WDM PON: Emergence from TDMA to WDM for FTTx based Applications

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Abstract
This paper describes the principles and prospective technology for one of the Next Generation Passive Optical Networks (NG-PONs) technology i.e. Wavelength Division Multiplexing Passive Optical Network (WDM PON) technology. In the background of the global information, broadband access is developing rapidly. Because fibre access has the great advantage of capacity and cost. Most of the countries have started deploying the FTTx fibre access as an important part of the national strategy. As the deployment of Fibre to the Home (FTTH) technologies in the access network accelerates, vendors and technology innovators are looking ahead to solve next-generation application’s bandwidth requirements. These applications, such as high-definition IPTV delivery and multimedia distribution systems will demand for greater bandwidth than current broadband access technologies requires. One attractive new option is Wavelength Division Multiplexing Passive Optical Network (WDM PON) technology which can serve a very large number of subscribers with high bandwidth demand. The WDM PON technology is somewhat new for Indian telecom network for higher data rate applications. This paper provides an overview of the WDM PON driving the requirement of future access networks.

1. Introduction
Wavelength-division multiplexing (WDM) is an approach that can exploit the huge opto-electronic bandwidth mismatch by requiring that each end-user’s equipment operates at electronic rate and multiple WDM channels from different end-users may be multiplexed on the same fiber. Under WDM, the optical transmission spectrum is carved up into a number of non overlapping wavelength (or frequency) bands, with each wavelength supporting a single communication channel operating at whatever rate one desires, e.g., peak electronic speed. Thus, by allowing multiple WDM channels to coexist on a single fiber can tap the huge fiber bandwidth. The corresponding challenges being the design and development of appropriate network architectures, protocols, and algorithms. Also, WDM devices are easier to implement since, generally, all components in a WDM device need to operate only at electronic speed, as a result, several WDM devices are available in the marketplace and more are emerging. The Internet has produced higher demands for
broadband services, leading to extensive growth in Internet Protocol (IP) data traffic and putting pressure on service providers to upgrade their existing networks.

WDM PON is capable of using ITU standard wavelengths impressively simplifying the standardization process. The Current systems support fully symmetrical speeds of up to 20 Gbps and up to 16 ONUs. Bandwidth is dedicated up to 1.25 Gbps increments to each ONU. The WDM PON technology has virtually unlimited scalability in terms of bandwidth and wavelengths. Future versions may have as many as 64 numbers of 10 Gbps wavelengths.

2. TDM PON to WDM PON
2.1 Time Division Multiplexing PON (TDM PON): Most of the FTTH and FTTB deployments in Asia Pacific are based on PON. The primary reason for the choice of PON is its cost effectiveness as the equipment outside the central office is passive and does not consume electricity. PON networks brings the advantages of both operational expenditure (OPEX) savings and capital expenditure (CAPEX) savings compared to active optical networks (AON). Different forms of PON including Broadband PON (BPON), Ethernet PON (EPON), Gigabit Ethernet PON (GEPON), and Gigabit PON (GPON) have been deployed in different markets.

Among the different PON technologies, Time Division Multiple (TDM) based point to multipoint PON technology standards, GPON and EPON have become the most widely deployed technologies for FTTH and FTTB. In the TDM based PON technologies there is a shared architecture, in which a single wavelength is shared amongst subscribers. There is an Optical Network Terminal (ONT) at the end of each fiber located in the home or building of the subscriber and a broadcast scheme is used for downstream data. For the upstream, each ONT has a time slot in which it communicates with the optical line termination unit (OLT) at the central office.

![Fig. 1: TDM PON Network](image)

Currently both EPON and GPON standards are being deployed. 10G EPON is the improved version of EPON that can deliver 10 Gbps downstream. The enhanced version of GPON, 10G GPON has also been developed which can support bandwidth of 10 Gbps.

