5G-Crosshaul: Towards a Unified Data-Plane for 5G Transport Networks

Luca Cominardi[1,2,*], Jorge Baranda[3], David Larrabeiti[2], Fabio Cavaliere[4], Philippe Chanclou[5], Jessé Gomes[6], Andrea Di Giglio[7], Per Ödling[8], Hsien-Wen Chang[9]

[1] InterDigital Europe, [2] University Carlos III of Madrid, [3] Centre Tecnològic de Telecomunicacions de Catalunya, [4] Ericsson Research, [5] Orange, [6] Fraunhofer HHI, [7] Telecom Italia, [8] Lund University, [9] Industrial Technology Research Institute

Abstract—**The increasing stress on mobile radio access performance in a context of declining revenues for operators is requiring the evolution of transport networks (backhaul and fronthaul), which currently work decoupled. The heterogeneity of the nodes and transmission technologies inter-connecting the fronthaul and backhaul segments makes the network quite complex, costly and inefficient to manage flexibly and dynamically. In order to meet 5G requirements in a cost-effective manner, 5G-Crosshaul is designing a 5G transport network that unifies the data, control, and management planes. On the one hand, this paper includes an overview, from a data-plane perspective, of the unified network architecture proposed by 5G-Crosshaul project, discussing the different enabling transport and multiplexing technologies. On the other hand, it also presents one of the main concepts of this project, a novel multi-layer switch architecture that enables the multiplexing of fronthaul and backhaul traffic within the same transport network.**

Keywords—5G architecture, fronthaul, backhaul, transport network, switch architecture

I. Introduction

The backhaul is the network segment that assures the connectivity between the core network and access network and is typically composed of several sub-systems including heterogeneous wired/wireless forwarding networks and fiber-based aggregation/routing networks. The backhaul network infrastructure includes several packet nodes, such as switches, routers, aggregators, etc., and it uses various transport protocols to communicate packets between these nodes such as Carrier-grade Ethernet, OTN, SDH, MPLS, IP, etc.

Recently, a new network segment called *fronthaul* has emerged, as the result of more centralized radio access network (C-RAN) architectures where the base station (eNB) is split into two elements, a remote radio head (RRH) and a baseband processing unit (BBU). The RRH simply keeps the RF functions necessary for the signal radiation at the cell site while the BBU takes all the baseband heavy computational functions to a separate location. To enable this split, new protocol interfaces have been designed, such as CPRI (Common Public Radio Interface) [1], OBSAI (Open Base Station Architecture Initiative), and ETSI ORI (Open Radio equipment Interface). CPRI is the most prominent interface adopted and deployed in the market.

The physical location of the BBU is variable (e.g., fully at the edge, in a local cloud, or fully central cloud), which can create situations where fronthaul and backhaul traffic may eventually share the same physical segment of the transport network. Different functional splits, and hence interfaces, impose different requirements (e.g., bandwidth, latency, jitter, BER) on the fronthaul interface that must be guaranteed within the network.

For increasing the network capillarity as required by 5G, the transmission technologies inter-connecting the different nodes in the fronthaul and backhaul must be heterogeneous. This requires a compromise between dedicated control for each type of technology and a common abstraction layer to set services and monitor end-to-end quality of service (QoS), transparently to the underlying technologies. With traditional technologies, the plethora of nodes, their control elements, and the technologies embedded make the fronthaul and backhaul networks quite complex, expensive and inefficient to manage flexibly and dynamically. Moreover, the new considered functional splits further blur the borders between fronthaul and backhaul, hence motivating the need for a unified management of both.

The 5G-Crosshaul project [2] envisages a unified data plane encompassing innovative high-capacity transmission technologies and novel deterministic-latency framing protocols to cope with the above problems while enabling a unified control plane, which together conform the 5G-Crosshaul network. This paper includes a short overview of the main fronthaul and backhaul traffic requirements in Section II to motivate the need of the proposed unified data plane architecture, which is presented in Section III. Transport and multiplexing technologies enabling the 5G-Crosshaul network are discussed in Section IV. Furthermore, Section V proposes a novel multi-layer switch architecture for combining different transport technologies in the integrated 5G-Crosshaul transport network. Section VI concludes this paper.

