, uplink and downlink powers are being considered, in order to estimate exposure. Effect on exposure of parameters such as movement, traffic usage and number of users are being considered. In this case, the objective is to have some kind of cost function to compare exposure between different systems when different situations are considered.

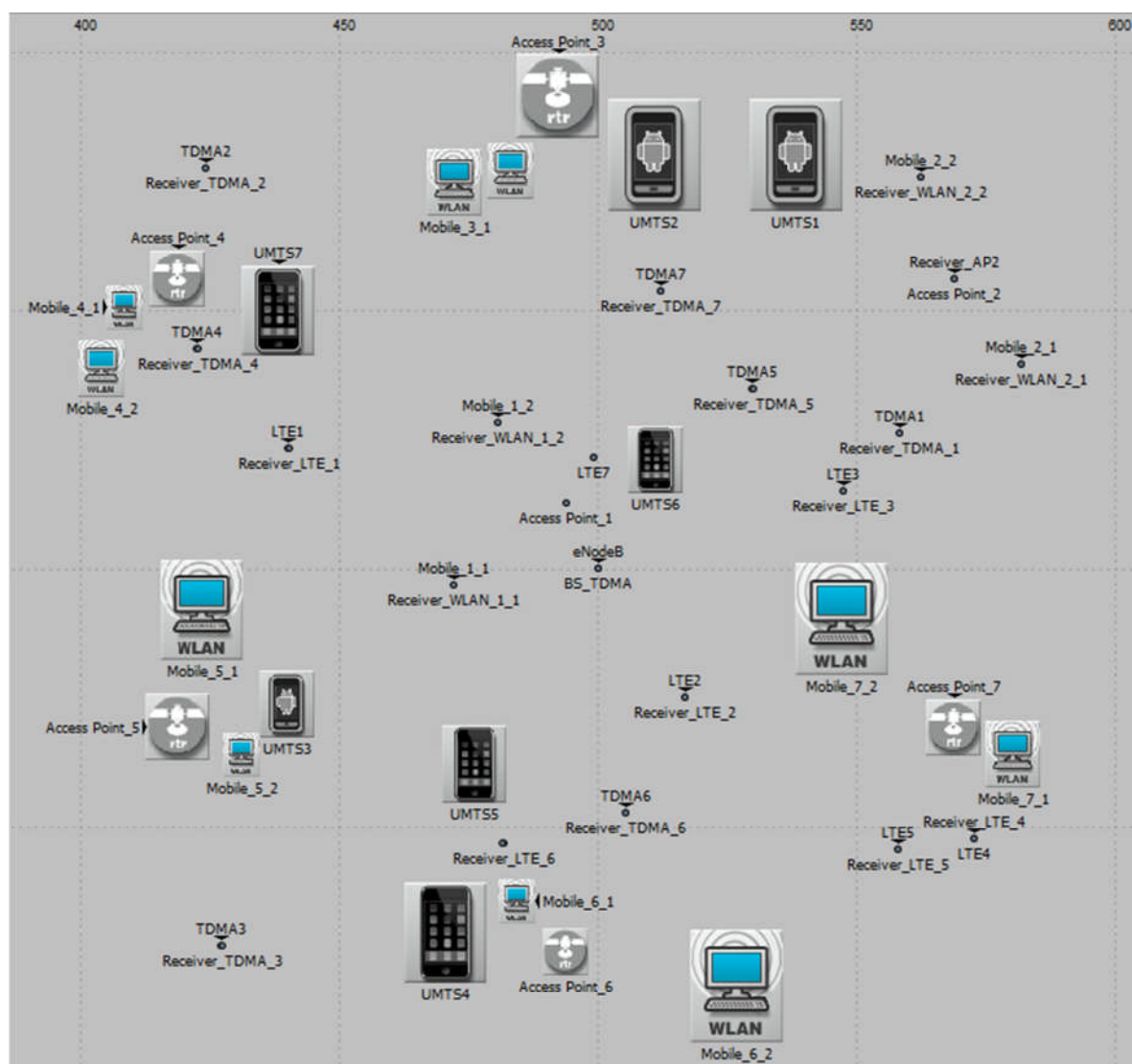


Figure 10: Implementation example of Outdoor scenario in a simulator tool

Another example is the multi-layer (macro and small-cells) scenario illustrated in Section 3.3, which is built from a real geographical map data, realistic base station deployments and deterministic propagation predictions. A macro-cell network layer composed of 19 sites and 19×3 sectors located on dominant rooftops are completed with outdoor small-cells (several densities may be selected) distributed in the streets. Path-loss maps are computed from a propagation ray-based model for all street locations but also indoors at different floor heights.

This scenario may be used in different evaluation contexts:

- DL/UL radio-planning-like simulations, to compare the performance of several network design strategies;
- Building of DL/UL QoS and EMF statistics to feed network management algorithms ;
- Prediction of a realistic propagation dataset to feed network management simulators.

2.7.2 Preliminary results from measurements in a live network

In this section, some preliminary results are presented concerning the verification of the assumptions made within different proposed strategies. Since the exposure depends on many factors including technology, radio and traffic conditions, application used etc., a comprehensive measurement campaign has been performed and is ongoing in Telekom Srbija live network.

First, cell statistics were gathered in a 7-day period and analysed, for different types of areas (urban/suburban/rural), using different technologies (GSM900, DCS1800, UMTS2100), and different types of cells (macro/micro). This served to evaluate traffic characteristics for different types of areas, technologies and cells, to determine high and low traffic load hours, observe possible differences in voice and data traffic day trends, determine the possible correlation between overall base station transmitted power and the amount of transferred data, etc. All these results will be presented in detail in deliverable D3.3, on Exposure Index assessment. Preliminary drive test measurements were performed to explore the possible correlation between UE Tx and Rx powers.

Furthermore, for several cells of interest 7-day network measurements (triggered network reports) were collected and analysed, per cell and per day, in high and low traffic hours. We observed urban macro GSM and UMTS cells overlaid over urban macro indoor with distributed antenna system (DAS) and reduced power, again GSM and UMTS. The distribution of UE Tx power in a cell was taken as the proxy metrics. Due to different measurement methodologies and characteristics of the radio interfaces in GSM and UMTS, some modifications were applied in order to compare these technologies.

In GSM, the UE measurement reports are sent to the network on regular basis, thus triggering reports just means logging them. For per-cell measurements, a representative sample of UEs is chosen by the network and due to huge amount of data, only part of measurements for a conversation is recorded (using Ericsson Operations Support System, Radio and Core (OSS-RC) version 12.3.1, Cell Traffic Recording module). The chosen option is recording 30 s in the beginning of a conversation. This implies that we have samples showing higher average values than in reality, as call establishment is always sampled, and that we need to make adjustments to the full length of a conversation (taking more low-power samples) in order to have right average (in time) power values. Such a correction is not needed in case of per-user measurements, as the whole conversation is recorded. Further, averaging in time needs to consider the occupancy of time slots (TS) in GSM, being a Time Division Multiple Access (TDMA) system: one out of eight TS in a GSM frame is used for voice traffic in the uplink, while for General packet radio service (GPRS) and Enhanced data rates for GSM evolution (EDGE) traffic multiple slots may be used. Thus, a correction of -9 dB needs to be applied for 1/8 time occupancy. In the end, additional adjustment should be made taking into account the so-called duty factor, or activity factor, on the GSM radio interface – samples are taken only when the transmitter is actually transmitting, while we should also consider the non-emitting periods in between i.e. Discontinuous Transmission (DTX) [3GPP TS 05.08] [3GPP TS 48.060]. In GSM, there are no measurement reports for data traffic, thus for the

evaluation of exposure resulting from data transmissions, drive-test measurements need to be performed.

In UMTS, reports are event-based (near handover etc.), so triggering reports means that UEs (16 simultaneous UEs in the per-cell measurement period) will perform measurements and send something they do not usually send. This also implies that power levels will be somewhat higher than in reality, when no forced reports are sent. UMTS signal is continuous so no time-adjustments need to be made. The methodology for obtaining network measurements and analyzing them, in order to compare different technologies and services (voice/data), will be further explored and explained in deliverable D5.2.

For comparing voice and data traffic in GSM and UMTS, drive-test measurements were performed, in good radio conditions, in high-load hours, with the same, static UE. Except for GSM data service, network measurements were performed as well, on per-user basis (using OSS-RC User Traffic Recording module), and a good correlation between drive-test results and values from network reports was found. UE Tx power distribution per user was analysed for different services (voice, voice 800 Hz, FTP UL, FTP DL, Youtube, internet browsing, sms; Skype), per technology (GSM900/1800/UMTS).

It is important to have in mind that the offered strategies need to consider many factors, including current traffic load, radio conditions, mobility, application used, available networks, UE capability, and that no one-for-all solution can be made, especially when considering both 3GPP and non-3GPP networks. For instance, looking at technologies and topology, under certain conditions and for some applications one solution may be better, while the change of conditions would require different strategies. In this document, only a compilation of main results is shown, while the full verification requires more measurements and more detailed analyses.

2.7.2.1 The correlation between UE Tx and Rx power

The relation between UE Tx and Rx powers is dependent on many factors. Roughly, users are spread across the cell, having different Rx levels, and are using different services, thus having different Tx powers for the same level of received power. The time of reaction of power control to the occurrences of fast fading also influences the relation. The Figure 11 shows this relation obtained from network measurements (UE measurement reports) for a GSM cell. UE Tx power is in steps, and for a very broad range of received powers we get the same transmit power samples.

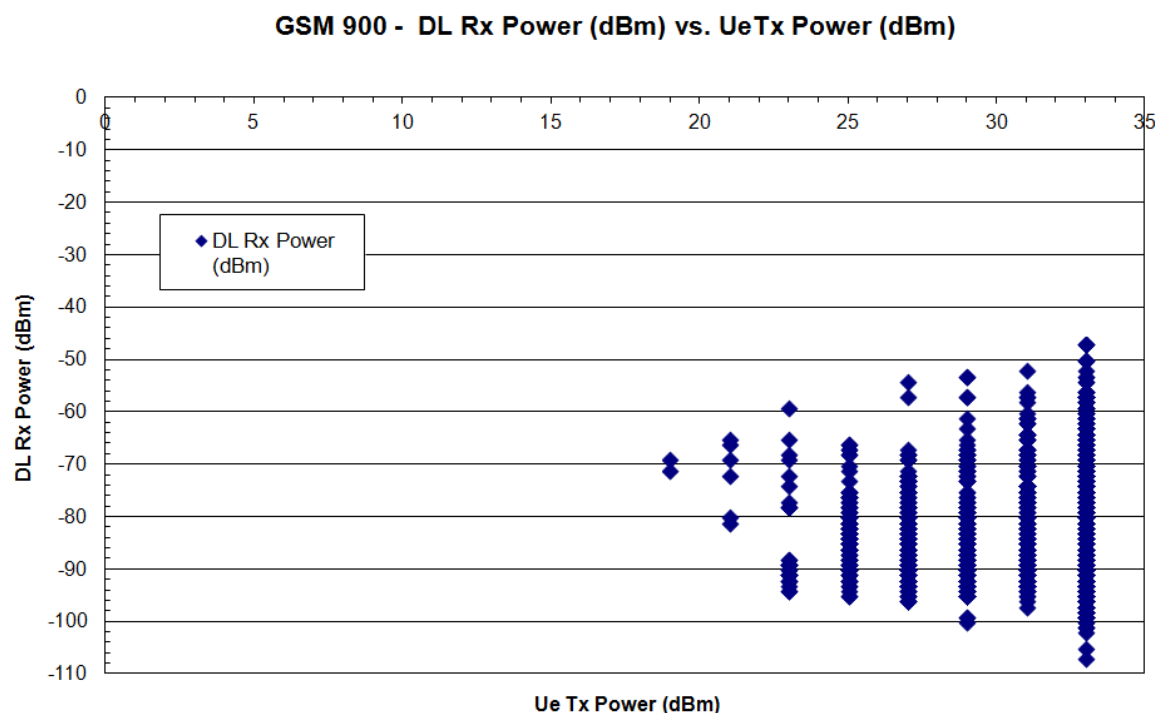


Figure 11: The correlation between UE Tx and Rx power for GSM900, obtained from Cell Traffic Measurements collected on network side for 1 urban cell during 15 minutes interval

This figure shows that in general there is no clear correlation between Tx power and Rx power levels for the total Circuit Switched (CS) traffic on one cell. The reasons include the facts that SMS's are sent with maximal Tx power, as well as voice samples immediately after handovers. Voice drive test measurements are better suited to explore if any linear dependency might be drawn and under which conditions [Sarrebourse, 2014].

The following Figure 12 shows the relation between UE Tx and Rx powers obtained from drive test measurement with long voice calls in a suburban area. Samples were collected on different cells along the route. There were a number of inter-cell handovers resulting in high UE Tx powers even in good DL radio conditions. Generally, it can be seen that DL radio conditions were good. Rx powers were roughly in a range from -40 dBm to -80 dBm.

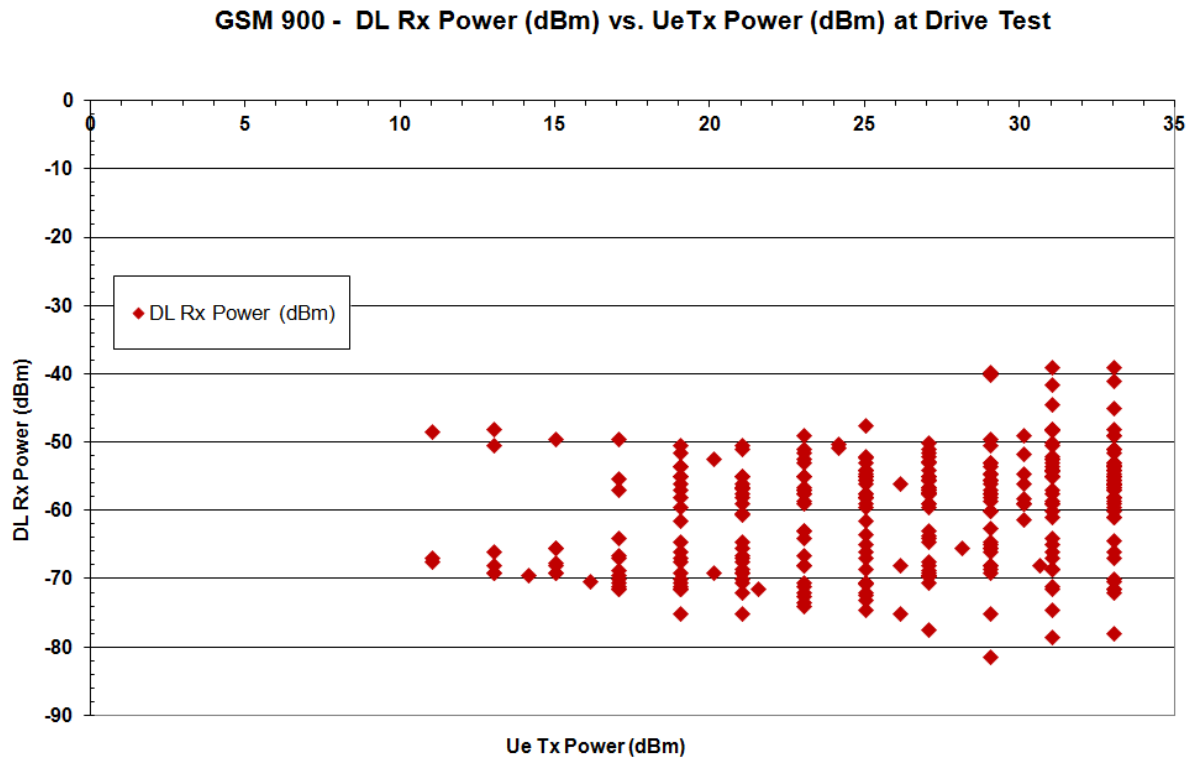


Figure 12: The correlation between UE Tx and Rx power for GSM900, obtained from drive-test measurements collected for different cells along the route in suburban area, for long voice calls

Comparing Figure 11 and Figure 12 it could be concluded that under realistic conditions i.e. mixture of cells and services used we get similar result from drive tests and network collected data.

The following Figure 13 shows the relation between UE Tx power and I_o , power of received signal on the DL, in UMTS. I_o is referred to as N_o (Noise Spectral Density), RSSI. The measurement was done in good radio conditions. A good correlation between the power of received signal on the DL and the Tx radiating power of the terminal in the UL is visible.

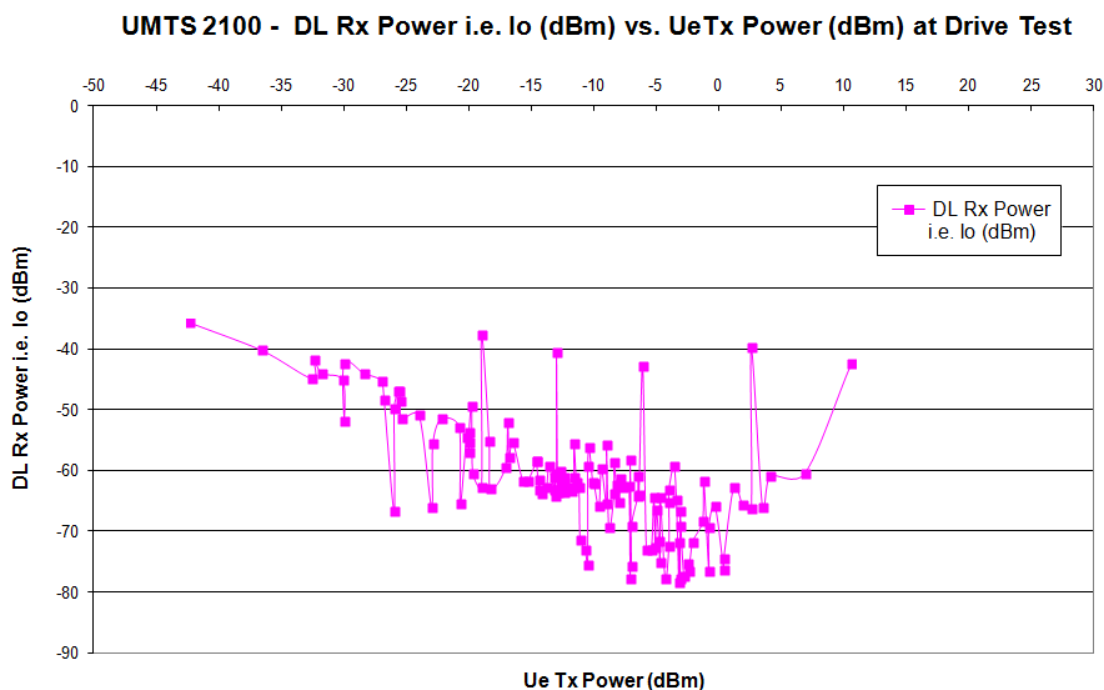


Figure 13: The correlation between UE Tx and Rx power for UMTS2100, obtained from drive-test data analysis

2.7.2.2 The correlation between transferred bits and power, UMTS

Figure 14 shows the correlation between transmitted data in the DL and average DL power, for two sectors of the macro UMTS site, and two sectors of the indoor UMTS DAS. It was made by analyzing cell statistics (network counters and KPIs, per-hour average values). The DL power is the overall power emitted by the BTS in the DL (in Watts). It depends on positions of all UEs, services used, etc. For demanding services we need good radio conditions and more power. But, more power is also required for users that are far away, even for “weak” services. For these two sites the subscribers are not much far away, thus this correlation is obvious (not masked by far-away users).

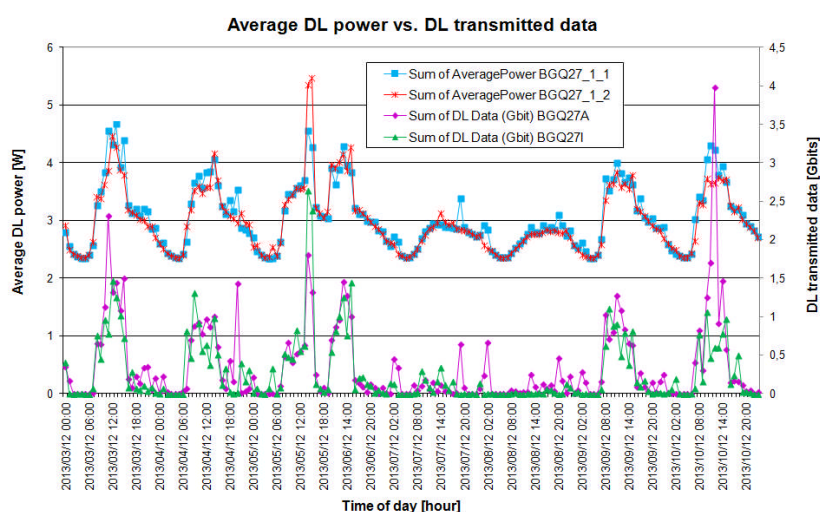


Figure 14: Correlation between average DL power and the volume of transmitted data in the DL, on a 3G indoor cell

2.7.2.3 Duty factor: GSM, UMTS, WLAN 802.11g

The measurements of the so-called duty factor, or activity factor, show the actual activity of transmitters, i.e. the appearance of the signal on the radio interface. This is important for time-averaging of uplink power, since the samples in the UE measurement reports or in drive-test measurements are taken only when the transmitter is actually transmitting.

Duty factor is identified as the key factor for exposure assessment. It depends on the application (service) and the radio interface used, and exposes the silent periods and DTX. It represents the ratio between activity periods and total time of transmission on the radio interface.

In order to determine the activity of UE transmitter in time, the UE was placed in the close proximity of the frequency-selective measurement equipment (field measurements). Transmitter activity was recorded for the voice call on GSM, UMTS and WLAN, and UMTS data call.

The signal levels shown in figures in this subsection are not of interest, only the frequency of signal occurrence in time, since the UE was placed at some distance from the measurement equipment. Samples were taken in the intervals of 100 μ s, which is enough to capture GSM time slots of 576.9231 μ s.

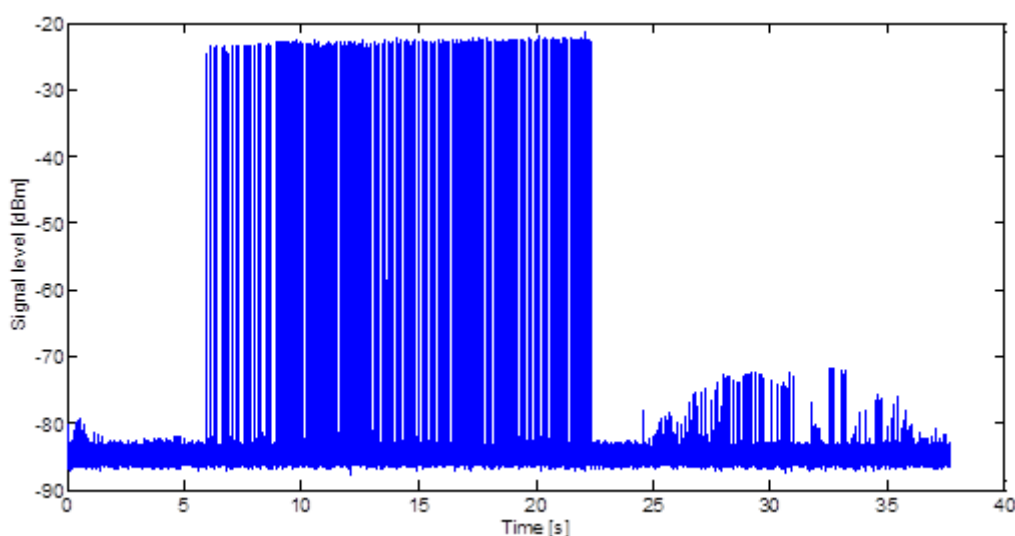


Figure 15: GSM voice call, uplink, measurement taken in 40s period

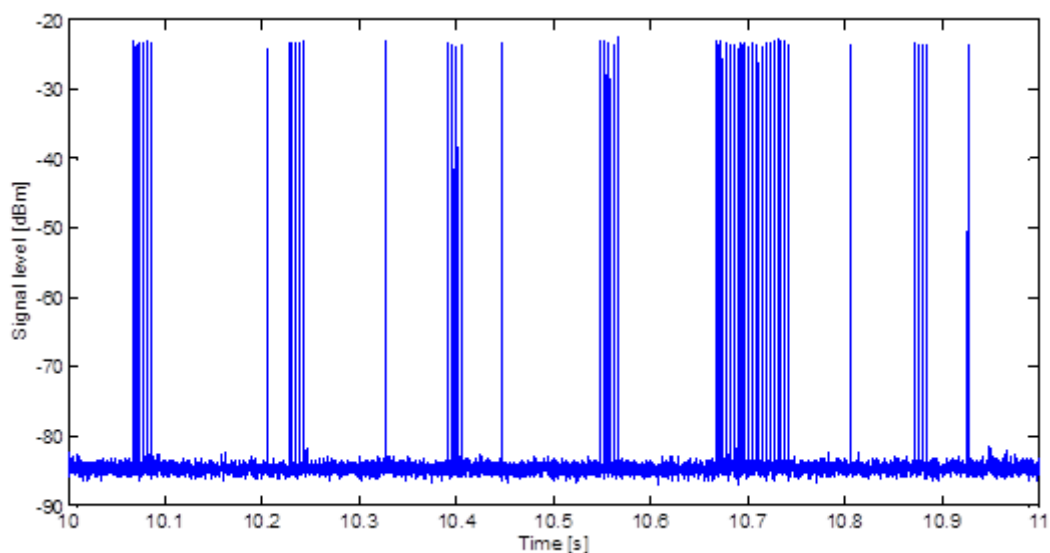


Figure 16: GSM voice call, uplink, sequence of 1s

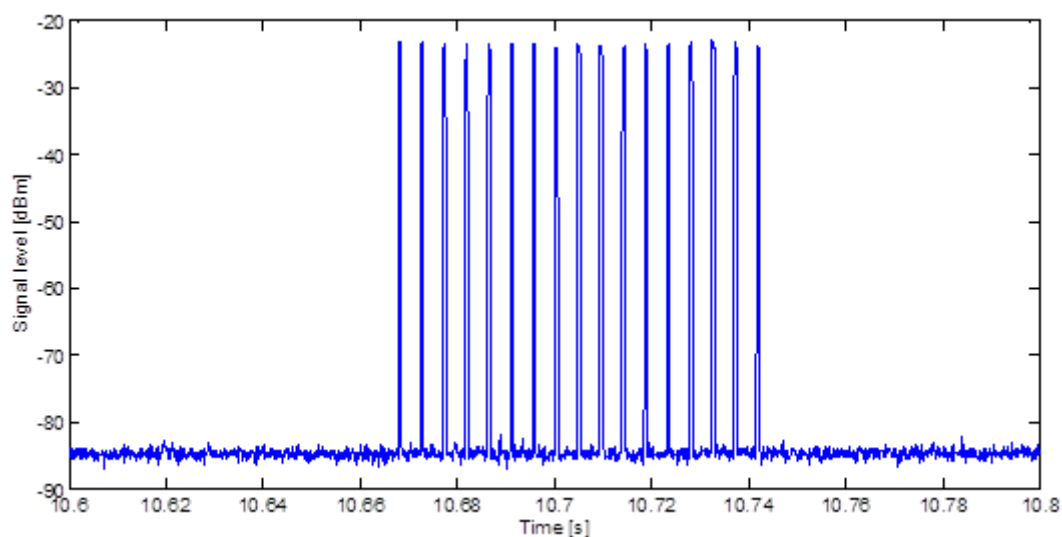


Figure 17: GSM voice call, uplink, sequence of 0.2s

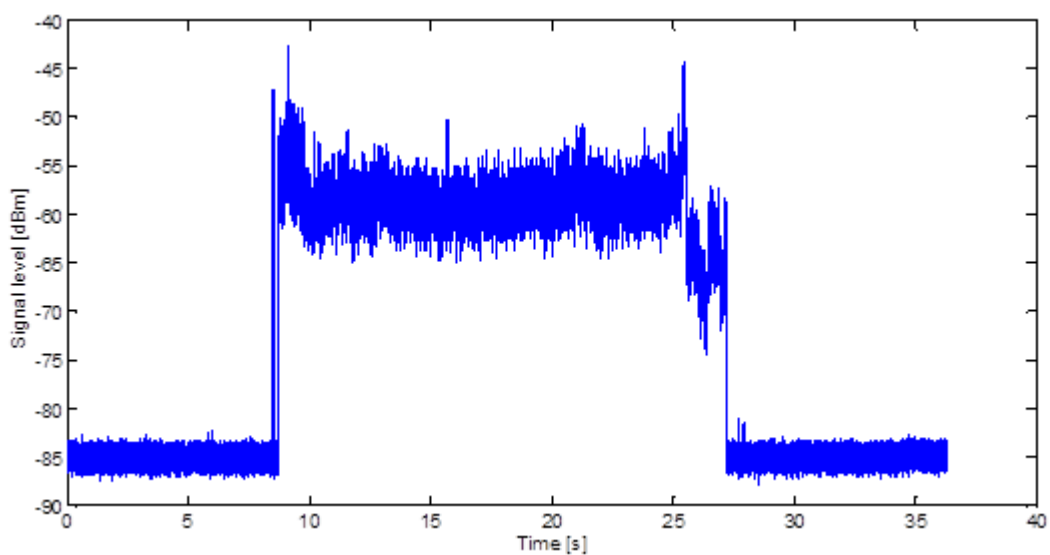


Figure 18: UMTS voice call, uplink, measurement taken in 40s period

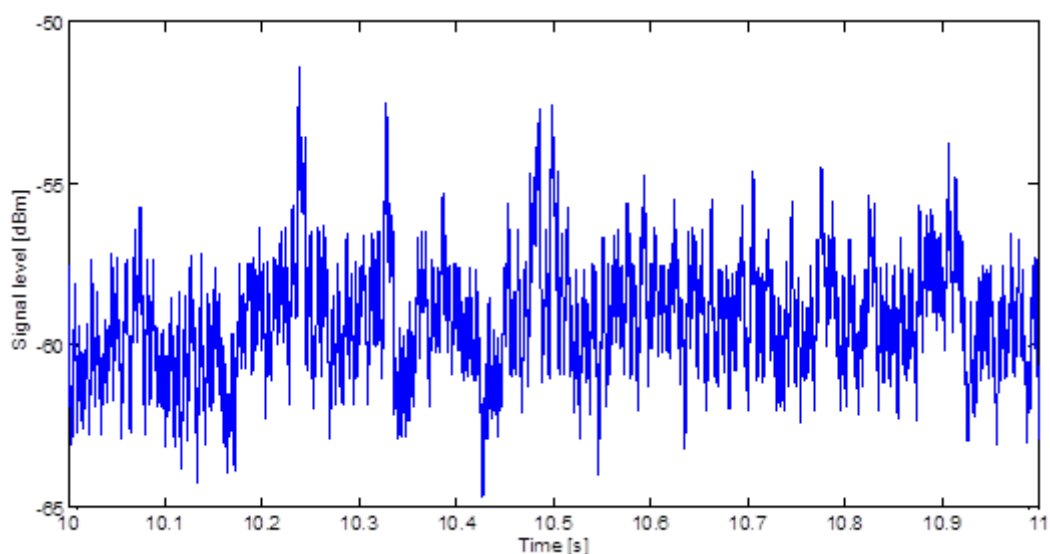


Figure 19: UMTS voice call, uplink, sequence of 1s

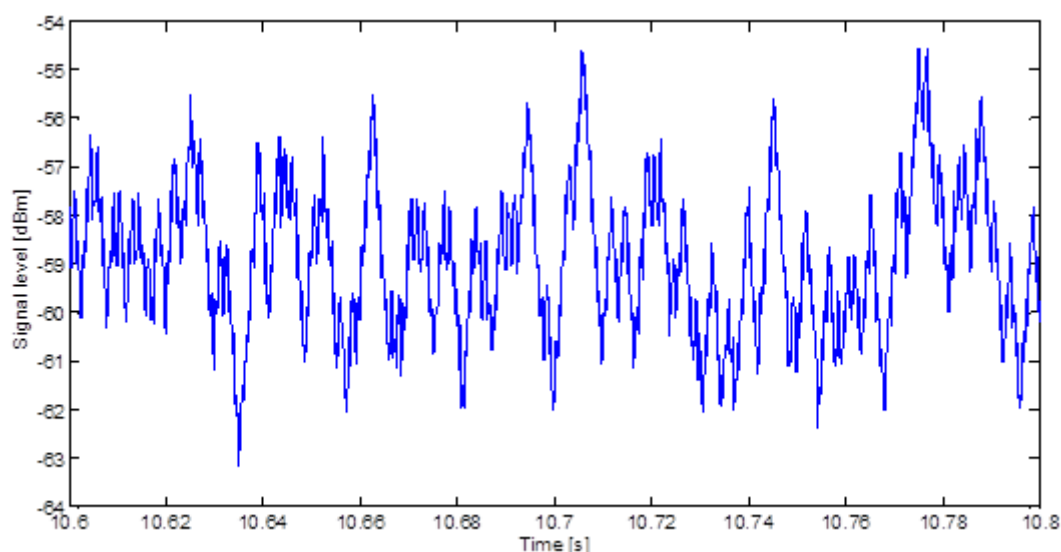


Figure 20: UMTS voice call, uplink, sequence of 0.2s

The figures Figure 18-Figure 20 and Figure 15-Figure 17, respectively, show the continuity of the UMTS signal and the abruptness of the GSM TDM access scheme, along with periods of silence (voice activity). All these need to be taken into account for the comparison of time-averaged powers per technology. The property of the voice service is the voice activity factor (VAF). In Figure 16: GSM voice call, uplink, sequence of 1s, periods of inactivity are clearly visible. The literature generally deals with different percentages for VAF, but the commonly used values are 40%-50%. The actual activity on the radio interface is higher, and depends on factors such as vocoder used and coding scheme. For the results shown in Figure 15, the overall activity on the physical layer including call establishment (signaling) was 2.05%, while the activity during the actual conversation was 3.35%. Taking into account 1/8 of TS occupancy for voice in GSM, this corresponds to the DTX activity of 24.72%, and

may be roughly considered as voice activity factor. The test call was made with one person speaking, having a lot of pauses.