2.2 Wavelength Division Multiplexing PON (WDM - PON): WDM PON adds multiple
wavelengths in the fiber to increase capacity in the access technology system. Although, physically it is similar to TDM based PON technologies, logically it is a point to point scheme. Each ONT at the subscriber has a dedicated wavelength and there is no time sharing of bandwidth. The limit to the bandwidth that the user can receive depends on what the wavelength can carry. The splitter in TDM PON systems is replaced by an arrayed waveguide grating (AWG) which routes each wavelength to its destination ONT. Unlike TDM PON system, a subscriber gets only the information destined for it. WDM PON has the promise of improving the metrics of bandwidth, split ratio and reach over traditional PON technologies. With WDM PON, a virtual PON can be created for each subscriber using multiple waves on a single fiber.

Although WDM-PON standards are still being developed, manufacturers and service providers anticipate that it will use the same physical architecture as today’s PON systems, with an OLT feeding 32 ONTs. The difference is that each ONT will be fed by a separate wavelength, enabling each customer to get higher bandwidth. WDM-PON expands on the idea by increasing the number of wavelengths in the fiber from the OLT to a neighborhood node.

This WDM - PON is known as now a promising new technology for future access network. The performance of a novel 2.5 Gbps WDM-PON Network architecture which employs new PON Optical Add/Drop Multiplexer (OADM), in order to support high coverage in unlimited scaling. Based on the architecture, higher installation and maintenance costs can be reduced, and the access network design can support symmetric transmission rate 10 Gbps for distance up to 30 km.

WDM-PON offers an alternative to the GPON time-shared transmission scheme by having each ONT transmitting and receiving at a specific wavelength. Thus, the main difference between WDM-PON and the use of wavelengths on GPON (for overlaying several GPONs and/or 10G GPONs) is that WDM-PON may not use the GPON protocol but can use for example point-to-point Gigabit Ethernet.

2.3 Combination of WDM-TDM: Combination of WDM and TDM is possible way for increasing bandwidth. When evolving from standard NG-PON1 to NG-PON2, more technologies are available for long-term evolution. Therefore, upgrades with more intense innovations can be envisioned - by various multiplexing techniques of WDM PON. The possible multiplexing schemes can be coarse wavelength division multiplexing (CWDM) or dense wavelength division multiplexing (DWDM). The ODSM PON (Opportunistic and Dynamic Spectrum Management PON) topology based on TDMA+WDMA dynamically manages user
spectrum without modifying the ODN and ONUs. The third prospect is OCDMA-PON. OCDMA-PON (Optical Code Division Multiple Access PON) uses code division multiple access (CDMA) to encode ONU singals, thereby avoiding the timeslot assignment for data transmission required by a time division multiple access (TDMA) systems. The O-OFDM PON (Orthogonal Frequency Division Multiplexing PON) topology is an option that uses orthogonal frequency division multiple access (OFDMA) technology to differentiate ONUs, thus effectively improving bandwidth usage. However, most of these technologies are still in the research phase. More study and test are highly desired to promote them as industry standard.

The selection of XG-PON1 is driven by technology availability and economic reasons. When evolving from NG-PON1 to NG-PON2, however, more technologies are available for long-term evolution. Therefore, upgrades with more intense innovations can be envisioned.

3. WDM PON System and Principle

One of the most promising concepts for high capacity communication systems is wavelength division multiplexing (WDM). Each communication channel is allocated to a different frequency and multiplexed onto a single fiber. At the destination wavelengths are spatially separated to different receiver locations. In this configuration the high carrier bandwidth is utilized to a greater extent to transmit multiple optical signals through a single optical fiber.

Fig. 2: General schematic of WDM PON

The various WDM PON topologies are briefly described below:

3.1 Point-to-point systems: For single frequency point-point links the bit rate is limited ~100 Gb/s due to dispersion. This is well below the capability of the optical carrier frequency. WDM can increase the total bit rate of point-to-point systems.

