Next Generation Fiber-Wireless Fronthaul for 5G mmWave Networks

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The authors try to identify the major challenges that inhibit the design of the Next Generation Fronthaul Interface in two upcoming distinctively highly dense environments: in Urban 5G deployments in metropolitan areas, and in ultra-dense Hotspot scenarios. They propose a novel centralized and converged analog Fiber-Wireless Fronthaul architecture specifically designed to facilitate mmWave access in these scenarios.

Abstract

mmWave radio, although instrumental for achieving the required 5G capacity KPIs, necessitates the need for a very large number of access points, which places an immense strain on the current network infrastructure. In this article, we try to identify the major challenges that inhibit the design of the Next Generation Fronthaul Interface in two upcoming distinctively highly dense environments: in Urban 5G deployments in metropolitan areas, and in ultra-dense Hotspot scenarios. Second, we propose a novel centralized and converged analog Fiber-Wireless Fronthaul architecture, specifically designed to facilitate mmWave access in the above scenarios. The proposed architecture leverages optical transceivers, optical add/drop multiplexers and optical beamforming integrated photonics towards a Digital Signal Processing analog fronthaul. The functional administration of the fronthaul infrastructure is achieved by means of a packetized Medium Transparent Dynamic Bandwidth Allocation protocol. Preliminary results show that the protocol can facilitate Gb/s-enabled data transport while abiding to the 5G low-latency KPIs in various network traffic conditions.

Introduction

The prediction for mobile data traffic growth from 14 ExaBytes/month in 2017 to 110 ExaBytes/month by 2023, already finds network operators struggling to keep up with the demand caused by the smart-device explosion [1]. Broadband access in mobile networks is respectively targeting Downlink (DL) and Uplink (UL) rates at 300 Mb/s and 50 Mb/s per user, respectively, while in hotspots such as stadiums, and so on, the DL and UL goals are set at 25 Mb/s and 50 Mb/s, respectively [1]. Translating these numbers into requirements can explain the reason why the current mobile networks are no longer viable: assuming up to 2500 connected devices per km^2 in urban areas, the DL area capacity approaches 1 Tb/s/km^2, while a stadium with 30,000 connections raises the UL bandwidth to 7.5 Tb/s/km^2. To this end, 5G networks are promoting the enhancement of several established technologies, such as massive MIMO (mMIMO) and beamforming, that have already been included in the LTE Release 12 and onward, as well as further small cell (SC) deployment, that is already underway by major providers worldwide. However, the most recent solution path proposed for achieving the 5G KPIs is the introduction of higher spectrum, such as mmWave, at the access part of the network. Indeed, Rel. 15 of the New Radio (NR) standard includes radio frequencies up to 52.6 GHz. However, introducing mmWave radio into the access part of the network imposes the placement of the access points (APs) in very close proximity to the end-user due to the high propagation and penetration losses exhibited by the former. This is expected to severely impact costs, due to the need for AP densification by several orders of magnitude, and consequently translates into three major problems:

- 5G Radio Access Network (RAN) deployments cannot rely exclusively on fiber connections reaching all mmWave APs, since this would require extensive and expensive fiber deployment.
- Hauling numerous multi-Gb/s data links from multiple antenna sites back to the operator's central office (CO) becomes challenging since currently deployed digital state-of-the-art Passive Optical Network (PON) architectures reach up to 10 Gb/s, whereas currently deployed mmWave backhaul links are strictly point-to-point (PtP) and therefore impractical for ultra-dense AP deployment.
- The involved antennas must become functionally simple and energy efficient to maintain feasible investment and operational costs.

RAN centralization is currently the most widely proposed solution for decreasing the cost of densification [2] and offers many advantages, such as reduced power and cost, capacity improvement, adaptability to non-uniform traffic, network extensibility, and so on. The prevalent centralized RAN architecture is the Cloud-RAN (C-RAN) that decouples the baseband unit (BBU) and the remote radio heads (RRHs), placing the intelligent BBU in a common centralized location and dispersing the operationally simple RRHs across the access sites. C-RAN predominately employs fiber for the BBU–RRH connection, but PtP wireless links have also been considered for ultra-dense deployments [3]. On the protocol side, communication between the BBU and RRH components is almost exclusively using the digitized Common Public Radio Interface (CPRI), which until now remains the base for commercial Fronthaul (FH) solutions by all major vendors. However, CPRI

