# Evolution to Mesh 5G X-Haul Networks

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**Abstract:** Development of optical x-haul networks is driven by 5G wireless radio requirements. The potential of a mesh optical x-haul architecture merging WDM-PON and DWDM-ROADM networks is examined with respect to 5G requirements in metropolitan networks.
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## 1. Introduction

The evolution of 5G wireless radio technology has driven new developments in optical networks in recent years. Traffic volumes anticipated for various applications and services such as video streaming, cloud computing, and virtual reality (VR) gaming are motivating greater use and functionality out of optical infrastructure. Low latency requirements together with the increased capacity and reliability in these networks in particular demonstrate a need to push the optical connectivity near end-to-end, forcing greater flexibility and scalability in the optical systems. In order to improve network performance via coordinated multipoint (CoMP) and enhance energy efficiency through shared facilities, radio access networks (RANs) are expected to evolve from distributed-RANs (D-RAN) to centralized- or cloud-RANs (C-RANs). More generally, the network can be organized in to radio units (RU), comprised of the remote radio heads (RRHs), distributed units (DU) with full or partial baseband processing, and centralized units (CU) with cloud or hotel organized baseband units (BBUs) [1] forming a front-/mid-/back-haul or x-haul network, shown in Fig. 1(a).

The capacity requirements of 5G x-haul optical networks have brought attention to wavelength division multiplexing (WDM) as a key technology. With individual user access rates as high as 10 Gb/s and additional capacity required for transmitting the full digitized radio waveforms, transmission capacity requirements can reach into the 100's of gigabits per second. As a result, both passive and active WDM are in use or under consideration for access networks. The WDM passive optical networks (WDM-PONs) offer simple tree topologies, low cost implementation, and easy management. The active WDM approach such as reconfigurable optical add drop multiplexer (ROADM) networks provide greater flexibility in topology and configuration ability, but are expensive and complex to control, particularly if more dynamic operation is sought. Nevertheless, mesh-like cross connects and peer communication has been proposed for WDM-PON networks and ROADM networks continue to see cost reductions and more advanced control capabilities [2]. Here we explore the potential of a mesh topology 5G x-haul optical transmission network and trends in both passive and active WDM technologies leading in this direction.

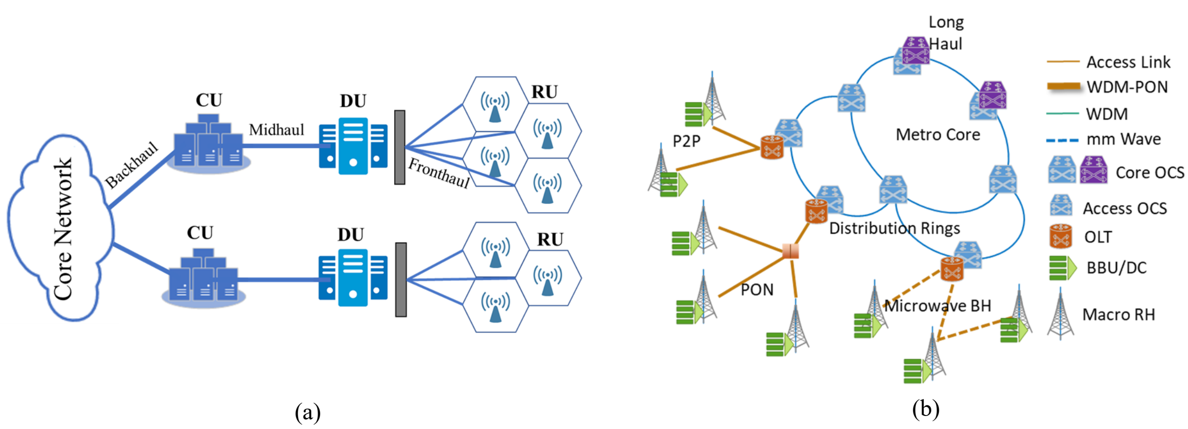


Fig. 1. (a) 5G x-haul networks with centralized units (CU), distributed units (DU), and Radio Units (RU); (b) current wireless and optical hierarchical RAN backhaul (BH) networks using layer 2 optical circuit switches (OCS).

