

## FTTH/FTTC Technologies and Standards

**Steven S. Gorshe**

**Principal Engineer, PMC-Sierra, USA**

### ABSTRACT

Providing the “triple play” services of voice, video, and high-speed data access is an important way for carriers to increase their revenue and compete with other access providers such as the CATV operators. For both telephone network providers and CATV providers, the most flexible and “future-proof” medium for providing triple play services is fiber, with its virtually unlimited bandwidth availability. Since providing a direct optical connection between the CO and each subscriber is cost prohibitive, most optical access systems share a passive optical network (PON) among multiple subscribers. PON decreases the real estate of the CO, the labor cost involved in fiber access deployment, and length of fiber plant to maintain. This paper summarizes the evolution of the use of fiber and optical technology in access networks, and provides an overview of PON standards and technologies.

**Key words:** FTTH, FTTC, optical fiber, technology, standard

### I. INTRODUCTION

A number of factors are increasing the interest among telecommunications providers in offering the “triple play” services of voice, video, and high-speed data access. Most importantly, subscribers are finding a growing number of applications that drive their desire for higher bandwidth, including Internet access, interactive

games, and video delivery. Network providers are anxious to provide new services that increase their revenue opportunities. This is especially important as incumbent telephone network providers compete with wireless mobile providers and VoIP for voice service revenues. In North America and some other regions, community access television (CATV) providers (sometimes called “cable” providers) are also competing to offer subscribers triple play services over their cable networks. In some cases, national or regional governments have been strongly encouraging and subsidizing a triple play service-capable infrastructure. The resulting potential regional/national advantages could include the use of telecommuting to reduce transportation infrastructure costs, improving the workforce skill level through distance learning, and creating a more desirable location in order to attract new companies and workers to the region. Although there has been interest in the potential of triple play services for over 25 years, we are finally reaching the point where there are enough subscriber applications to create adequate demand for the services, and the technology has matured to the point where it is becoming cost effective to deliver them.

Telephone and CATV networks both have historically relied on copper wires to connect through the “last mile” to their subscribers. The coaxial cable of the CATV companies has superior bandwidth capabilities relative to the twisted pair wiring from telephone companies, and some telephone companies have considered deploying

their own coaxial cable networks. However, the coaxial cable must be shared by many subscribers in order to be economical. Also, most of the coaxial cable's bandwidth is divided into channels for downstream broadcast video channels, leaving limited bandwidth available for broadband upstream traffic and services such as video on-demand (VoD). Clearly, the most flexible and "future-proof" medium is fiber, with its virtually unlimited bandwidth availability. For telephone network providers, fiber connections are attractive as a way to leapfrog the capabilities of the CATV providers.

## II. INTRODUCTION TO FITL AND PON

### 2.1 A brief history of FITL

The first serious interest in fiber to the home (FTTH) began in the late 1980s as the telephone companies gained experience with ISDN wideband services to subscribers. Rapid advances in the technology of optical transmitters, receivers, and fibers made FTTH appear to be potentially just over the horizon.

The first generation of FTTH systems attempted to directly replace the copper loop with a fiber. An optical network terminal (ONT) was installed at (or near) the subscriber's premises. The network side of the fiber was terminated on a line card in an optical line terminal (OLT) or a traditional digital loop carrier (DLC). This topology is known as an active star, or an active double star if a set of optical transceivers is used in a DLC remote terminal (RT) in order to reach the ONTs. Most of the large equipment manufacturers built prototype or field trial versions of this type of system. (E.g., [21]) Typical bandwidth over the fiber to the subscriber on these systems was a DS1 or E1 signal.<sup>1</sup>

Passive optical networks (PONs) were explored as a way to reduce the number of optical transceivers and fibers. As illustrated in Figure 1, a PON system uses a single optical transceiver at the OLT to serve mul-

multiple subscribers over a fiber tree or bus constructed with passive optical signal splitters. The first FTTH trial PON system was developed and deployed by British Telecom around 1989 [20]. First generation PON systems were developed by both major equipment vendors and start-up companies.

The first deployments of commercial PON systems targeted business customers. The market was relatively small, however, since it was uncommon to have a cluster of business customers wanting access to bandwidth greater than DS1/E1 that were all reachable by the same PON. Surprisingly, the circumstance that greatly accelerated PON deployment to business customers was the demand for high-speed Internet access by residential customers. DSL (digital subscriber loop), which was the most cost effective technology for residential subscriber

