Fiber to the Home Using a PON Infrastructure

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Invited Paper

***Abstract*—Traffic patterns in access networks have evolved from voice- and text-oriented services to video- and image-based services. This change will require new access networks that support high-speed ($>$ 100 Mb/s), symmetric, and guaranteed bandwidths for future video services with high-definition TV quality. To satisfy the required bandwidth over a 20-km transmission distance, single-mode optical fiber is currently the only practical choice. To minimize the cost of implementing an FTTP solution, a passive optical network (PON) that uses a point-to-multipoint architecture is generally considered to be the best approach. There are several multiple-access techniques to share a single PON architecture, and the authors addressed several of these approaches such as time-division multiple access, wavelength-division multiple access, subcarrier multiple access, and code-division multiple access. Among these multiple techniques, they focus on time-division multiplexing (TDM)-PON and wavelength-division multiplexing (WDM)-PON, which will be the most promising candidates for practical future systems. A TDM-PON shares a single-transmission channel with multiple subscribers in time domain. Then, there exists tight coupling between subscribers. A WDM-PON provides point-to-point optical connectivity using a dedicated pair of wavelengths per user. While a TDM-PON appears to be a satisfactory solution for current bandwidth demands, the combination of future data-rate projections and traffic patterns coupled with recent advances in WDM technology may result in WDM-PON becoming the preferred solution for a future proof fiber-based access network.**

***Index Terms*—Fiber to the home (FTTH), fiber to the premise (FTTP), optical access network, passive optical network (PON).**

I. INTRODUCTION

RECENTLY, we have experienced a change of paradigm in access networks. Voice- and text-oriented services have evolved to data- and image-based services due to the popularity and growth of the Internet and worldwide web (WWW). This evolution is continuing toward video-based services that will require much higher data speeds. In addition, it has been observed that the traffic patterns are becoming more and more symmetric [1]. This change of paradigm will require new access networks that support high-speed ($>$ 100 Mb/s), symmetric, and guaranteed bandwidths for future video services with high-definition TV (HDTV) quality. Telcordia has predicted that by 2010, 50% of the revenue of large telephone companies will be based on video services [2]. For efficiency, the access network should be prepared and structured to converge voice, data, and video traffic with a focus on higher bandwidth applications such as video and image services.

When all services become video centered, the traffic patterns of the access network will substantially differ from that of the current data-centered services. Video-centric services demand not only broad bandwidth but also a high quality of service (QoS). In addition, subscribers will demand multiple and simultaneous services during specific time intervals (for example, peak-evening viewing of multiple high-definition video channels at each home). Thus, it is not expected that statistical multiplexing gain, as in the data-centered networks, will be that useful. Future access networks will need to offer guaranteed-symmetric bandwidths of 100 Mb/s [3] instead of only a peak bandwidth of 100 Mb/s that is shared with many subscribers. In addition, the transmission lengths should be designed to meet 20 km, which is the established international standard based on distances from subscribers to current central-office (CO) locations.

It is well known that the conventional access networks based on twisted-pair copper cable have very limited bandwidth-distance products. At data rates of 100 Mb/s, the transmission distance is limited to about 100 m and requires the use of highly sophisticated transmission technologies [4]. To overcome this limitation, it is essential to use single-mode optical fiber as the transmission media in future access networks. Single-mode fiber provides essentially unlimited transmission bandwidth over extremely long distances. The end goal is to provide an optical fiber to each customer premise or home. This type of network is commonly referred to as Fiber to the Home/Premise (FTTH/P). In general, the term FTTH/P does not restrict the type of fiber architecture used. Fig. 1 shows four different types of FTTH/P. However, since FTTH/P typically refers to a passive optical network (PON) that uses a point-to-multipoint architecture, as shown in Fig. 1(c) and (d), this convention will be used within this paper. We will also use the more general term "FTTP" that includes any type of premise and not only a home or a residence.

The term PON means that there are no active elements between the CO and the customer premises. In other words, only optical fibers and optical passive elements do not require any electrical power or active management. In addition, the lifetime of the outside passive plant should be greater than

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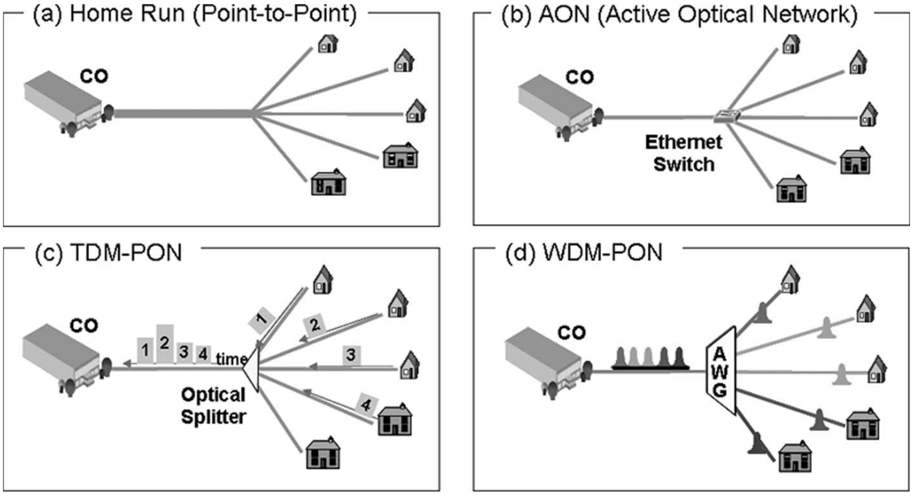


Fig. 1. Four different approaches of FTTH/P. (a) Point-to-point connection. (b) Active optical network that has active equipments in the filed. (c) and (d) Passive optical network considered in this paper.

25 years to justify the installation costs and maximize the savings in operational expenses.

Analysis and studies have estimated that the cost of providing FTTP connectivity has dropped considerably in the last several years. Capital expenses (CAPEX) are estimated to have dropped from about \$4000 in the year 2000 to approximately \$1000 in 2005 [5]. In addition, it is also estimated that operation-and-maintenance-expense (OPEX) savings can be over \$125 per year per subscriber by replacing the current copper plant with a passive fiber plant [5]. Due to the compelling advantages in OPEX savings combined with the continuing drop in CAPEX, installation of FTTP is expected to accelerate. Examples of this can be seen in Japan, where FTTP subscribers exceeded two million at the end of 2005, while in the United States, approximately three million subscribers as of October 2005 have been "passed" by an FTTP-PON infrastructure [6]. In addition, Korea, Germany, France, and China have begun or are seriously considering the introduction of FTTP.

In this paper, we will start by reviewing the current legacy methods for access solutions and point out their limitations. In the next section, we will then discuss the four main schemes for providing access to multiple subscribers over a shared fiber-based PON. These four main schemes can be summarized as using time-domain multiplexing (TDM), wavelength domain multiplexing (WDM), subcarrier multiplexing (SCM), and code division multiplexing (CDM). The following section will focus in more detail on what the authors believe are the two most likely candidates for future PON systems, which are TDM-PON and WDM-PON solutions. Finally, we will discuss some interesting historic perspectives on bandwidth growth, past technology trends, and possible evolution directions related to PON systems.

II. LEGACY TRANSMISSION MEDIA AND ACCESS TECHNOLOGIES

The most widely deployed transmission media in access networks are twisted-pair copper cables that have been used for telephone lines for more than 100 years. Recently, many sophisticated high-speed transmission technologies have been developed to maximize the data throughput over this legacy copper-wire plant. Multilevel-transmission methods, such as quadrature-amplitude modulation (QAM) and discrete multitone (DMT), have been used to mitigate the bandwidth limitations of the twisted-pair copper cables. These relatively complex transmission technologies are generally described by the term x digital subscriber loop (xDSL). Although highly sophisticated technologies are used, the transmission distances are still quite limited. A figure of merit for the bit-rate-times-distance product of twisted-pair copper cable is about 10 Mb/s · km. This means that a 100-Mb/s signal can be transmitted only over a distance of about 100 m, which greatly limits its use in high-speed access networks.

To provide a better understanding on the relative capabilities of the different media choices, Table I compares the bandwidth-distance products of various transmission media. This table clearly illustrates the transmission advantages of using single-mode fiber for future access networks. Transmission capacity for a single-mode fiber is on the order of 10^6 Mb/s · km for a single-wavelength channel, and if multiple wavelengths are used, this value can be orders of magnitude larger. It should also be pointed out that fiber transmission losses can be as low as 0.2 dB/km and are independent of the transmission bandwidth unlike copper-based solutions. This enormous capacity for single-mode fiber is many orders of magnitude larger than any of the other listed solutions. It may be noted that a multimode fiber has a bandwidth-distance product that is about twice that of coaxial cable and can be useful for some shorter distance applications.

