Next-Generation Broadband Access Networks and Technologies

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(Invited Paper)

***Abstract*—This paper reviews the future directions of next generation passive optical networks. A discussion on standardized 10 Gb/s passive optical network (PON) systems is first presented. Next, new technologies that facilitate multiple access beyond 10 Gb/s time division multiple access (TDMA)-PONs will be reviewed, with particular focus on the motivation, key technologies, and deployment challenges. The wavelength division multiplexed (WDM) PON will be discussed and in combination with TDMA, the hybrid WDM/TDMA PON will be reviewed in the context of improving system reach, capacity, and user count. Next, discussions on complementary high-speed technologies that provide improved tolerance to system impairments, capacity, and spectral efficiency will be presented. These technologies include digital coherent detection, orthogonal frequency division multiple access (OFDMA), and optical code division multiple access (OCDMA).**

***Index Terms*—Coherent access networks, long-reach PON, optical code division multiple access (OCDMA), orthogonal frequency division multiple access (OFDMA), 10 GE-PON, WDM PON, XG-PON.**

I. INTRODUCTION

THE exponential growth in Internet traffic and bandwidth-intensive applications is continuing to fuel the penetration of fiber networks into the access network segment. A recent Cisco forecast projects that between the years of 2009 and 2014, global Internet traffic will grow by a factor of four with video-rich services being the most prevalent traffic [1]. Advanced Internet video such as 3-D video and super HD video, is projected to increase by 23 fold, whereas video communications traffic, e.g., video calling and video conferencing, will increase by 7 fold [1]. By 2014, 66% of mobile data will comprise video traffic [1]. Emerging applications such as Ultra HD video and free viewpoint video will continue to push bandwidth requirements even further. In future-proofing against the forecasted increase in bandwidth demands, Fiber-To-The-x (FTTx) networks have been deployed in various parts of the world. The models of FTTx, namely FTTH (home), FTTC (curb) and FTTB (building) offer direct fiber connection to or close to the home. The FTTx models are based on either a physical point-to-multipoint (P2MP) or point-to-point (P2P) topology [2], as illustrated in Fig. 1.

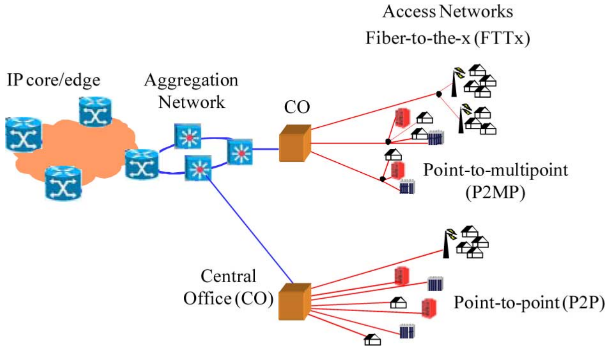

Fig. 1. Schematic of network structure showing the physical topology options of access networks.

Most FTTx models are based on the passive optical network (PON) due to its cost effectiveness and low energy consumption per bit [3]. The PON which has a physical P2MP topology, has many benefits stemming from its passive power splitter based optical distribution network (ODN). For N subscribers, a PON requires a single transceiver at the central office (CO), giving rise to $N+1$ transceivers overall. The shared feeder fiber saves CO space and allows for easy termination. Its disadvantage lies in the limitation in further scaling of bandwidth, reach, and user count due the power splitting nature of the ODN. The dedicated bandwidth and fiber between the CO and each user in the P2P topology overcomes this limitation, in addition to providing other beneficial features such as data privacy and security. The main disadvantage of P2P is the large fiber count and terminations at the CO requiring high density fiber management. Nonetheless, it is important to note that although the focus of this paper is on PON technologies, P2P Ethernet is popular in some parts of the world, e.g., Japan, China and Sweden, and has been deployed to connect business customers with high bandwidth needs [4].

Owing to key enabling technologies such as low loss passive optical splitters and high-speed burst mode transceivers, Gigabit PON (GPON) is now being deployed in North America and Europe, whereas Gigabit Ethernet PON (GE-PON) has emerged as the dominant PON system in Asia. These commercial PON systems are based on the ITU-T G.984 Gigabit PON (GPON) standard [5] and the IEEE 802.3ah Gigabit Ethernet PON (GE-PON)

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standard [6], respectively. Both GPON and GE-PON are classified as time division multiplexed/time division multiple access (TDM/TDMA) PONs. In the downstream direction, encrypted information is broadcast to all end users in timeslots at a line-rate of 2.5 Gb/s for GPON and 1.25 Gb/s for GE-PON. Each end user receives all timeslots but selects data addressed only to it. In the upstream direction, burst mode TDMA is used between network users to share the aggregate 1.25 Gb/s upstream bandwidth for GPON and GE-PON. A dedicated radio frequency on a wavelength channel distinct from the upstream and downstream wavelength channels can be added for broadcast TV/video transmission.

While the passive splitter based ODN of GPON and GE-PON brings with it many advantages as discussed in the preceding paragraph, its splitter loss is a strong function of the number of supported users thereby constraining any possible increase in user count, reach, and/or average user data rate. In that respect, 10 Gb/s PON systems have recently been standardized to support future high bandwidth business, residential, and backhauling services. These standards, defined by both IEEE and ITU-T, allow backward compatibility and co-existence with the current generation PONs, enabling progressive upgrades with minimal financial investment on the ODN and minimal operational impact on existing users.

According to [7], the requirements of major carriers for future access networks include: (a) simultaneous support of legacy, new, and mobile backhaul services; (b) maximum reuse of existing ODN; (c) flexible bandwidth upgradeability and management; (d) capability to provide higher bandwidth/capacity and split ratio than existing access networks; (d) optimized technology combinations in terms of cost, performance and energy savings; and (e) non-intrusive fault diagnostics with rapid restoration of services. New access technologies beyond the 10 Gb/s TDM/TDMA systems must be designed to support symmetrical average data rates of $\sim$1 Gb/s per user, an extended system reach of 60 to 100 km, a high user count of up to 1000, and heterogeneous service convergence, while meeting the cost constraints of the access market.