## 2. 5G Requirements and Technology Evolution

The convergence of wireless and optical networks for 5G wireless standards is driven by substantially higher capacity and lower latency end-to-end as well as higher reliability for specific applications compared to previous generations. Three application/service use case spaces have been identified: (1) enhanced mobile broadband (eMBB), (2) ultra-reliable and low-latency communication (uRLLC), and (3) massive machine type communication (mMTC). While these three categories have been identified with separate requirements, they are expected to be delivered over the same network infrastructure through a network slicing approach. Thus the underlying x-haul network will need to serve all three application category requirements.

A representation of current wireless and optical access networks is shown in Fig.1 (b). It is based on D-RAN with tiered WDM-PONs feeding ROADM based aggregation and metro backhaul networks. Using the analogy with data centers, much of the traffic in this network is 'North-South' aggregating toward gateways and large data centers in the regional or long haul networks. PONs can provide optical transmission with low cost, simple maintenance and operation by using passive point-to-multipoint or point-to-point connections. When integrated with WDM, PONs can offer higher bandwidth and low split loss for each optical network unit (ONU) at the RUs. Multiple wavelengths carried by each fiber from/to the BBU/DC or macro/micro RUs are aggregated/disaggregated to/from an optical line terminal (OLT) connected to the ROADMs with layer 1/2 optical circuit switches (OCS) without any inline amplifiers. As the densification of access points increases by 100-1000x, this architecture would require a massive buildout of radio infrastructure, which has motivated the C-RAN approach, minimizing the hardware at the RUs and sharing the baseband processing through centralized and/or cloud infrastructure.

Several important advances are under investigation to evolve this current model in order to meet the 5G x-haul requirements of applications/services. Link capacity can be increased by using dense WDM (DWDM) instead of coarse WDM (CWDM) or WDM in point to point or PON systems. Advanced modulation formats such as 256 QAM with coherent receivers can be used to improve data rate and bandwidth efficiency. There are many efforts to realize lower cost coherent capabilities through co-propagating local oscillators or Kramer-Kronig receivers and variants [3]. It is also the case that pluggable coherent transceivers are available today and rapidly driving down costs, which could motivate their use in access networks. Higher speed PONs, however, do not solve the limitations of the PON tree topology and therefore, mesh connections have been proposed that allow for ONUs to communicate with neighbors [4]. While digitized radio-over-fiber technology such as Common Public Radio Interface (CPRI) is inefficient, new functional splits between RU, DU, and CU are proposed in evolved CPRI (eCPRI) to enable a 10 times reduction in the required fronthaul bandwidth. At the same time, there are ongoing efforts to reduce the cost of ROADM systems and improve their software control capabilities. Open line systems and disaggregated optical systems have received interest to drive down cost through greater hardware commoditization. These open systems also create a market for third party SDN controllers and potentially allow for more integration of the optical controls into higher layer network SDN and NFV approaches [5]. OpenROADM is a public multi-service agreement that supports the use of fully disaggregated ROADMs for use in these environments. While some level of performance is expected to be lost in a disaggregated system, smaller scale metro deployments are expected to see little impact [6]. Figure 2(a) shows a representation of the evolution of these technologies by using WDM PONs and point to point connections with a dense ROADM-based mesh backhaul network moving closer to the edge.

**3. Mesh 5G x-Haul Network**

These evolutionary steps expected for fronthaul and midhaul networks, when taken together largely appear as a convergence toward the coherent optics based, mesh networks developing in the metro core and aggregation backhaul networks. If low cost coherent modules are widely used in the backhaul (as well as for long haul and data center interconnect networks), it is reasonable to conceive that the signals would not need to terminate at the access network and instead more efficiently (and at lower latency) continue to the RU access point. Of course, PON networks will not go away and provide efficient sharing of capacity in bursty traffic environments. However, as the Internet of Things (IoT) is more widely used and the number of devices per user continues to increase, the traffic at a home, enterprise, or cellular access point can be expected to be less bursty—carrying aggregated traffic from a larger number of devices. Densification of access points works in the opposite direction, creating more bursty traffic at any individual access point. Nevertheless, the physical network dimensions over which such traffic would persist can be expected to decrease. In this scenario, PONs might be used in the home or office building, aggregating traffic from multiple radio heads or WiFi units located within a building or within line of sight for mmWave connections. A proliferation of DUs would be a natural aggregation mechanism for such signals, feeding into a dense WDM extended fronthaul or midhaul network. Such a scenario, however, might still be supported by the network of Fig. 2(a) and does not depend on the use of a mesh network.

