EVOLUTION OF ACCESS NETWORK FROM COPPER TO PON — CURRENT STATUS

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ABSTRACT

There was a time when data services were available at 56kbps using dial up connections over the conventional pots network based on copper local loop. But with the introduction of bandwidth thirsty data and video applications, the telecom data networks have gradually evolved from copper based network solutions like ISDN and DSL to the fiber based HFC network, SDH based Access networks (FTTC and FTTB) and finally to the Passive Optical Networks (FTTB and FTTH). In this paper we have reviewed these technologies with emphasis on ITU-T PON technologies. We also discuss the future trend of PON based solutions and report on the current progress.

Key words: copper, passive optical networks, GPON, NGPON, EPON.

INTRODUCTION

With the evolution of Internet the demand for data networks has ever been increasing. When only the need was to access emails and web browsing, the data lines using dial up via 56kbps modems were also sufficient but it had the problem that this line could be used for voice or data at a time not both (Maes *et al.* 2015). Therefore the concept of ISDN lines was introduced in 1976 (Jean-Alainle *et al.* 1980) and later to Digital Subscriber Line (DSL). A typical ISDN line consisted of two 64kbps data channels combined to give128kbps data rate termed as BRI requiring proprietary Customer Premises Equipment (CPE). DSL was first introduced in early nineties (Syed *et al.* 1981). It got popularity due to having standardized CPE with universal user interface. The first DSL standard getting wide popularity was ADSL standardized in ITU-T G.992.1 in 1999. It could provide a maximum data rate of 7Mbps (Downstream) and 800Kbps (Upstream) up to a distance of 3.5km but later on with more advanced modulation techniques like ADSL2 in 2002, ADSL-RE in 2003 and ADSL2plus defined in ITU-T standards G.992.1, G.992.3 and G.992.5 with a downstream maximum data rate / distance of 8Mbps / 4Km, 8Mbps / 7km and 24Mbps of peed of up to a maximum distance of 5.5Km. Later on VDSL was also introduced in 2004 with a data rate of 52Mbps downstream but its distance was limited to just 500m. The maximum data rate for DSL was dependent on the distance between the user and Central Office .The Shannon limit of copper had reached then and the need of the hour was optical fiber media with virtually unlimited bandwidth (Pauline *et al.* 2015).

Thereafter the Hybrid fiber-Copper solutions like HFC networks started gaining famous for the provision of data and video services with increased data rates and reach.

With the invasion of more bandwidth hungry applications like online gaming, Video on demand and IPTV, the network operators started looking at fiber based solutions or hybrid of fiber and copper. The SDH equipment that was being used typically in backbone networks was dragged in the local loop for providing ADSL, VDSL, HDSL and Triple play services to the customers by terminating the fiber in an area or building (Werner, 1994). These topologies deployed an Optical Network Unit (ONU) near to customer's homes or inside apartments to reduce the copper span to a customer's home. The drawbacks of this approach were: (1) Power was required in the ONU for optical to electrical conversion (2) More infrastructure cost as the network was in a ring topology (3) Still the copper in the last mile restricted the data rates beyond 50-100Mbps.

The P2P fiber for every customer appeared to be an attractive option but was not economically affordable by a general customer. So the most cost effective, flexible, easy to extend solution fulfilling the present and future bandwidth requirements was PON. The first PON based system was demonstrated by researchers at BT Laboratories in 1987. (J. R. Stern *et al.* 1987). Afterwards the Operators started looking at PON based FTTH solutions and formed FSAN in 1995 which formulated the first PON based solution using ATM as a transport mechanism with a split ratio of 32, a reach of 20km and data rates of 622Mbps (Downstream) and 155Mbps (Upstream) per channel. It could carry data and voice both using different wavelengths for upstream (1310nm) and downstream (1490nm) on the same fiber, while separate fiber was used for video transmission. This was named as APON and is standardized in ITU-T G.983.1 in 1998. (Gerd, 2006) Later on renamed as BPON with the addition of wavelength of 1550 nm for carrying video on the same fiber with an increased rate of 1.2Gbps (Downstream) and 622Mbps (Upstream) (Paul, 2008). Soon after GPON was finalized by ITU-T in 2003 standardized in G.984 with data rates of 1.2Gbps and 2.4Gbps in downstream and up to 2.4Gbps in Upstream and EPON with a symmetric data rate of in 1.2Gbps by IEEE. The EPON is mostly deployed in Asia like Japan, China and Korea while GPON is deployed heavily in Europe (Luying *et al.* 2010).The research for 10G PONs is quite mature but its deployment is still in progress. Actually since 2007 FSAN committees have been working on two different proposals. The first was supposed to be compatible with earlier solutions while the other had no such obligation. Both these proposals were termed as NGPON1 and NGPON2. The result of NGPON1 is XGPON1 standardized in ITU-T G.987 series recommendations with a data rate of 10Gps (downstream) and 2.5Gpbs (Upstream) standardized in 2010. There is also a proposal of symmetric 10Gbps upstream and downstream termed as XGPON2 but it's not still practically suitable due to higher hardware cost. Both XGPON 1&2 are backward compatible with GPON. The NGPON2 proposal is still under research but the selected candidate for it is TWDM PON (Frank, 2011).

