An Overview Of Optical Architectures Necessary To Achieve 5G's Key Performance Indicators

A Technical Paper prepared for SCTE•ISBE by

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1. Introduction

Over the past year wireless operators around the world have focused on the deployment of broad 5G coverage. As we are just now beginning to see true 5G devices enter the consumer market, these recent upgrades will support new spectrum options and greater spectral efficiency provided by the 5G standard. The near-term objective is simple: make sure network capacity keeps up with consumer demand.

As we look beyond near-term consumer demand, the 5G standard includes a series of Key Performance Indicators (KPIs) to address a series of use cases beyond today's wireless networks capability. Consider remote driving or e-health use cases where not only bandwidth but also ultra-high reliability communications are required.   And possibly the use case supporting rapid forms of transit such as high-speed trains travelling up to 300+ miles per hour. Finally, consider the use case of remote driving cars where one millisecond of latency is critical to avoid a disastrous accident.

Each of the use cases noted and many more can be summarized into three categories: Ultra-reliable and low-latency communications (URLLC), Enhanced mobile broadband (eMBB) and Massive machine type communications (mMTC).   Figure 1 shows how the 5G KPIs are assigned to aforementioned categories. To achieve the full potential of one or more categories operators will need to acquire new spectrum and deploy fiber-based radio access network (RAN).