New access technologies that can potentially satisfy the above criteria can be grouped into those that deploy wavelength division multiplexing (WDM) technology and those that combine WDM technology with high-speed technologies through a hybrid PON solution. In a pure WDM-PON, each user is given dedicated capacity through the assignment of unique upstream and downstream wavelengths. In a hybrid WDM/TDMA-PON, capacity on each wavelength is shared dynamically via TDMA between many users. With regards to multi-user wavelength sharing, competing multiple access technologies such as orthogonal frequency division multiple access (OFDMA) [8]–[12] and optical code division multiple access (OCDMA) [13]–[15] offer a more flexible allocation of upstream bandwidth without the constraint of burst mode operation associated with TDMA operation. The use of advanced modulation formats and digital coherent detection [16]–[18] in combination with some of the above mentioned hybrid PONs can further increase the capacity, system reach, and user density, and also provide wavelength selectivity without overhauling the ODN. Fig. 2 charts the future trends of next generation passive optical networks, highlighting a number of competing access technologies that are complementary to the WDM technology.

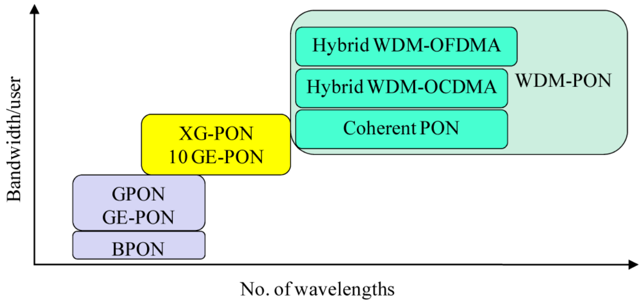


Fig. 2. Future trends of next generation passive optical networks.

This tutorial paper will provide a review of the emerging trends in next generation passive optical networks and technologies. In Section II, a discussion of the standardized 10 Gb/s PON systems, namely 10 GE-PON and XG-PON will be presented. In Section III, key technologies and typical colorless architectures of WDM-PONs will be discussed. In Section IV, long-reach passive optical networks will be reviewed, with particular focus on extender reach technologies and challenges in deploying these networks. In Section V, technologies that complement the WDM technology such as digital coherent detection, OFDMA, and OCDMA, will be discussed. The focus in this section will be on recent research that investigates the feasibility and relevance of applying these technologies in the access segment to meet next-generation requirements. A summary of this paper is provided in Section VI.

II. 10 G PASSIVE OPTICAL NETWORKS

In view of supporting future bandwidth growth over existing ODNs, the IEEE and the ITU-T with the Full Services Access Network (FSAN) group, have defined their respective 10 Gb/s solution, namely IEEE Std. 802.3av 10 GE-PON [19] and ITU-T XG-PON [20]–[22]. For both these standards, sharing of upstream capacity is coordinated via TDMA.

Efforts in standardizing 10 GE-PON was carried out by the P802.3av Task Force, resulting in the IEEE Std. 802.3av 10 GE-PON which supports symmetric (10.3 Gb/s downstream and upstream) and asymmetric (10.3 Gb/s downstream and 1.25 Gb/s upstream) line-rate operations. The latter option was included to reflect the asymmetric traffic of IP video services [23]. Field trials of symmetric 10 GE-PON have been reported, primarily by China Telecom and China Mobile, for their multi-dwelling units (MDU) market [23].

In comparison, the FSAN group has been studying next generation solutions to facilitate high provision, large split ratio, and extended reach. In addressing NGA1 which main focus is to develop a PON that is compatible with an operational GPON, ITU-T with FSAN has defined XG-PON1 which supports an asymmetrical bandwidth capacity of 10/2.5 Gb/s [20]–[22]. The XG-PON1 system is described in the ITU-T G.987 series of recommendations. Enhancing security through authentication of management messages and minimizing energy consumption through powering down parts or all of the ONU are key features introduced in the specification of XG-PON1. The specified methods in minimizing the energy consumption of the ONUs include (a) powering down user network interfaces that are not actively used (b) operating in "doze" mode whereby the ONU transmitter is powered down when the user has no real data to send, and (c) operating in "sleep" mode whereby both transmitter and receiver are powered down when the ONU is idle. Further, ITU-T is providing a concept specification for XG-PON2 with a symmetrical bandwidth capacity of 10/10 Gb/s [20]–[22]. To date, Verizon has successfully tested both XG-PON1 [24] and XG-PON2 [25] over its existing GPON FiOS network, demonstrating co-existence with its commercially deployed GPON system with video overlay.

To compensate for the decrease in optical sensitivity of 10 Gb/s receivers, forward error correction (FEC) has been specified in both standards. For XG-PON, non-return-to-zero (NRZ) line coding is used with FEC being mandatory in the downstream direction. The selected FEC code is based on the RS(248, 216) block code. FEC is optional in the upstream direction [7]. For 10 GE-PON, FEC is mandatory for the symmetric network with the selected FEC code based on the RS(255, 223) code. For the asymmetric 10 GE-PON network, the upstream 1 Gb/s links can optionally use the IEEE GE-PON FEC [23]. To enhance coding efficiency in 10 GE-PON, 64b/66b line coding is used instead of the conventional 8b/10b coding in GE-PON.

Fig. 3 illustrates the upstream and downstream wavelength bands for XG-PON, 10 GE-PON, GPON, GE-PON, and RF video overlay. GPON and GE-PON use 1480–1500 nm for downstream transmission and 1550–1560 nm for RF video overlay. For upstream transmission, GPON uses the 1290–1330 nm waveband whereas GE-PON uses the entire O band. In order to coexist with legacy systems and those implemented with RF video overlay, both XG-PON and 10 GE-PON specify the O-minus band (1260-1280 nm) for upstream transmission and the L-band (1575–1580 nm) for downstream transmission. Note that since the upstream waveband of 10GE-PON overlaps with that of the GE-PON, multi-rate upstream reception at the OLT is specified in the 10 GE-PON specifications. The multi-rate upstream burst mode receiver must however be able to accommodate 10 Gb/s 64b/66b coded packet bursts as well as 1 Gb/s 8b/10b coded packet bursts. Further, existing 1 Gb/s as well as new 10 Gbp/s ONUs must coordinate their transmissions via TDMA [23].

In terms of link budget, 10 GE-PON specifies a loss budget of 29 dB in addition to supporting channel insertion losses of 20 dB and 24 dB of the GE-PON standard [23]. As for XG-PON, two loss budgets have been specified. Nominal 1 budget is 29 dB, allowing XG-PON to coexist with standardized GPON and GE-PON systems. Likewise, Nominal 2 budget is 31 dB, allowing XG-PON to coexist with the super-standard 29.5 dB GPON system [26].