The following figures, Figure 18-Figure 23 and Figure 24-Figure 27, show the time distribution of transmitter activity for data service on GSM and UMTS, respectively. In Figure 23, as well as in Figure 17, the periods of “service inactivity” (voice inactivity or time between sending packets) are clearly visible, and may be distinguished from “breaks” in the signal originating from its TDMA nature (only one out of 8 time slots in a frame is used for voice service, and 1-3 time slots for data, depending on UE capability). The activity on the physical layer for the sequence shown in Figure 21 was 13.04%. Accounting for 2/8 TS occupancy, this corresponds to 52.16% activity.

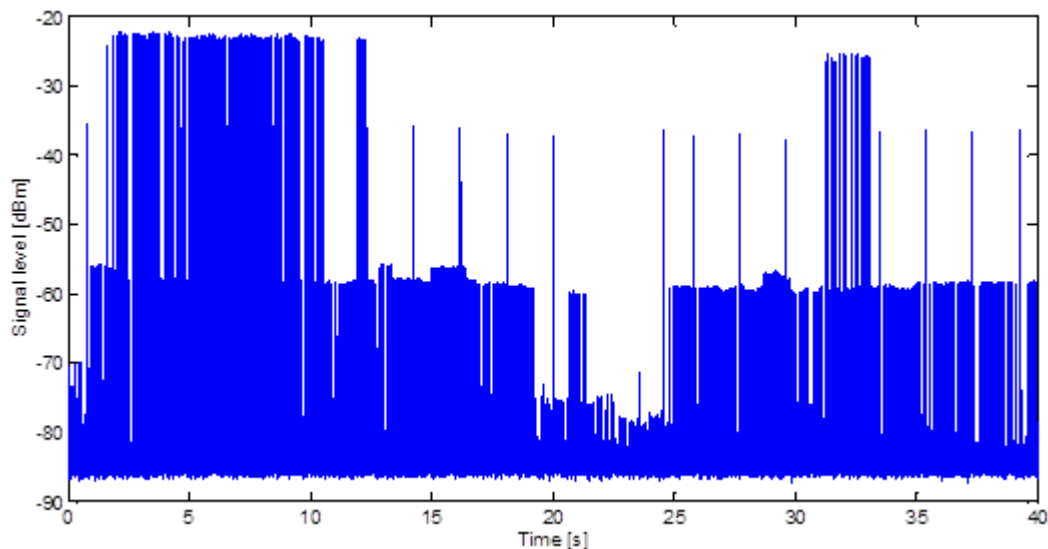


Figure 21: GSM data, uplink, measurement taken in 40s period

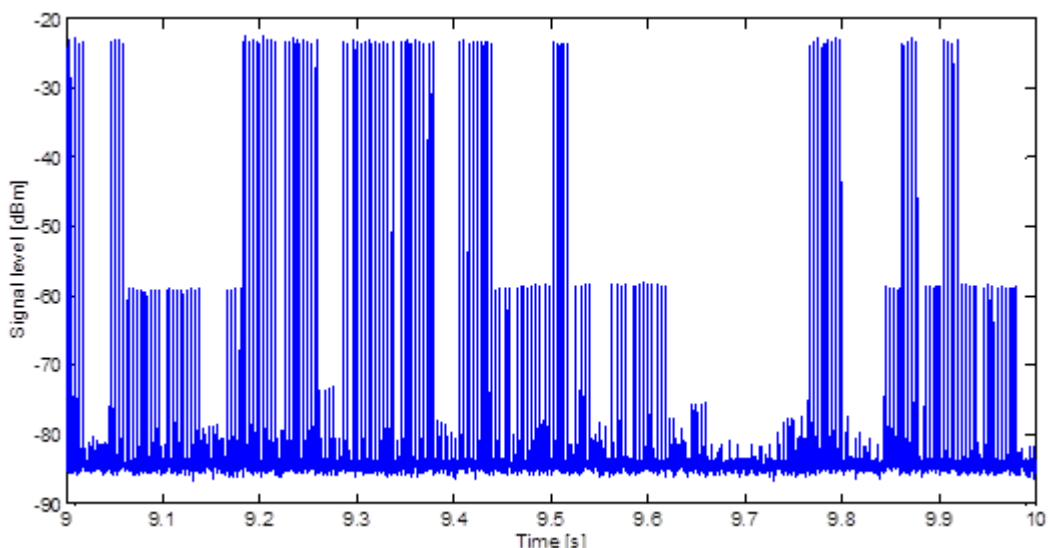


Figure 22: GSM data, uplink, sequence of 1s

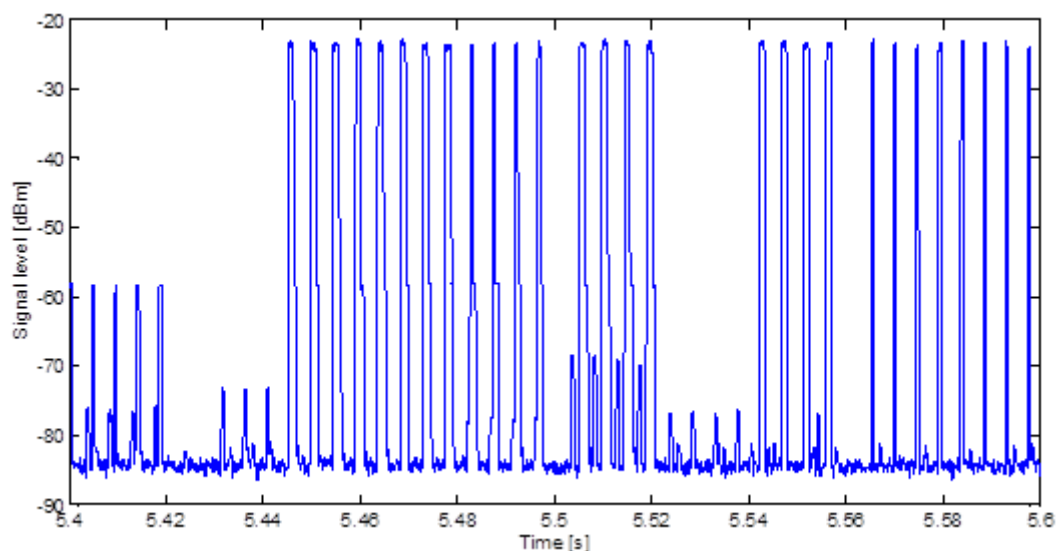


Figure 23: GSM data, uplink, sequence of 0.2s

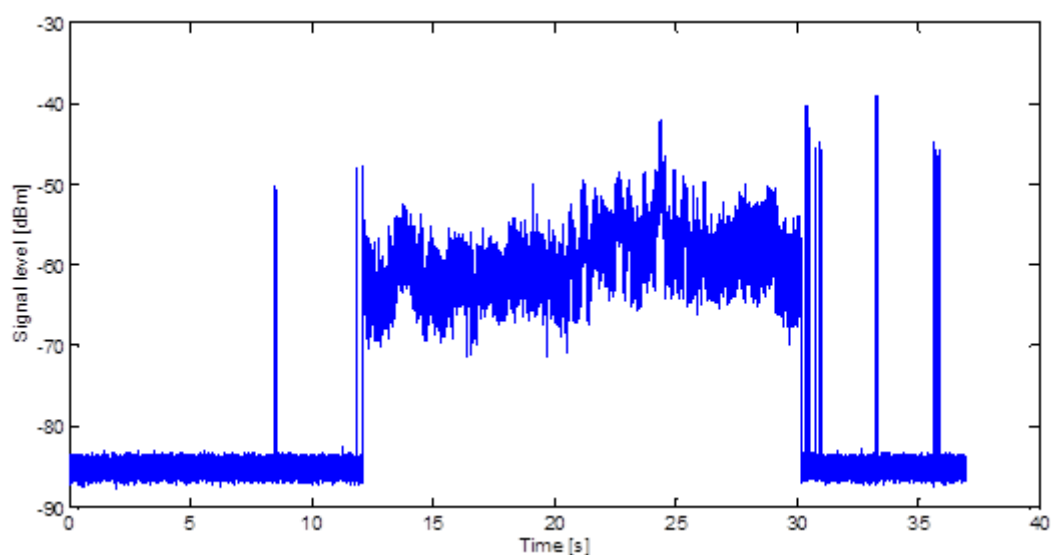


Figure 24: UMTS data call (web), uplink, measurement taken in 40s period

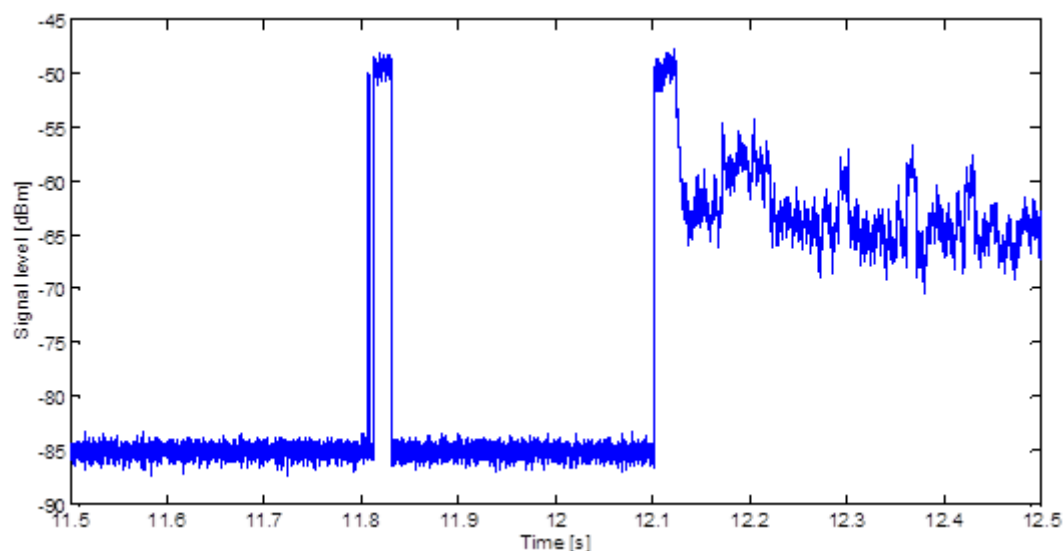


Figure 25: UMTS data call (web), uplink, a sequence of 1s

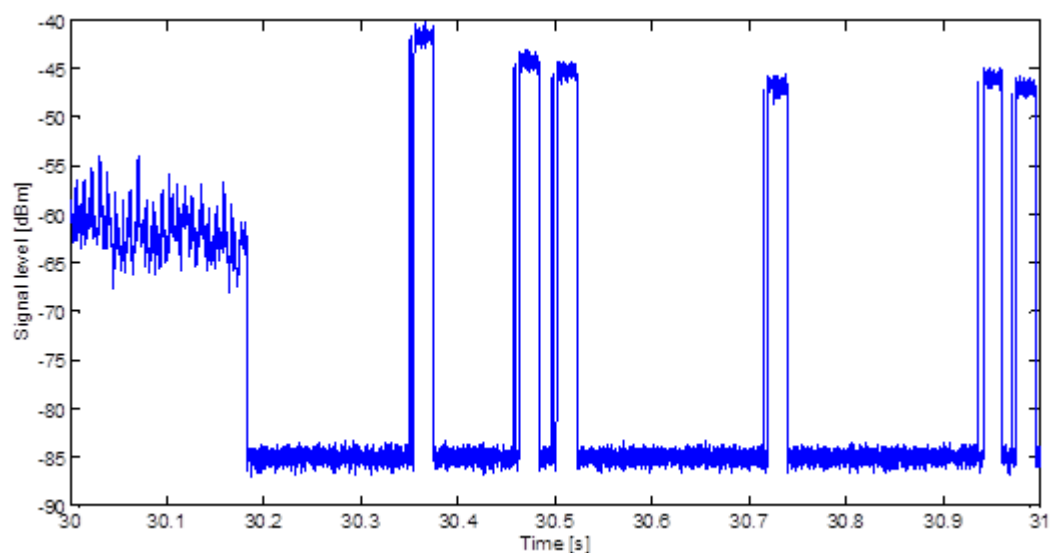


Figure 26: UMTS data call (web), uplink, another sequence of 1s

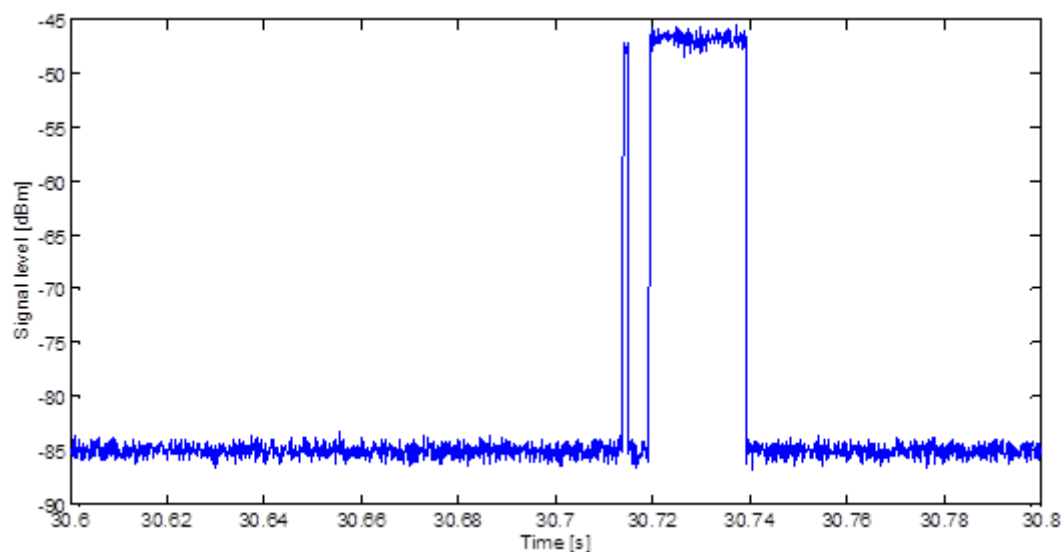


Figure 27: UMTS data call (web), uplink, sequence of 0.2s

The presented figures Figure 24-Figure 27 show that in UMTS data transmission is discontinuous, i.e. there are periods of inactivity. In UMTS, data is normally transferred over HSPA, and inactivity leads to Radio Resource Control (RRC) state transition depending on inactivity timers, from dedicated channel (DCH) state down to forward access channel (FACH) state, and further, Idle state [3GPP TS 25.331]. The activity on the physical layer for the sequence shown was 50.02%. The introduction of the CPC (Continuous Packet Connectivity) [Holma, 2010] would lead to smaller “drops” of signal in its continuous part in Figure 24, as no control channels would be emitted in silent periods shorter than inactivity timers.

Presented figures clearly shows that the time-averaging of powers for exposure assessment and comparison needs to consider the periods of silence and that some estimates on data activity of different services need to be made.

The following figures, Figure 28-Figure 30 and Figure 31-Figure 33, show the activity of UE transmitter for the voice over IP (Skype) service and file upload service over WLAN 802.11g network.

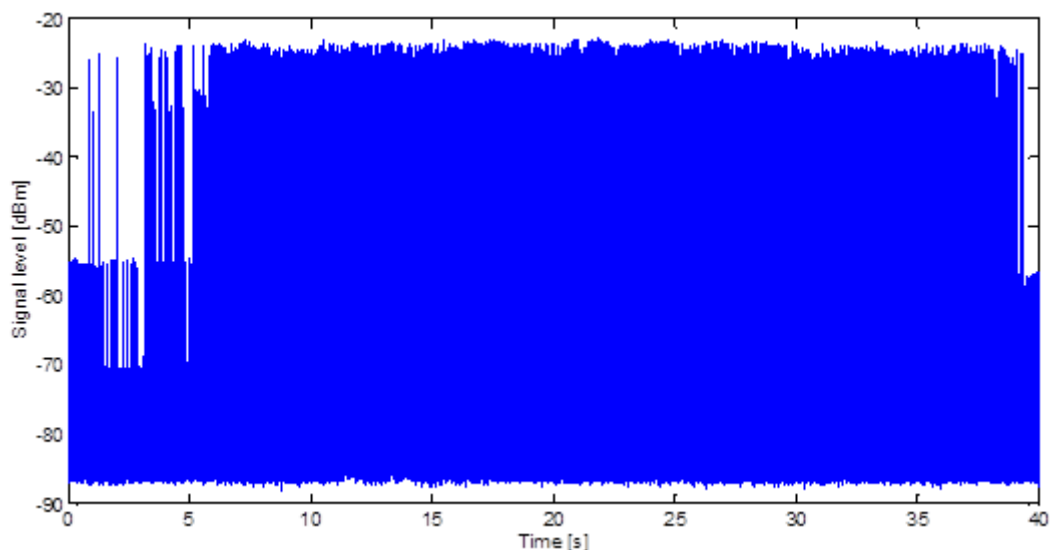


Figure 28: WLAN 802.11g voice call (over IP), uplink, measurement taken in 40s period

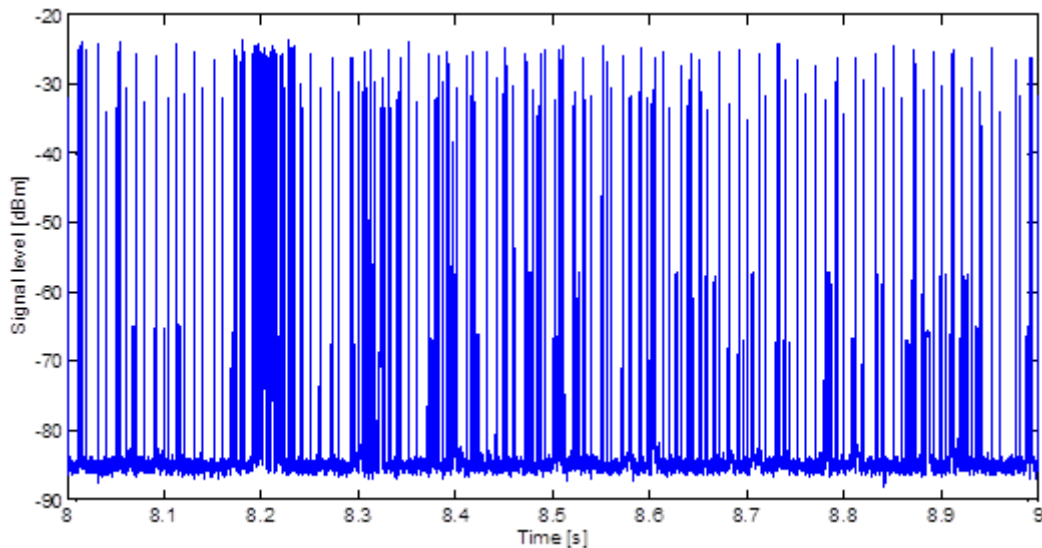


Figure 29: WLAN 802.11g voice call (over IP), uplink, sequence of 1s

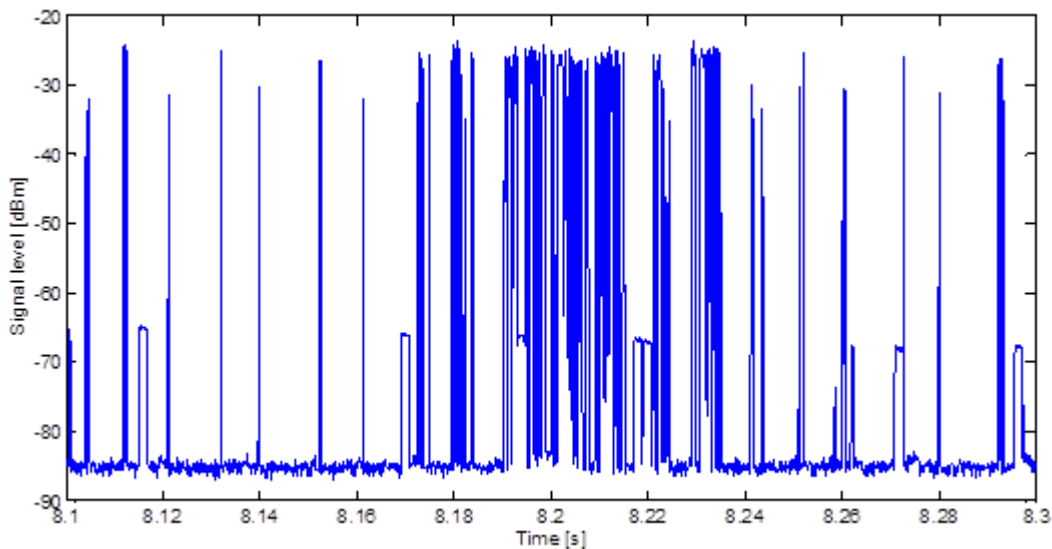


Figure 30: WLAN 802.11g voice call (over IP), uplink, sequence of 0.2s

WLAN radio interface uses the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), i.e. all nodes operate in the same channel. Figures Figure 28-Figure 30 show the signal captured on the WLAN radio interface for the voice call over IP. The mobile phone connected to the WLAN network was placed in the close proximity of the measurement device, while the AP was located approximately 15 m away, with two walls in between. Thus, it is expected that uplink signals dominate over the downlink ones. Further, the filter of the measurement device can capture only 8 MHz frequency width, while the WLAN signal is 20 MHz wide, meaning that only part of the signal was captured.

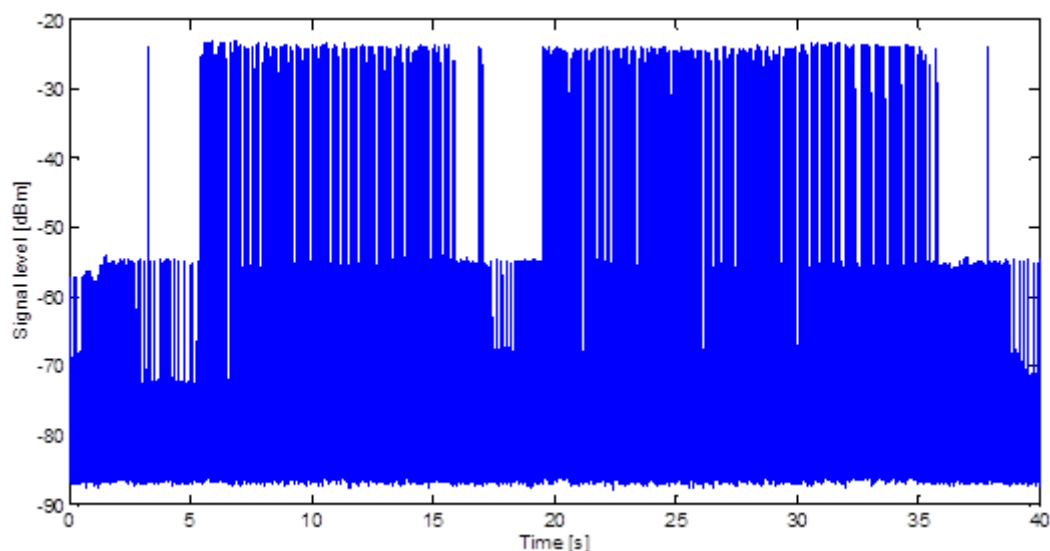


Figure 31: WLAN 802.11g data (file upload), uplink, measurement taken in 40s period

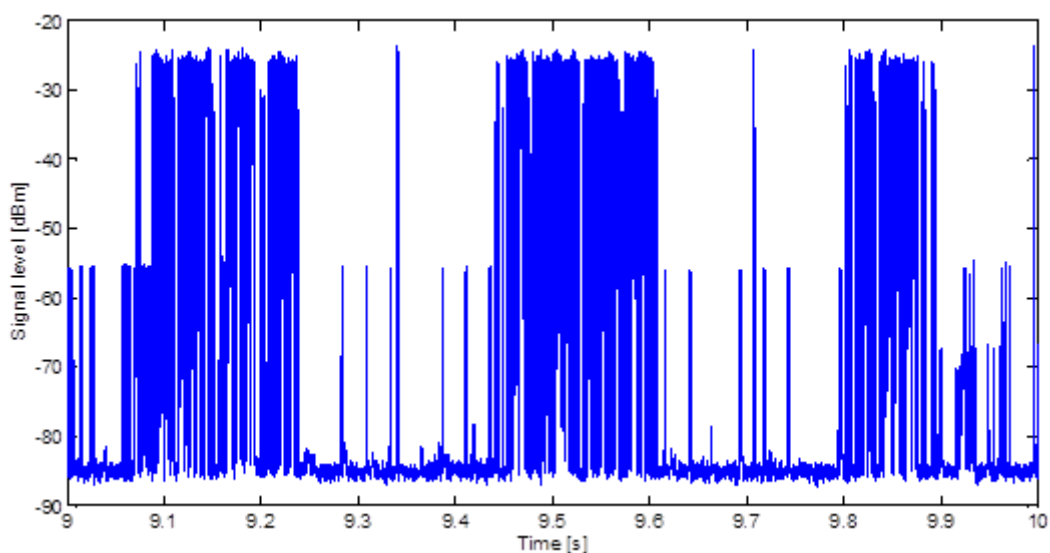


Figure 32: WLAN 802.11g data, uplink, sequence of 1s

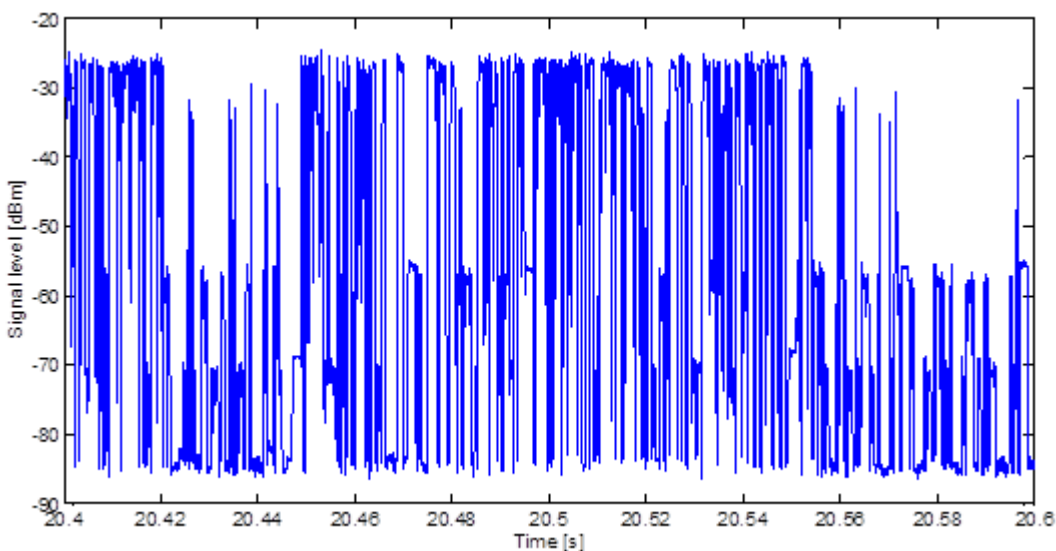


Figure 33: WLAN 802.11g data, uplink, sequence of 0.2s

The figures Figure 28-Figure 33 show that for exposure assessment careful analysis needs to be performed and right estimations made, especially because the statistics on client Tx/Rx powers cannot be logged from the WLAN system.

Duty factor stands out as an important element in assessing exposure and comparing different technologies and services. For 3GPP networks, the statistics on UE Tx power must be mapped with time activity of the transmitter per different services. The figures above indicate different time profiles on the radio interface, which depend on technology used, type of application and current radio and traffic conditions.

As an illustration, the following figures (Figure 34 and Figure 35) show characteristics of voice and data service on GSM, when active. Voice service uses 1 out of 8 time slots in a frame when active, while data service may use several time slots in the uplink, depending on the multislot class of the UE [3GPP TS 45.002]. Usually, 2 to 3 time slots are used. The number of used time slots is indicated in the drive-test tool during measurements.

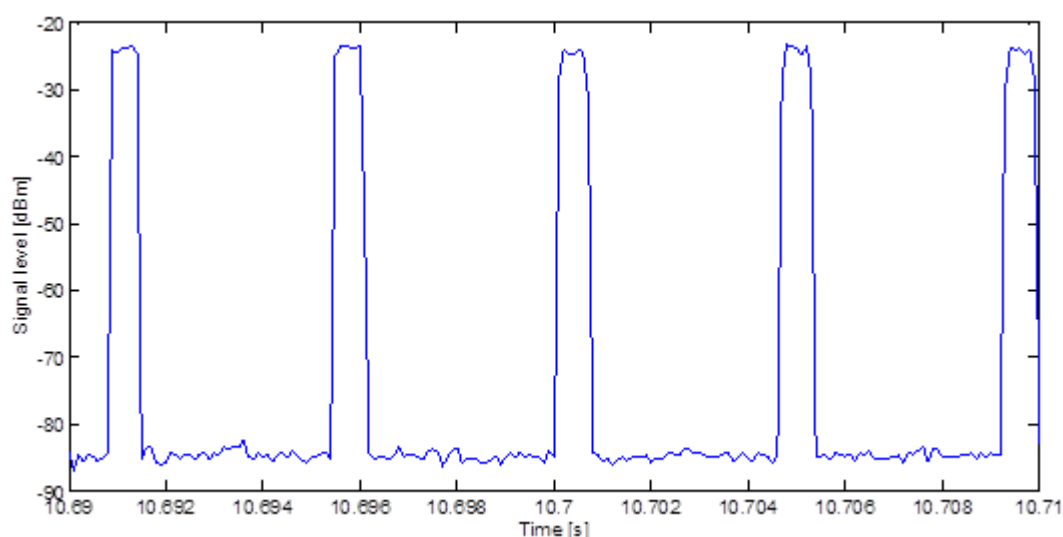


Figure 34: GSM voice call, uplink, sequence of 20ms

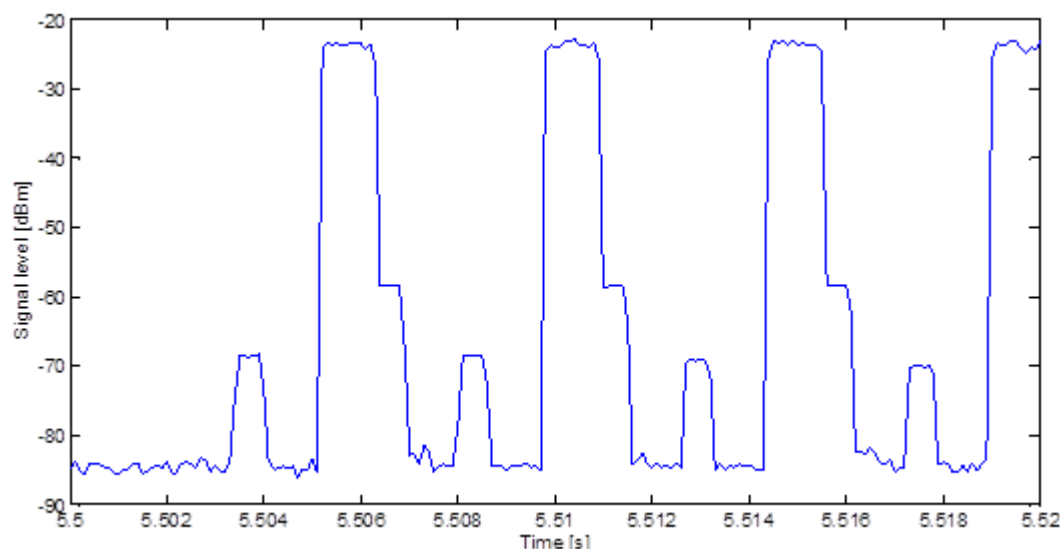


Figure 35: GSM data, uplink, sequence of 20ms

This practically means that for the comparison of the dose of exposure, i.e. time averaging, the samples obtained from network reports (samples are taken when the transmitter actually transmits) need to be scaled accordingly.

While this is a GSM-specific correction, another correction needs to be made for the actual activity of the service in both technologies. In GSM, DTX factor needs to be taken into account (“breaks” in transmission). In UMTS we distinguish a voice call (Release '99), where even during DTX control channels are emitted, so the signal is continuous, and the data call, where we do have „breaks“ in transmission due to RCC state transitions with specific signaling. For all technologies, data activity factor on the physical layer depends on the type of application used (its activity) in the first place, but also on technology and current traffic and radio conditions.

2.7.2.4 The comparison of different technologies and cell types

Figure 36 shows UL Tx power histograms for four different cells: GSM and UMTS; outdoor macro and indoor macro (with distributed antenna system and reduced power, therefore considered as a micro cell). Macro cells are overlaid over the indoor cells. Measurements were done on per-cell basis, during high load hours. Due to different measurement methodologies, GSM results were corrected taking into account average full voice call duration. The extrapolation of power profile to the full average length of a conversation (taken from call record statistics) was made empirically, taking more samples with lower powers than recorded.

