D2.7

Report on Optical and Wireless Network Integration

Dissemination Level: PU

- **Dissemination level:**

  PU = Public,
  RE = Restricted to a group specified by the consortium (including the Commission Services),
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Abstract:

The present deliverable provides a general introduction and an up-to-date view on wireless and wired network consolidation. The approached from the ongoing discussions in the research area around 5G wireless networks are used to present and elaborate the DISCUS access network view for fixed and mobile convergence in LR-PON architectures. In the deliverable the general architecture is described to realize a consolidation of the metro-access space as well as for systems, i.e. wired and wireless services. The network offers the advantages of a software-defined networking approach and serves customers for the residential, business and enterprise market simultaneously. It can be concluded that the DISCUS LR-PON architecture and the M/C node design is capable to serve current and future mobile services applying different air data rate requirements. Local solutions and variations may be applied to the DISCUS architectures and the overall ODN fiber length may be limited to 20…40 km in particular cases. Two wireless and wired convergence scenarios and solutions are discussed: the first approach focuses on a fixed and radio access converged network scenario for 2020 applying structural convergence and base stations hoteling within the M/C node (fronthaul case), whereas the second approach is related to a future scenario (beyond 2020) which focuses on the functional convergence and Ethernet transport in the access area.

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1 Introduction

Up to now, mobile networks are developed independently from the fixed networks used to deliver services for residential customers. The usage of the infrastructures for wireless and wired services is only joined rarely at the aggregation stages of the networks. Typically, radio access networks (RAN) for 2G, 3G and 4G are connected via coarse wavelength division multiplexed (CWDM) optics (in case a wired connection is used at all) to the aggregation switches which may also be used by wired network elements. However, in the access space dedicated fiber links are often arranged so that they do not provide either the use of common technologies nor of a simple sharing of the fiber infrastructure. In the core segment typically the transport mechanisms are shared for the wired and wireless networks, but still separate control, operation and management functions are used. In this deliverable, the optical (fixed) and wireless (mobile) network convergence is introduced, discussed and analyzed for the long-reach passive optical network (PON) infrastructure of the DISCUS project.

A fixed and wireless network convergence will help to manage traffic more efficiently, to provide more capacity with seamless multiple access and providing best connection in each situation [1]. In general, different approaches exist for the wireless and wired convergence of the network architectures, e.g. a structural convergence and a functional convergence [2]. The structural convergence simplifies the overall network by a common use of resources, e.g. infrastructure, system technology, interfaces and transport mechanisms. Contrary, the functional convergence presents a unification of the fixed and mobile network functions.

The 5G Infrastructure Public Private Partnership (5G PPP) describes a network vision for the next generation of communication networks and services that will strongly influence the future European society and economy. *The impact will go far beyond existing wireless access networks with the aim for communication services, reachable everywhere, all the time, and faster. 5G is an opportunity for the European ICT sector which is already well positioned in the global R&D race. 5G technologies will be adopted and deployed globally in alignment with developed and emerging markets' needs* [3]. 5G wireless networks are currently heavily studied within EU-FP7-projects such as: METIS, 5GNOW, iJOIN, TROPIC, Mobile Cloud Networking, COMBO, CROWD, MOTO and PHYLAWS and within many company research centers.

In the future 5G networks will be used that may offer fully new network characteristics at an operational level [3]:

- 1000 times higher mobile data volume per geographical area
- 10 to 100 times more connected devices
- 10 times to 100 times higher typical user data rate
- 10 times lower energy consumption
- End-to-End latency of < 1ms (< 5 ms)
- Ubiquitous 5G access including in low density areas
- Fast deployment of novel applications using software-defined networking (SDN) approaches

- Offer robust security and authentication metrics suitable for a new era of pervasive multi domain visualized networks and services
- Optimal and seamless quality of experience for the end user [1]

The massive increase in capacity demands (more subscriber and higher throughput demand), the high reliability (e.g. medical application or in automotive sector), the increasing mobility of the users, their need to connect to the Internet at every time and everywhere using each device as well as the growing number of connected devices (smart metering, M2M communication, Internet of Things (IoT)) will change the network paradigm and will put pressure on operators to ensure an acceptable average revenue per user. Thus, the major driver for a convergence of the wired and wireless networks is to offer an optimized network infrastructure ensuring increased performance and flexibility by significantly reducing the cost to deploy and operate the network [1].

The DISCUS consortium focuses on the implementation of a heterogeneous access network space offering access for wireless as well as wired residential, business and enterprise customers. Such network architecture is based on a long-reach and high-split access network with a transparent outside plant, a massive consolidation of central offices to few metro/core nodes eliminating the metro space and a meshed core network. The overall DISCUS approach for the integration of the wireless and wired services is based on a point-to-multi-point (ptmp) PON approach in which the wireless base stations and/or the remote radio units (RRU) are co-located with optical line terminations (OLT) or optical network units (ONU). This way, a unified access and metro (aggregation) network is constructed that allows the structural convergence with converged physical layer supporting heterogeneous access for fixed and mobile services. A massive base station hoteling at the M/C node can enable a cost-attractive mobile fronthauling (separation of RRU close to customer site and centralized base stations) solution. The fronthaul as well as the mobile backhaul (base stations close to customer site) incorporated into the DISCUS TWDM-PON offer the possibility of centralization of radio access network functions into the M/C node in which traffic aggregation, switching and routing towards the DISCUS core network or to the Internet may be achieved at the same place. The DISCUS convergence approach also includes the capability to incorporate radio core equipment into the M/C node so that radio core functions can be handled close to the customer reducing latencies. The wired as well as the wireless network data is terminated with OLTs within the M/C nodes. The signals are launched afterwards to the L2 Ethernet access switches and L3 IP core routers for joint processing and aggregation. These switches and routers are controlled by a SDN approach taking care of optimal resource allocation for the OLT-ONU communication as well as the core traffic demands depending on the customer's requirements. This way, the DISCUS consortium separates the data plane, the control plane as well as the application plane to realize an access network that is based on commodity hardware with a generic control interface. The centralization of the wired and wireless network functions at the M/C node via the long reach DISCUS access space is also an enabler for future network upgrades towards network function virtualizations (NFV). NFV and SDN approaches are currently a strong research topic in academia and industry. The DISCUS network approach focuses mainly on the structural convergence and is generated in a way to enable a network that may be easily upgradable to offer also functional convergence at a later stage.

The DISCUS consortium collaborated with the FP7-project COMBO on wireless and wired network integration scenarios. Phone conferences and a collaboration meeting took place at the optical fiber communication conference (OFC 2015) between four representatives of COMBO project and three representatives of DISCUS project. It has shown that the results of both projects are complementary, in particular in terms of proposed network architectures [2].

In the following chapters the DISCUS optical and wireless network integration is discussed and analyzed in more detail. Few parts of the work of this deliverable are also presented in D4.11 "Consolidated Long Reach Access Network View". This document delivers the required theoretical background of todays and possible future of wireless networks and also extends the DISCUS work on fixed and mobile convergence. In chapter 2 trends and definitions in wireless networks are presented and chapter 3 is used to explain the DISCUS view on wired and wireless convergence. In chapter 4 a cost analysis for fronthauling versus backhauling approaches are presented and in chapter 5 specific challenges for wireless integration are presented, i.e. backhauling with group assured bandwidth and energy consumptions in converged networks. Chapter 6 summarizes and concludes the document.

2 Introduction to Wireless Networks

In this chapter, the wireless services and the wireless architectures and approaches are introduced and discussed along with a view on possible approaches for a 5G network. This work can be considered as a general introduction to wireless network approaches, requirements, evolutions and the relation to the optical wired networks. With this knowledge the following chapters which are used to introduce and analyze the DISCUS wireless and wired network realization can be understood. Most of the work follows closely the paper [4].

In section 2.1 an introduction to wireless networks is provided. Centralized processing is expected to bring about substantial benefits for wireless networks both on the technical and on the economic side. While this concept is considered an important part of future radio access network architectures, it is more and more recognized that the current approach to fronthauling by employing the CPRI protocol (Common Public Radio Interface) will be inefficient for large scale network deployments in many respects, and particularly for the new radio network generation 5G. In the sections 2.2-2.6, an overview is given of currently available optical fronthaul technologies, of recently started activities towards more efficient and scalable solutions, and finally an outlook is provided onto which 5G specific service characteristics may further impact future backhaul and fronthaul networks.

2.1 Wireless Network Architectures and Mapping to Optical Architectures

Today's wireless networks are usually based on a distributed radio access network architecture (distributed RAN). Since some years, however, there is a trend towards building radio access networks by employing centralized processing (centralized radio access network: centralized RAN). (Note: the frequently used term 'C-RAN' is not used here, in order to avoid confusion with terms like Cloud RAN or Converged RAN; the generic term 'centralized RAN' will be used throughout this deliverable, instead). Currently, the related efforts are mostly spent in research and development, but there are also a few centralized RANs in operation already today. In the following, some essential elements and architecture concepts of radio networks are briefly reviewed, taking LTE radio technology as an example (Fig. 1).

In the distributed RAN architecture, the base stations (eNodeB) are each connected by backhaul links to their peering point in the mobile core network, the serving gateway/mobility management entity (S-GW/MME). These backhaul links provide transmission pipes both for user data as well as for control and management data between the base station and the radio core network (logical interface S1-u/c). They also carry data that are exchanged between base stations for handover and for coordinated transmission schemes involving neighboring cells (logical interface X2-u/c). The backhaul connections are established across switched/routed Ethernet/IP/MPLS aggregation and last mile networks in the regional, metro and access domain, see Fig. 2. The backhaul connections between the radio core network and the base stations extend over long distances of up to several tens of kilometers leading to high latencies in the range of several tens of milliseconds during hand-over processes. The antennas, in turn, are directly connected to the base stations over short copper or fiber links (< 100 meters).

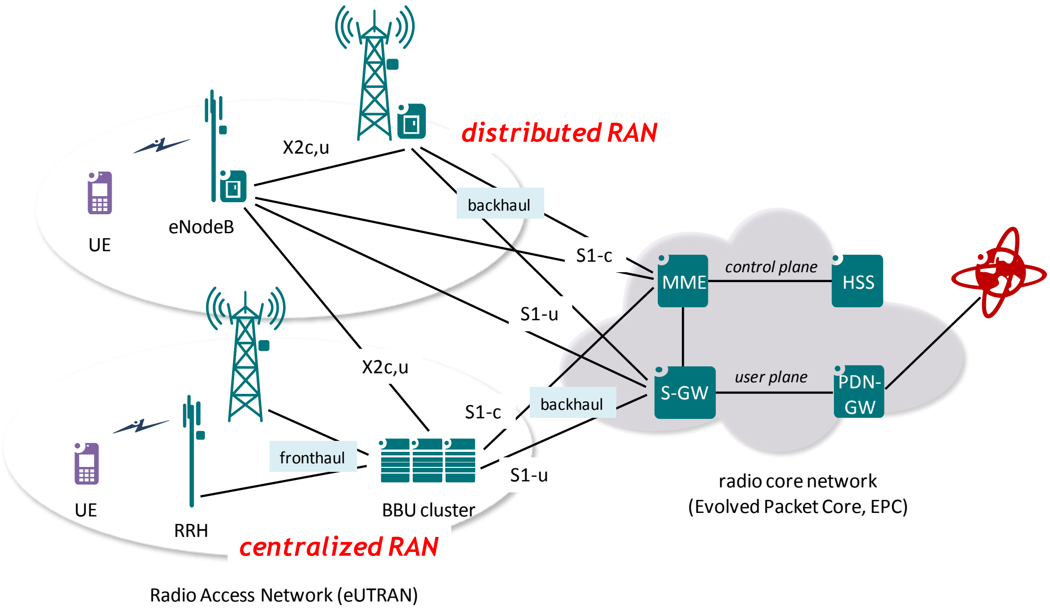

Fig. 1: Distributed RAN and Centralized RAN architectures, and radio core elements in an LTE network. (UE: user equipment; RRH: Remote Radio Head; BBU: Baseband Unit; MME: Mobility Management Entity; S-GW: Serving Gateway; PDN-GW: Packet Data Network Gateway; HSS: Home Subscriber Service; eUTRAN: evolved Universal Terrestrial Radio Access Network; EPC: Evolved Packet Core).

From a technology perspective, backhaul networks for distributed RAN are straightforward to implement with today's metro and access network technologies and architectures.

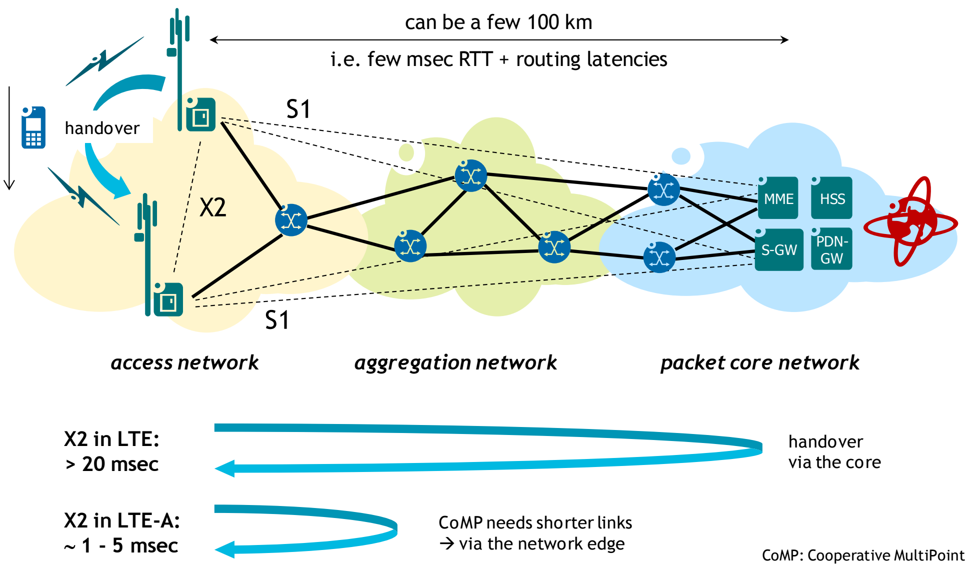

Fig. 2: In the distributed RAN architecture, the base stations (eNodeB) are each connected by backhaul links to their peering point in the mobile core network, the serving gateway/mobility management entity (S-GW/MME). The backhaul connections between the radio core network and the base stations extend over long distances of up to several tens of kilometres leading to high latencies in the range of several tens of milliseconds during hand-over processes.

The traffic characteristics, such as data rate, latency and packet statistics, are comparable with those encountered in DSL, cable or fiber access networks. Mobile backhaul can therefore be accomplished by using the same aggregation networks as those and can even be combined with them on the same platform.

In the centralized RAN architecture, the digital baseband processing hardware (baseband unit: BBU) is moved from the base stations to a common central location, serving a large group of remote radio heads (RRH) that then do not need much more hardware other than RF electronics. The BBUs and RRHs are connected by high speed digital fronthaul links for transmitting digitized IQ samples. The centralized RAN architecture can be implemented in many different variants regarding the cooperation between BBUs and RRHs and regarding the implementation of the BBU functionalities. For the purpose of this deliverable they shall be coarsely classified into the following groups (Fig. 3):

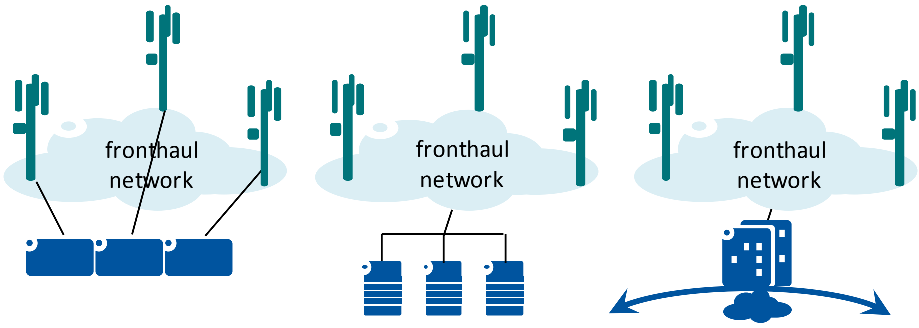

Fig. 3: Centralized RAN architecture variants; BBU hoteling (left), BBU pooling (middle), BBU cloud (right).

- BBU hoteling: many BBUs are collocated, but remain separate and are each individually connected to a dedicated RRH
- BBU pooling: a cluster of collocated and cooperating BBUs serves a cluster of RRHs
- BBU cloud: the processing functions of a BBU pool are implemented on servers that can flexibly be configured, and the processing load can be shifted between different pools in different locations. This solution is still a topic of intensive research.

The centralized RAN concept offers cost savings by allowing for relaxed hardware specifications (environmental hardening is needed for only few components), by requiring smaller footprint and less power consumption of outdoor equipment, by sharing infrastructure in the BBU location, by simplifying repair and maintenance and by easing system upgrades. In addition to these CAPEX and OPEX benefits, the centralized RAN architecture also eases implementation of advanced radio transmission techniques that have been considered for helping improve RAN coverage, bit rate and throughput by way of intercell cooperation (coordinated multipoint: CoMP): intercell interference coordination (ICIC), coordinated scheduling/coordinated beamforming (CS/CB), joint processing/joint transmission (JP/JT) or joint reception (JR), to name a few. Some of these concepts benefit from short latency links between the involved processing units which is favored by collocated or even pooled BBUs. Moreover, pooled configurations offer opportunities to reduce the amount of processing hardware by taking advantage of statistical multiplexing effects within large cell clusters, with achievable gains depending on the specific network scenario.

In the following, the current fronthaul approach will be discussed along with suitable optical transport solutions, taking into account most recent developments and research results in this space. In the subsequent section, some newly started standardization activities are highlighted that will lead to more efficient and flexible centralized RAN architectures than possible with today's technologies. In the last section, finally, an outlook will be given on new features and characteristics expected for 5G radio networks, that will have an impact on backhaul and fronthaul network architectures (see also [5]).

