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Architectures for Fronthaul Infrastructure in Fifth-Generation Mobile Networks

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Abstract—The next wave of innovation will certainly generate numerous new opportunities for emerging technology solutions based on networking services and applications with stringent key performance indicators (KPIs) such as ultra-low 1 ms latency, a 1000 fold bandwidth increase, 99.99 % reliability and availability, which are immensely above those supported by current mobile networks. A new architecture of mobile networking called cloud radio access network (C-RAN) has been introduced over the last few years not only to supporting these indicators, but also to increasing scalability, manageability, and flexibility of mobile systems. In this context, this paper addresses the principal technology enablers and their features for C-RAN fronthaul architectures of the 5th generation (5G) mobile networks, namely space-division multiplexing (SDM), massive multiple-input multiple-output (MIMO) signaling, analog radio-over-fiver (A-RoF), and millimeter wave (mmWave) frequency technology. These technologies pave the way towards a truly viable and efficient fronthaul infrastructure for 5G mobile communications with connectivity for thousands of users and strict latency control. In this fashion, we perceive a network infrastructure scenario with seamless starting and ending interfaces by exploiting space diversity in both radio frequency and optical domains with efficient integrated photonics technology - all combined with adaptive softwaredefined network programming, so as to satisfy the 5G KPIs. Furthermore, we address the most relevant features of these technologies as a potential guideline for potential fronthaul infrastructure deployment of next generation mobile networks.

I. INTRODUCTION

The infrastructure of 5G networks will potentially adopt disruptive technologies to enable networking services and applications never commercially offered before in the era of mobile communications [1]. Furthermore, the next wave of innovation will certainly generate numerous new opportunities for solutions based on emerging services and applications such as tactile Internet, augmented and virtual reality, and efficient autonomous driving [2]-[5]. By its turn, these applications require quality-of-service guarantees (e.g., 1 ms latency) that can only be supported through a novel concept of fronthaul architecture and its corresponding infrastructure technologies for 5G mobile networks.

The new 5G fronthaul infrastructure requires not only further manageability and flexibility, but also aims to support, at an operational level, mainly a 1000 fold increase in current network capacity as well as user data rates 10 to 100 times higher than the current standards, and latency levels down to 1 ms - all under similar cost- and energy-expenses as those of today's networks [5]. In addition, the 5G key-performance indicators (KPIs) further recommend that user data rates should reach 1 Gb/s for a few devices and 25 Mb/s for up to 30.000 users, highly concentrated in hot-spot areas like for example football stadiums. These high-rates and -density system requirements certainly are on a scale well beyond those currently supported by long-term evolution (LTE) systems. Amongst several different technologies developed to potentially support these KPIs, the following stand out in 5G mobile networks: optical space-division multiplexing (SDM) [6], multiple-input multiple-output (MIMO) signaling [7], [8], analog radio-over-fiber (A-RoF) [9], [10], and optical beamforming [11], [12]. These technologies, when combined together, become part of a new concept of mobile networking architecture, the so-called 5G cloud radio access network (CRAN) fronthaul [13]-[18].

The C-RAN fronthaul architecture accounts for moving some parts of the radio access network (RAN) control and signal processing functions from the cell site, to centralized locations within the network like the central office (CO) [14], [15]. This new C-RAN fronthaul architecture provides several benefits by not only offering better control of operational costs, but also by increasing the manageability and flexibility of the network. Moreover, it can support larger network capacity over smaller-cells such as densely deployed shortrange base stations [19] using directional massive MIMO along with the immense available spectrum in the millimeter wave (mmWave) frequency bands around 27 GHz and above [8], [20]. Massive MIMO and beamforming systems can focus the transmission and reception of a signal energy into eversmaller regions of space, which brings improvements in throughput and energy efficiency [7], [8].