This paper is organized as follows. The first Section discusses the copper based data access solutions. Second discusses HFC and SDH based Access Networks. Third discusses in detail the Passive Optical Networks. Then we discusses the Future Trends conclude the work.

Copper based access solutions

Copper has been traditionally used for carrying voice services but with the digital revolution, data services were also provided on it using dial up modems,128kbps BRI and later on 2Mbps PRI lines on copper. Both PRI and BRI required a proprietary CPE to be installed at the customer premises to separate/combine voice and data using FDM. In the late nineties DSL was introduced following the same concept but with a universal standard interface and CPE. The basic concept remained the same i.e. divide the copper bandwidth into multiple virtual channels using FDM and Transmit and receive data in addition to voice simultaneously on the same copper line. Two techniques CAP and DMT have been used in DSL but DMT has gained more popularity and has become a standard (Kamran, 1993) as it can adapt to higher data rates easily without the crosstalk problem. The main difference between two is that CAP divided the available bandwidth into three bands: 0-4KHz for voice, 25-160 KHz for Upstream, and 240 KHz to 1500 KHZ for downstream data transmission. While DMT divides the available bandwidth into 255 separate channels of 4kh each termed as bins. The bin1 allocated to voice, bin 2 to 6 left as guard bands, bin 7-31 for upstream and 32-255 for Downstream data communication. DMT modulates data stream on each individual channel using Quadrature Amplitude Modulation (QAM) (Kamran, 1993).

The most popular standard for general customers have been the ADSL2 which used four dimensional 16 – state trellis-coding and 1-bit quadrature amplitude modulation (QAM) constellations. It achieves higher coding gain by employing the Reed-Solomon code (RS). On the other hand it doubles the copper bandwidth utilization from 1.1 MHZ to 2.2 MHZ, thereby increasing the virtual channels and data rates but on the cost of reduced distance i.e. up to a maximum of 1.6 Km.

HDSL and its variants like SHDSL and G.SHDSL were developed to carry E-1 or T1 lines on copper over a distance of 5km.They are mostly used for provisioning of leased lines to commercial customers using conventional copper access network using digital cross connect systems. These techniques use adaptive line equalization and 2B1Q line encoding to increase channel capacity and reduce Inter Symbol Interference (ISI) (Daniel *et al.* 1994).

VDSL offers the highest data rate of 55Mbps on twisted pair cable and 85 Mbps on coaxial of all the DSL technologies introduced in 2006 (Maes *et al.* 2015). It does so by increasing the bandwidth to 10 MHZ but on the other hand compromising on the distance and reducing it to only 500 meters. So it can't be extended directly on copper to a customer from the central office. It requires some optical transport network like HFC or SDH access networks to carry it near the customer home from where it could be provisioned on copper.

The latest developments in copper based broadband technology is Vectored VDSL2,G.Fasrt and XG-FAST technologies that offer maximum data rates of 150Mbps,1Gbps and 10Gbps with typical distance ranges of 500m,10m and 30m (Coomans Werner *et al.* 2015). These technologies cannot be used alone to provide direct access to the customers from the CO but can be used in a hybrid fiber configuration at the last mile.

Hybrid Fiber-Copper solutions

HFC networks have typically been used for the distribution of Cable TV services over a Fiber and Copper hybrid type network in till 90's. The structure of this network is point to multipoint tree and branch comprising of a Headend node connected to satellite dishes to capture different video channels and a router interface to data cloud for the provisioning of data service connected to remote nodes via optical fiber where opticl to electrical conversion take place serving 50 to 2000 users via coaxial cables. A regional hub can optionally add its local channels or advertisements as per requirement and distribute the services through a fiber based network. Sometimes it might have telephony equipment for extending voice services but these networks were designed for CATV service and are not designed to work with traditional telcom operators. The main standard for these networks approved by ITU-T is DOCSIS. DOCSIS V1.0 was approved by ITU-T in 1998 (Ying-Dar Lin *et al.* 2000) which paved the way for Data services over existing CATV network in the frequency band of 5-42 MHZ. The initial specification D1.0 used QPSK modulation leading to a data rate of 2Mbps. Soon D1.1 was introduced which used 16 QAM and enhanced the data rate to 8Mbps. D2.0 was introduced in 2001 and it added the option of higher symbol rate modulation schemes like 32-QAM and 64-QAM thus increasing the peak downstream data rate to 30 Mbps. DOCSIS 3.0 was introduced in Jan 2009 increasing the datarate and bandwidth further for the data transmission from 42 MHZ to 85 MHZ. D3.0 standard uses 64 QAM and 256 QAM modulation schemes and can provide peak downstream data rate around 150Mbps and Upstream data rate of 100Mbps (George, 2011).