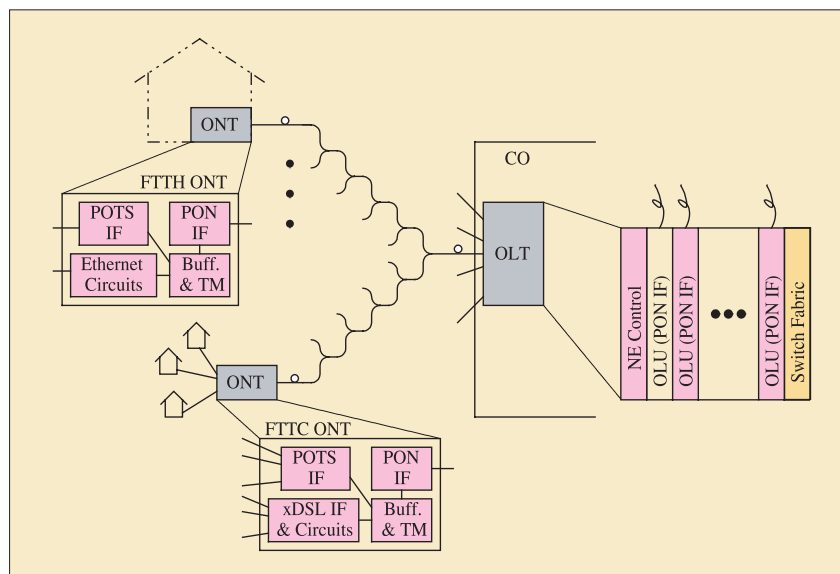


Fig.1 PON example

applications in the late 1990s, required moving the T1 signals from the copper bundles due to spectral compatibility issues. As a result, PON became the most attractive option for serving business customers, freeing the copper cables for residential DSL service.

Another approach to reducing the cost of FITL systems was to serve multiple subscribers from the same ONT. Fiber to the curb (FTTC) systems, which typically served 4 to 12 subscribers from the same ONT, provided three major cost benefits. First, it reduced the number of optical components relative to FTTH<sup>2</sup>. Second, FTTC preserves the copper loop

connections from the ‘curb’ over the last hundred some meters to the home. Installing fibers on this final subscriber drop is very expensive. The short loop length (typically less than 300m) allows using DSL technologies to potentially deliver the same data and video services, with the analog POTS riding along in its native frequency range. The third advantage to FTTC was that it was better suited for having the network provide power to the subscriber’s phone. (See section 2.2.2 for further discussion of powering issues.) Variations on the FTTC theme include fiber to the cabinet (FTTCab), where the cabinet serves more subscribers than a typical curb unit, and fiber to the premise (FTTP) where the premise is a multi-tenant building. FTTN (Fiber to the Node) has become a popular term for FTTC/P/Cab systems in the U.S.

The cost effectiveness of FTTC/FTTCab/FTTP systems depends on numerous factors, including the number of ONTs per OLT optical transceiver, the cost of the fiber and its installation, the cost of the DSL transceivers at the ONT and subscriber premise, the overall cost of powering the ONT, and the real estate cost of placing the ONT.

FTTC with VDSL is the current preferred plan for some European and U.S. carriers. FTTC/FTTCab/FTTP systems, however, are clearly less flexible for high bandwidth services than FTTH systems since there is much more equipment impact whenever the subscriber wants a different service rate.

## 2.2 FITL technical challenges

### 2.2.1 Optical components

First generation FITL systems faced a number of technology challenges. Although multi-mode fiber was less expensive for the fiber drop to the subscriber, single-mode fiber was preferred due to its superior bandwidth capabilities. Single-mode fiber, however, requires laser transmitters since the core diameter is too small for coupling adequate optical energy from LED transmitters. The inexpensive lasers used in CD players couldn’t be used since their wavelengths (typically 750nm and 810nm) propagate as

multi-mode in glass single-mode fibers. The least expensive lasers that allowed single-mode transmission used 1310nm, and these lasers were very expensive in the 1990 time frame. Fiber transceivers are still not cost effective for direct connections to each subscriber.

The development of fused fiber splitters dramatically reduced their cost, making PON more attractive.<sup>3</sup> Passive splitters divide the optical energy between the branches of the splitter, and as the number of splitters increases between the OLT and ONT, the power decreases quickly. Consequently, split ratios of ONTs per OLT transceiver typically range between 16-to-1 and 64-to-1. Higher split ratios would require optical amplifiers. Since the cost of the optical amplifier is shared among multiple subscribers, it can be cost-effective if the PON system data rate is high enough to still deliver adequate bandwidth to all the subscribers.

Time domain multiple access (TDMA), in which the ONTs take turns transmitting their upstream data in bursts, is typical for current PON systems. See Figure 2. One of the limiting technology factors in a TDMA PON system is the amount of guard time required between the upstream transmissions of different ONTs. The guard time includes the times required for one ONT’s laser to be turned off and the next ONT’s laser to turn on, and the time required for the OLT to adjust to the optical signal level and achieve clock and data synchronization for the new burst. As the PON data rate increases, the guard time

