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Charting the Future of Optical Access Networks

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Abstract *Whereas the access segment of data communications was a relatively late adopter of optical technologies compared with backbone and metro, it quickly became the main battleground. Based on Verizon's experience, we analyze the operator's broadband strategy, review the standardization landscape, and discuss recent innovations in optical access. ©2022 The Authors*

Introduction

In recent years, fast-evolving digital consumption habits and new business models are calling for network re-design to address the complexity of the ecosystem and to provide sufficient flexibility. Architecture designs utilizing existing fiber networks and the build-out of 5G infrastructure will power solutions to achieve low latency and increased broadband capacity.

As a company which has been offering commercial services using the passive optical network (PON) access technology for over 30 years, Verizon has designed the conceptual architecture known as Intelligent Edge Network, or iEN, to meet the new demands. Figure 1 shows a diagram of iEN, in which unified transport, NG-PON2 OLT, and centralized RAN equipment share an access site to provide mobile wireless, fixed wireless, fiber-to-the-home/ building/cell, and point-to-point fiber connectivity.

In this paper, we first outline Verizon's broadband strategy for its "FiOS" fiber-to-the-premises service, wireless back/fronthaul (xHaul) transport, and Fixed Wireless Access (FWA) services, followed by an overview of optical access systems and standards. We then discuss several challenges encountered during commercial deployments and technology innovations derived from these challenges before the conclusion.

Verizon's broadband strategy

For a network operator, it is imperative that the network is architected to be flexible, resilient, and cost effective in order to support a wide range of business cases and provide the network as a service. As the optical fiber infrastructure is fundamental to such architecture, it has been Verizon's strategy to invest heavily in building out and managing its own fiber infrastructure, as well as in converting central offices to all fiber. By transforming the network onto fiber, annual operational and energy savings of about $180 million USD and 60M kWh have been realized.

As a major wireline and wireless service provider, Verizon uses its optical fiber infrastructure as the foundation for three key broadband services: FiOS, wireless xHaul transport, and FWA. In this paper, we focus the discussion of technology innovations supporting these three services.

<u>Fiber-to-the-Premises (Verizon FiOS)</u>

Since its rollout in 2005 as the first fiber-to-the-home service in the US, FiOS continues to be a fast-growing service for both residential and business customers. Passive optical network (PON) is the enabling technology for FiOS. Currently, the majority of the FiOS network is on G-PON, which allows providing customers with the service rate of nearly 1 Gb/s. The higher service rates, reaching approximately 8.5 Gb/s,

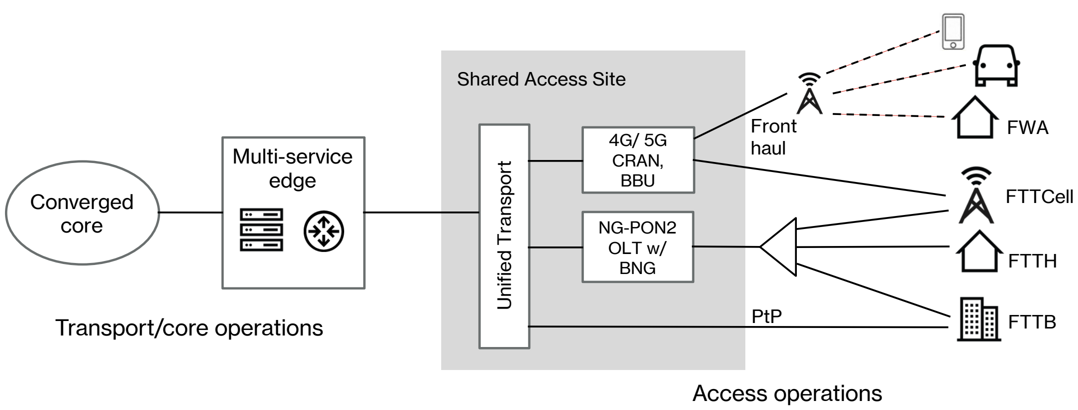

Fig. 1 Conceptual architecture of Verizon's Intelligent Edge Network

with symmetrical upload and download speeds, are made possible by upgrading from G-PON to NG-PON2 [1][2][3]. One example is the multi-gig home internet service that Verizon offers in New York City. The further service rate increase, up to theoretical 34 Gb/s, can be realized by bonding multiple NG-PON2 wavelength channels.