III. WAVELENGTH DIVISION MULTIPLEXED (WDM) PONS

The WDM-PON is currently being considered by the FSAN group as a potential base technology for NGA2. The main focus of NGA2 is on a long term access solution beyond the 10 Gb/s TDMA system with an option of an entirely new optical network type [26]. The use of WDM in access networks was conceived in the late 1980s [27]–[29]. Significant progress in key enabling technologies such as the athermal arrayed waveguide grating (AWG), WDM filter, reflective semiconductor optical amplifier (RSOA) and Fabry–Perot laser diode (FP-LD) has fueled the resurgence of WDM-PON research in the last 10 years, resulting in a number of commercialized systems that are currently deployed for business and wireless/wireline backhaul markets [30], [31].

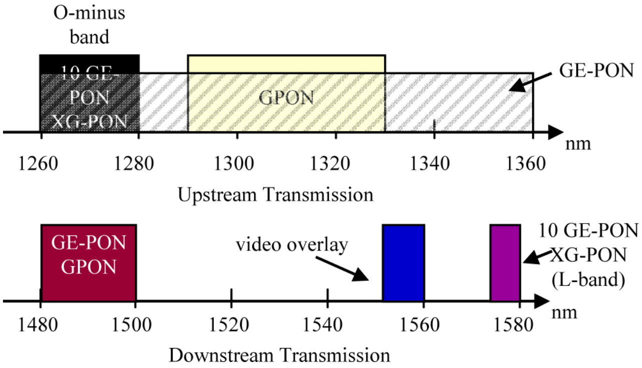


Fig. 3. Upstream and downstream wavelength plan for XG-PON, 10 GE-PON, GPON, and 1 GE-PON.

The use of WDM in the access segment is further justified in networks that support video services. As discussed in the introduction, video traffic is expected to increase significantly over the next few years. The quality of service (QoS) of video services is paramount and must be maintained over a long period of connection time. This requirement reduces statistical multiplexing gain amongst multiple users and necessitates a dedicated bandwidth per user. As such, WDM is particularly suited as a multiple access technology in video rich access networks.

A. *WDM PON Architecture*

Fig. 4 illustrates a typical WDM PON architecture comprising a CO, two cyclic AWGs, a trunk or feeder fiber, a series of distributions fibers, and optical network units (ONUs) at the subscriber premises. The first cyclic AWG located at the CO multiplexes downstream wavelengths to the ONUs and demultiplexes upstream wavelengths from the ONUs. The trunk fiber carries the multiplexed downstream wavelengths to a second cyclic AWG located at a remote node. The second AWG demultiplexes the downstream wavelengths and directs each into a distribution fiber for transmission to the ONUs.

The downstream and upstream wavelengths allocated to each ONU are intentionally spaced at a multiple of the free spectral range (FSR) of the AWG, allowing both wavelengths to be directed in and out of the same AWG port that is connected to the destination ONU. In Fig. 4, the downstream wavelengths destined for ONU 1, ONU 2, ..., and ONU N, are denoted $\lambda_1, \lambda_2, \ldots$, and λ_N respectively. Likewise, upstream wavelengths from ONU 1, ONU 2, ..., and ONU N, that are destined for the CO are denoted $\lambda_{1'}, \lambda_{2'}, \ldots$, and $\lambda_{N'}$ respectively. In a typical WDM PON, wavelength channels are spaced 100 GHz (0.8 nm) apart. In systems classified as dense WDM-PON (DWDM), a channel spacing of 50 GHz or less is deployed.

Although a WDM PON has a physical P2MP topology, logical P2P connections are facilitated between the CO and each

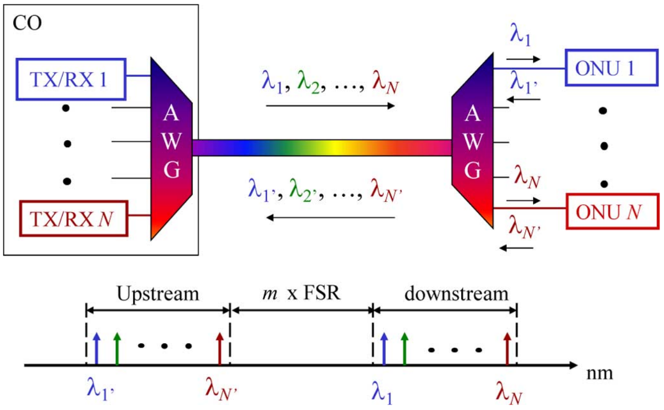
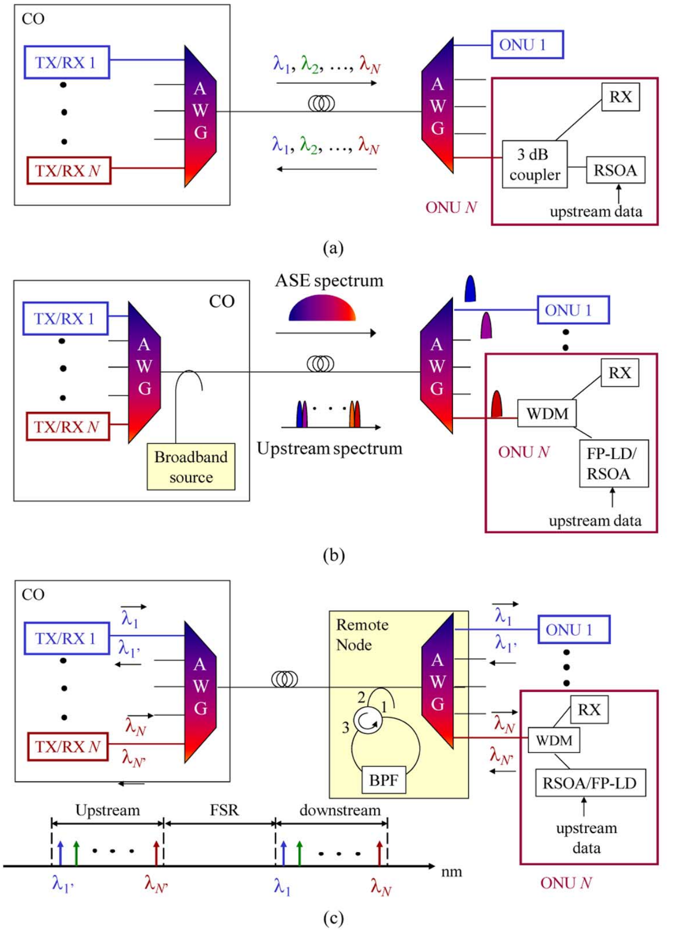


Fig. 4. Architecture of a WDM-PON. Inset: Allocation of upstream and downstream wavelength channels into two separate wavebands.