Similarly Optical fiber based access networks using SDH as a transport protocol are also being used by telecom operators for the transport of DSL, telephone and

VOL. 10, NO. 18, OCTOBER 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

IP TV services. All the three services can be provisioned to a customer on his copper pair from an Optical Network Unit (ONU) which is part of SDH based optical fiber ring network. This scheme works in Fiber to the Curb (FTTC) scenario. Figure-1 shows the topology of a SDH based optical fiber access ring of Huawei Telecom deployed by Pakistan Telecommunication Company. The main components of this ring are Optical Line Terminal (OLT) located at CO and Add Drop Multiplexers (ADM) located inside ONU. OLT is like a Gateway for all the video, data and voice services and is interfaced to voice switch, DSLAM and Video server. SDH is used as the transport protocol for all these services. Due to the reduction of copper length now VDSL service with a data rate of 55Mbps can be easily provided to some customer from the nearest ONU.

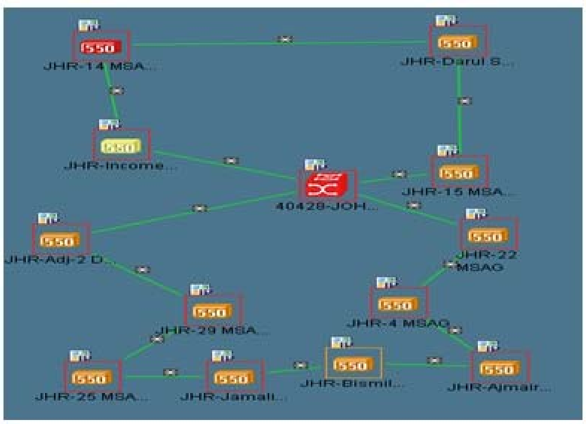

Figure-1. Figure of an SDH based Optical Access Ring (Courtesy of Pakistan Telecommunication Company Ltd).

HFC and SDH networks suffer from following disadvantages;

- Active components are required in the local loop requiring and consuming for every ONU (Glen, 2012).
- Site rentals for ONU installation in case of FTTB or FTTA increase recurring costs.
- Copper is still involved in the last mile and imposes restriction on the data rates higher than 85Mbps (VDSL on Coaxial) and 155Mbps (STM-1 on Coaxial).

So what is the alternative then? The answer is to have a Passive Optical Network (PON) base access network. We discuss the PON in the following section.

Passive optical networks

Although the concept of Copper based PON (CuPON) has been proposed in [Martin Maier at El, 2012] but it again has distance and data rate limitations as compared fiber based PONs and this has not been deployed by any telecom operator practically. So the term PON Passive Optical Networks is generally applied to Fiber based Access Networks. As the name implies it uses no active component between the customer premises and CO equipment. This technology uses power splitters to branch the light signal to different directions in the access network. The OLT at the CO broadcasts the voice and data on a single wavelength and receives at another. While video is broadcasted at a different wavelength. The equipment at customer premises termed as Optical Network Terminal ONT, sometimes also termed as ONU, receives the optical signal based on its pre-assigned ID and serves the customer. The OLT uses TDMA to receive upstream signals from all the ONTs. Such PON technologies are termed as TDM PONs. It is also possible to communicate between OLT and ONTs on different wavelengths (WDM) which would require tunable lasers and receiver's so off-course it would be costlier solution as tunable lasers and optical receivers are still very costly.

Up till now TDM PON has been widely deployed in the access network. We discuss the protocols and access technique in each PON in the below sub-sections.

APON / BON

APON and BPON both used ATM as transport protocol. Both standards provided 32 splits and a span of 20Km. APON was initial version which required separate fiber for the transmission of video while voice and data could share the same fiber. Both used broadcast for downstream and TDMA upstream like all other TDM PONs (Gerd, 2006).The downstream frame consists of 56 cells of 53 bytes each. There were two types of cells, Data and Operation and Management (OAM). Data cells carry user data, signaling and ATM operation, administration and maintenance information. The OAM cells termed as PLOAM cell were responsible for synchronization, frame error control, security and bandwidth allocation using grants. Each PLOAM cell carried 27 grants for Upstream transmission that could be read by an ONT. So for a 155.52 Mbps frame rate two PLOAM cells were required (Biswananth, 2006).