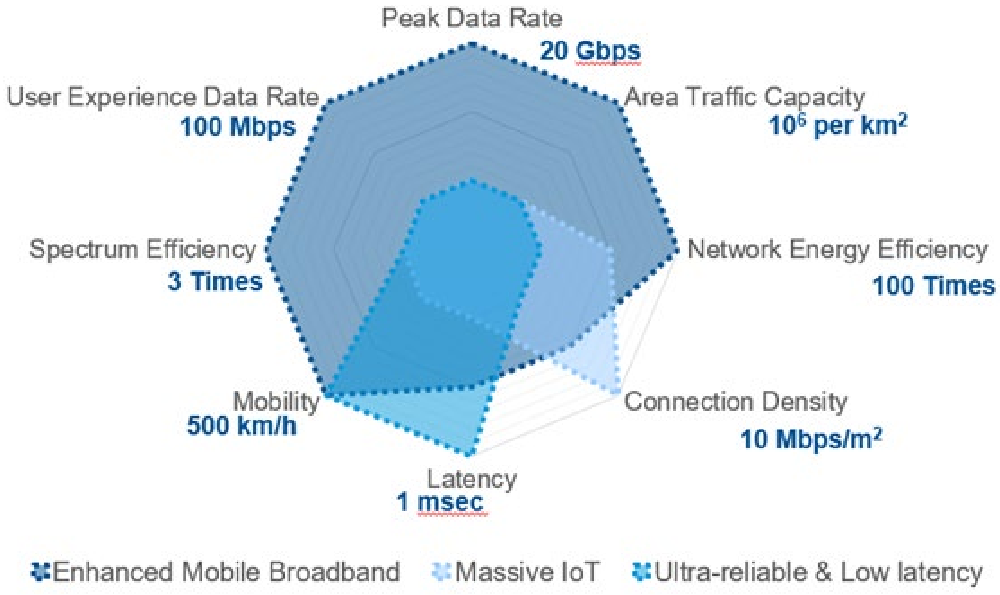


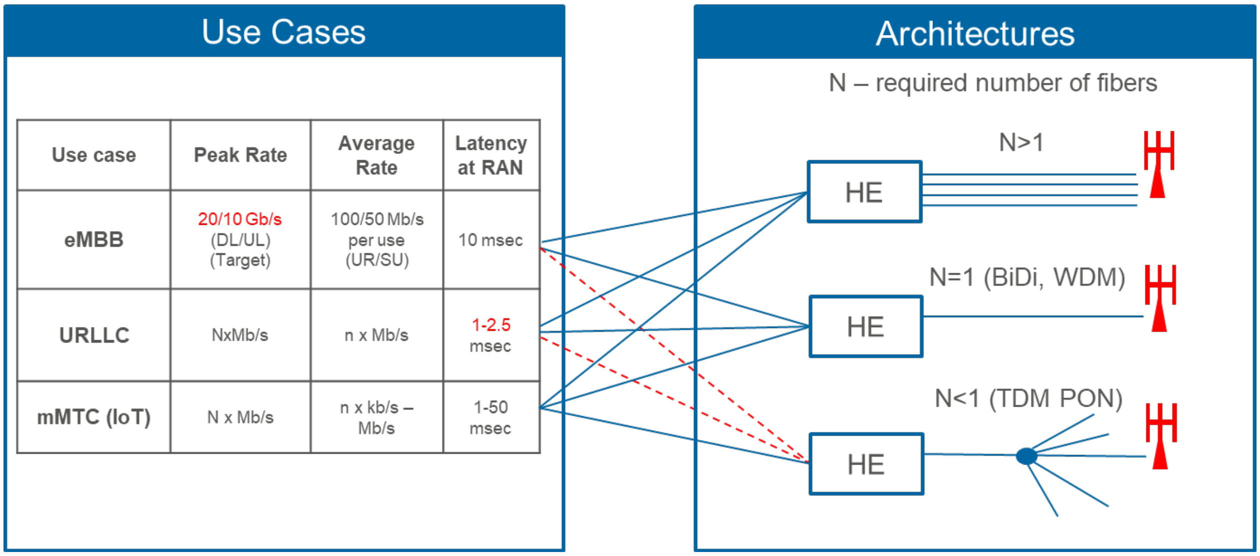
Figure 1 The 5G KPIs help define a set of categories which can be applied to use cases for the deployment of 5G services as depicted on this graphic

Existing spectrum deployed today by operators can support 4G subscriber’s user experience; however, to address many of the 5G KPIs operators will need to look at new spectrum options such as higher frequency spectrum typically referred to as millimeter wave (mmWave). The mmWave part of the spectrum has large (measured in hundreds of Megahertz(MHz)) available spectral bands to achieve user experience capacity demands. However, mmWave spectrum is more impacted by environmental factors such as rain and snow. In order to overcome those challenges operators must densify their wireless network deploying small cell radios along roadways rather than traditional towers which today have an

Inter Site Distance (ISD) in urban areas on the order of 1,500 feet. The next section will describe a series of architectures that provide the necessary capacity and performance requirements to meet the 5G KPIs. Each of the sections will provide an overview of the architecture, describe some of the salient features of the architecture and provide some guidance on when an architecture should be considered.

2. Optical architecture considerations to support 5G deployments

As operators look to densify their wireless networks to support 5G small cell technologies, transport of network capacity from radio head to extensible Radio Access Network (xRAN) locations is predicted to grow at a rate of ~32% per year between 2019 and 2025, according to the Ericsson Mobility Report[1]. (Corning research). This increased demand for 5G transport drives operators to deploy an optical infrastructure. Figure 2 illustrates how the different architectures to be discussed provide support for the various KPIs associated with 5G. The following sections provide guidance on network architecture considerations when densifying a 5G network.



Use case	Peak Rate	Average Rate	Latency at RAN
eMBB	20/10 Gb/s (DL/UL) (Target)	100/50 Mb/s per use (UR/SU)	10 msec
URLLC	NxMb/s	n x Mb/s	1-2.5 msec
mMTC (IoT)	N x Mb/s	n x kb/s – Mb/s	1-50 msec

Figure 2 High-level overview of the various use cases or categories for 5G services and how they align with different architecture choices (adopted from ITU G.sup.5GP draft)

2.1. Network architecture: Point-to-point or point-to-point WDM

The most direct way to provide a high-performance link for mobile transport (from xRAN to the radio) is a fixed, dedicated point-to-point (P2P) architecture. Historically, this is the de facto solution for mobile transport. This architecture requires a dedicated fiber connection from the xRAN location to each drop fiber serving the 5G radio. The optical fibers may reside within a dedicated cable supporting xRAN transport or may reside alongside other optical fibers in the cable supporting other services such as fiber to the home or enterprise-based services. The fiber, cable, connectivity, and infrastructure costs of a dedicated P2P architecture scale as demand for network connectivity grows. Proper up-front planning and over-provisioning of the infrastructure is critical to ensure that long-term growth opportunities will be accommodated with costs.