II. Fronthaul and Backhaul traffic requirements

A necessary step for the definition of the 5G-Crosshaul network is the identification of the traffic requirements,

---

The authors of this paper have been sponsored in part by the project H2020-ICT-2014-2 "5G-Crosshaul": The 5G Integrated fronthaul/backhaul" (671598)

* Corresponding author email: luca.cominardi@interdigital.com

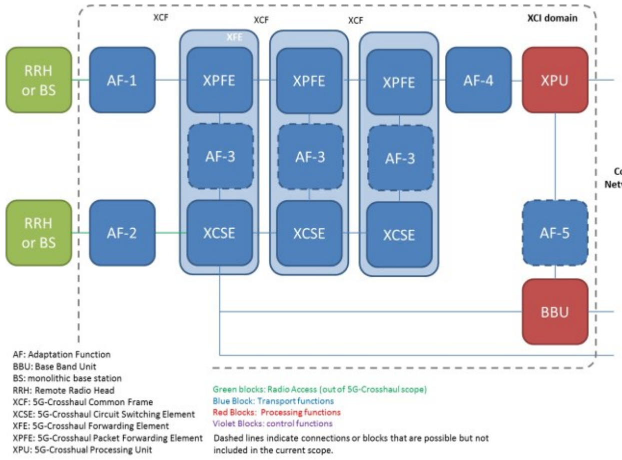

Figure 1: 5G-Crosshaul data plane architecture

especially in terms of latency and bandwidth. Fronthaul interfaces pose tight requirements in terms of required bandwidth and admissible latency and jitter. Specifically, the closer the functional split to the RF layer, the tighter the requirements become. That is why the requirements for the CPRI interface are quite tight, which makes this interface quite rigid (static) and costly. For example, a single-sector LTE 2×2 MIMO base station with a 20MHz bandwidth channel requires a maximum backhaul throughput of 150 Mbit/s, with an average of 21Mbit/s, while the CPRI fronthaul requires a constant capacity of 2.457 Gbit/s for an end-user maximum data rate of 150 Mbit/s, according to the NGMN Alliance [3].

In addition to this, CPRI demands about 100 µs of maximum end-to-end latency for up to 10km of distance between RRU and BBU [16] with a strict link delay accuracy of ± 8 ns difference between master clock and slave ports, and 2 ppb frequency deviation from the CPRI link to the BBU. Therefore, a packet-switched network requires a jitter compensation buffer and a careful QoS engineering design in order to match the CPRI delay accuracy requirements. For instance, 50 µs of latency budget are spent on propagation over 10km of fiber and the remainder 50 µs are the margin for switching [17].

Compared to LTE/LTE-A, 5G should achieve a hundredfold data rate growth (10 Gbit/s) for each sector. Such data rate requires an ultra-high fronthaul capacity with a very low latency. In such context, the best transmission medium to meet LTE and 5G requirements is fiber. However, a fiber deployment may not be cost-effective in some cases. This is why both academia and industry are working on different functional splits on the attempt to relax the requirements of today's fronthaul and reach a more scalable interface for the future, so that lower cost and flexible means to transport the fronthaul traffic can be used.

In addition, 5G PPP defines a broader set of performance KPIs for future 5G networks [4]. 1000 times higher wireless area capacity and more varied service capabilities shall be provided with respect to that offered in 2010. Very dense deployments of wireless communication links to connect over 7 trillion wireless devices serving over 7 billion people shall be facilitated. Similarly, the next-generation wireless technologies shall allow ubiquitous connectivity also in low density areas, a necessary requirement for Internet of Things and Smart Cities scenarios.

Clearly, the design of the 5G-Crosshaul data plane requires a holistic view, encompassing radio protocols, optical and wireless transmission and switching, and integrated and intelligent management.