The upstream frame transmission was based on TDMA scheme comprising of 53 ATM cells each of 56 byte with first three bytes as overhead that can be utilized by ONT for various purposes. The overhead bytes comprise of a minimum 4 bits of a preamble and a delimiter field in addition to guard time. Since ONT are located at different distances therefore OLT uses a burst mode receiver [Masaki *et al*., 2010) to adjust the received power from different ONTs located at different distances. OLT also need to use Ranging Process (Cedric, 2011) to estimate ONT distance so that the delay between the upstream transmissions is maintained between the ONT. In the upstream direction ONT use the PLOAM cells to transmit their queue sizes to the OLT which then based on Dynamic BW Allocation (DBA) allocates Bandwidth ONTs using grants.

Giggabit Passive Optical Network (GPON)

It is an upgraded version of BPON with increased data rates. Its frame comprises of 38880 bytes and frame duration is 125us with a sampling rate of 8 leading to a

VOL. 10, NO. 18, OCTOBER 2015 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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downstream rate of 2.488Gbps. It supports variable data rates but typical data rates that most vendors implement are 2.4Gbps (Downstream) and 1.2Gbps upstream. In addition to ATM, GPON introduced another transport protocol called GPON Encapsulation Method (GEM) which is actually a slightly modified version of G.7041 Generic Framing Procedure which is a specification of transmitting IP packets over SDH or SONET. In the current version of GPON only GEM is used and ATM has been deprecated. Unlike ATM GEM uses variable length frame to accommodate different types of services. A GPON downstream frame is shown in Figure-2 and fields are described in Table-1 and Table-2.

Table-1. GEM PCBd fields functions.

Field Name	Bits	Fucntion
PLI	12	The PLI indicates the length L, in bytes, of the payload following this header. There can be one or more Port-IDs transmitted within an Alloc-ID/T-CONT
PORT-ID	12	Port-ID is a key to identify the GEM frames that belong to different downstream logical connections. Each ONU filters the downstream GEM frames based on their GEM Port-IDs and processes only the GEM frames that belong to that ONU.
PTI	03	The PTI field is used to indicate the content type of the payload like user datagram or OAM and end of frame or not.
HEC	13	the HEC provides error detection and correction functions for the header.

Table-2. PCBd fields functions.

Field Name	Bytes	Fucntion
Psynch	4	32 bit periodic pattern. Its value is 0xB6AB31E0. It is not scrambled. Two consecutive receiptions leads to SYNC state.
Ident	4	Its first bit indicates if FEC is being used in downstream or not,2nd bit is reserved and rest 30 bit form a super counter used for synchronization and lower rate ref. signals.
PLOAMd	13	13 byte field tha t contains the PLOAM messages.
BIP	1	the bit-interleaved parity of all bytes transmitted since the last BIP
Plend	4	specifies the length of the Bandwidth map (Blen= first 12bits) and the deprecated ATM partition (alen= next 12bits). Last byte is CRC of incoming bytes with polynomial x8 + x2 + x + 1). Sent twice.
US BW MAP	8 * N	Comprises of N allocation structures mentioned in Plend field, each belonging to a particular TCONT. Sub fields shown in Figure 6 and described further in Table 3

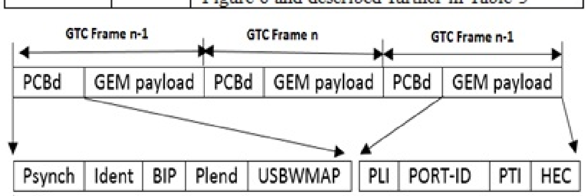

Figure-2. Figure showing GPON downstream frame.

The upstream transmission in GPON uses TDMA that is each ONT transmits in its assigned time slots. Each frame from an ONT has a guard band to avoid collisions, managed by OLT while assigning bandwidth slots in the **US BW Map** field as described in Table-2. Upstream frame structure consists of a header and payload section. The Header section is divided into four fields namely; Physical Layer Overhead (PLOu), Physical Layer OAM (PLOAMu), Power leveling sequence (PLSu) and Dynamic Bandwidth Report (DBRu) as shown in Figure-3. The PLSu field is now depricated.

The upstream burst is scrambled using a burst-synchronous scrambling polynomial. The polynomial used for scrambling is x7 + x6 + 1.

Figure-3. GPON upstream frame.

The first field contains the preamble for burst mode receiver; the second is used for Ranging, ONT activation and Alarm notifications using PLOAM messages. The PLSu field contains Laser Power Level Information at the ONTs. The DBRu field is used by the ONT to report its queue length so that ONT can use appropriate DBA Algorithm for Time Slot Assignment. GPON also incorporates security mechanism for downstream transmission ensuring that only intended ONT receives data.