TX: transmitter RX: receiver FSR: free spectral range
CO: central office ONU: optical network unit AWG: arrayed waveguide grating
RSOA: reflective semiconductor optical amplifier FP-LD: Fabry-Perot laser diode
ASE spectrum: amplified spontaneous emission spectrum

Fig. 5. Architecture of WDM-PON showing colorless sources based on the (a) wavelength reuse scheme, (b) injection-locking/wavelength-seeded scheme, and (c) self-seeding scheme.

ONU. In the example shown in Fig. 4, ONU N receives downstream signals on λ_N and transmits upstream signals on $\lambda_{N'}$. The capacity on these wavelengths is solely dedicated to that ONU. Commonly cited benefits of WDM PON resulting from this unique feature include protocol and bit-rate transparency, security and privacy, and ease of upgradeability and network management.

B. Low-Cost Optical Sources

Since each ONU is assigned a unique upstream wavelength, distinct wavelength transmitters must be deployed at the subscriber premises. The simplest solution is to utilize fixed wavelength transmitters. Long transmission distances and high speed transmission can be achieved with this solution. However, such a network deployment would be cost prohibitive with increased complexity in network operation, administration, and management. Alternatively, identical tunable lasers can be utilized in all ONUs with each laser tuned to the pre-assigned transmission wavelength [32], [33]. Potential candidate technologies include tunable distributed feedback (DFB) laser [33] and tunable vertical cavity surface emitting lasers (VCSELs) [34]. The use of tunable lasers avoids the need for centralized broadband light source(s) as compared to other solutions, and subsequently the Rayleigh backscattering penalty from using these broadband source(s). However, true colorless feature necessitates prior knowledge of which wavelength each laser has to be tuned to. Also some form of wavelength control must be implemented to ensure that crosstalk is minimized between the wavelength channels during operation and that the wavelength alignment between the AWGs and lasers is maintained. Reducing the cost of tunable DFBs and VCSELs are challenges that are currently being addressed. An additional constraint on tunable lasers for use in a dynamic WDM PON is the tuning speed [7], [35], [36]. In a dynamic WDM PON, the wavelength assigned to each ONU can be dynamically reassigned during operation to (a) achieve efficient bandwidth utilization among the ONUs that share the same wavelength and (b) provide resilience in the event of line card failure at the CO [36], [37]. At low network loading levels, multiple ONUs may share one single wavelength, and as network loading increases, each ONU may eventually be assigned its individual wavelength channel. Distributed Bragg reflector laser diodes (DBR-LDs), such as sampled grating DBR-LDs and super structure grating DBR-LDs, are potential candidates to meet the cost and speed requirements of dynamic WDM PONs [38], [39].

In wavelength reuse schemes such as those proposed in [40] and [41], the optical source is eliminated altogether in the ONU. Downstream wavelength channels are remodulated with upstream data, and then sent upstream towards the CO. Fig. 5(a) depicts a WDM PON that uses the wavelength reuse scheme. Aside from carrying downstream signals, the downstream wavelength is used to wavelength seed an RSOA located at the designated ONU. Each RSOA is intentionally operated in the gain saturation region such that the amplitude squeezing effect can be used to erase the downstream modulation on the seeding wavelength [42]. The resulting amplified RSOA output has a wavelength identical to that of the downstream wavelength and can be directly modulated with upstream data. Hence, as illustrated in Fig. 5(a), the downstream and upstream wavelengths designated to and from an ONU are identical.

The benefits of the wavelength reuse scheme includes the remodulation of the downstream wavelength channel, thereby eliminating the need for seeding sources, is less costly than using tunable lasers, and direct modulation of the RSOA. However, upstream performance can be severely degraded by the interference between the residual downstream and upstream data at the CO. A solution to minimise residual downstream modulation is to ensure that the upstream and downstream modulation formats are orthogonal. In [43], phase modulation and frequency shift keying modulation are used for the downstream modulation with upstream being modulated with the on-off keying (OOK) format. In another solution reported in [44], data is RF subcarrier modulated onto a carrier and sent downstream towards the ONU. At the ONU, the carrier is filtered and then modulated with upstream data. Therefore, to minimize residual downstream signal, unconventional modulation formats and thereby unconventional transceivers must be used. Recently, line coding approaches such as Manchester coding [45] and DC balanced line coding [46] have been demonstrated to eliminate the DC component on the downstream data to improve upstream performance in a WDM PON.

In addressing the potential large inventory and cost of wavelength specific sources, researchers have been concentrating on developing cost-efficient and wavelength independent sources termed “colorless” sources. The earliest proposals involved the use of broadband incoherent light sources such as the directly modulated light-emitting diode (LED) and super-luminescent diode (SLD) at each ONU [47]. The broadband spectrum from each ONU would be spectrally sliced by the AWG in the upstream direction. This scheme has a short system reach and a limited upstream bit rate that is determined by the sliced bandwidth. To compensate for these drawbacks, FEC can be implemented to improve system reach and bandwidth efficiency [48], [49].

In yet another category of colorless sources, optical light originating from the CO is fed into the ONUs to injection-lock Fabry–Perot laser diodes (F-P LDs) [50]–[52] or to wavelength-seed reflective semiconductor optical amplifiers (RSOAs) [53]–[55]. As illustrated in Fig. 5(b), the injection-locking or wavelength seeding light may be furnished by spectrally-sliced light from a centralized broadband light source located at the CO. The wavelength seeding scheme is identical to the injection-locking scheme except for the use of an RSOA which amplifies and modulates the incoming continuous wave (CW) light. As the transmitting wavelength of a colorless ONU is determined externally by the wavelength of the incoming light, all ONUs may be implemented with identical FP-LDs or RSOAs. Nonetheless, these schemes require the use of additional broadband light source(s) and most importantly, the transmission performance is limited by fiber dispersion, Rayleigh backscattering noise, and broadband amplified spontaneously emission (ASE) noise from the broadband light source and the colorless source. Further, the upstream transmission bit rate is limited by the modulation bandwidth of the colorless source used (i.e., <1.25 GHz for FL-LD and <3 GHz for RSOA) which in turn is dependent on the carrier lifetime of these semiconductor devices. In addition, in injection-locking the FP-LD, wavelength control is required to ensure that the incoming ASE light at each ONU is locked to the intended cavity mode of the multimode FP-LD. In addressing the need for higher transmission bit rates, proposals which employ multi-level narrow-bandwidth modulation formats [56], [57], electronic equalization [58]–[60], optical offset filtering together with electronic equalization [61], and optical equalization [62] have successfully demonstrated wavelength seeding of RSOA at 10 Gb/s operation. Coherent detection at the CO to improve system reach of RSOA-based WDM-PONs has also been successfully demonstrated [63].

