The Role of Optical Networking in the 6G Era

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Abstract: Sixth-generation (6G) networks will revolutionize the way we communicate and connect, with promises of higher data rate, lower latency and higher reliability. To efficiently support the 6G use cases and service requirements, the optical networking community needs to introduce a number of innovations at a component, system and control level. In this paper, we provide our view on these innovations and discuss their adaptation to the x-haul network. © 2024 The Author(s)

1. Introduction

As the deployment of more bandwidth-intensive applications continuous unabated, the total traffic originating at the access part of the network scales with close to 30% CAGR [1], spurring the telecom/datacom networks to offer higher user data rates and concurrently satisfying the lower latency requirements. With the widespread deployment of 5G networks and the emergence of 6G requirements aiming to support even more demanding mobile use case classes, the optical networks that form the backbone infrastructure, spanning from the edge part of the network all the way up to the core, are challenged to provide new capabilities [2-3]: i) transporting of high capacities, of the order of hundreds of Tb/s per link and beyond, ii) low latency, of the order of sub-ms, iii) fast reconfigurability, of the order of μs, iv) low energy consumption, of the order of few tens of fJ/bit at the transmitted side and v) improved overall security/reliability via deploying mechanisms securing the network end-to-end. Evidently, the various segments of the optical network require different capabilities, resulting in diverse sets of specifications for the associated subsystems. In this invited paper, we discuss the envisioned characteristics and key innovations of optical front-haul, mid-haul and back-haul (known as x-haul) network infrastructures for 6G mobile networks, initiating and pursuing research directions to efficiently support the 6G network requirements.

2. The optical x-haul transport network

The evolution of optical networks towards the 6G era is adapting to the trends prevalent in the entire telecommunications ecosystem and associated standardization bodies defining the key features of evolving 5G and emerging 6G networks, across multiple dimensions. The central role in this process is played by the 3GPP which has specified a number of functional-split (FS) architectures for the disaggregated Radio Access Network (RAN) which are associated with different levels of decentralization of the traditional baseband unit (BBU) processing functions. In particular, a set of eight digital radio over fibre (D-RoF) FS options (in addition to the analogue A-RoF option, each to serve particular network characteristics, traffic features, and service requirements for mobile operators, at the expense of corresponding levels of network resources usage [4]. Each of these proposed FS options offers distinct advantages and trade-offs, and their choice depends on the requirements of the specifically targeted use case families, e.g. FS1 for low latency applications in edge computing use cases, and FS8 for more efficient centralized radio resource management such as Cell Free Massive MIMO. The processing of the old BBU functions is now partitioned among three logical entities: the radio unit (RU), the distributed unit (DU), and the centralized unit (CU), defining the front-haul (FH), the mid-haul (MD) and the back-haul (BH) network segments in-between (collectively the x-haul), as per Fig. 1, wherein key innovations of future x-haul networks are illustrated. In this scheme, FS1 places all radio processing functionalities (i.e., RU, DU and CU) within the cell site, which becomes more complex and requires more power, whereas bit rate demands remain low. On the other end, FS8 places high bit rate and low latency demands on the front-haul as the various functionalities are distributed across the network. The CUs and DUs can be grouped together in virtualization pools/clusters and the associated processing can be implemented in virtual machines/servers, without the use of dedicated hardware, resulting in open and cost-effective RAN implementations.

In Fig.1, the front-haul network interconnects the RUs, located at the edge of the network, with the DUs. Today's front-haul infrastructure may be as simple as a pair of optical fibers, or as complex as a time-sensitive packet-switched network over a dense wavelength division multiplexing (DWDM) optical transport network [5]. Optical access network architectures based on point-to-point (P2P) and point-to-multipoint (P2MP) optical distribution networks (ODNs), for the front-haul, are typically implemented with P2P Ethernet, P2MP TWDM PON, and P2MP WDM PON [6]. In the front-, mid-, and back-haul, the RUs/CUs/DUs are connected to IP core/aggregation/access routers. Aggregation and core IP routers are deployed on top of Optical Nodes (ON) endowed with reconfigurable optical wavelength channel add/drop/switching capabilities (ROADMs) and are interconnected together via the mid- and back-haul network segments. These IP routers interface with the optical transport networks through optical transponders. Commercial optical transponders are now evolving from 800 Gb/s line interfaces to 1.6 and 3.2 Tb/s, while even higher rates are expected in the future. The traffic originating from the RUs is directed via the front-haul to Aggregation Routers that are connected to the optical transport network via ONs. The purpose of all ONs across the network is to route and add/drop traffic from/to the corresponding routers, serving the needs and requirements of each particular network segment. Upon introducing the ONs, the requirements for the Router capacities are relaxed, therefore their port counts are decreased, saving energy and cost (Routers cost more and are more power-hungry per processed bit). The ONs in the different x-haul segments can have enhanced capacities enabled by combinations of spectral and spatial super-channels add/drops and be capable of switching traffic at different granularities by operating at multiple spatial and spectral lanes on demand. The corresponding optoelectronic interfaces for each of the connections between the 6G cell sites and the ONs, as well as among the ONs, need to support rates from a few hundred Gb/s to even more than 1 Tb/s in a single lane (be it either spectral or spatial).