III. A UNIFIED DATA-PLANE ARCHITECTURE

The main goal of the 5G-Crosshaul project is to provide an integrated, flexible and software-defined reconfigurable backhaul and fronthaul mobile transport network able to accommodate the requirements of any 5G radio access network (RAN) functional split. Bearing this in mind, 5G-Crosshaul proposes two main network architectural elements: the XFE (5G-Crosshaul Forwarding Element) and the XCI (5G-Crosshaul Control Interface).

The XFE, further described in Section V, is the fundamental block of the 5G-Crosshaul data-plane architecture, which is the object of this section. In its most general implementation, the XFE is a multi-layer switch composed of a packet switch (5G-Crosshaul Packet Forwarding Element, XPFE) and a circuit switch (5G-Crosshaul Circuit Switching Element, XCSE), as depicted in Figure 1. The rationale of such proposed design resides in the fact that a packet interface alone may not be suitable for 5G services and interfaces with demanding timing constraints, like CPRI [1].

Hence, the 5G-Crosshaul transport network will consist of the interconnection of XFEs integrating heterogeneous physical transmission technologies (either wired or wireless) through a common data frame and forwarding behavior.

Green blocks in Figure 1 represent access radio units, which are connected to the XFEs through adaptation functions (AFs) that perform protocol and/or media adaptation. As mentioned before, radio units can be based on different split options of the radio protocol stack, which may be served by pure backhaul (e.g., Ethernet), pure fronthaul (e.g., CPRI), or any split in-between defining new packet fronthaul interfaces.

The purpose of AF-1 is media adaptation and translation of vendor specific radio interface (CPRI, new proprietary 5G fronthaul packet interface, Ethernet, etc.) into the proposed 5G-Crosshaul Common Frame (XCF), which is then switched by the XPFEs. The XCF is a packet interface that evolves the Ethernet standard and is considered as the transport frame format used within the 5G-Crosshaul transport network. Therefore, it is designed to support various types of traffic and to be carried over the various types of link technologies present in the forwarding network.

Besides media adaptation, AF-2 maps the radio interface into the protocol used by the XCSE, e.g., optical transport networks (OTN) or the ones proposed in section IV. AF-2 is suitable when packet conversion may risk compliance with the requirements, as it could be the case for CPRI links. The XPFE may be connected to the XCSE, through the AF-3 that maps the XCF into the protocol used by the XCSE. This connection can also be used to offload the XPFE layer, hence avoiding congestion situations that might lead to packet loss.

Figure 1 presents other functional blocks: the XPU (5G-Crosshaul Processing unit), which is the logical unit in charge of hosting baseband processing or other virtual network functions (VNFs). AF-4 is needed in case the interface between the XPFE and the XPU is not based on the XCF. Another adaptation function, AF-5, might be required if pre-existing BBUs need to be communicate with XPUs.

The 5G-Crosshaul data-plane is controlled by the XCI, which will have a detailed view of the fronthaul and backhaul traffic and resources, and it will expose the appropriate abstracted view to the application layer, sitting on top of the XCI, enabling intelligent resource, network functions, and topology management across the transport network.

IV. Transport and Multiplexing Technologies

A RAN encompasses different levels of interconnection between base stations, baseband processing units and remote radio units. To make the transport network as independent as possible on the specific radio implementation, the 5G-Crosshaul network supports any kind of splitting option of the 5G radio protocols between remote and processing sites.

A. Transport technologies to enable 5G-Crosshaul

In the 5G-Crosshaul network, different transport technologies are combined, as a one-fits-for-all approach does not apply to the different deployment scenarios. This subsection gives an overview of technologies suitable for the 5G-Crosshaul unified data plane.

1) Wireless networks

Wireless links are a suitable solution at the edge of the mobile transport network, to increase capillarity, when optical fiber or copper connections are not available or economically viable. However, traditional frequencies below 50GHz are already very crowded and fragmented. The current focus of industry is moving towards higher frequency bands, from 50 to 90 GHz (mmWave), where large contiguous spectrum chunks exist.