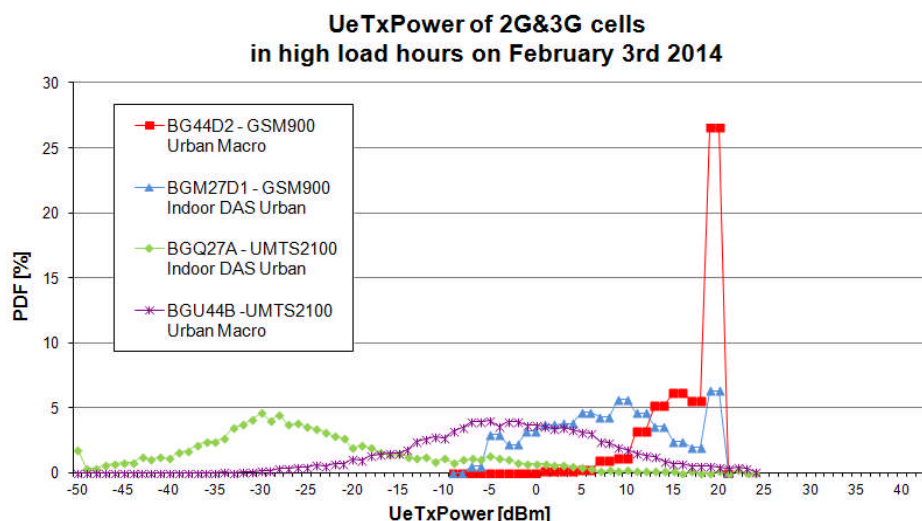


Figure 36: Comparison of different 2G/3G cells in high load hours by UE Tx power per cell PDF

Exposure-related comparison of the technologies needs to take into account time-averaged values, related to the average “dose” as defined by EI [Conil, 2014]. Since all GSM samples were taken when the transmitter is actually transmitting, a correction was applied for 1/8 time activity (1 time slot) for voice on GSM (property of the radio interface), and for voice activity factor, taken to be 40%. It is clear that the 3G generates much less UL power than 2G, and that indoor cells generate less UL power than the macro cells. If there was no indoor site (as it once was), the power distribution of the macro would be even worse, with lots of subscribers in deep indoor radio conditions.

2.7.2.5 The impact of type of service

We additionally demonstrate that the type of service could increase the exposure, meaning that different strategies could be used to identify the best connectivity according to the service flow requested. Figure 37 shows comparison of UL Tx power histograms for two different services, voice and FTP upload, on 2G (GSM900) and 3G cells, where UMTS and GSM base stations are collocated. Drive-test measurements were performed with the UE using different services (voice, 800 Hz test tone, FTP UL, FTP DL, youtube, internet browsing, sms; Skype) and technologies (GSM900/1800/UMTS), and here only a part of results is shown.

Measurements were done on per-user basis, in good radio conditions, during high load hours, and the UE was static. It is clear that in 3G voice service generates much less UL power than data upload. For comparison of time-averaged values, 2G results were corrected for 1/8 time slot voice occupancy in a frame on GSM, 2/8 time data occupancy on GSM (multislot transmission), and 40% voice activity factor. Again, voice generates less UL power than data transmission, while overall 2G emissions are with higher powers than 3G. The exposure assessment needs to map this data on powers with the distance of the UE to the body – although voice UL power profile is better, the UE is close to the head, while for data transmissions the UE is typically at 30 cm distance from the body, so the question is what are the actual exposure levels in these two cases.

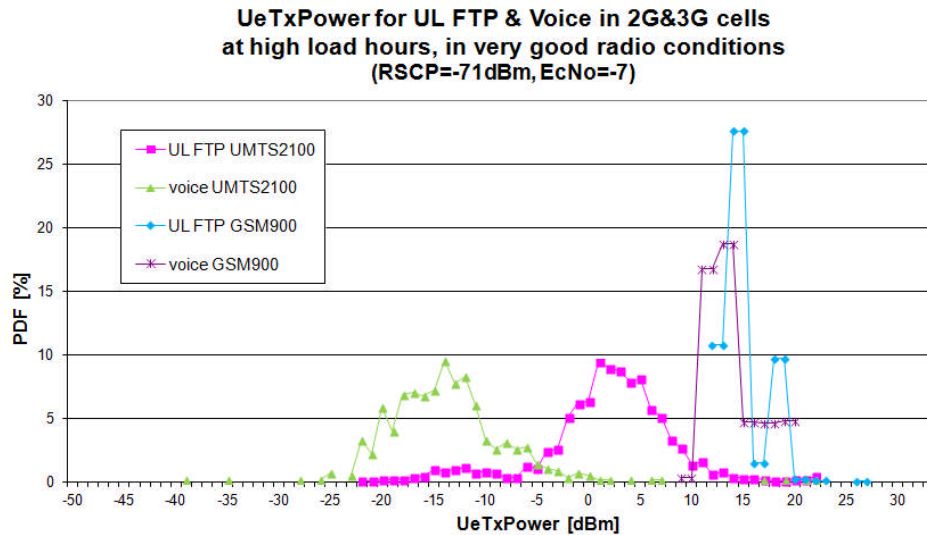


Figure 37: Comparison of UL FTP and voice services over 2G/3G cells in high load hours by UE Tx power per user PDF

Results similar to GSM900 were obtained for GSM1800.

The following Figure 38 shows comparison of power profiles for various services (FTP DL, internet browsing, Youtube, SMS, 800 Hz test tone) on 2G and 3G cells, at high load hours and in good radio conditions. The 800 Hz test tone is a continuous signal intended to exclude DTX functionality.

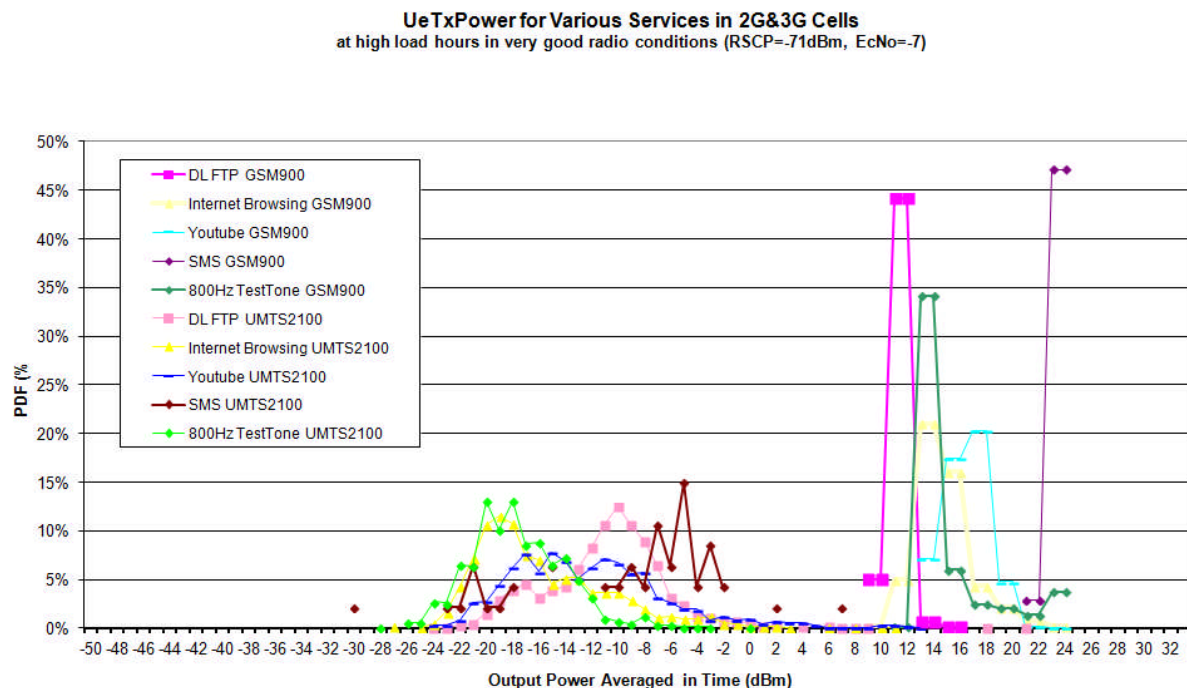
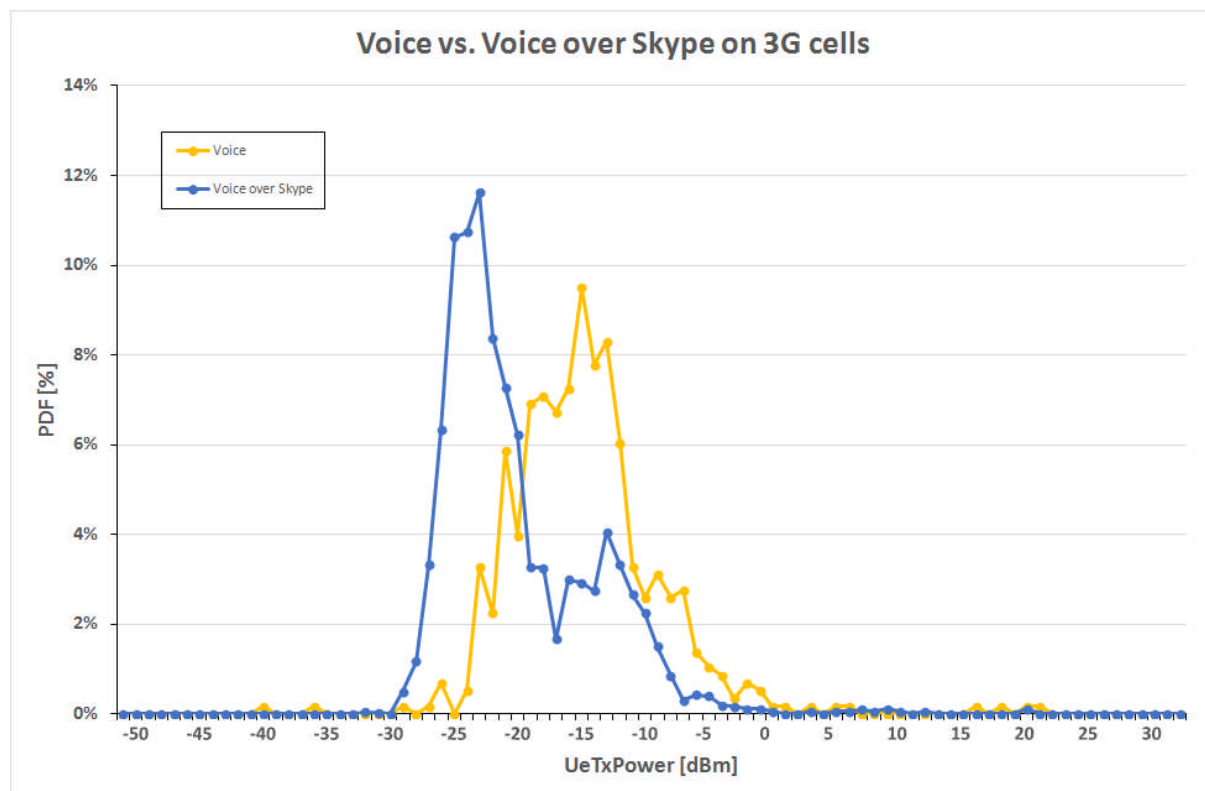


Figure 38: Comparison of various services over 2G/3G cells in high load hours by UE Tx power per user PDF

The following Figure 39 shows the comparison of voice service over 3G and voice service using Skype over 3G network. Measurements were conducted with different user equipments in different time, on the same location, in good radio conditions. The histograms show that voice over Skype is transferred with lower power levels compared to normal voice over 3G.



Voice: DL CPICH Ec/No=-8.4dBm, CPICH RSCP=-78.1dBm

Voice over Skype: DL CPICH Ec/No=-6.6dBm, CPICH RSCP=-70.9dBm

Figure 39: Voice vs. Voice over Skype, over 3G cells in high load hours by UE Tx power per user PDF – same location, different UE, different time

These results verify the assumption that the application used has a great impact on the power profile, and consequently, the exposure. Here, the technology used must be taken into account. Voice service is transferred over Rel'99, while data (Skype) uses HSPA. HSPA is more energy efficient than Rel'99. For data services, losses of packets due to errors may be compensated with retransmissions, while for classical voice service, significant losses and retransmissions may not be afforded as directly impact the deterioration of the service quality. Thus, under the same radio conditions, energy per bit for Skype data service may be lower than for voice. The effects of speech coding, signalling channels, radio conditions on the uplink, impact of the UE type and time of the measurements also need to be considered. Hence, the comparison of voice service and voice over Skype requires more detailed measurements and analysis.

Furthermore, for the exact comparison of average powers on different radio interfaces, statistics on duty factor (i.e. exact activity on the radio interface) for various services needs to be taken into account.

2.7.2.6 Conclusions and ongoing work

The measurement results shown above clearly indicate the importance of methodology for comparing results in terms of EMF exposure with the aim of choosing the right strategy for exposure reduction, as well as the necessity for conducting a thorough measurement campaign under many different conditions (technology used, radio and traffic conditions, user context). Since many various factors impact the exposure, it is important to quantify, at least in relative terms i.e. comparatively, their contributions to the total exposure in order to establish the most beneficial decision algorithm and develop the strategy to be used.

Key factors for the methodology for comparing results, that are distinguished through performed measurements, are:

- Methodology of network reporting:
 - o Per-cell GSM measurements: The correction for GSM to the full length of a conversation was done empirically, taking first 5s of recorded samples (call establishment, higher power values), and then repeating the residual 25s to the average length obtained from network statistics. This needs a more thorough analysis and justification.
- Voice activity factor:
 - o In GSM, the actual DTX on the physical layer is of interest. It is generally different than voice activity factor, but may be roughly considered the same. Measured values differ from those found in literature, they are smaller, so the actual DTX depends a lot on specific conversation, among other factors.
- GPRS multislot:
 - o UEs nowadays mostly use 2 or 3 time slots for data transmission in the uplink. The number of used TSs may be seen on the drive test tool during measurements.
- Duty factor:
 - o Its statistical properties need to be investigated for every service and technology, under different radio and traffic conditions.
 - o DTX factor represents service inactivity on the physical layer. For GSM, duty factor consists of activity factor (100%-DTX factor) multiplied with TS occupancy.

The ongoing work is focused on more thorough analysis of already performed measurement and new measurement campaigns for evaluating proposed strategies. Further development of strategies depends on measurement and simulation results.

UE Tx power is identified as one of the main proxy metrics for the assessment of UL exposure in the real network, with the duty factor to be taken into account. These power profiles (power distributions) are to be further mapped to the EI, using the data from other network resources (call records, data on subscribers, cell statistics) on a specific cell. DL power profile also needs to be taken into account, as the DL is always present.

Further measurements will include:

- more detailed UL duty factor measurements (per type of application, in different radio conditions)

- DL power measurements
- WiFi vs. macro using field measurements, in different radio conditions and high/low (macro) traffic hours
- on/off micro/indoor (with overlaid macro/outdoor)
- forcing different voice codecs
- highway scenario measurements (frequent handovers)

Concerning WLAN vs. 3GPP networks, in the WLAN network no UE Tx power data can be obtained from the system, thus field measurements need to be used.

Detailed elaboration on strategies will be given upon the verification of specific scenarios.

3 EMF REDUCTION WITH SMALL CELLS

3.1 Access network selection

In the current cellular technology, a UE selects the eNB that is associated to the strongest RSRP [Parkvall, 2011]. Due to the power imbalance between Small Cell eNBs (SCeNBs) and Macro eNBs (MeNBs) in heterogeneous networks (HetNets), this solution may prevent UEs to be served by the closest access node. Hence, this increases the power required at the UEs to communicate with the serving eNBs, which in turns augments the user's EMF exposure.

Moreover, this approach limits the data rate and increases the interference in the UL, lowers the battery life at UEs, and reduces the macro cell offloading. To deal with these problems, a CRE technique can be used, where a positive bias is added to the strength of measured signals associated to small cells.

This approach implemented jointly with enhanced inter-cell interference coordination, which protects UEs attached to range expanded cells, results in improved fairness and network capacity [Lopez-Perez, 2012]. Nevertheless, some studies have shown that, by using large values of range expansion bias, too many UEs may be associated to the same SCeNB, which leads to overload issues [Lopez-Perez, 2012]. Recently, researchers have investigated joint cell association and resource allocation to achieve fair load balancing in HetNets [Ye, 2013]. To summarize, recent works have mainly proposed solutions for enhancing the overall network DL capacity, by optimizing the cell association process. Here we focus on the user quality of experience (QoE), and we propose a mechanism that jointly reduces the EMF exposure due to the UL and improves the user satisfaction. We neglect the DL exposure, since in cellular networks, due to the large distance between the user and the eNB, its impact (compared to the UL effect) on the overall exposure is limited [EHFRAN 2010]. We further investigate the trade-off between the aggregate network capacity and the users' QoE.

3.1.1 EMF assessment

In order to assess the impact of the EMF radiation in HetNets, here we use a simplified version of the EI. The EI is able to cover the day-to-day exposure of different categories of people in the coverage area of different technologies; however, here, we only focus on the UL of cellular networks, and we only consider adult users. With these assumptions, the EI can be computed as the sum of the contributions due to different usages (i.e., data and voice) in the considered time periods (day and night):

$$EI = \sum_t^{N_t} \sum_u^{N_u} d_{t,u} \cdot P^{UL} \quad \left[\frac{mJ}{Kg} \right] \quad (1)$$

where P^{UL} is the power emitted by the UE and $d_{t,u}$ is a coefficient associated to the exposure induced by the UL and expressed as an absorbed dose:

$$d_{t,u} = \frac{t_{t,u}^{UL} \cdot SAR_u^{UL}}{P_{tx}^{ref}} \quad \left[\frac{s}{Kg} \right] \quad (2)$$

In Eq. (2), $t_{t,u}^{UL}$ is the time spent in the usage u during the time period t and the ratio $\frac{SAR_u^{UL}}{P_{tx}^{ref}}$ represents the whole body averaged SAR, that characterizes an adult during the usage u and an incident reference power P_{tx}^{ref} (see Table 2).

Table 2: Daily Usage Time of Wireless Devices and Associated Whole Body SAR [LEXNETD2.4]

	Voice/ Indoor	Voice/ Outdoor	Data/ Indoor	Data/ Outdoor
t=Day	4',2"	4',2"	22',50"	8', 44"
t=Night	2',1"	2',1"	38', 55"	5', 6"
$\frac{SAR_u^{UL}}{P_{tx}^{ref}}$	3.95e-06	3.95e-06	4.14e-06	4.14e-06

3.1.2 System Model

Coherently with the study on small cell enhancement, which is currently under investigation in 3GPP [3GPP TR 363GPTR36.872], our research focuses on HetNets, where SCeNBs are densely deployed and operate in a dedicated carrier (see Figure 40). Small cell deployment is currently seen as a main enabler to improve the user throughput and to limit the energy consumption of the whole system (with a direct impact on the EI, as we will show here).

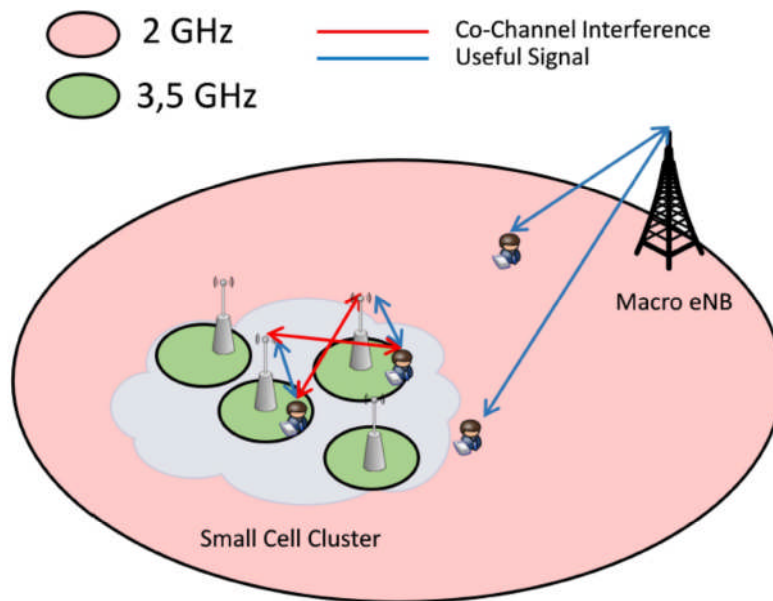


Figure 40: The heterogeneous network deployment under investigation

We consider a set of users U that can be served by the nearby B eNBs. The link quality between a user i and an eNB j can be modelled through the average SINR as:

$$SINR_{i,j} = \frac{P_j \cdot \Gamma_{i,j}}{I_{i,j} + \sigma^2} \quad (3)$$

where P_j is the transmission power at j and $I_{i,j}$ is the aggregated interference experienced at i .

Moreover, σ^2 is the additive thermal noise power and $\Gamma_{i,j}$ is the channel gain (that includes path loss, shadowing, and antenna gain), which both characterize the radio link.

Note that the average SINR in (3) is due to measurements on the eNB control channels and it is independent on cell loads, fast fading, and resource allocation.

We further denote

- the connectivity matrix $\mathbf{A}$, where $a_{i,j}$ equals 1, if a user i is in the coverage area of an eNB j (i.e., $\text{SINR}_{i,j}$ is larger than a given threshold) and 0 otherwise;
- the set of all the possible service matrices $\mathbf{X}=\{\mathbf{X}_1, \dots, \mathbf{X}_n\}$, where $n = \prod_{i \in U} \sum_{j \in B} a_{i,j}$

Moreover, $\forall \mathbf{X}_k$, $x_{i,j,k}$ equals 1 if a user i is served by a eNB j (0 otherwise), $\sum_{j \in B} x_{i,j,k} \leq 1$, $\forall i \in U$ $x_{i,j,k} \leq a_{i,j,k} \forall (i,j) \in U \times B$.

For a given $\mathbf{X}_k$, the achievable data rate associated to the link between i and j can be modelled as

$$C_{i,j,k} = x_{i,j,k} \cdot B_{i,j,k} \cdot \eta_{i,j} \quad (4)$$

where $B_{i,j,k}$ is the fraction of the frequency resources that eNB j allocates to end-user i and $\eta_{i,j} = \log_{10}(1 + \text{SINR}_{i,j})$ is the spectral efficiency of the link between eNB j and end-user i .

When considering that an eNB allocates more bandwidth to those users that are characterized by greater spectral efficiency, we have

$$B_{i,j,k} = \begin{cases} \frac{B \cdot \eta_{i,j}}{\sum_{y \in U} x_{y,j,k} \cdot \eta_{i,j}} & \text{if } \sum_{y \in U} x_{y,j,k} \cdot \eta_{i,j} \cdot B_{y,j,k} \leq C_j^{BH} \\ \frac{C_j^{BH} \cdot \eta_{i,j}}{\sum_{y \in U} x_{y,j,k} \cdot \eta_{i,j}^2} & \text{Otherwise} \end{cases} \quad (5)$$

Eq. (4) indicates that when the DL throughput at an eNB j is constrained by the backhaul capacity C_j^{BH} , the eNB cannot allocate its entire available band (B) i.e., spectral resource usage has to be limited.

Finally, in 3GPP LTE, fractional power control is used at the UEs in the UL to mitigate inter-cell interference and increase the battery life-time of UEs. Accordingly, the UL power required by the UE i to connect to the eNB j can be modelled as [Castellanos, 2008]

$$P_{i,j} = \min\{P_{max}, P_0 + 10\log_{10}(N_{RB}^{UL}) + \lambda \cdot \Gamma_{i,j}\} \quad (6)$$

where P_{max} is the maximum transmission power (23 dBm) at the UE, P_0 is a UE-specific parameter (-78 dBm), N_{RB}^{UL} models the number of allotted resource blocks in the UL, and λ is the cell-specific path-loss compensation factor (0.8).

3.1.3 Problem Statement

As already introduced, in this work we aim to jointly reduce the user EMF exposure due to the UL, on one hand, and increase the number of UEs that meet their DL data rate target, on the other hand. On one hand, due to the vicinity of the UE to the body, the EMF exposure is mainly related to the UL; on the other hand, in current wireless technologies the service load is strongly asymmetric and enhancing the DL capacity is currently the main target of operators.

For a given chosen service matrix $\mathbf{X}_k$, let us define:

$$P(\mathbf{X}_k) = \sum_{i \in U} \sum_{j \in B} \delta(x_{y,j,k} \cdot C_{i,j,k} - C_{min}) = \sum_{i \in U} \sum_{j \in B} p_{y,j,k} \quad (7)$$

as the function that measures the number of UEs for which the minimum DL capacity requirement (C_{min}) is satisfied and:

$$EI(\mathbf{X}_k) = \sum_{i \in U} \sum_{j \in B} x_{y,j,k} \cdot EI_{i,j,k} \quad (8)$$

as the aggregate user exposure to the EMF due to UL.

Then, our optimization problem is given as follows:

$$\begin{aligned} \mathbf{X}^* &= \underset{\mathbf{X}_k \in X^*}{\operatorname{argmin}} EI(\mathbf{X}_k) \\ \text{s. t. } P(\mathbf{X}_k) &\geq P(\mathbf{X}_n) \quad \forall \mathbf{X}_k \in X^*, \mathbf{X}_n \in X \\ \sum_{j \in B} x_{y,j,k} &= 1 \quad \forall \mathbf{X}_k \in X^*, \forall i \in U \end{aligned} \quad (9)$$

where X^* is the subset of X , which contains all the service matrices that maximize (6).

Proposition: *The above defined problem is NP-hard.*

The generalized assignment problem (GAP) is a combinatorial problem in which each of n tasks is optimally assigned to m machines, given the profit and the cost associated to each task as well as the total resource available at each machine [Martello1990]. Accordingly, part of our assignment problem, i.e., finding the subset X^* can be mapped as a GAP, where:

- the UEs and the eNBs are mapped to the tasks and to the machines, respectively;
- the user satisfaction $p_{y,j,k}$ and the data rate $C_{i,j,k}$ are mapped to the profit and cost of each task, respectively;
- the backhaul capacity C_j^{BH} is mapped to the resource constraint at each machine.

The GAP is known to be NP-hard, while deciding if a feasible solution exists is NP-complete; therefore, the overall described problem is NP-hard.

3.1.4 Proposed Solution

In this section, we present a centralized algorithm to manage the cell selection problem in a near-optimal way.

This algorithm requires coordination amongst eNBs: a distributed approach is feasible, but it increases the algorithm overhead. A practical implementation is to determine a solution at the macro cell, by gathering information related to the neighbouring small cells. Note that the proposed cell association process can be seen as a self-organizing network (SON) functionality, which does not require fast adaptation to mobility and fast fading [3GPPSON]; on the contrary, reporting can be exchanged on a second time scale, which limits the backhaul requirements in terms of capacity and latency.

The proposed algorithm starts from a given solution of the cell selection problem (e.g., the SINR based), and iteratively evolves towards a more beneficial association. In each iteration it evaluates each possible single change in the current association (first step) and then selects the change which is more beneficial (second step). The algorithm stops after a limited number of iterations, when the achievable gain becomes lower than a small non-negative value (ε).

Due to the lack of space, we briefly describe here these steps, more details can be found in [De Domenico, 2013], which inspires the proposed solution.

Let $\mathbf{X}_n$ be the user assignment that maximizes $SINR_{i,j} \forall (i,j) \in \mathcal{U} \times \mathcal{B}$,

1) Initialization step

- Calculate $EI(\mathbf{X}_n)$ and $P(\mathbf{X}_n)$
- $\forall (i,j)$, compute (7) and (8) whether we change $\mathbf{X}_n$ by associating (respectively, de-associating) the user i to (respectively, from) j ; then, compute the gain(s) Δ_p and Δ_{EI} with respect to the reference association, due to the possible reassignments.

2) One-user reassignment step

- Find the set $\mathbf{X}^*$ which maximizes Δ_p ;
- If $\Delta_p \leq \varepsilon$ exit (the algorithm outputs the current user assignment);
- Else, find $\mathbf{X}_k \in \mathbf{X}^*$ that minimizes Δ_{EI} and update the user assignment, accordingly.
- Set $\mathbf{X}_n = \mathbf{X}_k$, then go to step (1).

Proposition: *In the proposed solution, the number of satisfied users is improved in each new iteration. Hence, the algorithm converges when a further improvement is not possible by a new reassignment of one single user.*

3.1.5 Simulation Results

In this section, we present preliminary results to assess the effectiveness of the proposed user centric solution, by comparing its performance with respect to the classical approach, where each UE is associated to the eNB characterized by the strongest RSRP. These results will be updated in the next deliverable. Here, we further consider CRE biases equal to 3 and 6 dBi to increase the macro cell offloading. Note that, a mechanism that optimizes the CRE bias such that the EMF exposure is reduced is presented in Section 3.2.3. Our evaluation scenario is composed of a tri-sectorial macro cell, three clusters of 4 SCellBs, and 60 UEs. 80% of the UEs are indoor, 2/3 of them are located in the small cell hotspots, and remaining UEs are uniformly distributed in the macro cell. A mechanism that defines the optimal small cell deployment such that the EMF exposure is reduced is presented in Section 3.2.2. Other parameters relevant for this study (such as path

loss model and shadowing) follow 3GPP TR 36.872 [3GPP36.872]. The results are averaged over 10^3 independent runs. At the beginning of each run, the clusters of SCeNBs and UEs are randomly deployed in the macrocell area.

Figure 41 describes the user satisfaction ratio with respect to the minimum DL data rate requirement. Squared marked, circle marked, diamond marked, and star marked curves respectively correspond to our proposal, RSRP with CRE bias equals to 6 dB, RSRP with CRE bias equals to 3 dB, and RSRP solution without CRE. Simulation results show that CRE enhances the user satisfaction rate, by offloading UEs from overloaded MeNBs to lightly loaded SCeNBs. In particular, implementing CRE is beneficial in the region characterized by higher rate requirements, where notable gain (up to 17%) can be achieved with respect to the classic RSRP scheme. On the contrary, implementing the proposed user centric solution is always beneficial: our scheme ameliorates the user satisfaction through an optimized load balancing that jointly takes into account the backhaul constraints and cell loads. Our approach gains up to 58% on the user satisfaction with respect to the classic RSRP solution.

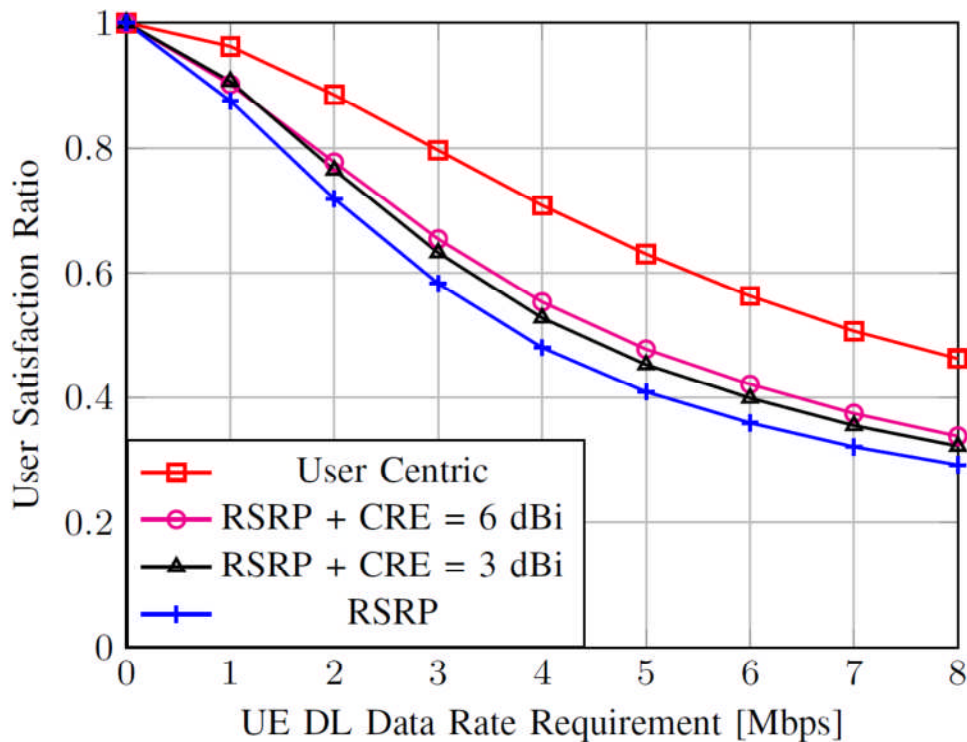


Figure 41: User satisfaction ratio with respect to the minimum DL data rate requirement for different association schemes

Figure 42 shows the overall network DL capacity achieved by the different association schemes. This figure clearly describes the tradeoff between the overall network performance and the user performance. Our solution may achieve limited capacity, from the network perspective, since it tries to fairly distribute the network resources amongst UEs, which experience different path losses. Accordingly, cell edge UEs may meet their data rate requirements at the cost of lower throughput experienced by UEs located nearby the eNBs. Furthermore, when UEs are not characterized by specific rate constraints, reducing the EMF becomes the main objective of our scheme.