Regardless of the target throughput, new multiplexing techniques like, for example, SDM [6], are being considered in the optical distribution network

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(ODN) as an alternative solution to current technologies in the fronthaul architecture [6], [21], [22] to support increased data rates and number of required channels. One of the first SDM schemes in the fronthaul portion of a RAN architecture employed singlemode fibers (SMFs), which renders several mechanical limitations. On the other hand, SDM can be an elegant and efficient solution when implemented by using multicore fibers (MCFs) [21]. The combination of SDM and MCF provides several spatial channels for separate delivery of multiple signals, as well as control signals and continuous wave (CW) carriers for upstream transmissions from the remote radio head (RRH). Indeed, SDM can provide even more spatial channel diversity and parallelism via wavelength-division multiplexing (WDM) techniques and potentially achieve further system capacity enhancement when combined with advanced modulation formats [23] and spectral slicing techniques [24], as it adds an additional independent and fully compatible dimension.

Furthermore, SDM techniques can establish parallel independent connections between the CO and the RRHs in 5G networks, which enables direct implementation of both reconfigurable MIMO transmissions [25], [26] and remote beamforming techniques [27]. SDM also allows both digital radio-over-fibre (D-RoF) and analog radio-over-fiber (ARoF) signal transmissions [28], [29] to coexist in the same network. Finally, an SDM-based RAN system can be seamlessly combined with passive optical networks (PONs) [30], [31] and consequently offer a unique solution for a selfcontained fiber infrastructure that can be reconfigured by software-defined networking (SDN), network function virtualization (NFV) [32], adaptive beamforming techniques, and massive MIMO [35]. This future proof fronthaul infrastructure will push the radio frequency (RF) spectrum towards the mmWave range, which results in the latter already playing a key role in 5G network trial setups, especially for vertical industries that require the 5G KPIs to be fulfilled [36].

The first 5G roll outs are foreseen already for the coming years with the EURO 2020 football championship event considered by the European Union as a potential 5G “launch event” in stadiums and fan zones [37], with augmented and virtual reality services providing fully immersive experiences to entertain a large number of users before, during and after the game, and also around the stadium.

In this context, this paper addresses the main technologies that are being used in the imminent fronthaul infrastructure deployment of 5G mobiles networks. These technologies, massive MIMO, SDM, A-RoF, mmWave, and optical beamforming, are perceived here as key enablers to deliver the challenging 5G KPIs. The combination of these technologies represents a step towards a truly efficient fronthaul infrastructure for 5G networks with seamless interoperability that can enable thousands of users (in a hot-spot scenario), improved coverage and enhanced mobile broadband capabilities for high-bandwidth low latency applications, including, e.g., real time content generation and fully personalized immersive experiences. In addition, we introduce an overview of the 5G KPIs that are expected to be supported by the fronthaul infrastructure of mobile networks at a global scale to ensure interoperability among systems. These demanding 5G KPIs are essential for supporting emerging networking applications with potentially reduced energy consumption. Finally, the evolution of the fronthaul architecture towards the C-RAN concept is investigated, followed by discussions about the principal features of key technologies that are being deployed in fronthaul infrastructures of next generation mobile networks.

II. 5G KEY PERFORMANCE INDICATORS

Next generation 5G networks aim at overcoming the current technology’s limitations in terms of performance indicators like, for example, extremely low-latency, low power consumption, high capacity, as well as network robustness and flexibility. 5G network concepts are pushing for the adoption of new infrastructures and technologies during the coming years to support these requirements at a larger scale. These KPIs, expected to be delivered by 5G networks, are key enablers for applications such as autonomous driving, cooperative robotics, transport and processing of large volumes of video and images.

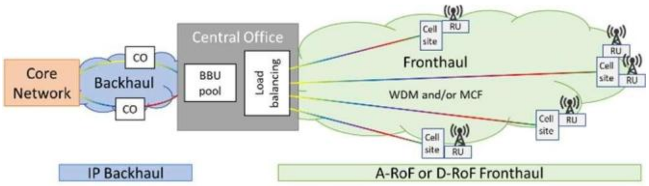

Fig. 1. Centralized radio access network architecture with IP based backhaul, a shared BBU pool for baseband processing and a joint fronhaul network for signal distribution to RUs via A-RoF or D-RoF protocol.