Regarding backhaul networks, the 5G-Crosshaul project develops a reconfigurable mesh mmWave point-to-multipoint (PtMP) backhaul network. This enables the deployment and cost advantages of current sub-6GHz PtMP non-line-of-sight (NLoS) systems while offering higher capacity (tens of Mbps/user). In the case of fronthaul, 5G-Crosshaul develops a novel spectrally efficient modulation technique based on [5] to solve the limitations observed in current microwave fronthaul systems in terms of rates and distance.

Finally, optical wireless (OW) technology is also considered, either LED or laser-based, as an attractive alternative technology due to its unlicensed spectrum band, immunity to electromagnetic (EM) interference and performance. The LED backhaul link is able to transmit up to 500 Mbit/s over 100 m [6], while laser based devices provide bit rates up to 10 Gbit/s over a few kilometers. In addition, OW can be used in conjunction with the above wireless technologies, for improving the link availability, or as gap filler in fiber links.

2) Fixed access networks

The reuse of current installed fiber and copper infrastructure are an appealing alternative for fronthaul or backhaul applications with respect to new deployments. Point-to-multipoint passive optical networks (PtMP PONs) are popular architectures for supporting fiber-based broadband access to a set of customers [7]. PONs have several advantages, as they are very simple, easily scalable and do not need excessive maintenance, providing a cost-effective way for the overlay of mobile traffic in the context of 5G-Crosshaul networks. Such a converged architecture is challenging since it has to fulfil the aforementioned requirements for the new fronthaul/backhaul services.

Although Gigabit-capable PON networks offered bandwidth (2.5/1.25 Gbit/s DL/UL) may be sufficient for backhauling residential users, it is clearly insufficient for the transport of fronthaul traffic in C-RAN scenarios according to the CPRI specification [1]. The advent of 10Gbit/s line rate and Time and Wavelength division multiplexing (ITU-T G.989 [14]) opens the door to support current and future fixed and mobile operation on the same optical infrastructure.

Copper infrastructure is also abundant: the interest for 5G-Crosshaul networks is mostly on Ethernet based transmission over copper cables, since they provide high bandwidth (up to 40Gbit/s are being standardized [8]) and allows power savings during periods with low traffic, especially interesting for backhaul purposes.

3) Optical networks

In absence of legacy infrastructure, optical transmission technologies are very suitable due to high achievable capacity and transmission distance. Coarse and dense Wavelength Division Multiplexing (WDM) are examples of optical transport technologies [9][10]. In some particular case, like extending base station coverage inside train tunnels, analog Radio over Fiber (RoF) is an interesting alternative to digital transmission to reduce bandwidth and latency in fronthaul links while increasing their energy efficiency. Analog RoF just requires electrical-to-optical conversion and RF circuits, which may lead to cost saving compared to digital transmission. Recent work [15] shows and experimental C-RAN deployment with 20 km fiber link using analog RoF and PtMP PON in combination with DWDM to achieve high aggregate capacity.

DWDM metro networks support multi-channel transmission over optical fiber with bit rates spanning from 1 to 100 Gbit/s per optical channel, but higher rate transmission interfaces are being introduced: 400 Gbit/s units could be installed within 2018, followed by 1 Tbit/s channels in 2020. Further increases will be possible with the introduction of 1 Tbit/s channels by means of advanced spectral compression techniques, such as Time-Frequency Packing [13], overcoming the Nyquist bandwidth limit that holds for digital transmission systems with orthogonal signaling. In the extreme case of Tbit/s transmission over both C (1530-15665 nm) and L (1565-1625 nm) bands, the aggregate capacity can be as high as 67.2 Tbit/s over a single optical fiber. The high aggregate capacity makes WDM especially suitable to support broadband services and the densely populated scenarios that 5G has to support.