As an intermediate step before installing fiber directly to each home, fiber is currently being use to provide high bandwidth closer and closer to the access edge. Commonly used names to describe these interim solutions are fiber-to-the-curb (FTTC) and fiber-to-the-node (FTTN). In FTTN, fiber is used to provide high bandwidth to an active remote node (RN) that can serve up to about 1000 subscribers within a range of about 3 km. FTTC typically refers to smaller groups of about ten subscribers

TABLE I
BANDWIDTH COMPARISON OF VARIOUS TRANSMISSION MEDIA

		BL product [MHz·km]	Signal format	Bit rate x Distance [Mb/s·km]	100 Mb/s reach [km]
Copper	Twist pair	2.4	QAM/DMT	10	0.1
	UTP (Cat. 5)	10	MLT 3	10	0.1
	Coax	300	QAM (256)	2,019	< 20
Fiber	Multimode (Silica)	500	Binary (NRZ)	500	5
	Multimode (POF)	200	Binary (NRZ)	200	2
	Single mode	600,000	Binary (NRZ)	600,000	Unlimited

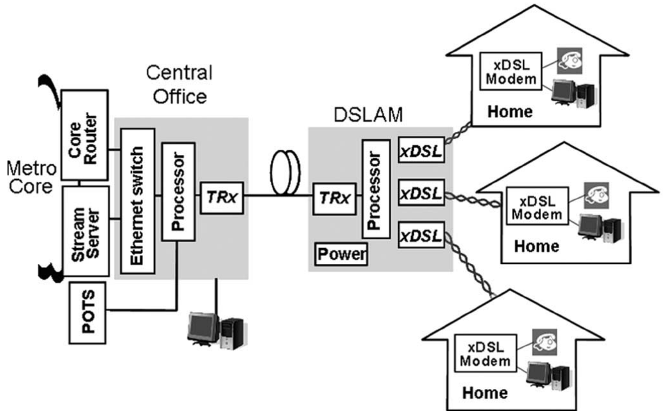


Fig. 2. Typical configuration of xDSL with DSLAM.

within a range of a kilometer or less. These two methods rely on using the existing twisted-pair copper wires for the last drop distance to the home.

Fig. 2 illustrates this solution in a typical telecom application, where one or more single-mode fibers are used to connect the CO to a remote digital-subscriber line-access multiplexer (DSLAM). The connection from the DSLAM to each home uses the legacy copper wires that were originally intended for delivering only the 4-kHz plain-old-telephone-service (POTS) signal. At the home, these copper wires are connected to an xDSL modem. This modem uses relatively sophisticated and complex signal-processing techniques such as QAM or DMT to maximize the data-rate transmission over the limited bandwidth of the twisted-pair copper wires. The length of the copper wires limits the data rate that can be delivered between the DSLAM and home. For distances under 1.5 km, asymmetric digital subscriber loop (ADSL) can deliver about 8 Mb/s while the newer very high speed digital subscriber loop (VDSL) technology can deliver up to 26 Mb/s for distances under 1 km. One role of the electrically powered DSLAM is to aggregate the multiple streams of lower bandwidth data from each subscriber into a higher speed signal for optical transmission to the CO.

The other most popularly deployed access medium is coaxial copper cable used for cable TV transmission. Since an NTSC (PAL) analog TV channel has analog bandwidth of 6 MHz (8 MHz), it is almost impossible to transmit a TV channel any significant distance using existing twisted-pair copper wire. Coax cable can deliver much larger bandwidths than twisted-pair wire since the electrical signal is guided between an inner conductor and a grounded outer shield conductor. Typical transmission loss is about 1 dB per 100 feet at a frequency of 55 MHz and then scales as the square root of the frequency at higher carrier frequencies. This allows multiple TV channels to be transmitted along a single-coax cable up to a few hundred meters. In practical applications, electrical amplifiers are used every 100 to 200 m with gains of about 20 dB. The number of amplifiers is limited by the required signal-to-noise ratio (SNR) to deliver an acceptable quality video signal. This places practical limits on the transmission distance using only coax cable. To overcome this limitation, single-mode fiber is used to feed the broadcast analog-video signals (50–100 channels) to a fiber node (FN). They are then converted to electrical-video signals for transmission along multiple-coaxial cables. These final transmission links use periodically amplified coax-cable networks that typically consist of a tree-and-branch architectures [7]. This combination of fiber and coax cables is called a hybrid fiber-coax (HFC) network. Each FN typically covers a "cell" of about 500–1000 homes.

Recently, QAM-modulation technology was introduced to send digital data through a coaxial cable. The home equipment that terminates the QAM signals is called a cable modem, while the corresponding equipment located at the CO or head end is called the cable-modem termination system (CMTS). In this network, a maximum downstream data rate of 2.8 Gb/s (450–870 MHz) and upstream bandwidth of 150 Mb/s (5–42 MHz) can be achieved [7]. However, since 500–1000 subscribers share the bandwidth within a cell, the guaranteed bandwidth per subscriber is only 2.8–5.6 Mb/s for the downstream signal and 0.15–0.3 Mb/s for the upstream signal. This is comparable with the bandwidth offered by xDSL over twisted-pair copper.

In summary, the major advantage of the above xDSL solution for twisted-pair wire and the HFC solution for coax cable is that they leverage the existing legacy infrastructure

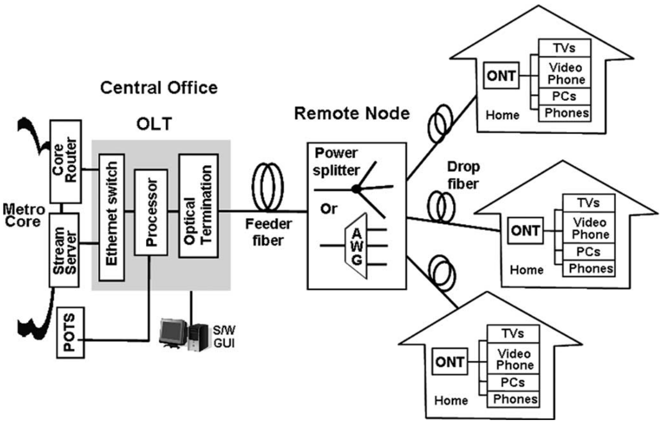


Fig. 3. Generic configuration for a FTTP PON.

to deliver digital data. As bandwidth demands increase, trying to squeeze increasing data rates out of this bandwidth-limited legacy infrastructure becomes increasingly expensive. Another main drawback of these two approaches is that they both require electrical-powered equipment in the field, except for customers close to the CO. This leads to high-operational costs associated with powering, maintaining, and managing this remotely located active equipment. It is quite clear that these existing solutions have limited lifetimes, and eventually, fiber connections will have to be provided to each home.

III. MULTIPLE-ACCESS AND MULTIPLEXING METHODS IN THE OPTICAL DOMAIN

Traditionally, in the legacy telephone network, a point-to-point architecture was used to connect each subscriber to the CO through a dedicated pair of copper wires. This same point-to-point architecture is also the most logical method for providing FTTP since it provides a futureproof architecture capable of delivering effectively unlimited bandwidth [see Fig. 1(a)]. Although this would be the ultimate network, it is not considered the best solution due to many practical constraints. These constraints are related to the large number of fibers that would need to be managed in both the field and CO. Dealing with such large numbers of fiber connectors and optical splices is currently much more difficult than with copper wires. Also, since customers can be 10 to 20 km from the CO, it is costly to install large fiber counts over these long distances.

In light of these constraints, it appears that the preferred choice for building an FTTP network is to use a point-to-multipoint architecture. In this architecture, a single strand of feeder fiber is connected from the CO to a subscriber location whose distance can be up to about 20 km. At the RN location, a passive optical device is used to connect the single-feeder fiber to multiple drop fibers that go to each home. This architecture is illustrated in Fig. 3. This FTTP architecture is referred to as a PON that allows many customers to share a single-feeder fiber running to the CO. At the CO, the feeder fiber terminates at the optical line terminal (OLT) that manages the communications to the multiple subscribers. At the remote subscriber location, the drop fiber terminates at an optical network termination (ONT) that converts the optical signal to electrical signals for use by various devices such as phones, computers, TVs, etc., [8].

To communicate with the multiple subscribers connected to the PON, many different methods can be used. For clarity, we will separate our discussion to first consider the various multiple-access methods for dealing with the upstream traffic (subscribers to CO) [8]. These schemes can be generally categorized as time-division multiple access (TDMA), wavelength-division multiple access (WDMA), subcarrier-division multiple access (SCMA), and code-division multiple access (CDMA). These four schemes are illustrated in Fig. 4. After discussing the various upstream techniques, we will discuss the corresponding methods for multiplexing the OLT traffic in the downstream direction.

A. *Time-Division Multiple Access (TDMA)*

TDMA is currently the most popular method being considered for building a PON infrastructure to provide FTTP services. This technique relies on assigning dedicated time slots to each of the multiple subscribers connected to the PON. Each subscriber can then use the full upstream bandwidth of the optical link for the duration of its allotted time slot. Since a PON can typically service $N = 32$ or more subscribers, the average dedicated bandwidth to each subscriber is usually only a few percent of the channel capacity. To connect the multiple subscribers to a single-feeder fiber, a passive optical-power splitter is used at the RN. This passive power splitter couples $1/N$ of the power from each subscriber into the feeder fiber for transmission back to the OLT at the CO.

One function of the OLT is to assign time slots to each user to avoid any collisions of the data in the upstream direction. To accomplish this, each ONT needs to negotiate with the OLT of when it can send its data. In practice, the algorithms for managing the multiple users over a single-feeder fiber are very complex and require considerable processing power.