Indicatively, broadband access in 5G KPIs is expected to reach 1000x the capacity of current LTE and LTE-A technology and an ultra-low latency down to 1 ms, 90 % energy savings, 10x better battery lifetime, improved and ubiquitous coverage, and 10 to 100 times higher peak user data rates, while maintaining cost effective solutions. The inclusion of SDM techniques in the RAN segment is one of the most viable technologies to potentially fulfil the principal requirements faced by today’s network operators and consequently to increase the system capacity and satisfy the forward looking 5G targets.

The latency on the other hand should also be reduced as a means to improve the end user experience and enable new, time critical applications. Traditional D-RoF approaches, where common public radio interface (CPRI) processing at the RRH imposes a bottleneck in network performance, will be eventually replaced by new open source standards. On the other hand, A-RoF has also been proposed as a promising alternative solution [10], [38] to completely eliminate the digital processing at the RRH.

Another important 5G KPI target is the reduction of power consumption, which can be supported by means of PONs for fronthaul and infrastructures. In addition, the adoption of ARoF avoids the need for high-speed analog to digital conversion and additional modulation/demodulation stages, which are highly demanding in terms of energy consumption. SDM techniques can be implemented without employing active elements that require power for operation. On the top of that, the future fronthaul infrastructure will use SDN controllers that grant an overall view of the whole network, specifically useful for system management. This eventually allows for simplified and low power consumption routers and switches. Therefore, it is expected that a significant energy consumption reduction can be achieved with the novel fronthaul infrastructure.

III. FRONTHAUL INFRASTRUCTURE

A. Evolution of fronthaul network from D-RAN to C-RAN

The first 5G efforts were focused on the modification of the distributed radio access network (D-RAN) architecture to enable C-RAN fronthauling features for a cost-efficient and high-performance implementation. Nonetheless, in previous generations of mobile networks, the RF and baseband processing was from the RU to the CU with strict and challenging requirements on data rates, latency and jitter.

The described scenario is acceptable if the number of base stations is small compared to what is expected and will be required for 5G networks, e.g., with the dense and ubiquitous deployment of pico- and femto-cells. However, maintaining such and architecture becomes prohibitive, with total costs and power consumption not scaling well as the number of cells increases. Hence, a more advanced C-RAN architecture along with improved fronthaul and increased capacity is expected to be provided by novel solutions. Fig. 2 presents possible fronthauling network realizations, indicating different front/backhaul functional splits that can be implemented, as well as their required transmission bandwidth. It further illustrates the functional

performed at the remote site and mainly the payload data with signaling overhead was transferred to the CO via IP backhauling, the new network architectures were based on a fully centralized approach for embedding several wireless subsystems into a joint fronthaul network, as shown in Fig. 1. In this approach, the RF and baseband processing of the wireless signals is partitioned between the remote unit (RU) at the antenna site and the central unit (CU) at the CO site. This requires fronthauling of the digitized wireless signal

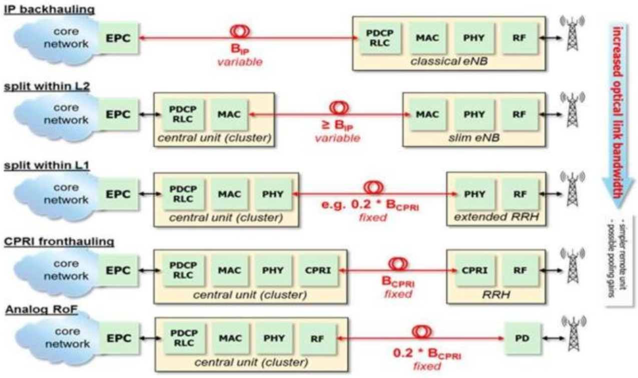

Fig. 2. Comparison of functional split options between traditional IP backhauling, a range of intermediate splits (L2, L1 and CPRI) for D-RoF and A-RoF with full centralization of all processing functions.