2.2 Digital Fronthaul Employing CPRI Transmission

The CPRI specification introduces a functional split of radio base stations into Radio Equipment Controller (REC) and Radio Equipment (RE) and describes the interface connecting them [6]. In its present form, CPRI specifies the transmission of digitized radio signals (IQ data) across this interface along with Control & Management (C&M) data, synchronization, signaling and other auxiliary information for GSM, UMTS, WiMAX and LTE radio access technologies (RAT). It is indicated in the document, but not further specified, that transmission of also other types of data as well as different RATs can be supported. In the centralized RAN architecture the RRH and BBU are representing the RE and REC, respectively.

It must be noted that CPRI is not a standard, but an industry agreement. It still contains vendor specific elements and does hence not guarantee full interoperability. It neither contains specifications of an optical transport layer, but merely recommends using existing optical hardware such as the one used for high speed serial links for Ethernet, Fiber Channel or Infiniband transmission. The Open Radio equipment Interface (ORI) standard [7] from ETSI takes over most of the lower layer CPRI specifications, but neither specifies optical parameters other than connector types (LC or SC) for single or dual fiber links. It does, however, provide the framework for multi-vendor interoperability. It also specifies compression of IQ data for LTE channel bandwidths of 10, 15 and 20 MHz.

A physical CPRI link can contain one or multiple IQ data flows, each carrying the data of one antenna for one carrier. Currently, there are 10 bit rates defined for CPRI links, ranging from 491.52 Mbit/s (base rate for a 10 MHz wide LTE carrier) to 11796.48 Mbit/s (= 24 * base rate). These net bit rates provide capacity for the IQ data plus overhead information (1/16 of the total bit rate). For transmission, the data are further encoded by applying an 8B/10B (options 1 to 7) or a 64B/66B (options 7A, 8, 9) line code, resulting in line rates for a single CPRI link ranging from 614.4 Mbit/s to 12165.12 Mbit/s. The bit error ratio must be BER = 10^{-12}. Forward error correction (FEC) is not precluded, but neither recommended.

Real implementations of remote sites frequently contain multiple antennas for a single or for multiple different mobile network operators (MNO), for multiple RATs and/or for MIMO radio configurations (multiple input multiple output). Each antenna is individually assigned its own dedicated IQ data flows. Since these data represent the analogue radio signals, regardless of the user data content, the CPRI bit rate has to be sustained and no advantage can be taken from statistical multiplexing. So the aggregated bit rates can easily extend into multiple tens of Gbit/s. Even with compression applied to the IQ data payload, typically allowing for reducing the channel capacity by a factor of 2 – 3, the required bit rates are still very large. When considering an entire fronthaul network with many RRHs connected by CPRI to a common BBU cluster, then the overall transport capacity for the fronthaul network will quickly extend into multiple 100 Gbit/s.

For multi-sector and multi-antenna configurations the total bit rate for the CPRI fronthaul links is

$$B_{CPRI} = S \cdot A \cdot f_s \cdot b_s \cdot 2 \cdot (16/15) \cdot LC\,, \qquad (1)$$

Here, S and A are the number of sectors and antennas per sector, respectively; f_s represents the sample rate (= 15.36 MS/s per 10 MHz radio bandwidth) and b_s the number of bits per sample (= 15 for LTE, = 8 for UMTS). The remaining factors take into account the separate processing of I and Q samples (factor 2), the additional overhead information (factor 16/15) and the rate increase caused by line coding (LC = 10/8 or 66/64, depending on the CPRI net bit rate option).

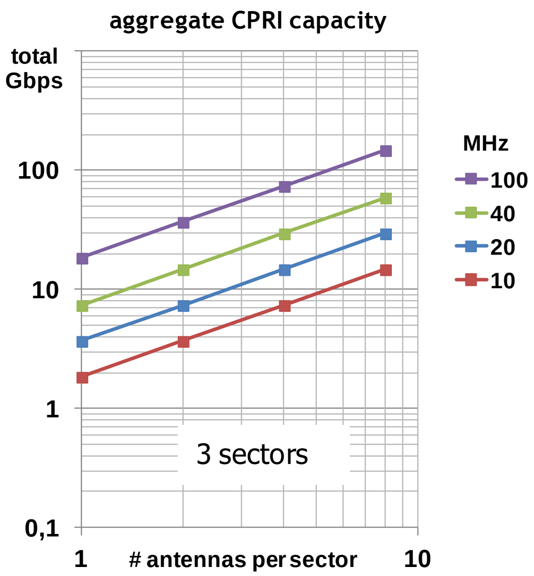

Fig. 4: Aggregate CPRI line rates for a 3 sector site vs. number of antennas for different radio spectra.

In Fig. 4, the aggregate CPRI link rates are displayed for a 3 sector LTE antenna site (b_s = 15) having multiple antennas per sector and for different radio bandwidths (8b / 10b line coding assumed). In Table 1 some sample site configurations are also presented. The extreme configuration of (3 sectors) x (8 antennas) x 100 MHz relates to an LTE site supporting peak rates in downlink of up to 1 Gbit/s over the air interface, as targeted by LTE-Advanced, resulting in a total CPRI link rate of 148 Gbit/s.

Table 1: CPRI line rates for some LTE site configurations, carrier aggregation is assumed for > 20 MHz spectra.

LTE site configuration	CPRI line rate [Gbit/s]
Small cell 1 sector, 2x2 MIMO, 20 MHz	2.5
Macro cell for 2 MNOs, each with 3 sectors, 2x2 MIMO, (20 + 20) MHz	29.5
Tower with different configurations 3 x (4x4 MIMO) x (20 + 20) MHz, 3 x (2x2 MIMO) x 20 MHz, 1 x (8x8 MIMO) x (20 + 20) MHz	56.6
Requirement for 1 Gbit/s on downlink 3 sectors, 8x8 MIMO, (5 x 20) MHz	148

Besides the requirement for high link capacities, there are also constraints on latencies in fronthaul transport. However, the latencies are not constrained by the fronthaul protocol, but rather by the chosen RAT. Among the current radio access technologies, LTE imposes the most stringent requirements on transport latencies. They result from the uplink hybrid automatic repeat request (UL-HARQ) process, in which the BBU must indicate within 4 ms to the user equipment (UE) to retransmit an erroneous packet. The typical latency budget left for the fronthaul transport segment for carrying antenna data is of the order of a few hundred microseconds with the actual numbers varying from vendor to vendor based on implementation considerations. This transmission latency relates to the round trip time from the RRH to the BBU and return, including travel time over the fiber as well as signal processing time in the optical system equipment. Depending on the optical transmission technology, the fiber length between BBU and RRH is thus limited to below 20 km (with very low processing delays: up to 40 km assumed within DISCUS). Whereas with UMTS these constraints can be more relaxed, it is expected that for some applications in future 5G radio networks the latency constraints will be even tighter.

2.3 Optical Transmission Technologies for Digital Fronthaul

While the CPRI link for a single antenna can be established via a dedicated fiber, it is obvious that e.g. for sites incorporating multiple antennas the CPRI links should preferably all be multiplexed onto a common fiber. In commercial fronthaul solutions this is typically accomplished by passive CWDM, a most cost efficient optical multiplexing technology. However, in more complex configurations, or in networks with many RRHs connected to a central BBU cluster, the channel numbers available from CWDM may not be sufficient. Wavelength tunable DWDM-type multiplexing may help here, provided it can be established at access compliant cost figures, thus not jeopardizing the cost savings offered by the centralized RAN concept. With the new NG-PON2 standard [8], a kind of DWDM technology is now about to be introduced into networks that is compliant with cost figures and operational needs as required for running optical access networks. Aside from the bare wavelength tuneability of the end nodes, it also offers dynamic management of the channel assignment per node while in service and hence is an attractive candidate technology for future fronthaul networks. Currently, the wavelength channel numbers in NG-PON2 are still small (up to 8), but it is to be expected that with future releases the channel numbers will be further increased. Concepts for the implementation of such systems, offering even multiple tens of wavelength channels in passive metro-access networks, have been elaborated in a number of research projects, such as our European project DISCUS.

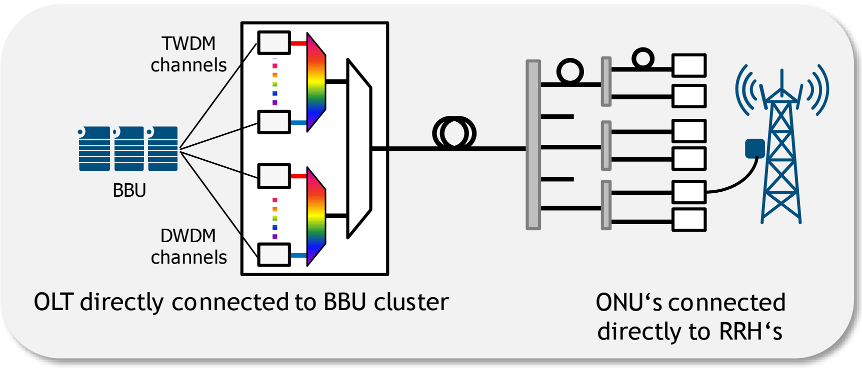

Fig. 5: Schematic NG-PON2 architecture for centralized RAN with ptmp TWDM and ptp DWDM subsystems, both simultaneously using the same ODN.

NG-PON2 networks support two different kinds of DWDM-type subsystems: a) multiple unshared point-to-point (ptp) connections via DWDM and b) multiple TDM/TDMA point-to-multipoint (ptmp) connections on a separate set of DWDM channels (TWDM: Time Wavelength Division Multiplexing), both subsystems being simultaneously operational on the same optical distribution network (ODN) (Fig. 5).

Finally, cost efficient transmission at higher than the currently supported 10 Gbit/s serial bit rates are being investigated which will further enhance the capacity of such networks [9].

High bit rate CPRI links with up to 9830.4 Mbit/s (option 7) are listed as possible client signals for the ptp-DWDM subsystem, being transmitted in native format, i.e. without encapsulation or mapping onto a specific transmission protocol. For ease of operation, however, non-intrusive addition of suitable control & management information to the optical signals is needed. Possible solutions are currently being discussed in FSAN, ITU-T and DISCUS (AMCC: auxiliary management and control channel). In certain scenarios with small CPRI bit rates per RRH, e.g. for small cells, also the TWDM subsystem of NG-PON2 can be used for fronthauling, offering economic benefits by sharing a single wavelength channel by multiple sites. In order to guarantee constant bitrates on the client interfaces and to avoid jitter accumulation caused by random access to the PON, the TDM/TDMA channel must be operated in fixed bandwidth mode with DBA switched off (dynamic bandwidth assignment). Each ONU is assigned multiple slots per TC layer frame (transmission convergence layer frame = 125 µs), thus reducing the buffer time in the end equipment on either end of the link to only a few ten microseconds. The quiet windows in upstream direction, which are required for ranging and registering new ONUs (new RRHs), have to be as short as possible. For short optical links, the ranging window can be reduced to the duration of a single TC layer frame or even less. Likewise, the equalization delay for the ONUs must be reduced. So altogether, for fiber links of up to only a few kilometers length (more generally: up to only a few kilometers of differential distance between any two remote sites on the network), the total latency can be reduced to below 100 µs per direction: buffering for accommodating the slot sequence per frame (30 µs), compression/decompression (20 µs), FEC encoding/decoding (5 µs), travel time (5 µs/km) and buffering for ranging windows (e.g. 20 µs); the values in brackets are given as examples (see also [10]).

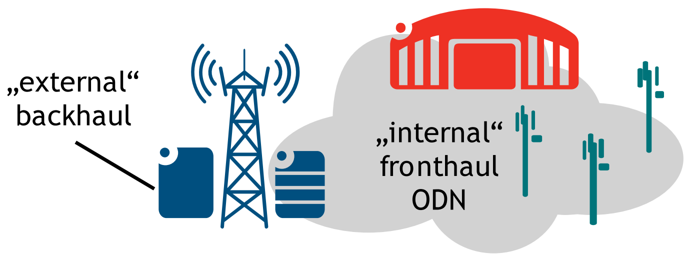

Fig. 6: Local centralized RAN network for small cells being fronthauled from a nearby macro cell. The macro cell is backhauled from the radio core network with data for the macro and small cells.

This configuration can be used for e.g. fronthauling 10 small cells per wavelength, each with 2x2 MIMO for 20 MHz radio spectrum, from a nearby macro cell that incorporates the BBU functions for the small cells (local centralized RAN). Practical use cases can be found in malls, stadiums or other large venues (Fig. 6). In scenarios with only few cells, a single uncolored (TDM-PON instead of TWDM-PON) optical channel may be sufficient, thus further reducing the optical systems cost. Besides for the mere amount of parallel optical channels available for fronthaul links on a common fiber, WDM technologies also provide for the opportunity to have multiple network operators or multiple services sharing a common fiber infrastructure in metro-access networks, thus supporting wireline/wireless convergence on the physical layer (Fig. 7). The individual wavelength channels are operated either by a common transmission system or by separate systems [11].

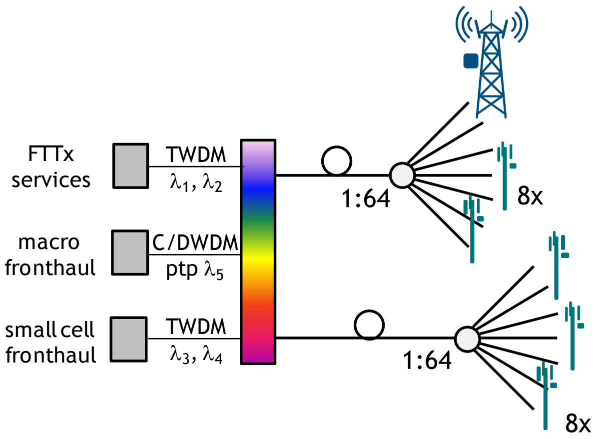

Fig. 7: Shared fiber infrastructure providing fronthaul links for macro cells and small cells, along with FTTx services (residential ONUs are not shown). The colored box generically represents a suitable combination of passive DWDM (de)multiplexers and splitters. An urban scenario is assumed, with 1 macro cell in every other 1:64 split PON and 8 small cells per 1:64 split PON.

2.4 Improvement to the Transport Network in Current Centralized RAN Architectures

As outlined in the previous sections, CPRI fronthaul requires high sustained transport bit rates which in case of only few links can be provided over dedicated fibers and/or by employing wavelength (and time) domain multiplexing. When it comes to large centralized RANs, however, it is generally recognized that the technical and economic effort for the fronthaul links counteracts the possible savings on the wireless side. Therefore, modifications to the conventional CPRI based centralized RAN architecture have been proposed early on in research [12, 13] and have been considered also by the NGMN Alliance [14].

For the current CPRI fronthaul approach, the analogue radio signals are digitized in the same format as they are transmitted over the air (except for down/up-conversion), requiring a fixed line rate on the transport link, regardless of how much valid information is actually conveyed. The RRH in this architecture remains most simple, incorporating mainly RF electronics. Instead, when splitting the wireless processing chain at a point, where the resulting interface capacity is dependent on the amount of data to be transmitted over the air (user data or auxiliary signals like pilot tones), then the user traffic dynamics can be taken advantage of, such that the optical link capacity benefits from statistical multiplexing effects. In the processing chain, there are multiple such split point conceivable (Fig. 8), moving the atomic processing functions more to the central or more to the remote site. For obvious reasons these architectures can be called midhaul with dual site processing or split processing. At the last point in downlink direction, where the user data statistics still take effect (interface PHY2 in Fig. 8), the interface capacity dynamically ranges from zero (for no traffic) up to about 20 % of the CPRI rate in case of fully loaded radio channels [15].

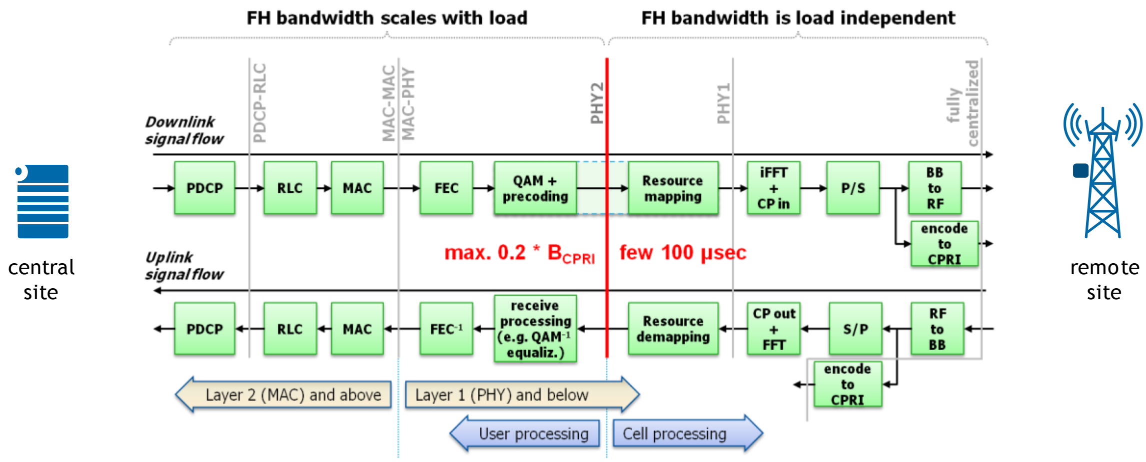

Fig. 8: Possible split points in the LTE processing chain. "PHY2" separates processing of user data from processing of cell signals. At this point, the bit rate ranges from 0 to about 20 % of the CPRI bit rate. For more details see [12]. (PDCP: Packet Data Convergence Protocol; RLC: Radio Link Control; CP: Cyclic Prefix; P/S: parallel-to-serial; BB: baseband).

With these split architectures, all the available CoMP technologies can be applied, except for the uplink joint reception which can only be applied with PHY1 or PHY2 splits, as it is based on soft combining and needs digitize IQ samples. It must be noted, however, that for all split points the same stringent latency constraints apply as with the conventional CPRI approach (few 100 µs). Only the PDCP-RLC split supports latencies in the millisecond range. For more detailed discussion of this architecture see [12].