B. Multiplexing strategies

Multiplexing is a method by which multiple data streams are combined into one signal over a shared medium. This allows reducing the costs of deploying and operating a network. 5G-Crosshaul considers three multiplexing strategies for a unified fronthaul and backhaul transport:

1) Physical layer multiplexing

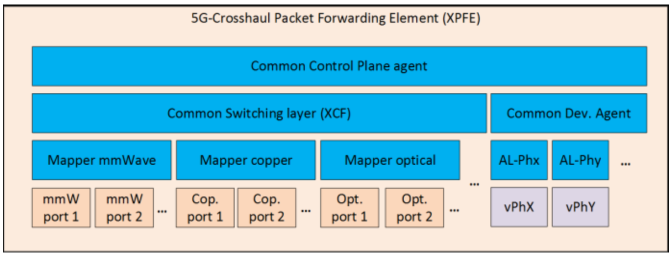

Figure 2: XPFE functional architecture

The most trivial solution for C-RAN is to provide point-to-point fiber links from the RRHs to the BBUs: typically, fiber access cables include from 12 to 144 fibers, making possible to upgrade an existing backhaul network to C-RAN exploiting unused fibers. Coarse and dense wavelength division multiplexing (CWDM/DWDM) are multiplexing strategies for fiber optic networks, where different types of traffic (fronthaul and backhaul) are segregated to different wavelengths.

Passive CWDM provides up to 18 channels with a channel bit rate up to 10Gbit/s and it is the most cost-effective deployment option since it requires neither active components nor synchronization features. Sub-channel CWDM allows increasing channels up to 54 based on technology approaching DWDM. When the number of wavelengths increases, a colorless approach is required to simplify operation. PtP DWDM PON (G.989 [14]) and G.metro propose this approach based on a pilot tone channel to control the wavelength and allowing a transparent fronthaul transmission (no framing). Research and industry are active in studying new cost effective solutions based on integrated photonics, for instance, silicon photonics.

2) Time division multiplexing

A further multiplexing level can be realized mixing fronthaul and backhaul traffic on the same wavelength channel. ITU G.709 (also known as OTN), G.989 and NG-PON2 [14], are optical transport network standards that define a common framing for transporting data payloads widely adopted in WDM and access networks. As of today, the practical use of CPRI over OTN and TWDM appears to be limited to the case of synchronous mapping of CPRI signals belonging to a single synchronization island, which is in contrast with the 5G-Crosshaul concept of fronthaul and backhaul integration.

To overcome this issue, the 5G-Crosshaul project proposes a less time-sensitive circuit multiplexing, where the multiplexed frame is synchronous to the fronthaul client signal in order to avoid degradation of synchronization accuracy from client to line. The clock signal extracted from the fronthaul link is used by the transmitter to perform several tasks: serial to parallel conversion, removal of redundant bits, multiplexing of backhaul and fronthaul, buffering for the compensation of the difference between upstream and downstream delays, and scrambling.

3) Packet-based multiplexing

Packet-based multiplexing especially makes sense in the presence of multiple sources with load-dependent data rate, since this enables statistical multiplexing gain. Such load dependency is inherent for backhaul, but traditional fronthaul (e.g., CPRI) has fixed bit rate independent of traffic load. In order to multiplex backhaul and fronthaul on the same physical link, new link-level features and enhancements are needed to the Ethernet standard to support a more deterministic timing.

The Time-Sensitive Networking (TSN) Task Group in IEEE 802.1 is developing a set of standards addressing transmission of time-sensitive data over Ethernet, with very low latency and high availability. Particularly, the IEEE 802.1CM "Time-Sensitive Networking for Fronthaul" group will define a standard network profile for fronthaul traffic. IEEE 1904.3 addresses instead Radio over Ethernet (RoE) encapsulation enabling the transfer of In-phase and Quadrature (IQ) user-plane data [11], vendor-specific data and control and management information channels across an Ethernet-based packet-switched network. The IEEE 1914.1 group will go one step beyond the 1904.3 standard by addressing new functional splits compared to conventional CPRI [12].