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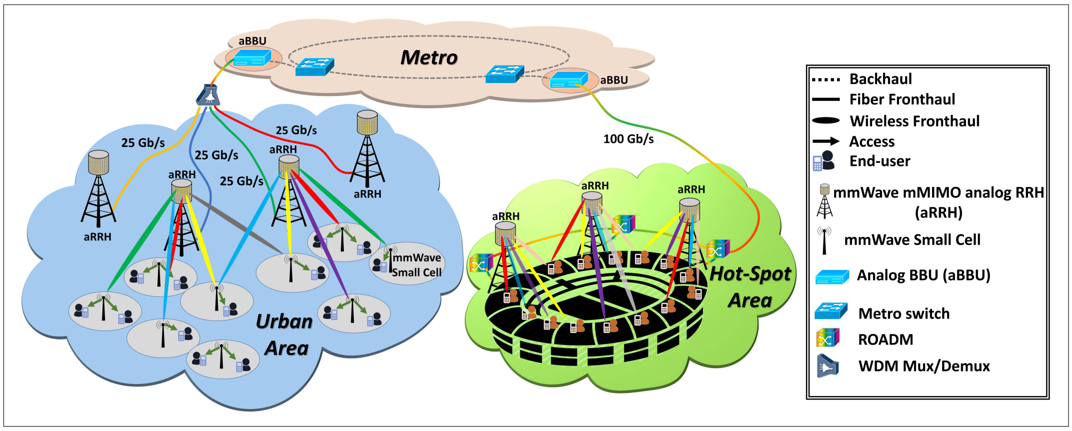

Figure 1. Schematic representation of the proposed Fronthaul architecture for (left) the Urban-area and (right) Hotspot scenarios.

The introduction of mmWave radio in large metropolitan areas poses the challenge of interconnecting the vast amount of dispersed mmWave APs in a high-speed, high-bandwidth and cost-effective way. Our solution for the UDN scenarios follows the centralized paradigm, where the analog-BBU (aBBU) is fiber-connected to a series of mMIMO analog-RRHs (aRRHs) scattered around the user service area.

is totally inefficient in supporting high-bandwidth mmWave channels [4], and this is proven by the fact that to this day no commercial mmWave 5G NR fronthaul solutions have entered the market. The digital nature of CPRI also creates added cost overheads since the RRHs carry added digitization equipment such as digital-to-analog-converters/analog-to-digital-converters (DACs/ADCs) which increase their cost. Also, the network segmentation created by the digital-to-analog interface division requires that the BBU–RRH transmission line is always on, even when no transmission to/from mobile entities (MEs) takes place, since there is no global view of both the optical and wireless resources by any involved entity. Based on the above, it is evident that the current CPRI-based FH cannot address the requirements for the introduction of mmWave access and the consequent AP densification, on two of the most critical Next Generation Fronthaul Interface (NGFI) scenarios [1]: the urban-area scenario where, thousands of users traverse the several km^2 city-landscape, and the hotspot scenario, where a highly concentrated population is located within very confined areas, such as stadiums. To address the above problem, recent research efforts have proposed the packetized Mobile FH [5] solution as a bandwidth-efficient alternative to CPRI, but their effectiveness comes at the cost of increased RRH hardware, mainly for two reasons. First, higher-layer splits are employed to relax CPRI's capacity and latency requirements adding more hardware to the RRHs, such as iFFT and modulation/mapping hardware. Second, Ethernet interfaces at the RRH become mandatory in order to be compliant with eCPRI's switched fronthaul specifications. The above increase the hardware and energy consumption properties of the RRHs, making them costlier and less suitable for urban-area deployment [6].

In this respect, analog-Radio-over-Fiber (a-RoF) has been deemed more promising as it employs all major hardware within the centralized BBU which feeds low-cost RRHs over long distances [6]. Although, a-RoF reduces RRH complexity and alleviates the need for large optical bandwidth, it may suffer more from transmission impairments to which digital-RoF is more resistant [6]. However, these impairments have been extensively studied and efficient solutions have been proposed [7]. Based on the above, it becomes evident that a-RoF properties will gradually become increasingly attractive as the industry begins to deploy mmWave access services.

Incentivized by the above issues, this article proposes an analog optical/wireless packetized FH solution that can optimally address the above challenges while meeting the 5G requirements. Our solution employs the physical layer split (split-PHY), while employing Digital Signal Processing (DSP) assisted a-RoF transmission that allows for high-order advanced modulation formats supporting ultra-high bandwidth data transfer. Resource allocation is supported by a Medium Transparent Dynamic Bandwidth Allocation (MT-DBA) scheme that offers holistic cross-medium administration of the optical/wireless/time resources, while employing a polling-based scheme for synchronization and ultra-fast contention resolution.