Ethernet Passive Optical Network (EPON)

EPON was developed by IEEE as a next step after BPON. Unlike BPON as well as GPON it did not used ATM rather it was inspired by CSMA/CD (Ethernet). Like every TDM PON the downstream transmission is also broadcasted here. Concerned ONTs receive frames matching their Logical Link Identifier (LLID) while the others discard the frames. These LLIDs are assigned to ONTs during their registration process. In EPON the OLT can dynamically register new ONTs using a discovery process. The downstream frame format is very similar to an Ethernet frame except for the first two fields; preamble and SFD which replaced with four new fields namely; Start of Packet Delimiter (SPD), Reserved, LLID and Frame check Sequence FCS as shown in Figure-4.

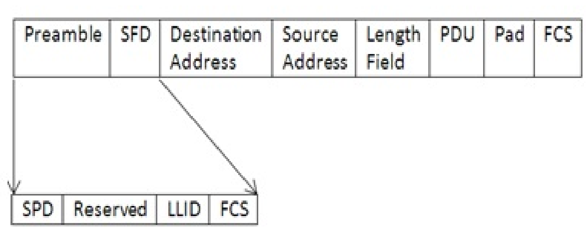

Figure-4. EPON downstream frame structure.

VOL. 10, NO. 18, OCTOBER 2015 ISSN 1819-6608
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The first byte contains synchronization marker sent by OLT every 2ms for keeping ONT synchronized. Three bytes are reserved for future use. An LLID field is necessary to include identity of the target ONT. In standard Ethernet ARP protocol is needed for target discovery. A FCS field is introduced for error detection in the EPON frame.

For the upstream communication Ethernet can't be used as it doesn't support server client architecture. So a special protocol Multipoint Control Protocol (MPCP) is used for arbitration between the ONTs and to avoid collisions. This protocol also helps in upstream bandwidth allocation to the ONTs. This protocol is specially developed for EPON for the following purposes,

- Auto discovery and Registration of New ONTs.
- Bandwidth allocation and assignment.
- Ranging

It uses different type of messages for performing the above functions. REPORT message is used by the ONTs to report their queue sizes while the GATE message is used by the OLT to allocate bandwidth by communicating the Grant times and Lengths as shown in Figure-5. The discovery process is performed with the help of 4 more messages. A Discovery_Gate message is broadcast periodically to the entire ONUs indicating a starting and ending time for the discovery window.

Any new or offline ONU transmits its MAC address using a Register_Request message. The OLT after receiving this message registers the new ONT, allocates a LLID and transmits the RGISTER message. The OLT then assigns upstream time slot using a GATE message. The ONT acknowledges via REGISTER_ACK.

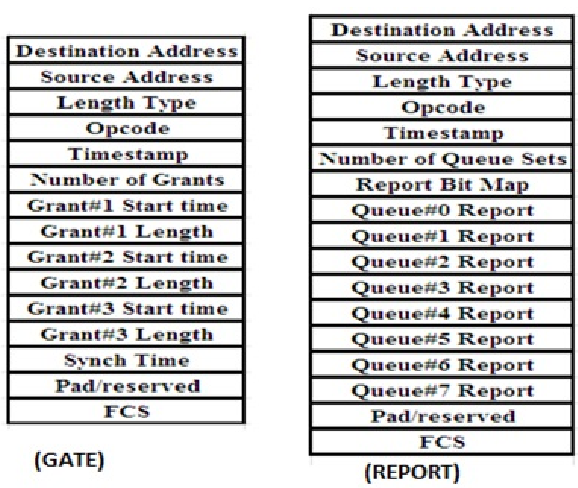

Figure-5. Frame format of GATE and REPORT messages.

10G-EPON

It's the next step above EPON now also termed as 1G-EPON. It was standardized by IEEE working group as 802.3av in 2009. 10G-EPON wavelengths assignments are different than the simple EPON. Some more frequency bands been added to the scheme as shown in Table-3 to keep the co-existence with the 1G-EPON as it is already heavily deployed. The 10Gbps downstream signal is transmitted on a separate frequency of 1577nm for 10G ONTs while the upstream band is completely overlapped with 1G wavelength (Hajduczenia *et al.*, 2008). All the three wavelength bands are multiplexed in the downstream direction while in case of upstream, the OLT operates in dual rate to receive both 1Gbps and 10Gbps signals from their respective line codes. Although the wavelengths of both are partially overlapping but there line coding are different. The 1Gbps ONTs transmit data using 8b/10b coding in the range of 1260-1360nm at a data rate of 1.25Gbps, while the 10 Gbps ONTs use 64b/66b line coding between 1260-1280nm band at a data rate of 10.3125Gbps. Such implementation also requires separate lasers for 1G & 10G in downstream transmission and a single dual rate burst mode receiver for receiving both signals in the upstream.

