BEYOND FTTH - FROM FTTH TO FIBER IN THE HOME

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Abstract

FTTH has enjoyed worldwide deployments since the mid 2000s. The main technology for FTTH today is TDM PON, but in the future this may migrate to other technologies such as WDM PON, OFDM PON, and advanced modulation. In this paper, we first review the FTTH standards development and then discuss the migration of the last-mile fiber networks beyond FTTH – the extension of fiber network infrastructure from access networks to home networking, related architectures, technologies, as well as applications.

Keywords: FTTH, Fiber in the Home, TDM PON, WDM PON, POF, M-PAM

I. INTRODUCTION

FTTH (Fiber to the Home) is a last mile optical access network architecture. It has Point-to-Point (P2P) and Point-to-Multi-Point (P2MP) architectures. These architectures are distinct from the fiber topology and the protocol layer. The class of P2P architecture can be further split into P2P fiber and active Ethernet. P2P fiber architecture, as its name indicates, has a fiber termination between a headend or Central Office (CO) and a customer premise. Due to the high cost of outside plant (OSP), P2P fiber architecture is relatively unattractive in access networks. Active optical Ethernet, as shown in Fig. 1, has a P2P architecture from the protocol point of view. However, it actually has a P2MP fiber topology.

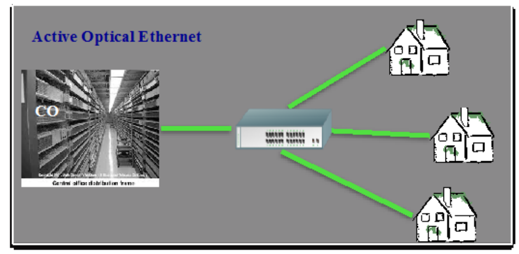

Fig. 1. The active optical Ethernet architecture

In Fig. 1, if we replace the active Ethernet switch, which is located in the field, with a passive optical power splitter, we get a passive Optical Distribution Network (ODN) that Time Division Multiplexed Passive Optical Networks (TDM PONs) are built upon today, as shown in Fig. 2.

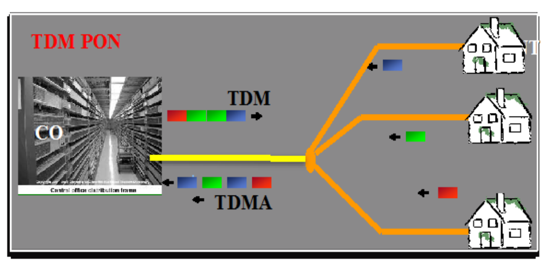

Fig. 2. TDM PON with P2MP passive ODN

Wavelength Division Multiplex (WDM) PON also has a P2MP fiber topology, though an Arrayed Waveguide Grating (AWG) could replace the passive optical splitter in the ODN. Alternatively, a WDM PON can have a hybrid AWG and power splitter ODN architecture.

TDM PON has reached 10Gbps today. For example, IEEE 10G EPON supports up to 10Gbps in both downstream and upstream directions [1]. ITU-T XGPON1 [2] supports 10Gbps in the downstream direction and 2.5Gbps in the upstream direction. The FSAN/ITU-T is currently developing a NG-PON2 standard that has aggregated 40Gbps system capacities with 4 pairs of wavelengths on a hybrid AWG/power splitter ODN. Meanwhile, IEEE has begun Next Generation EPON studies.

WDM PON is still in the research stage; there are no industry standards for WDM PON as of today. However, NG-PON2 can be viewed as a hybrid TDM and WDM PON.

With FTTH system capacities reaching 10Gbps and beyond, service providers now offer Gigabit services to residential and business customers. When bandwidth reached Gigabit/s and beyond to the home gateway, the old copper-based home networking infrastructures became the bottleneck. New home networking physical media and standards are needed for Gigabit service FTTH. Plastic/Polymer Optical Fiber (POF) is a new promising medium for Fiber in the Home networking (FITH).

In this paper, we will first review the next generation PON standard developments at IEEE and ITU-T, followed by a discussion of current home networking standards, and then discuss the Fiber in the Home and Fiber to the Device (FTTD) concepts with POF for home networking and related architectures, technologies as well as applications.

II. NEXT GENERATION PON STANDARDS

TDM PON is the main technology behind FTTH. The first TDM PON standard was APON (ATM PON); it has symmetric 155Mbps upstream and downstream bandwidth and was developed at FSAN/ITU-T in 1998 as G.983.1 [3]. APON has very limited deployment; it was shortly replaced by asymmetric Broadband PON (BPON), which has 622 Mbps downstream and 155Mbps upstream bandwidth. The BPON standard was published in ITU-T G.983.3 [4] in 2001. BPON had mild deployment, and was quickly replaced by GPON, which was published in G.984.1 to G.984.6 [5] in the 2004 to 2008 time frame. GPON has been deployed worldwide. ITU-T since then completed G.897 asymmetric 10G/2.5G XGPON1 [2] in 2010. There is little to no commercial deployment of XGPON1 as of today. FSAN and ITU-T are currently working on NG-PON2 that is based on hybrid TDM and WDM technologies.

