Optical Network Evolution for 5G Mobile Applications and SDN-based Control

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***Abstract*— The tight connection between advanced mobile techniques and optical networking has already been made by emerging cloud radio access network architectures, wherein fiber-optic links to/from remote cell sites have been identified as the leading high-speed, low-latency connectivity solution. By taking such fiber-optic mobile fronthaul networks as the reference case, this paper will consider their scaling to meet 5G demands as driven by key 5G mobile techniques, including massive multiple input multiple output (MIMO) and co-ordinated multipoint (CoMP), network densification via small/pico/femto cells, device-to-device (D2D) connectivity, and an increasingly heterogeneous bring-your-own-device (BYOD) networking environment. Ramifications on mobile fronthaul signaling formats, optical component selection and wavelength management, topology evolution and network control will be examined, highlighting the need to move beyond raw common public radio interface (CPRI) solutions, support all wavelength division multiplexing (WDM) optics types, enable topology evolution towards a meshed architecture, and adopt a software-defined networking (SDN)-based network control plane. The proposed optical network evolution approaches are viewed as opportunities for both optimizing user-side quality-of-experience (QoE) and monetizing the underlying optical network.**

Keywords*— *optical networks; 5G; mobile fronthaul; mobile backhaul; software defined networking (SDN).

I. Introduction

Although an official standards definition of 5G mobile does not yet exist, the term already has strong connotations that have been drawing significant interest [1]. For instance, Internet of Things (IoT) and machine to machine (M2M) communication are two high-profile acronyms that have been linked with 5G [1-3]. In keeping with historical trends of a new mobile generation per decade, the projected timeline for 5G mobile is beyond 2020. However, unlike previous mobile generations, 5G is not expected to be primarily about a data rate increase. Although peak rates in 5G are expected to climb to 10Gb/s, from the user side, the key performance metric is the overall quality of experience (QoE), which is composed of several underlying factors [1]. In a 5G setting, one QoE factor is envisioned to be the efficacy of realizing a mobile IoT, which may consist of a dozen or so mobile connections per person, ranging from smart phones and tables to wearable and sensor technologies. Enabling fluidity in handoffs across services, devices, and spectrum bands, and establishing a quality of service (QoS) hierarchy that supports on-demand traffic flow differentiation can thus be viewed as vital 5G QoE criteria. In addition, legacy metrics such as latency, outage probability, system spectral efficiency, network capacity and coverage and even battery consumption are also crucial for 5G QoE optimization, creating a challenging problem that mandates a new set of technical solutions as well as a general network evolution from a "cell-centric" to a "device-centric" entity.

In terms of technical solutions, there has been an advent of an several powerful and concrete 5G mechanisms to take on QoE challenges. Massive multiple input multiple output (MIMO) techniques are a prime example. While MIMO is already an important part of modern wireless standards, including Wi-Fi and 4G, massive MIMO is a super-scaled version involving hundreds of antenna elements. By spacing transmitter and receiver antennas such that channel path gains amongst them are independent, capacity gains that are linearly proportional to the total number of antenna elements become theoretically possible. Consequently, hundreds of antennas can translate to 100× capacity gains. Moreover, by exploiting high radio frequency (RF) carriers, the required antenna element spacing can be reduced to the centimeter scale. The 5G demonstration in [2], for example, exploited 128 antennas (64 transmitter, 64 receiver) and a 28GHz RF carrier to realize up to 1Gb/s transmission over up to 2km distances. In addition to antenna densification, network densification through a higher number of increasingly smaller cells is also envisioned to enhance QoE by enabling significantly higher spatial reuse of spectrum. In tandem, massive MIMO and dense small/pico/femto cells can enable ultra-advanced spatially-distributed co-ordinated multipoint (CoMP) and enhanced inter-cell interference cancellation cancellation (eICIC) mechanisms that have been shown to enable dramatic gains in both uplink and downlink throughput. Uplink throughput increases in the 40-100% range, as well as up to 30% gains in downlink throughput can be expected from CoMP techniques, provided that centralized processing and very low latency can be supported by the network [3]. Additionally, to mark the shift from cell- to device- centric networking also heralded by the rise of smart machines, wearables, and sensors, device-to-device (D2D) communication that enables data transfer via network bypass is also envisioned to become part of 5G, supporting low latency, any-to-any connectivity. Finally, given the heterogeneity of mobile devices that 5G may need to address, an intelligent and dynamic network management framework optimized for a somewhat unpredictable "bring your own device" (BYOD) environment can be regarded as an important requirement for 5G. From this perspective, 5G has ramifications not only for the data plane, but also the network control plane. Specifically, a device-oriented network policy that can differentiate between devices and traffic flows in order to provide hierarchical QoS as well as enforce security in a BYOD setting may ultimately be just as important to QoE as a high-speed, low-latency data plane.