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[1] Ericsson, "Mobile data traffic outlook". June 2020. https://www.ericsson.com/en/mobility-report/reports/june-2020/mobile-data-traffic-outlook

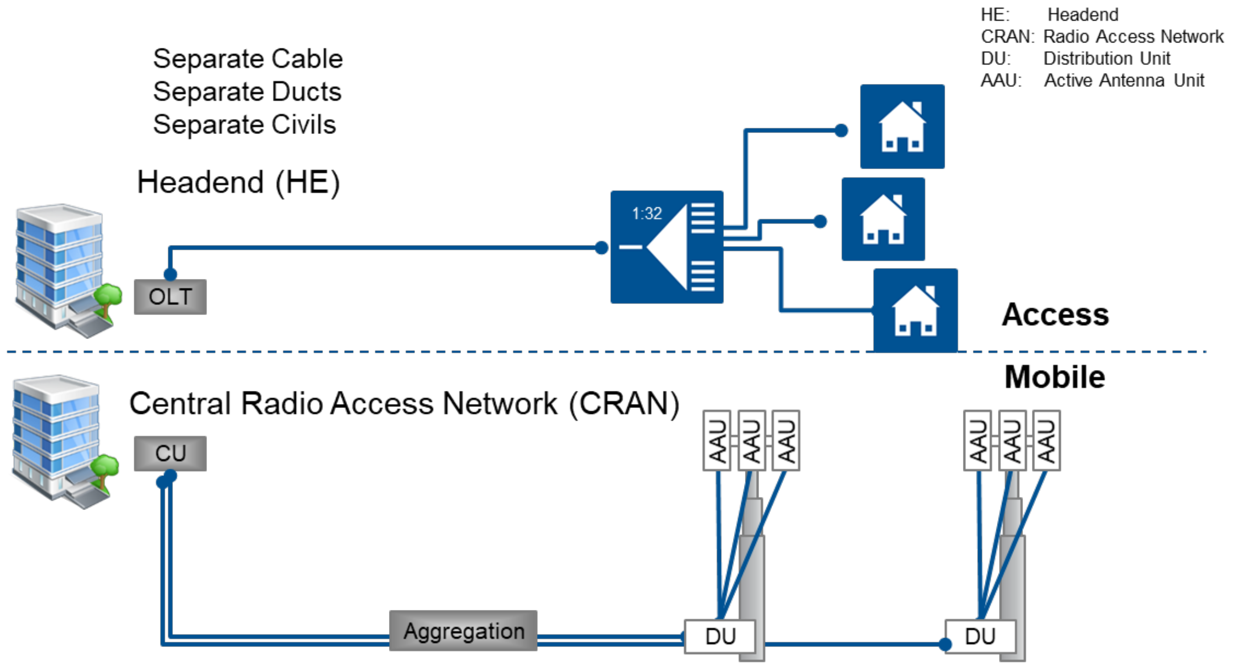

Figure 3 - A dedicated point-to-point network architecture employs a separate ODN for access and mobile radio connections