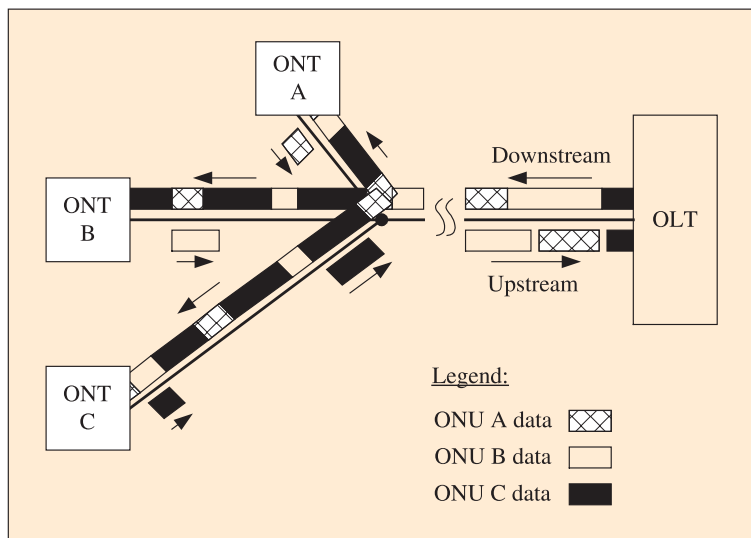


Fig.2 TDMA illustration

becomes an increasing percentage of the upstream transmission time, necessitating even higher burst transmission rates relative to the desired upstream data rate.

### 2.2.2 Powering the loop

The biggest single obstacle to FITL systems in many countries is not the cost of the optical components, however, but providing reliable power to the ONTs and subscribers. The telephone company typically powers the subscribers' telephones through a -48Vdc power feed, and usually provides back up power for about eight hours of typical usage in the event of an outage from the power utility company<sup>4</sup>. The resulting high service availability is often referred to as 'lifeline POTS service since subscribers can count on the service being available for emergencies. DLC RT equipment, which is powered by a local connection to the utility company, and CO equipment use co-located batteries for back up. In the event that a major disaster (e.g., flood) causes a longer utility power outage, generators are used at the CO and portable generators can be used at the RT to charge the batteries. Portable generators are impractical for FTTH/C due the large number of ONT locations.

More significantly, batteries must be replaced every 5-10 years, which is very costly and manpower intensive. Battery research (also motivated by the automotive industry) has improved battery life and capacity, but it's still not adequate for FTTH/C. Note that while the ONT components have become more power efficient, they have always been a small percent of the peak power, which is associated with powering and ringing the subscriber's telephones.

Another factor is the number of connections to the power utility company, each of which must be metered. One alternative to per-ONT power utility connections is to use a separate 'Power pedestal' that powers multiple ONTs and contains their back-up batteries. For FTTH, another option is to have the subscribers provide their own power with the FTTH service cost effectively discounted to cover the subscribers' power expense.

So, while power many seem like a mundane topic in the glamorous world of lasers, fiber, and high-speed data access, it's a significant problem with no easy solution. The widespread use of cellular/mobile telephones has changed the situation, however. As subscribers have become accustomed to providing their

own power and maintaining their own batteries for their phone service, customers desiring broadband services over FTTH may be very willing to take responsibility for the power and back-up of their ONTs. Also, it's highly likely that any FTTH subscriber is already a mobile phone subscriber and can use that phone for lifeline service. This phenomenon, plus the growing desire for broadband services, has opened the door for residential PON deployment.

## 2.3 Introduction to PON systems

### 2.3.1 PON system overview

As shown in Figure 1, the ONT typically provides the subscriber with a POTS interface and a high-speed interface that may be Ethernet or DSL. The OLT consists of a number of PON interface units, a switch fabric for the data services (and potentially a simple fabric or multiplexer for the voice channels), and a NE controller. The ONTs are ultimately also managed by the NE controller, which is responsible for all ONT provisioning and OAM&P reporting. The OLT and ONTs together form the PON system, making it logically function as a single NE. The fiber interconnection can be thought of as an extended backplane.

In the downstream direction, the OLT broadcasts the data to all ONUs<sup>5</sup>. This downstream signal contains the downstream data for all the ONTs, overhead for OAM, and synchronization information for the upstream transmissions. The ONTs extract their downstream data based on information such as time slots, cell/packet addresses, wavelength, or CDMA codes.

In the upstream direction, the ONUs need a medium access control (MAC) protocol to share the PON. The most common MAC protocol is TDMA in which the ONTs are each granted a time slot in which to transmit their upstream data.

As noted in section 2.2.1, a guardband time is required between the upstream burst transmissions of the ONTs so that their transmissions don't overlap at the OLU receiver. The ONT signals propagate through the fiber at the speed of light divided by the index of refraction of the fiber (approximately 2 m/s). Most modern PON systems have a ranging protocol to measure this delay so that the ONT bursts can be aligned when they reach the OLT with a minimum guardband time between them.

Basic TDMA PON systems pre-assign a fixed portion of the upstream bandwidth to each ONT, regardless of how much data it has to send. Dynamic bandwidth allocation (DBA) allows more efficient upstream bandwidth use. With DBA, each ONT communicates its bandwidth requirements to the OLT. This information could include its input queue fill levels for different classes of service. The OLT evaluates the requests from the ONTs, and assigns the bandwidth for the next upstream transmissions. The OLT can include service level agreement (SLA) information associated with the data flows in its DBA algorithm. These bandwidth assignments are sent downstream, and are typically communicated as transmission start and stop/duration times relative to a common reference. In some systems, the ONT is responsible for determining how to accommodate the relative priorities of its transmit data within the granted upstream transmission slot.