In the self-seeding scheme proposed in [64], the RSOA in each ONU is self-seeded by its own spectrally-sliced CW light. As illustrated in Fig. 5(c), ASE light emitted from each RSOA is spectrally-sliced by the AWG located at the remote node. The wavelength channels $\lambda_{1'}, \lambda_{2'}, \ldots,$ and $\lambda_{N'}$ in Fig. 5(c) represent the upstream self-seeding wavelengths whereas the downstream wavelengths are denoted $\lambda_1, \lambda_2, \ldots,$ and λ_N. Using a passive reflective path comprising an optical circulator and a bandpass filter (BPF) with a passband comparable to the FSR of the AWG, each RSOA will be self-seeded by only one spectrally-sliced light. For example, ASE light emitted from the RSOA in ONU 1 in Fig. 5(c) is spectrally sliced by the AWG at the remote node. This spectrally sliced light which is centered at $\lambda_{1'}$ is subsequently fedback via the reflective path to seed the RSOA in ONU 1. The reflected spectrally sliced seeding light, establishes self-seeding of the RSOA with measurements in [64] showing the self-seeded output to be incoherent with low relative intensity noise.

Self-seeding removes the need for active temperature tracking between the optical components within the remote node and between the remote node and each RSOA. Further, identical RSOAs can be placed at all ONUs since the wavelength of the seeding light and hence the transmitting wavelength from each RSOA is solely determined by the spectral characteristics of the AWG and BPF. A drawback of this scheme is that the upstream performance is dependent on the initial optical seeding power which affects the level of ASE noise suppression of the self-seeded upstream signal. Further, due to non-zero polarization dependent gain of the RSOAs, the self-seeding scheme is polarization dependent. The solution proposed in [65] to alleviate polarization dependency, uses a Faraday rotator mirror in the feedback path such that light is reflected back to the RSOA with an orthogonal state of polarization.

IV. LONG-REACH ACCESS NETWORKS

The long-reach passive optical network (LR-PON) enables network operators and service providers to deliver a rich mix of conventional and high-bandwidth traffic to a vast number of end users at a low cost. The consolidation of metropolitan and access networks achieved with LR-PONs reduces the number of active network interfaces and elements in the field and minimizes network planning. This in turn lowers capital expenditure (CAPEX) and operational expenditure (OPEX) of the integrated network [66], [67]. LR-PONs are also particularly suited to alleviating the high installation costs associated with sparsely distributed customers located in rural and remote areas [68].

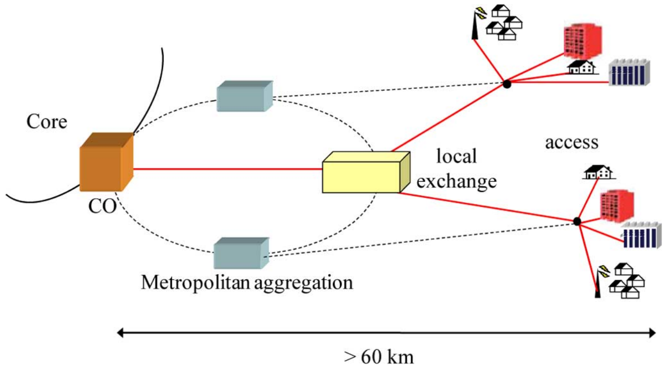


Fig. 6. Schematic diagram of a long-reach PON showing consolidation of central offices (COs) previously connected to the metropolitan aggregation network.

Fig. 6 shows a LR-PON connecting a large number of end users to the core network via a local exchange. As illustrated, the LR-PON (solid line) consolidates multiple COs previously connected to the metropolitan aggregation network (dash line). By exploiting optical amplification in combination with WDM, system reach can be extended from the conventional 20 km to 60–100 km while maintaining a 1:32 or higher split ratio. In a long-reach WDM/TDMA PON, different wavelengths are multiplexed at the CO and transmitted simultaneously through a feeder fiber to the local exchange where the WDM wavelengths are optically amplified and demultiplexed. Each TDMA PON attached to the local exchange is assigned a pair of upstream and downstream wavelengths which is then shared between the multiple users within that PON. The wavelengths allocated to each TDMA PON can be static or dynamic in which wavelength conversion can take place at the local exchange [5]. The idea of extending the reach of a PON is not new with many significant demonstrations and field trials carried out in the 1990s [69]–[72]. However, advances in optical amplification and WDM technologies in recent years along with the volume manufacturing of optical components such as SOAs, AWGs, and WDM filters, have lowered the cost of LR-PONs to a point that is competitive in the business and access market.

A. Reach-Extender Technologies

The ODN of a typical LR-PON comprises an extended-reach feeder fiber which connects the CO to a local exchange, and distribution fibers which connect the local exchange to the users. In some LR-PONs, a reach extender is housed in the local exchange to compensate for power loss due to the long transmission distance and high split ratio. A review of reach extender technologies will be presented next.

1) Optical Amplification: Optical amplification at the CO and/or the local exchange is indispensable in ensuring that the power budget of the LR-PONs is met [73]. Amplification in the optical domain provides transparency to bit-rate and format, and depending on the type of optical amplifier used, amplification over a wide wavelength region. The obvious choices of optical amplification include the erbium doped fiber amplifier (EDFA), SOA, and distributed Raman amplification (DRA).

In the WDM-TDMA Photonic Integrated Extended Metro and Access Network (PIEMAN), EDFAs were deployed at the OLT and remote node to optically amplify 32 wavelength channels though a 100 km link. Each wavelength feeds into a 1 × 128 PON [74]. EDFAs provide excellent gain power and noise performance in the C- and L-bands. However, optical amplification is limited to these wavelength bands and unless gain control through optical gain clamping or pump power variation is implemented, the relatively slow speed in adjusting the EDFA gain makes this option disadvantageous to the bursty nature of upstream TDMA traffic.

The SOA, on the other hand, benefits from the fact that it can operate at any wavelength of interest including the O band and with better gain dynamics than the EDFA, as demonstrated in [75]. Other benefits include compactness and the ability to facilitate additional functionalities such as wavelength conversion and all-optical regeneration. However, the SOA operates on a per-channel basis. The inability to provide simultaneous amplification across multiple channels is its main drawback.