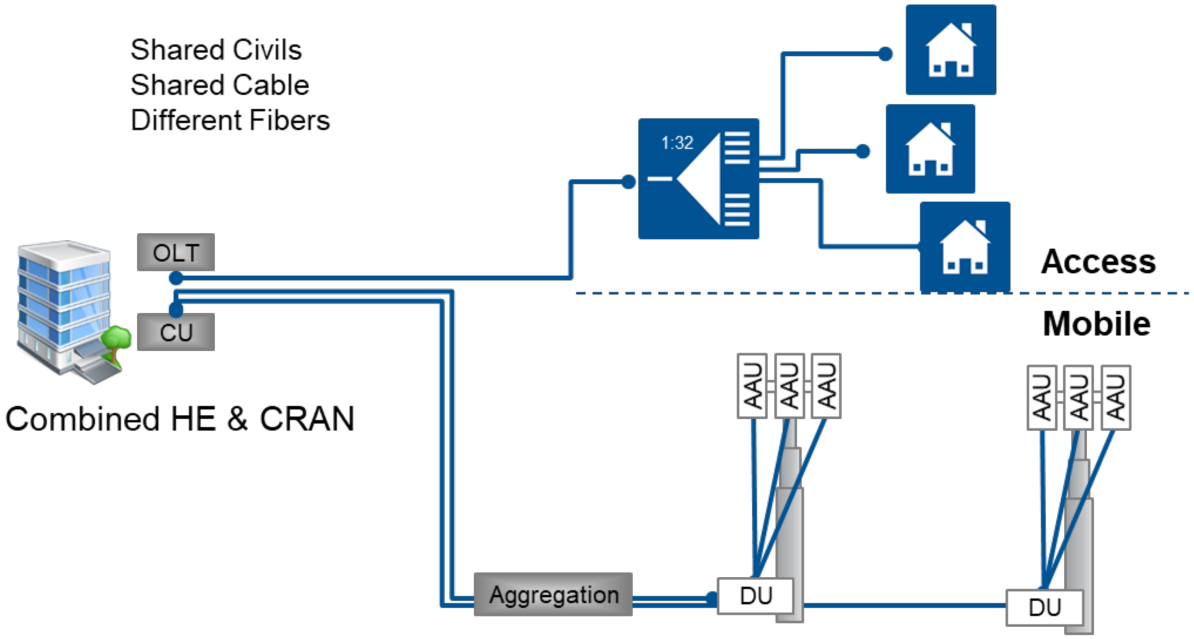

Figure 4 - A shared point-to-point network architecture has common infrastructure and cable in the feed portion of the ODN for access and mobile transport

If an operator's existing infrastructure has additional dark fiber within the feeder and distribution cables available for 5G transport or the operator has decided to deploy a new network, a P2P shared architecture is more viable for mobile transport. The low incremental cost and flexibility of dark fiber in a high fiber count cable to support network growth can help manage the uncertainty of future demand (new subscriber transport, connectivity, mobile densification). Since the incremental cost of fiber is small, sharing cable minimizes incremental cost in the feeder, and sharing duct avoids costly civil work and delays to acquire construction permits if duct capacity is available. Network access points that are already in place might also defer the cost of connectivity if they are adequately sized.

Both dedicated and shared P2P architectures as depicted in Figure 3 and Figure 4 benefit from commoditized, relatively low cost actives, utilizing standardized optics that don't require precise wavelength control or temperature control.

Sharing a cable sheath clearly reduces cable and installation costs in a fiber rich environment, and savings are improved as the number of antennas in the mobile transport links grows.   In many markets the availability of dark fiber is low in distribution areas which have experienced significant demand for network infrastructure. These are typically areas where network densification is necessary challenging operators to deploy new optical fiber to support small cell deployment. Hence, operators are very interested in reusing installed fiber in more fiber-lean transport options such as wavelength division multiplexing (WDM) and bi-direction transceivers (BiDi).

2.2. Network architecture: xWDM and BiDi technology

In situations where fiber planning cannot or did not over-provision fiber and cable, or where fiber is exhausted, a dedicated or shared P2P architecture will necessitate new cables and the possibility of significant civil costs if existing duct is not available. An alternative path operators may consider is leveraging WDM technology to extend the capacity carrying capability of exhausted or limited fibers deployed. These technologies enable multiple data channels at different wavelengths to be transmitted through one optical fiber simultaneously. The first and simplest example is the use of Bidirectional optics (BiDi), where two simplex fiber connections for carrying upstream and downstream signals are combined into a single fiber. BiDi technology utilizes a pair of distinct optical signal wavelengths for transmission in downstream and upstream directions. Because the wavelengths are different, upstream and downstream traffic do not conflict. This approach is similar to that used in a Passively split Optical Network (PON), which employ bidirectional transceivers with integrated WDM multiplexers (diplexers) to separate upstream and downstream channels. Since synchronization of upstream and downstream data streams is critical between an adaptive antenna unit (AAU) and distributed unit (DU), BiDi optics minimize the asymmetry in propagation delays since both upstream and downstream signals share a common optical fiber.

BiDi optics are more costly as a result of integrated transceivers with WDM multiplexers, but duplex transmission in a single fiber delays or avoids fiber exhaust, offsetting that cost. BiDi optics also help preserve space in the headend (HE) terminal, providing more shelf space for expansion. BiDi optics are increasingly common, relatively simple to implement, and can be installed in a greenfield or brownfield environment because no additional external optical modules (like WDM multiplexer) required.