While each of the aforementioned techniques readily merits a standalone discussion, in this paper, the focus lies on examining their ramifications on optical network evolution. Advanced mobile techniques have already begun strongly relying on optical networking through the emergence of cloud radio access network architectures [4], wherein fiber-optic links to/from remote cell sites have emerged as the leading high-speed, low-latency connectivity solution. By adopting such optical fronthaul networks [5, 6] as the baseline case, this paper will consider optical network evolution to meet 5G demands, as driven by the 5G mobile techniques outlined above. Ramifications on fronthaul network signaling formats, choice of optical components and wavelength management, topology selection and network control will be examined. The need to move beyond native common public radio interface (CPRI) solutions, support all wavelength division multiplexing (WDM) optics types, enable a dynamic topology that can evolve towards a meshed architecture, and adopt a software-defined networking (SDN)-based network control plane will be emphasized. The proposed optical network evolution strategies are viewed as opportunities for both optimizing user-side QoE, and monetizing the underlying optical network.

II. The Reference Case: Optical Fronthaul Networks

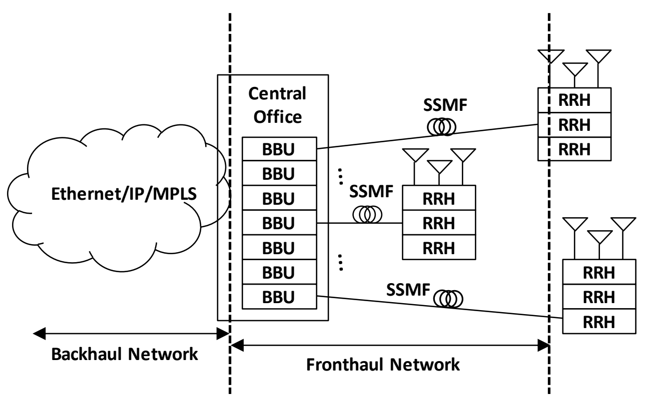

Fig.1 Reference architecture for optical mobile fronthaul networks; IP = Internet Protocol; MPLS = Multiprotocol Label Switching; BBU = baseband unit; SSMF = standard single mode fiber; RRH = remote radio head.

A reference architecture for optical fronthaul networks that will seek to undergo evolution in support of future 5G mobile is shown in Fig. 1. Unlike in conventional mobile backhaul networks [3], wherein Ethernet/IP/MPLS functionality is extended all the way to the remote cell site, in optical fronthaul, network processing is largely centralized, greatly simplifying remote equipment and enabling cloud-based processing benefits in the context of mobile applications support. To achieve this, the baseband unit (BBU) processors are re-located from the remote cell sites to the central office, and stacked to form a powerful BBU processing pool, as shown in Fig. 1. Standard single mode fiber (SSMF) links are then used to interconnect the BBU pool with remote radio heads (RRH), illustrated in Fig. 1 for the traditional three-sector antenna configuration. The RRHs contain RF transmitter and receiver components (including power and low noise amplifiers, duplexers, etc.) Through the centralization of processing in the BBU pool, a more efficient use of computational resources can be made, and more intelligent interference management approaches can be adopted to optimize performance over the wireless channel. Perhaps the most prominent example of this is CoMP, the use of which is known to significantly improve both downlink and uplink wireless transmission rates. Operational tasks (e.g. software upgrades) can be moreover be simplified and streamlined with the cloud-based approach. It is noted that the architecture of Fig. 1 is compatible with additional RRH-side functions, such as Ethernet and Optical Transport Network (OTN) de-capsulation and CPRI decompression, and potentially additional processing functions, so long as the wireless channel performance guaranteed by centralized cloud processing is not compromised, the RRH interface does not become overly complex, and the system can support robust operation in outdoor environments (if needed).