The CPRI specifications do not provide for a well defined optical layer, nor do they provide for transport OAM (operation, administration and maintenance) and networking functions such as e.g. protection switching. This lack of suitable transport features in CPRI fronthaul, as well as the desire to define the transport across midhaul links recently triggered new standardization activities at IEEE towards specifying an optical transport layer for these architectures by employing Ethernet technologies. These approaches are also driven by the hope to reduce equipment cost and to converge wireless and wireline services on a common transport platform.

The IEEE Access Networks Working Group in 2015 started the new activity IEEE 1904.3: Radio over Ethernet, Encapsulations and Mappings [15]. This activity is targeted at the elaboration of rules for mapping CPRI frames, for encapsulating bare IQ samples or for encapsulating midhaul data into the payload of Ethernet packets. It is focused on the optical transport across a given link.

In addition to this, there is a work item called "Time sensitive networking for fronthaul", which is in preparation by the Time Sensitive Networking Task Group in IEEE 802.1. It targets at transmitting such data over switched Ethernet networks together with other, best effort type traffic, being present on the same network.

These transport and networking mechanisms obviously tend to violate the strict timing requirements in fronthaul and midhaul, such as total latency, timing accuracy and jitter accumulation. In the process of standardization, it will be of paramount importance to accommodate these fundamental radio requirements on the transport network side. While timing information can be provided by additional means such as GPS, SyncE or

IEEE 1588v2 protocols, the latency constraints will need appropriate measures during processing in the network nodes.

Despite these open issues, there seems to be an increased interest currently emerging in parts of the industry that the future centralized RAN will move towards splitting the processing chain in order to benefit from user data statistics and using Ethernet based networking for transport. China Mobile recently published a White Paper [16] in which they promote the NGFI concept (Next Generation Fronthaul Interface) which is built around these approaches. With this technical basis, future fronthaul networks will become more complex than just a simple ptp link, possibly hosting also local aggregation points near the RRHs which may incorporate some of the remote processing functions and in turn are connected to the central BBU by switched Ethernet links. The connection from such aggregation points to the nearby RRHs could be accomplished by networks like those discussed in the local centralized RAN scenario shown in Fig. 6.

The future centralized RAN architecture will thus conceptually turn into one or multiple of the variants schematically shown in Fig. 9. In the conventional fronthaul approach (left column), where all but the RF hardware is moved from the remote sites into the central site, the IQ data are transported over Ethernet, either in native format or encapsulated into CPRI frames prior to transmission. In case of using a CPRI-type RRH, an additional gateway function will be needed for adapting it to the Ethernet transport layer (upper row). In the new midhaul approach with dual site processing (right column), the transport of the split point interface data over the network will be accomplished by Ethernet. Now the remote site takes over some processing tasks, so that a CPRI-type RRH has to be adapted by a suitable gateway for performing this processing. Which of these options will economically and technically make most sense in which network scenarios, will be the topic of near future research and development activities and standardization efforts.

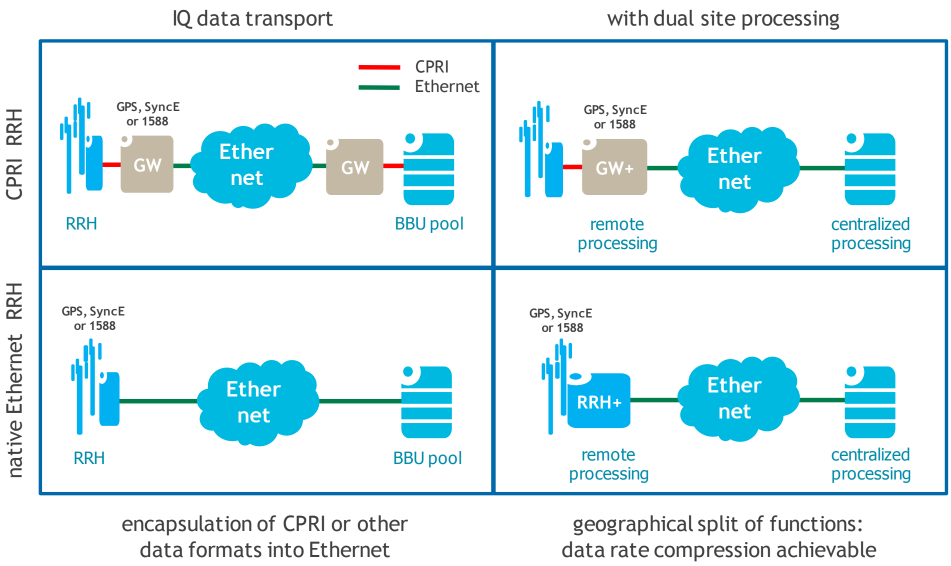

Fig. 9: Ethernet transport variants for centralized RAN (figure by courtesy of P. Sehier).

The optical fronthaul (or midhaul) transport in these networks will benefit from further progress in optical access system technologies that, as outlined in the previous section, keep moving to higher line rates and to multiple wavelength channels at access compliant cost levels. With dual site processing, TDM/TDMA based optical transport solutions will become even more attractive contenders, since they are made for statistical traffic in one of the most cost sensitive network segments, the residential access, and will thus benefit from this increasing market.

However, the latency related challenges as discussed further above, still need to be kept in mind for all of the above scenarios. In particular, when considering complex networks with multiple (e.g. redundant) path options between central and remote sites, then rerouting traffic onto a different route may have a negative impact on the relative timing between individual flows, possibly resulting in degraded performance of CoMP enabled RANs. These aspects need further investigation.

2.5 Evolution Towards 5G Radio Networks

Currently deployed radio technologies, even further evolutions of 4th generation systems, will not be able to cope with the requirements on future wireless networks. Researchers, operators and system vendors have hence been working since a few years ago, trying to specify requirements and to identify suitable radio technologies and architectures for 5G radio networks. Respective standardization activities are on their way and first commercial 5G services are expected to be started in 2020.

Although there is no common agreement yet, as to which technologies 5G will encompass in detail, there are a number of characteristics and features of 5G networks that can be outlined already now [17, 18]. On a high level perspective, three major trends can be named: massively increased capacities by exploiting new and wider radio spectra, huge amounts of devices and a vast diversification of services and traffic patterns correlated with a respectively diverse set of radio technologies.

At the one end of the range of requirements, high consistent bit rates on the radio channels are needed, up to 1 Gbit/s per UE (> 50Mbit/s everywhere) for various kinds of data, particularly for streaming and real time services (provide user experience continuity). For some services, peak rates will go up to even 50 Gbit/s. At the other end, the expected massive proliferation of sensor networks and of machine-to-machine-type (M2M) communication will lead to new traffic patterns on the air interfaces, such as to spontaneous and sporadic transmission of short data bursts with long idle times in between (> 20 billion human-oriented terminals, 1 trillion of Internet of Things (IoT) terminals). These M2M-type communications will come with enhanced requirements on latencies, service availability (e.g. reliability of 99.999 %) and transmission security. End-to-end latencies as short as 1 ms [19] or 5 ms [3] are in discussion for interactive services (mission critical services), obviously calling for rethinking error-correcting processes such the UL-HARQ process in LTE. At the opposite extreme, there are requirements for accommodating very high speed mobility, up to speeds of 500 km/h.

These evolutions will have ramifications on the architecture and on the physical layer of the RAN, both on the air interface and on the supporting x-haul (back-/mid- or fronthaul) networks.

- Improved coverage as well as increased capacities will be enabled by massive deployments of small cells cooperating with macro cells in HetNet architectures

(Heterogeneous Networks), by employing high order MIMO transmission and CoMP technologies, and by exploiting radio spectra in the frequency range 20 to 90 GHz. These architectures and technologies will benefit from flexible, reliable high capacity x-haul networks, building on efficient and scalable transport solutions as outlined in the previous sections. In addition to the use cases mentioned, there may also be cases (e.g. massive MIMO) where even analogue fronthaul may be beneficial over digital x-haul, despite the susceptibility of analogue waveforms to distortions induced during generation, transmission and reception.

- Spontaneous and sporadic transmission of short data bursts over the air interface in M2M-type applications calls for connectionless transmission, eliminating or at least substantially reducing signalling overheads both on the wireless links and on the wireline x-haul networks. Technologies allowing for asynchronous or weakly synchronized transmission in the time and frequency domain are preferred for both these network segments. Special time domain waveforms, exhibiting spectra that are particularly favourable in this respect, have been recently proposed for radio links in 5G networks [20].
- Very low latency requirements are currently in discussion for different applications such as for interactive services or for improving the efficiency of CoMP techniques. Short links are thus needed on the x-haul network, by interconnecting neighbouring remote sites on a local passive optical mesh network [21] or by placing small active nodes in the neighbourhood of remote sites offering local compute and/or higher layer processing capabilities. The latter could e.g. help reduce the latencies in IPsec secured transmission which currently involves processing deep in the core network, thus inducing latencies of more than 20 ms [18].

In view of the above examples, the presently considered approaches for fronthaul and midhaul transport as discussed in the previous sections will likely have to be revisited for 5G networks and the optimum approach may even vary with the specific application. As an example, it is to be debated whether a conventional fronthaul solution is still viable for mm-wave antennas transmitting 100 MHz wide radio spectra or more.

The specification of 5G networks will benefit from close alignment between the development of the radio access technologies and of the wireline x-haul solutions, in order to meet the challenging requirements of this new generation of wireless networks.

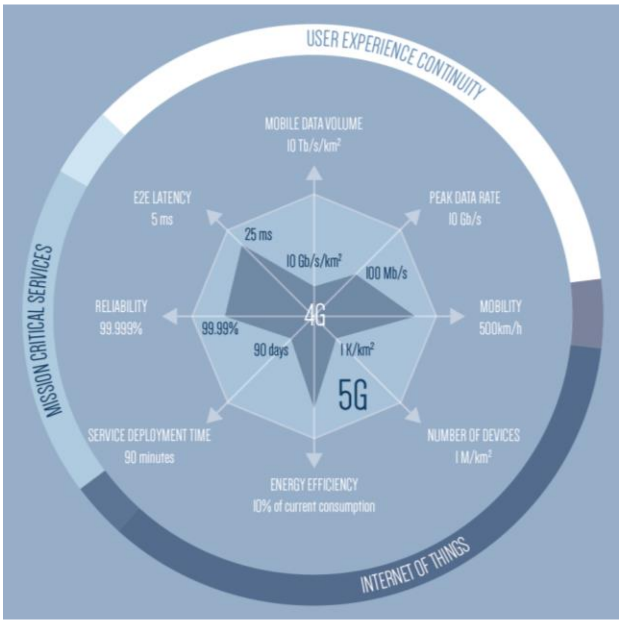

Fig. 10: Radar diagram of 5G disruptive capabilities, the figure is taken from [3].

The discussed 5G requirements and capabilities are summarized with the radar diagram in Fig. 10 [3]. Here, additionally, some needs are listed:

- A high capacity of 10 Tbit/s/km^2 to cover e.g. a stadium with 30,000 devices relaying the event in social networks at 50 Mbit/s. This bandwidth is rarely required and should be flexibly allocable.
- In general a 10 % improvement in energy efficiency compared to current consumption is requested.
- The network devices and network functions should be programmable which will ease the service deployment time and system upgrades. Here, recent suggested initiatives such as the software-defined network and the network function virtualization could be used.

3 Integration of Wireless Networks into the End-to-End DISCUS Wired Architecture

In this chapter the integration of wireless networks into the end-to-end DISCUS wired architecture is introduced. In section 3.1, we introduce the optical (wired) DISCUS long-reach PON network. Following, in section 3.2 the DISCUS strategy on wireless and wired network integration is presented and in section 3.3 a fixed and radio access converged network for 2020 is elaborated. In section 3.4 a DISCUS network view for beyond 2020: a first 5G vision over LR-PON is introduced.

3.1 Optical DISCUS LR-PON Network

The DISCUS LR-PON infrastructure connects the metro/core (M/C) node(s) to residential, business, enterprise and wireless customers. The general architectures within the DISCUS project are based on a total fiber reach of 0…125 km with a drop section length of typically 10 km and a typical split ratio of 1:512. The optical distribution network includes local exchange (LE) sites in which optical amplifiers are used to increase the signal power. The optical distribution network (ODN) does not contain any wavelength selective filter elements. In D4.3 "Integrated architecture for LR-PON supporting wireless and wireline services", D4.2 "System specifications for LR-PON implementation" and D4.6 "Updated specifications for LR-PON system" were shown realizations of such network scenarios that are achievable using various architectures, i.e. the lollipop (multi-stage tree), a hybrid bus-tree and also a ring infrastructure. The optical amplifiers considered within the DISCUS access network are erbium-doped fiber amplifiers (EDFA) and semiconductor optical amplifiers (SOA). Advantages and disadvantages of the different optical amplifier technologies are studied within the deliverable D4.11 "Consolidated long reach access network view". The access network scenario uses up to 50 wavelengths in the downstream and upstream direction, respectively. Each wavelength may be used for a legacy access system (co-existence in the early deployment stage) such as the GPON, XG-PON or NG-PON2, for a DISCUS TWDM-PON channel offering 10 Gbit/s symmetrical rate, for a 40 Gbit/s high-speed TDM-PON using duobinary modulation, for a coherent PON based on an UD-WDM approach, or even for ptp-WDM systems, e.g. 100 Gbit/s signal with advanced modulation formats (core bandwidth in access space). The access network is designed to operate in the C and L-band. In case the use of additional wavelength bands become necessary, the wavelength transparent outside plant does not prevent from using other wavelength windows of the fiber (imply the use of optical amplifier with the correct gain bandwidth or gain peak in the local exchange). Further, the access network may offer few case-specific solutions by using bespoke network configurations in which the data signal can be directly looped back within the access space without the need for termination within the M/C node. The wavelength transparent ODN is achieved by employing wavelength selective elements at the OLTs and at the customer site (ONU or ptp-TRx). This tunability is related to a tunable filter (TWDM-PON) or a tunable coherent receiver (ptp-WDM) in the downstream direction and to a tunable transmitter (laser, TWDM-PON) or a coherent receiver(ptp-WDM) in the upstream direction.

The handover from the access network spanning also into the metro space to the core network is performed within the M/C node. The M/C node offers the functionality of optical-electrical-optical conversion and is considered the only part of the network requiring for electronic switching and routing functions (except for local processing needs for wireless networks elaborated later in the deliverable). Beside terminating the optical signal from the access space also optical island can be present in which the optical signal is transparently switched by means of the optical switch in the M/C node to the core network directly. The M/C nodes are connected by a meshed network. The overall DISCUS network is controlled and managed by a SDN framework in which a network orchestrator controls the access and core controllers that in turn control the access and core network elements (e.g. switches, routers, optical switch), respectively.

Dynamic bandwidth allocation (DBA) and dynamic wavelength allocation (DWA) algorithms are used to efficiently offer various services requiring different amount of bandwidth to the end-user. For example, the delivery of a high-definition video service may require a sustained bandwidth for a particular customer or a business user may request for a dedicated 10 Gbit/s wavelength channel.

Protection mechanisms and management of the access network are also part of the infrastructure, as e.g. discussed in D4.13 "Resilience heterogeneous long reach access networks".

More details on the overall access infrastructure of the DISCUS consortium can be found in the D4.3, D4.2, D4.6 and D4.11.

3.2 DISCUS Strategy on Wireless and Wired Network Integration

The DISCUS consortium follows mainly two directions for the wireless and wired network convergence. The first approach focuses on a fixed and radio access converged network scenario for 2020 applying structural convergence and base stations hoteling within the M/C node (fronthaul case). The second approach is related to a future scenario (beyond 2020) which focuses on the functional convergence and Ethernet transport in the access area.

<u>First approach</u>

In recent years, new converged possibilities for joint deployment, management and control of fixed and wireless networks have emerged, such as the introduction of all-IP architecture in the Evolved Packet System (EPS) for mobile networks and the joint deployment of 4G mobile and FTTH fixed networks with a single infrastructure.

On the other hand, the increase in traffic demand and access bandwidth both in fixed and mobile access networks and the network operator's needs for an efficient investment to upgrade their networks as well as to decrease the operational expenditure have moved network operators to explore convergence and sharing possibilities between fixed and mobile networks. Structural convergence between fixed and mobile networks consists of the sharing of network and infrastructure resources (cable plants, cabinets, buildings, sites, links, equipment and technologies) for both types of networks. Fixed-wireless convergence aims at defining joint fixed/mobile equipment and infrastructures for access, aggregation and core networks, thus allowing streamlining of broadband access networks. Some 5G scenarios such as advanced heterogeneous RAN or mobile fronthaul with Cloud RAN will impose structural fixed-mobile converged networks to support a low latency, a high capacity (around symmetrical 10 Gbit/s/wavelength), seamless interoperability with fixed/mobile network elements, scalability, protection and carrier-grade operations, as well as compatibility with legacy networks.

The DISCUS LR-PON appears as an architectural and technological option for structural fixed-mobile convergence and new business models, aiming at the minimization of network deployment cost (Metro-Core nodes minimization), as well as the maximization of network flexibility.

The DISCUS TWDM PON primary solution offers up to 50 x 10 Gbit/s symmetrical optical channels in LR-PONs with up to 100…125 km fiber length and 1:512 split ratio, simultaneously. Some wavelengths can be used to transport traffic from fixed customers between customer premises and M/C nodes, while other wavelengths can be used to transport the traffic from base stations to the Evolved Packet Core (EPC) equipment (distributed processing) or to the base band unit equipment (centralized processing). The reduction of the number of wavelengths by mixing different services in the same wavelengths can be found in [22] for different traffic scenarios. Nevertheless, we consider the use of separate wavelengths between fixed and mobile traffic for simplicity and because of the inherent operational and technological advantages of this approach.

In order to show and analyze the details and challenges of structural convergence between wireless and wired networks in LR-PONs, we consider a future realistic scenario for 2020 with a peak access speed of 1 Gbit/s both for fixed and mobile services. Both distributed and centralized baseband processing approaches are considered for mobile traffic.