Fig. 3: point-to-point system

3.2 Broadcast and select system: This type uses a star coupler to mix signals of different wavelengths and wavelength tunable filters to extract the information. Although the power is
decreased by a factor of 1/N this loss can be offset with the use of an optical amplifier prior to the second star coupler. During the past few years dense WDM (DWDM) systems have been proposed and are being developed.

![Fig. 4: broadcast and select system](image)

**3.3 DWDM Ring Topology:** The hub acts as a controller to route information over the network. This topology is illustrated below.

![Fig. 5: DWDM Ring Topology](image)

**4. WDM-PON variants Classifications**

The WDM-PON variants can be classified by choosing one option from each of the following categories:

- Broadcast + select (splitter PON with wavelength - selective ONUs) vs. wavelength routed.
- Shared upstream (downstream) vs. dedicated upstream (downstream).
- Single-fiber vs. dual-fiber working.
- Single-stage optics in remote node vs. cascaded optics.
- Coloured ONUs vs. colorless ONUs.
- Colourless ONUs: spectrum slicing vs. shared source/seed approach.
- Seed approach: reflective semiconductor optical amplifier (SOA) - vs. reflective electroabsorption modulator (EAM) vs. injection-locked Fabry-Perot laser.
- Direct modulation vs. sub-carrier modulation
- Modulation for colorless ONUs: On-off keying (OOK) vs. OOK/Frequency-shift keying (FSK).
- Un-amplified vs. amplified (“active PON”: booster/pre-amplifier vs. remotely pumped amplifiers)
- Unprotected vs. protected (end-to-end protection vs. protection for link OLT-Remote Node).

**5. WDM PON Architecture and Components**

The few components of WDM PON architecture are shown in figure 6 for four-channel WDM solution where a WDM multiplexer (mux) combines four independent data streams, each on a unique wavelength, and sends them on a
fiber; and a demultiplexer (demux) at the fiber’s receiving end separates out these data streams.

6. Migrating from GPON to WDM-PON

Recently, a great deal of industry discussion has focused on what the next technology is beyond GPON. Some of the options mentioned are a hybrid GPON/CWDM PON, 10G GPON or an active Ethernet solution over a GPON infrastructure. But each of these technologies has its drawbacks, to the point that none of them makes a lot of sense from a competitive or financial perspective. Ultimately, the real upgrade path for GPON is WDM PON.

WDM-PON is the viable solution for upgrading GPON. It combines the best elements of private, point-to-point networks-security and dedicated bandwidth-with the best elements of traditional PON low infrastructure costs due to shared fiber resources and passive components in the outside plant. In addition WDM-PON uses “colorless” optics, which eliminates the inventory management issue associated with other DWDM/CWDM solutions and reduces provisioning to plug-n-play.

WDM-PON’s detractors argue that the technology is too expensive, not standardized, and too large for high density applications or an inefficient use of bandwidth. Although there is some merit to these points with existing systems but the future potential of the technology easily overcomes these concerns. The Current WDM-PON systems are more expensive than GPON, but they also provide 16 times more bandwidth today. The primary cost in a WDM-

Fig. 6: Typical WDM-PON architecture

The main components of WDM PON architecture are: -

- Thin Film Filters.
- Passive Optical Elements (POE): waveguides, arrayed waveguide gratings AWGs, star couplers, grating devices.
- Acousto-Optic devices – Bragg cells, tunable optical filters.
- High speed optical modulators – Mach Zehnder interferometers.
- Liquid Crystal Devices.
- Temperature Tunable Integrated Waveguide Devices.