In terms of inter-BBUs communication, in the reference case of Fig. 1, this is assumed to be done locally (i.e. within the central office) over a standard X2 interface [5, 6], which is an attractive solution provided that the X2 interface latency can be sufficiently low and the required data rate is also low. BBUs can also communicate with each other by accessing the backhaul network, but this notably increases latency and is thus regarded as a suboptimal solution. In terms of BBU-RRH communication, the most obvious and commercially-mature solution is the extension of Common Public Radio Interface (CPRI)-based signaling— initially intended for local BBU-RRH connectivity within a remote site [7] — across the optical fronthaul network.

It is noted that while a mobile fronthaul network is taken as the reference case considered here, mobile backhaul also has beneficial features that can be attractive in certain scenarios [8]. For example, distributed baseband processor architectures adopted in backhaul networks have less stringent bandwidth, time accuracy and latency requirements: 1-10ms latency from the central office to the remote sites of Fig. 1 would be acceptable in this case, even for tight coordination scenarios [3]. This would however require deploying backhaul connections to each remote antenna that support the needed time/phase accuracy and latency requirements, which can be challenging for a dense network. With centralized baseband processing, a backhaul connection is needed just to the central office, while all other connections can be CPRI. On the other hand, for such a mobile fronthaul scenario, <1ms latency is now needed between central and remote sites, along with highly accurate (~μs level) time and phase synchronization [3, 5, 6].

III. 5G Mobile Ramifications on Optical Network Evolution

In this section, the ramifications of each of the presented 5G mobile techniques on optical network evolution are discussed in detail. Specifically, massive MIMO is treated as a strong motivating factor for moving beyond native CPRI signaling techniques, while network densification is regarded as an argument for supporting all WDM optics types in optical networks supporting 5G. An evolution of network topology to a mesh is called for by D2D communication paradigms, while an SDN-based control plane is proposed as an attractive solution for dealing with a BYOD networking environment.

A. Massive MIMO → Beyond CPRI

In the reference case of Fig. 1, optical fronthaul networks are intended to carry one CPRI stream per antenna. While this provides the benefit of fully-centralized baseband processing, it also exerts a very large bandwidth penalty. For example, for a 100MHz signal (e.g. LTE), with 16 bits/sample resolution, 30% compression ratio, and just $M = 2$ antennas per cell site, the required data rate for CPRI transmission over the optical fronthaul network is 20.644Gb/s [9] — a two orders-of-magnitude expansion compared to the native signal bandwidth. Moreover, since the underlying analog waveform must continuously be digitized for CPRI transmission, the high data rate overhead is fixed whether the signal is modulated or not, obviating the possibility for statistical multiplexing in the electrical domain. Nonetheless, while the large overhead can be accommodated for a $M = 2$ antenna case by exploiting multiple 10Gb/s wavelengths, for example, in a massive MIMO system with $M = 100$ antennas, the native CPRI bandwidth requirement expands to ~2.1Tb/s per cell site, which becomes exorbitant. Even if 100Gb/s/λ optical transceivers could be used to handle the resulting bandwidth expansion, deploying >20 per single cell site in a dense network with hundreds or thousands of sites is prohibitive. Alternately, higher CPRI compression ratios could be invoked to gain additional bandwidth savings (e.g. up to 50%). The trade-off for this benefit is increased processing latency, which can be on the order of tens of microseconds [10]. Given that the total latency budget projections are 100-150μs for future optical fronthaul systems [11], tens of μs is a significant fraction. Moreover, the factor of two bandwidth savings is dwarfed by the orders-of-magnitude increase in M. Consequently, additional bandwidth efficiency mechanisms that operate by moving beyond native CPRI signaling are needed for optical network evolution towards 5G mobile fronthaul. The current set of beyond CPRI options include [6, 10]: CPRI to Ethernet mapping; CPRI to Optical Transport Network (OTN) mapping; and baseband processing function re-allocation such that what is sent over the optical network are not native time-domain CPRI samples but a lower-bandwidth variant. With CPRI-to-Ethernet mapping, multiple CPRI channels of variable rates could be multiplexed via Ethernet in the electrical domain, increasing bandwidth efficiency. CPRI-to-OTN mapping operates on an analogous bandwidth efficiency via multiplexing premise, albeit in the optical domain. Key advantages of both mapping options lie in their reliance on mature standards that also offer management functions. A disadvantage of both is that they do not address the bandwidth expansion inherent to time-domain CPRI itself. The third option, however, does take this into account and comes in several potential variants, as summarized in Table 1. As shown in Table 1, the native CPRI solution transmits time-domain in-phase/quadrature (I/Q) samples— i.e. a high-resolution digitized version of the underlying signal—resulting in the high bandwidth overhead. CPRI does boast the advantage of fully-centralized processing, which enables rich resource pooling, downlink (DL) and uplink (UL) CoMP, is compatible with various mobile technologies and generations, and perhaps most importantly, has already been standardized and field-deployed. To reduce bandwidth overhead of native CPRI, it is also possible to move Fast Fourier Transform (FFT) operations to the RRH, such that what is carried over the optical links are frequency-domain modulated data symbols. In this case bandwidth requirements can be reduced by about 50% compared to time-domain I/Q CPRI. However, given that time-domain CPRI compression can achieve similar results without sacrificing resource pooling capability, the benefit of the modulated symbols approach is somewhat limited. By additionally moving modulation and layer mapping, pre-coding and resource mapping functions to the RRH, a frequency-domain bit stream can be carried over the fronthaul network, reducing bandwidth requirements by approximately 90% compared to native CPRI. In this case, the bandwidth savings are compelling and bidirectional CoMP remains supported since scheduling and transmission configuration is still done centrally. The bit stream approach is OFDM-specific, however, and would mandate that additional control information be transmitted over the fronthaul link in order to perform the required set of functions at the remote end. It would moreover require additional standardization efforts. Finally, by moving the channel coding and scrambling functions to the remote end, essentially transferring the entire function chain to the RRH, bandwidth overhead can be minimized by transmitting a frequency-domain data transport block over the fronthaul link. The trade-off for this bandwidth efficiency gain is a further reduction in resource pooling capability, which is in this case restricted to layers 2 and 3, as well as in CoMP, which becomes restricted to the DL case only. Due to the high degree of distributed processing, the bit stream and transport block options of Table 1 may be regarded as analogous to IP backhauling with encapsulation. Novel CPRI compression options as well as alternate centralized-versus-distributed processing splits are under discussion by standardization bodies with the goal of identifying the optimal "beyond CPRI" strategy.