PON systems typically transmit both upstream and downstream data over the same fiber. While directional couplers are sometimes used to allow the same wavelength for both directions, higher speed systems typically use different wavelengths in each direction. The most common is a coarse wave division multiplexing (CWDM) in which 1490 or 1550 nm is used for the downstream direction and 1310 nm for the upstream. This puts the less expensive 1310 nm lasers at the ONTs.

Note that some PON systems use 1490 nm for the downstream PON signal with video transmitted downstream at 1550 nm. Using WDM for video overlay provides a simple upgrade to existing deployments and increases the downstream capacity. Analog video transmission also avoids such problems as lack of digital content and regulations involving digital content.

### 2.3.2 PON protocol evolution

The first generation of PONs was based on TDM signals such as DS1/E1 signals. The downstream frame was a TDM frame with time slots assigned for each ONT's data. With any TDMA protocol, the data transmitted upstream must be broken up into blocks that can be transmitted in bursts. These early PONs collected the data from their upstream TDM time slots and transmitted them at a higher rate during their assigned upstream burst time slot. For voice signals, this corresponded to a number of voice samples. For

packet data, it was simply the number of bytes of the packet that would have been transmitted during that frame in a corresponding point-to-point TDM signal.

The second generation of PONs was based on ATM, which provided a convenient protocol for chopping the upstream data into blocks for the upstream transmission bursts. ATM provided the mechanism for carrying TDM traffic and packets, and assisting QoS support. Also, at this time ATM was regarded as the likely basis for next generation networks and was already being used for broadband access in DSL systems. The upstream burst time slot allocated by the OLT to the ONT was essentially the number of ATM cells it was allowed to send. The ITU-T G.983 Broadband PON (B-PON) series defines an ATM PON (APON) system and protocol developed by the Full-Service Access Network (FSAN) consortium.

With IP packets comprising more of the subscriber data, and the IP packets typically carried in Ethernet frames, it makes sense to use packet technology for routing. Consequently, in order to avoid the adaptation complexity and high overhead bandwidth associated with ATM, the third generation of PON systems have been based on, or optimized for, carrying Ethernet frames. The two primary high-speed PON standards are Gigabit PON (GPON) from the ITU-T (G.984 series) and Ethernet PON (EPON) from the IEEE (802.3ah). The upstream formats for these two protocols are described in the next section.

## III. B-PON

Most of the PON systems currently being deployed in North America and Europe, including Verizon's ambitious FiOS project, use the ITU-T G.983 series B-PON. The G.983 series includes specifications of the ONT and OLT functional blocks, the upstream and downstream frame rates and formats, the TDMA upstream access protocol, physical interfaces, ONT management and control interfaces, survivability enhancements, and DBA. The B-PON features are summarized in Table 1.

The downstream transmission is a stream of ATM cells. A downstream frame consists of 56 53-byte cell slots for 155 Mbit/s and  $4 \times 56 = 224$  cell slots for 622 Mbit/s, with a physical layer OAM (PLOAM) cell inserted every 28 cell slots. The PLOAM contains a

framing bit to identify the PLOAM cells. Otherwise, the PLOAM cells are programmable and contain information such as upstream bandwidth grants and OAM messages. The ONTs use the ATM VPI/VCI addresses to identify their data in the downstream signal.

The upstream frame consists of 53 56-byte time slots. Each time slot is comprised of an ATM/PLOAM cell and 24 bits of overhead. The overhead consists of guard time, a preamble to allow timing and signal level recovery by the OLT, and a delimiter to indicate the end of the overhead. The overhead field lengths and contents are programmable by the OLT. ONTs transmit PLOAM cells when they are requested by the OLT.

The bandwidth grant information from the OLT tells each ONT which upstream time slots it may use for its upstream data. The B-PON DBA protocol allows the OLT to learn the ONT bandwidth needs either through explicit reports from the ONTs, and/or by observing the number of ATM Idle cells the ONTs transmit. The OLT can decrease the bandwidth of an ONT sending Idles and increase the bandwidth of an ONT that is filling all its upstream transmission slots with data.

The OLT periodically halts upstream transmissions so that it can invite any new ONTs to announce themselves. The new ONTs transmit a response during this window, using a random time delay in order to minimize the risk of collisions if there are multiple new ONTs. The OLT determines the distance to each new ONT by sending it a ranging message and measuring the time until it receives the response. The OLT then sends the ONT an equalization delay time value such that the sum of the round trip and equalization delays is the same for each ONT. This allows the upstream transmissions from the ONTs to arrive at the OLT with a minimum of guard time.

#### IV. EPON

IEEE 802.3ah EPON, which was developed to exploit the advantages of Ethernet technology, was the next major TDMA PON protocol to be standardized. The features of EPON are summarized in Table 1.

The downstream transmission is a stream of Ethernet frames. The frames are the same as for a point-to-point Gigabit Ethernet link except that the preamble

and start of frame delimiter have been modified in order to carry the logical\_link\_id field (LLID) that uniquely identifies the ONU MAC. In the upstream direction, the ONUs transmit bursts of Ethernet frames in time slots assigned by the OLT.