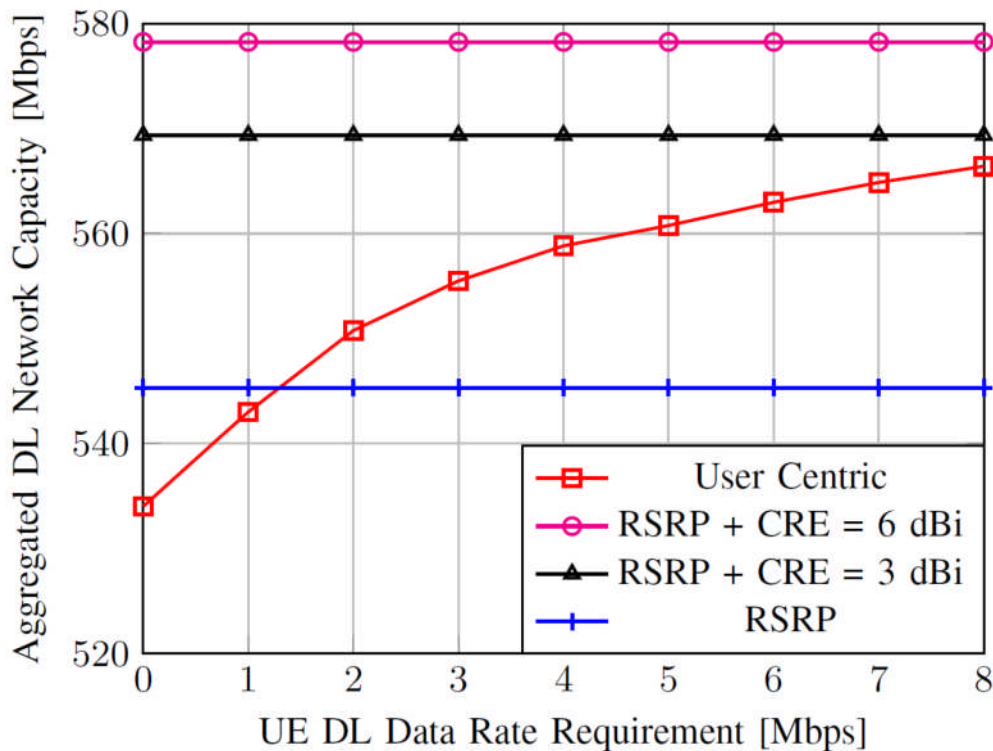


Figure 42: Overall network DL capacity with respect to the minimum DL data rate requirement for different association schemes

On the contrary, by implementing the classic solutions, the association is not dependent on the UE service requirements: without CRE, cell edge UEs suffer from large path loss, while by introducing CRE, UEs located at the macro cell edge can connect to lightly loaded SCellNBs and improve their performance as well as the overall network capacity.

Figure 43 shows the daily average EI due to UL with respect to the minimum DL data rate requirement. We can note that the higher network capacity achieved by the RSRP schemes with CRE comes at cost of higher EMF exposure. In general, CRE may offload macro UEs to nearby small cells; however, since this technique takes into account the overall DL SINR (and not just the channel gain, which impacts P^{UL}), it may also increase the distance between the UE and the serving eNB, if the perceived interference generated by the neighbouring MeNBs is larger than the interference due to the neighbouring SCellNBs. Finally, our user centric proposal can achieve large gain, in terms of the EI, either when the data rate is not the main system goal, or when the rate target cannot be reached. In particular, our approach gains up to 21% on the EI when compared to the classic association solution based on RSRP.

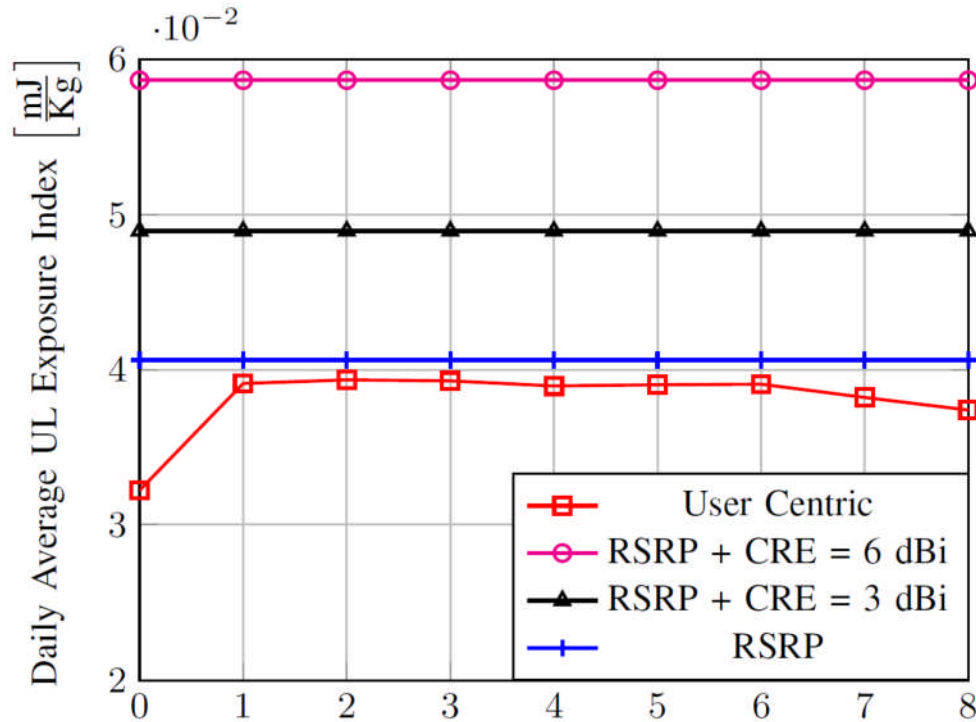


Figure 43: Daily Average Exposure Index with respect to the minimum DL data rate requirement for different association schemes

3.2 Autonomic networking with EMF reduction objective

3.2.1 Self-organizing strategies for EMF reduction in heterogeneous network

This section extends the analysis and introduces additional techniques for EMF exposure reduction in heterogeneous network with small cells. Section 3.1 has focused on UL exposure reduction by means of optimised association of mobiles to base stations. Section 3.2 introduces both UL and DL transmission components to the EMF exposure model and shows that indeed the UL component is the dominant one in spite of its local impact. The activation criterion and the guideline for small deployment to reduce EMF exposure are described. Two self-optimization algorithms aiming at reducing EMF exposure while enhancing network capacity (using an eICIC algorithm) or while maintaining minimum DL QoS are proposed. The general framework of self-organizing networks (SON) is addressed in Section 2.2.2.5.

3.2.2 Small cells deployment guidelines with self-optimizing enhanced Inter Cell Interference Coordination (eICIC)

This first approach is developed in the particular context of Heterogeneous Networks (HetNets). HetNet is a promising approach for capacity and coverage extension in macro-cells network using small cells. The aim is to locally enhance the network performance and energy efficiency compared to macro-cells networks. However, when deploying small cells (SCs) in the cellular network, a special care should be given to their location. In fact, SCs can be more effective from capacity point of view when deployed near cell edge or at hotspots but not too close to the base station. From the overall exposure perspective when a SC is active, it generates an additional DL exposure by radiating all over the network area. On the other hand, in UL it has a

more local effect due to power control and a higher impact on EMF exposure due to its proximity to the user. Thus, both UL and DL exposure and capacity, must be taken into account for an EMF efficient planning of the SCs deployment including dimensioning, parameters settings and optimization. This section thus aims at evaluating the impact of a single SC on EMF exposure taking into account both UL and DL transmissions. Then we analyse the minimal distance from the macro-cell for deploying the SC. The analysis is then extended to a more general network configuration where we compare dense and sparse deployment of SCs.

3.2.2.1 Small-Cells activation and Exposure gain

To measure the exposure gain resulting from the deployment of SCs in HetNet we first look at the exposure gain brought about by activation of a single SC. When the SC b with coverage area A_b is activated in the coverage area A_m of macro cell m , it generates an UL related SAR due to EMF radiation, and an EI given by $E_b^{UL} = \int_{A_b} \psi(P_{r,b}) T_r \lambda(dr)$, $\lambda(dr)$ being the intensity of users' spatial distribution in the network during the entire period of EI calculation, $P_{r,b}$ is the power transmitted by user in network location r during time duration T_r . ψ is a linear transformation of power into SAR (obtained through measurements and electromagnetic simulations) [Conil, 2013]. In the simulations below, a stationary traffic has been assumed, and the EI has been calculated for a duration of 6h40. Conversely when the SC b is turned off the total amount of UL exposure (EI) increases by:

$$\Delta E_b^{UL} = \int_{A_b} \psi(P_{r,m}) T_r \lambda(dr) - E_b^{UL}. \quad (10)$$

Note that ΔE_b^{UL} is the gain in exposure obtained after SC b activation. From the DL perspective, the activation of SC b contributes to the overall exposure (EI) in the network by:

$$E_b^{DL} = \int_A \psi'(P_b \cdot h_{b,r}) T_r^D \lambda(dr), \quad (11)$$

where ψ' is a linear transformation of the DL incident power density into SAR, T_r^D is the DL communication time, P_b is the DL emitted power of SC b and $h_{b,r}$ the path-loss from SC b (i.e. the antenna location) to the user location in the network area A . It is noted that the exposure of non-communicating users will be obtained using a scaling factor of (11).

The activation of the SC is thus EMF beneficial if:

$$\Delta E_b^{UL} > E_b^{DL} \quad (12)$$

It is noted that, for sake of simplicity, we use the pessimistic assumption that after activating the SC the macro cell transmissions remain the same. This relation defines the activation condition for a given SC. The activation policy depends only on the users' spatial distribution intensity, exposure duration and the assumed propagation model.

3.2.2.2 Relationship between distance to macro-cell and activation

The position of the SCs with respect to the macro-cell has an important impact on the level of EMF exposure in the network. This interdependence between SC location

and EMF can be inferred from the activation condition and is described in Appendix 2: Small cell position and activation condition.

A simulation of the activation rule composed of a single SC deployed at a certain distance from the central macro site shows (see Figure 44) that the number of users being served is a dominant component for the SC activation compared to the distance from the macro-cell. The number of n users transmitting and exposed to UL transmissions represents 40% of the total population (UL transmissions are assumed to have local impact). All the population is exposed to DL transmissions originated by the remaining 60% having DL transmissions. Unless otherwise stated, the simulation parameters are all presented in Table 3. In the simulation results, the small-cell is activated when the traffic load is significant, which typically occurs when the number of active users served by the SC is high even if the gain in exposure and capacity is not necessarily significant. To further decrease exposure to EMF and increase the network capacity, an optimization of the SCs coverage relying on eICIC is presented in the next section.

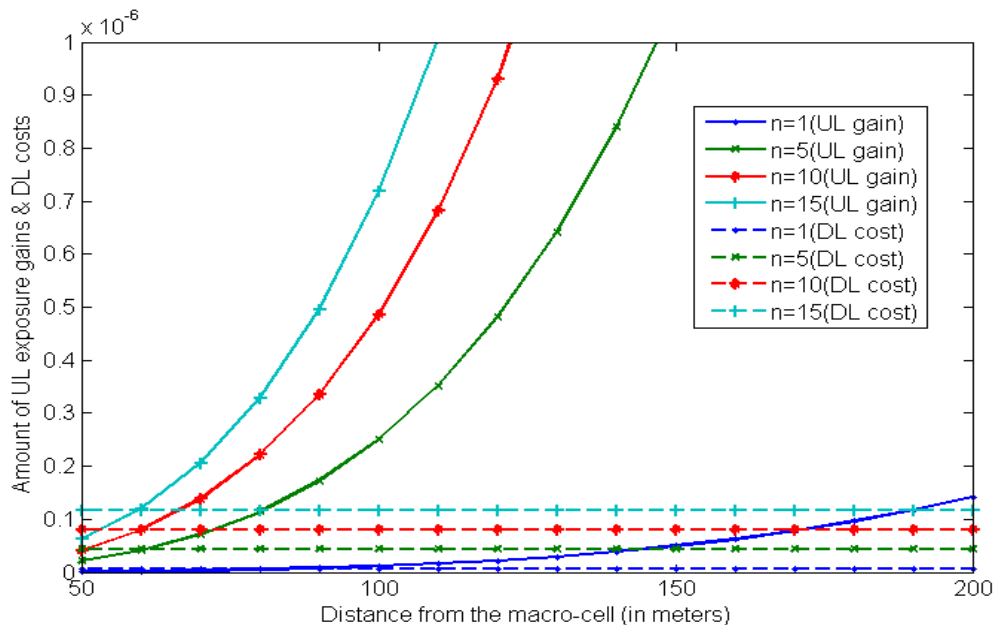


Figure 44: UL exposure gain (J/Kg) as a function of the distance to the macro cell with n users in the SC coverage area

3.2.2.3 EMF exposure reduction using self-optimised eICIC

This section is devoted to the analysis of an adaptive mechanism to increase the SCs coverage and its contribution to EMF exposure reduction. The mechanism relies on the coverage range expansion method of LTE technology defined in [3GPP TS 36.300] allowing the increase of SCs coverage by increasing the value of the Cell Individual Offset (CIO). The CIO is used in the network selection/reselection and handover (HO) procedures [3GPP TS 36.300] [3GPP TS 36.331]. We note that the increase of coverage is achieved without increasing RSRP values of the pilot signal power of the cell. As a consequence, users in the extended part of the coverage are highly interfered by the neighboring cells, mainly by the macro-cell, and thus experience poor network performance. To circumvent this, the 3GPP has

standardized the time domain interference coordination mechanism named eICIC. The eICIC is based on the Almost Blank Sub-frame (ABS) procedure that allows protecting users in the extended part of the SC coverage by muting interfering macro-cell during the ABS duration.

Let the mute ratio or ABS duty cycle θ be the proportion of time, the macro-cells do not schedule any users on some specific ABS sub-frames and during which the SCs' users are scheduled without being interfered by macro-cells. To avoid performance degradation, the value of θ must be optimised in order to preserve or enhance users DL QoS. Let $U(r, \theta)$ be the average throughput of a user in location r . The network utility can be written as follows:

$$\mathcal{U}(\theta) = \sum_{r \in A} \frac{1}{U(r, \theta)} \quad (13)$$

Optimizing the harmonic sum $\mathcal{U}(\theta)$ of users rate $U(r, \theta)$ (all over the network area A) allows to minimise the file transfer time and thus exposure duration of users. It is easy to see that the defined utility is convex and thus a minimum can be found rapidly with on-line implementation. Simulation results using the optimal value of θ are gathered in Table 4. Here the simulation settings consider two types of SCs deployment, namely dense and sparse with 100 users randomly generated in the simulation area. For each deployment 10 (resp. 4) SCs are randomly positioned in each sector of the central macro-site with a minimum inter-site distance of 50m (resp. 100m) between SCs. The deployment of SCs allows not only to increase the mean users DL rate, but also to reduce the overall exposure. Interestingly, the activation of the eICIC can be preferable in comparison to further densification of the network in terms of exposure reduction but not for the average users' rate. As expected the activation of the eICIC is on the average beneficial for capacity improvement. The activation may also lead to performance degradation particularly when the number of users is low at the SCs and the macro-cell is highly loaded. Finally the best performances are obtained for the scenario of dense deployment of SCs combined with the activation of the eICIC mechanism.

Table 3: Parameters settings

Parameters	Settings
System configuration	LTE, 10 MHz bandwidth (50 PRBs) UL and DL
Maximum Tx powers: eNB SCs	46 dBm 30 dBm The CIO values are set to 9dBm only with eICIC activation.
Macro-cell deployment	Hexagonal, 500 m inter-site distance, 21 sectors simulated, statistics maintained over 3 central sectors
SC deployment	4 SCs per sectors randomly positioned for sparse deployment, 10 SCs for dense deployment.
User deployment	100 users uniformly generated in the central cells. Maximum of 8 users in other cells
Pathloss Macro-to-UE SCs-to-UE Shadowing standard	128.1(dB) + 37.6(dB) log 10(R(km)) 140.7(dB) + 36.7(dB) log 10(R(km)) 4 dB

deviation	
Scheduler	Round Robin
Exposure [Conil, 2013] DL SAR weight UL SAR weight	4.7e-3 1/Kg 8e-5 1/Kg

Table 4: Simulation results for dense and sparse SC deployment

Deployment	Metrics			
	No eICIC		eICIC	
	Average Exposure Gain	Mean User DL Rate	Average Exposure Gain	Mean User DL Rate
Macro only	0%	0.54 Mbps	-	-
Sparse SCs	3.45%	1.30 Mbps	20.69%	1.45 Mbps
Dense SCs	10.34%	2.32 Mbps	48.28%	2.95 Mbps

3.2.3 Uplink based load balancing with downlink QoS constraints

This section describes the second Self-Organizing Network (SON) approach for reducing the overall EMF exposure, expressed in terms of the EI. The proposed SON method is a load balancing algorithm, based on a stochastic approximation. It adapts the small cells' coverage based on UL loads and on DL QoS indicators. The rationale for the proposed solution is that, to a certain extent, by off-loading macro-cell traffic towards small cells, UL transmit power of cell edge users is decreased. However, above a certain CRE, DL QoS can be jeopardized, and should be therefore introduced as constraints in the SON algorithm. It is noted that this approach is of interest when self-optimised eICIC described above cannot be implemented.

3.2.3.1 Optimization problem formulation

For sake of clarity, Figure 45 shows the heterogeneous network layout with the UL and DL transmissions that contribute to the EMF exposure. In order to reduce the EI in the network one can seek to minimise a well-defined cost function that combines the joint effect of both UL and DL transmissions. More specifically the focus is to reduce the average level of UL Tx power from UEs to their serving cells as an intermediate metric to reduce EI. Such objective can be achieved by increasing SCs' coverage, and off-loading macro-cell traffic towards SCs. In fact, off-loading the macro-cell with low power nodes such as SCs allows, not only to bring more users to transmit to a closer serving cell with reduced power, but also to a certain extent, to increase the network capacity by off-loading loaded nodes [Combes, 2012]. However, as more users are off-loaded to the SCs it is likely to observe a fast decrease of the UL/DL QoS of the SCs' traffic. This is due to a large number of new-interferers (in UL) inside the macro-cell coverage area and the additional interference produced by the SCs that see their loads increase (in DL). It is also related to the fact that in DL, as CIO increases, more users are attached to SCs which are not their best servers (see also Section 3.1). The EI reduction problem is formulated as a QoS constrained optimization problem which is addressed using an off-loading method relying on SCs coverage's expansion/contraction. Indeed by expanding their coverage, SCs can collect more users from the macro-cell relying on the user-to-cell

best server attachment criterion [3GPP TS 36.300]. As previously mentioned, coverage extension is achieved, not by increasing the Tx power of the SCs but rather by increasing/decreasing the value of the CIO.

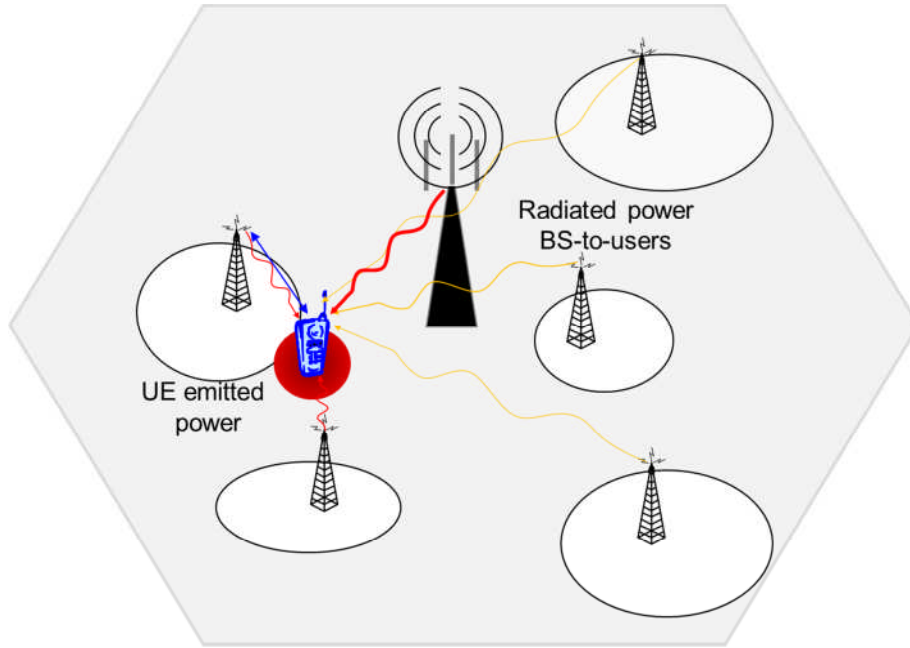


Figure 45: EMF sources in HetNets

The problem thus formulates for each small-cell as follows:

$$\begin{aligned} \min_{CIO_s} & (\rho_M^{UL} - \rho_{sc}^{UL}) \\ \text{s.t. } & QoS_{DL} > QoS_{target} \end{aligned} \quad (14)$$

where ρ_M^{UL} is the UL load of the macro-cell (i.e. percentage of UL allocated resources averaged over a time interval), ρ_{sc}^{UL} is the UL load of each small cell in the network, QoS_{DL} and QoS_{target} are respectively the actual and target DL QoS levels defined by a certain QoS indicator. The small-cell load and the small-cell DL QoS indicator are measured locally, whereas the macro-cell load can be broadcasted or transmitted to the SCs via the X2 interface. As DL QoS constraint, the cell outage is considered and is assumed to be increasing with the cell load. It increases with the cell coverage area and hence with the CIO value. We define the cell outage $\mathcal{O}_s(CIO(t))$ of SC s at an instant t as the probability that a given user experiences a SINR smaller than a predefined threshold.

3.2.3.2 Self-optimization algorithm

In order to solve the proposed optimization problem and given a DL outage constraint $\bar{\mathcal{O}}$, an iterative stochastic load-balancing algorithm has been designed as follows:

$$CIO_s(k+1) = CIO_s(k) + \epsilon h_s(CIO_s(k)) \quad (15)$$

where:

$$h_s = \begin{cases} \rho_M - \rho_s & \text{if } \mathcal{O}_s < \bar{\mathcal{O}} \\ \bar{\mathcal{O}} - \mathcal{O}_s & \text{if } \mathcal{O}_s \geq \bar{\mathcal{O}} \end{cases} \quad (16)$$

Note that h_s is a discontinuous upper semi-continuous function taking values in the compact convex set $[-1,1]$. The motivation for the definition of h_s is to try to balance the macro and small cells' loads as long as outage is low. Hence when $\mathcal{O}_s < \bar{\mathcal{O}}$ the dynamic is driven by the load-balancing objective and the SCs increase their coverage's to absorb more UL traffic from the macro station. On the other hand, when the condition $\mathcal{O}_s \geq \bar{\mathcal{O}}$ holds, the dynamics goes toward the fulfillment of the constraint namely to remain in the constraint set for the outage. It is assumed that the macro-cell broadcasts regularly its load to the SCs while the outage threshold is introduced by the operator via the management plane. The load and the outage of the small-cells can be measured locally at each SC s . The convergence properties of the algorithm are studied in [Sidi, 2014].

The exposure calculation has been defined in Section 3.2.2.1. We assume that DL EMF exposure over the entire population is obtained from the calculated exposure of the active DL users multiplied by a coefficient $C1 = 20$, namely 5 percent of the population is in communication. We recall that in the UL, the exposure to EMF of active users only is taken into account due to the local nature of UL transmissions (i.e. low power transmissions supported by power control mechanism).

3.2.3.3 Use case and performance of the algorithm

Performance evaluation of the self-optimization algorithm for EMF exposure reduction is performed in this section by means of numerical simulations. We consider a geographical area of a LTE network with two rings of tri-sectored BSs in a dense urban environment. The simulation configuration parameters are defined and set in Table 5.

Table 5: Simulation parameters settings

Parameters	Settings
System configuration	LTE, 10 MHz bandwidth (50 PRBs) UL and DL
Maximum Tx powers: eNB SCs	46 dBm 30 dBm The CIO values are adjusted in the range -2 -12 dB
Macro-cell deployment	Hexagonal, 500 m inter-site distance, 57 sectors simulated, statistics maintained over 3 central sectors
SC deployment	4 SCs per sectors located randomly closed to the edge of each sector coverage
User deployment	Poisson Arrival at rate $\lambda = 5$ at central cells. Maximum of 8 users in other cells
Service Type File Size UL/DL traffic load ratio DL Coverage target rate	File download/Upload 15Mb 30% 1.5Mbps
Pathloss Macro-to-UE	

SCs-to-UE Shadowing standard deviation	128.1(dB) + 37.6(dB) $\log_{10}(R(km))$ 140.7(dB) + 36.7(dB) $\log_{10}(R(km))$ 6 dB
Scheduler	Round Robin
Exposure DL SAR weight UL SAR weight Users activity coef.	4.7e-3 1/Kg 8e-5 1/Kg 20

The distributed self-optimizing algorithm is activated in the SCs with a target outage of 5% and a threshold rate of 1.5Mbps. The simulation is performed during 6h40, which is the time the EI is calculated. Stationary traffic is assumed. Figure 46 depicts the evolution of the maximum power plus CIO as a function of the algorithm iterations (6s per iteration). It is observed that the CIO does not systematically grow to its upper limit of 12dB and adapts to the QoS constraint according to the traffic in each SC. Note that the pilot powers plus CIO from the macro-cells are kept constant as they are not concerned with the coverage expansion. In Figure 47 one can see that the outage barely grows above the defined limit and is indeed monitored and controlled by the self-optimizing mechanism. The upper three curves correspond to the three macro cells while the lower twelve curves – to the SCs. Exposure gain is now quantified as the relative exposure reduction with respect to the base line scenario without the SON mechanism.

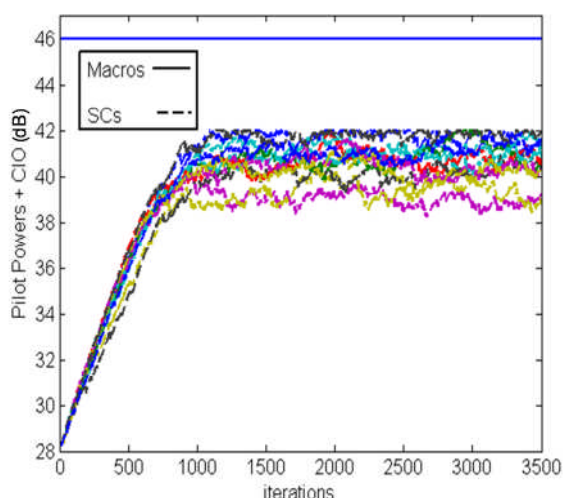


Figure 46: Convergence of Pilot Powers + CIO values using self-optimization. One iteration represents 6 seconds.

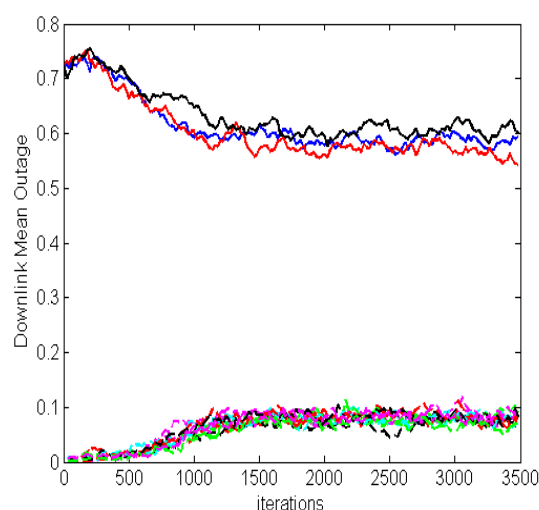


Figure 47: DL mean outage values using self-optimization (outage of 1 corresponds to 100%).

A reduction in exposure is translated into a positive gain, and vice versa. The baseline scenario is considered for a $CIO = -2dB$ for all SCs. Figure 48: Percentage of mean UL exposure gain using self-optimization and Figure 49: Percentage of mean DL exposure gain using self-optimization show the main results of the numerical analysis, namely the exposure gain for the UL, DL and the total (i.e. UL and DL combined) EI, respectively, brought about by the self-optimizing algorithm during a period of 6h40. The combined UL and DL average exposure gain for the macro-cells is around 30 percent (see Figure 50), which is similar to that in the UL (see Figure 48: Percentage of mean UL exposure gain using self-optimization). This result shows that the UL

component comprizes the dominant contribution to EMF exposure. In the DL, a relative exposure increase varying between 10 and 20 percent can be observed (see lower curve in Figure 48: **Percentage of mean UL exposure gain using self-optimization** **Figure 49: Percentage of mean DL exposure gain using self-optimization**), which is accompanied by an increase in outage of DL users at the SCs. It is recalled that the outage level is controlled by the self-optimizing algorithm. The overall EMF reduction computed over the cells implementing the SON algorithm varies between 15 and 20 percent.

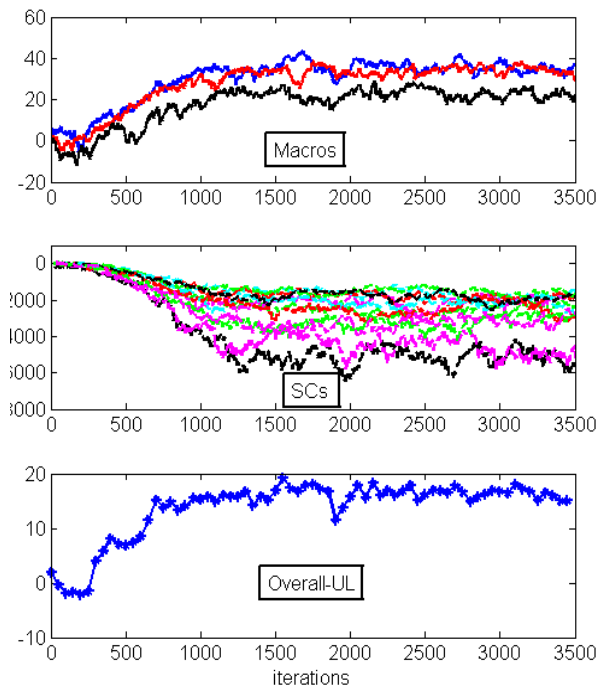


Figure 48: Percentage of mean UL exposure gain using self-optimization

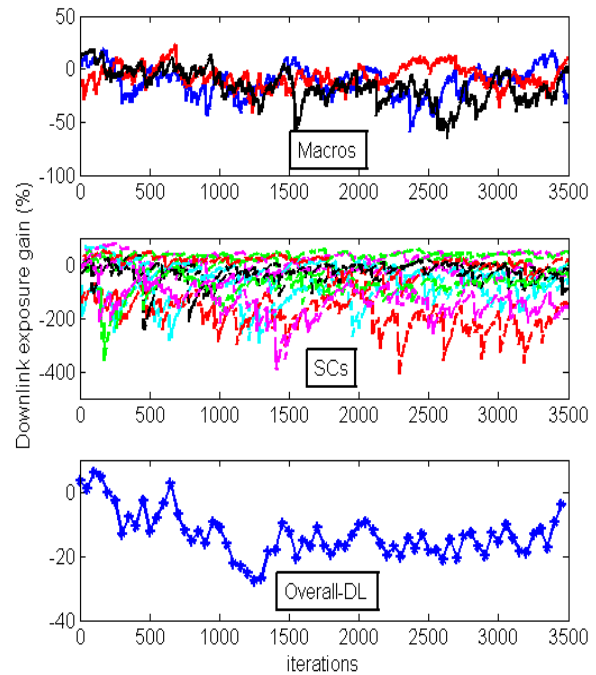


Figure 49: Percentage of mean DL exposure gain using self-optimization

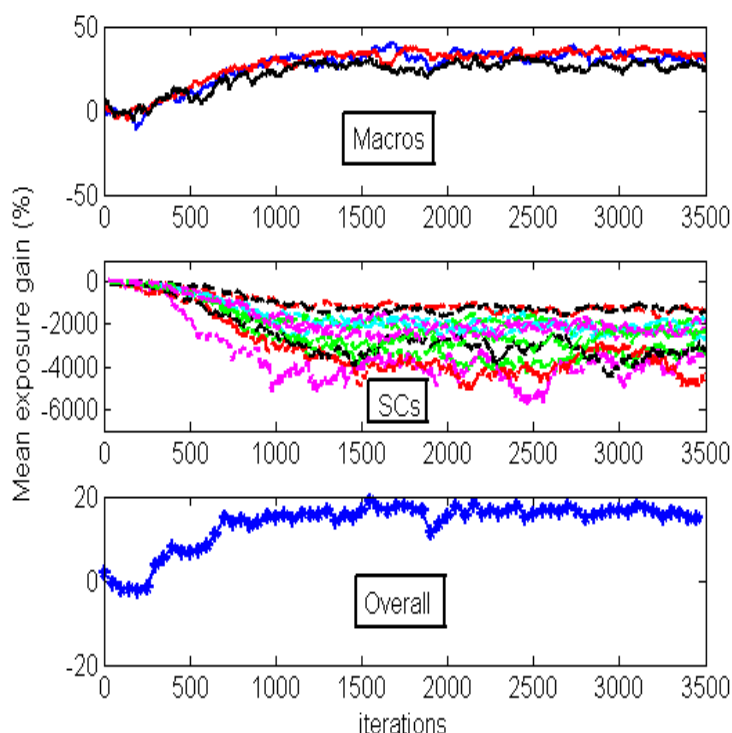


Figure 50: Percentage of mean EMF exposure gain for combined UL and DL using self-optimization

3.2.3.4 Conclusions

This section derives the expressions for UL and DL exposure to EMF, in terms of SAR, exposure duration and the traffic distribution, as defined by the Exposure Index. The activation condition of the SC is given, and the gain of exposure which considerably grows with the distance of the SC to the macro cell is illustrated. Two self-optimizing mechanisms have been proposed, namely UL load balancing under DL QoS constraints, and self-optimizing eICIC which dynamically adapts the SC coverage and manages its interference. The latter mechanism is particularly effective and, for a dense SC deployment scenario, has achieved 48 percent exposure gain.