V. 5G-CROSSHAUL MULTI-LAYER SWITCH

5G-Crosshaul forwarding elements (XFEs) are multi-layer switching units envisioned by 5G-Crosshaul project that support single or multiple link technologies (e.g., mmWave, Ethernet, Fiber, microwave, copper, etc.). As mentioned in Section III, the XFE, in its generic implementation, encompasses two macro switching units: the 5G-Crosshaul Packet Forwarding Element (XPFE), which deals with packet forwarding, and the 5G-Crosshaul Circuit Switching Element (XCSE), which deals with circuit switching. The circuit layer may be further split in two sub-layers having different granularity. In optical networks, the sub-layers correspond to wavelengths and time slots in a wavelength, as in current reconfigurable add drop multiplexers (ROADMs) and according to time division multiplexing techniques described in Section IV.B.2), respectively. It is not necessary that all the layers always coexist but one or two of them could be skipped depending on the type of deployed network. For example, a mesh network of packet switches connected by dark fibers (where only the packet layer is exploited); 5G RRHs, based on new radio protocol split and packetized fronthaul interface, connected to a DWDM network (where both wavelength and packet switches are present); the same network where also CPRI tributaries are carried and multiplexed over time-slots in a wavelength, so that a TDM switch needs to be added.

Figure 2 depicts the functional architecture for the XPFE, which includes several internal components such as the common device agent, the common switching layer, and the common control-plane agent, which is in charge of the communication with the 5G-Crosshaul control infrastructure (XCI), as mentioned in Section III. The device agent is common to all peripherals and exposes to the XCI all the device-related information and available operations on the device. For example, the device agent might support several power states, resource slicing, and statistics collection, like CPU usage, RAM occupancy, battery status, GPS position, etc. In order to provide a harmonized view of the device capabilities, an adaptation layer (noted as AL-Phx, AL-Phy, etc.) is introduced between the common device agent and the peripherals (noted as vPhX, vPhY, etc.) as shown in Figure 2. Such layer adapts the peripheral-specific parameters to the common peripheral model used by the common device agent.

A key part of the XFE envisioned solution is a common switching layer for enabling a unified and harmonized traffic management. In particular, the switching engine is technology-agnostic and relies on (*i*) an abstract resource model (i.e., bandwidth, latency, BER, jitter, latency, etc.) of the underlying interfaces (i.e., mmWave, Optical, etc.), and on (*ii*) traffic requirements (i.e., fronthaul/backhaul, jitter tolerance, packet loss, etc.). As a result, the common switching layer enables forwarding in the network between heterogeneous protocols (fronthaul and backhaul), interfaces and physical technologies by leveraging the 5G-Crosshaul Common Frame (XCF) format.

Mappers for each physical interface reside under the common switching layer and are in charge of enforcing the control-plane policies by mapping the commands to protocol and technology-specific interfaces/peripherals. XCF can be mapped on any physical interface as long as the XCF traffic requirements are satisfied. For example, Next Generation Fronthaul Interface (NGFI) digital samples could be carried by XCF and transmitted over a copper interface only if a low-bandwidth-demanding functional split is adopted. If a more demanding functional split is adopted, a different physical interface (e.g., optical, mmWave) is required. This means that multiple physical interfaces can coexist in the unit including different technologies (i.e., fiber optic, mmWave, µWave, copper, etc.).

As mentioned in Section III, the XCF is the transport frame format used within the 5G-Crosshaul transport network, and it is worth highlighting that it does not impose any constraint on the payload protocol carried within. Currently, the 5G-Crosshaul project is still discussing about the XCF definition. Nevertheless MAC-in-MAC or Q-in-Q Ethernet framing are identified as baseline for XCF design due to their scalability and multi-tenancy properties, benefiting of the already extensive work performed in provider networks.

Assuming XCF as Q-in-Q and an XPFE with mmWave and fiber optic interfaces under the control of the same common switching layer, an example of XCF forwarding over multi-technology links follows. The XPFE receives a frame over a mmWave link, which employs IEEE 802.11ad as MAC layer. Next, the XPFE maps the mmWave frame to XCF and passes it to the common switching layer which, based on the information contained in the XCF, decides how and where to forward the packet. Finally, the XCF is mapped onto a fiber optic frame (e.g., IEEE 802.3av) and sent over the optical link.