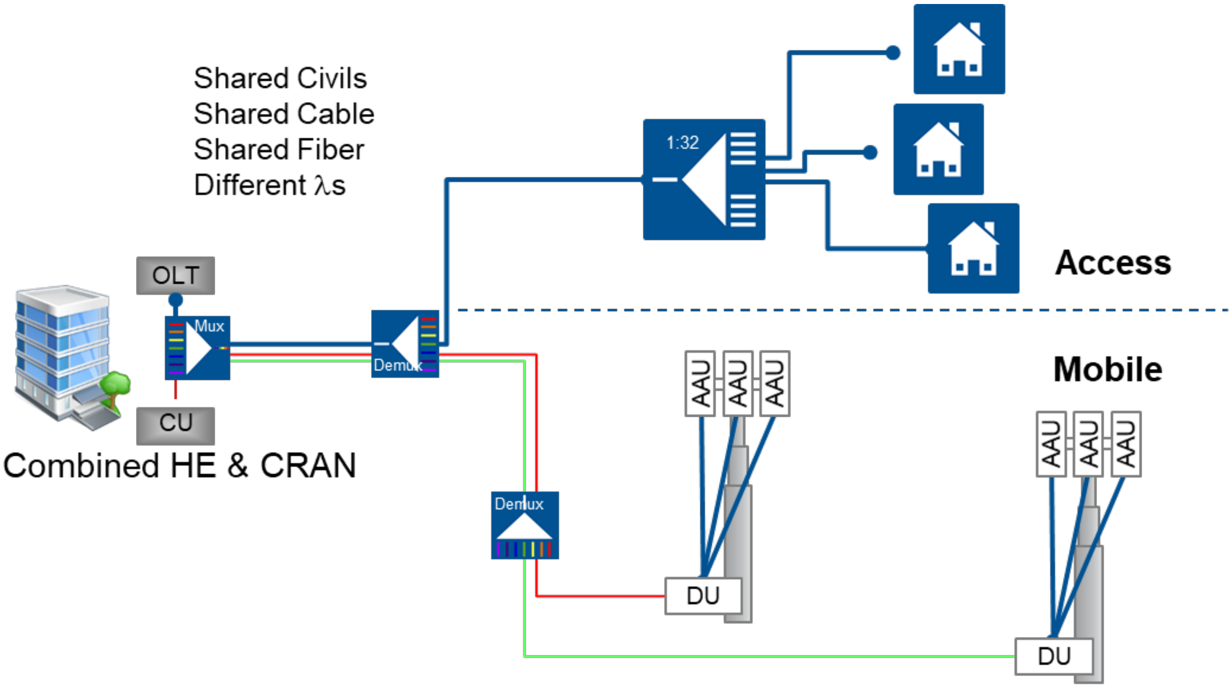

Figure 5 - xWDM converged access networks share infrastructure fiber and connectivity in the ODN extensively

Both Coarse (CWDM) and Dense (DWDM) xWDM technology are emerging in radio access networks, including unidirectional or BiDi optics. At the transmitter, a xWDM multiplexer combines the output from several optical transmitters for transmission over a single optical fiber. At the receiving end, a demultiplexer separates the combined optical signals and passes each channel to a matched optical receiver. Only one optical fiber per transmission direction is needed between multiple xWDM transceivers, unless BiDi optics are employed, in which case both directions are supported with a single fiber. Since multiplexer and demultiplexer channel ports are specific to a wavelength, transceivers must normally be manually selected to match a specific port’s wavelength channel.

Adding an additional mobile transport connection involves connecting a new optical transceiver at the HE or xRAN core to an open optical multiplexer port, and a new optical transceiver to a matched optical demultiplexer port at the radio head. While CWDM technology commonly supports 4, 6, 8 or 12 channels, the much high channel density associated with DWDM technology provides extensive capacity growth for areas with extremely high connection density or where cabling/infrastructure costs/civils are prohibitive.

Most optics in xRAN networks are being deployed at or below 10 Gbps today. More recently, 25 Gbps optics have emerged utilizing CWDM and Local Area Network WDM (LWDM) channel plans, leveraging cost reduced optics resulting from massive deployment of 25 Gbps in hyperscale data center applications. LWDM optics can operate in the O-band where fiber chromatic dispersion (CD) is low, minimizing chromatic dispersion penalty at longer distances, extending the reach of the Optical Distribution Network (ODN).

xWDM technology enables xRAN densification with ODN infrastructure costs that grow as the network grows. WDM multiplexer and demultiplexer technologies increase capital expenses, and xWDM transceiver optics are more costly than standard optics, especially at higher channel density, but once the initial capital expense is invested, adding additional capacity-becomes a matter of purchasing additional xWDM transceiver channels as densification increases.