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PON is a light source that is required to provide the seed light necessary for wavelength locking, a key component of the “colorless” optics scheme. Significant cost reductions are occurring and will continue as the technology becomes more widespread. Standardization is a critical issue in GPON and 10G GPON, and even with it, there still isn’t universal interoperability between vendors. However, WDM-PON is a transport platform that delivers exactly what is put into it. Therefore, there are no interoperability issues at either end of the WDM-PON network. This flexibility, coupled with the point-to-point nature of the technology, allows it to support multiple services and multiple bit-rates in the native format. Today, although these systems are Ethernet-only because the prevailing thought is that IP over Ethernet will be ubiquitous; adding TDM interfaces is relatively simple and non-service affecting for existing customers. In addition, if the wavelength plan should ever change due to further standardization, WDM-PON systems that employ “colorless” optics technology would only be minimally impacted as the change would only affect the Arrayed Wavelength Grating (AWG), a device that determines the wavelength plan, rather than the ONUs or OLT line cards. That’s because the AWG is also responsible for multiplexing/demultiplexing the wavelengths into and out of the feeder fiber.

One of the key advantages of WDM-PON is that it provides the simplest upgrade path for GPON, with the least amount of service impact. WDM-PON uses an AWG to multiplex and demultiplex wavelengths between the feeder fiber and the distribution fibers instead of a traditional Planar Lightwave Circuit (PLC) splitter. In a WDM-PON system that uses “colorless” optics, the AWG is also responsible for spectrally slicing a seed light, generally provided from the OLT, into the individual wavelengths that are passed to the ONTs. The AWG can be packaged in the same form factor as existing PLC splitters. This enables service providers to insert a module inside an existing GPON splitter cabinet to support WDM-PON.

### 7. Comparison of emerging PON Technologies

The basic difference among few emerging PON technologies is summarized in the following table:

<table>
<thead>
<tr>
<th>PON Technology</th>
<th>10 GEAPON</th>
<th>10G PON (XG-PON1/ XG-PON2)</th>
<th>WDM PON</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard</strong></td>
<td>IEEE P802.3av</td>
<td>ITU-T G.987/ FSAN</td>
<td>ITU G.983</td>
</tr>
<tr>
<td><strong>Maximum Bandwidth</strong></td>
<td>10.3125 Gb/s</td>
<td>2.5 Gb/s &amp; 10 Gb/s</td>
<td>1 - 10 Gb/s per channel</td>
</tr>
<tr>
<td><strong>Maximum Downstream Line Rate</strong></td>
<td>IP; 2.4 Gbps, Broadcast; 5 Gb/s On-demand; 2.5 Gb/s</td>
<td>10 Gbit/s</td>
<td>1 - 10 Gbit/s per channel</td>
</tr>
<tr>
<td><strong>Maximum Upstream Line Rate</strong></td>
<td>2.5 Gbps</td>
<td>2.5 Gbps</td>
<td>1 - 10 Gbit/s per channel</td>
</tr>
<tr>
<td><strong>Downstream wavelength</strong></td>
<td>1577 nm</td>
<td>1577 nm</td>
<td>Individual wavelength/h/channel</td>
</tr>
<tr>
<td><strong>Upstream wavelength</strong></td>
<td>1270 nm</td>
<td>1270 nm</td>
<td>Individual wavelength/h/channel</td>
</tr>
</tbody>
</table>
### 8. Benefits and features of WDM PON Technology

The various benefits and features of WDM-PON include:

- (Physical layer) un-contended bandwidth similar to point-to-point fiber, i.e. no bandwidth scheduling is needed as in GPON.
- Effective use of fiber - up to 64 subscribers/fiber (similar to GPON).
- Longer reach is possible, using the low-loss AWG in contrast to the high-loss power splitter needed for GPON. Using the 28 dB link-budget of Table 1 and assuming a 64-way split, a WDM-PON at 1550 nm could reach >80 km compared to around 16 km for a GPON.
- Physical separation of subscriber signals.
- WDM-PON solutions provide the dedicated bandwidth of a point-to-point network with the fiber sharing inherent in PON networks. The architecture is somewhat similar to that of EPON and GPON, except an AWG (Array Waveguide Grating) filter separates the wavelengths for individual delivery to subscriber ONTs, being used instead of the splitter used in TDM-PON architectures.
- A key advantage of WDM-PON is the use of a completely separate downstream wavelength for each of the subscribers. This separate wavelength provides more bandwidth to each subscriber, better security, and enhanced operational control since there is no potential interference between wavelengths in the downstream direction. Figure 5 shows a generic WDM-PON architecture.
- WDM-PON has inherent features that can provide a major competitive advantage for service providers that target the enterprise market. For example, TDM-PON technologies such as BPON and GPON send the same signal to all subscribers’ ONUs, creating a security risk that must be mitigated by using encryption. WDM-PON avoids that security risk altogether by allowing the service provider to put each customer on a separate wavelength. That ability can be a plus in the eyes of security-minded enterprise CIOs and IT managers.
- WDM-PON is the only PON technology capable of providing the scalability and dedicated, symmetrical bandwidth that many business applications demand. As a result, service providers can use WDM-PON’s capabilities as a powerful market-differentiator.
- Delivery of different bit rates and protocols over the same PON.

<table>
<thead>
<tr>
<th>Traffic Modes</th>
<th>Ethernet</th>
<th>GEM</th>
<th>Protocol Independent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Video</td>
<td>RF/IP</td>
<td>RF/IP</td>
<td>1550 nm overlay/IP</td>
</tr>
<tr>
<td>Max PON Splits</td>
<td>128</td>
<td>128</td>
<td>16 - 32</td>
</tr>
<tr>
<td>Max Distance</td>
<td>10 Km</td>
<td>20 Km</td>
<td>20 Km</td>
</tr>
<tr>
<td>Average Bandwidth per User</td>
<td>&gt; 100 Mbit/s</td>
<td>&gt; 100 Mb/s</td>
<td>1 - 10 Gbit/s</td>
</tr>
<tr>
<td>Cost</td>
<td>High</td>
<td>High</td>
<td>Very high</td>
</tr>
</tbody>
</table>
• An end-to-end solution with colorless DWDM ONUs, which translates into low inventory costs.
• Delivery of mixed services enabled by independent wavelength links.
• Guaranteed network security through dedicated wavelengths.
• Point-to-point wavelengths are easily upgradeable without service interruption to other users.
• The higher BW of WDM PON provides a number of benefits:
  - More subscribers per PON
  - More bandwidth per subscriber
  - Higher split counts
  - Video capabilities
  - Better QoS
  - Cost - reduction applications
• The network can be upgraded and no disruption of the services in network operations during the upgradation of the network. Migration from EPON to 10G EPON by upgrading the OLT then migrating the ONUs as needed.

9. Summary
This paper summarized the general idea about functionalities of WDM PON technology in term of basics, deployment strategy, benefits, drawbacks, features, evolution etc. There are several approaches to WDM-PON that vendors are developing today, with a number of proprietary approaches, and it will take considerable time for the standardization process to run its course. It will also take significant time for many of the WDM-PON solutions that have been proposed to date to gain the level of maturity needed to fully progress down the cost curve and become cost competitive across a wide variety of network applications. WDM-PON leverages fiber and passive wavelengths to provide the most scalable, cost effective, and future proof solution available to address the capacity, security, and distance capabilities that service operators require while leveraging the benefits of a passive infrastructure. All these factors combine to make WDM-PON poised to become the disruptive next-generation access solution. The main obstacle to WDM-PON is the cost, since the transmitters need to emit at a specified wavelength. This is especially critical for the subscriber units (ONTs) since this cost directly affects each subscriber line. At the CO side, the cost of the multi-wavelength signal can be lowered by optical integration. The most of the WDM PON technology solutions are still in development phase and require more study and test.

10. References and Links
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[9] Alex Vukovic, Khaled Maamoun, Heng Hua, Michel Savoie ‘Performance Characterization of PON Technologies’, Broadband Applications and Optical Networks, Communications Research Centre (CRC), Ottawa, ON, Canada, K2H 8S2.