The use of DRA in counter [76] and co-propagation [68] configurations enables amplification across a wide wavelength region over a bidirectional fiber link. Raman amplifiers can be tailored to provide a flat optical gain bandwidth that encompasses wavelengths exceeding those of common optical amplifiers. Using simultaneous launching of multiple pump wavelengths, DRA can achieve a flat Raman gain of up to 100 nm of bandwidth. Combining the benefits of EDFA and SOA, DRA allows simultaneous multichannel amplification, fast gain dynamics, and the ability to provide gain at any wavelength contingent on the pump wavelength. Using DRA does however require high pumping power, thereby adding to the power consumption at the local exchanges and COs.

2) Electronic Repeater-Based Networks: An alternative to optical amplification is to use an electronic repeater at the local exchange [67], [77]. The electronic repeater can facilitate 1R or 2R regeneration of both upstream and downstream signals. Other benefits include the option of wavelength conversion and optical power equalization of the burst mode signals in the upstream direction. However, a drawback of electronic repeaters is the need for bit-rate specific burst mode receivers that must also be capable of handling a wide dynamic range.

3) Purely Passive LR-PONs: The ODN of LR-PONs that utilizes optical amplification or electronic regeneration is no longer passive as a result of powering equipment at the local exchange. It is however possible to maintain a purely passive external plant in return for a more complex CO and ONU configuration through the use of advanced modulation formats and/or digital coherent detection. For example, in [78], the use of a low loss G.652 compliant fiber along with duobinary modulation format facilitated an unamplified 100 km TDMA-PON with a 1:128 split ratio. The low loss fiber allowed for an extra 2.5 to 3 dB power margin in the loss budget. Further, the use of doubinary modulation format allowed for an increase of 2 dB in nonlinear threshold over the 100 km span, thereby mitigating dispersion and nonlinear impairments. The use of digital coherent detection and advanced modulation formats in access networks will be reviewed in detailed in Section V.

B. Challenges

1) Dynamic Bandwidth Allocation (DBA): One of the major challenges in long-reach TDMA PONs is the dynamic allocation of upstream bandwidth. Whilst downstream bandwidth is shared and broadcast to all users, the upstream bandwidth needs to be efficiently polled between ONUs depending on bandwidth requests, service level agreements, and available capacity. Conventional dynamic bandwidth allocation (DBA) algorithms are unsuitable for LR-PONs. These DBA algorithms rely on an OLT-ONU polling scheme that involves the transmission of REQUEST messages to request for bandwidth (ONU to the OLT), and GATE messages to allocate bandwidth (OLT to the ONU). Upon receiving its GATE message, each ONU transmits data up to the granted bandwidth and appends to it a REQUEST message. In an LR-PON, the increased round trip time (RTT) of the OLT-ONU will increase the duration of the polling cycle. This will result in an increased amount of buffered data in the ONU and consequently, longer end-to-end delay and lower utilization of the upstream bandwidth. In addressing this issue, a multi-thread polling scheme was proposed for LR-PONs and reported in [73], [79]. Using this polling scheme, multiple simultaneous polling processes can be established between each ONU and the OLT. That is, one or more REQUEST messages can be sent from the ONU to the OLT prior to receiving its GATE. To maximize upstream utilization, the number of polling threads for each ONU and the time interval between adjacent threads can be dynamically adjusted [79].

2) Wavelength Dependent Transmitters: Inventory issues in WDM-PONs as discussed in Section III are also a challenge in extended reach networks, more so due to the increased number of supported ONUs. Low-cost wavelength specific transmitters such as VCSELs may be suitable candidates for such networks but without adequate optical amplification, reach will be limited due to low optical launch powers of such devices. The use of colorless ONUs based on wavelength-seeded RSOAs and injection-locked FP-LD have been demonstrated for extended-reach purposes. However, Rayleigh backscattering which is amplified along with the signal at the local exchange, limits the maximum transmission distance. The investigations in [80] reports on Rayleigh backscattering induced power penalties as a function EDFA gain and placement in a long reach RSOA-based WDM PON. Results highlight that the location at the center of the transmission link is the optimum position for optical amplification such that both backscattered seed light and backscattered upstream signal can be minimized.

3) Network Resilience: Network protection against fiber/device failures are significant considerations in the deployment of any extended-reach network due to the increased network reach and large number of supported users. As described in the ITU-G 984 standard, dual-parented GPONs can be implemented to provide protection against fiber failures and device failures at the CO [5], [81]. With dual-parented GPONs in which each ONU is connected to two COs, protection can be complex, requiring (a) the quick diversion of traffic to the second headend and (b) alteration in the routing of frames and packets through the core network to reflect the corresponding change of the destination headend. In a recent field trial, namely the SARDANA network [82], a ring and spur topology was implemented to facilitate protection switching. The network comprised TDMA single fiber passive tree sections that is connected to a main WDM ring via add drop remote nodes. In the event of a fiber failure within the main WDM ring, each add-drop remote node can switch its TDMA traffic onto the part of the ring that is still connected to the CO.

In optically amplified LR-PONs, customers are in direct contact with the optically amplified link. Measures to detect and remove hazardous high power laser exposure at the fiber break are therefore critical. Due to the high optical losses associated with extended reach systems, highly sensitive detection modules must be implemented to rapidly activate protection switching upon fiber failure detection. To address this requirement, a fast-response protection module was proposed in [83] with a sensitivity of -51.5 dBm. Amplifier shutdown and protection switching were achieved within 2 ms and 12 ms, respectively of fiber failure detection.

V. COMPLEMENTARY ACCESS TECHNOLOGIES

This section presents a number of alternative access technologies that not only provide improved impairment tolerance, capacity, and spectral efficiency, but also the possibility of reusing the existing ODN. When combined with WDM as a hybrid PON solution, these technologies are envisioned to meet capacity demands of emerging new services and applications. Currently, practical implementation of these technologies at the CO and ONUs is a major challenge with many requiring unconventional and complex optics and/or electronic hardware. Considering the continuing advances in photonic integrated circuits and high speed digital signal processors in combination with an increased number of supported users, the high CAPEX of initially deploying these technologies may potentially be offset by low OPEX per user.

A. Coherent Optical Access Networks

Recent interests in applying digital coherent detection in the access segment have been fueled by the need to extend the system reach and to support high user density. Digital coherent detection combines optical coherent detection with electronic digital signal processing. In optical coherent detection, a six-port optical hybrid comprising linear splitters and combiners, outputs four vectorial additions of the signal of interest and reference local oscillator (LO) [17], [18], [84], [85]. The four outputs are then detected by balanced photoreceivers. Using electronic digital signal processing, the amplitude and the relative phase information between the signal of interest and the LO can then be extracted. Coherent detection can be classified into two categories depending on the LO source used [84]. In homodyne detection, the LO is derived from the same source as the signal of interest and hence is of the same frequency as the signal of interest. In heterodyne detection, the LO is derived from a different signal source which is intentionally tuned to nearly the same frequency as the signal of interest.