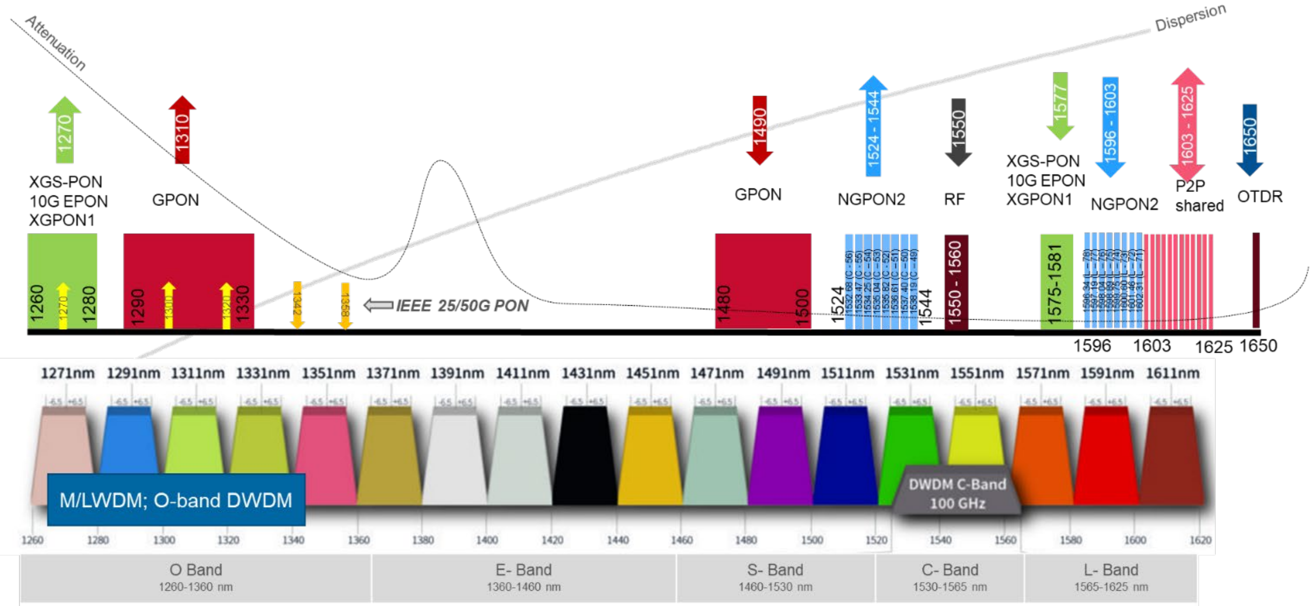

Figure 6 - Illustration of the various wavelengths utilized within the access network including IEEE and ITU-T PON standard wavelengths and xWDM (illustration courtesy of Mark Hess from Corning Optical Communications)

A xWDM based architecture also offers potential flexibility that cannot be achieved with a fiber rich P2P architecture utilizing standard optics. The origin and destination of traffic in the optical transport layer is normally fixed and inflexible in a dedicated or shared P2P architecture. Since the path in a xWDM architecture is dictated by the wavelength channel selected, multiple mobile antenna sites can be fed from a Macro or xRAN core over a common transport fiber. Extending this futher, technology such as reconfigurable add-drop multiplexers (ROADMs) may also be considered to support network topologies with path redundancy enabling the ability to route critical mobile traffic around failure points in the network.

Tunable and auto-tuned optics also offer the potential for simplifying implementation and maintenance through no-touch provisioning. Transport service to a new antenna or other end point can be turned up without having to carry stock and manually select or match transceiver wavelengths to specific WDM ports.

WDM convergence has emerged as way to further extend the capacity and performance of mobile transport networks. Employing a xWDM architecture retains an independent P2P connection from each xRAN terminal at the HE to each radio head, while sharing a common optical fiber in the feeder network.

2.3. Network architecture: Passive split optical networks (PON)

Since the early 2000's operators have been deploying fiber to the home networks utilizing passively split optical technology typically referred to as Passive Optical Networks (PON). The attraction of a PON network is the ability to deploy a single optical fiber deep within the network, passively splitting the fiber to support a number (e.g. 32 or 64) of subscribers. In comparison to a point-to-point active ethernet network where there is a dedicated optical fiber from the headend to the subscriber in a 1:1 ratio, within a

PON network the ratio is on the order of 1:32 or 1:64 thereby reducing the electronics needed at the headend and fiber capacity within the feeder network.