Wireless xHaul transport

To support 5G network rollout, Verizon has been connecting cell sites to its own fiber assets. This fiber connection enables the network to scale transport easily and cost effectively, and improves reliability, especially as data usage grows. As the bandwidth demand continues to grow significantly, high speed 100 Gb/s bidirectional point-to-point optical access technology servicing 10-40km is a desired near-term solution for wireless xHaul transport.

Fixed wireless access (FWA)

FWA technology provides broadband services to customers through connecting wireless network enabled customer premise equipment to the public wireless network. FWA is arguably the fastest growing service offering especially in urban and dense urban areas. In 2021, the total number of Verizon’s FWA subscribers was about 100,000. This number is expected to grow to up to 5 million in 2025, with 50 million household and 14 million business locations passed.

As FWA relies on the wireless network, it also requires the same high-speed xHaul solution as for the wireless xHaul transport.

Overview of optical access systems and standards

The concept of optical access refers to the first mile network connecting client equipment to the network provider's central offices. The connection can be over direct point-to-point (PtP) or point-to-multipoint (PtMP) optical distribution network, Typically, PtP links are specific for enterprise business customers or wireless xHaul transport, while PON-based PtMP networks can serve all customers.

Point-to-point optical distribution

Operators are experiencing growing demands for bidirectional (BiDi) PtP links to support data center interconnects, high bandwidth Ethernet virtual private line, and wireless xHaul transport. Deployments of 100 Gb/s for 10-40km distance are currently in small volumes; however, strong customer demands are fuelling the growth. Bandwidth of 400 Gb/s is currently being planned targeting deployments in around 2023.

The two leading standards-developing organizations in the industry, ITU-T and IEEE 802.3, have been collaborating on specifying high speed BiDi PtP systems for optical access. The IEEE 802.3cp Task Force completed the PHY and MAC layer specifications in 2021 covering 10/25/50 Gb/s for 10/20/40km reach [4]. The ITU-T Study Group 15 Question 2 (Q2/15) group published end-to-end specifications (PMD, TC, service requirements, OAM) covering 10/25/50 Gb/s for 20/40km distance and begun the project on 100 Gb/s [5]. A new project tackling the PHY and MAC layer for up to 400G BiDi PtP is under discussion in IEEE 802.3.

Point-to-multipoint optical distribution

Since the initial standardization in early 2000, PON systems have gained world-wide acceptance as the primary PtMP technology for fiber-to-the-x services [6]. The overall number of optical network unit (ONU) ports that have been shipped worldwide since then is approaching one billion.

The G-PON system with the line rates of 2.5 Gb/s downstream and 1.25 Gb/s upstream is the most widely deployed PON system to date. Following the success of G-PON, multiple PON generations supporting nominal line rates of 10 Gb/s and higher have been standardized. Mass commercial deployments of 10 Gb/s PON systems are well underway.

For a single-wavelength system, asymmetric 10 Gb/s PON (XG-PON), symmetric 10 Gb/s PON (XGS-PON), and 50 Gb/s PON have been standardized by the ITU-T [6]. In a parallel development, the 25G-PON multi-source agreement group is creating solutions to address different operators’ needs.

Exploring the wavelength domain, the ITU-T published the NG-PON2 standards, which adopt the time and wavelength division multiplexing (TWDM) technology with four, and potentially eight, bidirectional TDM wavelength channels, each having the symmetric line rate of 10Gb/s. The aggregate service capacity is about 34 Gb/s in each of the transmission directions. An optional overlay of eight 10 Gb/s PtP WDM channels is also part of the standard. The IEEE 802.3 followed suite and standardized a 50 Gb/s Ethernet PON system by multiplexing two 25 Gb/s TDM wavelength channels [7].

Currently, an ongoing project in the ITU-T aims to standardize a WDM-PON with up to 20 logical PtP wavelength channels, each having symmetric 25 Gb/s line rate per transmission direction [8].