There exist many properties of digital coherent detection that makes it advantageous as a multiple access technology. Coherent detection provides the flexibility of frequency selectivity and wavelength channel switching through the re-tuning of the LO. In a WDM PON, this wavelength selectivity feature allows the wavelength routing AWG to be omitted, thereby providing a smooth migration of an existing ODN to a coherent detection WDM PON through the upgrade of the end terminals. Additionally, coherent detection has the potential to reach quantum limited receiver sensitivity [85] thereby improving system reach, split ratios, and wavelength density. Further, dispersion compensation can be performed in the digital domain through digital signal processing (DSP). An ultra dense WDM PON using digital coherent detection was recently demonstrated in [16]. A 64 wavelength channel operation was demonstrated using heterodyne detection to differentiate between channels spaced at 2.5 GHz. The LO source used at both the ONUs and OLT is a tunable laser that also serves as the light source for downstream and upstream transmissions respectively. A 1.244 Gb/s data rate is achieved using differential quadrature phase shift keying (DQPSK) format. Clock recovery and data processing is done in real-time using field programmable gate arrays (FPGA) at the OLT and ONUs [16].

The use of coherent detection in PONs has also been reported in long-reach applications, whereby amplification is eliminated altogether, thereby achieving a truly passive network [86], [87]. A 2.5 Gb/s RSOA based WDM PON with a maximum reach of 68 km was reported in [86]. Self homodyne coherent receivers at the CO were demonstrated for the upstream transmission. To enhance its cost-effectiveness, the coherent receivers were realized using a fraction of the seed light as a LO and an inexpensive 3×3 fiber coupler as a 120 degree optical hybrid. To achieve the polarization stability of the upstream signal at the input of the coherent receiver and without having to use costly polarization diversity receivers, a 45 degree Faraday rotator was placed in front of the RSOA in the ONU. As a result, the state-of-polarization of the upstream signal will always be orthogonal to that of the linearly polarized seed light at the input of the coherent receiver located at the CO, regardless of the birefringence in the transmission link. Field trials were carried out using the proposed coherent receiver in a 68 km link to realistically evaluate the effects of polarization fluctuations occurring in the installed fibers. No significant degradation in receiver sensitivity was reported during the 10 hour trial despite large polarization fluctuations in the installed fiber.

Often, advanced modulation formats are also utilised to enhance channel capacity. In [87], a maximum reach of 100 km and an operating speed of 5 Gb/s were achieved in a RSOA based WDM PON that combined digital coherent detection and quadrature phase shift keying (QPSK) modulation. The use of QPSK signal generated by directly modulating the ROSA with a 4-level electrical signal allowed the increase in operating speed of the RSOA from 1.25 Gb/s to 5 Gb/s. The optical coherent detection technique used was similar to the self-homodyne receiver in [86]. Error free transmission over the 100 km link was achieved without the use of optical amplification and electronic equalizers.

In [8], symmetrical data rates of up to 10 Gb/s was achieved with source free ONUs through a combination of OFDM-16QAM modulation format and coherent detection. The uplink and downlink signals of the PON resided on different RF bands. For uplink signal generation, the downstream RF-OFDM-16QAM signal was remodulated at the source free ONU with an independent RF-OFDM-16WAM. At the OLT, heterodyne detection with an LO tuned to the corresponding uplink band, was utilized to down-convert the uplink signals to baseband.

B. Orthogonal Frequency Division Multiple Access (OFDMA) Access Networks

Originally used as a modulation method for copper and radio, OFDM is currently being considered by many research groups as one of the strongest candidate for future PON implementation due to its attractive features that satisfy the needs of next generation access networks [10], [12]. In OFDM, multiple low bit rate orthogonal subcarriers carrying different QAM symbols, are simultaneously transmitted in parallel. A major benefit of OFDMA is that the complexity of transmitters and receivers is transferred from the analog to the digital domain using advanced DSP [11]. For example, practical and cost-efficient implementation of the orthogonal subcarriers is achieved at the transmitter via the Inverse Fast Fourier Transform (IFFT) algorithm and at the receiver via FFT algorithm [11]. Another advantage of OFDM lies in the orthogonality of low bit rate subcarriers, thus allowing high spectral efficiency. A high aggregate transmission bandwidth can be maintained using low bandwidth transceivers. Further, advanced modulation formats can be implemented to achieve high-speed transmission.

In OFDM, different subcarriers can be assigned to different users, thereby making this technology particularly suitable as a multiple access scheme. The bandwidth of subcarriers can be dynamically provisioned to different services in both frequency and time domains. The implementation of OFDMA capability in a PON was first demonstrated in [12]. Communication between the OLT and ONUs was through the transmission of OFDMA frames in which subcarriers were either dedicated to ONUs or shared between multiple ONUs in time. In the demonstration, 256 sub-carriers were generated over a 2.5 GHz channel bandwidth and equally split into 2 subchannels, each assigned to an ONU [12]. The OFDM-16QAM modulation format was implemented at the OLT and ONUs, achieving a data rate of up to 10 Gb/s/λ over the 2.5 GHz channel bandwidth when all 256 subcarriers were assigned to one ONU [12].

In [88], polarization multiplexing (POLMUX) in combination with direct detection was implemented, achieving a record of 108 Gb/s/λ over 20 km single mode fiber (SSMF) with 1:32 passive split. Downstream transmission from the OLT to the ONUs was demonstrated. In POLMUX, the OFDM signal is transported via two orthogonal POLMUX bands, thereby further increasing the spectral efficiency of the system. Direct detection at the ONU was proposed through a combination of two separate photodiodes, followed by two OFDM receivers and a polarization demultiplexing receiver [88]. The proposed receiver alleviates the complexity and cost associated with digital coherent detection normally used in POLMUX-OFDMA systems.