To realize an efficient use of the shared communication channel, the OLT should have precise time-delay information to each ONT since they are all at different distances from the CO. This information is needed to control the time when each ONT can transmit to ensure that no packets overlap when they reach the summing location at the RN. The process to identify the actual delay time to each ONT is known as ranging or discovery. This ranging process needs to be repeatedly updated since time delays change due to temperature effects on the drop fibers. Currently, there are two different algorithm standards for controlling this multiple-access process. One has been developed through the IEEE 802.3 standards group [9] and is based on the popular Ethernet standard. The other is through the ITU-T standards body [10] and puts more focus on supporting legacy telecom services such at connection-based circuits historically used for voice traffic.

Another key requirement to realize an efficient TDMA system is the need for a burst-mode optical receiver at the OLT. Since the time delay and optical loss to each ONT is different, the burst-mode receiver needs to quickly adjust its clock-synchronization and receiver gain for each data packet from the different subscribers. These OLT receivers can be technically

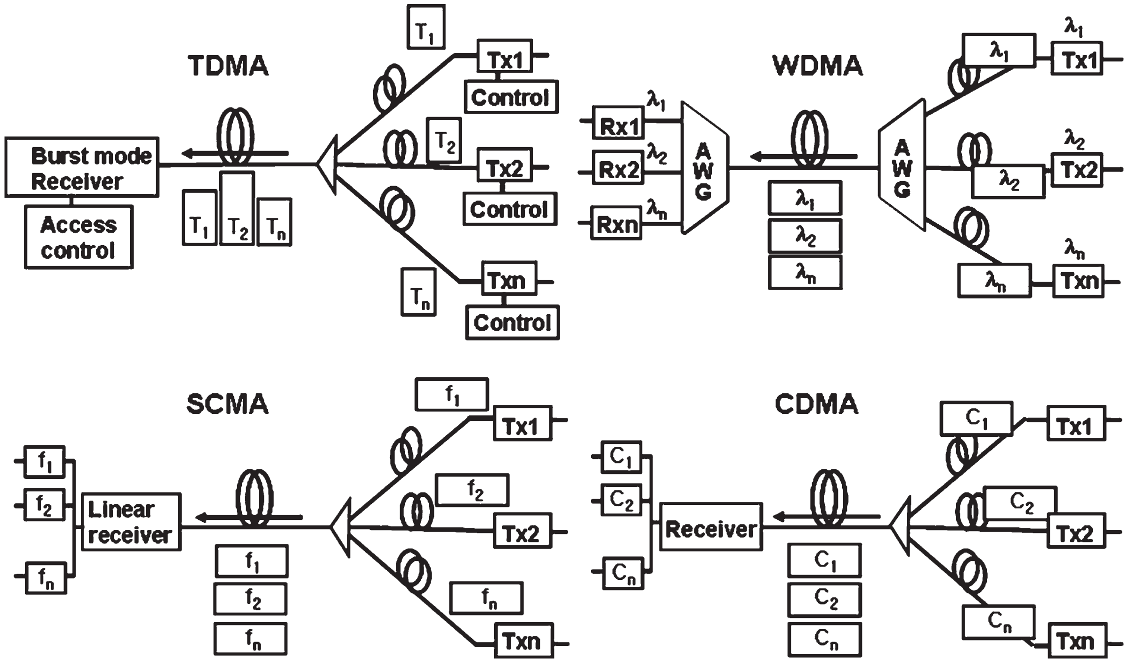


Fig. 4. Configuration of various multiple access methods for upstream data transfer.

challenging since they should have a wide dynamic range for the different incoming burst signals and they require a very short guard time for the clock-synchronization process. Another complementary requirement is the burst-mode transmitter at each ONT that needs to start stable optical transmission within a short start-up interval. In addition, each ONT transmitter must be sure to completely shut down after its time slot is over since any residual background light will interfere with the upstream data signals from the other ONTs. One potential problem related to this is the case of an ONT failure causing light to be transmitted at an incorrect time. If this happens, it can shut down the operation of the entire PON.

One useful characteristic of the TDMA approach is that when some ONTs do not have much data to send, the unused channel capacity can be allotted to the other ONTs if they have more data to send. This feature is known as dynamic-bandwidth allocation (DBA). This process allows the shared bandwidth of the single-feeder fiber to be used more efficiently and can be thought of as a statistical multiplexing gain. There exist many DBA algorithms, and extensive research is currently ongoing in this area [11], [12]. Although DBA can increase the PON efficiency when user demand is nonuniform, it adds to the complexity of the total control algorithm and results in a stronger coupling between all the ONTs connected to the PON. When bandwidth demand becomes high, this stronger coupling can lead to QoS issues such as how to fairly assign capacity to multiple high-demand users. This also leads to requiring larger buffer memories for users waiting to send data and issues regarding time delays and packet loss. As a result, QoS can be limited even though error-free optical transmission over the actual PON infrastructure was guaranteed.

Typically, the management and control functions are performed in high-density silicon-based application-specified integrated circuit (ASIC) chips called the OLT media access controller (MAC) and ONT MAC. Many companies have developed these MAC ICs that comply with various protocols defined by either the IEEE [9] or ITU-T standards bodies [10].

It is useful to understand how the SNR in a TDMA architecture scales with increasing the number of users "N" connected to the PON. Since a power splitter is used at the RN, the optical power reaching the OLT reduces in proportion to $1/N$ as the number of users increases. Also, since each ONT receiver requires a transmission data rate that is N times its dedicated data rate, the receiver noise is increased due to both the larger integrated-noise bandwidth and the smaller receiver impedance needed for the increased detector speed [13]. These above scaling effects result in an SNR (in the electrical domain) that is proportional to $1/N^4 \sim 1/N^5$. Table II summarizes some of these features for the various upstream multiple-access schemes.

B. *Wavelength-Division Multiple Access (WDMA)*

WDMA is a highly efficient method for sharing a PON architecture. In this scheme, each subscriber is assigned a pair of dedicated wavelengths; this contrasts to the TDMA case where a single pair of wavelengths is shared among all the subscribers connected to the PON. This means that each user can send data to the OLT at any time, independent of what the other users are doing. In other words, there is no interaction or coupling between the subscribers on a WDM-PON; this eliminates any management issues related to sharing the PON. Each subscriber gets a dedicated point-to-point optical channel to the OLT, although they are sharing a common point-to-multipoint physical architecture.

To realize this WDMA functionality, a WDM multiplexer is used at the RN instead of a power splitter, and an additional WDM demultiplexer is located at the CO to separate the multiple-wavelength signals at the OLT, as shown in Fig. 4. The mux/demux operation can be realized using an arrayed

TABLE II
SUMMARY OF MULTIPLE ACCESS METHODS FOR UPSTREAM DATA TRANSMISSION

Multiple access method	TDMA	WDMA	SCMA	CDMA
Guaranteed BW	Line rate/N	Line rate	Line rate	Line rate/gain*
Burst mode at	OLT and ONT	No	No	No
Statistical gain	Yes	No	No	No
MAC/Aggregation	Yes/no	No/Needed	No/Needed	No/Needed
Timing control	Must	No	No	Depends on scheme
QoS	Priority management	No issue	No issue	No issue
Splitting loss [dB]	$10 \text{ Log } N + \alpha^{**}$	WDM loss (3 – 5 dB)	$10 \text{ Log } N + \alpha$	$10 \text{ Log } N + \alpha$
SNR penalty	$N^4 \sim N^5$	Reference	$N^3 \sim N^4$	$N^4 \sim N^5$
Transparency limited mainly by	Link budget	NA	Modulation BW	Link budget
Protocol transparency	No	Yes	Yes	Yes
ONTs are	Dependent	Independent	Independent	Independent
In service upgrade	No	Yes	Limited	No
wavelength control	No	Yes	Partial	No
OLT specials	Burst mode receiver	WDM DEMUX	Linear Rx	Linear Rx
Remarks	- High speed transmission - Burst mode receiver	- Color free optical source	- OBI suppression	- OBI suppression - High speed Transmission

* Gain is larger than N
** Excess loss

waveguide grating (AWG) or also by thin-film dielectric filters. Using dense-WDM (DWDM) technology, the channel spacing for each wavelength can be as narrow as 50 or 100 GHz, similar to that used in long-haul WDM transmission. The WDM multiplexer can efficiently couple many wavelengths onto the single feeder unlike the TDMA case that uses an inefficient optical-power splitter.

For WDMA, there are no QoS issues related to sharing the PON since the network is based on dedicated optical point-to-point connections. In addition, there are no requirements for burst-mode receivers or transmitters and no need for any sophisticate MAC algorithms to manage the timing of the ONT transmissions. This makes the operation of a WDMA network very simple. Also, since a wavelength mux/demux is used instead of an optical-power splitter, the insertion loss at the RN is considerably smaller and effectively independent of the splitting ratio. In addition, since the receiver bandwidth for each ONT is matched to its dedicated bandwidth, there is no additional penalty related to the number of users on the PON. These features make the SNR essentially independent of the number of subscribers "N," allowing efficient scaling and flexibility for a WDMA-PON architecture.