To support the x-haul, the optical links between the ONs need to transport very high capacity at the order of Pb/s and beyond. To achieve this, multiplexing approaches utilizing a combination of spectral multiplexing (i.e., Ultra-Wide-Band WDM – UWB) and spatial multiplexing (i.e., Space Division Multiplexing – SDM) are foreseen to be utilized. Once such UWB/SDM multiplexed optical links are networked to neighboring ONs, the ONs throughput may be enabled to scale to tens of Pb/s. Interconnection of these ONs with the UWB/SDM links forms the 6G transport network, arranged in interconnected rings in a mesh architecture to enhance network resilience and offer high reliability/availability. An important network characteristic affecting the latency and other requirements is the switching speed of the ONs, which may depend on the 6G transport segment as follows. On one hand, ONs located in the back-haul support large throughputs, but their switching speeds may be less demanding. On the other hand, ONs closer to the network edge need to switch faster to support the low latency requirements, but their capacities will be smaller, especially for low FS. In our opinion, future ONs will increasingly rely on faster and higher capacity ROADMs and optical cross-connects (OXCs) and a new breed of transmission and switching technologies needs to be developed to satisfy the diverging requirements across all network segments.

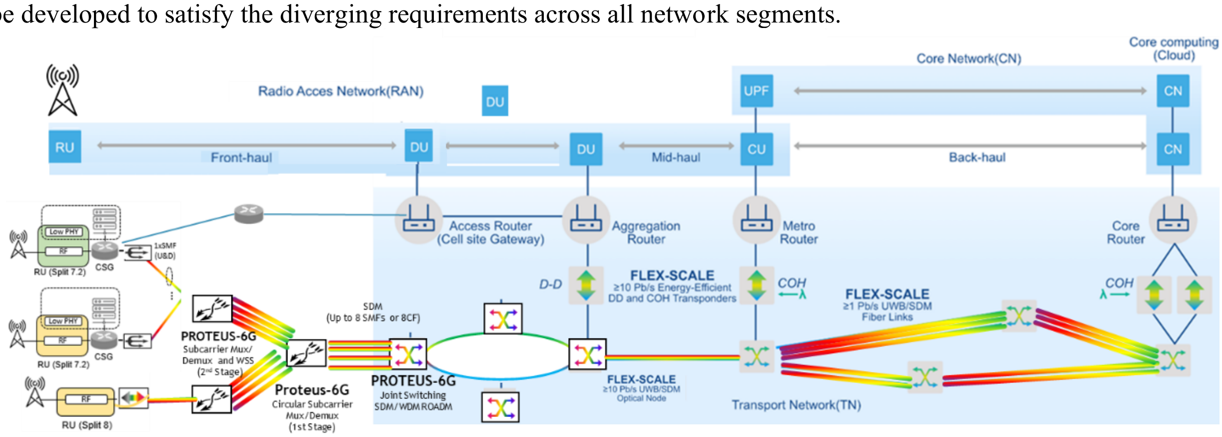

Fig. 1. Disaggregated RAN depicting the x-haul network segments (i.e., front-, mid-, back-haul; FH, MH, BH) and the processing units (i.e. Radio-, Distributed-, Centralized- Units; RU, DU, CU) and showcasing key innovations investigated within the PROTEUS-6G & FLEX-SCALE EC-funded SNS projects.

3. Optical communications systems and network innovations for the x-haul

The efficient support of the x-haul with the capabilities outlined in the introduction requires the development of i) novel higher rate, more flexible, and more energy-efficient optical transceivers; ii) higher capacity optical transmission; iii) more flexible and of faster switching time all-optical switching technologies increasingly relying on UWB/SDM implemented using integrated programmable Silicon photonics; iv) intelligent control, energy efficient resource management, and orchestration of the entire x-haul network. These innovative elements, some of which will be developed at the EC-funded SNS projects of FLEX-SCALE and PROTEUS-6G, are expected to bring about substantial enhancements with respect to conventional optical networks.