TABLE I. Comparison of CPRI Alternatives

	Fronthaul Transport Options			
	CPRI (time-domain I/Q)	***Modulated Symbols***	***Bit stream***	***Transport Block***
Bandwidth	100%	~50%	~10%	<10%
Resource Pooling	Full	Partial	Partial	Higher-layer only
CoMP	DL + UL	DL+UL	DL+UL	DL only
Technology	Multi	OFDM	OFDM	Multi
Standards	Available	TBD	TBD	TBD

B. Network Densification → All WDM Optics Types

As the number of antennas per cell site increases, and the number of cell sites per area also grows, extensive use of WDM technologies in optical mobile fronthaul networks becomes inevitable. Indeed, WDM-based connectivity for mobile systems support is under consideration in both point-to-point and point-to-multipoint/passive optical network (PON) topology scenarios. However, while a strong reliance on WDM is clear, exactly which type of WDM optics will prevail — coarse WDM, dense WDM, colorless WDM, coherent WDM, etc. — is currently unclear. It seems that a single one-size-fits all WDM solution may not be feasible due to a plethora of unknown factors and variables that jointly create an underdetermined problem space. For example, a crucial factor for selecting the optimal WDM optics type is the required wavelength count per site, which can vary greatly depending on user density, network topology, regional specificity, etc. Different WDM optics might also be better suited to indoor versus outdoor deployments, with both in-door and outdoor cases expected to be prominent in future systems. Network topology can also plays a role in this space, with certain WDM optics better suited for PON versus point-to-point architectures. Network heterogeneity (i.e. the degree of coexistence between 2G, 3G, 4G and 5G systems, or any combination thereof, per site), is also an important consideration that involves potential back-compatibility constraints. Finally, parallel developments and trends in WDM optics for other short-reach optical network segments (such as WDM for datacenter applications, for example), as well as state-of-the-art advances in silicon photonics could also influence WDM selection type given that the deployment timeline for 5G is still several years away.