Besides the above advantages of the WDMA architecture, there are some challenges in developing a practical system. For example, each ONT requires a wavelength-specific source that matches the transmission window defined by the mux/demux at the RN. Finding a cost-effective solution for this requirement has been a key bottleneck in the commercialization of WDMA networks. Recent advances addressing this issue will be dealt with in more detail in the later WDM-PON section. In addition, to realize a dedicated optical connection to each subscriber, the OLT requires "N" separate transceivers. This leads to $2N$ transceivers compared to the $N + 1$ transceivers needed in the TDMA case. Another potential concern is that the peak data rate to each user is equal to their dedicated data rate. This means that the unused channel capacity of a subscriber cannot be shared by any of the other users on the PON. Many of these perceived drawbacks are a fundamental consequence of providing a simple, uncoupled, and highly efficient PON solution capable of delivering > 100 Mb/s to each subscriber, which is expected to be needed for the many video-centric future applications.

C. Subcarrier-Division Multiple Access (SCMA)

Subcarrier multiple access enables dedicated point-to-point connectivity over a PON architecture by allocating a different RF frequency for each subscriber. In this scheme, each subscriber transmits at essentially the same wavelength but is allotted a unique RF frequency for encoding its data. A single receiver at the OLT detects the N different RF frequencies and demultiplexes them in the electrical-frequency domain. The RF frequencies are the subcarriers, while the transmitted upstream-optical wavelength is the main carrier. As in the TDMA case, an optical-power splitter can be used at the RN location. This architecture allows N users to share a common wavelength, while providing a dedicated and uncoupled communication channel.

Although this looks like an ideal and efficient system at first glance, it has many drawbacks in its practical realization.

One disadvantage is that the electrical bandwidth of the OLT receiver needs to be at least two times the sum of the N data-rate channels. This occurs due to the double-sided nature in the frequency domain of a modulated-RF carrier. As an example, to provide a data rate of 75 Mb/s to each subscriber would require a receiver bandwidth of about 5 GHz. In practice, this bandwidth would need to become about 10 GHz since the subcarriers need to be assigned within an octave of frequency to avoid nonlinear distortions induced by the optical receiver.

A more critical problem related to SCMA is due to optical-beat-interference (OBI) noise [14] that occurs due to optical beating or interference from the mixing of the N different laser wavelengths on a single detector. This noise is dependent on the optical linewidth and wavelengths of the ONT lasers used for the upstream transmission. Assuming identical lasers, OBI noise scales as N^2 in the electrical domain. Many methods have been proposed to reduce the OBI noise. One method uses optical sources with broad linewidth to spread most of the beat-frequency noise outside the electrical bandwidth of the receiver [14]. This can be realized by using light sources such as light-emitting diodes or multimode lasers, although it can be difficult to modulate these sources at high-RF frequencies. Another possible way to reduce OBI is to use narrower linewidth lasers and control their center wavelengths. Although this method can be useful for small N, as the number of users becomes large, the required wavelength control becomes tighter and eventually more stringent than WDMA.

Electrical-receiver SNR for SCMA scales on the order of $1/N^3 \sim 1/N^4$. This scaling relationship is mainly due to the optical-power splitter that gives a $1/N^2$ factor combined with the thermal noise of the receiver and the method used for trying to reduce the OBI noise. One advantage of SCMA when compared to TDMA is that the receiver-noise bandwidth associated with each user is only twice the dedicated data rate instead of N times.

D. *Code-Division Multiple Access (CDMA)*

CDMA is a well-known technique used in cellular-phone networks. These cellular networks allow multiple users to simultaneously share a common frequency channel by using orthogonal codes to transmit "zero" and "one" data bits. Similarly, this technique can be used in the optical domain, where the multiple users share a common upstream wavelength. Each subscriber is assigned a unique and effectively orthogonal code for transmission at any time regardless of when the others are transmitting. At the OLT receiver, all the overlapping codes are detected using a single receiver and correlated with sets of matching codes associated with each user-data channel. High-correlation peaks occur for matched codes, and very small correlation peaks occur for the mismatched codes. This allows simultaneous and independent data transmissions to occur through a single-OLT receiver.

For code lengths of "M," the correlated peaks can be M times larger than the uncorrelated signals. This provides an SNR increase of M for matching codes after the correlation process. The ratio between the chip rate (code bit rate) and the information data rate is referred to as the correlation-processing gain. Since the chip bit rate is larger than the information data rate, the required OLT receiver bandwidth has to be M times larger than the dedicated data rate. To find the suitable orthogonal codes for N different subscribers typically means the code length "M" has to be larger than the number of users. This leads to receiver-bandwidth requirements that are larger than for the previously discussed TDMA method.

Although CDMA supports dedicated and uncoupled communication channels for each of the users on the PON, it may need time synchronization for the optically generated codes [14]. Although asynchronous CDMA is possible, it results in a correlation-peak penalty. It is also possible to use multiple wavelengths to generate orthogonal codes [15]; however, this may require arrays of optical sources at each ONT that may not lead to a cost-effective approach. Various methods of CDMA have been demonstrated with the help of fiber Bragg gratings [16] and AWGs [17].

Regarding the scaling of a CDMA-PON network, since it uses an optical-power splitter at the RN, it suffers the same power-insertion-loss penalty as for the TDMA case. Also, since code lengths are larger than the number of users, the bandwidth requirements at the OLT/ONT receiver can be greater than for the TDMA case. Although the correlation-processing gain helps in the SNR, there is multiaccess-interference noise. In addition, there is also optical-beat-interference noise as in the SCMA case. As a result, the electrical SNR for the upstream data transmission is approximately the same as for TDMA and scales as $1/N^4 \sim 1/N^5$.

E. *Multiplexing Methods for Downstream Data Transmission*

The above sections described the four basic multiple-access techniques that allow multiple users to share a point-to-multipoint PON architecture in the upstream direction. For the downstream direction, the problem is generally considered much easier. In this section, we will briefly discuss the related multiplexing schemes for downstream-data transmission. The key features for these four techniques are summarized in Table III.

TDM uses a broadcasting scheme where a single high-speed data signal is distributed to each ONT. Each ONT then selects their specific portion of the broadcast data by either an address at the beginning of the data packet or in some cases by predetermined time slots. There are no requirements for burst-mode receivers or transmitters in the downstream direction since the single-OLT transmitter broadcasts at constant data rate and signal strength. Another advantage is that it is relatively easy to assign different bandwidths to each user since the OLT has control of which user it addresses and the length of the data packets. One potential concern is related to security since each ONT has access to all the data sent to any of the other users on the PON. To address this concern, data encryption is typically required for the downstream traffic. Also, similar to the TDMA case, each user on the PON has a dedicated data rate equal to only $1/N$ of the total downstream-transmission data rate.

In the case of WDM, a separate dedicated wavelength is used for the downstream transmission to each user. This requires a separate laser source at the OLT for each subscriber connected

TABLE III
SUMMARY OF VARIOUS MULTIPLEXING METHODS FOR DOWNSTREAM DATA TRANSMISSION

Downstream multiplexing	TDM	WDM	SCM	CDM
Signal delivery	Broadcast and select (time)	Dedicated	Broadcast and select (frequency)	Broadcast and select (code)
Guaranteed BW	Line rate/N	Line rate	Line rate /N	Line rate/gain*
Statistical gain	Yes	No	No	No
Splitting loss [dB]	10 Log N + α**	Insertion loss of WDM	10 Log N + α	10 Log N + α
SNR penalty	$N^4 \sim N^5$	Reference	$N^4 \sim N^5$	$N^4 \sim N^5$
Transparency limited by	Link budget	NA	- Link budget - Optical nonlinearity	- Link budget - Optical nonlinearity
Protocol transparency	No	Yes	Yes	Yes
Security in Physical layer	No	Guaranteed	No	No
Optical source/ wavelength control	1/No	N/Yes	1/No	1/No
OLT specials	No	WDM MUX	- Linear Tx - Optical amplifier	- Linear Tx - Optical amplifier
Remarks	- High speed transmission	- Low cost optical source	- High power transmission	- High power transmission

* Gain is larger than N, Electrical multiplexing for CDM case
** Excess loss

to the PON. These laser sources also need to be wavelength matched to the optical passband of the wavelength multiplexer used for combining all the signals onto a single PON. Since a wavelength demultiplexer at the RN directs a different wavelength to each user, there are no security issues since other users on the PON do not have access to any of the other downstream wavelengths. Security is guaranteed by the architecture of the physical network. WDM provides dedicated point-to-point connections to each user without any of the concerns associated with multiple users sharing a single downstream-transmission channel.

For the case of SCM, all the individual signals for each user are multiplexed in the electrical-frequency domain before being imparted onto a single-laser wavelength for downstream transmission. As in the SCMA scheme, the required modulation bandwidth is typically quite large due to the double-sided nature of the RF-modulated signals and the required RF-frequency locations to avoid any nonlinear distortions [18]. In addition, extra care is required to avoid any clipping noise induced by the threshold characteristics of the laser transmitter [19]. Also, due to the high-linearity requirements, the individual RF signal received at each ONT must decrease in proportion to the number of signals multiplexed onto the downstream-optical carrier. This can be overcome by use of an optical amplifier to boost the transmitted signal, but higher optical powers can then lead to optical nonlinearities in the transmission fiber [20]. These factors result in an SNR that scales as $1/N^4 \sim 1/N^5$ for SCM.