A mesh network as shown in Fig. 2(b) is advantageous for improving the RAN, increasing reliability, and decreasing latency. Studies have shown that the ability to form CoMP clusters for more efficient and high bandwidth wireless access improves with the density of the mesh network connecting the access points [7]. It also provides greater flexibility to reach radio signal processing resources, which plays a role in reliability. This approach extends recent FiWi architectures with converged access/metro infrastructure, fixed wireless, and disaggregated mobile processing resources [8]. If an optically switched approach is needed in order to provide deterministic low latency, then the use of a mesh network becomes even more advantageous in order to avoid contention. This does not mean that wavelength circuits will be switched in response to individual user requests, instead wavelength switching can be used for traffic management in order to ensure open sub-wavelength circuits as the traffic load varies across the network and efficient use of edge cloud computing resources [9]. A diversity of application processing locations throughout the network will also benefit from a mesh optical network in order to increase the probability that a low latency connection can be establish to a given application processing location as a user or device moves through the geographic area.

Optical technologies are also evolving to better support a mesh network approach to 5G x-haul networks. Photonic integrated chip (PIC) based wavelength selective switch ROADMs were first introduced more than 15 years ago. At the time, their performance was lagged MEMS and LCOS technologies and therefore they did not see widespread adoption. In this low cost, high volume x-haul network environment, PIC based ROADMs could take a foothold and potentially drive down the cost of WDM optical switches. Switch losses are unavoidable and since multiple hops would be needed in mesh networks, the use of optical amplification would be a key enabling technology. Low cost optical amplifiers are available in pluggable modules today, although with performance and power limitations that might be overcome with further development. Perhaps the greater challenge is the nonlinear dynamics of optical amplifiers, particularly when optical switching is used. The use of advanced control techniques, saturated amplifiers, and noise-loaded amplifiers are promising solutions. The extension of SDN control, particularly for multi-domain transmission which would be expected in such an x-haul network, to optical networks will also be an enabling technology and much research is currently underway in the area [10]. Finally, it is worth noting that dense fiber deployments are underway in most cities, particularly where 5G is being introduced, in routes and volumes that would naturally allow for the formation of mesh networks [11].

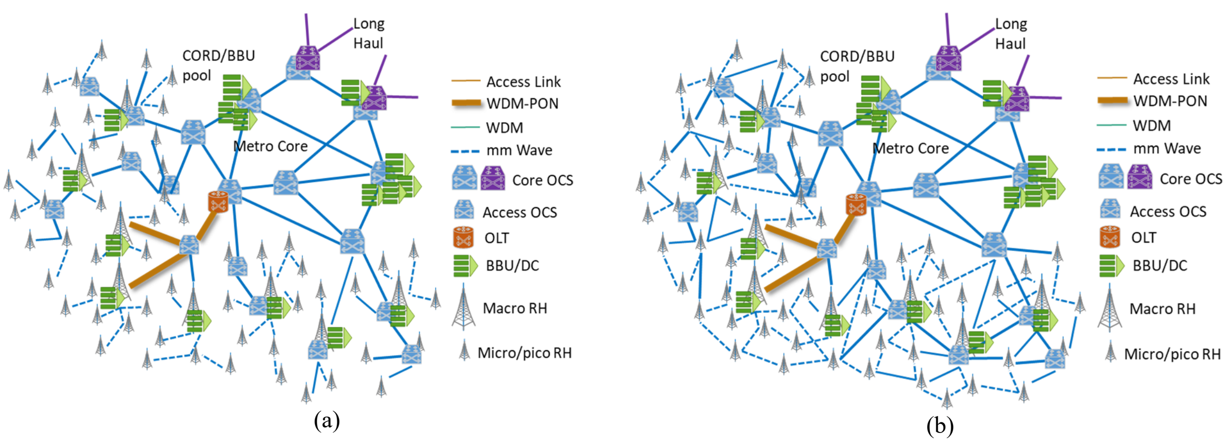


Fig. 2. (a) 5G x-haul networks without mesh structure. (b) 5G x-haul networks with mesh structure.

Optical mesh networks are a promising approach to 5G x-haul networks that allow for a convergence of access and core network technologies while providing the improved performance and resilience of a mesh topology. Key enabling technologies and application requirements are coming together in advantageous ways to support such an evolution.

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