3.3 Small cell densification

The deployment of novel HetNets is today considered as a consistent solution for mobile network capacity rise. In LTE-A networks, HetNets commonly refer to the deployment of SC either independent or coordinated with the existing MeNB [3GPP R1-070674]. Despite the increase in the number of EMF sources, low transmit powers of SC combined with LTE-A interference management mechanisms such as eICIC [Pedersen, 2013] could lead to an efficient offload of the usual macro layer and therefore minimise EMF exposure. The power control in the uplink (UL) should also reduce UE transmit power as the path loss between UE and SC is often lower than between UE and MeNB. HetNets need to cope with the challenge of offering an always better QoS while minimizing the EMF exposure.

The study reported in this section aims at the identification of small-cell network topologies and configurations that minimise EMF exposure for constant or comparable QoS. The analysis jointly considers metrics of interest for the cellular

operators, end-users and whole population as well. The user QoS is characterized by the DL/UL service coverage outage and the user peak throughput statistics. The energy efficiency is assessed by considering the average DL power consumed by eNodeB's transmission with respect to their traffic load according to the model published in [Klessig, 2011], which distinguishes the power consumption between macro and micro base-stations (the micro model is assigned to the SC). Finally, the EMF exposure of the population is characterized in both DL and UL. In the DL, the exposure is characterized by the total field strength (sum of all DL contributions coming from neighbor base stations) that is directly proportional to the SAR. In the UL, the SAR of active users proportionally depends on the transmit power of their device, which is characterized in this study by the mean UE transmit power during active communication.

These exposure metrics are actually the expected inputs in the computation of the LEXNET EI [Conil, 2013], which is however not computed in this work.

The analysis of the UL/DL LTE-A network performance relies on an extended version of the 3D coverage simulation tool presented in [Brau, 2012]. Path-loss predictions are computed at different heights based on a real 3D environment representation and the Volcano technology (site-specific ray-based propagation models [Corre, 2009]). The user traffic is modelled by several profiles (i.e. network usages) and a 3D heterogeneous spatial distribution. The framework integrates ICIC and eICIC techniques to mitigate interferences. In DL, a static ICIC Fractional Frequency Reuse (FFR) scheme is considered for MeNB. It is complemented with a Time-Domain eICIC to enhance the cell edge experience of SC users [Pedersen, 2013]. Two main parameters can be tuned to modify the eICIC configuration: the CRE and the ABS duty cycle. The CRE is typically used as an offset on the SC received power to encourage offloading, i.e. attachment of users to a SC instead of a MeNB. The ABS duty cycle defines the ratio of resources that are dedicated to SC cell-edge users over total radio resources. In UL, the power-control relies on the conventional Open-Loop Power Control technique, which is driven by two cell-specific parameters: a path-loss compensation factor to adjust the link quality and transmit power as a function of the path-loss; and the UL SINR target. UL ICIC is also enabled in case of high interference levels [Castellanos, 2008].

3.3.1 Scenario and methodology

The scenario relies on a typical macro network layout in a dense urban environment, which is densified with co-channel SC. Figure 51 presents the simulation setup and the study area of 0.98 square km in Paris VII district. MeNB are deployed over a larger area, on two rings around a central three-sector site in order to take into account realistic interference patterns. The ICIC scheme is defined by a re-use factor of 3 and 5% of total radio resources being allocated to each FFR sub-band.

Active users are spread in the study area with following rules:

- 1000 active users per square km; one third is served by the considered operator.
- 20% outdoor users, uniformly distributed over the area.
- 80% indoor users, uniformly distributed in the building floors (meaning that the number of users in a building is proportional to its height).

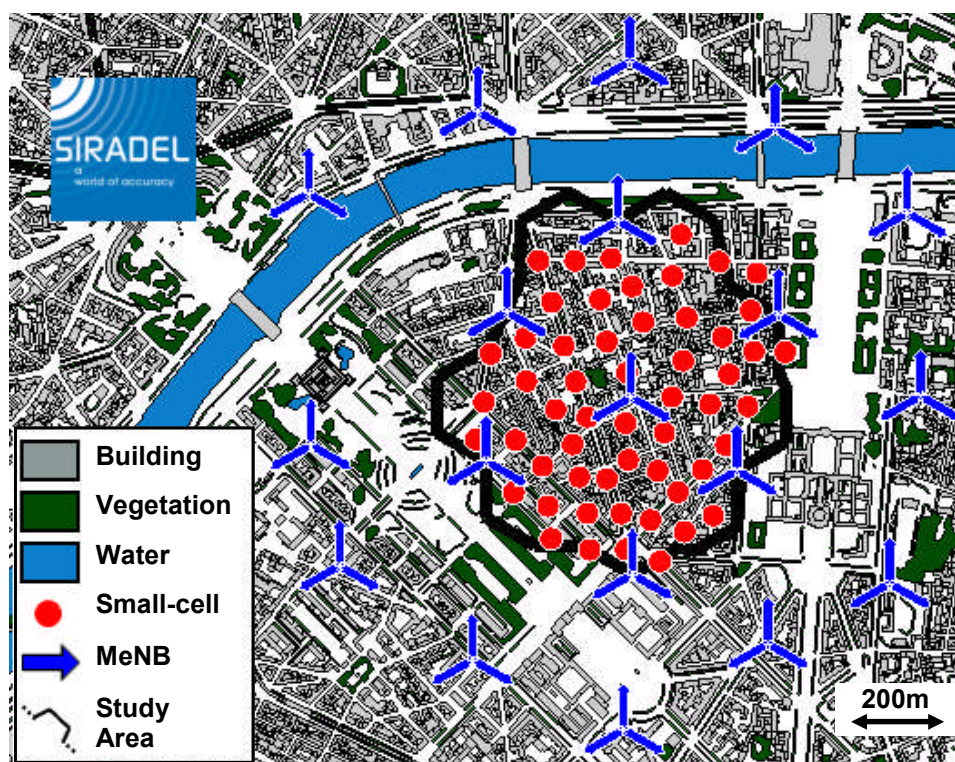


Figure 51: Simulation setup (Small-cell ISD 100m)

SCs are introduced into the network infrastructure to enhance the coverage and boost the capacity. Reduced population exposure and improved energy efficiency are expected as well. SCs are deployed on urban furniture along the streets at a moderate height of 6 m. They are uniformly deployed within the whole study area leading to a quasi-constant Inter-Site Distance (ISD). Three different SC deployment topologies are evaluated in the present study, respectively with ISD of 200 m, 100 m and 50 m (see Figure 51). SC antennas are omni-directional. The maximum transmit power can take values from 100 mW to 5 W. Other main simulation parameters are summarized in Table 6.

Table 6: Simulation parameters

System	LTE FDD 2x10 MHz. Central frequency: 2.6 GHz. UL/DL MIMO configuration: 2 x 2. UL path-loss compensation factor: 1. UL SINR Target: 20.8 dB (when UL ICIC is disabled).
Macro-cell layout	Hexagonal site deployment: two rings around the central site, i.e. 19 sites corresponding to 57 cells (see Figure 51). Inter-site distance (ISD): 450 m. ICIC FFR scheme: 5% of total radio resources being allocated to each sub-band, re-use factor of 3. Average antenna height: 32 m above ground. Maximum total transmit power: 40 W. Antenna: directional, 14 dBi, 6° electric down-tilt, 32 m above ground. UL noise figure: 2.5 dB
Small-cell layout	Spectrum usage: co-channel. SC deployment: Uniform with ISD from 50 m to 200 m.

	Maximum total transmit power: from 100 mW to 5 W. Antenna: omnidirectional, 5 dBi, 6 m above ground. UL noise figure: 2.5 dB
User equipment	UL total transmit power: from -40 dBm to +23 dBm. Antenna: omni-directional, 0 dBi, 1.5 m above ground. DL noise figure: 9 dB.

The same throughput demand is assumed for all users. The study starts with mean throughputs of 90 kbps in DL and 30 kbps in UL. The DL mean throughput has been chosen such that the interference level in the initial macro network leads to 10% of user service outage (i.e. percentage of users that cannot be served with the demanded throughput). Then, in order to subject the network to a realistic traffic increase, we consider an evolution of user data traffic demand based on the Cisco Visual Networking Index forecast [Cisco, 2013]. The projection notably plans a Compound Annual Growth Rate of the mobile traffic of 47% during the five years following 2015. We apply this figure to our scenario and extrapolate LTE mean DL/UL throughput demands from the initial state. We make the assumption that the number and the distribution of active users are kept constant over the years but that their UL/DL throughput demands increase. The obtained evolution thus goes from 90 kbps at Y0 to 610 kbps at Y0 + 5 years (Y5) in DL and from 30 kbps at Y0 to 205 kbps at Y5 in UL, as illustrated in Figure 52. Note that these throughput values represent the mean user throughputs during active communications.

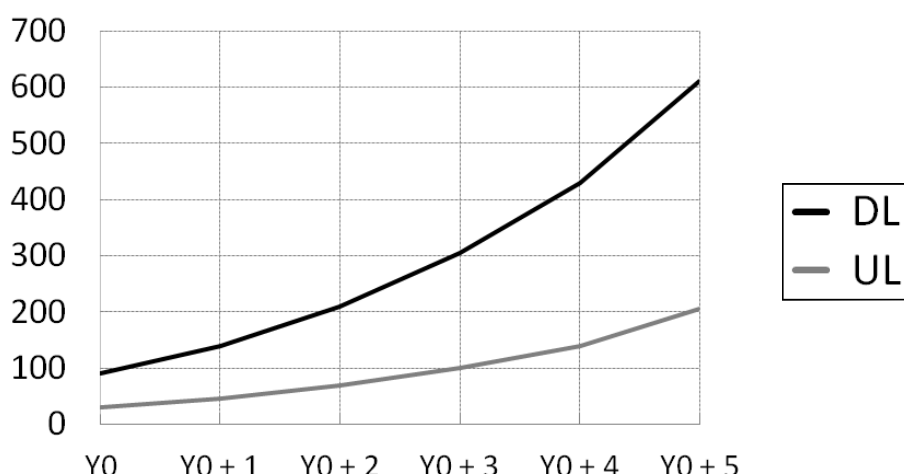


Figure 52: Forecast of mean active user DL and UL throughput demands (in kbps) considered in the study

The proposed analysis involves many variable parameters related to topology, offloading, user traffic, and interference management. A rough and exhaustive presentation of results would be unreadable. We made the choice to structure the results in two main scenarios, as follows:

- (1) The impact of the network configuration is studied with initial user traffic demand (considered as “moderate”). First, the optimal configuration (CRE and ABS) is found for each ISD. Then the different SC densification strategies (from the three simulated ISD) are compared.
- (2) We go further in the evaluation by characterizing the performance of the three SC densification strategies over a period of 5 years. Operators must indeed

anticipate the evolution of the network performance over several years before starting the initial densification stage. We analyse how a HetNet configuration found suitable, or even optimal, to accommodate the current network traffic at a given time may be impacted when traffic increases.

3.3.2 Optimal SC deployment strategies for moderate user traffic

In the first part of this study, we consider a SC deployment with a fixed ISD and search for the optimal configuration (transmit power, CRE, ABS duty cycle) based on the joint analysis of the network capacity, EMF exposure and energy efficiency. Detailed results for ISD 100 m are given in Section 3.3.2.1. The second part of the study is reported in Section 3.3.2.2, where the performance of optimal configurations for ISD 200 m, 100 m and 50 m are compared.

3.3.2.1 Evaluation at ISD 100 m

Simulated results for ISD 100 m are presented in Figure 53. The transmit power of SCs varies along the x-axis, while the different curves correspond to different CRE values. The horizontal dotted lines give the macro-only performance as a reference. Only results with ABS duty cycle equal to 12.5% are shown.

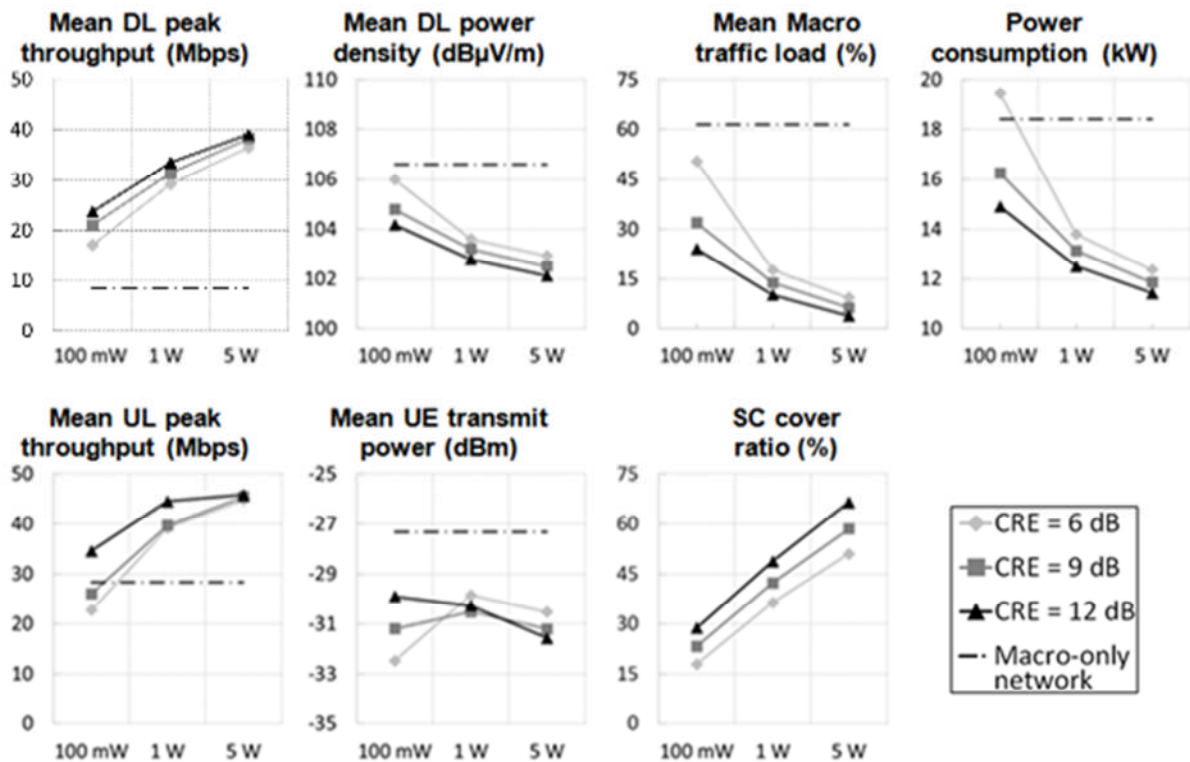


Figure 53: Network performance KPIs for various SC transmit powers and CRE

It is observed that all tested small-cell configurations allow for full service coverage, on the contrary to the macro-only network. Basically, increasing the SC transmit power and CRE value leads to an increased offload from the MeNB to the SC. For instance, increasing the CRE value by 3 dB with the highest transmit power leads to

an increase of about 8% in SC cover ratio. Besides, the DL peak throughput is at least doubled whatever the transmit power and CRE values are. The UL peak throughput is also significantly increased for a SC transmit power higher than 1 W. Further increasing the SC transmit power jointly enhances the QoS and reduces DL EMF exposure thanks to an efficient offloading of macro-cells. Besides lightly loaded SC address user traffic more locally than macro-cells.

The UE transmit power given in Figure 53 is an average over the whole duration of the communication. It is reduced by 1.5 dB to 2.5 dB with the introduction of the SC layer, but with different impacts of CRE values depending on SC transmit power level. From medium and high SC transmit powers, the proportion of UE attached to distant eNBs is strongly reduced thanks to a significant reduction of MeNBs coverage especially at cell-edges. Therefore mean UE transmit powers and interferences jointly decrease. The behaviour is different for low SC transmit powers for which the ICIC-based power-control mechanism efficiently regulates the UE transmit power to limit interferences and leads to better performances for low than for high CREs.

Besides, the mean DL power density is decreasing with the offloading level, up to 3 dB when the SC transmit power and CRE are at their maximum. Same conclusion is also drawn on power consumption as the reduction goes up to 40% at maximum offloading.

These results stress the great benefits of SC deployment that gives higher capacity along with a reduction in the global EMF exposure and eNodeB DL power consumption. Except for the UE transmit power, we observe that the greater the offloading is, the better our metrics of interest are. Same tendency is observed for SC deployments with ISD 200 m and 50 m, i.e. the optimal configuration is obtained when SC transmit power and CRE are maximal.

3.3.2.2 Comparison of different SC inter-sites distances

We now compare SC densification topologies respectively with ISD 50 m, 100 m and 200 m, with the optimal network parameters identified in the previous section. Figure 54 gives the statistical distribution of the DL power density and UE transmit power.

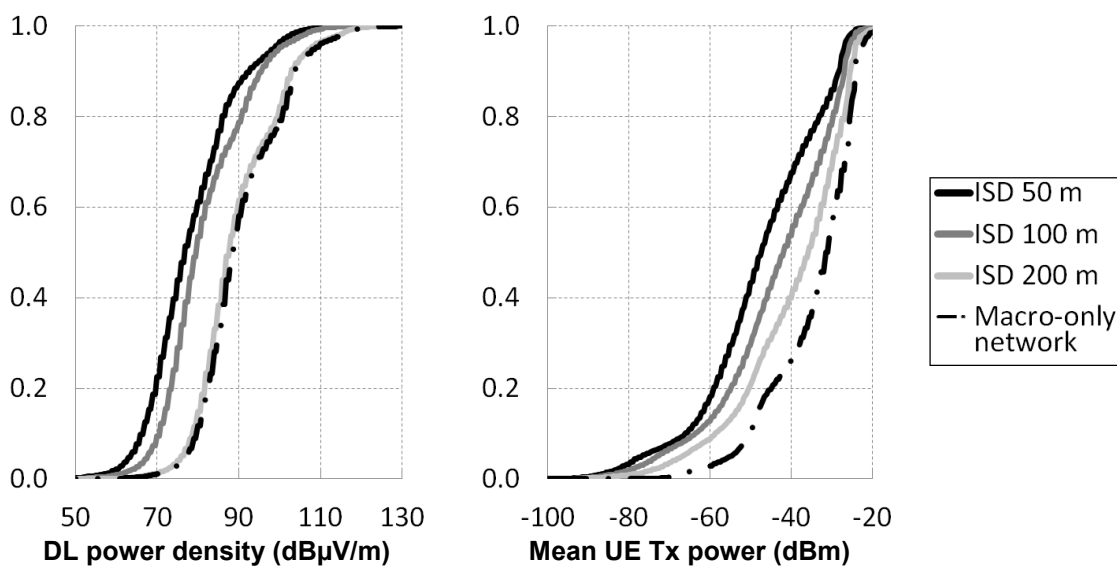


Figure 54: CDF of EMF proxies for the different topologies.

SC deployment brings a strong reduction on DL power density with ISD 100 m and 50 m. This is the combination of three positive effects:

- The DL spectral efficiency is globally improved thanks to the introduction of SCs, then less resources have to be allocated to transmit the same amount of traffic.
- Except in close proximity of the SC, the main contribution to DL power density is coming from the macro layer; and the reduction of this contribution is directly proportional to the macro offloading.
- As for the power density, the main contribution to the co-channel interference is coming from the macro layer; the macro offloading allows for significant reduction of the global interference level, leading to an improvement of the spectral efficiency.

Besides, the increase in the DL power density by the SC is limited to the close vicinity of the antenna.

The UE transmit power is also globally decreasing with small-cell densification:

- The path-loss of SC users is significantly improved and therefore the required transmit power for those users is much below the one required with the MeNB.
- The main contribution to UL co-channel interference is coming from the macro users at the cell edge. The macro offloading thus leads to a significant reduction of the global interference level, causing an improvement of the spectral efficiency.

The positive influence of these phenomena is predominant compared to co-channel interference in the SC layer.

Note that the above conclusions are only valid for a moderate user traffic, thus for limited interferences. Section 3.3.3 presents complementary results with higher traffic levels. Table 7 and Table 8 give additional results (median and quantiles) for all tested topologies.

Table 7: Network performance KPIs versus ISD

			Relative gain		
		Reference – Macro only	200 m	100 m	50 m
DL peak throughput	Median	4.7 Mbps	× 3.4	× 8.9	× 10.9
	<i>5%-ile</i>	<i>0.7 Mbps</i>	<i>× 8.6</i>	<i>× 25.1</i>	<i>× 42.9</i>
UL peak throughput	Median	30.3 Mbps	× 1.2	× 1.6	× 1.7
	<i>5%-ile</i>	<i>13.6 Mbps</i>	<i>× 1.6</i>	<i>× 2.2</i>	<i>× 3.0</i>

Table 8: EMF exposure KPIs versus ISD

			Relative gain (dB)		
		Reference – Macro only	200 m	100 m	50 m
Mean DL power	Median	89.1 dBμV/m	- 3.4	- 9.5	- 12.3

density	95%-ile	108.7 dB μ V/m	- 3.5	- 8.8	- 10.0
Mean UE transmit power	Median	-31.5 dBm	- 5.9	- 10.3	- 15.8
	95%-ile	-22.6 dBm	- 0.8	- 3.2	- 4.4

Figure 55 shows the map of DL and UL EMF proxies for the highest SC deployment density. As expected, the maximum exposure to EMF in DL and UL are not co-located. The DL power density is at its maximum close the MeNBs and SC, while the maximum UE transmit powers are observed in poor coverage area. In particular, users located in deep indoor are exposed to strong UE transmit powers due to poor radio coverage by the macro but also by the SC layers. It can be noticed in the UE transmit power CDF (Figure 54) that the highest quantiles (mainly related to deep indoor locations) only slightly decrease with SC densification. Offloading on indoor cells such as femtocells or existing WiFi APs seems necessary to sensibly reduce this deep indoor UL exposure.

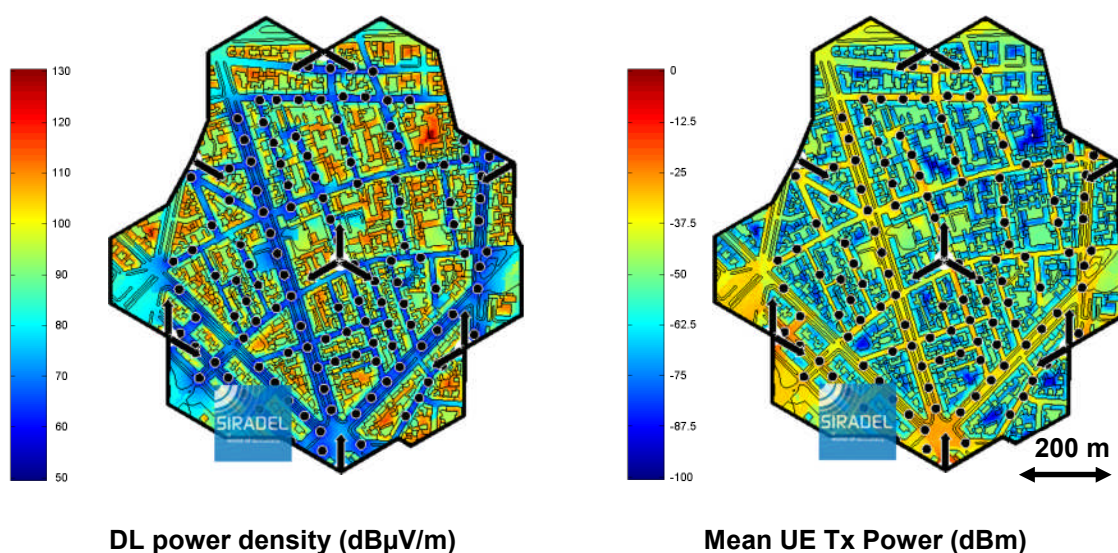


Figure 55: Map of EMF proxies for SC ISD 50 m.

Lastly, Table 9 gives the total power consumption of each deployment as well as the percentage coming from MeNB. The macro-only network shows the highest consumed power. In heterogeneous topologies, the percentage of MeNB consumption decreases with ISD, while the SC consumption strongly increases. A minimum is reached with ISD 100 m. ISD 200 m indeed allows for only limited macro offloading; and ISD 50 m leads to a high proportion of energy consumed by the SC layer.

Table 9: Network power consumption versus ISD

ISD	Reference – Macro only	200 m	100 m	50 m
Total consumption (kW)	18.40	17.02	11.74	15.08
<i>% from MeNB</i>	<i>100.0</i>	<i>92.8</i>	<i>75.0</i>	<i>53.0</i>

3.3.3 Impact of future network traffic growth

This second study focuses on the performance of different SC deployment strategies against the network traffic growth over a period of five years.

The analysis consists in assessing the impact of this network traffic evolution on the three previously-considered SC densifications. First, the service DL/UL outage is plotted in Figure 56 as a function of the time. The availability of radio resources is commonly the main limiting factor in DL (overloading) whereas it is the service coverage on UL (low SINR).

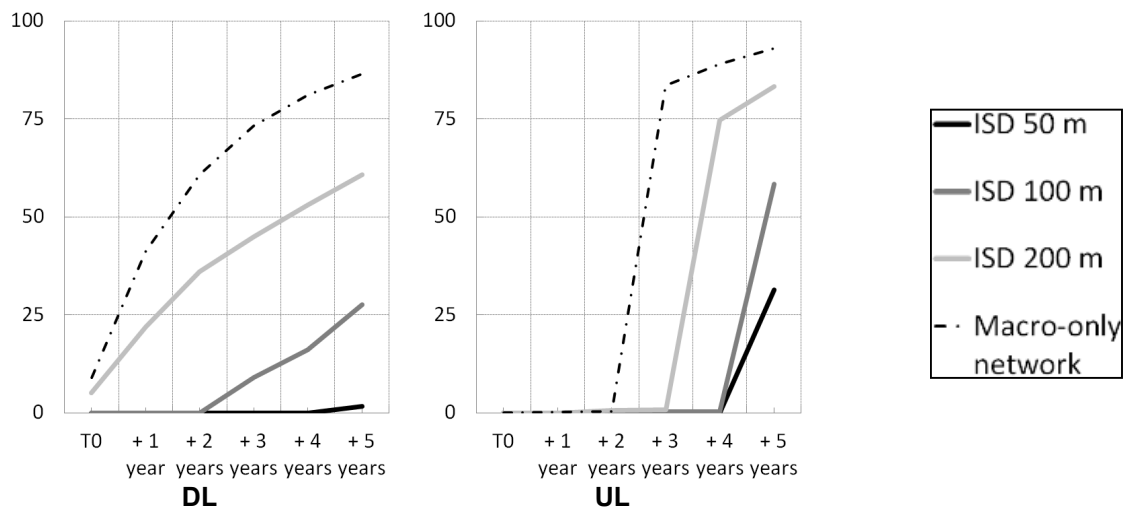


Figure 56: Service outage (%) evolution over time.

It is observed that the service outage remains below 10% up to Y3 (Y0 + 3 years) with the intermediate densification (ISD 100 m) and Y4 with the highest densification (ISD 50 m). Besides, the lowest densification (ISD 200 m) and the macro-only network go beyond this outage threshold from Y1 demonstrating they are not appropriate as a mid-term solution. Finally, none of the tested SC densifications allows for satisfactory user coverage in Y5. The first limiting factor for low to medium SC densifications is the DL network capacity. On the contrary, the highest densification undergoes first a significant loss of coverage in the UL, due to strong interference levels. This observation highlights the importance of considering both DL and UL coverage-limited criteria when designing dense HetNets. The analysis of user peak throughputs, EMF exposure and energy efficiency is only relevant when the network outage remains acceptable. That is why in the following, we only compare those metrics for scenarios having a network service outage lower than 10 %. Main results are reported in Figure 57.

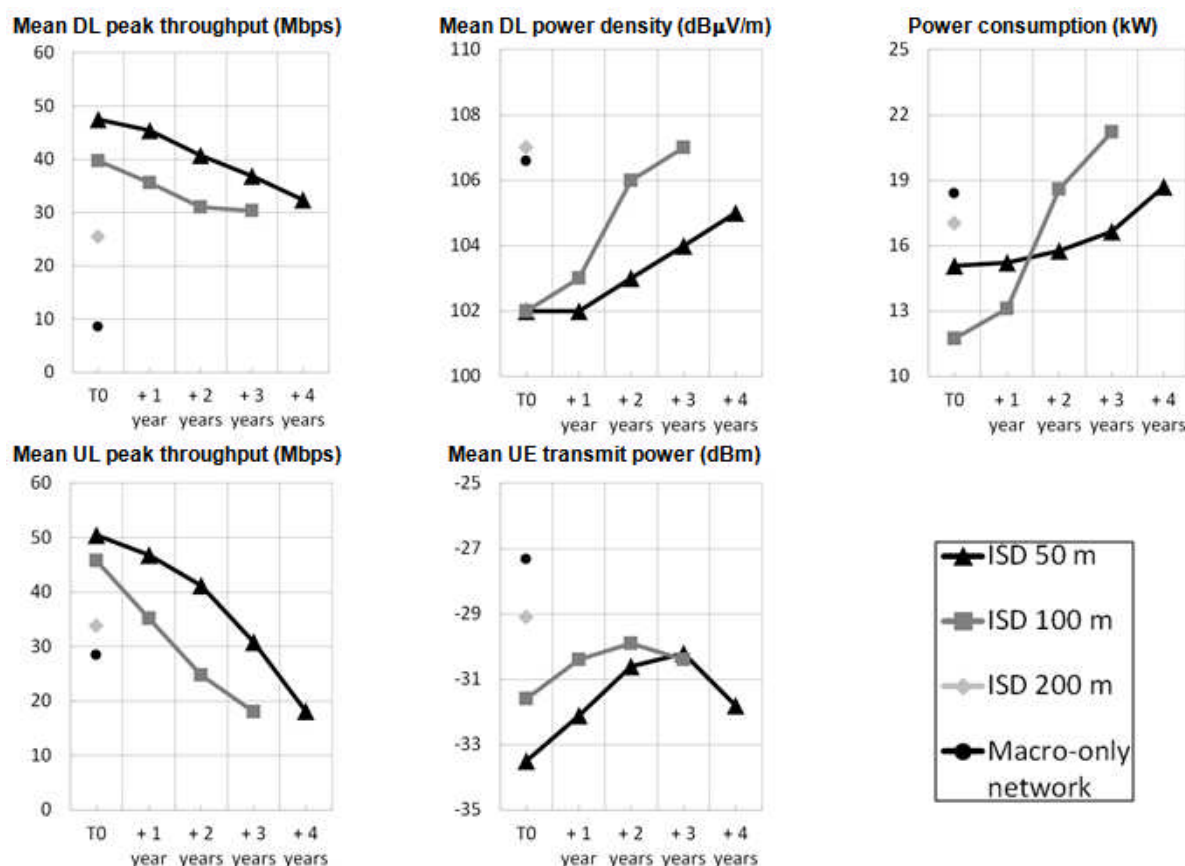


Figure 57: Network KPIs evolution over time.

The increase of user data traffic leads to significantly degraded mean DL and UL peak throughputs over time. For instance, they are respectively reduced by 30% and 64% at Y5 with ISD 50 m. Nevertheless the densification with ISD 50 m clearly remains the best option for almost all KPIs. The impact on the EMF exposure is positive. Even with much higher traffic, the densification with ISD 50 m or 100 m generates an average DL power density that remains below or roughly equal to the one generated at Y0 by the macro-only network.

Whatever the traffic level is, the UE transmit power in the HetNet is always below the one in the initial macro-only network. Actually we observe in Figure 57 that the UE transmit power first increases when the traffic demand goes up; indeed the SINR is degraded by the growing interference, thus more resources are needed. Then we have a decrease of the UE transmit power in Y3 (ISD 100m) and Y4 (ISD 50m). This is quite unexpected and comes from the ICIC-based power control, which forces the cells to sensibly reduce their UL SINR target in presence of high interference levels [Cisco, 2013]. This observation is highly dependent on the implementation and parameterization of the UL ICIC in the simulation tool; such behaviour seems improbable in reality and is thus considered as an artefact.

The best energy efficiency (ratio between the DL power consumption and DL user traffic) is provided by ISD 100 m up to Y1 and by ISD 50 m in following years. As soon as the traffic load grows up in the macro layer, the total DL power consumption significantly increases, thus the SC deployment with maximum offloading becomes

the most efficient. This demonstrates that the best strategy at Y0 (based on current traffic conditions) does not necessarily remain the best strategy in the long-term.

The current study gives inputs for evaluating the impact of small-cell densification on network performance, EMF exposure and base station DL power consumption, in different traffic conditions. Such analysis can help in the definition of a densification strategy over the years. Of course, when dealing with network optimization strategies, we must consider cost (CAPEX/OPEX), installation and backhauling constraints. This is out of the scope of the LEXNET project, but we guess that a progressive network densification, starting with the minimum density providing a significant gain at mid-term (e.g. 100 m in the context of our study), should be relevant and adequate. This enables the operator to distribute the installation costs over several years and to optimise the costs related to power consumption and maintenance, as well as to adjust the network performance according to the user demand. Furthermore, by anticipating the different steps of the deployment, the operator may efficiently design the required infrastructures (such as the backhaul) and work on an optimal iterative deployment plan.