The rest of this article is organized as follows. The following section presents our proposed a-RoF 5G FH architecture. Then we present the underlying optical technologies. Following that we describe the MT-DBA scheme, and finally we conclude the article.

Next-Generation Analog RoF 5G Fronthaul Interface

The introduction of mmWave radio in large metropolitan areas poses the challenge of interconnecting the vast amount of dispersed mmWave APs in a high-speed, high-bandwidth and cost-effective way. Our solution for the urban area scenarios, depicted in the left part of Fig. 1, follows the centralized paradigm, where the analog-BBU (aBBU) is fiber-connected to a series of mMIMO analog-RRHs (aRRHs) scattered around the user service area. The C-RAN architecture dictates that the aBBU will be placed at the operator's CO, whereas the aRRHs will be placed at the premises of the current 4G cells that are predominantly fiber-connected, with the average fiber length being around 5km and reaching up to 20km. The aRRHs exploit the mMIMO configuration to create point-to-multipoint (PtMP) mmWave links to numerous SCs that provide the access to the MEs. The SCs can use any desired access radio technology. However, this work focuses on the implications of mmWave introduction in the access part of the network, and so we strictly

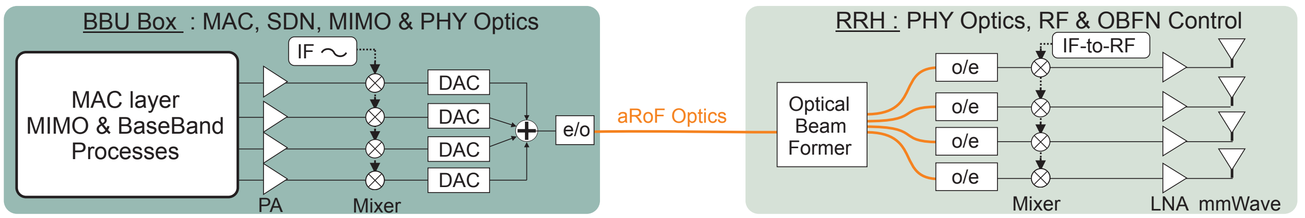

Figure 2. The proposed split-PHY fronthaul architecture solution.

consider mmWave access SCs (either 5G NR or IEEE 802.11ad/ay). The SCs contain two network interfaces: a mmWave access interface for connectivity with the MEs, and a static mmWave link back to the aRRH. These communicate through an Ethernet interface, which enables the interoperability with an extensive list of vendor equipment and future Ethernet-based packetized FH solutions. The static PtMP aRRH-SC link employs a high-order modulation and coding scheme, such as high-order QAM modulation over OFDM waveforms, which greatly enhances link capacity and spectral efficiency. This can be achieved due to high Signal-to-Noise Ratio conditions produced by the mmWave mMIMO high-gain antennas and the line-of-sight communication between the immobile end-points. In the fiber domain we also consider a dedicated wavelength pair for DL/UL communication from the aBBU to the aRRH, therefore dynamic resource allocation is only necessary in the wireless domain, that is, in the UL direction of the PtMP aRRH-SC link, and is performed by means of the MT-DBA protocol. However, depending on the desired service levels and the cost budget, the operators could opt for employing a smaller number of wavelengths as compared to the number of aRRHs.

Our proposal divides the urban-area mmWave access RAN into two tiers: the access tier, where a massive number of very small-range, street-level, mmWave SCs provides access to the MEs; and the aggregation tier, where the multi-Gb/s data streams are hauled back to the CO through the fiber-connected aRRHs. This separation greatly relaxes the latency requirements, since the MEs access is resolved within the small-range of the SC and no delay-sensitive ME signaling has to traverse back to the CO. The employment of high-speed mmWave links to haul aggregate multi-Gb/s datastreams through strategically-placed fiber-connected aRRHs, instead of fiber-interconnecting every SC, also greatly reduces new fiber installation. Finally, our architecture carries the centralization benefits in the aBBU-to-aRRH portion of the network, meaning that:

- The aRRH modules become functionally simpler, cheaper and more energy-efficient since air-conditioning and onsite power-consuming equipment is greatly reduced compared to 4G cells. This creates huge savings considering the number of 4G cells in metropolitan environments (average inter-cell distance up to 500m).
- The analog C-RAN has great adaptability to non-uniform traffic. Whereas digital CPRI-based RRHs are constantly transmitting, irrespective of whether there is incoming traffic, analog C-RANs employ resources only when there is actual data transmission and can adapt to traffic fluctuations according to the area attributes (business-districts/residential areas).
- Statistical capacity is improved since several virtual base stations are aggregated in a large physical aBBU pool where they can easily share hardware.
- Centralized architectures are easier to upgrade and expand from the aggregated point.