Multi-Point Control Protocol PDUs (MPCPDUs) are basic 802.3 MAC control frames used by the ONUs to make their requests for bandwidth (Report messages), and by the OLT to assign it (Gate messages). The OLT periodically sends Gate messages to the ONUs to allow them the opportunity to report their bandwidth needs. The ONUs can also send their Reports along with an upstream data frame transmission. The Gate messages contain the start time and duration of transmission for the ONU. The bandwidth requests and grants include any bandwidth required for inter-frame gap and forward error correction (FEC). DBA can also be performed with EPON.

The EPON upstream time slots and ranging protocol are different than for B-PON and GPON due to the lack of a regular downstream and upstream frame structure. The OLT and ONUs maintain separate local counters, incremented every 16 ns. Each MPCPDU carries a timestamp, which is the value of the sender's local counter. The ONU sets its local counter to this received timestamp value. The OLT determines roundtrip delay by comparing the received timestamp to its own counter value. The OLT takes this roundtrip delay into account when it assigns ONU upstream transmission start times relative to the ONUs' local counters.

The ranging and activation are similar to B-PON, except that the local counters eliminate the need for the OLT to send an equalization delay time to the ONUs.

#### V. GPON

The second FSAN TDMA PON protocol is the ITU-T G.984 series GPON, which was built on the experiences of B-PON and EPON. The features of GPON are summarized in Table 1.

While GPON supports ATM payloads, it introduces a new payload adaptation mechanism called GPON Encapsulation Method (GEM) that is optimized for carrying Ethernet frames. GEM is based on G.7041 Generic Framing Procedure (GFP), except GEM optimizes the frame overhead for the PON application, allows map-

Table.1 Feature summary of the TDMA PON protocols

Feature	B-PON	GPON	EPON
Responsible standards body	FSAN and ITU-T SG15 (G.983 series)	FSAN and ITU-T SG15 (G.984 series)	IEEE 802.3 (802.3ah)
Data rate	155.52 Mbit/s upstream & 155.52 or 622.08 Mbit/s downstream	Up to 2.488 Gbit/s upstream & downstream *	1 Gbit/s upstream & downstream
Split Ratio (ONUs/PON)	1:64	1:64	1:64 **
Line code	Scrambled NRZ	Scrambled NRZ	8B/10B
Number of fibers	1 or 2	1 or 2	1
Wavelengths	1310 nm up & down or 1490 nm down & 1310 nm up	1310 nm up & down or 1490 nm down & 1310 nm up	1490 nm down & 1310 nm up
Maximum OLT to ONU distance	20 km	10 and 20 km	10 and 20 km
Protection switching	Supports multiple protection configurations	Supports multiple protection configurations	None
Data format (encapsulation)	ATM	GEM and/or ATM	None (uses Ethernet frames directly)
TDM Support	via ATM	Direct (via GEM or ATM) or CES	CES
Voice Support	via ATM	Via TDM or VoIP	VoIP
Multiple QoS levels	Yes (Mix of fixed, assured, and best effort bandwidth assignments )	Yes (Mix of fixed, assured, and best effort bandwidth assignments )	Yes (802.1Q priority levels)
FEC	None	RS(255, 239)	RS(255, 239)
Encryption	AES - 128 bit key	AES - 128 bit key required, 192 & 256 optional	None***
OAM	PLOAM and ATM	GTC frame fields and ATM/GEM OAM	802.3ah Ethernet OAM frames
<p>* The CTS specifies 2.488 Gbit/s downstream and 1.244 Gbit/s upstream for GPON, and a single fiber for both directions.</p> <p>** While the EPON optical parameters were initially designed around a 1:16 split ratio, current implementations support 1:64.</p> <p>*** A multi-company protocol using 128-bit key AES has become the de facto standard for EPON.</p>			

ping fragments as well as whole Ethernet frames into the GEM payload, and supports TDM mappings.

GPON uses a 125 μs GPON Transmission Conversion (GTC) frame structure for both downstream and upstream. The downstream frame begins with a PLOAM overhead field, followed by a payload area consisting of GEM frames and/or ATM cells. The PLOAM includes framing information and the bandwidth map for the

ONT transmission grants in the next upstream frame.

The upstream frame consists of the upstream transmission bursts from the ONTs. Each burst begins with physical layer overhead that is functionally similar to B-PON, but also includes a summary of the ONT's bandwidth requests. Additional PLOAM fields and more detailed bandwidth request reports are sent in the upstream burst if they are requested by the OLT. The

OLT assigns upstream transmission times for each ONT as transmission start and stop times relative to the beginning of the next upstream GTC frame.

The 125  $\mu$ s GTC frame structure allows carrying TDM signals such as DS1/E1 or voice by simply mapping the appropriate number of bytes of the signal into a GEM frame during each GTC frame.

The GPON activation and ranging protocols are similar to B-PON and EPON except that the equalization delay value sent to each ONT is the offset between the start of the received downstream frame and the start of its upstream frame.

## VI. IEEE 10 GBIT/S ETHERNET PON (IEEE 802.3 AV)

IEEE 802.3 has recently approved a project to develop a standard for EPON at the 10 Gbit/s rate. Recent field trials have demonstrated that the component technology already exists to implement such a PON.