3.3.4 Summary

This section analyses multi-layer LTE-A network performance in terms of usual QoS, energy efficiency and EMF exposure, based on a dense-urban co-channel SC densification scenario. The main objective is to identify network deployment rules that would allow achieving optimal performance from multiple key indicators taking into account a realistic and well accepted forecast over a period of five years of wireless data traffic demand growth. Three different SC deployment topologies are evaluated, respectively with ISD of 200 m, 100 m and 50m. For each topology, the optimal network configuration is first derived from a moderate user traffic (i.e. the one considered at Y0 by the tuning of SC maximum transmit power (set to 100 mW, 1 W or 5 W), CRE (set to 6, 9 or 12 dB) and ABS duty cycle (set to 12.5% or 25%).

This study relies on simulation results obtained with an innovative network coverage and analysis tool taking into account both UL and DL. The EMF exposure, in particular, is assessed by two complementary metrics: the DL power density (affecting all people in the network area) and the UE transmit power (affecting users during the wireless communications). Results show that the highest tested offloading configuration (SC transmit power of 5 W and CRE of 12 dB) and largest tested ABS duty cycle (25%) leads to the best user QoS and minimum DL EMF exposure at moderate user traffic. The impact of SC deployment on the UL exposure is also positive, but does not necessarily increase with the SC coverage ratio (or macro offloading). EMF exposure remains sensibly reduced with SC densification in both DL and UL as long as the DL traffic demand remains well below the network capacity.

The highest tested SC densification (ISD 50 m) generally gives the best coverage, highest peak throughputs and lowest EMF exposure; and it is the only one supporting the four-year traffic growth tested in the study (initial traffic demand x 4). All these results tend to demonstrate the interest of deploying SC to jointly absorb expected traffic increase, reduce EMF and DL energy consumption.

4 EMF/QoE TRADE-OFFS IN CELLULAR NETWORKS

In this chapter we will show that it is possible to reduce the EMF while maintaining the QoE of a multimedia application at a satisfying level.

This chapter offers a definition of the QoE of an application and put it in perspective through corresponding models, methods, and metrics so that we can properly evaluate its influence on the EI, as defined by WP2 [Conil, 2013].

Then, the chapter studies a scenario in which we will show that it is possible to reduce the EMF exposure by modifying the behaviour of the Radio Link Control (RLC) layer of an eNodeB and by modifying the transport protocol (level 4 of the OSI model) between the two multimedia devices.

4.1 Problem statement

When talking about communication, there are three concepts regarding quality: Quality of Service (QoS), Quality of Perception (QoP) and QoE. While QoS is a technology-centred approach to measure the quality of communication, both QoP and QoE are user-centric approaches. QoS is mainly used for defining the technical parameters of applications, such as network delay, packet loss, time to perform a task and the accuracy of the result. It is probably the most widespread approach within the works and studies which analyse quality in communication systems. QoP refers to the perception of the user regarding the quality and it used to measure changes variations in the quality or the acceptability of a given quality level.

QoE is complementary to QoP and related to user-experience. The ITU-T Study Group 12 (SG12) has focused on Performance, QoS, and QoE, and is has defined QoE as [ITU-T P.10/G.100, 2008]: “The overall acceptability of an application or service, as perceived subjectively by the end-user”. The QoE concept is gaining importance not only for the users but also for the network operators, vendors (software and hardware), and service providers [Baraković, 2010].

From the point of view of the LEXNET approach, it becomes relevant to analyse the influence of the EMF exposure over the QoE value. Reasoning about QoE instead of QoS will allow to introduce more parameters to reduce the EMF exposure. For example, the way a multimedia application is encoded can have an impact on the EMF exposure because the more the compression is high, the lower the EMF.

4.2 A Scenario reducing the EMF exposure

In this section, our objective is to tackle a main objective of the LEXNET project, i.e., reducing the exposure induced by wireless networks while keeping an acceptable QoE, by proposing a novel IP architecture for multimedia services over LTE systems. In the first subsection, existing works on the reduction of the electromagnetic exposure in wireless systems are outlined. The second subsection introduces our scenario of interest, i.e., multimedia service (video transmission) over LTE, whereas, the third subsection discusses the issues and opportunities of modifying the existing IP architecture for reducing uplink electromagnetic exposure. Then, in the fourth subsection we propose a novel solution to reduce the exposure in LTE networks by

categorizing the RLC frames (critical vs. non-critical) and decreasing the number of retransmissions for non-critical ones. We also propose an enhanced 3GPP compliant architecture that can be used to implement our reduced exposure solution. Section 4.3 draws the main conclusions of this work, advocating some items that are left for future work, in particular how the proposed scheme will be evaluated.

4.2.1 Existing works on the reduction of the electromagnetic exposure

As was mentioned earlier, LEXNET proposes a metric to assess the total exposure induced by telecommunication networks [Conil, 2013]. The metric, named Exposure Index (in J/kg/s), gathers both the average power emitted by the personal devices and the average incident power density to which the population is exposed. It can be therefore seen as the combination of the exposures induced by the access points and the personal devices of the telecommunication networks located within the same geographical area. As previously mentioned, the assessment, done at different periods of the day, takes into account the characteristics of the applications used by the users, the particularities of the telecommunication networks, the morphology of the users, and the relative position of the terminals with respect to the users.

As far as exposure reduction is concerned, it has been shown in [Derakhshan, 2004] that using lower frequency bands in universal mobile telecommunication systems (UMTS) can reduce the EM radiation density of a BS by about 13 dB. In 2010, Kelif et al [Kelif, 2010] showed that it is possible to decrease the downlink exposure (power density) by a factor of two without jeopardizing the QOS of a LTE network, by increasing the number of base stations in an area. Consequently, exposure to electromagnetic fields can be reduced by deploying small-cells. The rationale of their solution is to off-load the users located at the edge of the macro-cell towards the small-cells, in order to decrease their uplink transmissions. Other techniques based on SAR shielding have also been proposed in the literature [Ragha, 2010] for reducing the uplink exposure by using special material inside communication devices.

Up to date, most of the works on exposure reduction has focused on physical layer techniques and solutions to lower the power received at the end users and emitted by the user terminals. In contrast, we propose here a scheme for reducing the electromagnetic exposure by combining techniques belonging to the link and transport layers.

4.2.2 Scenario of interest

We consider (see Figure 58) the typical architecture of a LTE network. The control plane relies on the IP Multimedia Subsystem [Camarillo, 2008], which uses session initiation protocol (SIP) to control the different multimedia sessions [Rosenberg, 2002]. In the control plane, the service centralization and continuity application server [3GPP TS 23.237] ensures the continuity of multimedia sessions at the wireless devices.

In the scope of this work, we will focus on a multimedia service; in this sense, a wireless device sends a video stream to a remote device. The video is encoded with

H.264/AVC, the recommended codec by the 3GPP. The corresponding video slices are transported over UDP/IP datagrams.

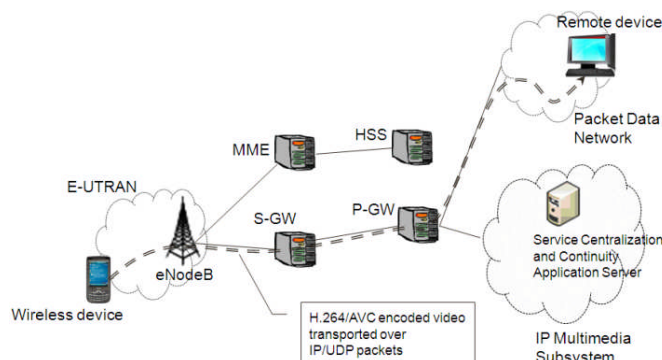


Figure 58: Architecture of the investigated scenario

The Evolved Universal Terrestrial Radio Access Network (E-UTRAN) transmits each UDP/IP datagram over one or several RLC frames, as it can be seen on Figure 59.

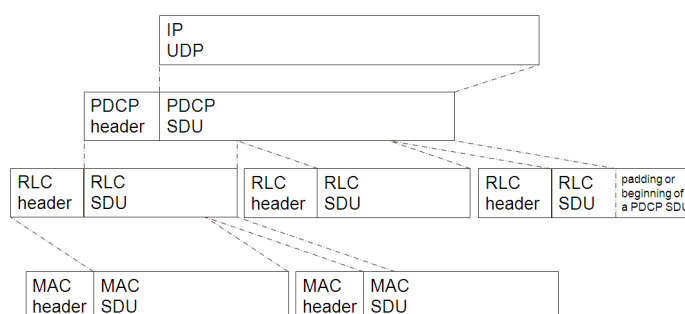


Figure 59: IP/UDP packet transported over RLC frames

4.2.3 Issues and opportunities for reducing the exposure in LTE

In the scenario, when one RLC frame belonging to a particular UDP/IP datagram is lost or erroneous, the eNodeB requests the wireless device to retransmit it, when the RLC entity is configured in acknowledged mode [3GPP TS 25.322]. If such frame is not received after (MaxDAT-1) attempts, where MaxDAT is the maximum number of (re)-transmissions, the eNodeB discards all the RLC frames of the corresponding UDP/IP datagram, which clearly wastes a considerable amount of radio resources.

If the eNodeB were able to not discard an entire UDP/IP datagram when just a small part of it was not correctly received, the remote device could receive the remaining information of the whole datagram. In turn, this information could be used by the H.264/AVC decoder to interpolate the missing video slices. As more packets are effectively received by the decoder as the Quality of Experience (QoE) of the video application could be improved.

Here, instead of increasing the QoE, our objective is to maintain the QoE at a satisfying level, while decreasing the number of RLC retransmissions. This would in

turn bring an exposure reduction. In order to achieve it, the following issues must be tackled:

- At the RLC layer of the eNodeB, the loss of particular RLC frames belonging to a UDP/IP datagram could cause the loss of critical information, such as the IP addresses and UDP ports of the connection. To avoid this situation, those RLC frames carrying critical pieces of information, for instance those identifying the connection, shall be protected;
- In its regular operation, the UDP receiving entity would discard a datagram when its Cyclic Redundancy Check (CRC) is wrong and therefore it would not send it to the decoder. This, for instance, would be the case for uncompleted UDP datagrams. To overcome this behaviour, the erroneous chunks of the uncompleted datagram should not be included in the CRC computation, as shown in Figure 60. In this sense, those bytes not covered by the checksum (within the UDP datagram) must not be critical for the decoder, and they might be useful just to enhance the perceived QoE;
- At the architectural level, we need to assess the QoE and ensure that it is kept at an appropriate level, despite the increase in block error ratio (BLER) due to fewer RLC frame retransmissions.

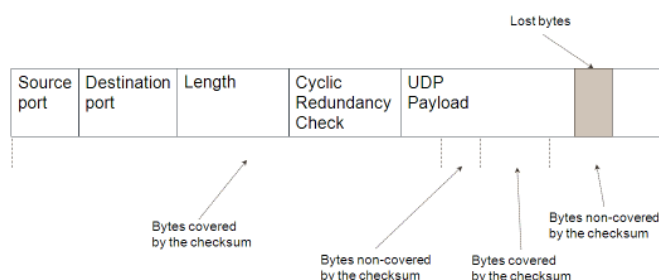


Figure 60: CRC computation over an uncompleted IP/UDP packet

4.2.4 Design of a 3GPP architecture for reducing the exposure

As already mentioned, we aim at decreasing the maximum number of RLC frame retransmissions, while keeping the QoE at an appropriate level; this goal requires modifications in the architecture design.

First of all, we propose the following modification to the 3GPP legacy specifications of the RLC layer acknowledged mode. When the eNodeB (acting as a receiver) does not receive a RLC frame, it requests the transmitter, i.e., the user terminal, to retransmit the frame. When the information carried by the RLC frame payload is critical for the decoder (for example the IP addresses and UDP ports of the connection), the maximum number of retransmissions is set to (MaxDAT-1). On the other hand, if the information is not such relevant for the decoder (we can state that it provides a higher QoE), the maximum number of retransmissions is reduced to $\lfloor ((\text{MaxDAT}-1))N \rfloor$, where N can vary between [1,MaxDAT]. In this sense, the higher the value of N, the lower the electromagnetic exposure. In order to allow for this new functionality, we require some cross-layer interaction; the RLC layer of the transmitter shall be aware on how critical/relevant is the information contained within each of the RLC frame payloads to establish the maximum number of retransmissions. We

propose to modify the transport protocol, by adding a new field within the UDP header (see Figure 61) to indicate the bytes that are covered by the checksum. When the RLC layer receives a UDP/IP datagram from the packet data convergence protocol (PDCP) layer [3GPP TS 36.323], it checks this new field to assess whether or not the payload contains critical bytes.

Source port	Destination port	Length	Cyclic Redundancy Check	Bytes covered by the CRC
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Figure 61: New UDP header indicating the bytes covered by the checksum

Then, at the PDCP layer, the 3GPP specifications are changed according to the following rule: when the wireless device receives a PDCP status report coming from the eNodeB, it reads the payload of this message to know what are the PDCP frames to be retransmitted. If a PDCP frame does not carry a critical IP/UDP packet, it may not be retransmitted according to the QoE threshold.

Last, but not least, we need to include a new monitoring method to periodically evaluate the QoE of the video application in order to ensure that it remains at a satisfactory level. Currently, the evaluation of the QoE can be done by means of two different approaches [Ketyko, 2010]. The first one, called "objective method", is based on the use of probes that analyse the video signal and/or various network parameters to estimate a quality score. The validation of these tools is based on perceptual measures, involving the assessment of video applications' quality. In fact, these perceptual measures, which are referred to as "subjective method", are the second type of QoE evaluation methods. We consider here the use of an objective method, which was originally proposed by the ADAMANTIUM project [ADAMANTIUM, 2008] named as the mean opinion score (MOS). The MOS enables a numerical evaluation of the QoE, and it is estimated by using Eq. (17) [Khan, 2010], which is based on the following parameters: the frame rate (FR) of the H.264/AVC codec, the sender bit rate (SBR) of the codec, the complexity of the video content (CT), the BLER, and the mean burst length (MBL).

$$\text{MOS} = a + \frac{(be)^{\text{FR}} + c \log(\text{SBR}) + \text{CT} * (d + e \log(\text{SBR}))}{1 + (f * (\text{BLER}) + g * (\text{BLER})^2) * h * \text{MBL}} \quad (17)$$

In order to keep the QoE of an ongoing multimedia connection, we introduce a dynamic algorithm, able to modify the parameters of such a session. Its main steps (see Figure 62) are as follows. The MOS is periodically evaluated by means of Eq. (17); if it is higher than a threshold, no further action is needed. On the other hand, when the MOS value is lower than such threshold, some actions are taken. A first option would be to decrease the SBR in order to increase the MOS, since decreasing the SBR decreases the number of lost packets. Afterwards, a new MOS measurement is carried out; if the corresponding value is higher than the threshold, no further action needs to be taken. On the other hand, a new action shall be triggered; if selecting another radio network is possible, then the algorithm initializes the radio network reselection process. If this fails, then the QoE is finally lowered and stored in a database, since network planning tools might use this information to carry out off-line strategic analysis (this particular aspect is beyond the scope of this work).

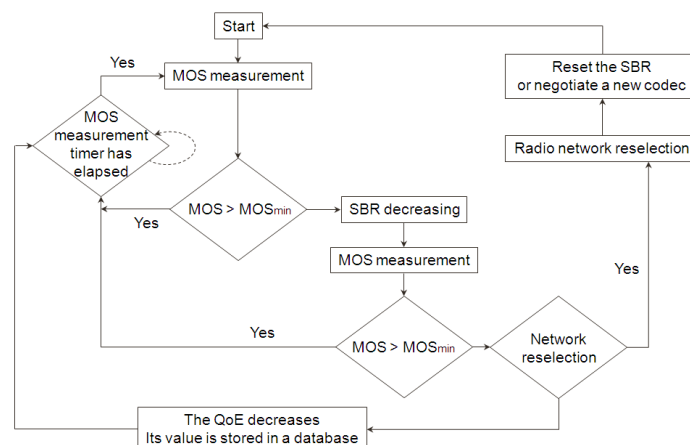


Figure 62: Main steps of the algorithm

The implementation of the different algorithm steps requires some architectural enhancements. They basically consist on defining the messages that need to be exchanged between the involved entities and the interfaces between them.

The exchanged messages, which are depicted in Figure 63, are as follows. Message #1 is sent by the service centralization and continuity application server (SCC AS) to the eNodeB to request the BLER and the MBL; these metrics are needed to evaluate the MOS according to Eq. (17). It is worth noting that the SCC AS manages the SIP sessions, and it is therefore aware of the SBR and the FR of the codec. Message #2 contains the response sent by the eNodeB. After having evaluated the MOS, the SCC AS stores the value in a database (#3). The message flow also shows the information exchange with the database; in this regard, #4 is sent by the Access Network Discovery and Selection Function (ANDSF) [3GPP TS 24.312] to request the MOS values for a particular end user terminal, while #5 is the response sent by the database. #6 is a SIP message containing the value of the SBR of the codec, computed by the SCC AS. #7 triggers the reselection process, when maintaining the QoE level is not possible and is sent by the SCC AS to the eNodeB, requesting a handover (the eNodeB is the entity that initiates the reselection processes [3GPP TS 36.300]). #8 is sent by the eNodeB to the ANDSF, which can provide a list of candidate radio networks based on criteria such as the MOS experienced by a wireless device when it is connected to a particular radio network; this list is included in message #9. Finally, #10 is sent by the eNodeB to the SCC AS to indicate a handover event. Upon reception of this message, the SCC AS prepares the new SIP session towards the target radio network.

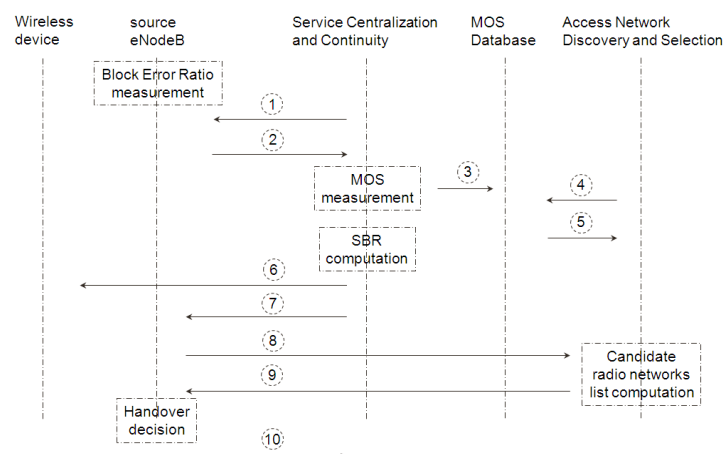


Figure 63: Messages between the entities involved in the implementation of the algorithm

The messages are exchanged through the two new interfaces that are highlighted in Figure 64. The first interface is included between the eNodeB and the SCC AS and is used by the SCC AS for retrieving the information that characterizes the link layer and requesting a handover. The second interface connects the eNodeB and the ANDSF, and it is in charge of the network reselection process, which enables the eNodeB to retrieve information about candidate radio networks.

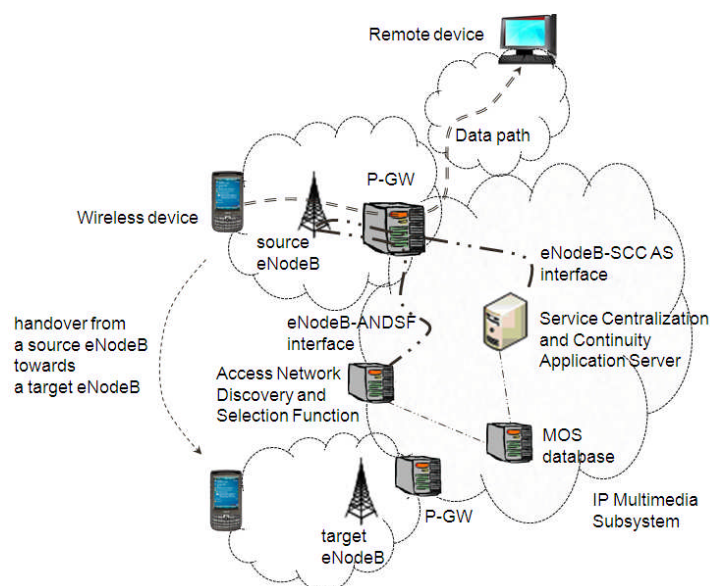


Figure 64 Definition of the eNodeB-SCC AS and eNodeB-ANDSF interfaces

4.3 Conclusions and way forward

Most existing works on electromagnetic exposure reduction has focused on developing physical layer techniques and solutions to lower the power received and emitted by the user terminals. In this section, we have proposed a novel approach for reducing the electromagnetic exposure in LTE networks by combining techniques belonging to the link and transport layers, while ensuring an acceptable Quality of Experience of a video application. We have proposed to categorize the Radio Link Control frames into critical and non-critical ones and to decrease the number of retransmissions for non-critical ones. In turn, this will reduce the radiated power, i.e.,

exposure. We also proposed an enhanced 3GPP compliant architecture for accommodating our reduced exposure approach.

The implementation of the proposed solution involves enhancements in both the E-UTRAN and IMS core network. In our future work, we will carry out the performance analysis of the proposed solution. As this heavily depends on the chosen QoE model, several models will be required to be implemented. Another aspect to solve is related to the compression of the UDP header at the PDCP layer. Even if the header is compressed, the information characterizing the importance shall be made available for the RLC layer.

5 ROUTING FOR MULTIHOP NETWORKS

5.1 A reward based routing algorithm and protocol (RBRP)

This research topic aims at reducing the exposure to electromagnetic fields of the individual users over a multi-hop (device-to-device) wireless network. Ideally, each node would try to be least exposed, but in a limit situation this would be equivalent to shutting down the node, which is not desirable for most of the users. Here, we propose a routing strategy that fosters using those paths with the minimum sum of exposure between intermediate nodes, while also considering that each newly forwarded packet causes additional exposure. We have modeled the degree of exposure of a node as an amount of virtual monetary reward that is granted when a node forwards a packet. Hence, in our proposal, hereinafter Reward Based Routing Protocol (RBRP), each source node tries to pay the least cost possible in order to achieve its goal, sending out a new packet and making it reach its destination; this, in terms of exposure, would translate into avoiding the exposure of the same intermediate nodes. This is in fact the key to the understanding of RBRP.

5.1.1 Antecedents

Although the research on routing protocols for multi-hop networks started already in the mid 90's, the relevance of such topologies has recently increased. They were originally conceived as communication alternatives in rather particular scenarios (for instance, natural disasters) and this certainly limited their real applicability. In recent years, the use of mesh networks is proposed as a means to extend the coverage of more traditional topologies. Some key examples of such usage are the IEEE 802.11s standard or the *device-to-device* communication, that is currently under consideration by the 3GPP in the latest LTE specifications. In addition, we should also reflect the relevance of *machine-to-machine* communications and the key role that multi-hop topologies have in the corresponding wireless sensor networks.

As a consequence, we have seen a reactivation of the technical activities in the MANET working group of the IETF, which has recently (April 2014) submitted various *Request For Comments*. In a nutshell, there are two main approaches to handle routing in such types of networks: reactive, in which nodes trigger route discovery procedures only when they need to; and proactive, where nodes periodically send topology related information that is afterwards used to establish the corresponding routes. One of the main advantages of the first group is that (especially for moderate traffic loads) it exhibits a better energy consumption profile. Therefore, we will use the Ad-hoc On-Demand Distance Vector (AODV) core functionality, in fact one of the most well-known reactive protocols [Perkins, 2003], to develop the protocol proposed herewith since the energy consumption is somehow related to the radiated power. It is worth highlighting that the optimization criterion of AODV is the distance (i.e. number of hops), hence it is expected to behave fairly well in terms exposure (i.e. accumulated transmission power).

The second foundation of this work is the exposure suffered by the end-users. As already mentioned, and in parallel with the unstoppable increase of wireless communications, we have recently seen a growing concern of the end-users on the potential risks of such networks. Related to this, we should also highlight the *Green Networking* motto, which has gathered the attention of the scientific community. The main idea behind it is promoting an energy-aware behavior, mostly by means of reducing the transmitted power, and aimed at increasing battery life. Most of the existing proposals [Auer, 2011] [Correia, 2010] deal with cellular communications, while not much attention has been paid to multi-hop network topologies.

In order to combine the two aforementioned pillars, we propose a distributed *reward-based* routing scheme. The effect is somehow similar to that pursued by load-balancing protocols. The reader might refer to the survey by Toh *et al.* [Toh, 2009] for a succinct discussion of the most interesting proposals. They classify the existing solutions into three main groups, depending on the type of metric they foster. The traffic-based approach is the closest to the one we propose here, although they foster a *dynamic* load balancing, while we are more interested on the *cumulative* characteristic of the EI. For instance, Hassanein and Zhou [Hassanein, 2001] proposed Load Balanced Adhoc Routing (LBAR), which used the degree of nodal activity (number of active paths) as a novel routing metric. They showed that their proposal outperformed legacy approaches in terms of delay and throughput, but they did not study how the load was *really balanced* amongst the nodes. Likewise, Altalhi and Richard [Altalhi, 2004] did not analyse the load-balancing capability of the Traffic-Size Aware (TSA) routing protocol, which was based on the combination of the number of packets of each node and its neighbors. More recent works on load balancing schemes for multi-hop and mesh networks are those from Li *et al.* [Li, 2012], which use a greedy routing scheme based on geographical information, and Yamamoto *et al.* [Yamamoto, 2012], which propose a rate adaptation mechanism, instead of changing the routes.

5.1.2 Exposure-aware auto-configuring routing protocol for a technology-agnostic mesh network

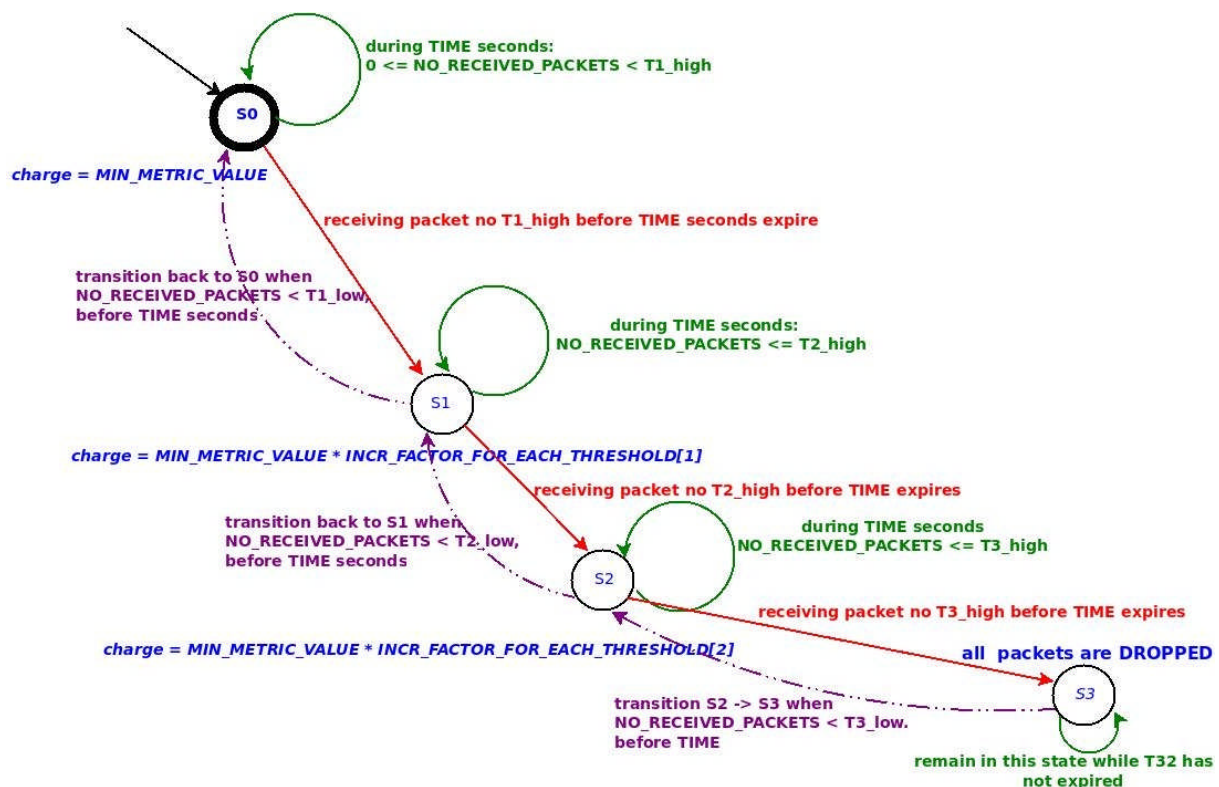
RBRP is designed as a technology-agnostic routing protocol that fosters a correlation between route cost and population exposure, to avoid the most exposed areas. RBRP makes use of virtual money (reward) to forward packets, so that if a node causes more exposure, the higher reward it needs to forward traffic. Note that RBRP accounts for the exposure in terms of number of packets, which is a valid proxy for the aforementioned EI.

The principle behind RBRP is twofold: (1) to modulate the hop cost in an exposure-aware manner; and (2) to establish and maintain the routes of least exposure. The former aspect is presented in the next section, while the implementation details concerning the route maintenance can be found in Appendix 3: RBRP Signaling.

The cost and reward management component is responsible for controlling the hop cost variations so that the protocol is able to decrease, or at least fairly distribute, the exposure suffered by end-users.

In order to fully understand the operation of the cost and reward management, RBRP is built upon the following assumptions:

- 1) Each individual node would ideally prefer to generate as low exposure as possible.
- 2) To make the multi-hop network functional, rewards have been envisaged for cooperative forwarding, that encourage nodes to keep the network connected. These rewards are based on virtual money, which is included in data packets, so that nodes can receive their corresponding fee. As a node becomes more exposed, the fees it receives gradually increase; this is modeled by means of a staircase-like function, whose state machine is presented in Figure 65.
- 3) Each node spends the money when it needs to send its own packets by giving a reward to the intermediate node according the fees they set, this is their costs.
- 4) Each node earns money by forwarding data packets sent by other nodes. In fact, it can be seen that the node's cost increases on a proportional way to the *accumulated exposure* it causes (i.e. the amount of previously forwarded packets) in the forwarding procedure.
- 5) Each node has its own initial amount of money. When a node has no longer enough money to send its own packets, it has to earn money first by forwarding packets of other nodes.



As can be seen in Figure 65, each node starts in state 0, and a finite number of states are defined. Only transitions between adjacent states are allowed, i.e., if a

node is at state S_i it can only go to S_{i+1} or to S_{i-1} . For every pair of states, and for each direction of transitions (upper transitions, i.e. S_i to S_{i+1} , and lower transitions, i.e., S_i to S_{i-1}) some thresholds are established, which are computed as the number of forwarded packets within a fixed period of time (*Check Window*).

- Upper transitions: RBRP defines a unique time window during which, for each individual state, we have defined thresholds for the maximum number of packets that can be forwarded in order to stay at the same state, in the context of a specific scenario. This threshold is represented in Figure 65 as T_i^u (for every state i). If the number of forwarded packets during *Check Window* (Fp) exceeds that threshold, the node moves to the upper state. In fact, a node at the higher states has generated more exposure and therefore it will require a higher fee to act as an intermediate node. As a consequence, it would be less likely that it is used in minimum cost routes, and therefore, it would become less exposed, the ultimate goal of RBRP.
- Lower transitions: RBRP also defines a lower threshold for a state i (T_i^l), that sets the minimum number of forwarded packets in order to stay at the same state. If the number of forwarded packets during a *Check Window* period (Fp) is *lower* than this threshold, the transition to the lower state takes place. In this sense, when a node is at a lower state, it generates lower exposure and will therefore collect less money to forward packets. Hence, routing through these nodes would be preferred, and the exposure within other areas would be reduced, balancing the overall exposure within the whole network.

Thanks to the signaling component of RBRP, if a node changes its cost (i.e. it performs a state transition), that change is propagated to the source and to the intermediate nodes on the route, so as to ensure that all of them keep updated information.

5.1.3 Evaluation and experimental validation of RBRP

This section depicts the two simulation campaigns that have been carried out to assess the behavior of RBRP, and to compare its performance with the one shown by the traditional AODV protocol [Perkins, 2003]. The study has been performed with the NS-3 platform [NS-3, 2014], for which RBRP has been implemented. We will also discuss some interesting results, especially from the point of view of how the exposure index is behaving, since the main goal of this work is the study and improvement (i.e. decrease) of the EMF exposure caused by wireless networks.

In order to measure the impact of the presented solution on the EI, we have used as proxy the cumulative power radiated by the nodes within the mesh network, which is proportional to the EMF exposure. In this sense, we have been use of a regular grid (with a separation of 5 m) of probes, covering the whole area (which is here chosen to be a square with a side of 100 m). These have been implemented as passive WiFi nodes, able to measure the cumulative received power (in Watts), as a consequence of incoming data packets. We randomly deploy a number of nodes (routers), which randomly start traffic flows with a fixed duration. We also need to ensure that the routers form a connected graph and that all the flows finish within the simulation time.

All the flows have the same destination, which is the closest router to the center of the grid. Table 10 summarizes the main simulation parameters. It is worth highlighting that the propagation follows a *disc model*, so that there are no losses within the coverage range and the received power is 0 without that range. In this sense, the values obtained during the simulations show the aggregated power (and not the E-field) received by the probes, which is a valid *proxy* for the EI, as it is proportional to the exposure at each point. On the other hand, this methodology is anyway meaningful for the comparison based analysis that we foster.

On the other hand, we have configured the *Cost/Reward Management* with 4 states. A node will increment its cost by a factor of 1.6 when shifting from state S_i to S_{i+1} . The corresponding *Check Window* and thresholds (in number of packets) to change the state are also indicated in Table 10. It is worth highlighting that the current configuration ensures that a node never runs out of money. Consequently, packets are never dropped. Otherwise, the comparison of the protocols, in terms of generated exposure, would not be fair.