The hotspot requirements differ from the urban-area considerably. While the latter considers large metropolitan areas containing thousands of scattered MEs requesting services constantly, the hotspot use-case defines confined and usually privately-owned premises, such as football-stadiums or concert-halls, containing several thousand users, for the duration of specific events. To this end, our hotspot-tailored proposed solution provides a framework to meet the extremely challenging capacity conditions while maintaining cost-efficiency properties so as to limit capital and operational expenditures. As displayed in the right side of Fig. 1, in the hotspot architecture the RRHs provide mmWave access directly to the MEs. The hotspot FH consists of a short fiber bus that links the aBBU to a series of aRRHs that surround the hotspot area, since having a dedicated fiber link between the BBU and all the RRHs, as it has been defined in the early versions of C-RAN specifications, would lead to increased fiber and transceiver costs that inhibit its cost-efficiency for sporadic use in private premises. To support the single bus and lower transceiver costs, the proposed solution supports a dynamic wavelength selectivity scheme, by taking advantage of cost-efficient PICs that incorporate all WDM circuitry onto the same chip avoiding the use of discrete modules. Moreover, by exploiting PIC-based Reconfigurable Add/Drop Multiplexers (ROADMs) and the MT-DBA protocol that dynamically allocates optical/wireless/time resources based on the location and current demands of the MEs, it is possible to share a lower number of available wavelengths among the aRRH modules and dynamically reallocate them as traffic migrates to/from residential and commercial areas, translating into both capital and operational cost savings. The short hotspot case fiber length between the aBBU and aRRHs enables the access control to be performed directly between the aBBU and the MEs.

Figure 2 displays our a-RoF Split-PHY architecture, which consolidates the majority of the equipment on the aBBU, while installing only the minimum components to the aRRH. The aBBU hosts the main processing operations, such as DSP and MAC functionalities, alongside the ADCs and

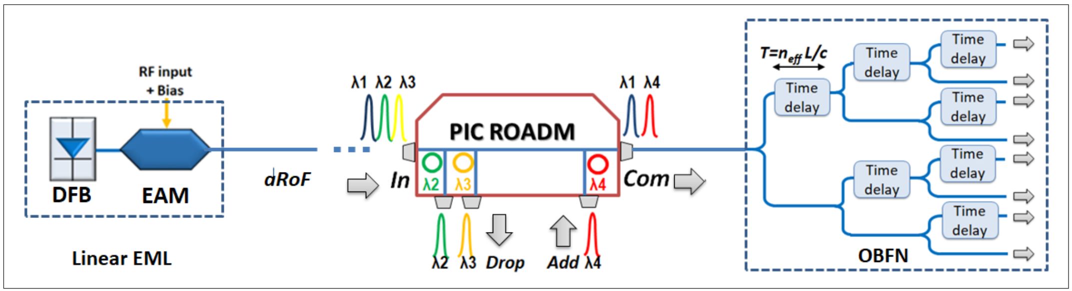

Figure 3. End-to-end communication of the analog Fiber-Wireless link using an EML, an Optical Beamformer and a Silicon Photonic ROADM.

Beamformers comprise specialized circuitry that provides the delays required by the antenna elements in order to transmit/receive wireless signals to/from the desired direction by means of constructive and destructive waveform interference, a function known as beamsteering, and exist in three main types: digital, analog and hybrid beamformers.