One potential market driver for a 10 Gbit/s PON system is digital video delivery. This bandwidth would allow delivering multiple high-definition, IP-encapsulated video streams to each ONT, even with OLT/ONT split ratios of 1:64 or greater<sup>6</sup>. In contrast, if we assume 20 Mbit/s for a high-definition IP video stream, then a B-PON system with 622 Mbit/s downstream could barely deliver a single VoD channel to each ONT for a 1:32 split ratio, and GPON could deliver less than two VoD channels per ONT with a 1:64 split ratio.

## VII. WDM PON

WDM PON uses wavelength division multiplexing instead of TDMA. The OLT uses a separate wavelength to communicate with each ONU in a point-to-point manner. Each ONU has an optical filter to select the wavelength for its received data, and the OLT has a set of filters, one for each ONU. The primary advantage to WDM PON is that communication can occur with each subscriber using its preferred, native data rates (e.g., DS1/E1/DS3, 10/100/1000Base Ethernet, etc.), independent of the signal rates and formats used by other subscribers.

The primary drawback of WDM PON is cost of the optical components to create and filter the different wavelengths. Multiple alternatives have been explored for generating the different ONU wavelengths, including the following.

- Field installable optical modules to select the ONU wavelength. Lack of flexibility and module stocking and tracking costs are drawbacks to this approach.
- Tunable lasers at the ONUs. While very flexible, tunable lasers are not yet cost effective for this application.
- Spectrum slicing, in which a light source with a reasonably broad optical spectrum is used at the ONUs. Filters are used to select the ONU transmission carrier wavelength.
- Passive approaches in which the OLT provides the optical carrier signals to ONUs. Each ONU modulates the carrier in some manner as it reflects it back to the OLT.
- Using the downstream signal to control the output wavelength of the ONU laser. For example, it has been shown that inserting some of the downstream signal into a vertical-cavity surface-emitting laser (VCSEL) will cause the VCSEL output to lock to the same wavelength as the downstream signal. This technique is known as optical injection locking.

Athermal Arrayed Waveguide Gratings (AWGs), illustrated in Figure 3, appear to be the most promising receiver filter technology. An AWG is a passive device that can be used in an outside plant environment. Since they can be implemented with the silica-on-silicon technology that is used for other optical integrated circuits, they have the potential to become reasonably cost effective.

The one significant deployment of WDM PON to date is in South Korea. This system appears to use AWG receiver filters with spectrum slicing at the ONUs. The spectrum slicing is performed with acousto-optic tunable filters (AOTFs). With the AOTF, an acoustic wave is used to create a long-period diffraction grating that acts as a notch filter for the desired wavelength.

While WDM PON has some flexibility advantages with respect to carrying different client signals and higher data rate per subscriber, the high number and relative complexity of the optical components have kept it less cost effective than the TDMA-based PON systems such as EPON and GPON, or point-to-point fiber connections using media converters. WDM can also be combined with TDMA PON protocols to up-

grade their capacity.[22]

### VIII. CDMA PON

Code-division multiple access (CDMA) technology can also be applied to PON applications. Like WDM PON, CDMA PON allows each ONU to use a different signal rate and format corresponding to the subscriber's native client signal. Optical CDMA can also be used in conjunction with WDM for increased bandwidth capabilities. A basic, classical implementation, illustrated in Figure 2, is described here.

The concept behind CDMA is to carry multiple client signals with their transmission spectrum spread over

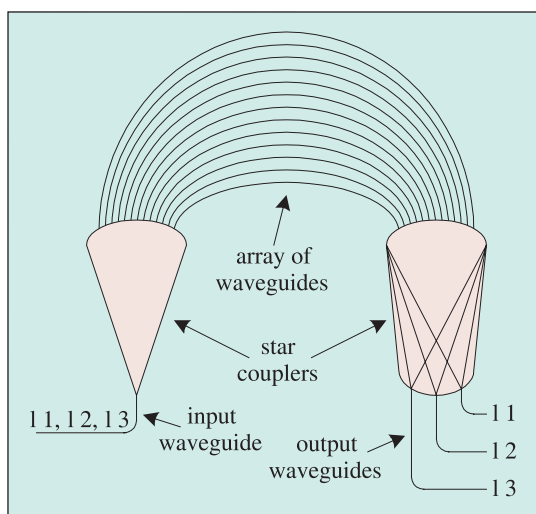


Fig.3 Array waveguide illustration

the same channel. The symbols from the constituent signals are encoded in a manner that is recognizable by the decoder. The most amenable technique is direct sequence spread spectrum in which the symbols (e.g., 0 and 1) of each client signal are encoded as a longer string of symbols at a higher rate. Each ONU uses a different string value for its symbols.

Fortunately, optical direct sequence CDMA can be implemented with passive diffraction filters. A typical implementation uses Bragg diffraction grating, which can be constructed using UV exposure of standard single mode fibers through a mask with the desired pattern. Other grating types can also be used.