Second approach

In the future beyond 2020, the introduction of ultra-dense, flexible, small-cell deployment is required to further meet the future 1000x capacity and density requirements discussed for 5G networks. Ultra-dense, small-cell deployment is bound to create problems involving frequent switching between cells and signal interference. These problems must be resolved through a centralized control plane, as well as closer air interface coordination between macro cells and small cells [16]. The ever increasing capacity demands in 5G networks will cause severe issues for the traditional CPRI approach in which a fixed-rate fronthaul interface transmits CPRI streams even in the absence of traffic load and thus makes inefficient use of the resources (contrary CPRI seems to be still applicable for in-door applications). Obviously, traditional CPRI will struggle to support the future networking demands of centralized deployment. Approaches which offer adaptive bandwidth changes responsively to the statistical multiplexing and payload of the air interface are required. The general discussion shows that a new interface for the fronthaul links are required. We follow here the ideas presented in chapter 2 about improvement on transport network for centralized RAN as well as the paper [16]. In general, the application of two new properties is required for a future-proof Cloud RAN. First, processing functions are shifted from the base stations to the remote radio units leading to a change in the base station and remote radio unit architecture. According to [16], this results in a re-definition of the baseband unit into the Radio Cloud Center (RCC) and the RRU becomes the Radio Remote System (RRS, also called RRH+ in chapter 2). Second, the fronthaul changes from a ptp connection into a many-to-many fronthaul network making use of a packet exchange protocol. The new interface should be capable of supporting not just 4G LTE-A, but also future 5G technologies, meaning that the interface between RCC and RRS must satisfy all principles of 4G and 5G air interface technologies. Ethernet is suggested to be used for fronthaul transmission to achieve a fast rollout and to offer the statistical multiplexing and flexible routing benefits of packet transmission raising transmission efficiency and flexibility of the network. In this approach one RCC may transfer baseband processing to another RCC along with RRS functions. However, a RRS can only be connected to one RCC at a time. When traffic volumes are high, RRS connections will be dynamically adjusted to balance payload, when traffic volumes are low, processing can be centralized to reduce energy waste and allow better statistical multiplexing of resources within the RCC. The RRS includes beside the antenna and the RRU functions also the capability of aggregation, a radio aggregation unit (RAU). The RAU function may also be combined with the RRU or instantiated in a separate piece of physical equipment. A summary of the introduced scenario can be seen in Fig. 11.

Beside the changes to BBU and RRH, the network should offer the possibility to incorporate a significant number of sensor devices producing sporadic data as well as the WIFI technologies.

It should be noted here, that the race towards 5G wireless networks has just started and thus definitions on the air interface, the transport mechanisms and the requirements of RRS (RRH+) and RCC are still under research in industry and academia. Therefore, this second approach for the wireless and wireline integration may be considered as a first conceptual guess which contains various aspects which have to be considered for further study.

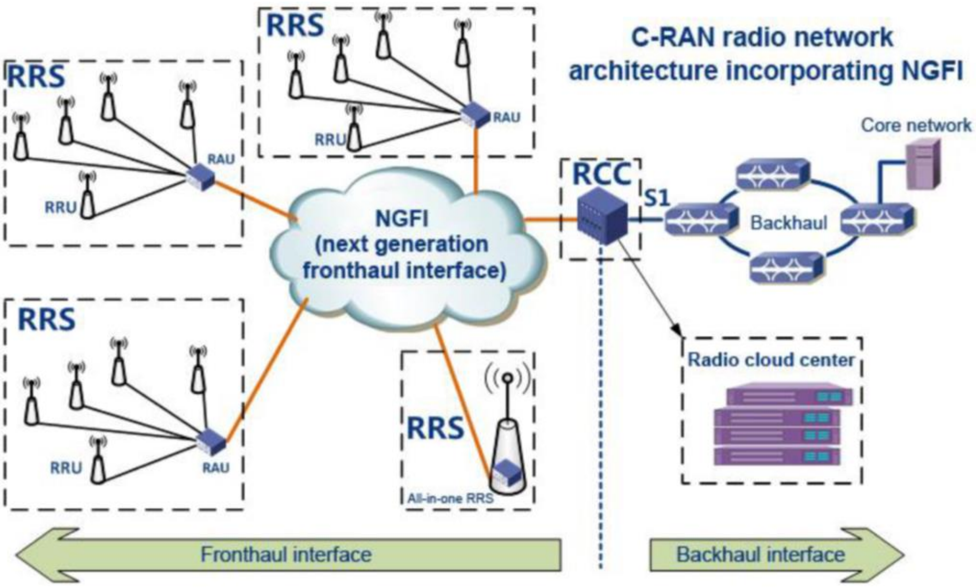

Fig. 11: C-RAN radio access network architecture based on a new fronthaul interface, figure taken from [16].

3.3 A Fixed and Radio Access Converged Network for 2020

The convergence of the wired and wireless services introduces constraints for the overall network in terms of fiber length and bandwidth allocation. In the following, we introduce and motivate the general DISCUS view on wireless integration. This particular section can also be found in D4.11 and is duplicated here to help the reader to understand the context.

In order to show and analyze the details and challenges of structural convergence between wireless and wired networks in LR-PONs, we consider a future realistic scenario for 2020 with a peak access speed of 1 Gbit/s both for fixed and mobile services. This scenario can be considered as a realistic target for LTE-Advanced in 2020 and a baseline speed for 5G networks. Due to the fact that for older generations of mobile services, the bandwidth, the latency and the transport requirements are less stringent, it can be considered that with such a scenario, the DISCUS network approach can also serve the existing 2G...3G legacy systems. In the following, we will mostly use the terms for base stations and remote radio units from the LTE-A definitions.

In general in the DISCUS wireless and wired integration scenario each mobile site should offer an air peak rate per sector of 1 Gbit/s (maximum IP data rate). In case that we assume an average user rate of about 100 Mbit/s...150 Mbit/s (peak of 1 Gbit/s), a possible realization can be done by using a 60 MHz radio spectrum width with a 4 x 4 multiple-in-multiple-out (MIMO) scheme with 12 antennas per macro cell site (3 sectors per macros site with 4 antennas each assumed) and a modulation of 64 QAM (LTE-Advanced), case A. Other realization also employing the massive MIMO technology could be considered too, e.g. using 40 antennas and a narrower radio spectral width of 10 MHz, case B.

Our general target is a macro cell deployment in which each cell site comprises 3 sectors. Additionally, depending on the area a macro cell is covering up to 20 small cells (e.g. in dense-urban areas) or down to 0 small cells (in rural areas). A small cell comprises a single sector.

More details on the wireline and wireless optimization work including the definitions of the cell sizes are described in D4.10 “updated optimization models and methods for wireless /wireline integration”. In the following both the distributed and centralized baseband processing approaches are considered for mobile traffic.

Distributed RAN approach:

The backhauling of the wireless data over the LR-PON infrastructure between the base stations and the radio core network (RCN) equipment requires a 1 Gbit/s IP peak bandwidth per sector. Obviously, for this distributed RAN case a 1…10 Gbit/s DISCUS TWDM-PON wavelength ONU is sufficient and even a wavelength could be shared between several base stations making use of the statistical multiplexing. The latency requirements for LTE-A backhaul are about 20 ms (round-trip time) for the S1 interface and about 2 ms (round-trip time) for the X2 interface for providing e.g. CoMP processing, see also D4.3 and D4.11. Here, it can be concluded that a fiber transmission latency of about 125 km is of no issue for the S1 interface and that the X2 interface has to be incorporated into the LE equipment, i.e. using a 10 km ODN fiber transport length. The general transport quality requirements are low, because FEC can be used (limited latency restrictions). In our DISCUS year 2020 scenario, 32 sites are backhauled via a single 10 Gbit/s TWDM-PON wavelength channel.

Centralized RAN approach:

The fronthauling of the wireless data over the LR-PON infrastructure between the centralized base stations (eNode-B in LTE-A) and the remote-radio units (RRHeads in LTE-A) requires a bit rate that depends strongly on the wireless air interface (bandwidth, antenna, sampling, coding, etc.) in case digitized radio-over-fiber (D-RoF) technologies such as defined by the CPRI or ORI is used. For example, the introduced target wireless rates per sector demand for a CPRI rate (transport rate between eNodeB and RRH) of about 15 Gbit/s per sector in case A and of 25 Gbit/s per sector in case B. Obviously, the transport bandwidth demand is significantly increased for fronthauling compared to the backhauling approach which also will be the case for the transport latency requirements. The overall round-trip-time latency is restricted from the radio technology, i.e. to few milliseconds (e.g. 3 ms) including processing times and fiber transport time. It can be considered that a fiber transmission time of 400-500 µs will be left (assuming that the processing units are massively optimized in the near future) so that a 40 km total length of the DISCUS fiber network has to be considered in this case. Because of the stringent latency requirements also the FEC use should be avoided even if the target BER of 1E−12 is still required. The TWDM-PON is a cost-effective approach to realize the fronthauling compared to the deployment of dedicated ptp-fiber links. This is because an optical fiber is shared by RRHs. However, there are some challenges to implement fronthaul links over TDM-sub-PON wavelength. The first is the latency limit introduced above which is stringent for TWDM-PON upstream. Therefore, a low-latency bandwidth allocation scheme is essential [10, 23]. The second is the delay jitter caused by packetization of CPRI signals. In order to meet the CPRI requirements on the link delay accuracy, a technique to suppress the delay jitter is essential. The third is the bandwidth reduction of the CPRI links for the efficient transport over the PON. In order to transport the D-RoF capacity using DISCUS 10 Gbit/s wavelengths of the TWDM-PON, some processing in the D-RoF signal is required. A CPRI compression ratio up to 1/3 has been recently demonstrated that could be useful for this purpose [10]. The resultant compressed CPRI bit rate is in the order of 10 Gbit/s, so that a dedicated wavelength channel of the TWDM-PON per sector can be used (1 ONU/sector). The application of compression techniques introduces additional requirements for the compression technique itself: EVM degradation < 3%, SNR degradation < 1 dB and a processing time for compression and decompression of < 100 µs (< 20 µs preferable) [24].

Latency requirements will also influence the location of the RCN equipment such as the S-GW or MME. In a distributed RAN scenario, the maximum distance from base station to the M/C node can be up to 125 km. Here, the RCN equipment has to be located within the M/C node to avoid large transmission and processing delays. Even when that distance is reduced at the fronthaul scenario, the same requirements have to be fulfilled for the RCN equipment.

In DISCUS, a single M/C node can serve distributed RAN and centralized RAN services including wired access applications either using a single TWDM-PON network or even separate TWDM-PONs which are connected to that M/C node.

In case that the introduced solution are not scalable enough to increase the number of sectors and to converge a large number of mobile sites into the same PON, coherent ptp wavelengths may be required over the PON infrastructure. Nevertheless, in D4.10, it is shown that even for a futuristic scenario with 16 small cells per macro cell, DISCUS TWDM-PON wavelengths are enough to support wireless convergence over PONs with little impact in the number of PONs required at a national level for Spain.

In the following, the overall DISCUS architecture of such a consolidated network for 2020 will be introduced. The following description can be considered a particular example of the realization of the DISCUS baseline architecture introduced in D4.6 and D4.11. Here, a lollipop (multi-stage tree) architecture is discussed, however it should be mentioned that the baseline architecture can also be mapped to e.g. hybrid-bus-tree and open ring architectures as already reported.

Fig. 12 shows a particular example of the consolidated access network architecture view. Processes related to SDN, to DBA and DWA as well as to monitoring aspects are not explicitly considered here, because they are part of deliverables in WP6 and WP4 (D4.12 and D4.13).

The left part of Fig. 12 is covered by the M/C node design. It comprises the primary and secondary OLTs for the TWDM-PON, high-speed TDM-PON and the coherent-PON, the ptp-WDM transceivers, the transceivers to establish fixed and flex-grid connections for the core network as well as the optical island for transparent connections. The non-blocking optical space switch can distribute any input port to any output port independently of the number of wavelength channels on that port. L2 and L3 electrical switches and routers aggregate and distribute the data. The connection to the core site is performed by means of optical add/drop multiplexers and flex-grid wavelength selective switches (WSS).

The upper part of Fig. 12 describes a DISCUS-PON which is particularly used for the wired services and the centralized-RAN fronthauling approach. Obviously, the feeder fiber has a typical length of 0...30 km and the ODN fiber length is typically 10 km long. A LE comprises either 1 single EDFA or 5 cascaded SOAs for the DS and US direction, respectively. The split ratio is 1:512 or 4 times 1:128. In the centralized-RAN approach the BBUs are hosted at the M/C node. The RRU or RRH are equipped with CPRI compression/decompression functions for the US/DS direction and an ONU. The corresponding decompression/compression is required at the BBUs for the US/DS direction; more details on the compression can be found in D4.11. Each sector of a macro cell/small cell comprises a dedicated 10 Gbit/s TWDM-PON wavelength channel. High-speed ptp-WDM transceivers, e.g. for 100 Gbit/s or beyond, can be present at the customer site for business access. Due to the fact that each sector requires a dedicated wavelength TWDM-PON channel, the number of connectable sites is strongly limited, i.e. at maximum to the number of DS and US wavelength channels. Thus, most of the wavelength channels in centralized-RAN wireless integration scenarios will be dedicated to the wireless service whereas the wired serves are used to “fill up” the PON by employing a limited number of wavelength channels for them. Such a deployment scenario seems reasonable for urban areas where a large number of customers are located close to the M/C nodes. The particular distribution of customers across the network is discussed in the deliverable of task 4.4 and it is summarized in D4.11.

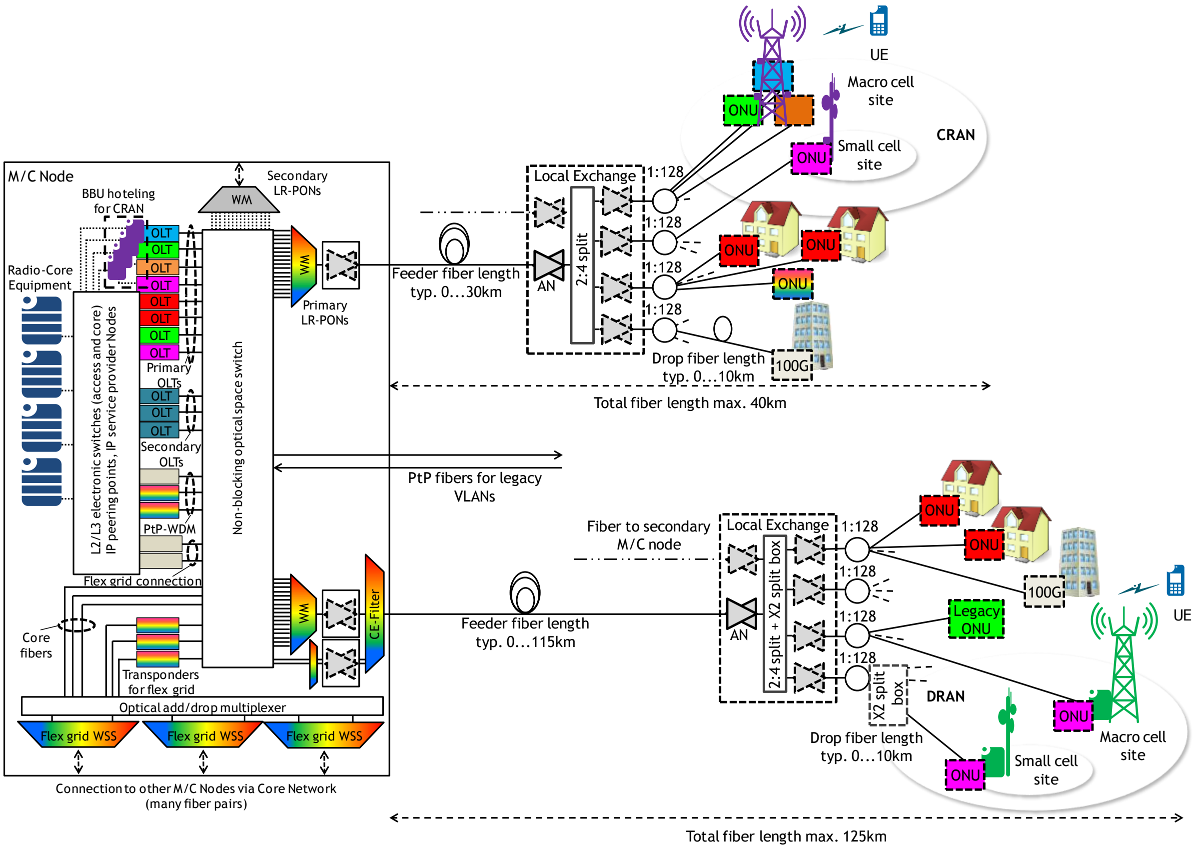

Fig. 12: Particular DISCUS access network scenario including wireless and wireline convergence. The overall network approach comprises distributed-RAN, centralized-RAN, "core-bandwidth" transmission over ptp-WDM channels, co-existence of DISCUS TWDM-PON with legacy PON systems and higher speed PON applications (DB-TDM-PON or coherent PON).

Contrary to the centralized-RAN approach, the lower part of Fig. 12 describes a DISCUS-PON which is particularly used for the wired services and the distributed-RAN backhauling approach. The feeder fiber has a typical length of 0...115 km and the ODN fiber length is typically 10 km long. A LE comprises either 1 single EDFA or 5 cascaded SOAs for the DS and US direction, respectively. The split ratio is 1:512 or 4 times 1:128. In the distributed-RAN approach the BBUs are located at the antenna site. Each sector of a macro cell/small cell comprises an ONU which will be assigned a part of a TDM-sub-PON bandwidth. High-speed transceivers, e.g. for 100 Gbit/s ptp-WDM, can be present at the customer site for business access. Such a deployment scenario seems reasonable for urban and rural areas, because both a large number of customers located closely to the M/C node or far apart from the M/C node can be served. A direct connection between eNodeB's to establish a local X2 interface, e.g. to realize CoMP services in LTE-A, can be setup by using a splitter box which is located at the 1:128 splitters and it distributes the X2 data locally to the nearest neighbors making use of another wavelength band. A more complicated and costly scheme can also be used to connect all eNodeB's with each other using a slightly modified splitter box located within the LE site connecting the 1:4 splitters and also feedback the data. Also here another wavelength band has to be used and a significantly higher number of wavelength channels are required to interconnect all eNodeB's. Details on the X2 interface are already presented in D4.3 and D4.11 and they are not repeated in this deliverable, but the interested reader is referred to these documents.