For CDM, different codes can be used instead of the different frequencies as in the SCM case. The resulting SNR scales similar to SCM and is in the range of $1/N^4 \sim 1/N^5$. It may be noted that the required bandwidth of the transmitter is larger than "N" times the offered bandwidth to each subscriber.

In summary, of the four general multiplexing methods described above, only the TDM and WDM methods are considered practical for use in next-generation PON applications. SCM can be used for broadcasting multiple-video channels over a PON (using HFC-modulation techniques), but this is currently not used for addressing individual subscribers. It looks questionable whether CDM techniques will find any practical use in PON applications. The next section will provide a more detailed discussion on the two more promising solutions, which are typically referred to as TDM-PON and WDM-PON.

IV. PON ARCHITECTURES

The previous section provided a brief overview of the various multiplexing and multiple-access techniques that can be used when multiple users share a point-to-multipoint PON infrastructure. Of these various approaches, the authors expect that the two most likely candidates to see widespread future use are the time-domain and wavelength-domain methods. The time-domain schemes can be referred to as a TDM-PON, and the wavelength-domain schemes can be referred to as WDM-PON. The only difference in the outside plant (OSP) between these two approaches is at the RN location. In a TDM-PON, a passive power splitter is used, while for a WDM-PON, a passive wavelength splitter is used, such as an athermal AWG.

It is also possible to use mixed or hybrid approaches. For example, in some TDM-PON implementations, an additional

TABLE IV
COMPARISON OF FSAN/ITU-T PON AND IEEE E-PON

Item		FSAN/ITU-T		IEEE E-PON
		B-PON	G-PON	
MAC Layer	Service	Full service (Ethernet, TDM, POTS)		Ethernet data
	Frame	ATM cell	GEM frame	Ethernet frame
PHY Layer	Distance	10/20 km (Logical : 20 km)	10/20 km (Logical : 60 km)	10/20 km
	Split ratio	32	64 (Logical : 128)	16 or over
	Bit rate	622 Mb/s (down), 155 Mb/s (up)	2.5 Gb/s (Down), 1.25 Gb/s (up)	1.25 Gb/s (Up & Down)
	Bandwidth	Same as above (NRZ coding)		1 Gb/s (8B10B coding)
	Optical loss (including split loss)	15/20/25/30 dB	15/20/25/28/30 dB	15/20 dB
	Upstream Burst Timing	Total 24 bits (Guard time : 4 bits (min.))	Guard time : 25.6 ns; Preamble : 35.2 ns (typical); Delimiter : 16.0 ns (typical)	Laser turn on/off : 512 ns (max); AGC setting & CDR lock : 400 ns (max)

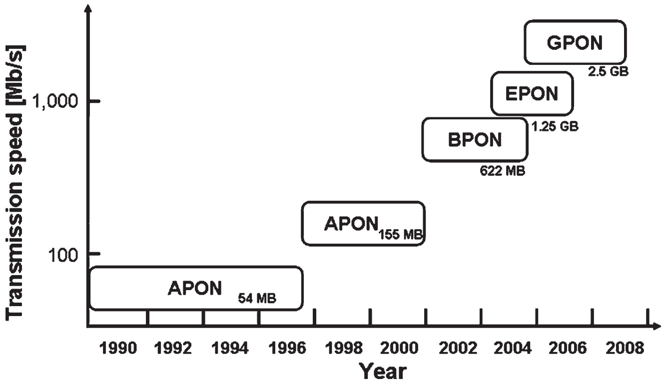


Fig. 5. History of TDM-PON development.

wavelength can be added in the downstream directions to provide a video-broadcast signal to deliver a limited set of TV channels to each subscriber. This results in a mixed PON that uses TDM for the data delivery and SCM for the broadcast-video signals.

A. TDM-PON

TDM-PON is currently the most popular FTTP approach and is starting to see significant deployments in various regions of the world. As mentioned earlier, since "N" users share a single upstream and downstream-transmission channel, the transmission data rate over the PON must be N times the dedicated data rate to each subscriber. This approach can provide a cost-effective solution since only a single transmitter and receiver is shared at the CO location. This solution is suitable as long as the bandwidth demand of the many users sharing the PON does not become too great. To address these limited bandwidth concerns, some TDM-PON have added a separate video-overlay wavelength to provide TV signals that are compatible with existing TV sets and home wiring.

To make TDM-PON cost effective and practical for widespread deployment, standardization of the algorithms and protocols must be established. This standardization process can be difficult due to the complexity of the time-sharing algorithms combined with ever increasing bandwidth demands and difficulty in predicting the specific future applications that will be used over the PON. The two main standardization bodies that have developed TDM-PON standards are the full service access network (FSAN) [10] group and the IEEE [9]. Currently, there have been many standards established, and they are summarized in Table IV. The development history for these different TDM-PONs is illustrated in Fig. 5.

The first TDM-PONs to be deployed was referred to as APON since it was based on the asynchronous-transfer-mode (ATM) communication protocol. This solution saw considerable deployment in Germany from about 1990 to 1996. It used a shared transmission data rate of 54 Mb/s and was mainly designed for compatibility with existing voice and phone services [21]. With the emergence of the Internet, the shared data rate was upgraded to 155 Mb/s in the latter half of the 1990s [22]. As bandwidth demand continued to grow due to the increasing popularity of the Internet and WWW, the downstream bandwidth was upgraded again to 622 Mb/s [23]. To reflect this increase in bandwidth, the acronym APON was replaced by broadband PON (BPON). In 2002, three major U.S. telecom carriers, Verizon, SBC, and Bell South jointly announced a request for products (RFP) based on the BPON standard.

With the growing popularity of the Ethernet protocol in access networks and the increase in Internet data traffic, the IEEE developed a TDM-PON standard based on the Ethernet protocol referred to as Ethernet PON (EPON). The EPON standard was designed to better handle packet-based data traffic compared to the A/BPON standard that was optimized for voice traffic. The EPON standard also increased the shared transmission data rate to 1.25 Gb/s in both the downstream

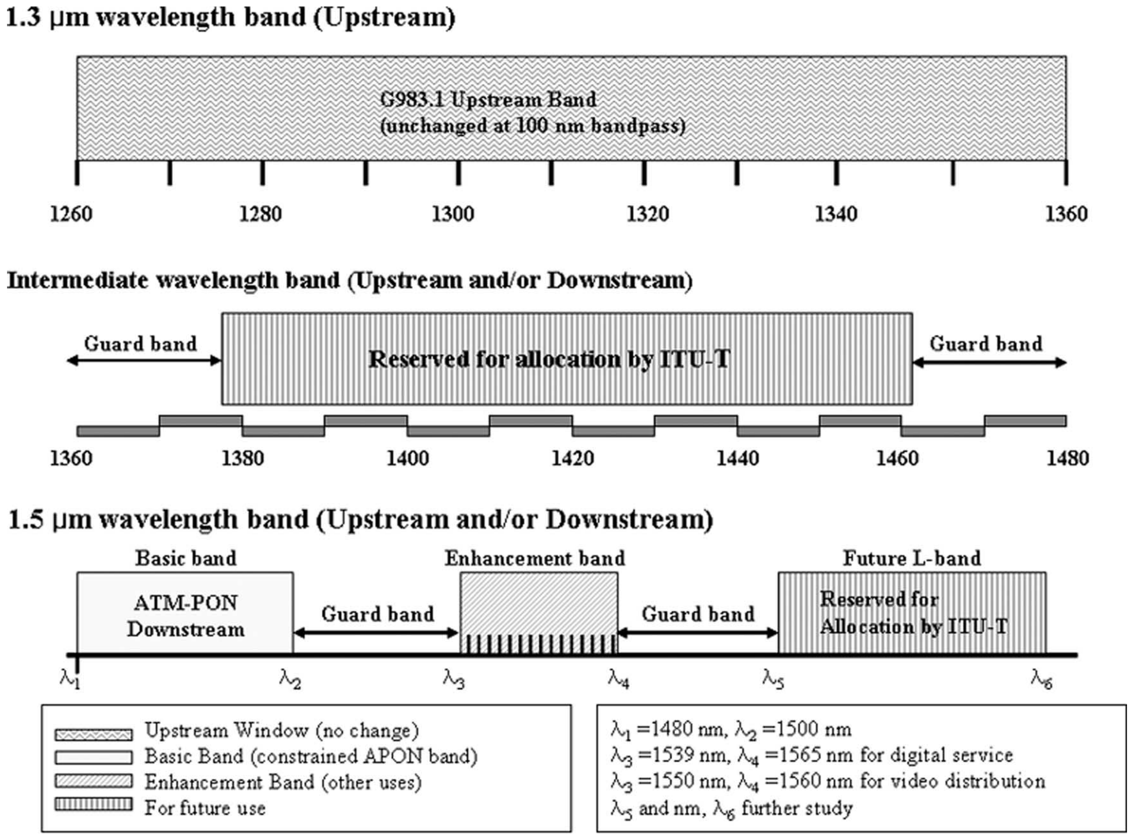


Fig. 6. Wavelength plan for ITU-T standard TDM-PONs.

and upstream directions [24]. One of the goals of this standard was to also reduce the cost of the transmission equipment by relaxing many of the specifications that were developed for the FSAN-BPON standard. The EPON standard is being actively deployed in Japan and is also been considered in some other Asian countries.