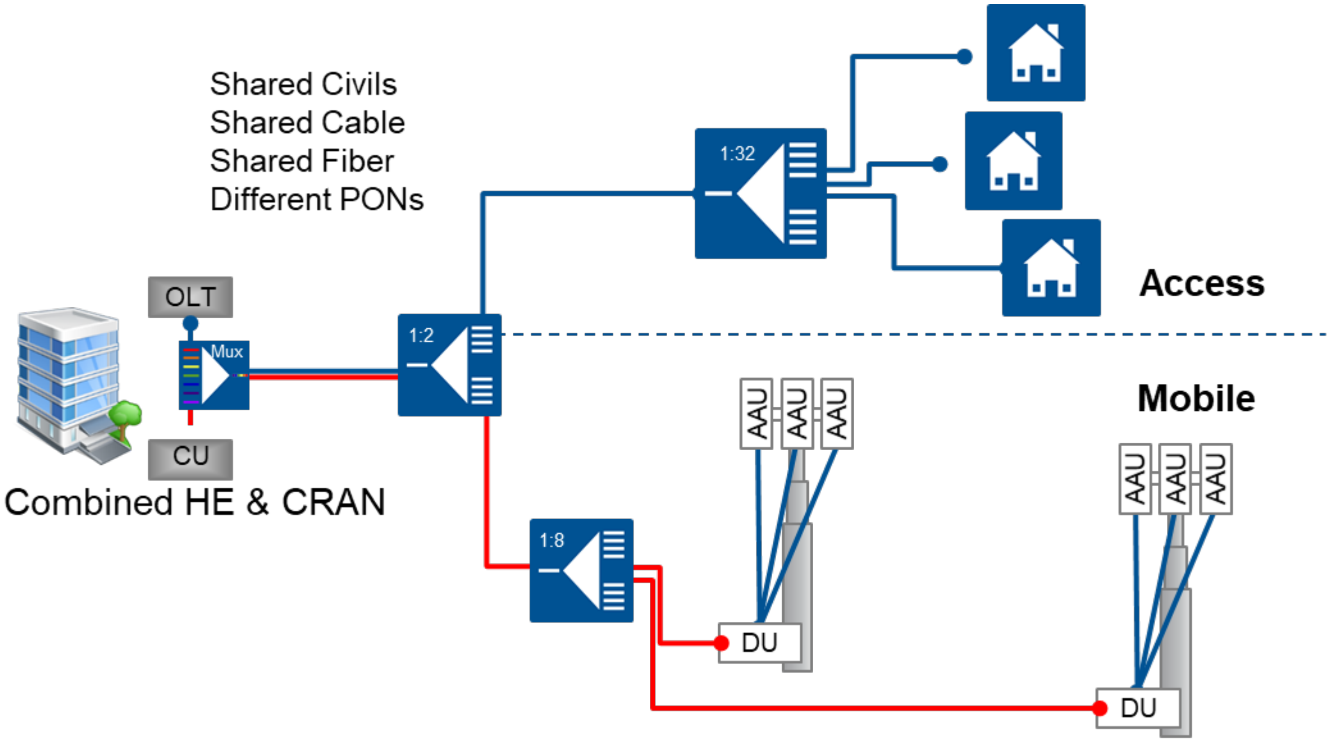

Figure 7 - Increases in capacity by PON standards allow for mobile transport and converged residential networks over a common ODN

Because a single fiber provides connectivity at the headend to multiple subscribers both ITU-T and IEEE have defined a series of standards to enable a one-to-many Time Division Multiplexing (TDM) (and more recently adding WDM) based communication protocol. This protocol is necessary to ensure upstream traffic from one subscriber device does not conflict with another subscriber. Both standards organizations have continued to evolve their PON standards to increase overall capacity provided over the PON while looking at ways to reduce latency and improve throughput.