transceiver optics, while the aRRH device includes only the necessary PHY optics, as well as the required RF electronics for transmitting/receiving the wireless signals. By exploiting the progress on direct detection communications, our proposal can load native radio signals on an intermediate frequency (IF) subcarrier. This scheme has been introduced in [8], including a DSP-assisted a-RoF fronthaul with RF beamforming chain at the RRH and promoting the use of a low IF frequency to relax the fiber dispersion-induced impairments, commonly encountered in a-RoF transmissions [7], while also allowing for cost-effective direct-detection schemes with low-bandwidth optics at the aRRH, avoiding the need for costly high-bandwidth and coherent optics. Transforming the IF into the final wireless mmWave carrier signal can easily be performed at the aRRH by employing respective IF-to-RF and RF-to-IF up-conversion and down-conversion circuitry. Also, by drawing from the recent development of high-capacity External Modulated Laser (EML)-based Fiber-Wireless (FiWi) mmWave/IF a-RoF links [9, 10] and integrated Optical Beamforming Networks (OBFNs) [11], our proposed solution employs OBFNs to maintain the phase of mmWave beams through IF-subcarrier modulation, to replace some costly RF-processing with efficient photonic alternatives, and alleviating the need for complex DSP at the RRH. The OBFNs are followed by an opto-electronic conversion to an electrical IF signal and up-conversion to mmWave RF purely for wireless transmission, simplifying greatly the cell site equipment and simultaneously reducing its power consumption since ADC/DACs are no longer required [7]. Instead, this architecture requires centralized DSP processing, capable of sampling, temporarily storing and digitizing the aggregate incoming a-RoF traffic with sampling frequencies of a few tens of GS/s [7–9].

Overview of Emerging Optical Technologies to Be Leveraged in Analog-RoF Fronthaul

The basic PHY components of the envisioned a-RoF FH may include:

- A linear modulator for the electro-optic conversion of the mmWave wireless signals on an optical IF-carrier.
- A low-loss optical beamformer to facilitate scalable mmWave mMIMO systems.
- ROADMs for wavelength selectivity and dynamic reconfiguration in the FH network, which are schematically shown in Fig. 3 and summarized in Table 1.

High-linear External Modulated Lasers (EMLs)

Considering the large available spectrum of NR systems, a-RoF techniques allow spectrally efficient fronthauling of a mmWave channel, by loading it on a low optical IF with simple intensity modulation/direct detection schemes without occupying excess spectrum [7], while multiple IFs can be synthesized on a single aggregate electrical signal of a few GHz bandwidth. However, the linearity of the a-RoF link will play a pivotal role in the overall system performance and thus a-RoF transmitters have mainly relied on costly Mach-Zehnder Modulators (MZMs), owing to their high linearity and chirp-free operation to alleviate the impact of the fiber chromatic dispersion [9]. Toward circumventing the associated costs when considering network densification deploying conventional chirp-free modulators with external laser source, EMLs exploiting a distributed feedback laser and an electro-absorption modulator (EAM) as shown in Fig. 3 form a more cost-effective solution [9] but have been primarily used in digital communications and advanced modulation format transmissions with DSP techniques recovering the non-perfect linearity. However, joint optimizations of the Fiber-Wireless links have been scarce and constrained to the use of MZMs, few-channels or low bandwidths, and only very recently EMLs were shown to support multiple IF channels with user-rates >1Gb/s and aggregate capacities beyond 10Gb/s [10], satisfying the respective KPIs for multi-user 5G network environments. In order to achieve this, EMLs need to operate in the linear region of their transfer function, with a steep curve between two voltage values [10], for low signal distortion recoverable by a simple DSP technique allowing to directly transfer the aggregate electrical analog IF signals to an a-RoF optical carrier with low signal distortion.

Optical Beamformers

Beamformers comprise specialized circuitry that provides the delays required by the antenna elements in order to transmit/receive wireless signals to/from the desired direction by means of constructive and destructive waveform interference, a function known as beamsteering, and exist in three main types: digital, analog and hybrid beamformers [12]. Digital beamformers utilize digital baseband processing with both amplitude and phase modulating RF chain dedicated per antenna element, providing enhanced flexibility and performance at a high-power consumption and cost. Analog beamformers employ simple architectures with multiple analog phase shifters (PSs) shared between different antenna elements, Beamformers comprise specialized circuitry that provides the delays required by the antenna elements in order to transmit/receive wireless signals to/from the desired direction by means of constructive and destructive waveform interference, a function known as beamsteering, and exist in three main types: digital, analog and hybrid beamformers.

	Novelty	Specifications	Advantages	Disadvantages
EML	Introduced in analog communication to transmit native wireless signals adopting DSP techniques known in digital communications.	Bitrates up to 25Gb/s, e.g. 6 IFs of QAM16, energy consumption <150 mW.	Cost effective (low bandwidth), spectrally efficient.	Dual sideband modulation, prone to chirp and dispersion, not perfectly linear.
OBFN	Optical steering/shaping.	Low loss SiN OBFNs less than <0.1dB/cm, true time delay >1ns or 30cm propagation.	Broad bandwidth, spurious free, low-optical losses, cost effective.	Thermo-optic, low steer speed, polarization sensitive, lower flexibility than digital beamforming.
ROADM	Reconfigurable fronthaul network, migrating from fixed point-to-point RRH-BBU links to switched networks.	1×4 SiPho-ROADMs with low insertion losses <1dB, channel spacing 100GHz, energy consumption <0.2W/ring.	Not availlable in mobile FH networks, cost-effective reallocation of resources.	Polarization dependent, losses increase with the number of wavelengths, temperature control.