As illustrated in Figure 4, the encoder and decoder can use the same basic implementation. The signal is

launched into one end of the filter. As the signal propagates through the filter, the grating pattern creates interference patterns as the light is reflected. The signal that reflects back out of the filter is thus modified in terms of both amplitude and phase, with the amount of symbol spread a function of the propagation time through the filter. At the receiver, the inverse operation converts the received spread spectrum symbol back into the original symbol.

Due to the linearity of the Bragg filter, the spread spectrum bandwidth is proportional to the number of ONUs. The OLT splits the received optical signal to multiple diffraction filters in order to recover the data from the different ONUs. In a classical optical CDMA implementation, the transmitter and receiver use identical Bragg gratings. More sophisticated receivers can use different gratings at the transmitter and receiver, and can use a combination of optical and electrical domain processing. Proper design of the grating patterns results in a system where the effects of crosstalk can be eliminated at the receiver.

Temperature control of the grating is important, since physical expansion or contraction of the filter changes the effective pattern. This feature can also be exploited, however, to achieve tunable filters. (Other tuning mechanisms also exist.) The lasers in an optical CDMA system, however, do not require frequency stability.

One major drawback to optical CDMA PON is that optical amplifiers are typically required to achieve an adequate signal to noise ratio. Due to the losses in the additional receiver splitter tree, circulators, and filters, ONU/OLT splitter ratios without amplifiers are only in the 2:1 to 8:1 range. The receivers are also relatively complex. Consequently, they haven't proven to be as cost effective as some of the other alternatives.

### IX. CONCLUSIONS

Telephone carriers have long been interested in the new revenue possibilities from residential video and high-speed data services. The convergence of subscriber demand for new applications requiring broadband access, optical and packet technology advances, and paradigm shifts in powering the home phone are

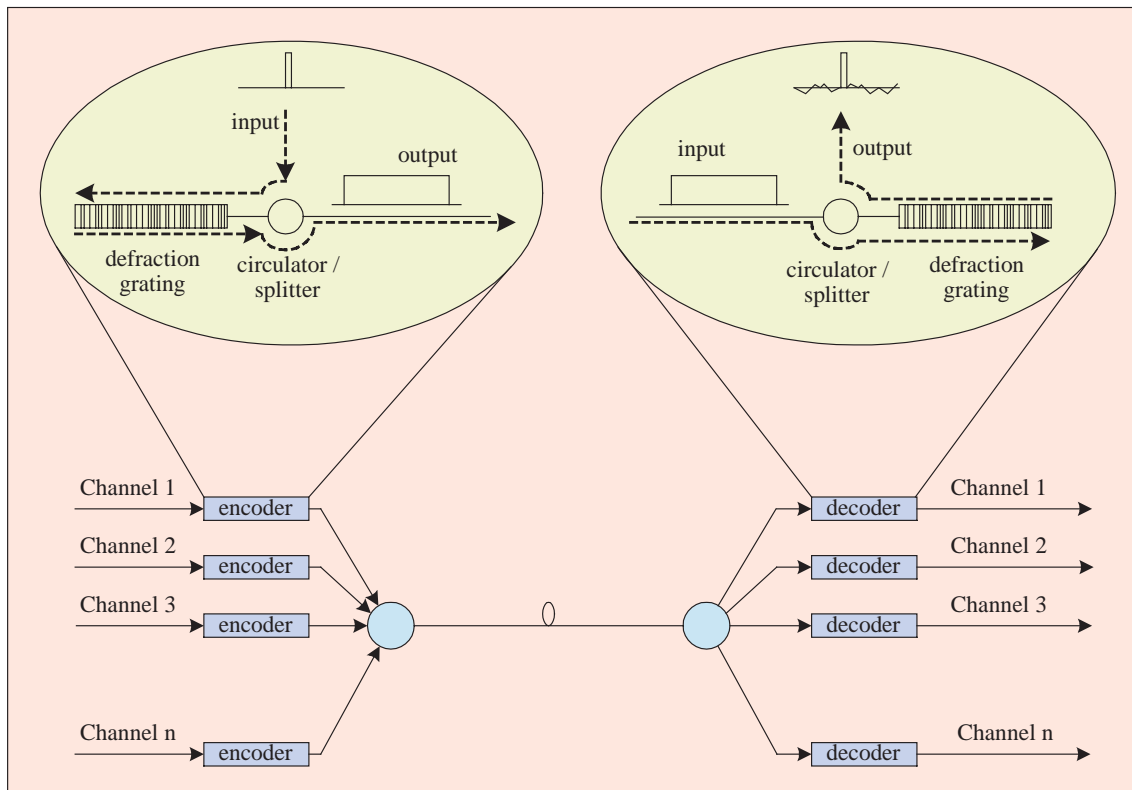


Fig.4 CDMA PON illustration

finally making FTTH and FTTN practical. Specifically, EPON and GPON now provide the bandwidth and OAM required to enable triple-play services.

## ACKNOWLEDGEMENTS

This paper is adapted from PMC-Sierra white paper PMC-2061015. The author especially thanks Onn Haran, Steven Haas, and Chris Look for their technical comments.