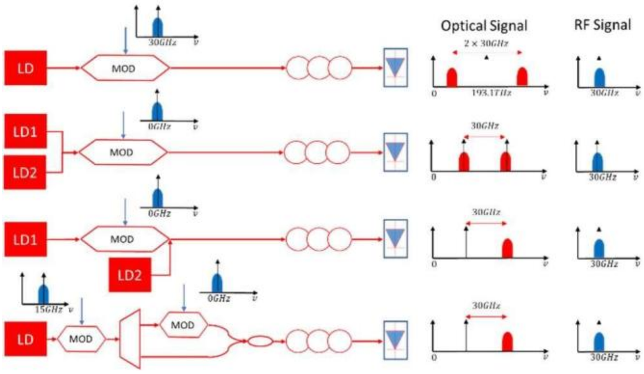

Fig. 3. Schematic block diagram of four different schemes for analog radio-over-fiber signal generation. LD: laser diode, MOD: modulator.

equivalent functional split for A-RoF, where all processing is centralized at the CO.

It should be noted, that a trade-off between the benefits from centralization of processing functions and the required fronthaul capacity increase is needed. Compared to the other implementations, the paradigm shift to A-RoF offers the most advantageous point in this trade-off, allowing full centralization, while requiring only very limited fronthaul bandwidth. In this way, better cost efficiency and network performance can be achieved when SDM and A-RoF solutions are adopted in the fronthaul architecture. On the other hand, power consumption at the RU remains an open challenge, even though by eliminating analog to digital conversion at the RU, A-RoF takes a significant step towards reducing power consumption. The use of advanced front/backhauling techniques, incorporating technologies like mmWave, optical beam forming, and ARoF, will boost infrastructure capabilities to an unprecedented level.

B. Analog radio-over-fibre based functional split

The use of A-RoF, characterized by optical heterodyning on a photodiode at the RU, is a key technology not only as it enables a functional split that provides a much more beneficial functional split, but also because it is a natural candidate for the generation of mmWave signals. An A-RoF scheme is briefly illustrated in the bottom of Fig. 3. In fact, there are many different ways to deploy an A-RoF system, with the principal possibilities shown in Fig. 3. The main difference among the options lies in the A-RoF signal generation and hence in which configuration the signal travels from the CO though the optical fiber to the RU. Accordingly, different implementations allow for distinct signal treatment at the RU premises. For example, the first option in Fig. 3 shows the simplest alternative for A-RoF mmWave signal generation, with the desired RF signal modulated on an optical carrier. This implementation produces low penalty concerning the RF signal stability as well as low phase noise, but requires a large modulator bandwidth and is strongly affected by chromatic dispersion (CD) during the optical fiber transmission inducing deep RF fading depending on fiber distance. The second ARoF implementation option shown in Fig. 3, requires only a small modulation bandwidth since it modulates the light from two laser sources, spaced at the desired RF frequency, with the baseband modulation signal. The main drawback of this technique is that the use of two laser sources causes signification variations in RF power and large frequency and phase noise. The generated RF signal is still affected by CD.

The third option for mmWave generation in A-RoF systems [39], also shown in Fig. 3, transmits data from only a single laser, which eliminated the effect of CD. In this technique, a second laser is used as a CW local oscillator for the optical heterodyning. Even though a second laser can mitigate the effects of CD, the signal will still be affected by RF power fluctuations and large phase and frequency noise. Finally, the fourth option shown in Fig. 3, solves both the problem of dispersion induced fading and of phase noise. This is based on optical two tone generation from a single laser [10], by modulation with a sinusoid and suppression of the original carrier. As the two tones are coherent, the phase noise on the resulting RF signal is minimized and if only one of the tones is modulated the problem of dispersion induced fading is avoided.