For the mid- and back-haul, state-of-the-art optical DACs (oDACs) have been proposed recently, adopting direct Digital-to-Optical conversion, improving the trade-offs between performance, energy-efficiency, complexity, and cost-reduction for optical transmitters (Tx's) by essentially eliminating the power-hungry high-order electronic DACs [7,8]. FLEX-SCALE aims to implement a novel multi-parallel oDAC architecture enabling coherent in-phase optical superposition of multiple optical PAM-4 signals, coming from S (=2, 3, ...) multiple parallel branches (paths) in the oDAC photonic integrated circuit (PIC), each comprising a properly biased optical Mach Zehnder Modulator (MZM) fed by an electronic PAM-4 driver. The resulting optical signal is a multilevel PAM-m signal ($m=4^S=16, 64, 256 ...$). Such PAM-m optical signals can be orthogonally I-Q multiplexed to generate high-quality m^2-QAM signals, by using just PAM-4 electronic drivers [7]. For the front-haul, novel flexible multiplexing and aggregation schemes need to be introduced based on electrical/optical Nyquist Frequency/Wavelength Division subcarrier multiplexing, multiple-access, and switching approaches. These schemes will support bandwidth-variable signal generation and routing, aiming to resolve the limitations of current TDM/TDMA-based point-to-multipoint access networks. This will result in fully programmable adaptive front-haul transceivers capable of achieving optimal flexible bandwidth allocations, avoiding the under-utilization of available resources, thus reducing the cost and power consumption at a network scale.

In the mid-/back-haul, novel ONs are required to provide Multi-Granular (MG) capabilities implemented by Waveband Selective Switching (WBSS) modules at ingress/egress fibre ports (top tier) and augmented by legacy OXC and wavelength selective switch (WSS) functions in support of (i) full fibre routing, (ii) full band routing and (iii) legacy wavelength routing. These MG-ONs need to hierarchically integrate new optical switching paradigms operating (i) at a full-fibre level switching for a total bandwidth of tens of THz, e.g. more than 21 THz, to include S, C and L-bands, (ii) at a flexibly defined band level, exploiting S and L bands, with total switching duration of 10 μs, as suitable for time-sensitive networks, while (iii) still being backward compatible with slow legacy networks based on single channel routing. The MG-ON switching architecture also allows for increased scalability of multi-Pb/s and the flexibility to support various data rates per single channel exceeding 1 Tb/s. The main novel element of the MG-ON is the PIC-based flex-WBSS, developed in FLEX-SCALE and expected to consume very low energy; normalized to traffic flow through it less than 3W/(3·80 Tb/s) which equals 12.5 fJ/bit.

Moreover, as Fig. 1 illustrates, the future front-haul may rely on a spatially-diverse-point to multi-point (SDPtMP) ODN providing connectivity of an access central office (CO) and its resources to a large number of remote cell sites. Multiple access COs and regional COs are interconnected via an optical ring network, allowing for uniquely enabling optical pathways between any cell site and any CO, as well as between access COs and regional COs. The regional CO consists of a metro computing datacentre, deploying a CU pool, as well as a metro router to aggregate traffic from different access COs. The access CO comprises an edge computing datacentre to deploy a DU pool or a CPU, along with an aggregation router for handling traffic from different cell sites. The cell sites comprise multiple RUs possibly connected to a cell site gateway (CSG) router, to aggregate the traffic and provide connectivity to a far-edge computing datacentre (in the cell site). To support future front-haul needs, the development of ultra-low energy (low-pJ/bit), ultra-high capacity (0.8 Tb/s), fast-reconfigurable (sub-ms) software-programmable transceivers, multiplexers and fast optical switches integrating tuneable lasers/filters, based on novel photonic processing/switching schemes are pursued.

All these optical networking elements across the x-haul segments need to be controlled and reconfigured by an intelligent control plane optimizing the utilization of resources across the front-/mid-/back-haul continuum and reducing unnecessary opto-electronic transitions in the IP layer, to improve performance while minimizing energy consumption. A key innovation addressed in PROTEUS-6G is the 6G network adaptation. It enables tailoring the most appropriate FS to each use case as well as dynamically reconfiguring the underlying packet-optical front-haul and mid-haul network to provide the transport capacity and latency demanded by the selected centralization level. In the x-haul, the allocation of packet and optical resources should be dynamic accounting for varying operational conditions, the spatial distribution of users and traffic demands, and the use-case requirements. This is feasible via developing a converged packet-optical x-haul infrastructure, with novel software-programmable PIC-based subsystems operated under an intelligent management system, simplifying and optimizing network operations in support of 6G applications.

4. Conclusions

In this paper, we have outlined how the optical networks are evolving to support the 6G use cases and services. We have also presented the x-haul network and the main innovative elements and technologies that need to be introduced.

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