Both scenarios comprise also the possibility for co-existence with legacy PON systems. Of course, for example the GPON system has a fiber length restriction to maximum 60 km, in intervals of 20 km. Therefore, legacy customers have to be connected to a particular PON network that satisfies the length requirements.

Note that always a large amount of PON networks can be connected to a single M/C node. A simple projection results in about 2000 access networks, 10E6 customers per M/C node/512 split size per PON. All access networks can be implemented to serve different purposes, i.e. distributed-RAN and centralized-RAN solutions can also co-exist in a single TWDM-PON.

3.4 DISCUS Network View for Beyond 2020: A First 5G Vision over LR-PON

Nevertheless, in the future beyond 2020, the capacity and latency requirements for inter-site coordination of heterogeneous networks with small cells and 5G scenarios may be more restrictive. A reduced centralization may be required in order to support the high user mobility 5G use case family [19] which comprises the use of high speed trains, remote computing in vehicles or public transport, moving hot spots (moving vehicles or crowds due to moving mass events) and 3D connectivity in aircrafts.

In the following, the DISCUS network needs to fulfil the 5G requirements are introduced, analyzed and discussed. It should be mentioned that the definition of the 5G network is currently ongoing so that the DISCUS architecture may be considered as a general solution to the 5G challenge. Additionally, the provided numbers for throughput, capacity, number of connected customers, number of small cells per macro cell, etc... are considered an educated guess for the future to underline the capabilities of the DISCUS LR-PON solution. These figures may be subject to change in the future or they may be realized by different solutions.

Wireless Air-Interface Peak-Data Rate of 10 Gbit/s per User

In future scenarios, flexible-split processing enhancements in base stations may improve the flexibility and cost-efficiency of the former architectures, by reducing the bit rates required between antenna sites and processing units, as well as reducing the cost and improving the flexibility of mobile functions in the network using virtualization in general purpose platforms.

Traditional CPRI fronthaul requires high sustained transport bit rates which in case of large air interface rates lead to lowest transmission efficiencies. It is believed that due to the disadvantages such as the mentioned low transmission efficiency, poor flexibility and poor scalability and particular due to the high cost of centralized deployment, traditional CPRI is unable to meet the evolving need for 5G-oriented fronthaul networking [16]. Therefore, modifications to the conventional CPRI based centralized-RAN architecture have been proposed early on in research [12, 13] and have been considered also by the NGMN Alliance [14].

The most attractive solution for the mentioned challenges is the use of mid-hauling with dual-site processing. At the last point in downlink direction, where the user data statistics still take effect, the interface capacity dynamically ranges from zero (for no traffic) up to about 20 % of the CPRI rate in case of fully loaded radio channels [12].

Assuming a target average user rate of 1 Gbit/s, an air peak rate per sector of > 10 Gbit/s (maximum peak rate per user) is required so that a CPRI rate of about 150 Gbit/s per sector can easily faced. Applying the concept of mid-hauling a rate of 30 Gbit/s results which can be addressed by either higher TDM rates per wavelength channels, e.g. by using DB with 25...40 Gbit/s in upstream and also in downstream direction [25]. Note that in the near-term future even more efficient mid-haul concepts optimized for the future 5G applications are expected as outcome of the ongoing immense research work. The final solution should offer user experience continuity enabling high traffic throughput for e.g. video services.

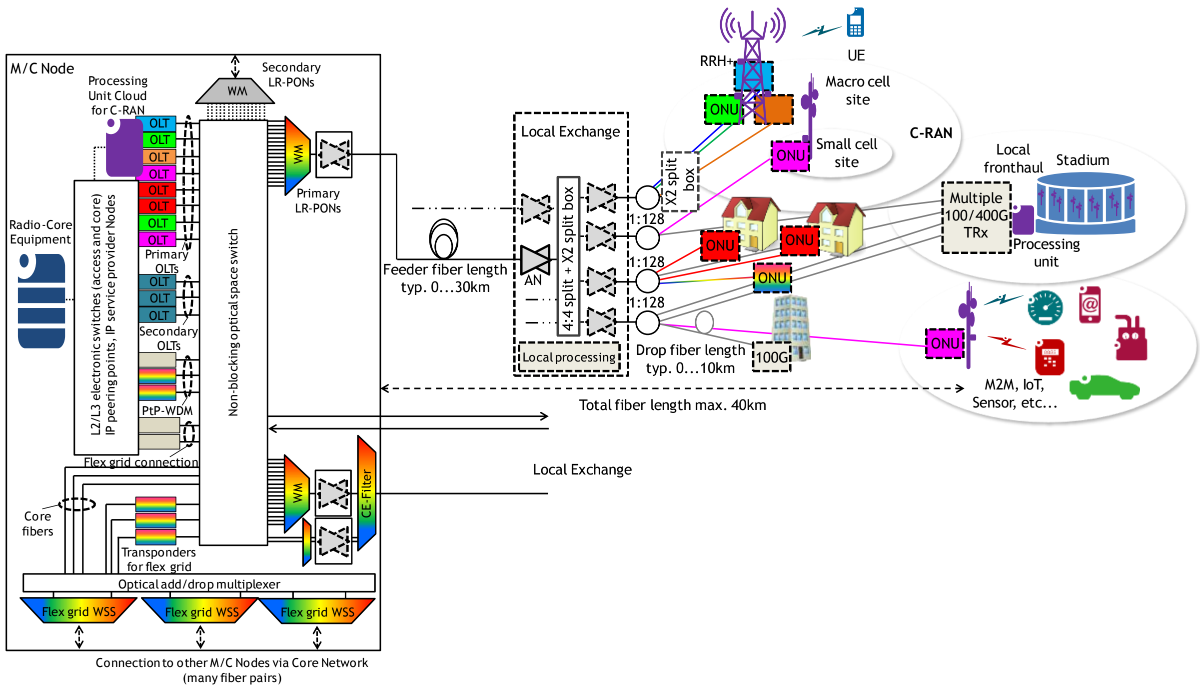

Fig. 13: Particular DISCUS access network scenario including wireless and wireline convergence for a possible future network including a 5G vision.

The remote units (RHH+) at the antenna site may also contain functions to establish Ethernet aggregation functions. In general TWDM-PON channels, as standardized by today GPON, XGPON, NGPON2, comprise the functionality to transport Ethernet packets which are either just encapsulated into the burst or are split into pieces and encapsulated step-by-step. To avoid latency restrictions, the DBA algorithms need to be adapted accordingly.

Additionally, the processing units located within the M/C node comprise the functionality to flexibly and efficiently allocate bandwidth to different RRH+ units. In Fig. 13, the processing unit enabling cloud RAN is directly connected to the OLT ports. Contrary, the processing unit could also become part of the L2/L3 switch/router configuration so that the OLT ports may be used flexibly and that they are not reserved for the wireless services. The general fronthaul configuration and thus the overall DISCUS network may stay unchanged which is preferable in terms of CAPEX from an operator's point of view.

Backhaul connections are not explicitly shown in Fig. 13, but to establish a maximum IP bit rate of 10 Gbit/s per sector, each of these sectors require a dedicated 10 Gbit/s TWDM-PON wavelength channel. This channel can be flexibly allocated by making use of the SDN approach.

Mobile Data Volume of 10 Tbit/s/km²

In future scenarios, the mobile data volume is anticipated to be locally very high. For example, a stadium (see Fig. 14(a)) comprising 60,000 people that demand for an average air interface rate of 50 Mbit/s per user could cause an incredible amount of wireless data of about 3 Tbit/s (worst-case assumption). This traffic is required rarely at those locations (at events) so that flexible allocation mechanisms as well as the capability to switch off devices are required.

In the following, a very simplified analysis to determine the requirements of fronthauling links in a stadium is performed. We assume the improbable case that 60,000 visitors are simultaneously uploading part of the "situation they are watching". We split up the stadium into 8 sections each comprising 40 small cell antennas, see Fig. 14(b). Thus, we are considering 120 small cells within the stadium (28000 m^2 area of stadium of FC Bayern München leading to 320 small cells / 0.28 km^2), i.e. a large density of 11474 small cells / km^2. Each small cell is able to handle maximum air interface traffic of 10 Gbit/s. In this approach, we neglect all kind of air interface challenges stemming from e.g. massive interference. The overall wireless network is determined by the air interface which is currently investigated in the 5G framework. Each realization of the wireless air interface may require a different fronthaul or backhaul scenario which may change configurations, technologies as well as the optical bandwidth demand. In each section of the stadium, we have allocated about 7500 people, so that 375 Gbit/s wireless traffic is caused per section. Using 40 small cells per section with 10 Gbit/s provides 400 Gbit/s/section. In this analysis, we consider that each small cell antenna comprises RRH+ functionality (split processing + Ethernet aggregation/ transport interface). In summary, our approach is able to handle > 10 Tbit/s/km^2.

An air interface rate of 10 Gbit/s results in a dual-site processing rate from the RRH+ units towards the central processing unit of maximum 30 Gbit/s. This way, 30 Gbit/s optical traffic times 40 small cells times 8 sections results in 9.6 Tbit/s traffic that is generated at the stadium. Obviously, a local fronthaul scheme should be used so that just few wavelengths are required to backhaul the data from/to the stadium.

A possible realization may be achieved by employing a dedicated TWDM-PON wavelength for each small cell antenna, see Fig. 14(c). Each wavelength carries 10...30 Gbit/s, i.e. either using a TWDM-PON with OOK modulation or with duobinary modulation. A TWDM-PON with 40 wavelengths is required per section. This way, 8 TWDM-PONs with 40 wavelengths each are required to satisfy the throughput demand. In case that the customers are generating a higher amount of uplink/upstream traffic, the use of unsymmetrical bit rate may be considered here.

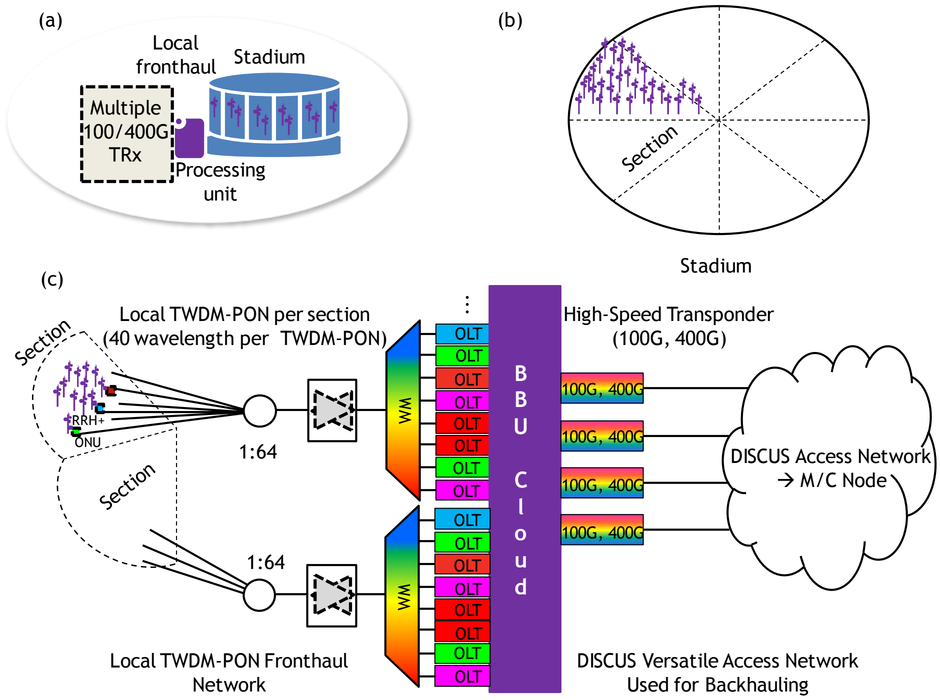

Fig. 14: An example of a mobile data volume of 10 Tbit/s/km^2, a stadium; (a) the general local fronthaul with the interfaces, (b) the segregation of the stadium in sections, (c) the local fronthaul within the stadium.

The local PON traffic is terminated in one of the OLTs which are directly incorporated within the BBU cloud processing unit. The data signals can be aggregated and may be backhauled via the DISCUS metro-access outside pant towards the M/C node using high-speed transponders. These high-speed transponders carry 100...400 Gbit/s (FP7-projects are in progress discussing 400Gbit/s or even 1 Tbit/s per wavelength: SPIRIT [26], ASTRON [27], MIRTHE [28]) per wavelength. In the introduced scenario, either 100 x 100 Gbit/s or 25 x 400 Gbit/s or 10 x 1 Tbit/s systems are required to backhaul the data signals. The use of wavelength channels that requires a bandwidth larger than 50 GHz has up to now not been explicitly considered within the DISCUS access network. In general, few wavelength bands of the 50 US and DS channels, respectively, may be designed for a larger channel bandwidth of e.g. 100 GHz or 200 GHz.

The M/C node takes care of the SDN functions of the full network and of the energy efficiency of the network. This way, in case no event takes place in the stadium, the network resources required within the M/C node can be reallocated by the optical switch to different services and customers. The PON wavelengths can be arranged also for another customer or service as well as the stadium equipment may be sent to sleep mode or it can even be switched off.

Number of Devices 1 Million/km^2

In a possible 5G future network, a large number of sensor devices serving various purposes can be connected to the network. The amount of data that is generated by such sensors strongly depends on the applications, e.g. IoT applying long-lived sensors. For the sake of simplicity, we assume in our approach a network with just two types of connected devices: the first devices generating constant low volume traffic (10 kbit/s) and the second devices generating once per day a larger amount of burst traffic (100 Mbit/day). In case that we distribute the total number of devices of 1E6 equally to the two different traffic demands, a total average throughput of 5.5 Gbit/s results. Assuming that a wireless access point takes care of all devices within 1 km^2, the throughput of about 0.5 times a TWDM-PON wavelength channel is required to fulfil the demand. In this case, the wireless access point has also to manage possible buffering and packetization mechanisms to enable a data transport over the TWDM-PON infrastructure. Other transport capabilities may also be considered achieving an increased efficiency. These solutions may be considered for further study.

For example, if we take the urban area of London of 1572km^2, 786 wavelengths are required to serve about 1572 x 1E6 devices using about 16 TWDM-PONs with 50 wavelengths each. Probably, only the upstream path of the TWDM-PON may be required so that the DS direction may be used for other purposes. A single ONU could be attached to each of the wireless access points which are connected to 1E6 devices, respectively, sending occasionally data packets.

E2E Latency of 5 ms or Even Lower

A couple of mission critical services such as car-to-car-communication, gaming, HF trading or tactile internet demand for ultra-low end-to-end latency. A target figure of 5 ms or even below has been specified for future 5G networks.

This challenge can be addressed within the DISCUS architecture by locating RAN equipment and in particular cases also RCN equipment closer to the end-user (e.g. locally at the customer access point, into the LE, into each M/C node). Moreover, local wireless networks (e.g. discussed in stadium solution) using local processing capabilities can be set up. These local networks are connected to the DISCUS access architecture. In this scenario, the traffic is kept locally avoiding long distance communications via the aggregation and core network. Additionally, the DISCUS LR-PON fiber distance could also be further reduced even down to few kilometers to reduce the transport latency. Of course, these solutions do not come for free, because it could increase the number of the total metro/core nodes.

In general, the demanding E2E latency requires the use of advanced processing techniques applying no or low buffering, preferably avoiding the use of FEC and DSP, low processing times and possibly an improved HARQ timing procedure to name just a few.

Service Deployment Time (90 minutes, see Fig. 10)

A fast and simplified launch of new services is a key target in 5G and it is also addressed by the DISCUS project by making use of a software-defined networking approach. This way, general multi-purpose hardware is used at the customer site and re-configurable elements are placed within the M/C node (optical space switch, electronic L2 switch/ L3 routers) so that the network becomes programmable by using network control elements for the access and core network.

Reliability (99.999% for Particular Users)

The DISCUS architecture contains mechanisms for protection and supervision to establish reliable connections for end users. For example, each LR-PON is connected to a primary and a secondary M/C node protecting M/C node or feeder fiber damages. Customer equipment (use of two transceivers) can be connected to a 2nd LR-PON using a disjoint ODN protecting ONU or drop fiber damages. The M/C node comprises BBU pooling and cloud functions protecting possible BBU outages. Here, the transparent outside plant of the LR-PON is used to establish new connections using the wavelength tuneability of ONU and OLT transceivers. This functionality also protects OLT-port failures.

To establish highest reliabilities for particular users also the wireless air interface and mobile end user devices need to incorporate protection mechanisms. These details are out of scope of this deliverable and are for further study.

Energy Efficiency

The overall DISCUS architecture is designed to achieve a low number of centralized electronic processing units within the M/C node, few optical amplifiers within the LE, wavelength tuneable equipment and a long-reach access network. The overall network approach is optimized in terms of cost to minimize the number of required equipment so that implicitly also the energy consumption is minimized. Additional mechanisms such as sleep, cyclic sleep, fast sleep, shut-down and dozing of equipment are important functionalities to reduce the overall power consumption. These functionalities have to be included in the wireless (e.g. BBU cloud functions to variable distribute data, shut-down/sleep/doze RRH+ in case of non-existing traffic) as well as in the optical (e.g. shut-down/sleep/doze transceivers) domain.

Mobility (Wireless Connections at Speeds of 500 km/h)

Enabling wireless connections for customers moving at high speed depends strongly on the air interface definitions, the protocols and the deployment of radio equipment and definitions of radio cells. The DISCUS architecture is capable to establish a large number of small cell connections as outlined and analyzed in depth in D4.10. The mobile interfaces are out of the scope of the DISCUS project.

4 Cost Analysis for Distributed vs. Centralized RAN

The centralization of the base-band processing of radio networks in centralized RAN appeared as an option to traditional distributed RANs because the former may reduce capital and operational cost, as well as facilitate the implementation of advanced radio features such as CoMP transmission and reception [12]. Some mobile operators have reported operational expense reductions greater than 50 percent from field trials of centralized baseband [29].

In centralized-RAN, the antenna sites are simplified with RRH with no base-band processing, in opposite to the distributed-RAN solutions.