In a first set of simulations, we studied the cumulative power that was received by the grid of probes during a simulation. We carried out 100 independent experiments with the two protocols, each of them with the duration of 100 seconds and 4 randomly generated traffic flows. Figure 66 and Figure 67 show the received power per probe, averaged over the 100 experiments. Furthermore, Table 11 shows the corresponding values. From this data, it can be concluded that RBRP yields better performance in terms of the global EMF exposure, since it is able to fairly distribute it by lowering the corresponding peak values, as shown in the contour figures. In Table 11 a remarkable reduction of the maximum achieved value can be observed, coupled with a lower standard deviation.

Table 10: Scenario Parameters

Topology		
Scenario size (m^2)		100 X 100
Coverage Range (m)		20
Number of nodes		50
Transmit power		16.026 dBm
Reception gain		1 dB
Transmission gain		1 dB
Traffic Flows		
Protocol		UDP
Packet Size		1024
Generation Rate (<i>sec.</i>)		0.15
Duration (<i>sec.</i>)		25
Cost/Reward Management		
Check Window (<i>sec.</i>)		10
State Number S_i	T_i^l (#packets)	T_i^u (#packets)
S_0	— —	50
S_1	25	120

S_2	100	190
S_3	150	--

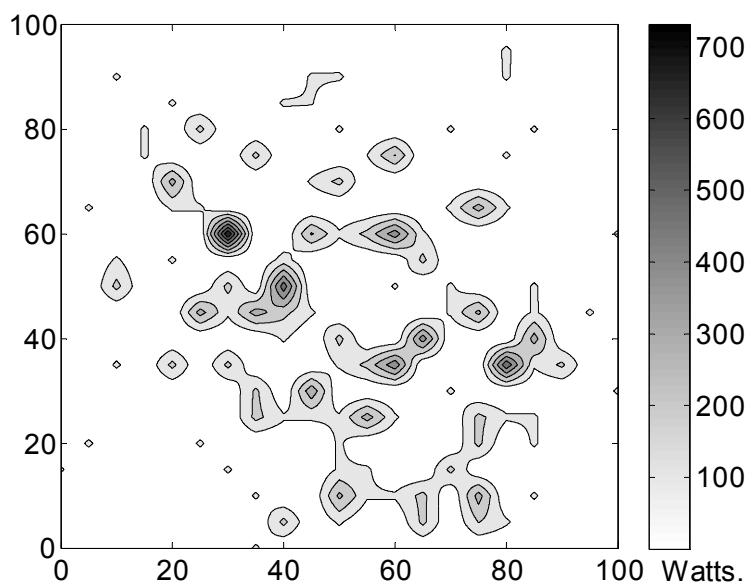


Figure 66: Cumulative exposure map of AODV

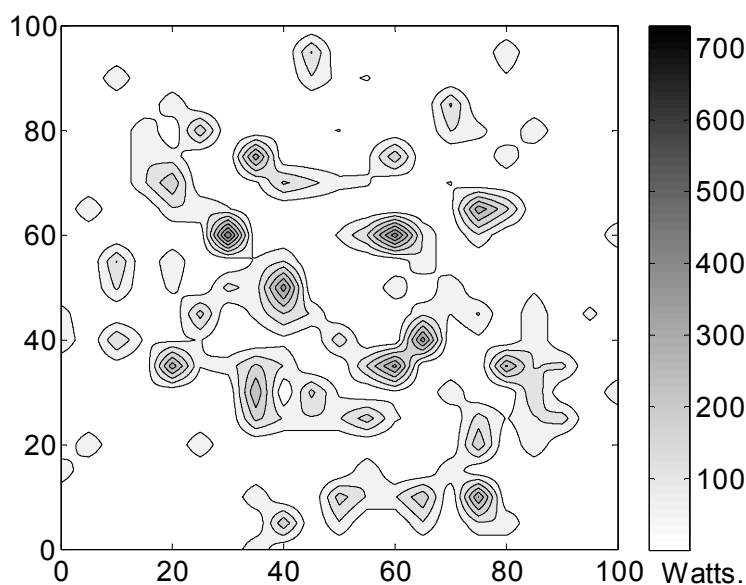


Figure 67: Cumulative exposure map of RBRP

After analyzing the global exposure, we carried out a study to assess the temporary evolution of the maximum exposure suffered by the probes. For that, we have run a further 300 experiments, each of them 1200 seconds long, with 48 traffic flows that are initiated in each simulation. Like before, all flows were sent to the same destination, which was the closest node to the center point of the scenario. In addition, we take the exposure from all the probes every 10 seconds (slot time), thus leading to 120 samples per simulation.

Figure 68: Maximum exposure levels observed during a single simulation/experiment shows the values of the exposure samples for a single experiment. As can be seen, in this particular case, RBRP was able to limit the exposure levels obtained for the AODV case, especially in the cases with highest exposure. Furthermore, Figure 69 represents the Cumulative Distribution Function (CDF) of the maximum of all the samples at each time slot during a simulation. The results yield that RBRP shows a better performance than AODV in most of the cases ($\approx 80\%$), while for the remaining percentage the difference is rather small.

Table 11: Global exposure statistics

Protocol	Max. (W)	Mean (W)	Std. Dev. (W)
AODV	730.9580	40.7738	91.9429
RBRP	445.9462	37.0287	72.8755

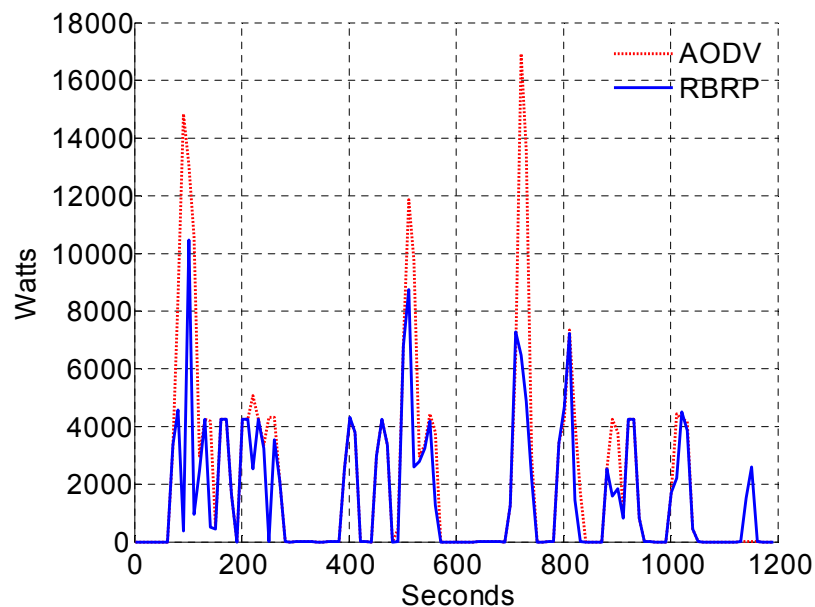


Figure 68: Maximum exposure levels observed during a single simulation/experiment

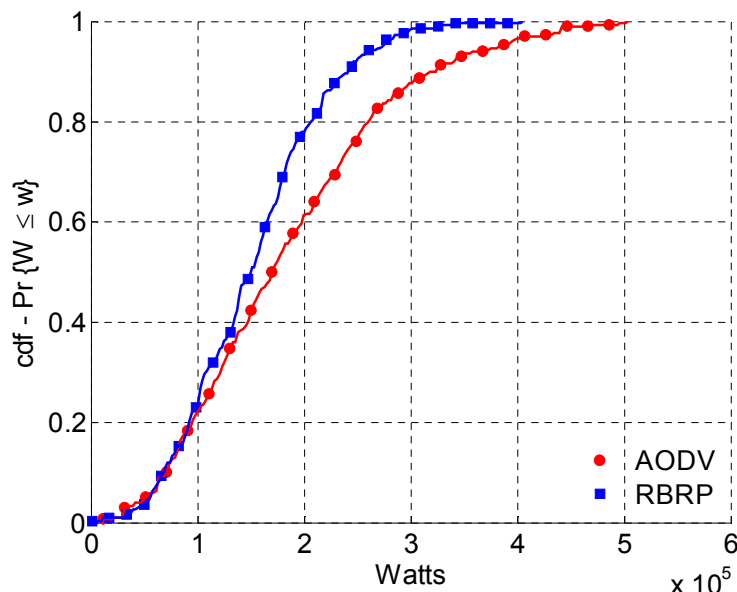


Figure 69: Comparative of CDF of maximum values during the whole simulation process

Although the main goal of this study was to assess the exposure reduction brought about by RBRP, we also wanted to study whether there were any trade-offs that could jeopardize the perceived QoE. Since the flows that were used did not saturate the wireless channel, we analysed the route lengths for each of the protocols. Figure 70 shows the Probability Density Functions (PDF) of such a parameter for both AODV and RBRP. In light of the results, the difference on the route lengths between the two protocols is almost negligible for this topology configuration. Hence, we can conclude that RBRP is able to improve the behavior of legacy routing protocols in terms of exposure, without a negative impact over the number of hops.

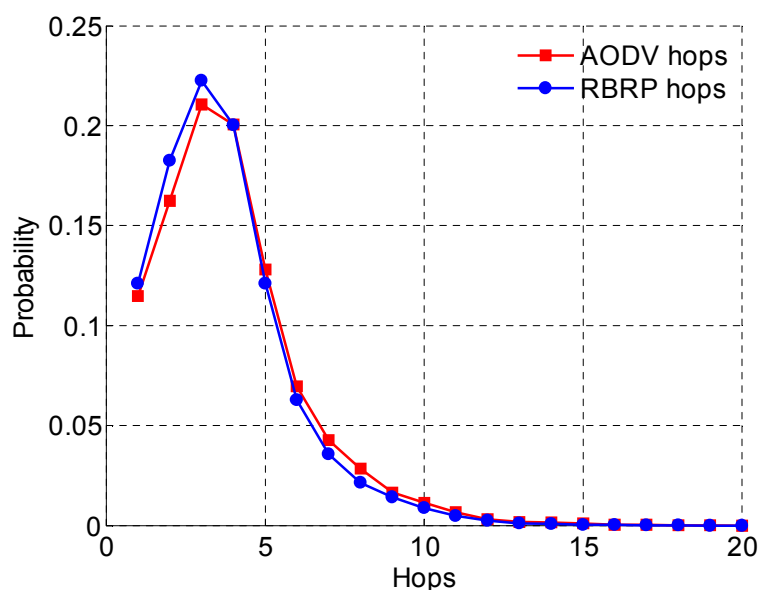


Figure 70: PDF of the number of hops to send a packet

5.2 Ongoing work

An interesting side effect of the RBRP behavior, which we have started to study, is that it seems to decrease the number of retransmissions, which in turn would actually help to further reduce the exposure. This is due to the fact that RBRP tries to avoid those routes that have higher loads, thus leading to fewer collisions and retransmission events. Another positive consequence of the load balancing fostered by the RBRP approach is a longer (average) battery lifetime, leading to an energy-aware behavior, due to both fewer number of retransmissions and fairer energy consumption amongst different nodes as a consequence of the dynamic route swap. We have already started to thoroughly study these RBRP effects. In addition, we will enhance the RBRP operation by adding an adaptive power management scheme, so that it would be able to decrease the transmit power for individual nodes.

The framework that has been created so far with the RBRP can be extended so as to be able to offer a better behaviour in terms of the exposure index.

First of all we can look at power-aware mechanisms. The Hello messages that are used to keep track of the neighbouring nodes can be used as well to estimate the RSSI towards each of them. Based on those measurements, we can assign a weight to each of the links, considering the transmit power that will be required to reach them. By combining this with the reward-based scheme that is fostered by RBRP, we believe that we will obtain a significant exposure reduction.

Another angle that has to be explored is the possibility to combine packets belonging to different flows by using network coding techniques. This can effectively reduce the number of 'real' transmissions within the network and therefore could bring about further reduction on the EMF exposure.

Last, but not least, the use of different gateway nodes will be as well analysed. Although multi-hop topologies might have a much broader scope, one of the most sensible use-cases is to use other nodes so as to reach a gateway (i.e. an access element to a higher level network). If there is a single access element available, this could create a higher exposure in the area, while if this is distributed amongst a number of gateways, it is sensible to believe that the exposure could be reduced; integrating a good gateway placement strategy, together with the RBRP behaviour could bring about additional gains in terms of the exposure index for multi-hop (or device-to-device) networking environments.

5.3 RBRP conclusion

RBRP's goal is twofold: reducing the overall EMF exposure, and balancing the level of exposure of various nodes. The novelty of RBRP resides in its *cost control and management component*, since it uses the *reward*, i.e. the virtual money, to modulate the *exposure* level. In this sense, the RBRP uses the *number of forwarded packets* as the metric to model the willingness to reduce the exposure. The behavior of the proposed protocol has been analysed by means of a thorough evaluation over the NS-3 [NS-3, 2014] simulator and the results show that it clearly outperforms a

traditional approach in terms of EMF exposure, while it does not impact the number of hops, which in turns affects the QoS (e.g. latency, throughput).

6 EMF-AWARE OPTIMIZATION OF WiFi SETTINGS

In the context of WiFi networks, EMF control is important as radiation exposure in the ISM band is increasing mainly due to WiFi networks. In this section we will look at a SURrogate MODELing (SUMO) optimization problem with exposure as one of its objective metrics and show how it can be reduced by optimizing network parameters. The complete description as referred from an article can be found in [Mehari, 2014]. Also note that the definition of exposure is not referenced to the definition of EMF EI described in this paper where it is used as a show case example during the optimization process. All calculations used in order to develop the exposure model are according to the authors' description [Plets, 2013] and will be updated at a later phase to include the latest EI definition from the LEXNET project.

6.1 Problem Statement

Wi-Fi network solutions have parameters that can be tweaked at the physical layer (transmit power, channel, modulation), MAC layer (inter frame spacing, contention window), network layer (routing protocol, mobility, topology) and application layer (throughput, server configurations). Optimizing all or a subset of these parameters in order to find the *optimum operating point*, is time consuming since the design space grows exponentially for every investigated design parameters. In particular, we look at a wireless conferencing scenario where audio quality and transmission exposure of an audio speaker are optimised by searching its transmit power and channel network parameters.

6.2 Wireless testbed

The wireless *iMinds w-iLab.t* testbed at Zwijnaarde (Ghent, Belgium), shown in Figure 71, is equipped with heterogeneous wireless devices used to conduct a variety of experiments.

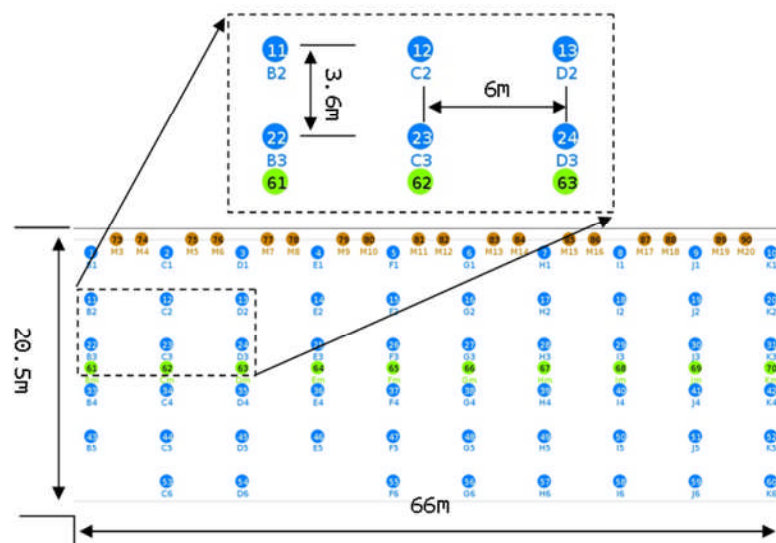


Figure 71: Top view of iMinds w-iLab.t wireless testbed topology

It has 60 nodes each consisting of an embedded Zotac PC having two Wi-Fi interfaces, a sensor node, a Bluetooth dongle and a wired control interface

connected to the testbed management framework. Furthermore, the testbed is equipped with advanced spectrum sensing devices. These include Universal Software Radio Platform (USRP), IMEC Sensing Engines, and Wireless open Access Research Platform (WARP) boards.

6.3 Experiment scenario

A wireless conferencing scenario composed of a wireless speaker and multiple microphones is shown in Figure 72. The wireless speaker broadcasts a speaker's voice over the air and the multiple wireless microphones receive the audio at the listener end. This type of wireless network is used in a multi-lingual conferencing room where the speaker's voice is translated into different languages, multiplexed into a single stream and broadcasted to each listener. Often, the speaker's audio quality is reduced by external interference and the surrounding environment is impacted by external interference. Thus, the main objective of the wireless conferencing scenario is to improve the received audio quality while keeping the transmission exposure at a minimum. To this end, the conferencing operator has the possibility to adapt the channel and power transmission parameters.

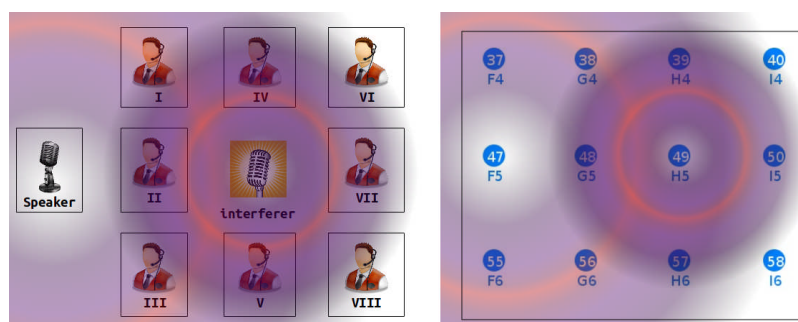


Figure 72: Wireless conferencing scenario consisting of 8 listeners, 1 speaker, and 1 interferer. Right: mapping of the conferencing scenario to the testbed nodes. The transmission range of the speaker and interferer is indicated

The experiment is composed of 1 interferer creating background interference and a System Under Test (SUT) having 1 speaker and 8 listeners. The speaker transmits a 12 second Wi-Fi audio stream and each listener calculates the average audio quality within the time frame. During this time frame, the interferer transmits a 10 Mbps continuous UDP stream on dual channels (i.e. 1 and 13) generated using the iperf application¹. The transmitters, receivers and interference generators are shown in Figure 72.

On the left hand side of Figure 72, the realistic wireless conference scenario is shown, where as on the right hand side, the experimentation scenario is mapped on the iMinds w-iLab.t testbed. All listener nodes (i.e. 38, 39, 40, 48, 50, 56, 57, and 58) are associated to the speaker access point (i.e. node 47). Background interference is created by the access point (i.e. node 49) using two separate Wi-Fi cards. The Wi-Fi card and driver used for this experiment are "Atheros Sparklan WPEA-110N/E/11n mini PCI 2T2R" and "Atheros ath9k" respectively.

¹ <https://iperf.fr/>

6.4 Optimization process

As was explained in the problem statement, the time overhead introduced in wireless conferencing scenario is optimised using an Efficient Global Optimization (EGO) [Gorissen, 2010] algorithm implemented in the SURrogate MOdeling (SUMO) toolbox (Appendix 4: SUMO optimiser). The optimization process is illustrated step by step in Figure 73.

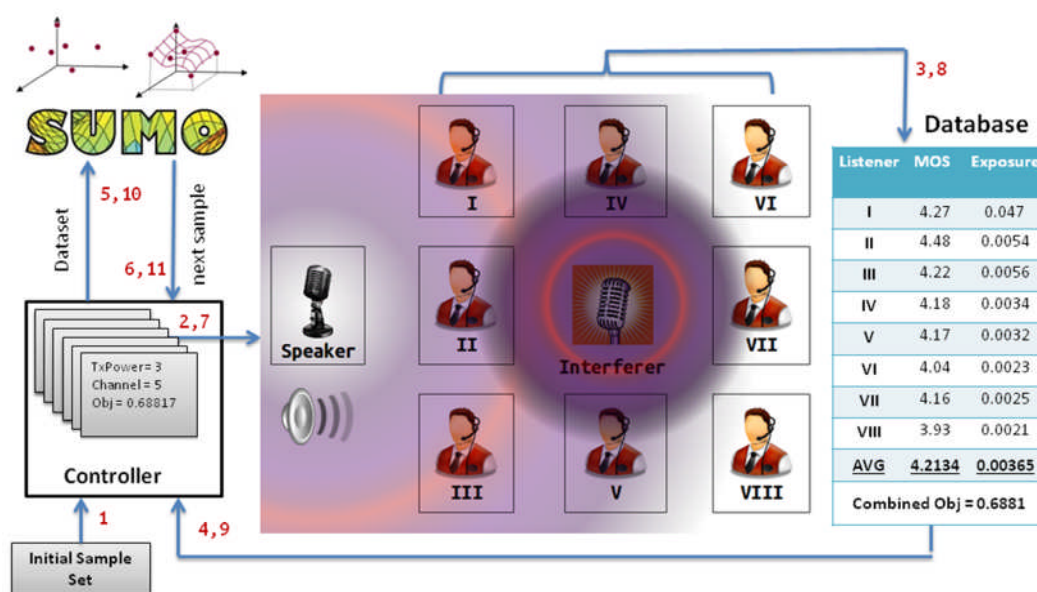


Figure 73: The process of SUMO optimization in the wireless conference network problem. The different sequential steps are numbered from 1 to 11

At (1) the controller is given a list of settings of the first experiments that needs to be configured on the wireless testbed. (2) Experiments are deployed on the wireless testbed using the requested settings, thus resulting in an initial sample set. (3) At the end of each experiment, the controller retrieves the evaluation criteria of the experiment. For the conferencing scenario, the evaluation criteria are the audio quality and exposure performances from all listeners. (4) An objective function is created by processing the evaluation criteria. (5) When the SUMO optimiser receives a sufficiently large dataset, it generates a surrogate model. (6) The next sample point with highest expected improvement is predicted. (7) The controller starts the next optimization experiment using the new design parameters. (8) Again, the evaluation criteria are retrieved and (9) the objective function is calculated for the new design parameters. (10) Based on the current dataset, extended by one record, the surrogate model is updated and (11) a new sample is predicted. The optimization process continues until stopping conditions are met.

6.5 Performance objectives

Dual objectives are applied in the wireless conference network problem. The first objective is maximizing the received audio quality which is measured using the Mean Opinion Score (MOS). MOS is a subjective audio quality measure represented on a 1 to 5 scale (i.e. 1 being the worst quality and 5 being the best quality). To

calculate the MOS score, the experiment described in Section 6.6 uses the ITU-T Perceptual Evaluation of Speech Quality (PESQ) P.862 standard. It calculates the PESQ score from packet loss, jitter and latency network parameters and maps it onto a MOS scale [Base, 2005]. The second objective is minimizing transmission exposure. In [Plets, 2013], an in depth calculation of transmission exposure is presented. The exposure at a certain location is a combined measure of received power and transmit frequency. Transmission exposure is an important evaluation metric related to potential health issues, leading the regulatory bodies to set maximum limits.

As maximizing the combined performance objective is the goal, the weight of performance metrics needs to be defined depending on the problem type. For example, a person who wants to install a wireless conference in urban areas applies tighter exposure requirement than in rural areas. We would also apply high audio quality requirement in parliament auditoriums compared to office meeting rooms. However in our case, the aim is to investigate methods to easily find trade-offs between EI and QoS and equal weights are applied on the normalized objectives. All performance objectives are normalized using maximum and minimum attainable values which are retrieved by doing an exhaustive searching experiment (see Section 6.6.1).

6.6 Result and Discussion

This section analyses the viability and efficiency of the SUMO optimization toolbox as used in validating the wireless conferencing scenario. First, an exhaustive search model is given in Section 6.6.1 which is used as a reference for experiment comparison. Next, sensitivity of experiments to the choice of the initial sample size is discussed in Section 6.6.2. After that, a potential stopping criterion is analysed in Section 6.6.3. Finally, the SUMO optimised experiment is compared against the exhaustive search model in Section 6.6.4.

6.6.1 Exhaustive search model

In this section, we describe a reference experiment that is performed to generate an exhaustive search model of the wireless conference network problem. Neither SUMO nor any optimization algorithm is used to generate the model. The exhaustive search model evaluates all possible combinations of settings and will be used as a reference model for comparing SUMO optimization experiments. In total, 260 experiments (i.e. 13 Channels X 20 Transmit Power) were required. Interference is created continuously on channels 1 and 13.

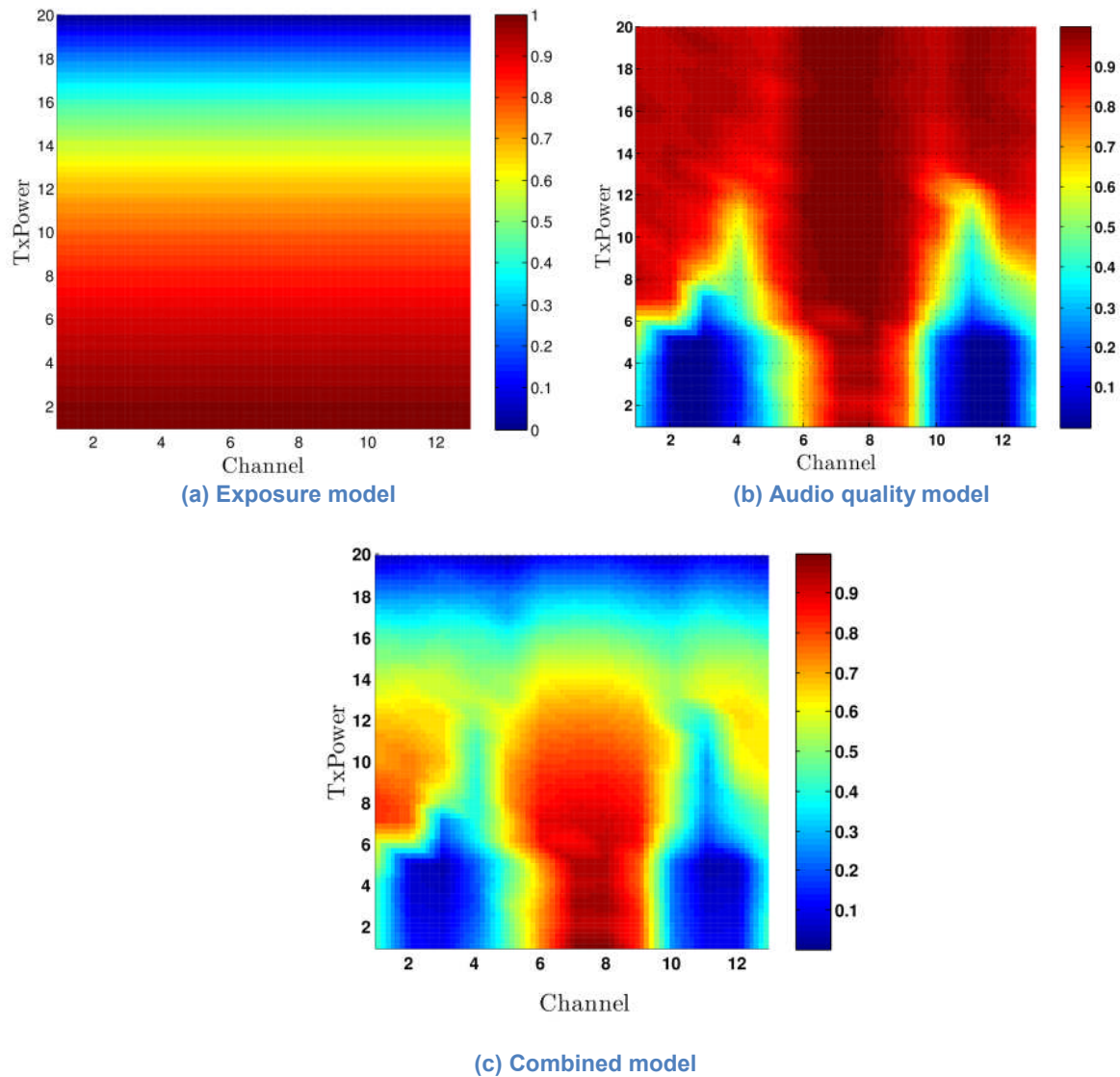


Figure 74: Exhaustive search model. Background interference is imposed at channels 1 and 13. Color bar indicates the objectives, normalized to a scale of [0 1].

Figure 74 shows the outcomes of the exhaustive search model for both performance criteria. The exposure model of Figure 74(a) only considers the exposure from the speaker but not from background interference, since the goal of the SUT is to reduce its own exposure. The exposure objective degrades with increased transmission power independent of the used channel. In contrast, the audio quality objective increases with increased transmission power and the influence of the interference can be noted on multiple channels. There is an area on the non-interfered channels (i.e. 6 to 8) where adequate performance is observed also for lower transmit Power (i.e. 1dBm to 6dBm). This area is of interest because it represents a region where exposure is low. The worst performance from the audio quality model is shown between channels 2 to 4, 10 to 12 and transmit power 1dBm to 7dBm. Interestingly, this region is not located on channels where background interference is applied on but on the neighboring channels. This is due to the fact that the speaker and interferer nodes apply CSMA-CA on identical channels but not on neighboring channels which results in degraded performance [Liu, 2013].

The combined objective model from Figure 74(c) is a combination of the exposure model and the audio quality model shown in Figure 74(a) and Figure 74(b) respectively.

6.6.2 Initial sample size sensitivity

As explained in Section 6.4, a surrogate model predicts the next experiment with highest expected objective value. However, the creation of the initial model requires a set of initial sample points on the design space and their outputs. This section investigates how many initial samples are required before a usable surrogate model can be created.

The initial sample points for any problem have to be selected carefully such that the optimization process quickly converges to the optimum. If the number of initial sample points is large, the optimiser spends too much time during exploration work. On the other hand, considering few initial sample points leads to the risk of missing global optimums and thus exploiting local optimums instead. One way to address the trade-off between exploration and exploitation during optimization is by selecting an appropriate initial sample size. Usually this depends on the complexity of a problem's global model. The more complex a problem's global model is, the larger the initial sample size needed to have good surrogate model approximation and vice-versa. It was indicated in [Zhou, 2006] that extreme points of a surface can be used to measure the complexity of a problem. These are the minimums, maximums and saddle points of a problem's global model. Moreover, it is also indicated that by setting the initial sample size to the number of extreme points, an optimiser has a higher chance to arrive at the global optimum in short amount of time. This assumption only works if the problem's extreme points are known beforehand. Most of the time this is not the case as we generally optimise unknown problems. Moreover, initial sample size selection depends on the problem type [Zhou, 2006]. For our specific problem, setting the initial sample size to 8 points is found a good choice. The 8 initial sample points together with the corner points which the SUMO optimiser adds, sums up to 12 initial points in total.

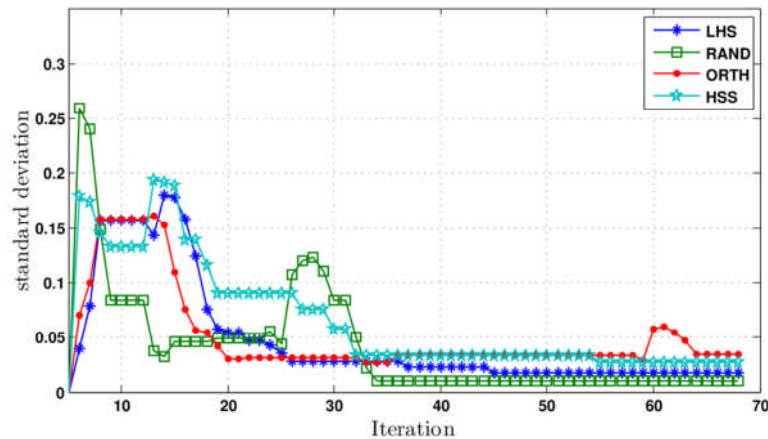
In the analysis of the coming sections, we will each time analyse four different sampling methods to pick the 12 initial sample points from the design space. These are

- Latin Hypercube Sampling (LHS)
- Orthogonal sampling (ORTH)
- Random sampling (RAND) and
- Hammersley Sequence Sampling (HSS).

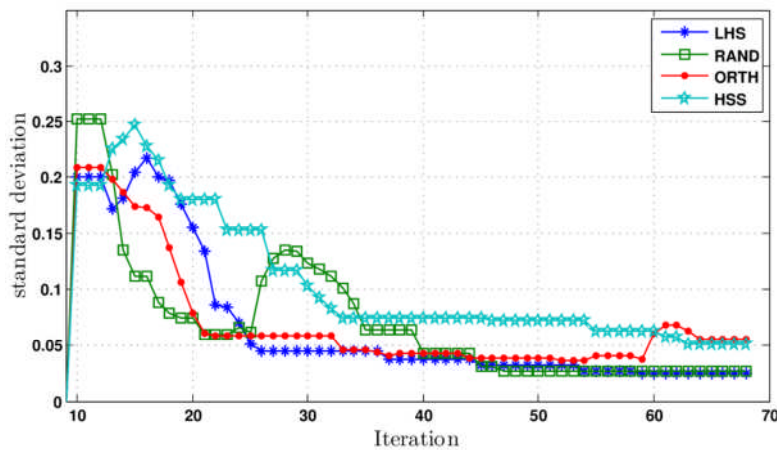
6.6.3 Stopping criteria

This section investigates the effect of an Objective Function Improvement (OFI) stopping criterion. The OFI stopping criterion looks at the relative difference in performance and stops the iteration when the standard deviation of the sorted last iterations falls below a certain threshold. The idea behind this concept is that the sorted objective function of a list of experiments ideally should approach a flat curve

as the number of experiment iterations increases. The OFI stopping criterion has two parameters to set. These are the STandard Deviation WIDTH (STD-WIDTH) which sets the number of objective performance values in the standard deviation calculation and the STandard Deviation THreshoLD (STD-THLD) which is used as a lower limit for the stopping criterion. Figure 75 shows the standard deviation curve as a function of iteration count for STD-WIDTH 6 and 10. Calculation starts after the iteration count reaches STD-WIDTH.