Consequently, rather than an a priori restriction to a single WDM type, a more flexible and harmonized approach might be to seek an optical network *topology* evolution strategy that can accommodate *all* WDM types. The motivation for this approach is the fact that a WDM connection between optical transceivers can be established either by choosing/tuning a wavelength, or routing/switching it. The latter approach is advantageous in that it enables reconfigurable WDM connections regardless of underlying optics type by essentially supporting topology re-configurability. In addition to promoting an inclusive WDM optics model, topology re-configurability is also naturally amenable to a de-centralized D2D networking paradigm, as discussed next.

C. D2D Communication → Meshed Topology

As shown in the reference model of Fig. 1, current optical fronthaul topology does not explicitly address any-to-any connectivity via localized D2D communication, which is regarded as an important differentiating factor for 5G. Consequently, significant benefits lie in enabling optical network evolution towards a meshed topology. A mesh-like topology is attractive in that it can dynamically support low latency high-speed data transfer by enabling a significant degree of legacy network bypass, as well offer as a plurality of connectivity options that enhance network fault tolerance between nodes without high static resource overprovisioning. Since cost-efficiency mandates maximal re-use of deployed fiber, and deployed fiber links are by definition fixed, optical topology evolution towards a mesh will require a hybrid of physical and virtual networking mechanisms. From the physical perspective, strategic use of centralized electrical and optical switching elements can be greatly beneficial in terms of overcoming fixed topology limitations and enabling on-demand connectivity between arbitrary network nodes. Recently, the first SDN-controlled optical topology-reconfigurable optical mobile fronthaul architecture for bidirectional CoMP and low latency inter-cell D2D connectivity in the 5G mobile networking era was proposed and experimentally demonstrated in [12]. Specifically, in [12], SDN-based OpenFlow control was exploited to dynamically instantiate the CoMP and inter-cell D2D features as match/action combinations in control plane flow tables of software-defined optical and electrical switching elements. Dynamic topology re-configurability was thus introduced into the optical mobile fronthaul network, while maintaining back-compatibility with legacy fiber deployments. 10Gb/s peak rates with <7μs back-to-back transmission latency and a 29.6dB total power budget were also experimentally shown.

D. BYOD Environment → SDN-based Control Plane

Given the dynamic topology-reconfigurable approach proposed in the previous section, it is highly-desirable that the optical and electrical switching elements used to accomplish this be controlled in a centralized, unified, protocol- and vendor- agnostic way. SDN-based control offers a highly-attractive way to realize this and implement a dynamic mesh-like architecture that incorporates fixed fiber links [12]. Moreover, SDN-based control is very well-suited to an unpredictable BYOD environment in which both security and QoS need to be enforced amidst high device and traffic heterogeneity. In particular, by binding traffic flows (e.g. packets with a common logical association) to a device with a unique name rather than to a lower level identifier, such as an IP address, SDN-based control can be exploited to realize device-oriented security and QoS policies [13]. This will moreover remain true even as the device moves around in the network. Different levels of network authorization and a hierarchical QoS policy based on traffic flow type can thus be efficiently supported, not only simplifying network management, but also enhancing network monetization. Specifically, it is anticipated that the ability to differentiate between and prioritize different traffic flows (e.g. an emergency phone call over a home temperature reading) will become one of the most important QoE aspects in 5G mobile systems and a compelling use case for SDN-based control. It is also noted that in cases where the fixed and mobile operator are not the same entity, the SDN control plane may also need to be under the domain of the mobile operator, depending on the optical backhaul network demarcation points.

IV. SUMMARY AND CONCLUSIONS

Optical network evolution for 5G mobile applications ought to provide more than just gains in transmission speed. It should forge a path from current "cell-centric" networking to a future "device-centric" paradigm. This evolution needs to take into account key 5G mobile techniques— including massive MIMO, ultra-high network density, D2D communication, and an increasingly heterogeneous and unpredictable bring-your-own-device networking environment. In this paper, approaches for responding to these 5G mobile challenges in the context of next-generation optical fronthaul networks have been proposed, including a move beyond raw CPRI signaling, support for arbitrary WDM optics types, dynamic topology evolution towards a mesh architecture, and SDN-based network control. It is envisioned that the proposed techniques would not only help optimize user-side quality-of-experience, but would positively contribute to monetization of the underlying optical network infrastructure as well.

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