Recently, there has been a growing consensus that the most efficient way to reduce capital investment and operational costs is to develop a common network platform capable of delivering the converged services of data, voice, and video. This offering is commonly referred to as triple-play service (TPS). Since it is questionable whether the existing standards such as BPON or EPON can deliver enough bandwidth or provide the required QoS, the FSAN body has recently developed another standard called Gigabit PON (GPON). This standard uses 2.5 Gb/s for the downstream-transmission channel and 1.25 Gb/s for the upstream [25]. It also uses a new frame-transmission format called generic encapsulation method (GEM) that allows it to efficiently handle either ATM or Ethernet-based traffic.

Although the data rates and protocols for the various TDM-PON standards have changed over time, the standards bodies have been careful not to change the wavelength bands for the downstream and upstream channels as defined by the ITU-T. This has been important for component vendors since they have been able to optimize their devices for these specific wavelength bands. Fig. 6 illustrates the assigned wavelength bands for TDM-PON networks. The upstream wavelength band is defined to be in the 1260–1360-nm range. This range was picked to try to reduce the expense of the larger number of lasers needed for the upstream transmission. For example, since this range is centered on the dispersion minimum in standard single-mode fiber, low-cost multimode Fabry–Perot laser diodes (FPLD) can be used at data rates of up to 1.25 Gb/s over distances of about 10 km. This shorter wavelength band also allows for more efficient laser diodes that can operate over large temperature ranges without the need for cooling. Since the downstream transmission can use a single more expensive DFB laser source, a narrower wavelength band of 20 nm centered at 1490 nm was selected. Also, since a video overlay was also considered when defining these standards, an additional downstream band is defined between 1550 and 1560 nm for a broadcast-video stream. This band was chosen since it overlaps with the optical-gain bandwidth of an erbium-doped fiber amplifier (EDFA) needed to preserve the SNR of the higher fidelity video signals. There are also additional bands reserved for future use.

Over time, low-cost and relatively complex optical components have been developed to address these defined wavelength bands. One important component is called a diplexer or bidirectional (BiDi) module that is used in all the remote ONTs. This compact module contains both a laser diode and a photodetector and uses a WDM filter at a 45° angle to separate the upstream and downstream wavelength bands. A typical configuration for a BiDi module is shown in Fig. 7. In situations where the video-overlay wavelength is required, a similar component called a triplexer is used that can separate three wavelength bands and houses a laser diode and two photodetectors. As an example,

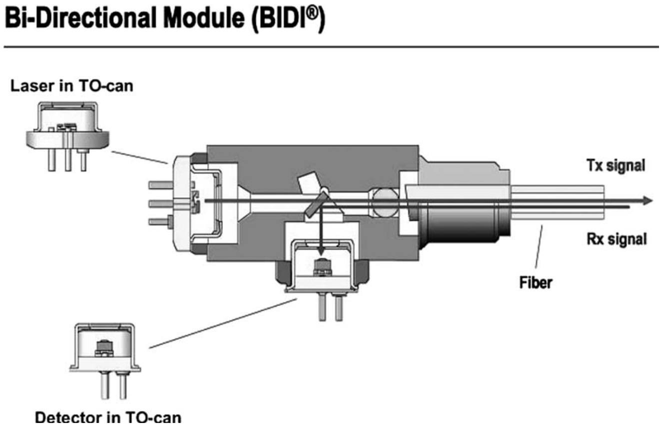


Fig. 7. Schematic diagram of BiDi module.

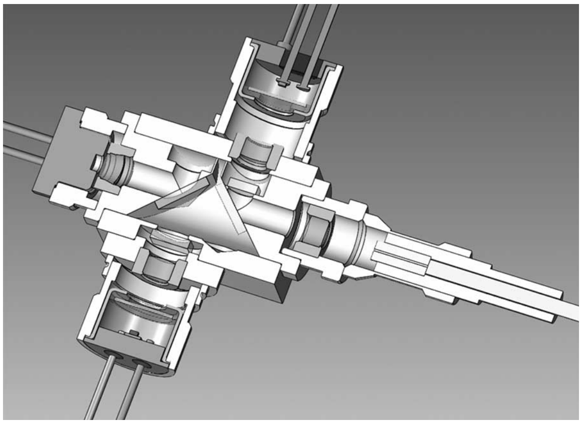


Fig. 8. Schematic diagram of Triplexer module.

triplexer is shown in Fig. 8. As packaging and integration technologies have matured, the package size and performance of these devices have been steadily improving [26]–[28].

One difficulty with the TDM-PON standardization process is that information and communication technologies are changing at very fast rates. This appears to be a fundamental issue related to the apparent limitless uses of the still growing Internet. This situation is quite different from the previous voice-based telecom network, whose primary application remained unchanged for over 100 years. Since the standardization process typically takes several years to complete, combined with an additional year or two for vendors to develop products for mass production, by the time the technology is ready for full-scale deployment, it is already outdated. This problem is more challenging than in other fast-changing technology markets since these choices affect widespread infrastructure decisions, which hopefully should last for 20 or more years. This trend in TDM-PON standards is illustrated in Fig. 5. With the newly started standard activities investigating 10-Gb/s PON data rates, the trend in Fig. 5 is likely to continue.

B. WDM-PON

As discussed in the previous sections, using WDMA can eliminate many of the time-sharing issues in a TDMA system. WDM-PON provides an optical point-to-point connection by allocating a pair of bidirectional wavelengths to each user connected to the PON. The only difference in the outside-fiber plant is replacing the optical-power splitter in a TDM-PON with an AWG to demultiplex the downstream wavelengths and multiplex the upstream wavelengths. The wavelength-channel spacing in an AWG can be 0.8 nm or less, which allows many users to be connected to a WDM-PON.

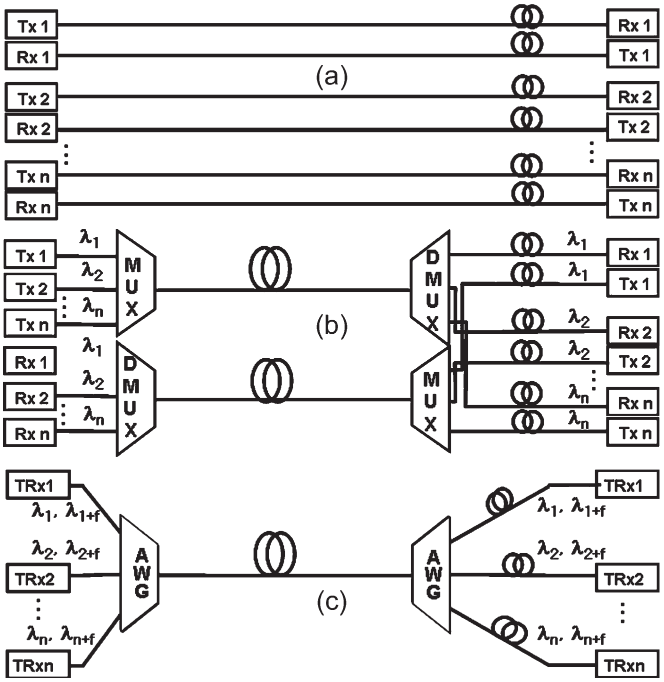


Fig. 9. Simplification of network that supports point-to-point connectivity with WDM-PON.

Fig. 9 shows some simplified concepts to better understand how a WDM-PON system provides an optical point-to-point connection over a standard PON architecture. The conceptually simplest method for providing a point-to-point connection would be to install two fibers from the CO to each subscriber [see Fig. 9(a)]: one for the upstream transmission and the other for the downstream transmission. This basic fiber infrastructure can be simplified with the use of WDM technology. A conventional WDM system [see Fig. 9(b)], as used in long-haul applications, assigns a different wavelength to each user and consolidates all the wavelengths in one direction onto a single-transmission fiber and typically uses AWGs at each end to separate out the wavelengths for coupling to either detectors or laser sources. One reason that long-haul WDM systems use unidirectional transmission is so that optical amplifiers, which typically require isolators, can be easily used. Since a PON infrastructure typically would not need any optical amplification, the efficiency of a conventional WDM system can be increased by allowing bidirectional-wavelength transmission along each of its fibers [see Fig. 9(c)]. This bidirectional functionality can be realized by using AWGs designed to be periodic or cyclic [29]. A cyclic AWG is designed to have a free-spectral range so that multiple wavelengths can be coupled onto each of its output fibers. By using cyclic AWGs, a WDM-PON architecture is a very efficient fiber infrastructure since dedicated bidirectional-WDM transmission can be preformed on each fiber in the PON