(a) STD-WIDTH = 6



(b) STD-WIDTH = 10

Figure 75: Standard deviation progress as a function of experiment iteration

As stated previously, the output of the plots for each standard deviation width approaches a flat curve when the optimization reaches the optimum. On the other hand, the randomness of the curves gradually decreases as the standard deviation width increases. This also increases the settling time until the lowest standard deviation value is reached. In addition, the benefit of the SUMO optimization toolbox is visually noticeable after the 12 initial experiments which is seen as a sharp declining curve. As the optimization continues, the standard deviation curve converges to a stable value.

There are two things we want the standard deviation curve to achieve. First, we want the curve to reach a stable value as fast as possible. This depends on the size of the optimum region in the problem's global model. The wider this area, the sooner the optimization locates the optimum and the standard deviation curve converges to a

stable value and vice-versa. Moreover, STD-WIDTH can assume the number of elements contained in the optimum region but the size of a problem's optimum region is not known beforehand. A good value for STD-WIDTH from experience is to use half the elements of the initial sample size. Second, we want the curve to reach a very small stable value. In fact, this value never approaches to zero as the wireless medium has a certain level of non-determinism. A threshold can be estimated by doing repeatability test around the optimum region which again is also not known beforehand. The work around is to perform repeatability tests on the problem itself but without applying background interference.

6.6.4 Performance comparison

Now we compare the SUMO approach to the traditional experimentation that exhaustively searches all parameters. For the comparison, we have defined the parameters of the OFI stopping criterion to the following: STD-WIDTH = 6 and STD-THLD = 0.032. Table 12 shows performance metrics of each conducted experiment when these parameters are applied. The four different sampling methods (i.e. Section 6.6.2) and their required *number of iterations*, before the stopping conditions are met, are also shown. The *Duration Gain* metric calculates the rate by which SUMO experiment duration is reduced compared to the exhaustive searching experiment that took 260 experiments. The *Performance Gain* metric evaluates how close the optimum solution of SUMO experiment is to the exhaustive searching optimum.

Table 12: Duration Gain and Performance Gain of SUMO optimised experiments using 4 sampling methods

Sampling Method	No. of iterations	Duration Gain	Performance Gain
LHS	26	260/26=10	0.9242/0.9287=99.51%
RAND	14	260/14=18.57	0.692/0.9287=74.5%
ORTH	20	260/20=13	0.772/0.9287=83.13%
HSS	55	260/55=4.72	0.9188/0.9287=98.93%

We see from Table 12 that LHS is the best sampling method in terms of performance gain: it stops the experiment at the 26th iteration with a duration gain of 10 and a performance gain of 99.51%. On the other hand, RAND sampling method converges the quickest but at the expense of a lower performance gain (74.5%). This is because of poor initial sampling and it leads to a local optimum instead of the global optimum. This is also seen in Figure 75 such that bumps appear on the curve (iteration 25-32) had we continue the optimization.

7 CONCLUSIONS

This deliverable has presented the main achievements made so far within WP5 of the LEXNET project, towards EMF exposure reduction through the use of novel topologies and network management techniques. The problem treated is complex, goes deep into network design and management, and the solutions are sought on various levels, from high-level planning and optimization to low-layer protocols. The quantification of the exposure in the context of LEXNET requires a novel methodology embracing different networks and technologies, which may be considered one of the main results of the project as well. The amount of data that needs to be processed poses a significant challenge on existing and novel networks.

The main strategies for exposure reduction tackle both topology changes and various optimization methods. Preliminary results have underlined the general advantage of deploying small cells. Yet, these results should be taken with care, as the full verification requires comprehensive measurements under all possible conditions. Further, the impact of user behaviour is stressed - their velocity, with handovers depending on network topology in the area, services used, UE capabilities – which impacts the selection of different techniques, from offloading to traffic shaping, delayed transmission, and device selection. The EMF awareness should be enforced through both planning and optimization. Similar to power control, both slow-loop and fast-loop EMF control are provided, depending on network measurement (reports) and processing capabilities. Such mechanisms are paving the way for future autonomic, self-optimizing network, which would optimise network performance, QoS and EMF. The strategies proposed are to be further elaborated, depending on measurement results.

These strategies require a characterization of the exposure gain, in order to validate specific techniques. Starting from the EI as a comprehensive measure of exposure originated from target networks, proxy metrics that could be further mapped to the EI are defined. While the EI requires processing of huge amounts of data from different network databases (usage data, UE types etc), sometimes including even manual check of inconsistent data, proxy metrics can serve for the assessment directly from network reports or drive-test and field measurements, or simulations. The purpose of EI is two-fold: (a) for operators, to assess exposure using network-available resources and reduce it using different strategies; and (b) for regulators and third parties, to assess the exposure using network and non-network resources and instruct the operators accordingly. WP2, WP3, and WP6, are working towards appropriately mapping the available data to assess the EI. To this aim, the role of WP5 is to find proxy metrics, as a link between raw network data and the EI.

Moreover, different technologies define different procedures for network reports, and therefore the obtained results need to be scaled according to time averaging defined by EI in order to appropriately compare them – here the attention is drawn to the signal shape on the radio interface and activity of the transmitters in time. Hence, even the methodology for assessing the exposure using proxy metrics requires special attention. The legacy technologies will most likely endure for a relatively long time, and their impact over the whole exposure is generally higher as the technology is older. For novel networks, new network commands and measurements for the purposes of EMF control may be standardized. Drive-test and field measurements

may serve for the verification of proposed scenarios but are too demanding for daily EMF control. Network reports may be triggered for a long period, and for many cells, so it is crucial to define a methodology for the comparison of results and make the network capable of assessing the EI through available resources. Thus, the focus is on providing right simulation tools, network reports, and methodology for EMF assessment in both legacy and novel networks, and providing new optimization techniques and network commands for EMF control. The preliminary results also show that there is no on-for-all solution [Plets, 2014], and the strategy selection depends on current traffic load, radio conditions, mobility, application used, and the duration of use, available networks and UE capabilities.

The importance of small cell concept is recognized by Chapter 3. This new concept arising from traffic demands, more efficient use of radio spectrum, coverage extension etc, finds its purpose in EMF exposure reduction as well. Small cells with respect to EMF are again analysed on different levels – from the new algorithm for access network selection between macro/SC, over specific strategies/algorithms in autonomic networks, to topology issues and small cell densification. The results obtained through simulations outline the advantages of proposed techniques.

Introducing EMF control into the network designed for performance and QoS optimization inevitably leads to conflicting policies, and their resolution based on priorities. The reduction of exposure often means lower signal levels, which in turn may jeopardize the end user experience. On the other hand, in specific cases, interventions in network design might help satisfy all requirements. Chapter 4 has shown, through a specific problem of a video application, that the altering of protocols on layer 2 and layer 3 may preserve QoE while reducing the EMF exposure. Similarly, Chapter 5 has shown that the implementation of a new routing protocol in multihop networks might bring a significant exposure reduction without negative impact on performance or QoE.

The EMF-aware optimization of settings in any type of network brings forth complex simulations and measurements. Chapter 6 has illustrated that using an optimiser, with EMF reduction and performance optimization goals, the number of experiments needed in a wireless testbed may be significantly reduced. Further, appropriate setting of various configurable parameters results in higher efficiency of the optimiser.

This deliverable has revealed many different directions of research towards EMF reduction in wireless networks. The ongoing work has focused around the following topics:

1. Cellular networks optimization algorithms
2. Network topology design and planning
3. Hetnets cell access selection
4. Handover due to user mobility
5. Impact of application: video codecs
6. Impact of application: voice services
7. Routing for multi-hop networks

Each topic defines specific scenarios that are being evaluated through simulations and real network measurements, and the detailed results will be presented in our forthcoming deliverable D5.2.

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APPENDIX 1: HANDOVER IN CELLULAR NETWORKS

Handover is the mechanism that transfers an ongoing call from one cell to another. This mechanism is of great importance for cellular systems, because it provides continuity of the wireless service, when the phone is moving away from the area covered by one cell and is entering the area covered by another cell. Beside coverage, other reasons for handover to be initiated are quality, load, user preferences and context, etc.

GSM

In GSM hard handover mechanism is used. Communication channel with serving cell is released first and the new channel is acquired later from the neighboring cell (see Figure 76). Thus, power control from serving cell is interrupted, and new power control from neighboring cell is established. In GSM, initial values for UL and DL powers are maximum values, and as a consequence EMF exposure is expected to be high.

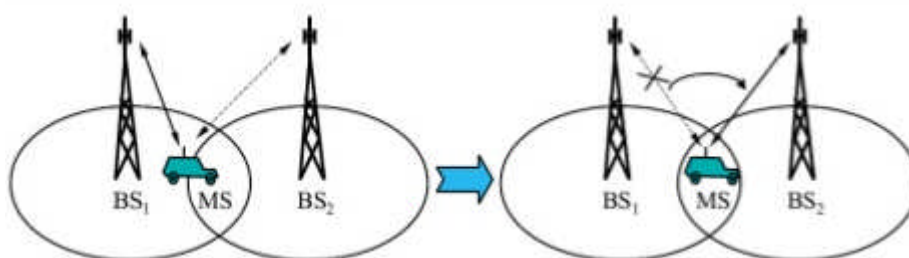


Figure 76: Hard handover

UMTS

Softer and Soft Handover

Softer and Soft Handovers are an essential interference-mitigating tool in WCDMA and they are needed to avoid near-far scenarios of a mobile station, penetrating from one cell deeply into an adjacent cell, without being power-controlled by the second one.

During softer handover (see Figure 77), a mobile station is in the overlapping cell coverage area of two adjacent sectors of a base station. The communications between mobile station and base station take place concurrently, via two air interface channels, one for each sector separately, but only one power control loop per connection is active.

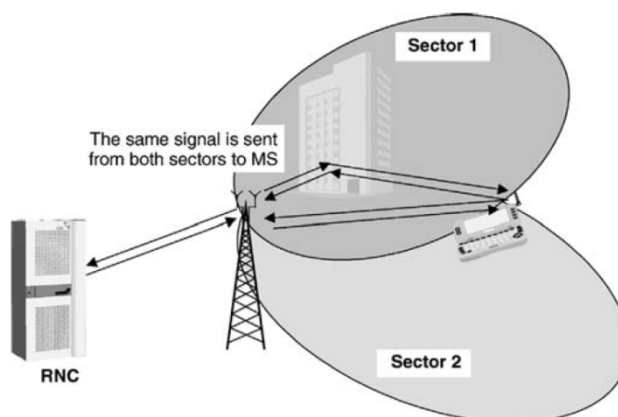


Figure 77: Softer handover

During soft handover (see Figure 78), a mobile station is in the overlapping cell coverage area of two sectors belonging to different base stations. The communications between mobile station and base stations take place concurrently, via two air interface channels from each base station separately.

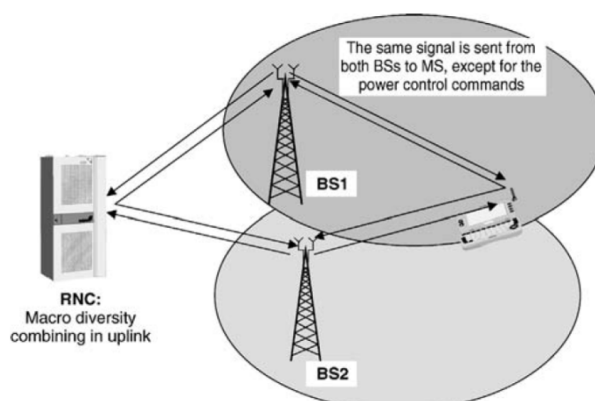


Figure 78: Soft handover

In the uplink direction, the code channel of the mobile station is received from both base stations, but the received data is then routed to the RNC for combining. This is typically done so that the same frame reliability indicator, as the one provided for outer loop power control, is used to select the better frame between the two possible candidates within the RNC.

It is important to keep in mind that, during soft handover, two power control loops per connection are active, one for each base station [Holma, 2010].

By using soft and softer handover, there is less overall interference in the network and, as a consequence, the EMF is reduced as well.

Hard handover

Intra-frequency hard handover in UMTS systems is used in some specific cases, for example, if an inter-RNC soft handover is not possible, the handover control initiates an inter-RNC hard handover.

Inter-RAT and inter-frequency handover

The UE performs inter-RAT and inter-frequency hard handover using the compress mode behavior. During compress mode, the UE makes gaps in transmission, in order to measure the signal of neighboring cells on other frequency, and select a suitable candidate for handover. Both uplink and downlink power control mechanisms aim at recovering the SIR target, as quickly as possible, after each transmission gap, in order to avoid block errors during and after the compressed frames. To achieve this recovery, UL and DL power are increased and EMF exposure is expected to be increased as well.

In some specific cases UE is instructed to perform blind handover, without compress mode and measurement of another frequency. In this case network selects what it believes to be the optimum target cell.

LTE

LTE does not support soft handover. Therefore, a centralised control, such as the one provided by the RNC in UMTS, is not needed. This ties in well with the distributed control of cell management, which is one of the core architectural principles underpinning LTE [Sesia, 2009].

Like in GSM, the hard handover mechanism is used. The difference from GSM is that the UE uses channel reciprocity to estimate the required power settings for the new uplink (not the maximum value), by knowing the transmission power of the DL reference signals (which is broadcasted by the base station) and their received power (which the UE measures).

Assuming that the distance from the eNBs is the dominant factor in signal quality, and that the transmit power of eNB #1 is much lower (small cell) than that of eNB #2, the handover to eNB #2 would happen when the terminal is still relatively close to eNB #1. The resulting increase in the distance from the serving station will now cause the UE to have to increase its transmit power, in order to maintain the same signal quality on the UL, thereby potentially increasing the EMF exposure of the user.

APPENDIX 2: SMALL CELL POSITION AND ACTIVATION CONDITION

This Appendix highlights the relation between the activation condition of a small cell and its position. The position of the SCs with respect to the macro-cell has an important impact on the level of EMF exposure in the network. The interdependence between SC location and EMF can be inferred from the activation condition, and is formalized below. Consider the following assumptions:

1. The DL path-loss is expressed (in linear scale) as: $h_{s,r} = k (d_{r,s})^{-\gamma} \xi$ where, $d_{r,s}$ is the Euclidean distance from r to s , γ denotes the path-loss exponent, ξ is used to model slow fading effects and k is a path-loss model parameter
2. The distance only dependent UL Tx power (expressed in dBm) reads:

$$P_{r,s}^d = \min\{P_{max}, \alpha_0^T \cdot \log_{\{10\}} d_{r,s} + 10 \log_{\{10\}} (\beta_0^T \cdot M)\},$$

3. For a given target SINR η the following relation subsists between $P_{r,s}^d$ and $P_{r,s}$ (here in Watts):

$$\frac{P_{r,s} h_{r,s}}{\sigma^2 + \sum_{\{s' \neq s\}} (P_{r',s'} h_{r',s})_{r' \in A_{s'}}} = \eta = \frac{P_{r,s}^d \xi h_{r,s}}{\sigma^2}$$

and

$$P_{r,s} = P_{r,s}^d \xi \left(1 + \frac{\sum_{\{s' \neq s\}} (P_{r',s'} h_{r',s})_{r' \in A_{s'}}}{\sigma^2} \right).$$

The assumption (2.) derives from UL power control equation proposed in [Carlos, 2008]:

$$P_{\{r,s\}} = \min\{P_{\{max\}}, P_0 + 10 \log_{\{10\}}(M) + \alpha \cdot 10 \log_{\{10\}}(h_{\{s,r\}}) + \Delta_{\{mcs\}} + f(\Delta_r)\},$$

where, $P_{\{max\}}$ (dBm) is the maximum Tx power of the UE, α is the cell specific path-loss compensation factor, P_0 (dBm) is nominal transmit power, M is the number of resources allocated to the user, $\Delta_{\{mcs\}}$ (dB) and $f(\Delta_r)$ (dB) some UE-specific and closed-loop correction factors. $\alpha_0^T = \alpha\gamma$, $\beta_0^T = k^\alpha \cdot 10^{P_0/10}$, σ^2 is the variance of the background thermal noise and the upper-script $T \in \{m, s\}$ is the type of the cell, namely macro-"m" or SC-"s". Note that on assumption (3.) powers are converted from dBm to watts. Relying on these three assumptions, one can rewrite the activation policy given in 3.2.2.1 as follow:

$$\begin{aligned} & \int_{A_b} \psi \left(\varphi(d_{m,b}, d_{r,b})^{\alpha_0^m} \cdot (\beta_0^m / \beta_0^s) - d_{r,b}^{\alpha_0^s} \right) \beta_0^s M T_r \lambda(dr) - E_b^{DL} \\ & + \int_{A_b} \psi \left(\frac{\sum_{\{s \notin \{b,m\}\}} I_s^m}{\sigma^2} P_{r,m}^d - \frac{\sum_{\{s \neq b\}} I_s^b}{\sigma^2} P_{r,b}^d \right) T_r \lambda(dr) > 0, \end{aligned}$$

where $I_b^s = (P_{r',b} h_{r',s})_{\{r' \in A_b\}}$ denotes the UL interference generated by a user in cell b over cell s and $\varphi(d_{m,b}, d_{r,b}) = d_{r,m}$ is the Euclidean distance from location r to station m . φ is introduced to express the distance between all SC b users and the macro-cell ($d_{r,m}$) as a function of the distance between the users and SC b ($d_{r,b}$) and the

distance between the SC and the macro cell ($d_{m,b}$). Note that it is non-decreasing with $d_{m,b}$. The activation rule goes to zero when the traffic load decreases at the SC or when the SC is very close to the macro-cell. Different combinations of these two factors determine the activation or deactivation of the SC. An online tracking of the activation rule thus make it possible to define activation/deactivation policies for the small-cells.

APPENDIX 3: RBRP SIGNALING

This section presents the signaling that has been defined for the RBRP. Special attention is paid to the *Cost/Reward Management* impact, in particular over the route maintenance procedure. As mentioned in Section 5.1, the proposed protocol is based on a ‘*simplified*’ AODV operation, over which new messages have been added so as to appropriately handle dynamical change of the route cost.

Besides those aspects that are traditionally used by routing protocols, such as sequence numbers or neighbor tables, a RBRP routing entry includes a field to indicate the state for such particular entry. This field can take the following values: *InUse*, if the node is using that entry to send locally generated data; *Active* if it is being used to forward data; *Active InUse* if it satisfies the two previous conditions; *Valid* if the entry has not expired but it is neither *InUse* nor *Active*.

The following four message types have been defined for both the route establishment and maintenance processes:

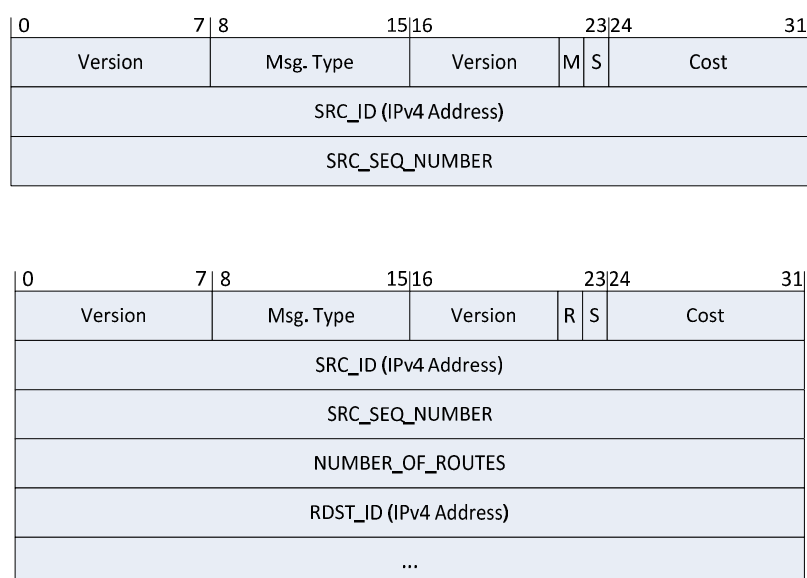


Figure 79: Route maintenance messages: up HELLO; down Link Report

- *Hello*: monitors the link between neighbors and notifies about potential cost changes.
- *Route Discovery* (RD): a broadcast message sent by the source node in order to find the cost and route towards a given destination. It includes the cumulative cost of the whole path, incremented by each intermediate node.
- *Route Discovery Acknowledgment* (RD ACK): sent as a response to the Route Discovery message (RD); we consider a route to be established upon the reception of a RD ACK.
- *Link report* (LR): broadcast message propagates information about cost changes.

While RD and RD ACK messages are used to establish routes, HELLO and LR play an important role on the route management and cost change dissemination. A node sends a HELLO message either periodically or when its own cost has changed. The format of the HELLO packet is shown in Figure 79. When it is sent after the expiration

of the periodic timer, the *Cost Modified* flag (**M**) is set to 0 and the cost is the value within the corresponding field. Otherwise, if the HELLO is sent upon a cost change event, the **M** flag is set to 1; in this case, the cost field shall be interpreted as the variation from the previous value, according to the *Sign* (**S**) flag.

On the other hand, the LR message, whose format is also shown in Figure 79, is sent to disseminate a cost change after the reception of a HELLO with the **M** flag activated. It carries the cost fluctuation and its sign, as well as the information required by other nodes to update their routing tables.

In a nutshell, upon a state transition of a node **N**, this node sends a HELLO message with the **M** flag active, to notify its neighbors. Afterwards, they check whether there are active entries with **N** being the next hop, i.e. *Active* or *Active InUse* states. If this is the case, they also propagate the cost change by employing a LR message. Its subsequent receptions are processed – to further propagate the information – only if there is an active entry for which the node that has previously propagated the packet is the next hop.

In this sense, Figure 80 illustrates the change propagation in a simple scenario. Assume a situation in which a route between **A** and **D** has been previously established. At some point, node **C** changes its state (i.e. a threshold has been trespassed) and then communicates its new cost to its neighbors (in this case nodes **B** and **D**) by means of a HELLO message. Upon receiving the HELLO from **C** containing the cost increment (ΔC), nodes **B** and **D** update their tables. In the case of node **B**, since it has an entry with **C** as next hop whose entry state is *Active*, it propagates the cost change indicating that the increment affects the route towards node **D** which has **B** as next hop (indicated as **RDST1** in Figure 80).

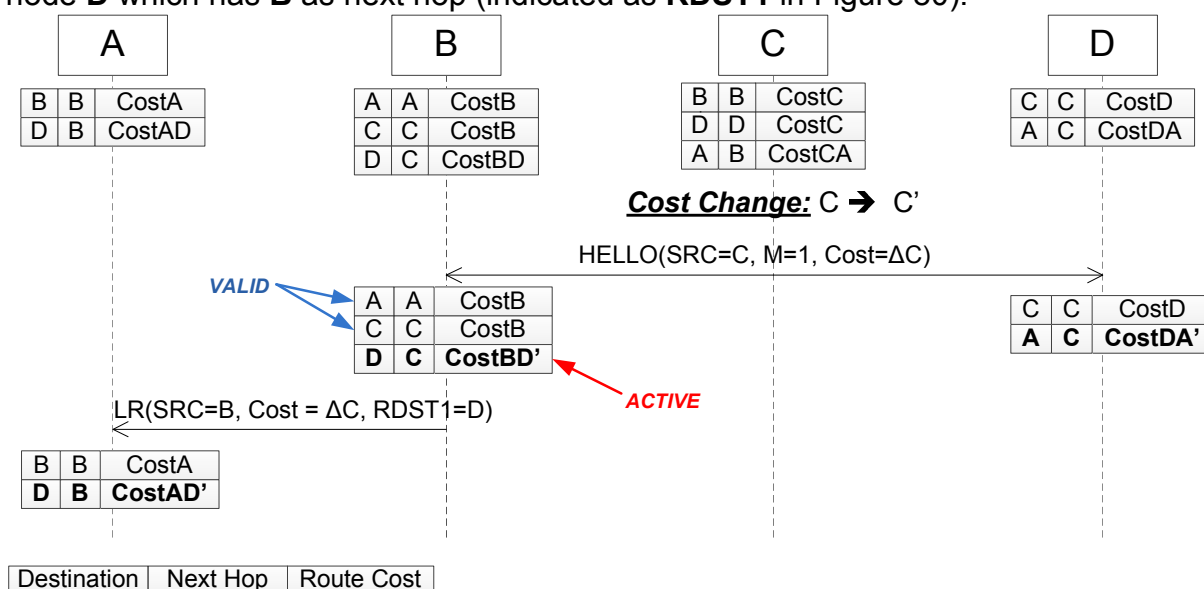


Figure 80: Cost change example

The design of the cost change dissemination process has two different goals, namely: first of all, the cost information stored in the routing table is local, so that a node needs incremental values to update it appropriately; and also, the use of the routing entry states avoids the broadcasting of unnecessary messages.

APPENDIX 4: SUMO OPTIMISER

The SUMO optimiser is an efficient implementation of the well-known Expected Improvement (EI) criterion, popularized by Jones et al in [Jones, 1998]. In this work, the optimiser is applied to accelerate the optimization of wireless network problems, because the execution of multiple experiments on a wireless testbed is often a time-consuming procedure. A typical optimization problem comprises a set of N network parameters, denoted by a vector $\mathbf{x}=\{x_i\}$ for $i=1,\dots,N$, which may consist of either discrete numerical or continuous variables. These parameters need to be tuned within the bounds of a pre-specified parameter range of interest $[L_i, B_i]$ in order reach an optimal network performance. The aim of the overall procedure is to optimise a given objective function $f(\cdot)$ (for example, to maximize the Quality of Service/Quality of Experience (QoS/QoE), or to minimise a certain cost such as energy consumption, etc...).

The optimization algorithm starts from a well-chosen initial experimental design, and a global (but only locally accurate) Kriging surrogate model of the objective function is computed. Such Kriging models are part of a broader class of approximation methods, called the Gaussian Processes (GP), and have some interesting properties that can be exploited by the optimiser. Whereas the standard approximation methods predict only a single function value, GP methods can predict the uncertainty of a function value as the realization of a normally distributed random variable $Y(\mathbf{x}) \sim N(\mu(\mathbf{x}), \sigma^2(\mathbf{x}))$, where $\mu(\mathbf{x})$ represents the predicted value for $f(\mathbf{x})$ and $\sigma^2(\mathbf{x})$ the prediction variance at an arbitrary point $\mathbf{x}$ in the parameter space. Based on this random variable $Y(\mathbf{x})$, different statistical criteria (such as the Probability of Improvement (PoI) or EI) can be computed to quantify how interesting a new point in the design space is. In this work, we adopt the EI criterion which simultaneously balances exploration and exploitation [Hawe, 2006] of the parameter space. This corresponds to the improvement that is expected to occur when compared to the optimum value obtained so far (i.e., $f_{\min}$ or $f_{\max}$). By picking additional points with the highest EI value in the parameter space, the optimization process is directed towards a configuration with optimal performance. For example, in the case of a minimization problem, it can be written in the form of an integral as in [Couckuyt, 2010] where $\phi(\cdot)$ represents the probability density function of a random variable and $I(\mathbf{x})$ is the improvement function.

$$E[I(\mathbf{x})] = \int_{-\infty}^{f_{\min}} I(\mathbf{x}) \phi(Y(\mathbf{x})) dY$$

where the improvement function is defined as

$$I(\mathbf{x}) = \max(f_{\min} - Y(\mathbf{x}), 0)$$

$E[I(\mathbf{x})]$ corresponds to the improvement that is expected to occur when compared to the optimal value of the objective. A graphical illustration of this criterion is shown in Figure 81.

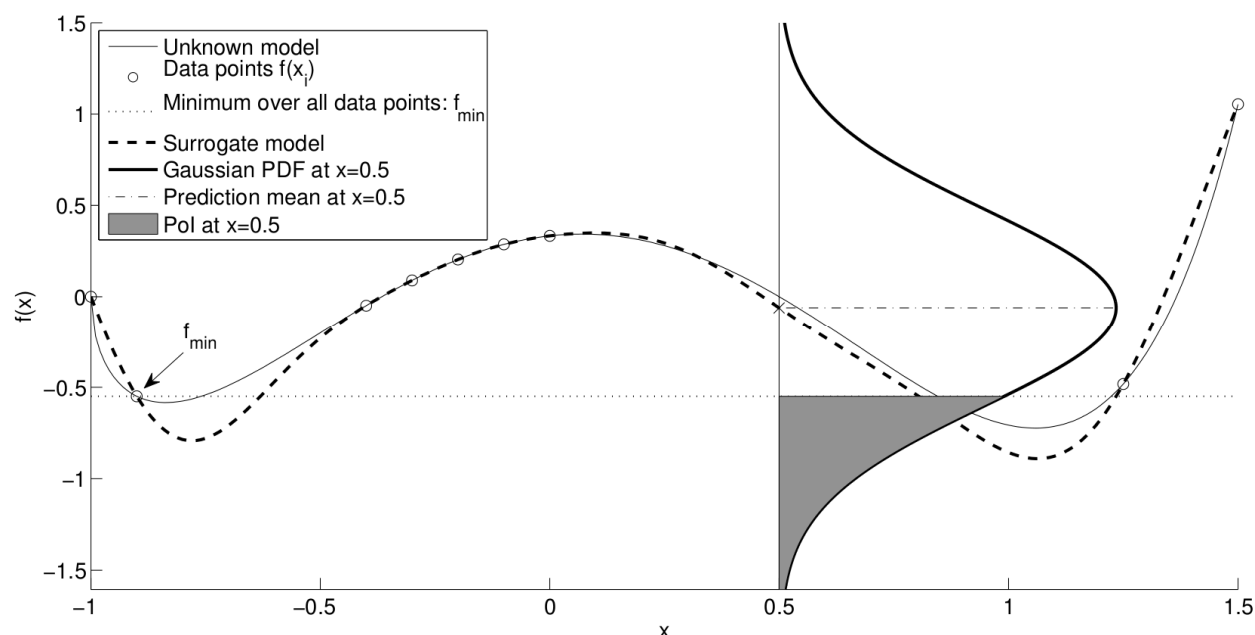


Figure 81: Graphical illustration of a Kriging model and the expected improvement criterion. A surrogate model (dashed line) is constructed based on a set of data points (circles). For each point the surrogate model predicts a Gaussian probability density function (PDF). An example of such a PDF is drawn at $x = 0.5$. The volume of the shaded area is the probability of improvement (Pol) and the first moment of this area is the expected improvement

A more detailed explanation can be found in Section II-B of [Couckuyt, 2010]. Note that this EI criterion can also be expressed and evaluated in a closed-form, and it is optimised over the parameter space. The selection of new points corresponds to the execution of new experiments on the testbed and the outcome of these results is used to update the Kriging surrogate model. The process of performing experiments and subsequently updating the model to optimise the objective function is iterated until a stopping criterion is met.

Typically, Kriging and the EI criterion are used to solve continuous optimization problems though it can be easily applied to discrete optimization problems too. The optimization of the EI criterion for discrete problems can simply be done by traditional discrete optimisers (such as a discrete pattern search or the discrete version of the CMA-ES algorithm [Hansen, 2001]). However, regarding the dimensionality of the problem in this paper it is chosen to evaluate the EI criterion over the complete (and limited) set of discrete possibilities and the best point is chosen. The discrete variables of this work are ordinal of nature, which means that standard Kriging can be directly applied (the standard continuous correlation functions can be used). Though, nominal or categorical variables can also be easily handled by Kriging by using an appropriate function to describe the correlation between the discrete data points [Zhou, 2011].

In short, the SUMO optimiser is an effective approach to optimise network performance on a real-life testbed. The experimental results confirm its effectiveness and robustness.

APPENDIX 5: INTERNAL REVIEW

Reviewer 1: Günter Vermeeren				Reviewer 2: Serge Bories		
Answer		Comments	Type*	Answer		Type*
1. Is the deliverable in accordance with						
(i) the Description of Work?	☒ Yes		☐ M	☒ Yes		☐ M
	☐ No		☐ m			☐ m
			☐ a			☐ a
(ii) the international State of the Art?	☒ Yes		☐ M	☒ Yes		☐ M
	☐ No		☐ m			☐ m
			☐ a			☐ a

2. Is the quality of the deliverable in a status

(i) that allows to send it to EC?	☐ Yes ☒ No		☐ M ☐ m ☐ a	☐ Yes ☐ No		☐ M ☐ m ☐ a
(ii) that needs improvement of the writing by the editor of the deliverable?	☒ Yes ☐ No		☐ M ☐ m ☐ a	☒ Yes ☐ No		☐ M ☒ m ☐ a
(iii) that needs further work by the partners responsible for the deliverable?	☒ Yes ☐ No	Clarifications of the choices made and textual improvements are mandatory	☐ M ☐ m ☐ a	☒ Yes ☐ No	Section 2 presents qualitatively lots of mechanisms and strategies but the lack of quantitative analyses don't allow any prioritization in term of most impacting solutions. Consider to synthesis this part which is may be too heterogeneous.	☐ M ☒ m ☐ a

* Type of comments: M = Major comment; m = minor comment; a = advice