Table 1. Key features of optical technologies introduced.

toward less expensive hardware but with lower system performance and antenna gains. Hybrid beamformers are an intermediate solution with multiple analog sub-arrays of PSs shared among groups of antenna elements offering a good compromise between system performance, cost and complexity. However, the bandwidth, delay, cost and energy requirements of electronic-only beamformers arise by the use of mmWave and mMIMO technologies.

On the contrary, optical beamformers so far rely on integrated photonic networks of phase shifting or true time delay (TTD) elements only [11]. The most typical configuration of an OBFN relies on tree-based networks of 1x2 splitters with interleaved optical ring resonator (ORR)-based TTD elements, as depicted in Fig. 3. The group delay response of the ORR is exploited by thermo-optically tuning its resonance frequency, while tuning the coupling coefficient between the bus and the ring waveguide changes the TTD. Implementing analog beamforming exclusively in the optical domain allows seamlessly interfacing with the envisioned optical fronthaul network, replacing digital beamformers with both amplitude and phase tunability, to release broad instantaneous bandwidth of tens of GHz, large tunable delays of hundreds of ps, cost-reduction and low energy consumption. However, toward making OBFNs a viable solution for 5G networks, they still have to overcome some inherent drawbacks of their optical nature, such as the polarization sensitivity and slow thermo-optic response.

Optical Add/Drop Multiplexers

Optical add/drop multiplexers (OADMs) have been widely deployed in Wavelength Division Multiplexing (WDM) optical networks for their wavelength multiplexing and selective routing capabilities. OADMs can serve two operations either to "Add," that is, insert a new optical wavelength-channel to an existing WDM light-stream, or "Drop," that is, remove one wavelength channel and re-route it toward a different spatial output. The two functionalities are schematically shown in Fig. 3, where a three-channel WDM-stream of λ1-3 is fed from the input (In) port at the left side. Two wavelengths-channels of λ2 and 3 are "Dropped" toward the Output ports at the bottom side, allowing for λ1 wavelength to continue its propagation through the Common (Com) port to the rest of the network. Respectively, one new wavelength, the λ4, is "Added" to the WDM stream of the Com port. In order to achieve this, OADMs consist of an optical demultiplexer at the input, an optical multiplexer at the output, and an intermediate wavelength-selective device that configures each lightpath connectivity. When the latter relies on static wavelength filtering devices, for example, Fiber Brag Gratings, free-space grating optics, planar lightwave circuits, OADMs are considered fixed with pre-defined lightpaths and when it relies on tunable devices traditionally based on micro-electro-mechanical systems (MEMS), liquid crystals on silicon (LCoS) or thermo-optic PLCs, OADMs are considered reconfigurable. Lately, integrated Silicon Photonics (SiPho) ROADMs [13], based on cascaded micro-meter thermo-optic or electro-optic Add/Drop rings, have attracted intense interest, as they support small footprint, low power consumption, fast reconfiguration times with CMOS-compatibility for reduced fabrication costs and recently also polarization insensitive operation. A possible architecture of a SiPho ROADM that implements the previously described Fixed OADM operation is shown in Fig. 3. Introducing ROADMs in FH networks allows migrating from the currently fixed PtP links between the RRH and the BBU toward a point-to-multipoint switched infrastructure with reduced hardware and increased gains stemming from statistical multiplexing of user traffic.

Packet-Based MAC Layer Resource Allocation for Converged 5G Networks

Fiber-Wireless convergence forces the redesign of MAC mechanisms in favor of schemes that are capable of maintaining a global view of the end-to-end optical/wireless/time resources. Our proposal, called MT-DBA, is based on the concept of medium transparency, such as the one proposed in the Medium-Transparent MAC (MT-MAC) [14], and allows for packetized transmission and direct negotiation of wavelength/frequency/time resources between the aBBU and the SCs or MEs without operational intervention of the aRRH.