The focus point for IEEE 802.3av task force was physical layer. It divided it into four sub-layers; the reconciliation sub-layer (RS), physical medium attachment (PMA), symmetric & asymmetric physical coding sub-layer (PCS), and physical medium dependent (PMD) sub-layer. The MAC protocol remained approximately same as of 1G-EPON therefore the discovery procedure, OMI and bandwidth assignment procedures remained same. The important changes made in 10G-EPON are as follows;

- 64B/66B line coding scheme was used for the10G-EPON which reduced the bit to baud overhead to 3% from 20% as compared to 1G-EPON.
- A 66 bit Sequence field with very high hamming distance termed as Burst Delimiter (BD) was added before the FEC protected code words for helping OLT in identifying the start of data.
- Similarly an End of Burst (EOB) sequence is also added at the end of the code words for indicating end of data to OLT.
- A new power budget class named PR / PRX30 was added to the scheme for extending the split ratio from 16 to 32 up to a distance of 20 km.
- Avalanche Photodiode was used as a receiver in the OLT for being more sensitive.
- A stream based FEC was declared as mandatory for all 10 Gbps links using RS (255,223) instead of RS (255,239) for 1G-EPON. This provided providing higher Coding gain (5.9db) and improved BER from 1.8 X 10-4 to 1 X 10-12 (Keiji, 2010).
- More flexible upstream data burst timing where depending on the quality of the burst-mode receiver and its design ONT laser's on / off times could be negotiated.

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Table-3. Bandwidth assignments for 10G-EPON.

Optical Signal	Wave Length Assignment (nm)
1G-EPON (US)	1260-1360
1G-EPON (DS)	1480-1500
10G-EPON (DS)	1575-1580
10G-EPON (US)	1260-1280
RF Video	1550-1560

The bandwidth assignment mechanism, ONT discovery process, OAM operation and messages remain same at the MAC layer as in 1GPON so same Network Management system can support both ONTs.

XGPON1 and XGPON2

FSAN had formed a study group in 2007 for working on future PON designs. In early 2008 seven proposals came to the table for discussion including XGPON1 (10Gbps downstream and 2.5 Gbps upstream) and XGPON2 (Symmetric 10Gbps upstream and downstream). Finally XGPON1 was chosen as the right candidate for standardization due to low cost and lesser complexity (Frank, 2011) with following new salient features;

- Enhanced security against masquerade attacks using stronger authentication for OAM messages and encryption.
- Equipment power saving as well as reducing load on backup batteries in case of power failures. With three power saving modes; Turn-off idle UNI, Dozing i.e. turn-off the transmitter if idle and Sleeping i.e. shutting down both Transmitter and Receiver.
- Two separate wavelengths 1260-1280nm for upstream and 1578nm for Downstream transmission.
- Mandatory FEC scheme, RS (248, 232) Upstream and RS (248, 216) downstream.
- More layered framework divided into three sub-layers namely; Service Adaptation sub-layer, Framing Sub-layer and Physical Adaptation sub-layer.

Service Adaptation Sub-layer is responsible for accepting Service Data Units (SDU) from the upper layer which could be user data frames or OAM traffic and form XGEM frames as well as assign XGEM Port-ID. Encryption could also be optionally performed. Similarly on the receiver side reverse operations are performed and delivering SDU to the respective clients.

The XGTC framing sub-layer is responsible for the construction and parsing of the overhead fields for the XGTC payload received from the Service Adaptation sub-layer.

The PHY adaptation sub-layer is responsible for FEC coding and decoding, synchronization and scrambling functions. The downstream physical frame has the fixed size of 135432 bytes comprising of the XGTC header and payload as shown in Figure-6.

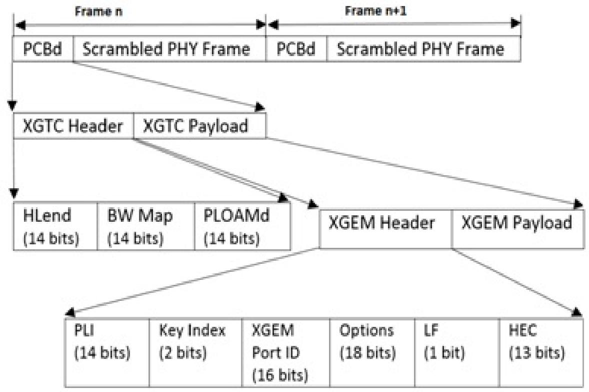

Figure-6. Figure showing the break-up of BWmap field.

The XGTC header is further divided into 4-byte HLend, variable size BWmap and PLOAMd fields. The HLend field comprises of three sub fields to control the size of the variable fields and one filed for Error correction scheme. The BWmap field indicates the number of allocation structures in the BWmap field using an unsigned integer value. The PLOAM count field indicates the no of PLOAM messages in the PLOAMd field.