This allows centralized-RAN to achieve a more easy installation of small RRH, also allowing reducing the overall base-band processing resources due to the statistical gain of centralization.

Nevertheless, it is well known that the demand of transport resources to deliver the signals from the RRH to the BBU, where the fronthauling signals are processed, increase drastically. This may reduce the opportunities for centralized-RAN to be a cost-effective scalable solution when considering 4G and 5G scenarios with ultra-high speed capacity (1 Gbps) offered to the mobile user equipment in the radio layer. Due to the high split ratio and scalable capacity of DISCUS LR-PONs, the support of distributed-RAN services by the fixed fiber network seems a feasible and cost-effective approach for fixed-wireless convergence. Nevertheless, DISCUS LR-PONs open also a new possibility for a cost-effective fixed-wireless convergence with centralized-RANs, because a high number of high speed CPRI signals can be transported into the same LR-PON using dedicated wavelengths in a ptp fashion, instead of requiring dedicated fiber links.

In order to estimate the total cost of ownership of a converged fixed-wireless access network, both capital and operational expenditures must be analyzed. Alternative advanced approaches such as functional split processing are still in an emerging phase thus reliable cost estimations are not available for this study. We focus our cost analysis in centralized and distributed baseband processing for a single converged mobile and fixed network operator.

First, when CAPEX (per sector) is analyzed, the following items must be considered:

- Site acquisition, civil works and installation. This comprises the cost of building the site for the installation of the mobile devices and their installation. On account of the smaller size and power consumption of RRHs when centralized-RAN technology is used, a cost saving is expected with regards to distributed-RAN. A 75 % CAPEX saving for this concept is assumed.
- Site equipment cost. This comprises the mobile devices that are installed in the mobile sites. In the case of centralized-RAN, the RRH cost is assumed to be a fraction of a complete distributed base station, while the remaining cost is attributed to the BBU processing that will be centralized. Three sectors are considered. An RRH is assumed to cost 60 % of a distributed base station.
- BBU equipment. In the case of distributed-RAN, this cost is already comprised in the site equipment cost of the distributed base station. On the other hand, in case of centralized processing, the corresponding cost is reduced on a certain amount,

on account of the statistical processing gain of BBU pooling. It is assumed that a 20 % cost saving (compared with a distributed base station) can be achieved when using BBU clusters of 50-100 sectors.

- Backhaul/Fronthaul equipment. In the case of centralized-RAN, fronthaul equipment is required to transport the digital radio over fiber signal from the RRH to the location of the centralized processing. A point to point logical resource is required per sector; on the opposite, in the case of distributed-RAN, backhaul equipment is required, a single one for the complete mobile site. Backhaul equipment is assumed to share the same optical resource than other mobile sites using TDMA. We assume a statistical multiplexing gain in the backhaul of 69 %, which is equivalent to a 3.2 overprovisioning factor.
- Backhaul/Fronthaul installation. This accounts for the installation of the ONU(s) and the connection to the fiber network. It is assumed that in 30 % of the cases, a direct fiber connection between the ONT and the antennas is not available, thus the cost of a microwave point to point connection is considered in the average cost.

Secondly, when considering the operational expenditures, the following items are considered:

- Annual site rental cost. This is a recurrent cost per year for renting the space where the mobile site is physically located.
- Annual site operations and maintenance cost. This is also a recurrent cost per year comprising the general maintenance required for the mobile site. It is assumed to be a fixed 25 % fraction of the capital expenditure cost of the mobile site.
- Power consumption. On account of the smaller size and power consumption as well as the higher reliability of RRHs in centralized-RAN, it is assumed that a 50 % cost saving can be achieved in the three former points.
- Aggregation network operational cost. This cost comprises the operational cost of an aggregation network. This cost is typically proportional to the Mbit/s of a connection. In the proposed scenarios of 4G services with 1 Gbit/s access speed and beyond (5G services), this cost can be dramatically high if business as usual technology was used. Due to the LR-PONs within DISCUS, this aggregation cost is avoided and a 90 % total operational cost saving is estimated with regards business as usual.

With the former considerations, the cost estimations for a 3 sector macro cell connected to the serving gateway located in a DISCUS metro-core node through LR-PONs are shown in the following graphs (Fig. 15 – Fig. 17)(in arbitrary cost units), both for centralized-RAN and distributed-RAN approaches.

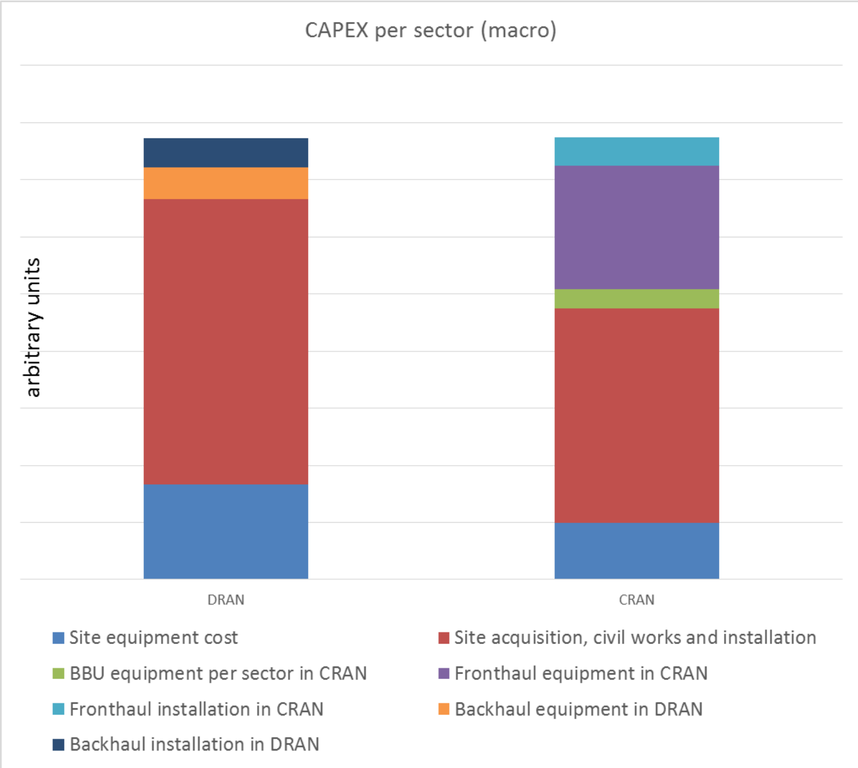

Fig. 15: CAPEX breakdown for a 3-sector macro cell: distributed-RAN/centralized-RAN comparative.

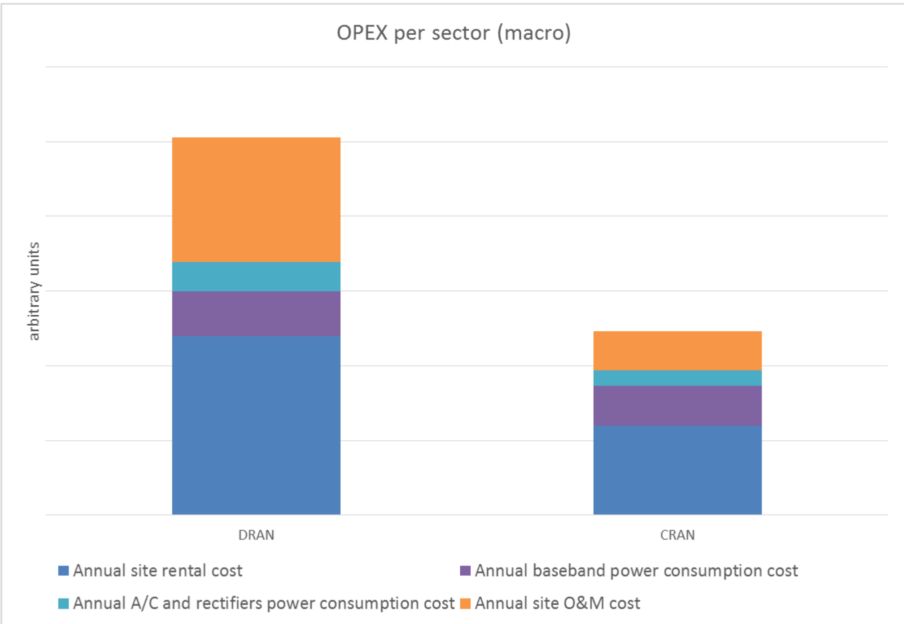

Fig. 16: OPEX breakdown for a 3-sector macro cell: distributed-RAN/centralized-RAN comparative.

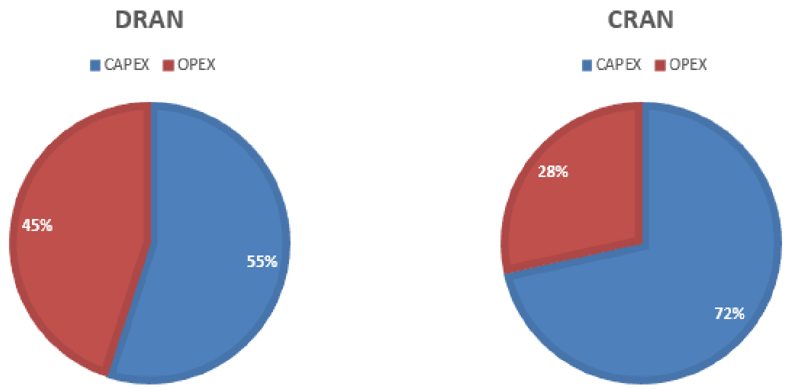

Fig. 17: Ratio CAPEX/OPEX for distributed-RAN and centralized-RAN macro cells.

For a macro cell deployment, a 23 % cumulated total cost of ownership (TCO) saving is estimated using centralized-RAN versus distributed-RAN in 5 years, as shown in the following graph, Fig. 18.

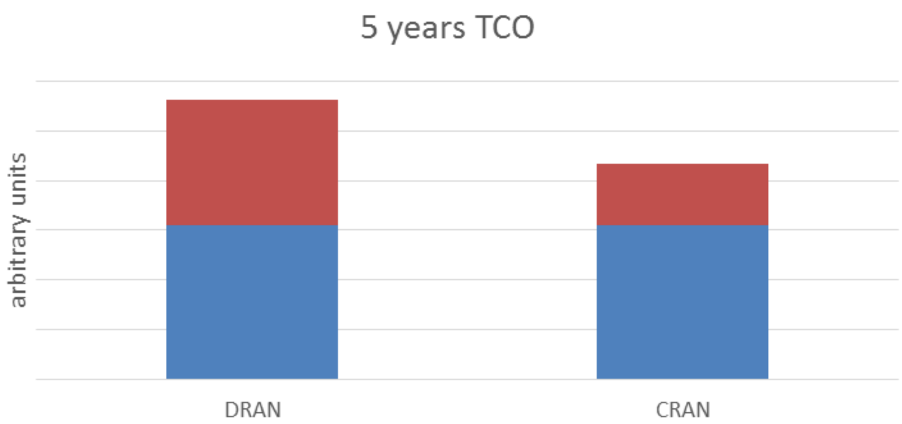

Fig. 18: Five years cumulative TCO for a 3-sector macro cell: distributed-RAN/centralized-RAN comparative: blue represents CAPEX, red represents OPEX.

We also analyze the cost estimations for a 1 sector small cell connected to the serving gateway located in a DISCUS metro-core node through LR-PONs, as shown in the following graphs (Fig. 19 — Fig. 21)(in arbitrary cost units), both for C-RAN and D-RAN approaches.

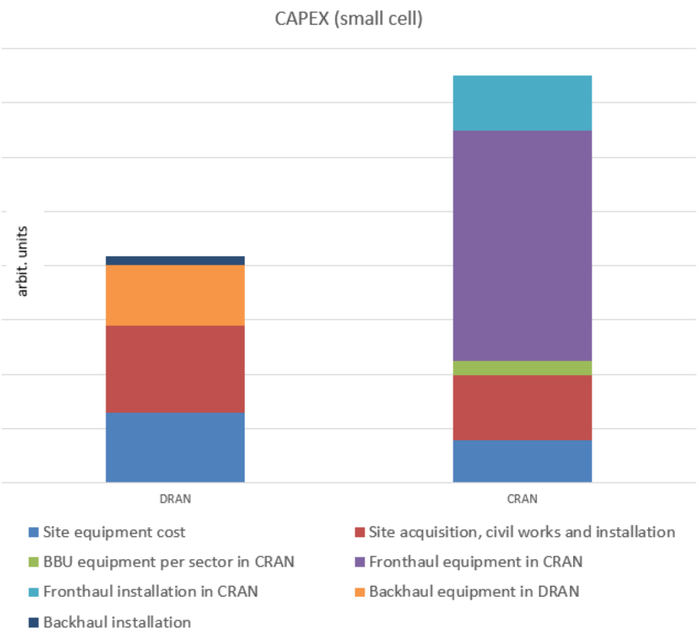

Fig. 19: CAPEX breakdown for a 1-sector small cell: distributed-RAN/centralized-RAN comparative.

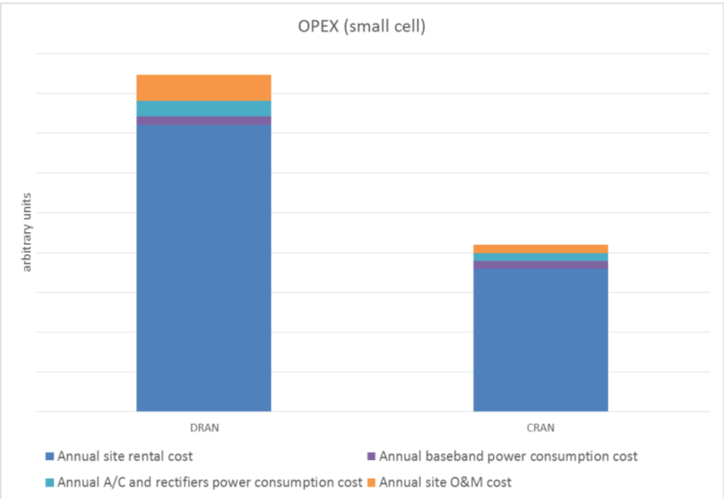

Fig. 20: OPEX breakdown for a 1-sector small cell: distributed-RAN/centralized-RAN comparative.

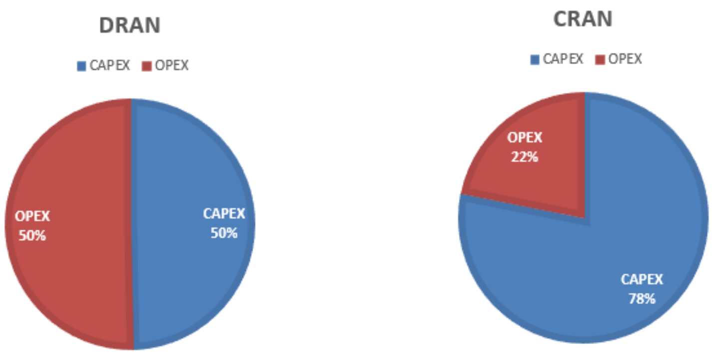

Fig. 21: Ratio CAPEX/OPEX for distributed-RAN and centralized-RAN small cells.

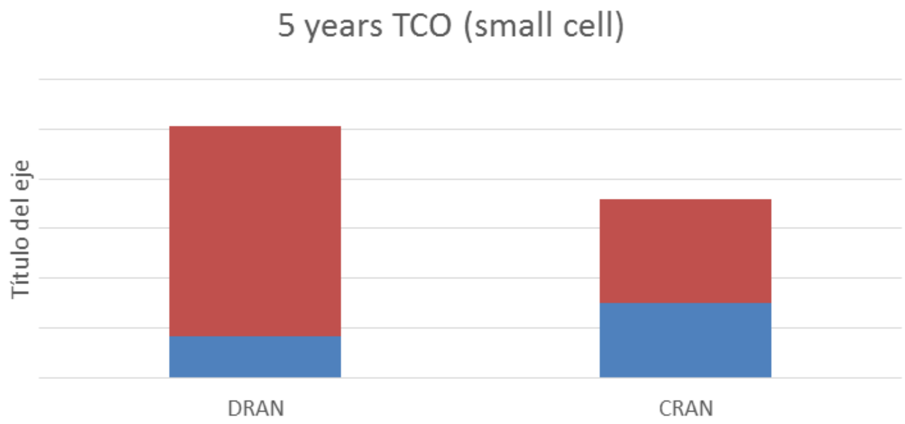

Fig. 22: Five years cumulative TCO for a 1-sector small cell: distributed-RAN/centralized-RAN comparative: blue represents CAPEX, red represents OPEX.

In case of small cells, a 29 % TCO saving in five years is estimated. A higher saving is achieved because, even in this case the CAPEX is much higher in case of centralized-RAN, the OPEX saving has a bigger impact in the TCO because the OPEX/CAPEX ratio in distributed-RAN is higher in small cells than in macro cells, see Fig. 22.

4.1.1 Discussion

In light of the former results, we see that centralized-RAN CAPEX rely on reducing overall eNodeB functions using BBU pooling gain, which should be experimentally validated in the field and confirmed in production networks. Similarly, the cost attributed to extra optical resources due to the point-to-point logical connection required per sector can be a sensitive parameter in the overall cost comparison.

In our current estimations, this extra cost in centralized-RAN macro cells is compensated by the CAPEX saving in the site acquisition and also because of the centralized hardware efficiency due to BBU pooling, but this compensation is not enough in the case of small cells, where the extra cost of fronthaul equipment is much higher than in the case of macro cells.

On the other hand, centralized-RAN OPEX savings are the most relevant point in both macro and small cells cases, which are mainly relying on reduced site rental costs and operations and maintenance of the equipment. Nevertheless, when upgrading already existing mobile sites using centralized-RAN macros, the reduction of rental cost will not exist, thus the TCO savings shown will only apply in Greenfield scenarios and, more likely, in new massive small cell deployments.

On the technological side, the proposed model relies on the real feasibility of CPRI compression ratio or new flexible split processing solutions, thus the algorithms to achieve this should be mature and standardized in order to be employed in real massive deployments.