It is worth pointing out that all four possible implementations may easily be modified to transport an intermediate frequency (IF) signal over the fiber, rather than the target RF frequency. This requires an additional upconversion process at the RU, but reduces the required modulation bandwidth and limits the impact of CD on the first two options. Finally, microwave photonic signal processing techniques can be used to potentially further reduce phase noise, improve signal stability, and to support optical beam forming.

C. SDM-based fronthaul network

The future C-RAN fronthaul infrastructure will potentially use SDM techniques to support the massive capacity requirements of next generation 5G systems. The adoption of SDM techniques in the physical layer can not only considerably increase the capacity of 5G fronthaul infrastructures in a cost effective manner, but also make use of existing SMF fibers from the optical distribution network (ODN) to pave a seamless upgrade path.

Fig. 4 illustrates a possible MCF infrastructure with an SDM based fronthaul architecture. This configuration allows for a massive deployment of remote units (RUs) in an A-RoF system. It is worth mentioning that such architectures are considered as a potential candidate to deploy future 5G A-RoF based C-RAN systems to accomplish the 5G targeted performance levels with regards to low latency, reduced power consumption, and large network capacity, while keeping the cost per transmitted bit at the lowest possible value. The effective cost per transmitted bit reduction can be expected mainly from integrated spatial multiplexing transceiver interfaces placed in the CO and RU. On the top of that, the C-RAN over A-RoF architecture enables the use of optical beam forming techniques with enhanced control over spatial signal distribution, which significantly increases the user data rate at a minor added cost at the RU side.

D. Advanced SDM-based beamforming

Optical beamforming has become a key technology option for wireless communication systems employing phased array antennas. The advance of integrated microwave photonics technologies offers a high level of integration with on-chip components, which enables the manufacturing of smaller modules with lower weight for phased array based 5G applications. Moreover, the manufacturing of complex circuits with reduced size, weight and energy footprint can improve efficiency and reduce the cost of optical beamforming systems. Broadband beamforming can be achieved in the RF domain (microelectronics), by using true time delays (TTDs) or phase corrections, or in the optical domain (photonics), by employing similar concepts but with improved performance, or through hybrid beamforming systems combining both approaches [40], [41].

Among several technologies available to build an optical beamforming system, the monolithic microwave integrated circuit (MMIC) chip technology can provide beamformers supporting a static number of antennas and beam ports with acceptable power usage levels. Integrated beamformers may be limited by modulation efficiency and protentional cross talk between closely spaced waveguides. To achieve high performance, phased-array antennas based on integrated microwave photonics should make use of Si3N4/SiO2 optical waveguide technology, where integrated losses as low as 0.1 dB/cm can be achieved with a minimum bending radius of 60 µm [42].

E. Massive MIMO and millimeter wave frequencies

The mmWave frequency bands have a wide range, from 30 GHz to 300 GHz, with several specific bands from 24 GHz to 100 GHz being more likely to be used in 5G systems. The current technology roadmap indicates K/Ka-band (~26.5 GHz) and V-band (~60 GHz) as potential candidates for 5G deployment and frequencies up to 100 GHz for 5G fronthauling. In previous generations of mobile networks, the use of high frequency bands was considered unsuitable for mobile communications due to the high propagation and penetration losses. Nonetheless, MIMO-based systems along with optical beamforming will be able to overcome at least partially these new difficulties arising from the use of mmWave frequencies.

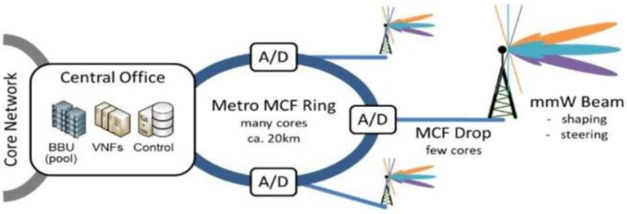

Fig. 4. Fronthaul architecture based on space division multiplexing with multicore fiber, optical beamforming, analog radio-over-fiber fronthaul for efficient mmWave signal generation and with fully centralized signal processing, and flexible SDN/NFV network control.