TABLE V
VARIOUS OPTICAL SOURCES FOR WDM-PON

			Wavelength control	Modulation Scheme	Modulation speed	Color-free ONT	Operation bandwidth	Remarks
Solitary source at ONT	Wavelength specific laser		Needed at ONT	Direct	10 Gb/s	No	Unlimited	
	Tunable laser		Needed at ONT	Direct	~ 2.5 Gb/s	Yes	40 nm	- Wavelength information
	Broadband light: ASE from	LED	No	Direct	~ 100 Mb/s	Yes	> 50 nm	- High slicing loss. - Dispersion limit for > 1 Gb/s
		SLD	No	Direct	< 1 Gb/s	Yes	> 50 nm	
		Doped fiber	No	External	> 10 Gb/s	Yes	30 nm	
Seed from OLT	Array of wavelength specific laser at OLT	External modulator	Needed at OLT	External	2.5 Gb/s	Yes	Unlimited	- Back reflection penalty -Two feeder fibers - Needs optical amplifier for EM
		RSOA	Needed at OLT	Direct	~ 1 Gb/s	Yes	> 50 nm	
		F-P LD	Needed at OLT and ONT	Direct	~ 2.5 Gb/s	Yes	50 nm	
	Broadband light at OLT	External modulator	No	External	> 10 Gb/s	Yes	30 ~ 50 nm (Limited by broadband light at OLT)	- High power seed light - Dispersion limit for > 1 Gb/s - Needs optical amplifier for EM
		RSOA	No	Direct	~ 1 Gb/s	Yes		
		F-P LD	No	Direct	~ 2.5 Gb/s	Yes		
	Remodulation of downstream data		Needed at OLT	Direct/ External	~ 2.5 Gb/s	Yes	50 nm	- Back reflection penalty - Limited dynamic range

system. To separate the upstream and downstream wavelengths at each transceiver, a small BiDi module can be used, which is similar to that developed for TDM-PON systems.

In addition to its efficient use of wavelengths, a WDM-PON also has advantages in its use of optical-transmission power. TDM-PON architectures typically use a 1 × 32 power splitter at the RN that results in an insertion loss of about 17 or 18 dB. In contrast, the loss through typical AWGs can be in the range of 3–5 dB. Although two AWGs are required in WDM-PON, the insertion-loss improvement between a transceiver pair is on the order of 8 to 11 dB. In addition to the much lower insertion loss, an additional optical efficiency occurs since the noise bandwidth of each receiver can be $1/N$ that of a TDM-PON approach. For a PON with 32 users, this can result in an addition improvement of about 10 dB in the receiver sensitivity. This improvement becomes even larger when the PON is scaled up to service more users since the insertion loss through an AWG is effectively independent of its splitting ratio. When compared with a TDM-PON, the WDM-PON approach offers large improvements in both optical-power penalty and in its ability to scale up to serve a large number of users sharing a single PON. These features are also important for realizing a long-reach PON [30].

These efficiency improvements are very important to the upgradeability and flexibility of a WDM-PON system. Since each user has a point-to-point wavelength connection, it is possible to provide different data rates and protocols to each subscriber. Since each user is uncoupled from others on the PON, data-rate upgrades can be done on an individual basis without causing disruption to any of the other users. Using an AWG splitter with a 100-GHz channel spacing, it would be possible to provide future bandwidths of up to about 40 Gb/s to each user. This flexible bandwidth upgradeability would be very useful if a WDM-PON is shared with a diverse set of users, such as business customers and home residents. There would be no issues regarding QoS or privacy since no optical signals are shared with anyone else connected to the PON. An additional feature of a WDM architecture is its ability to localize any fault or optical loss in the fiber plant by using a single wavelength-tunable OTDR located at the CO [31]. This could yield large operational and maintenance savings compared to PONs that use power splitters since it is very difficult to isolate problems in the fiber plant past the position of the RN.

Although a WDM-PON has many technical advantages, there have been several issues that have prevented it from being a suitable solution for access applications. One issue has been related to the wavelength stability of the AWG located at the passive RN. Until recently, AWG required temperature control to keep their optical channels locked to a wavelength grid. This would have required electric power at the RN that would be unacceptable for a PON solution. Technology advances have allowed the recent commercialization of athermal AWGs that can remain locked to a DWDM-wavelength grid over temperature ranges experienced at the passive-node location [29]. It is also projected that these athermal AWGs will have costs similar to optical-power splitters, since each will use the same planar-lightwave circuit (PLC) technology, and the major costs are in the packaging, which will be similar for each device.

Another issue is the concern of using wavelength-specific sources such as DFB lasers in a WDM-PON system. If DFB lasers were used, these lasers would require thermo-electric coolers (TEC) to stabilize their wavelengths that would result in relatively expensive packaging. Also, this scheme would require a different or "colored" transceiver for each user, resulting in high costs for inventory management and maintenance. To address this issue, much effort has been done on trying to develop low-cost sources that are "color-free" or wavelength independent so that all subscribers can have identical ONTs. Some of these approaches are listed in Table V. It may also be possible to provide color-free operation by using relatively expensive wavelength-tunable lasers, if prior information of the channel wavelength is known [33].

One promising approach has recently been proposed that enables color-free and identical transmitters by using an automatic wavelength-locking scheme [32], [34], [35]. This scheme relies on providing an optical-seeding signal generated at the OLT that can be used to wavelength-lock the identical optical transmitters located at each remote ONT. The identical ONT lasers can be a simple FPLD [32] or reflective optical-semiconductor amplifiers (RSOA) [34]. The FPLD or RSOA performs three functions: amplification, data modulation, and reflection of the reference-seed signal provided by the OLT. The reference-seed signal can be generated by an array of wavelength-specific sources such as DFB lasers or by a simple broadband amplified-spontaneous-emission (ASE) light source. Since this reference signal has to pass through the wavelength passband of the RN AWG, each of the identical ONTs is automatically aligned to the optical channel defined by the WDM-PON infrastructure. This wavelength-alignment process automatically occurs when using a broadband ASE source since after spectral slicing by the AWG, each ONT only receives the proper wavelength band to transmit back to the OLT receiver. It may also be possible to use the downstream data signal as a seed for the ONT transmitter, but large penalties result in both dynamic range and ONT complexity [36]. These schemes are currently an active area of research and development. Recently, commercial WDM-PON systems have been widely deployed in Korea [37].

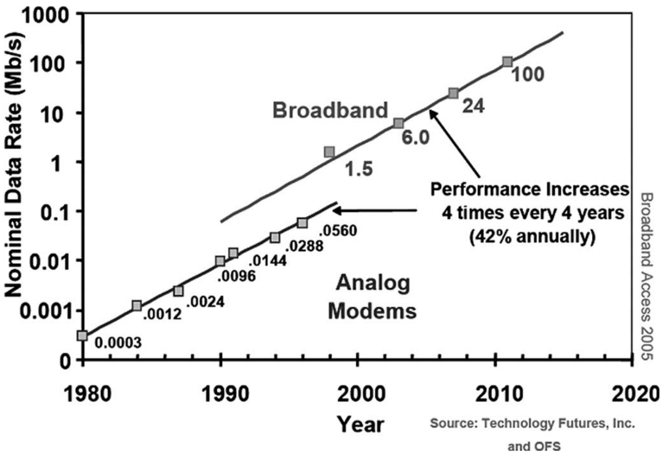
One important issue that currently needs to be addressed is the standardization of the wavelength bands used for the upstream and downstream channels in a WDM-PON infrastructure. Even if different methods and technologies are deployed, such as wavelength-specific or wavelength-independent laser sources, it will be important to specify the channel bands so that different methods can work over a commonly defined PON infrastructure.

V. EVOLUTION AND FUTURE OF FTTP NETWORKS

A. *Bandwidth Growth*

It is widely believed that we are just starting to experience a new video-centric world that will enable many new applications and opportunities. These opportunities will include services such as IPTV, video on demand (VoD), education on demand (EoD), HDTV, video conferencing, high-quality interactive-video gaming, and video surveillance. With the recent introduction of HD quality camcorders, it is becoming easier for consumers to generate high-bandwidth signals for upstream transmission.

Fig. 10 shows the historic and future projections for average data rates through the access network. The discontinuous step in access bandwidth in the late 1990s was a result of a technology switch from analog modems using narrowband voice channels to digital DSL transmission using larger bandwidths on the existing twisted-pair telephone wires. The bandwidth growth to each subscriber has grown about a fourfold increase every four years [38]. It is interesting to note the strong correlation with this bandwidth-growth rate and introduction of new TDM-PON standards (each with bandwidth increases of about four times), as discussed in the previous section. With the advent of new FTTP networks and the impending video-centric digital world, one might expect another discontinuous step in future bandwidth growth. An interesting point to note is that as data rates have grown, there has been a trend in traffic patterns to shift from being bursty and highly asymmetric to becoming steadier and more symmetric. This is being driven by increases in peer-to-peer applications and the constant streaming data rates required for video signals. Demands for higher QoS-over-digital links will increase as high-quality-video applications are developed. To satisfy these future demands, it is expected that dedicated and symmetric data rates of 100 Mb/s and greater per subscriber will be required. This places challenging constraints on the development of future access networks since any long-term infrastructure should be capable of supporting large symmetric data rates (> 100 Mb/s) with high QoS.



Source: Technology Futures, Inc. and OFS

Fig. 10. Bandwidth evolution in access networks.