The BWmap field contains Nx8 allocation structures against an Alloc-ID as shown in Figure-7. The Flags field contains DBRu bit indicating if the bandwidth report for this particular Alloc-Id is required or not. Similarly PLOAMu bit indicates if PLOAM message should be sent in upstream burst or not by the ONT.

The PLOAMd field contains PLOAM messages each of 48 bytes. The total no of messages is indicated by the PLOAMcount field as discussed above.

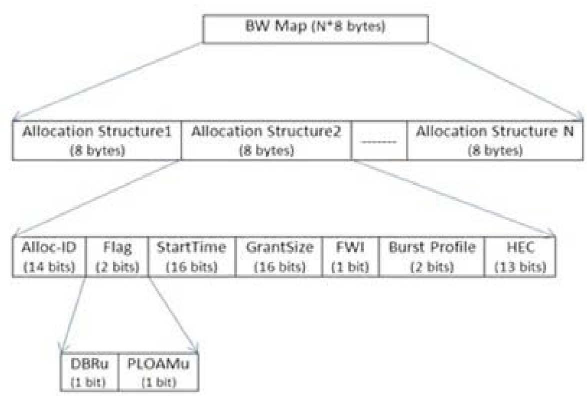

Figure-7. Break-up of BWmap field.

The XGTC payload field consists of one more XGEM frames. Each XGEM frame is further divided into XGEM header and XGEM Payload as shown in Figure-8 below.

XGEM Header field has increased to 8 bytes as compared to five bytes in GPON due to increase of field size of PLI and Port-ID field to support larger payload and more ports. A new field Key Index has been introduced to indicate the encryption key. It can point to four keys with two bit field size. The Options field is actually reserved field for future use. The LF field indicates fragmentation.

Finally the XGTC frame after passing though FEC and scrambling operation is transmitted on physical media with the addition of PSBd field as shown in Figure-8.

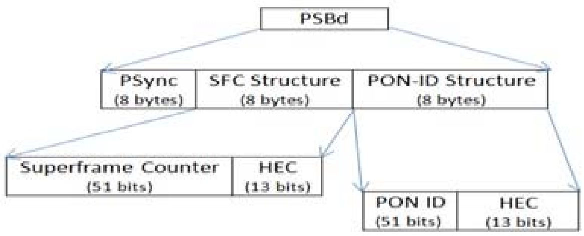

Figure-8. Break-up of XGEM header.

The PSync field is a 64 bit pattern used for frame synchronization. The SFC structure contains a Super frame counter that increments with respect to the previous frame. PON-ID is 51 bit identifier set by the OLT at its discretion.

In the upstream direction, the frame transmitted by ONT has a dynamically determined size. It comprises of XGTC Header, Trailer, and one or multiple DBRu and payload fields as shown in Figure-9.

The XGTC header includes a 4-byte fixed section and a non-fixed section. The fixed section consists of ONU-ID, Ind, and HEC. The non-fixed section has either zero bytes or a 48-byte PLOAM message, depending on the value of the PLOAMu flag of the corresponding BWmap allocation structure. The ONU-ID field is a 10-bit field that contains the unique ONU-ID of the ONU that is transmitting the burst. The ONU-ID is assigned to the ONU during the activation process. ONT uses the Ind field used to indicate local conditions and PLOAM message status signaling certain ONT conditions to OLT. The PLOAMu field has a single PLOAM message if it was requested in downstream transmission via PLOAMu flag.

The presence of DBRu is controlled by OLT using DBRu flag in the downstream transmission. If the flag was set then the DBRu is present and it consists of the four byte DBRu structure which carries a buffer status report associated with a specific Alloc-ID.

The 3 bytes long buffer occupancy (BufOcc) field has the information of the total amount of SDU traffic in associated with the Alloc-ID.

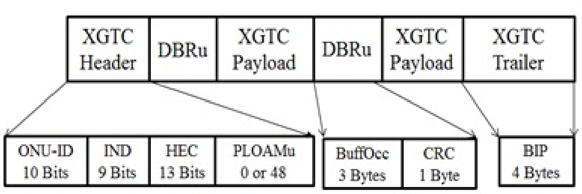

Figure-9. Break-up of upstream XGTC header and trailer.

The last field is the XGTC trailer which contains four bytes long bit interleaved parity (BIP) computed over the entire XGTC burst. OLT uses this field to compute the BER on the upstream link.

Finally the complete XGTC frame is passed to PHY adaptation sub-layer where it could be optionally passed though FEC process and scrambled. For addition of synchronization information this layer adds a PSBu header which comprises of Preamble and Delimiter patterns.

There is also a guard time between the physical frames transmitted by different ONTs to avoid collisions. This guard time is actually computed by OLT while assigning the upstream bandwidths.