Challenges and innovations of optical access technologies

NG-PON2 has become the optical access technology of choice for Verizon, not just because of the capacity, but also due to its coexistence characteristics and the unique carrier-grade properties that only a multi-wavelength optical access system can provide. NG-PON2, operating entirely in the S, C, L bands of the optical spectrum, allows a risk-free coexistence with G-PON which operates in the O-band. This feature distinguishes NG-PON2 advantageously from the single channel XG(S)-PON systems operating in the O-band and carrying an inherent risk of cross-system interference with G-PON in the upstream direction. Besides, NG-PON2 offers the wavelength channel protection to achieve increased service reliability, non-service-affecting ONU activation, non-service-affecting OLT maintenance, extended rogue mitigation capabilities, and other multi-wavelength-specific features of utmost importance to an operator.

Verizon is presently deploying NG-PON2 for multi-gigabit Ethernet residential FiOS service. We expect additional economies of scale by combining business, residential, and wireless transport services on the same infrastructure.

Several challenges encountered during NG-PON2 development and deployments have led to technological innovations that are essential to the successful commercial rollout.

The first challenge is the bulkiness of directly attaching an ONU to an infrastructure unit. Pluggable ONUs in the SFP+ form factor, also known as an ONU-on-a-stick, with NG-PON2 specific linear dimensions, were developed to address that issue and to eliminate the need for heterogeneous power sources. These pluggable ONUs connects directly into a backhaul SFP+ cage of any device, such as a 5G Ethernet-based integrated radio unit or an Internet-of-Things terminal, turning them into a PON client.

The second challenge is to provide service rates over 10 Gb/s to premium customers. This challenge is solved by the innovation of a bonded ONU. Such an ONU operates on multiple wavelengths simultaneously allowing to offer a single customer the service rates in excess of the capacity of single wavelength channel. In the case of NG-PON2, it means the service rates all the way up to 34 Gb/s.

The third challenge, which applies to all PONs, is the bandwidth efficiency at high line rates. Verizon contributed several protocol-based innovations that have recently been incorporated in the ITU-T standard to address this challenge.

From inception, the TDM PON systems have used the principle of direct bandwidth allocation to each active ONU, even if only a few ONUs have traffic to send. The OLT may choose to allocate bandwidth to multiple ONUs on a contention basis for performing a specific function, e.g., ONU activity indication, while suppressing direct allocations to individual ONUs. If the OLT detects a collision in a time interval associated with a contention-based allocation, it temporarily restores the directed allocations to identify the ONUs that do require upstream transmission bandwidth and to satisfy their needs. The use of contention-based allocation for ONUs with no upstream traffic typically may improve upstream bandwidth utilization by 15 to 25%.

During the ONU activation phase, the identities of ONUs are not known and, therefore, another collision resolution method is needed. The conventional time-randomized persistent retransmission method is losing efficiency with increased line rates. A new tree-splitting collision resolution protocol based on OLT feedback allows to notably improve overall activation time, especially after an event, such as line card reboot, that affects multiple ONUs concurrently.

For BiDi PtP systems at 100 Gb/s line rate and above for access applications, the general consensus is to adopt the optics developed for datacenter interconnects applications. However, the combination of high speed, long reach (up to 40 km), and wavelength resources in the O-band pose new challenges. Transmitter power and receiver sensitivity, chromatic dispersion, and fiber nonlinearity such as four-wave mixing need to be carefully investigated. At 100 Gb/s and 40km, these technical aspects are coming into forefront. At 400G and long reach, coherent technology might be the only option. These topics are currently being studied in the ITU-T and IEEE 802.3 [9].

Conclusions

New business models for fixed and wireless services such as FiOS, wireless xHaul transport, and FWA, have motivated Verizon to develop and deploy broadband access technologies using PON and BiDi PtP access. Innovations in NG-PON2 to solve challenges encountered during deployments include low power consumption pluggable SFP+ ONUs, wavelength channel bonding to achieve service rates over 10 Gb/s, and the contention-based operation of the PON to improve bandwidth efficiency. Further study is needed for BiDi PtP systems at line rates in excess of 100 Gb/s and reach longer than 40 km. The standardization discussions in the ITU-T and IEEE 802.3 are ongoing.

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