When building a PON infrastructure, analysis by Corning [5] has shown that the installation for the OSP costs about 60% with the remaining 40% required for the service equipment. Since installation costs are high and OSP lifetimes are expected to be greater than 25 years, these fiber-based networks should be designed with the future in mind. The costs and disruptions associated with installing additional fiber plant should be kept to a minimum. Keeping these constraints in mind, we can estimate possible evolution paths for existing and future PONs.

Before discussing PON evolution paths, it is interesting to look at the historic evolution of Ethernet, as illustrated in Fig. 11. The early origins of Ethernet started in the 1970s with the ALOHA project in Hawaii, where users on separate islands shared a single RF channel. These concepts were later used in wired systems to construct a local-area network (LAN), where multiple users shared a common communication channel. The line speeds of these LANs increased from 2.94 to 10 Mb/s by the mid-1980s. The protocol used for these earlier Ethernet LANs was carrier-sense multiple-access/collision detection (CSMA/CD). As the bandwidth demand per user increased, coupled with more users attempting to share the LAN, the efficiency of this technique started to decrease. In the latter half of the 1980s, Ethernet switches were developed to solve this bandwidth-sharing problem. By using a switch, each user could be given a dedicated point-to-point connection that could guarantee a dedicated communication channel to each customer.

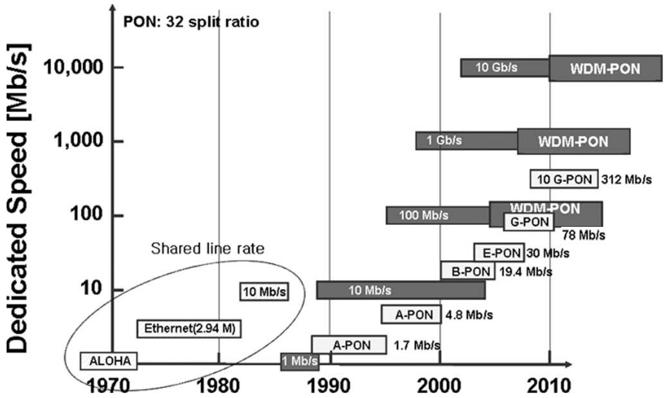


Fig. 11. History of Ethernet and PONs.

Soon after this, the shared Ethernet LAN disappeared. Point-to-point data rates increased relatively rapidly from about 1 Mb/s in the late 1980s to 1 Gb/s by the late 1990s. Currently, 10-Gb/s solutions are becoming increasingly popular. An interesting comparison can be done if we include the TDM-PON history, as shown in Fig. 5 with the Ethernet evolution in Fig. 11. The shared TDM-PON evolution appears to be following the shared Ethernet evolution. This tracking of Ethernet is expected to continue with PON systems eventually converting over to point-to-point systems to avoid the similar sharing problems that troubled early Ethernet LANs. One efficient method to realize this point-to-point connectivity is to use WDM-PON whose dedicated bandwidths per user can scale to values in excess of 1 Gb/s [34], [39]–[41].

B. Evolution Paths for PON

Currently, the most popular PON systems are based on TDM-PON solutions. These solutions have been commercially available since the early 1990s. One of the strengths of these approaches is that only a single shared transceiver is required at the CO location. Recently, relatively large deployments of EPON have occurred in Japan, and it appears that the BPON/GPON may start seeing significant deployment in North America.

A BPON system shared among 32 users provides a dedicated bandwidth of less than 20 Mb/s in the downstream direction and about 4 Mb/s for the upstream. The later generation EPON solution provides up to about 30 Mb/s per user assuming the same 32-split ratio. The next-generation TDM-PON solution will be GPON that will be capable of about 75 Mb/s [35 Mb/s] for the downstream [upstream] data rate. GPON systems are also capable of servicing 64 users per PON, but this lowers the dedicated data rate to about 37 Mb/s [17 Mb/s] per user. It may be noted that DBA, which can provide a statistical gain, may be used to enhance effective user bandwidths by allocating unused time slots to the busier ONTs [12], [42]. However, the actual amount of statistical gain may be reduced for continuous data-rate applications such as video and voice streaming.

With the expected bandwidth growth for the impending HD-video-centric world, these solutions will eventually need to be upgraded. The following will discuss some possible evolution paths assuming a network initially designed for providing a TDM-PON solution.

One of the most obvious methods for upgrading a TDM-PON system is to keep the PON architecture fixed and increase the transmission data rate shared by all the users. The IEEE standards body is already considering this concept by looking into the feasibility of increasing the EPON transmission data rate from 1.25 to about 10 Gb/s [43]. Due to the technical challenges associated with such a high data rate over a PON, it is currently unclear if a cost-effective solution is possible. Another difficulty with a bandwidth upgrade is that all the users sharing the PON must upgrade their ONTs at the same time. This can be inconvenient for many of the users if only a few of the subscribers on the PON actually need the higher bandwidth. It also results in a loss of service, while the hardware upgrade is being done.

Another upgrade solution would be to add additional wavelength channels in both the upstream and downstream directions. This would require inserting WDM filters at both the CO and ONT locations. These wavelength filters would have to be of high quality to avoid any data-modulation crosstalk from the multiple-broadcast wavelengths. To avoid these crosstalk issues, everyone on the PON would be required to simultaneously upgrade their ONT equipment causing inconvenience to many of the lower data-rate users. It may be possible to overcome this problem by initially including blocking filters into the design of the ONTs in advance of them being needed for the upgrade. This would allow for a wavelength upgrade without affecting the legacy PON users. The new wavelengths need to be chosen so as not to interfere with the wavelengths used in the legacy PON. This approach is currently under discussion in FSAN [12]. With the addition of blocking filters in the ONTs, it may also allow for an easier upgrade to WDM-PON at a later time by allowing the existing feeder fiber to transmit both the TDM and the WDM signals. It should be noted that these preemptive approaches would reduce the current link budget and increase PON costs many years in advance of the need for the wavelength upgrade.

Another possible upgrade path is to reduce the number of users that are sharing a PON. Assuming that 32 subscribers initially share a PON, it might be feasible to reduce the number to 16 or possibly eight users as bandwidth demand increases. This could provide a data-rate increase of either two or four times. This solution requires installing more feeder fibers and adding more power splitters at the RN locations. It also requires more OLTs at the CO that reduces the benefits of sharing the more costly and higher performance OLT controller and transceiver. This upgrade solution can also become very costly if no additional duct space is available either entering the CO or anywhere along the feed-fiber path. Since reducing the number of users on a PON requires upgrading the OSP, this may not be a desirable solution.

A likely scenario for upgrading a TDM-PON after it can no longer support the bandwidth demand is to convert it over to a WDM-PON system. This can be accomplished by replacing the power splitter at the RN with a wavelength mux/demux such as a 32-port athermal AWG. The OLTs and ONTs would also need to be upgraded, similar to two of the previous upgrade scenarios. Although there would be some disruption during this conversion, the resulting upgrade would result in an essentially futureproof PON that would provide dedicated point-to-point optical connectivity to each subscriber. Since the users sharing the PON would now be uncoupled, future bandwidth upgrades could be done on a case-by-case basis without affecting any of the other users. For service providers who have not yet committed to a TDM-PON solution, there may be advantages to initially install a WDM-PON solution since they could then avoid the complexities and difficulties of the above various upgrade options.

Another advantage of WDM-PONs is that they can allow for increased PON transmission lengths, which may offer significant cost savings in future access networks. These cost savings can be realized by reducing the number of COs between the metro network and the end customer [30], [44]. The consolidation would also enhance the QoS by reducing the number of hops experienced by the data signals [44]. Although extended ranges are also technically possible using TDM-PONs, they may require relatively expensive optical amplification and dispersion compensation techniques to overcome the inherent inefficiencies of this approach.

VI. SUMMARY

It is generally accepted that video-centric applications will drive bandwidth demand for future access networks. Required data rates per household are expected to be in the range of 100 Mb/s to supply multiple HD-video streams for applications such as HDTV, HD VoD, and interactive gaming. To satisfy the required bandwidth-distance product over a 20-km distance, single-mode optical fiber is currently the only practical choice. To minimize the cost of implementing an FTTP solution, a PON that uses a point-to-multipoint architecture is generally considered to be the best approach.

There are several general techniques for communicating to multiple subscribers sharing a single PON architecture, and we addressed several of these approaches, such as TDM, WDM, SCM, and CDM. Of these multiple techniques, the authors expect that TDM-PON and WDM-PON will be the most promising candidates for practical future systems. A TDM-PON shares a single-transmission channel with multiple subscribers reminiscent of earlier multiple-access Ethernet solutions. A WDM-PON provides point-to-point optical connectivity using a dedicated pair of wavelengths per user. While a TDM-PON appears to be a satisfactory solution for current bandwidth demands, the combination of future data-rate projections coupled with recent advances in WDM technology may result in WDM-PON becoming the preferred solution for a futureproof fiber-based access network.

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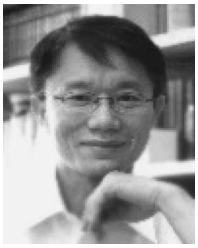

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Byoung Yoon Kim, photograph and biography not available at time of publication.