FUTURE WORK TRENDS IN PON

Although 10GPON versions of EPON and GPON namely; 10G-EPON and XG-PON have been tested in Labs successfully as described in (Y.Hotta *et al.*, 2009) as well as their Pilot demonstrations have also been made by different telecom operators around the globe like Technovus (Teknovus, 2009) and KT (Hosung *et al.*, 2008). But since network traffic increasing by 150-160% per year as well as Users bandwidth requirement and it is expected that till 2015 it would exceed 250 Mbps (Philippe *et al.*, 2012). Also there are some additional functional requirements like hybrid support for wired and wireless, dynamic resource sharing and be able to provide backhaul support to next generation wireless technologies like 3G and LTE (Xue *et al.*, 2013). So the next target technologies under research have a significant jump over current 10G technologies. The current research target is XGPON2 with 40Gbps downstream data rate. In the following we discuss the expectations from XGPON2, possible candidate technologies, the best candidate and the latest progress.

Expectations from NGPON2

Following are the expectations from NGPON2 (Xue *et al.*, 2013) (Fabrice, 2012);

- Should be able to meet higher bandwidth demands and provide significant bandwidth upgrade.
- Improve power efficiency especially in the access network. 10-30 % reduction in power is expected.
- Need arising for next generation PON due to new functional requirements like; survivability, hybrid support for wire and wireless, dynamic resource sharing.
- Greater per ONU (min 0.5G) data rate and OLT capacity greater than 40G.
- Increased splits (min 64. max up to 1000).
- Must not be disruptive rather operators recommend that it should possibly be compatible existing network.
- Should provide better QOS guarantee to residential, business and mobile backhaul customers to residential, business and mobile backhaul customers

Possible candidate technologies

In literature there is a lot of discussion on possible candidates for NGPON2. Some say that in near future a TDM and WDM mixed solution would be feasible for near future while in far future OFDM PON and coherent PON are stronger candidates (Xue *et al.*, 2013). But now FSAN has already gone through this brain storming process. They discussed various options like TDM PON using duobinary modulation (D. Van *et al.* 2012) and using bit interleaving protocol for reducing power consumption at the ONT (H. Chow *et al.*, 2012). WDM PON and its various variants like externally seeded (S-J Park *et al.*, 2004), wavelength re-use (L. Giorgi *et al.* 2013), tunable (M. Ropelt *et al.*,2011), ultra-dense coherent (S. smolorz *et al.*, 2011) and self-seeded (E. Wong *et al.* 2007), OFDM PON, TWDM PON (W. Poehlmann *et al.* 2011)(N. Cheng *et al.* 2011) and CDM PON (T. Kamijoh *et al.* 2009).

The best candidate

Although OFDM PON was also a very good option but the increased complexity of electronic circuit, intensive signal processing using DSP and laser phase noise problem (Yue Liu *et al.* 2015), barred its selection and finally the TWDM was declared as the best candidate for NGPON2. It uses four WDM bi-directional channels upstream each of 10G and downstream 2.5G so totaling up to 40G Up and 10G downstream data rates (Hang Zhao *et al.*2015)(Yong Guo *et al.* 2015). NGPON2 also has option of symmetric data rates of 2.5G and 10G. There is also an option of point to point WDM (PtP-WDM) overlay option in NGPON2 for higher capacity links provision.

CONCLUSIONS

The need for higher bandwidth has led to the use of newer techniques like DSL and better channel coding algorithms to maximize the possible data rate data rate using copper media. Due to Shannon limit increased data rates in copper media drastically reduced the travel distance so it was necessary to use hybrid fiber-copper solutions like HFC and SDH based metro access networks to reduce the copper length in access network. But on the other hand hybrid solutions increased power losses and maintenance costs in the access loop due to the presence of active components for converting optical signals to electrical. Therefore to cope up with the increasing bandwidth requirements, pure optical solutions were investigated resulting in the evolution of PON. All the PON architectures up till now have been using TDM in downstream and TDMA in upstream direction. With increased data rates now the 10G PON has reduced the time slot times very much and it is not possible to shrink the time slots further to increases the data rates to next step due to limitations of receiver's sensitivity. So the next focal technologies were mainly WDM and OFDM. But keeping in view the backward compatibility option and the operators requirements FSAN has finally selected the TWDM as the next step technology for the near future PONS. But other options are also being investigated like OFDM and CDM which could be the candidate technology for the far future PONs.

FSAN has up till now finalized general requirements (G.989.1) and PMD layer (G.989.2). They are still working on Transmission Convergence Layer (G.989.3). Expected completion is by the end of 2015 or start of 2016.

ACKNOWLEDGEMENTS

This This work is supported by Ministry of Education (MOE) and the administration of Universiti Teknologi Malaysia (UTM) for the project financial support through FRGS Fund vote number 4F565. The authors acknowledge the NED University of Engineering and Technology for the PhD Scholarship to the main author.

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