The left part of Fig. 4 depicts the MT-DBA operation for the urban area, where it facilitates the UL and DL between SCs to the aBBU by creating data transmission opportunities, while employing polling mechanisms to maintain syn-

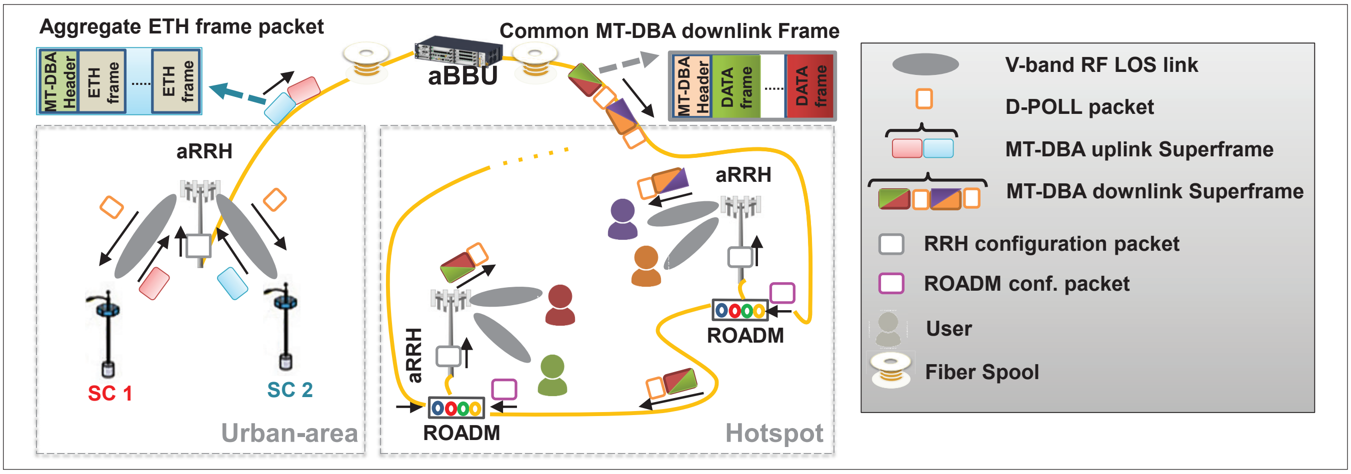

Figure 4. MT-DBA framework operation example for the integrated FiWi FH in the Urban-area and Hotspot scenarios.

chronization. The SCs communicate through a static link to a specific aRRH, therefore alleviating the need for beamforming/sector training periods. All DL/UL data frames (DFs) to/from different SCs are encapsulated within the MT-DBA frames, forming the superframe. The DF format is payload agnostic and supports native encapsulation of Ethernet packets. Initially, the aBBU that maintains a knowledge of all SCs and their coordinates, transmits a Schedule POLL (S-POLL) packet to each SC sequentially requesting their buffer status and desired Quality-of-Service (QoS) levels through transmission of REPORT messages. Upon the replies reception, the aBBU defines a transmission schedule and executes it in two-steps. It first transmits an aRRH Control packet (RRH-C) that instructs the OBFN controller of the upcoming DL/UL packet transmission schedule. Second, the aBBU transmits Data POLL (D-POLL) packets sequentially to each SC, which instruct the latter to transmit/receive a specific number of data packets, following the gated service paradigm. If a SC performs a UL transmission, it piggybacks its REPORT message after the last DF so as to speed up the formation of the transmission schedule. The transmission schedule follows the starvation-free gated round-robin paradigm. In case the number of available wavelengths is lower than the number of aRRHs, then the S-POLL transmissions employ a control wavelength, received by all aRRHs, and the RRH-C packet contains a micro-code instructing the aRRHs to tune their Photodiodes (PDs) and EMLs to a specific wavelength pair for the UL/DL data transmission.

In the hotspot case, depicted in the right part of Fig. 4, the MT-DBA communicates directly to the MEs. Toward increasing cost-effectiveness, wavelength selectivity is performed to support the large number of aRRHs using the minimum number of transceivers. Wavelength selectivity is accomplished by transmitting a ROADM configuration packet (ROADM-C) informing its electronic controller on the wavelength(s) to drop on this aRRH over a certain time-span. Afterward, the MT-DBA will transmit S-POLL packets to each antenna sector to perform a full sector sweep. MEs that pick up the S-POLL transmission, reply with a REPORT message after a random back-off period. Upon correct reception of the REPORT replies, the aBBU transmits the RRH-C and assigns a permanent ID to each ME. In case two or more terminals choose the same back-off timer, their transmissions will collide and the aBBU will retransmit S-POLL packets at that sector. After all MEs are correctly identified, the MT-DBA polls each ME sequentially using the gated round-robin discipline.