Another benefit which stems from the orthogonality of subcarriers in OFDM is the superior tolerance to chromatic dispersion. This feature makes OFDM particularly appealing for long reach deployments without the need for dispersion compensation. Most recently, a record rate-distance product of 1.2 Tb/s ($25\lambda \times 48$ Gb/s/λ) symmetric WDM-OFDMA-PON was demonstrated over 90 km SSMF with 1:32 passive split and without optical dispersion compensation [9]. Similar to [8], uplink transmission from source free ONUs was achieved through the remodulation of CW upstream carriers from the OLT. Uplink reception of the 16-QAM modulation format OFDM signals at the OLT is through digital coherent detection. The demonstrated system supports 800 ONUs with 1.25/10-Gb/s guaranteed/peak rates [9].

For practical implementation of OFDMA PONs, the feasibility of real-time end-to-end transmission is crucial. Many demonstrated laboratory experiments use off-line DSP approaches, which do not fully account for the limitations imposed by the precision and speed of practical DSP hardware [89]. A 41.25 Gbs real time variable rate DSP-based OFDM receiver was demonstrated in [80]. In [91], [92], end-to-end real-time OOFDM transceivers at 11.25 Gb/s with essential functionalities for adaptive operation such as on-line performance monitoring and live parameter optimization were reported. The same research group also demonstrated >20 Gb/s real-time OFDM transceivers using off-the-shelf, low-cost electrical/optical components in simple intensity modulation and direct detection (IMDD) transmission systems [89].

In trying to reduce transceiver costs, the un-cooled, low power VCSEL has been investigated recently as a potential alternative to the directly modulated DFB laser. Results reported in [93] show the feasibility of using VCSELs to directly modulate OFDM signals at signal bit rates of up to 11.25 Gb/s for end-to-end real-time transmission over 25 km SSMF IMDD systems. The use of SOA and RSOA were also investigated as potential substitutes to the DFB, achieving 23 Gb/s downstream and 8 Gb/s upstream over 40 km SSMF when single sideband subcarrier modulation is adopted in downstream [94].

When deploying OFDM over a common wavelength, optical carrier suppression of upstream transmission is necessary to alleviate inter-ONU optical carrier beating noise at the OLT. Optical carrier suppressed modulation can be achieved using a Mach–Zehnder modulator biased at its null point, as reported in [95]. The modulator connects the two PM branches of a polarization beam splitter/combiner to overcome polarization sensitivity and to make the ONU configuration reflective. Each polarization component of the incoming optical signal travels through the loop in opposite directions and is modulated independently though the MZM. In [96], the combination of optical carrier suppression at the ONU and coherent detection at the OLT successfully demonstrated the elimination of both in and cross polarization beating noise, thereby improving upstream performance.

Upgrading an existing PON to include OFDMA capability involves the upgrade of the OLT and ONUs with advanced modulation and DSP capabilities, thereby allowing the reuse of the existing ODN. However, as transmission bit-rate increases, the complexity and cost for hardware implementation of FFT, and the challenge to achieve real time end-to-end transmission will increase accordingly. Electronic component integration and mass production may provide a solution in alleviating transceiver costs and in making OFDMA competitive in the business and residential markets in the future.

C. Optical Code Division Multiple Access (OCDMA) Access Networks

Optical code-division multiple access (OCDMA) is based on the spread-spectrum technique used in satellite and mobile communications [97]. In a time-spread OCDMA system, the bits to be sent to each user are divided into chip time periods. Each chip is represented by a temporal waveform referred to as an optical code sequence. With each user designated a unique optical code sequence, the coded bits are transmitted over the ODN and then decoded using the exact optical code sequence at the receiver of the destined user. OCDMA is a promising multiple access technology especially for customers that require symmetric access and stringent data confidentiality and privacy. Other benefits include full asynchronous operation, low end-to-end delay, flexibility in either coherent or incoherent detection, guaranteed bandwidth per unique code user, and increased system reach. Asynchronous operation allowed by OCDMA enables all users to access the network without contention and with minimal access delay [13].

Though early laboratory demonstrations of OCDMA for local area network applications took place in the 1980s [98], it was the progress in optical en/decoder [99], [100] and optical thresholding devices [100]–[102] in the past decade that has enabled OCDMA to be potentially competitive in the access segment [13]. Recent investigations of OCDMA PONs have demonstrated 10 Gb/s capacity [103], [104] and an unamplified system reach of 100 km [105].

At present, many demonstrated high-speed PONs using OCDMA technology are complex and require unconventional optical devices (e.g., optical decoders and encoders). Recent efforts are therefore focused on reducing implementation complexity while maintaining high per user bandwidths. An example is reported in the demonstration of a 10 Gb/s WDM-OCDM-PON [103]. Key to the architecture is the use of a single multiport encoder/decoder (E/D) at the CO, which cost can be shared by all subscribers [15], [106]. The multi-port encoder with periodic frequency response can simultaneously process multiple optical codes in multiple wavelength bands. At each ONU, WDM demultiplexing and OCDMA decoding is simultaneously carried out by employing a low cost multi-level phase-shifted super structure fiber Bragg grating (SSFBG) decoder. The compact phase-shifted SSFBG E/D has the ability to process ultra-long time spread optical codes with polarization independent performance [107]. Other benefits include low loss and code-length independent insertion loss [107]. Field trials using the single multiport E/D and SSFBG E/D in a

10 Gb/s × 8 OCDM × 2 WDM system over a 100 km loopback configuration with dispersion compensating fiber, have been successfully demonstrated [103]. In [14], the implementation complexity of the ONUs is further simplified by employing a single multiport E/D at the remote node between the CO and the ONUs, thereby eliminating the need for an individual E/D at each ONU.

VI. SUMMARY

A review of the emerging trends in next generation passive optical networks and technologies have been presented. In meeting increasing capacity demands, standardized 10 Gb/s PON systems, namely XG-PON and 10 GE-PON, were discussed. The main reasons behind the push for these TDM/TDMA PON systems are to extend the longevity of existing ODNs and to allow co-existence with the current generation PONs such that the operational impact on existing users will be minimized. The basic architecture of the WDM PON and its various colorless schemes to alleviate inventory problems, were also presented. The advantages of the pure WDM PON system are its ability to facilitate symmetric applications and its flexibility in future scaling of bandwidth, reach, and user count. In combination with TDMA, an overview of the long-reach PON was presented with particular focus on key reach extender technologies and challenges in deploying these networks. The main reasons behind the deployment of such networks are to meet increasing capacity demand and user density requirements, while ensuring that the cost per unit bandwidth is minimized. Technologies that complement the WDM PON such as digital coherent detection, OFDMA, and OCDMA were also discussed. In order to successfully deploy these technologies, the implementation complexity must be minimized to a level that is comparable to existing commercialized systems and with a cost that is sufficiently low to meet the cost constraints of the access market.

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