Depending on the number of base stations in the serving area of a LR-PON, the global TCO may be different to the per sector cost estimations, because centralized-RAN approach is only applicable if M/C nodes are not further than 40 km from RRHs. As a consequence, the TCO in a real scenario will actually depend on the specific antenna distribution in a specific area, where centralized-RAN and distributed-RAN approaches will co-exist with a certain share each. In deliverable D4.10, a TCO comparison between centralized-RAN and distributed-RAN national-scale deployments integrated in DISCUS LR-PONs is reported for various European countries.

5 DBA & Energy Consumption in DISCUS Backhaul Network

The following chapter covers additional material that is addressed by the DISCUS wireless and wireline integration. In section 5.1, the hierarchical DBA as an enabler for virtualized access networks and in section 5.2 energy efficient transport solutions for dense indoor scenarios are described.

5.1 Hierarchical DBA as Enabler for Virtualized Access Networks

While PONs architecture have been developed to reduce the cost of deploying FTTH by sharing electronic equipment and optical fiber among many customers, additional effort is required to further reduce the still considerably high cost of ownership. For this reason, it is important that an access network can be shared across two dimensions: the service dimension, allowing multiple services to coexist in the same network, such as residential broadband services, small and medium business services, as other services like mobile backhaul; and the ownership model dimension, allowing multiple service providers to operate over the same physical infrastructure.

Sharing an access network across different services and providers requires virtualization of the network [30] to allow for independent operation and fair access to network capacity (e.g., in respect to SLAs). Virtualization enables allocating network slices to different providers, and within a given provider to different services. This work tackles the problem of PON virtualization by proposing an algorithm [31] that runs at the OLT, i.e., enabling partitioning of the PON upstream capacity among virtual slices.

As far as DBA is concerned, for the DISCUS PON the main reference standard we have used is XG-PON, which defines a TDMA MAC protocol that allows to dynamically assign bandwidth to the users' individual services. This enables PON operators to provide different levels of QoS to different services, according to their needs. To differentiate services, logical connections called XGEM ports are established between the OLT and the ONU, both in the upstream and downstream direction. In the upstream, XGEM ports belonging to the same ONU can be grouped into a group of logical connections called T-CONTs. To provide service to groups of ONU, it is necessary to be able to group T-CONTs into a single logical connection. For that reason we propose the grouped transmission container (gT-CONT), which is identified by the group AllocId (gAlloc-Id). We can see the hierarchy of the logical connections illustrated in Fig. 23.

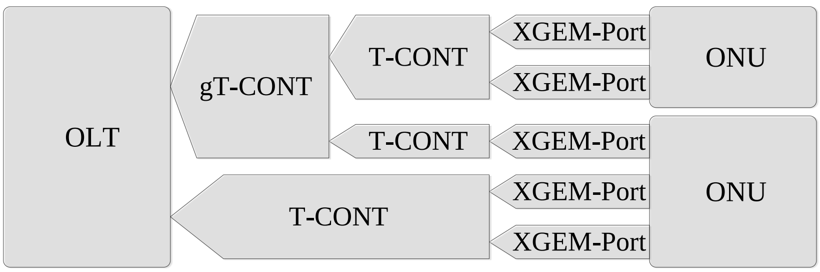

Fig. 23: Upstream logical connections, with gT-CONTs.

To characterize the QoS parameters of the T-CONT, XG-PON considers four different types of bandwidth: Fixed, Assured, Non-Assured and Best-Effort [30]. When T-CONTs from multiple ONUs can be grouped together, it is possible to create a new type of bandwidth, Group Assured Bandwidth. With this type of bandwidth, resources can be assured to a gT-CONT, rather than to individual T-CONTs.

This has the advantage that the mobile operator can make use of the properties of statistical multiplexing. Heterogeneous traffic from multiple base stations can be served with the same level of QoS and a smaller total amount of bandwidth using Group Assured Bandwidth when compared to using individual assured bandwidth.

It should be noted that group assured bandwidth does not stop a T-CONT from maintaining individual assured bandwidth to guarantee minimal service. In fact, group assured bandwidth can be obtained by sharing individual assured bandwidth that was unused by the T-CONT. Also, note that in assured bandwidth, unlike fixed bandwidth, resources are only assigned to the group if someone in the group needs it.

5.1.1 Group Assured Bandwidth Algorithm

To be able to assign group assured bandwidth, a scheduling algorithm that is aware of gT-CONT must be implemented at the OLT. To do this, we propose a variation of the well known GIANT scheduler [30], the gGIANT scheduler. In gGIANT, each type of bandwidth is characterized by two parameters: the service interval and the allocation bytes. The service interval, specified in frames, dictates how often the T-CONT gets served, while the allocation bytes dictate how many bytes on the upstream frame can be assigned to the T-CONT.

Since in XG-PON each T-CONT can have a mixture of all different types of bandwidth associated with it, in GIANT, the DBA engine needs to store these parameters for each type of bandwidth a T-CONT possesses. To know when to assign an upstream transmission, the DBA engine will also keep a counter per bandwidth type, that is decreased every upstream frame. When this counter expires, the OLT grants a transmission to the T-CONT and the counter is reset to its service interval value.

In gGIANT, the scheduler is capable of assigning group assured bandwidth by sharing unused capacity from individual assured bandwidth with other T-CONT of the same group. To do this, the DBA engine needs to be aware of the groups in the network. For this reason, a list of the T-CONT s in a group is maintained per gT-CONT. Also, each gT-CONT will keep a byte counter, which keeps track of the amount of bytes shared by the individual T-CONT at each upstream frame.

To perform the DBA process, first fixed and individual assured bandwidth are assigned as per the GIANT algorithm. When assigning individual assured bandwidth, if a particular T-CONT did not need all of the bytes reserved for it in the upstream frame, the amount that was not needed is added to the group's byte counter, to know how many bytes are available to the group. After assigning individual assured bandwidth, the DBA engine will go through all the groups, checking how many bytes are available from the previous stage. Unused bytes are then assigned to a T-CONT from the group that needs them, in a round robin fashion.

After finishing the assignment of the assignment of group assured bandwidth, non-assured and best-effort bandwidth follow, similarly to the GIANT scheduler. Note, that if no T-CONT in a group needed the group assured bandwidth, then the shared bytes become eligible for non-assured and best-effort assignment, as usual. This process is illustrated in Fig. 24, where four T-CONTs belonging to the same gT-CONT are depicted. Here 'SI' stands for service interval, which means T-CONT 1 has a service interval of 1 and T-CONT 2 has a service interval of two.

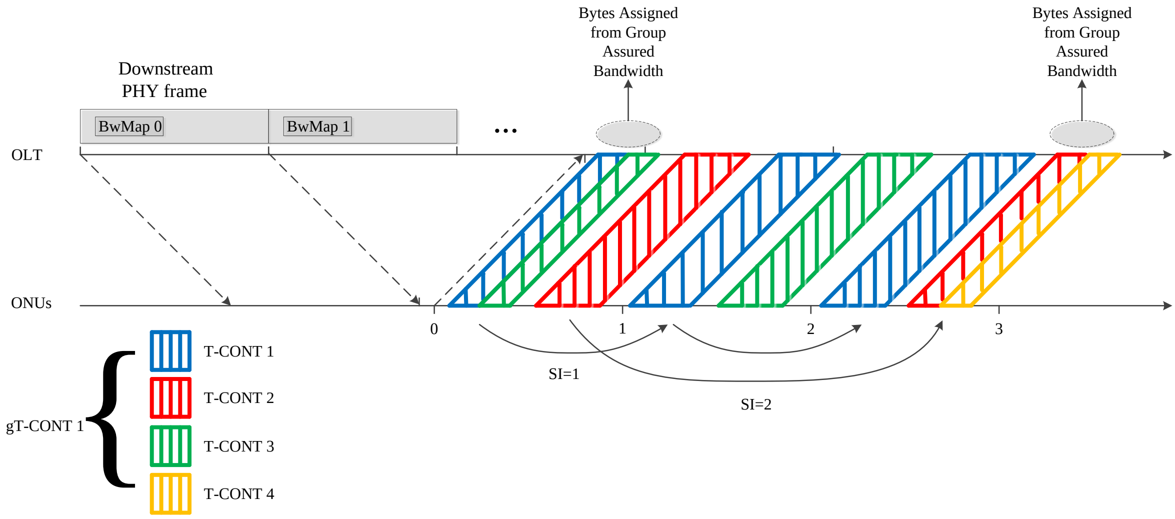

Fig. 24: gGIANT DBA Algorithm.

We can see on the first frame, that T-CONT 1 does not use all the bytes reserved for it and so some are assigned to T-CONT 3. Two frames later, it is T-CONT 2 which does not use all the bytes and so some are assigned to the next T-CONT in the group, T-CONT 4.

We show the pseudo-code for gGIANT algorithm in Procedures 1, 2 and 3. Here, Procedure 1 is the main procedure, which is called every 125 μs to generate the BwMap message, which is used to tell all the ONU when to transmit. In this procedure, bandwidth is assigned in a loop until the upstream frame is full or all bandwidth types (fixed, assured, etc.) of all T-CONTs have been served. This loop will call the 'GetNextTcontParameter()' function to obtain the next T-CONT parameter; a structure that contains the T-CONT to be served, the type of bandwidth being served, and the service parameters of the particular connection and type of bandwidth.

Procedure 1 gGIANT algorithm

```
while Upstream frame is not full do
    tcontParam = GetNextTcontParameter()
    bwType = GetBandwidthType(tcontParam)
    if bwType == FIXED_BW then
        allocateFixedBandwidth()
    else if bwType == INDIV_ASSURED_BW then
        allocateIndivAssuredBandwidth(tcontParam)
    else if bwType == GROUP_ASSURED_BW then
        allocateGroupAssuredBandwidth(tcontParam)
    else if bwType == NON_ASSURED_BW then
        allocateNonAssuredBandwidth(tcontParam)
    else if bwType == BEST_EFFORT_BW then
        allocateBestEffortBandwidth(tcontParam)
    end if
    if all bandwidth types of all T-CONTs were served then
        break
    end if
end while
UpdateAllTimers()
ClearSharedBytesCounters
UpdateGroupRoundRobinPointers()
FinalizeBwMapProduction()
```

The ‘GetNextTcontParameter()’ will get the bandwidth parameters in the following order of the priorities: Fixed, Individual Assured, Group Assured, Non-Assured and Best Effort. When ‘GetNextTcontParameter()’ reaches the group assured parameters, it will go through the list of T-CONTs in the group in a round robin manner. Only when all the individual T-CONTs in a group have been served, ‘GetNextTcontParameter()’ will move on to the next group parameter. Depending on the type of bandwidth obtained from the ‘GetNextTcontParameter()’ different functions will be called to allocate the bandwidth. We will focus on describing ‘allocateIndivAssuredBandwidth()’ and ‘allocateGroupAssuredBandwidth()’ since they differ from the GIANT algorithm.

Procedure 2 is the procedure used to assign assured bandwidth. In this procedure, first the allocation bytes, the current counter value, and the T-CONT queue length are obtained. With these values, in case the number of bytes in the queue exceeds the allocation bytes, all the capacity of the T-CONT is used. Instead, in case it does not exceed and the T-CONT belongs to a gT-CONT, the unused bytes are added to the shared bytes counter of the gT-CONT.

Procedure 2 AllocateIndividualAssuredBandwidth

```
tcont = GetTcont(tcontParam)
gtcont = GetGroupTcont(tcontParam)
allocBytes = GetAllocationBytes(tcontParam)
timerValue = GetCounterValue(tcontParam)
buffOcc = GetBufferOccupation(tcont)
if timerValue == TIMER_EXPIRE then
    if buffOcc! = 0 then
        if buffOcc > allocBytes then
            sizeToAssign = allocBytes
        else
            sizeToAssign = buffOcc
            if gtcont! = 0 then
                unusedBytes = allocBytes − buffOcc
                AddSharedBytes(gtcont, unusedBytes)
            end if
        end if
        Assign(tcont, sizeToAssign)
    end if
end if
```

Finally, in Procedure 3 group assured bandwidth is assigned. This procedure will get the amount of shared bytes from the gT-CONT and assign them if the selected T-CONT has bytes on the queue.

It should be noted that if the ONU of the selected T-CONT has not been served before, i.e., if a new burst is necessary, PHY overhead such as inter-gap spacing and preamble must be taking into account when assigning the shared bandwidth. When calculating the amount of bytes allocated to this T-CONT, this overhead must be deducted from the available bytes, and when calculating how much was used, the overhead must be taken into account.

Procedure 3 AllocateGroupAssuredBandwidth

```
gtcont = GetGroupTcont(tcontParam)
tcont = GetCurrentTcont(gtcont)
sharedBytes = GetSharedBytes(gtcont)
buffOcc = GetBufferOccupation(tcont)
overhead = phyOverhead+XgtcHeader+XgtcTrailer
if sharedBytes > 0 && buffOcc > 0 then
    if CheckServedTcont(tcont) then
        sizeToAssign = min(buffOcc, sharedBytes)
        DecreaseSharedBw(sizeToAssign)
    else
        availableBytesToShare− = overhead
        sizeToAssign=min(buffOcc, sharedBytes)
        DecreaseSharedBw(sizeToAssign + overhead)
    end if
    assign(tcont, sizeToAssign)
end if
```

5.1.2 Simulation Results

We have run the simulations to test the efficacy of the group assured bandwidth algorithm using anonymised call-detail records from an Irish mobile operator. These records hold information about mobile users' data transfers, such as session duration, transmitted bytes, base station location, etc., on multiple transmitters across Ireland, for both 2G and 3G technologies.

Despite the great value of these traces, they have a few limitations. Firstly, they record only the initial sector where a data session is initiated, without any mobility information. To cope with this issue, we use the approximation that the entire session is carried out on the initial transmitter. Due to the short duration of the sessions we do not consider this to be a significant limitation [33]. The second limitation is that instantaneous throughput is not recorded, only session durations and transmitted bytes, thus we can only approximate the load of each base station averaged over a certain duration of time. Despite such limitations such traces have proven invaluable for our work as they provided information about load correlation between adjacent base stations. We then generated traffic by adopting an exponentially distributed packet arrival statistical model, using the average loads calculated by the traces. While this method does not assure the exact reproduction of backhaul traffic, it creates a traffic load for our packet-based simulator where the load correlation between base stations reflects that of a real mobile system.

In our analyses, we consider a week's worth of traffic from a small area in Dublin, that could be served by a PON. We consider that the traffic from multiple co-located transmitters is aggregated into a single ONU. This area is comprised of 31 different sites, each site with multiple transmitters. We can see the normalized maximum, mean and standard deviation of the network load in Fig. 25. We can also see in Fig. 25 that the variation of the load is considerable, with the standard deviation being similar to the mean. The load's variability is due to two factors: first, some locations of the city are more heavily loaded than others; second, some of the sites are composed just of 2G transmitters, thus having low data rate, while others are composed of only 3G transmitters. This significant variability makes a good case for usage of group-assured bandwidth.

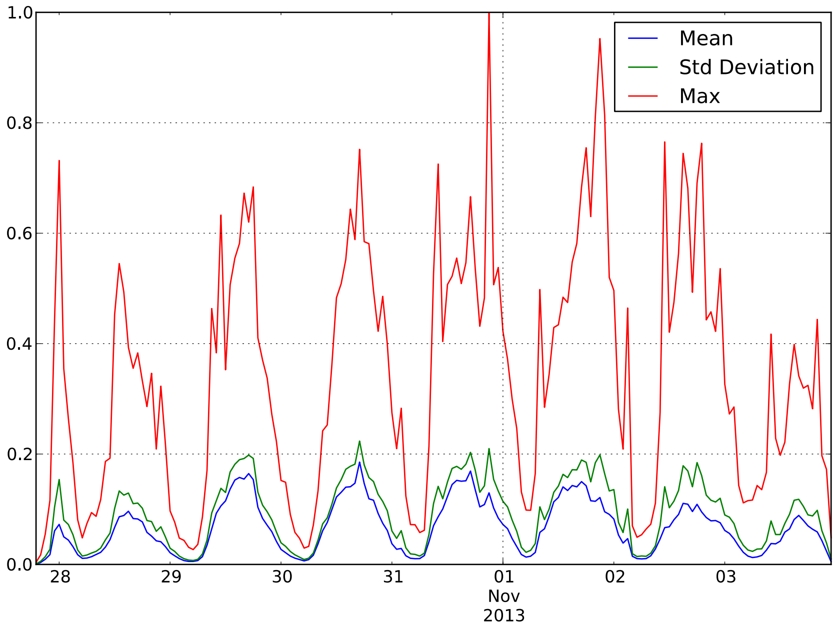

Fig. 25: Normalized mean, maximum and standard deviation of base stations' loads.

The evaluation of our gGIANT algorithm is carried out using an XG-PON module we developed for the ns-3 simulator, described in [34] and freely viable at http://sourceforge.net/projects/xgpon4ns3/ . We summarize the most relevant simulation parameters in Table 2. We carry out simulation over three scenarios: in the first, backhaul connections' assured capacity is provisioned to be equal to the average peak rate of the base stations; in the second, it is 30% of the average peak rate; in the third, it is 40% of the average peak rate. Results showing the average packet delay are reported in Fig. 26. This plot gives us three main insights. Firstly, if we assign capacity equal to the maximum, the GIANT algorithm still incurs in delay, due to the fluctuation of the packet arrival rate around the average peak value. Our gGIANT algorithm is instead able to eliminate such delay, because bytes that were reserved for particular T-CONT, are now shared with the group, which allows T-CONTs to make their transmissions sooner when there is capacity available from the group. Secondly, even if we assign a capacity that is 30% less than the average peak, gGIANT is still able to keep the packet delay negligible, while with GIANT the delay greatly increases. Finally, we see that if the capacity is decreased to 40% of the average peak, even the gGIANT starts introducing significant delay, as there is not enough capacity to be redistributed.