To achieve many of its initially established goals, 5G networks will employ novel massive MIMO systems and eventually use larger bandwidth channels at mmWave frequencies, especially for higher data rate transmissions. Massive MIMO uses several antennas arrays to provide signal amplification by beamforming and high spatial resolution so as to multiplex many simultaneous users. This innovative MIMO deployment requires large-scale antenna array systems with hundreds of active antenna elements operating fully coherently. The radio interface, which combines mmWave carriers with MIMO as well as beamforming and steering capabilities, maximizes the capacity and ensures signal quality regardless of user location and motion.

While in previous generations of mobile networks the use of massive antenna arrays was considered impractical due to form factor and size restrictions, it is with the introduction of mmWave carriers that many antenna elements can fit within a small area [43]. That is, with the short wavelength at mmWave, a large number of antenna elements at halfwavelength spacing can be placed within the same or even a smaller footprint as that of current antennas for sub-6 GHz systems. This allows moving from small MIMO implementation with a few antennas towards massive MIMO with antenna arrays of 64x64 or even larger, i.e., to systems with thousands of antenna elements.

Indeed, for the use of massive MIMO with 64x64 antenna elements in a fully digital fashion, the complexity and power consumption of the RF chain and digitizer at each antenna element are crucial parameters and for larger arrays may become prohibitive. The adoption of a hybrid solution using MIMO in combination with (optical) beamforming and ARoF fronthaul allows a reduction in the number of required RF chains and digitizers and a relocation of the remaining digitizers to the CO. Adopting such a hybrid MIMO scheme allows a significant reduction in energy consumption and processing requirements, while suffering only from minimal performance penalty [8], [44]. It further combines in an ideal fashion with optical beamforming and A-RoF fronthaul to seamlessly remove complexity from the RU to the CO. Therefore, regardless of the radio frequency range employed, MIMO antenna systems can be an elegant and robust solution to achieve higher data rates and spectral efficiency with practical acquisition of channel state information.

IV. Conclusions

In this paper, we have addressed the main technologies that will most likely be part of the C-RAN fronthaul infrastructure of next generation 5G mobile networks. We considered the following technology enablers: optical SDM as well as optical beamforming techniques, A-RoF fronthaul transport, the use of mmWave frequencies and increased bandwidths, the introduction of massive MIMO, and novel, flexible SDN schemes.

Among these technologies and techniques, the main challenges to be resolved are: cost efficient hardware solutions for A-RoF transceivers and simple adaptation of A-RoF techniques over MCF, optical beamforming in integrated photonics, compact SDM splitters and MCF adapters, enabling advanced SDM based ODN designs, adapted switching and interconnection hardware to enable SDM compatible CO implementations, seamless interfaces between SDM media and radiating elements in the RU sites, efficient remote power distribution to RUs from the CO over SDM techniques, as well as control via SDN and NFV orchestration to deploy virtual base-band units in the CO, as well as to allow slicing for multi-tenancy.

The development of 5G fronthaul systems relies not only on the technology itself, but also on common interoperability and standards to be satisfied at a global scale. Accordingly, we have discussed the main indicative 5G KPIs that are supposed to be delivered by next generation mobile networks and are fundamental for emerging networking applications such as autonomous driving, cooperative robotics, and virtual reality fully immersive systems, to name but a few. The technologies for 5G fronthaul infrastructures addressed here represent a step towards a completely overhauled radio access network architecture, in line with the demanding 5G KPIs, compatible with the current phase of 5G developments, where scalability, manageability, and flexibility are also targeted as major network requirements.

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