Today many operators are deploying symmetrical 10Gbps defined by standards such as IEEE's 10Gbps E-PON or the ITU-T XGS-PON. Other operators are considering much higher capacity PON standards such as NG-PON2 also defined by the ITU-T to provide up to 40Gbps of symmetrical bandwidth over four separate 10Gbps wavelengths. Recently the IEEE released a new standard providing support of either 25Gbps or 50Gbps symmetrical bandwidth. These significant increases in speed provide operators with excellent capacity headroom for the residential subscriber but in many cases are being considered for a converged network supporting both residential subscribers, small enterprises and 5G transport for small cells.

In recent standards development attention has been made to ensure backwards compliance with existing standards or providing multiple wavelengths over a common ODN. Operators could consider utilizing the 10Gbps E-PON standard for residential services while looking at 25G or 50G NG-EPON to provide transport of small cell radios leveraging a common ODN.

As noted above, a PON network utilizes TDM arbitration to ensure each device has a clear channel for upstream communication. This arbitration does highlight a downside of PON networks, increased latency and in some cases increased jitter. In some of the 5G use cases noted above where millisecond latency is critical for communication, a PON based network may not be able to meet the end-to-end service objectives.

The jury is still out as to whether PON can meet the requirements for KPIs that would support all three eMBB, URLLC and mMTC categories in 5G networks. Operators will need to decide on the trade-offs inherent to PON based networks: cost advantages and efficient use of feeder fiber versus increased latency and potential long-term capacity constraints as compared to point-to-point-based architectures. Each operator will need to evaluate these trade-offs and decide what is best for their 5G objectives and network environment.

In Table 1 the authors have summarized a series of different attributes for operators to consider as they look to prepare for the build-out of a 5G transport network. Each of the different architectures have various salient features which will guide an operator on how to proceed based on their current capital constraints and network infrastructure in place.

Table 1 - Summary of the various attributes of different mobile transport architectures to address 5G network deployments

	Dedicated PT-PT	**BiDi PT-PT**	**Shared PT-PT**	**xWDM**	**PON**
Application	Transport	Transport	Transport & FTTH convergence	Transport & FTTH convergence	Transport & FTTH convergence
Fiber count	Highest	High	Highest	Lowest	Low
Adoption	Standard	Emerging	Common	Standard	Under Evaluation
Complexity	Moderate	Moderate	Moderate	Complex	Moderate
Flexibility	Low	Low	Moderate	High	High
Path Redundancy	Low	Low	Low	Capable	Low
Construction cost	Highest	Higher	Lower	Lowest	Lower

3. Conclusion

The growing demand by consumers on the mobile network is predicted to increase at a rate of 30% per year. This demand alone will push existing wireless technology and architectures to the brink of capacity. The deployment of 5G wireless networks does provide operators an opportunity to gain additional spectral efficiency; however, this alone will not be enough. Further, emerging use cases are pushing additional capacity, latency and connectivity requirements, demanding new spectrum and increasingly dense radio networks.

This paper provided an overview of essential architectural approaches, describing deployment issues to consider based on a carrier's use cases. The authors are also aware that combinations of these architectures as well as other technologies are worthy of consideration. These may include the possible use of Cable Labs Data-over-Cable Service Interface Specifications (DOCSIS®) or Integrated Access-

Backhaul (IAB) technology to provide this transport from the radio site to the xRAN location (or intermediate location). Although these are acceptable technologies, we challenge each operator to look over the 10-year horizon to ensure the infrastructure dollars spent today are capable of meeting the demands of the longer-term network demands.

Abbreviations

AAU	Active Antenna Unit
BiDi	Bi-direction Transceiver
CD	Chromatic Dispersion
CRAN	Centralized Radio Access Network
CU	Central Unit
CWDM	Coarse Wave Division Multiplexing
DU	Distribution Unit
DWDM	Dense Wave Division Multiplexing
eMBB	Enhanced Mobile Broadband
HE	Headend
IAB	Integrated Access-Backhaul
ISD	Inter Site Distance
KPI	Key Performance Indicator
LWDM	Local Area Network Wave Division Multiplexing
MHz	Megahertz
mMTC	Massive Machine Type Communications
mmWave	Millimeter Wave
ODN	Optical Distribution Network
P2P	Point to Point
PON	Passive Optical Network
RAN	Radio Access Network
ROADMs	Reconfigurable Add-Drop Multiplexers
TDM	Time Division Multiplexing
URLLC	Ultra-reliable And Low Latency Communications
WDM	Wavelength Division Multiplexing
xRAN	Extensible Radio Access Network