VI. Conclusion

The 5G-Crosshaul project proposes a unified data plane architecture based on the 5G-Crosshaul Forwarding Element (XFE) and the 5G-Crosshaul Common Frame (XCF). The XFE is a multi-layer switch based on packet (XPFE) and circuit (XCSE) switching elements. While backhaul traffic is usually transmitted over the packet switch network, CPRI and future fronthaul traffic with stringent timing constraints are transmitted over the circuit switch network due the tight bandwidth and latency requirements the interface imposes to the network, which makes this interface quite rigid (static) and costly.

Aligned with new radio functional splits under study, NGFI relaxes the requirements of today's fronthaul in order to reach a more scalable interface so cheaper transport technologies can be used. At this purpose, packet switching enables statistical multiplexing when the peak to average radio access traffic load in 5G is high enough. Unified forwarding is enabled by the 5G-Crosshaul Common Frame (XCF) format that is common across the various types of traffic and the various link technologies in the network. As consequence, the unified data plane enables a common management of the integrated network through the control infrastructure (XCI). Therefore, traffic requirements, and hence services, could be easily enforced onto the network by leveraging the integrated and harmonized view provided by the unified data plane. As a result, the network operational costs can be significantly reduced. 5G-Crosshaul is working towards a more detailed functional definition of the different elements of XFE and its interaction with XCI. Moreover, XCF compatibility with different transport technologies and internal switch architectures are being studied to formally advance in the proposed unified data-plane for 5G transport network with final goal of XFE prototyping.

References

[1] CPRI Specification V6.1, "Common Public Radio Interface (CPRI)", July, 2014, 129 pages

[2] The 5G-Crosshaul project, Available at: http://5g-crosshaul.eu/

[3] Next Generation Mobile Networks (NGMN), "Backhaul and Fronthaul evolution", Version 1.01, 31 March 2015

[4] 5G PPP Key Performance Indicators, Availabl at: https://5g-ppp.eu/kpis/

[5] S. Blanc et al.,"High Capacity Wireless System and Methods", USA Patent PCT/EP2013/059, 236, 2013

[6] D. Schulz et al., "Robust Optical Wireless Link for the Backhaul and Fronthaul of Small Radio Cells" Journal of Lightwave Technology, Vol. 34, No.6 March 15, 2016, 1523-1531

[7] ITU-T Rec. G.984.2, "Gigabit-Capable Passive Optical Networks (G-PON): Physical Media Dependent (PMD) Layer Specification", 2003

[8] IEEE P802.3bq, "Standard for Ethernet Amendment: Physical Layer and Management Parameters for 25 Gb/s and 40 Gb/s Operation", 2015

[9] ITU-T Rec. G.698.1, "Multichannel DWDM applications with single channel optical interfaces"

[10] A. Novak and R. Waterhouse, "Advanced radio over fibre network technologies", Optics Express, vol. 21, no. 19, Sep. 2013,

[11] T. Wan et al., "A Performance Study of CPRI over Ethernet", Jan., 2015, Avialbale at: http://www.ieee1904.org/3/meeting_archive/2015/02/tf3_1502_ashwood_1a.pdf

[12] IEEE 1904, "PAR from NGFI", Dec., 2015, http://www.ieee1904.org/meeting_archive/2015/12/ anwg_1512_minutes_unapproved.pdf

[13] M. Secondini et al., "Optical Time–Frequency Packing: Principles, Design, Implementation, and Experimental Demonstration", Journal of Lightwave Technology, Vol. 33, No. 17, Sep. 2015

[14] ITU-T Rec. G.989.1, "40-Gigabit-capable passive optical networks (NG-PON2): General requirements", 2013

[15] C. YE et al., "A First Demonstration of a PON-based Analog Fronthaul Solution Supporting 120 20MHz LTE-A Signals for Future Het-Net Radio Access," in Asia Communications and Photonics Conference 2015, OSA Technical Digest, paper ASu3E.2.

[16] IEEE 802.1CM, "CPRI requirements for Ethernet Fronthaul", Nov. 2015, http://www.ieee802.org/1/files/public/docs2015/cm-CPRI-requirements-1115-v01.pdf Working Group discussions,

[17] A. de la Oliva et al. "An overview of the CPRI specification and its application to C-RAN based LTE scenarios", IEEE Comms. Magazine (in press), Feb. 2016