Figure 5 displays the packet delay versus load conditions for the urban-area MT-DBA protocol at the bottom-horizontal axis and for various wavelength-to-RRH ratios (WRs) on a network consisting of 40 aRRHs fiber-connected to the aBBU. Results were derived using a custom Java simulator, which is an extension to the one employed in [14]. By means of the 100 percent WR curve we notice that delay initializes in the sub-ms range and remains very low while the normalized load is under 0.8. When the load approaches channel capacity, delay values increase rapidly as packets remain longer in the buffer queue. The same applies in delay performance for all decreasing WRs, with the difference that lower WRs result in lower saturation points. For instance, the saturation point of 80 percent WR is reached at 0.6 load, whereas for 50 percent WR is reached at 0.4 load, revealing the impact of a decreasing number of wavelengths. As fiber length is a major and critical parameter in the urban-area scenario for large metropolitan areas, Fig. 5 displays the packet delay versus various BBU-RRH fiber lengths, ranging from 200m up to 10km at the top-horizontal axis, considering 100 percent WR for normalized load ranging from 0.1 up to 0.95. As can be noted, for low or medium load (up to 0.5), delay is very low and always sub-ms for all tested fiber lengths. At higher loads, the MT-DBA achieves sub-ms latency for gradually lower fiber lengths, since the added propagation delays accumulate and lead to larger SFs. For instance, sub-ms delay performance is achieved up to 8km for 0.6 load, but only up to 5km at 0.7 load. Therefore, by considering the desired service level and average load of the network, one can estimate the highest supported fiber length. For example, for enhanced Mobile Broadband (eMBB) services requiring lower than 4 ms delay and with an estimated average load of 70 percent, up to approximately 5km distance between the aBBU and the aRRHs can be supported. For Ultra Reliable Low Latency Communication (URLLC) services requiring lower than 1 ms delay and an estimated

Our proposal relies on cost-effective a-RoF-capable devices, including EMLs, OBFNs and ROADMs. The converged optical/wireless resource allocation is achieved by means of the MT-DBA protocol. Initial numerical results showed that the medium transparent protocol is efficient and can thus be incorporated into the era of 5G mmWave networks.

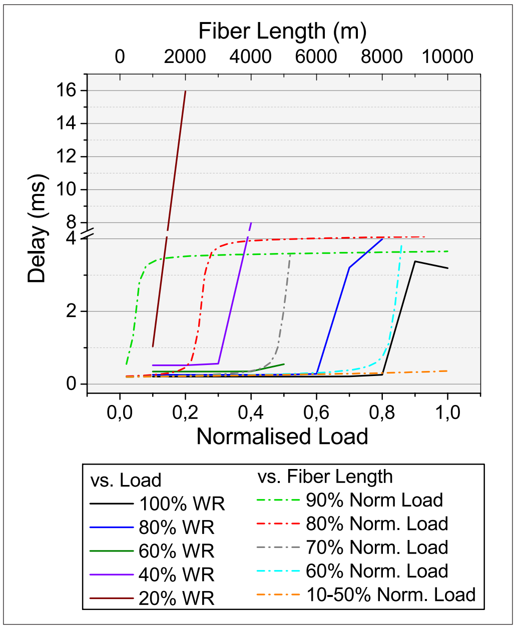

Figure 5. Delay vs. Normalized load and vs. length of the optical network.

average load of 80 percent, up to approximately 2km distance between the aBBU and the aRRHs can be supported. As plotted in Fig. 5, these specific delay values of 4ms and 1ms for eMBB and URLLC, respectively, can be achieved with WRs of 33 percent and 50 percent, meeting the respective 5G KPI requirements. Moreover, this highlights the pivotal role of wavelength availability, where a sufficiently high number of optical resources can ensure sub-ms delay, as also indicated by a similar preliminary evaluation of realistic hotspot scenarios [15].

Conclusions

This article has presented a novel FiWi C-RAN, capable of optimally meeting the needs of mmWave urban-area and hotspot scenarios. The proposed a-RoF C-RAN enables the wireless connection of the aBBU to a large number of mmWave SCs and MEs, through fiber-hauled RRH modules. Our proposal relies on cost-effective a-RoF-capable devices, including EMLs, OBFNs and ROADMs. The converged optical/wireless resource allocation is achieved by means of the MT-DBA protocol. Initial numerical results showed that the medium transparent protocol is efficient and can thus be incorporated into the era of 5G mmWave networks.

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