## REFERENCES

- [1] ITU-T G.984.1 (2003) Gigabit-capable Passive Optical Networks (GPON): General Characteristics
- [2] ITU-T G.984.2 (2003) Gigabit-capable Passive Optical Networks (GPON): Physical Media Dependent (PMD) layer specification
- [3] ITU-T G.984.3 (2004) Gigabit-capable Passive Optical Networks (GPON): Transmission convergence layer specification
- [4] ITU-T G.984.4 (2004) Gigabit-capable Passive

Optical Networks (GPON): ONT Management and control interface specification

[5] ITU-T G.Imp984.3 (2004) Implementers' Guide for ITU-T Rec. G.984.3

[6] ITU-T G.983.1 (2005) Broadband optical access systems based on Passive Optical Networks (PON)

[7] ITU-T G.983.2 (2005) ONT management and control interface specification for B-PON

[8] ITU-T G.Imp983.2 (2006) Implementers' Guide to G.983.2 (2002)

[9] ITU-T G.983.3 (2001) A broadband optical access system with increased service capability by wavelength allocation

[10] ITU-T G..983.4 (2001) A broadband optical access system with increased service capability using dynamic bandwidth assignment (DBA)

[11] ITU-T G.983.5 (2002) A broadband optical access system with enhanced survivability

[12] ITU-T G.983.6 (2002) ONT management and control interface specifications for B-PON system with protection features

[13] ITU-T G.983.7 (2001) ONT management and

control interface specification for dynamic bandwidth assignment (DBA) B-PON systems

[14] ITU-T G.983.8 (2003) B-PON OMCI support for IP, ISDN, video, VLAN tagging, VC cross-connections and other select functions

[15] ITU-T G.983.9 (2004) B-PON OMCI management and control interface (OMCI) support for wireless Local Area Network interfaces

[16] ITU-T G.983.10 (2004) B-PON ONT management and control interface (OMCI) support for Digital Subscriber Line interfaces

[17] IEEE 802.3ah (2004) Amendment to - Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 3: Carrier sense multiple access with collision detection (CSMA/CD) access method and physical layer specifications - Media Access Control Parameters, Physical Layers and Management Parameters for subscriber access networks

[18] A. Grunnet-Jepsen, et. al., "Fibre Bragg grating based spectral encoder/decoder for lightwave CDMA," *Electronic Letters*, June 24, 1999, vol. 35 no. 13, pp. 1096-1097

[19] ITU-T Recommendation G.7041/Y.1303 (2001), Generic Framing Procedure. (S. Gorshe - technical editor)

[20] T. Rowbotham, B. Ritchie, C. Hoppit, "Plans for the Bishops Stortford (UK) fibre to the home trials," *Proc. of IEEE Globecom '89*, Nov. 1989, pp. 1320-1325.

[21] T. Hasegawa, K. Kuritani, K. Makino, & Y. Shimada, and S. Gorshe, "Optical Customer Access Based on Digital Loop Carrier," *Proc. of IEEE ICC '90*, pp. 341.3.1 - 341.3.5

[22] M. P. McGarry, M. Reisslein, M. Maier, "VDM Ethernet Passive Optical Networks," *IEEE Communications Magazine*, pp. s18-s25, vol. 44, Feb. 2006

## BIOGRAPHY

*Steven Scott Gorshe is a Principal Engineer in PMC-Sierra's CTO organization. He received his B.S.E.E. (University of Idaho), and M.S.E.E. and Ph.D. (Oregon State University) in 1979, 1982, and 2002, respectively. He has been involved in applied research and the*

*development of transmission and access system architectures and ASICs since 1982, including over five years at GTE and over 12 years with NEC America where he became Chief Architect for NEC Eluminant Technologies. His current work at PMC-Sierra*



*involves technology development for applications specific standard product ICs, for telecommunications and data communications networks. Dr. Gorshe is a Senior Member of the IEEE, and Associate Editor-in-Chief and past Broadband Access series co-editor for the IEEE Communications Magazine. He also serves as Senior Editor for OPTXS (formerly T1X1) standards committee; technical editor for multiple standards within the SONET series; and a technical editor for multiple ITU-T Recommendations including G.7041 (GFP) and G.8011.1 (Ethernet Private Line Service). He is a recipient of the Committee T1 Alvin Lai Outstanding Achievement Award for his standards contributions. He has 29 patents issued or pending, and over 20 published papers.*

1 In the U.S. regulatory environment of that time, the incumbent carriers were restricted on what data or video services they could offer. Consequently, the state public utility commissions required carriers to justify the cost of any new access technology on the basis of its cost for basic telephone (POTS) service.

2 FTTC can be deployed as either an active star/double star or with a PON. Active stars were initially more typical since serving multiple subscribers per ONT would quickly exhaust the capacity of a PON.

3 Initially, passive splitters used quarter-wave mirror technology and were quite expensive.

4 While this lifeline POTS capability is mandated in the U.S. by the FCC, other countries (e.g., Japan) do not require it.

5 ONU (Optical Network Unit) and ONT are essentially equivalent terms.

6 Broadcast video could still use a separate wavelength, as done today in systems such as Verizon's FIOS.