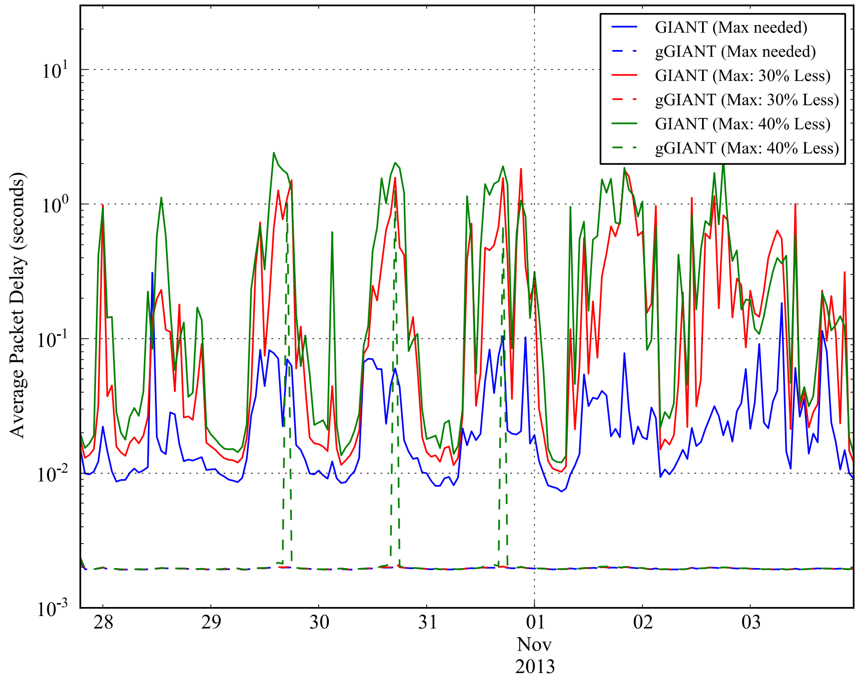

Fig. 26: Network average packet delay for group and individual assured bandwidth.

Fig. 27 shows similar results, but considering packet loss rate rather than delay. We can see from the plot that the results are consistent with those in Fig. 26.

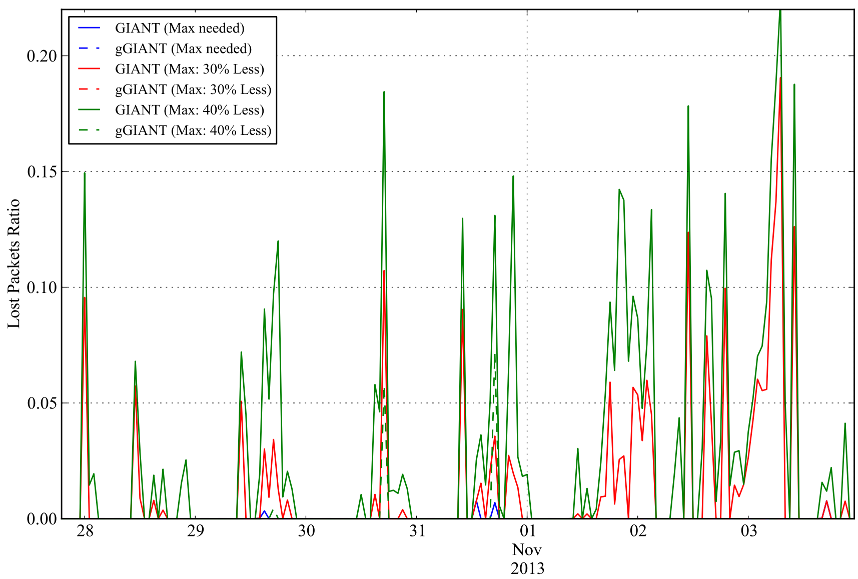

Fig. 27: Network average packet loss for group and individual assured bandwidth.

Table 2 PON Simulation Parameters

Simulated time	50 seconds
Fiber propagation delay	0.4 msec
Number of ONUs	31
Service Interval	8 frames
Buffer Size	1 MBytes
Packet size (Bytes)	64 (60%), 500 (20%), 1500 (20%)
Inter-arrival times	Exponentially distributed

5.2 Energy Efficient Transport Solutions for Dense Indoor Scenarios

Mobile operators are facing an exponential traffic growth due to the proliferation of portable devices that require high-capacity connectivity. This, in turn, leads to a tremendous increase of the energy consumption of mobile access networks. A mobile network is divided in two segments: the radio access network, which provides broadband wireless access to the end-users, and the transport network, which is responsible for interconnecting the radio network to the core network infrastructure. Current radio networks are mainly based on high-power base stations (BSs) with complex antenna systems, referred to as macro BSs. Macro BSs are deployed outdoor and are particularly energy inefficient when covering indoor users. A promising solution to this problem is the concept of heterogeneous radio networks, which is based on the dense deployment of low-cost and low-power BSs, in addition to the traditional macro BSs. However, in such a scenario the energy consumed by the transport network becomes significant and may limit the advantages of heterogeneous radio deployments. As a consequence, to deploy green mobile access networks a careful combined design of the radio and the transport networks is necessary. We have defined a methodology [34] to design and assess the power consumption of a mobile network taking into consideration both the radio and the transport segments. We applied this methodology to an urban area, with particular attention to indoor users that we assume being covered by femto cells (specific realization of a small cell defined in DISCUS). In the next sections we first introduce the design methodology and then we consider a number of transport architectures to identify the most promising solutions. On a final note we would like to highlight that the presented optical transport architecture are general concept and can be implemented leveraging on the DISCUS LR-PON concept.

5.2.1 Methodology and Radio Network Dimensioning

The methodology followed to assess the total energy consumption of a wireless access network (including the transport segment) in a dense urban area can be divided in four steps, as depicted in Fig. 28 [34].

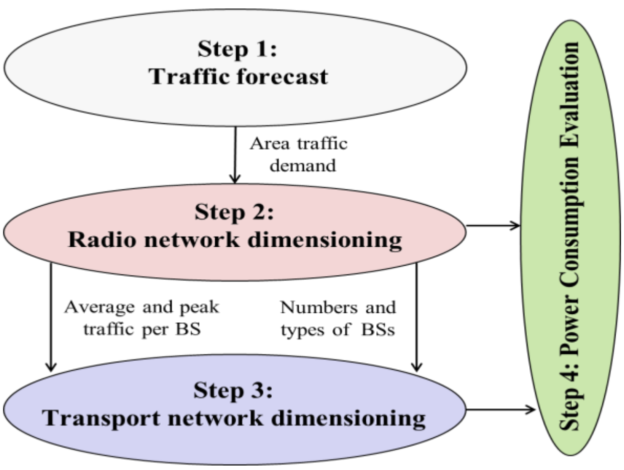

Fig. 28: Methodology for designing and assessing the energy consumption of a mobile network.

The first step is the Traffic Forecast phase. This step generates an estimate of the average area traffic demand for a dense urban area at the busy hour for the specific year under exam. This traffic estimate is based on long-term, large scale-traffic models and on forecasted data for network and service usage such as: (i) the population density, (ii) the percentage of users that are active at busy hour, (iii) their behavior (i.e., heavy vs. ordinary type), and (iv) the penetration rate of different terminal types (i.e., pc, tablet, and smart-phone).

The second step consists in the Radio Network Dimensioning phase. This step uses as input the traffic forecast generated in the first phase. This step returns the dimensioning for the wireless access segment, i.e., number of macro and femto cells with their peak traffic values. The residential femto cells are assumed to be randomly deployed by the end-users in their apartments (similarly to Wi-Fi systems). The number of deployed femto cells (N_{femto}) is calculated as a function of the femto penetration rate (θ) and of the total number of apartments (N_a) in the area: $N_{femto} = N_a \times \theta$. Since the macro-cellular network needs to serve the remaining active users (i.e., which are not covered by femto cells), the required number of macro BSs in a given network area A can be computed as:

$$N_{macro}^{hetnet,femto} = \frac{\rho \times (1-\theta) \times \alpha_{\max} \times A}{N_{active/BS}}$$

where ρ represents the average user density and α_{max} is the percentage of active users in the peak hour.

The third step represents the Transport Network Dimensioning phase. This step returns as a result the total power consumption of the transport segment in the time period under exam. The result is dependent on the output of the radio network dimensioning phase and on the specific choice for the transport technology. The main input parameters for this phase are: the backhaul network architecture and topology, the transmission/switching characteristics of the network equipment used, and their power consumption values. The transport network is dimensioned according to the peak capacity.

Finally, the last step of the presented methodology is about the Total Power Consumption Evaluation. In this phase the total power consumption of the access network is calculated as the sum of the power consumed by the radio segment and by the transport segment.

5.2.2 Transport Network Dimensioning

This section presents more details about the backhaul dimensioning phase. The first backhaul architecture is shown in the left side of Fig. 29, and is referred to as Femto-Based with curb backhaul (Femto-CB). Here, femto cells are backhauled using copper cables and very-high speed digital subscriber line (VDSL) transmission protocol. Each femto cell is connected to a VDSL modem that is in turn connected to a DSL add/drop multiplexer (DSLAM) located at the curb cabinet. The DSLAMs are connected to Carrier Ethernet metro/core switches located at the central office using grey optical PtP fiber links. The second backhaul architecture is shown in the right side of Fig. 29, and is referred to as Femto-Based with building backhaul (Femto-BB). All the femto cells inside a residential building are connected to an ONU using copper cables operating at 100 Mbps (e.g., LAN cable CAT 5/6/7). Each ONU is in turn connected to the OLT in the central office through TWDM–PON infrastructure.

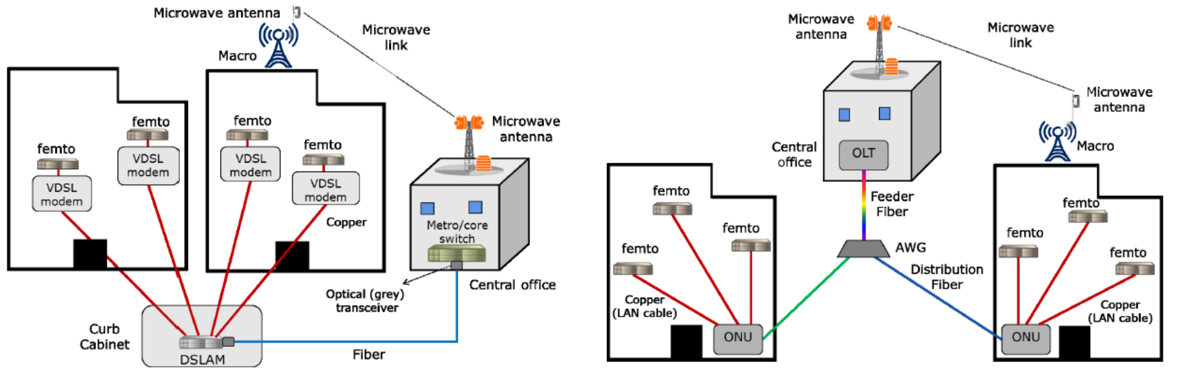

Fig. 29: Femto with curb backhaul (Femto-CB) (left), and femto with building backhaul (Femto-BB) (right).

5.2.3 Total Power Consumption Evaluation

Fig. 30 shows the power consumption of a mobile access network based on femto cells when considering the traffic forecast for the years 2018 and 2022 (~ 475 Mbps/km^2 peak area traffic demand at busy hours, [34]). Different values for the femto penetration rate (from 0 to 0.6) have been considered. Note that the case with θ = 0 corresponds to a macro densification, while the case with θ = 0.6 corresponds to the case where all the indoor users are served using the femto cells.

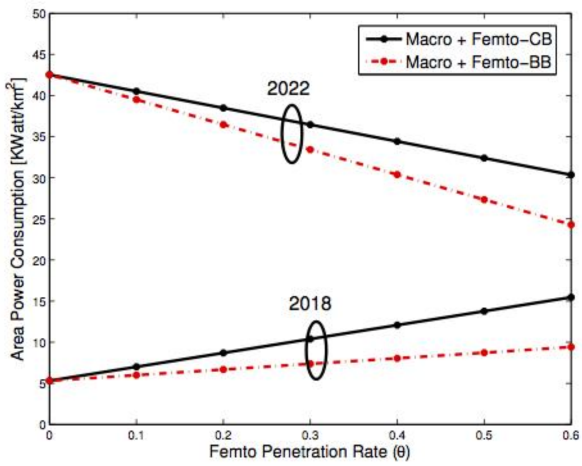

Fig. 30: Power consumption of the Femto-Based deployments.

The figure shows that in the year 2018 using a Femto-CB solution leads to higher energy consumption with respect to a macro BS deployment. This is due to the fact that the traffic requirements are not sufficiently high to cover for the extra energy cost of the transport infrastructure. Instead, the Femto-BB is much more energy efficient and the corresponding power consumption is lower than the macro deployment for the traffic levels forecasted for the year 2022. In the year 2022 the Femto-CB approach leads to lower energy consumption with respect to the macro BS deployment, but, the Femto-BB approach is still more energy efficient.

6 Summary and Conclusion

The present deliverable provides a general introduction and an up-to-date view on wireless and wired network consolidation. The ongoing discussions in the research area of 5G are used to present the DISCUS access network view for fixed and mobile convergence in LR-PON architectures. It describes the general architecture to realize a consolidation of the metro-access space as well as for systems, i.e. wired and wireless services. The network offers the advantageou of a software-defined networking approach and serves customers for the residential, business and enterprise market simultaneously. It can be concluded that the DISCUS LR-PON architecture and the M/C node design is capable to serve current and future mobile services applying different air data rate requirements. Local solutions and variations may be applied to the DISCUS architectures and the overall ODN fiber length may be limited to 20…40 km. This way, the LR-PON architecture may be considered as a high-split architecture rather than a long fiber reach architecture.

First, a general overview of the latest view on front-, mid- and back-hauling approaches of wireless data over a wired architecture is presented. Centralized processing is expected to bring about substantial benefits for wireless networks both on the technical and on the economic side. While this concept is considered an important part of future radio access network architectures, it is more and more recognized that the current approach to fronthauling by employing the CPRI protocol will be inefficient for large scale network deployments in many respects, and particularly for the new radio network generation 5G. An overview is given of currently available optical fronthaul technologies, of recently started activities towards more efficient and scalable solutions, and finally an outlook is given onto which 5G specific service characteristics may further impact future backhaul, midhaul and fronthaul networks.

Second, this knowledge is used to present and elaborate the DISCUS view on wireless and wired convergence in two scenarios. The first approach focuses on a fixed and radio access converged network scenario for 2020 applying structural convergence and base stations hoteling within the M/C node (fronthaul case). This solution considers a peak access speed of 1 Gbit/s both for fixed and mobile services. Both distributed and centralized baseband processing approaches are considered for mobile traffic. The second approach is related to a future scenario (beyond 2020) which focuses on the functional convergence and Ethernet transport in the access area.

Third, a cost analysis for the centralization of the base-band processing of radio networks in centralized RAN compared to the traditional distributed RANs is performed for a macro and small cell deployment scenario. In our current estimations, the cost attributed to extra optical resources due to the point-to-point logical connection required per sector in centralized-RAN macro cells is compensated by the CAPEX saving in the site acquisition and also because of the centralized hardware efficiency due to BBU pooling. However, this compensation is not enough in the case of small cells, where the extra cost of fronthaul equipment is much higher than in the case of macro cells. On the other hand, centralized-RAN OPEX savings are the most relevant point in both macro and small cells cases, which are mainly relying on reduced site rental costs and operations and maintenance of the equipment.

Fourth, the approach of group assured bandwidth is introduced to achieve infrastructure virtualization enabling sharing an access network across different services and providers to allow for independent operation and fair access to network capacity. Virtualization enables allocating network slices to different providers, and within a given provider to different services. Algorithms are briefly introduced and results are presented for PON virtualization by using the algorithm that runs at the OLT, i.e., enabling partitioning of the PON upstream capacity among virtual slices.

Finally, the energy consumption comparison of a femto cell with curb backhauling based on DSL versus a femto cell applying with building backhauling based on LR-PON fiber technology is performed. This scenario may be considered as a particular local solution at the edge of the DISCUS access network. The finding is that the fiber approach is in any case the most energy efficient solution.

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Abbreviations

AMCC	Auxiliary Management and Control Channel
BB	x-based with building backhaul
BBU	Baseband Unit
CoMP	Cooperative Multi-Point
CP	Cyclic Prefix
CPRI	Common Public Radio Interface
CS/CB	Coordinated Scheduling/Beamforming
Centralized-RAN	Centralized Radio Access Network
Cloud-RAN	Cloud Radio Access Network
CWDM	Coarse Wavelength Division Multiplexing
DBA	Dynamic Bandwidth Allocation/Assignment
Distributed-RAN	Distributed Radio Access Network
DWA	Dynamic Wavelength Allocation/Assignment
EDFA	Erbium-doped Fiber Amplifier
EPC	Evolved Packet Core
EPS	Evolved Packet System
FEC	Forward Error Correction
ICIC	Inter-Cell Interference Coordination
IoT	Internet of Things
JP/JT	Joint Processing/Joint Transmission
JR	Joint Reception
LE	Local Exchange
LR-PON	Long Reach Passive Optical Network
M/C Node	Metro/Core Node
MIMO	Multiple-Input-Multiple-Output
MME	Mobility Management Entity
MNO	Mobile network operators
NFV	Network Function Virtualization
NGFI	Next Generation Fronthaul Interface
OAM	Operation and Maintenance

ODN	Optical Distribution Network
OLT	Optical Line Terminal
ONU	Optical Network Unit
ORI	Open Radio equipment Interface
PDCP	Packet Data Convergence Protocol
PON	Passive Optical Network
RAN	Radio Access Network
RAT	LTE radio access technologies
RAU	Remote Antenna Unit
RCC	Radio Cloud Center
RCN	Radio Core Network
RE	Reach Extender
REC	Radio Equipment Controller
RLC	Radio Link Control
RRS	Radio Remote System
RRU, RRH	Remote Radio Unit, Head
SC	Service Channel
SDN	Software Defined Network
S-GW	Serving Gateway
SOA	Semiconductor Optical Amplifier
TCO	Total cost of ownership
UE	User Entity
UL-HARQ	Uplink hybrid automatic repeat request

Document versions

Version[1]	Date submitted	Comments
V1.0	16/10/2015	First version sent to the commissions.

[1] Last row represents the current document version