IEEE developed the symmetric 1Gbps EPON standard 802.3ah [6] in 2004, and large-scale deployment started shortly afterwards (mostly in China and Asia-Pacific countries), and continues today. The asymmetric 10G/1G and symmetric 10G/10G EPON standard 802.3av [1] was completed by 2009. The large-scale deployment of 10G EPON started in China in late 2013. IEEE started NG EPON Industry Connection (IC) activities in early 2014. The NG EPON IC may eventually lead to the NG EPON Study Group at IEEE.

A. ITU-T NG PON2

FSAN/ITU-T is currently working on NG-PON2 standardization. When completed, it will be published in the G.989.x series. The main parts of the NG-PON2 standard are expected to be complete at the end of 2015.

NG-PON2 has a hybrid WDM PON and TDM PON architecture, as shown in Fig. 3. NG-PON2 can be viewed as a TDM PON operating over WDM PON channels. As shown in Fig. 3, the first TDM PON OLT is connected to the first WDM wavelength channel, and the second TDM PON OLT is connected to the second WDM wavelength channel, and so forth. The output port of the Arrayed Wavelength Grating (AWG), a wavelength multiplexer, is fed into a power splitter ODN. In NG-PON2, an ONU can be assigned to any of the TDM PON OLTs during the ranging of the WDM PON. The TDM PON wavelengths are assigned during the WDM PON ranging. In order to do so, tunable lasers and tunable optical filters are needed at the OLT and ONU as well.

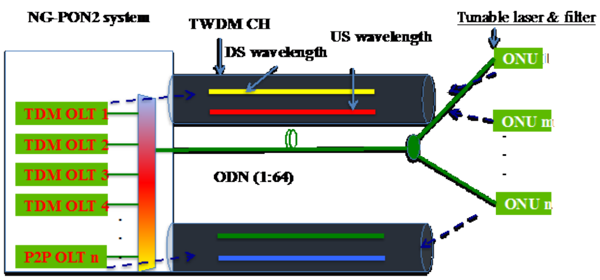

Fig. 3. NG-PON2 architecture

A NG-PON2 system has aggregated capacities of 40Gbps with 4 pairs of wavelength channels, assuming a 10 Gigabit TDM PON OLT is in each of the NG-PON2 channel.

In summary, the NG PON2 is a hybrid WDM PON and TDM PON, sometimes referred to as TWPON (TDM WDM PON). It supports four 10 Gigabit TDM PONs with an aggregated system capacity of 40Gbps. It is optional to support P2P WDM channels for a mobile front haul, or more TDM PON channels.

B. IEEE 802.3 NG EPON

IEEE started Next Generation EPON activities recently. The NG EPON IC (Industry Connection) activity was formed in Q4 2013. Industry Connection is a pre-standardization activity at IEEE. The goal of NG EPON IC is to raise awareness of the need for EPON beyond 10Gbps. Hopefully, the NG EPON IC will lead to the formation of a NG EPON study group at IEEE 802.3, and therefore lead to NG EPON standardization at IEEE.

There are many ways to achieve higher capacities for PON. As shown in Fig. 4 there are several architectural choices for NG EPON [7]. For example, WDM can be used at 10G EPON to achieve 40G aggregated capacities with 4 lambdas like that in NG-PON2. Or, we can go to a higher TDM rate first, for example, 25Gbps EPON, and then employ WDM to have 100G system capacities with 4 lambdas.

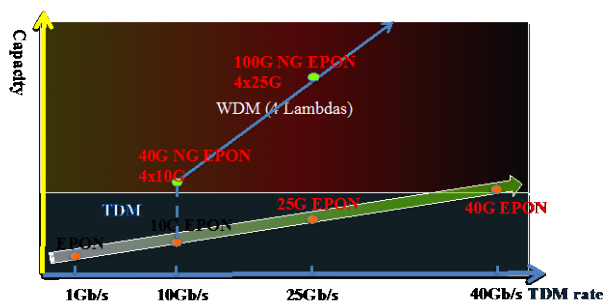

Fig. 4. NG EPON architecture choices

C. WDM PON

WDM PON has a P2MP ODN with P2P terminated wavelength channels between the subscribers and the headend or CO. As a result, it has the advantage of low CAPEX with P2MP passive ODN, high bandwidth, and high QOS with P2P wavelength channels. WDM PON is ideal in providing Gigabit services today and has the ability to provide scalable bandwidth to even higher data rates in the future.

WDM PON has been a research topic for many years; there is no single type of WDM PON architecture. The choice of different “colorless” technologies could affect the passive ODN architecture. Also, the choice of OLT light sources such as tunable lasers, laser arrays, single wavelength lasers, etc., may also affect WDM PON ODN architectures and protocols.

WDM PON is considered to be a future-proof architecture. However, major problems for WDM PON include immaturity of the key enabling technologies, the high cost associated with these technologies, too many architecture variations, and a lack of standards. However, the recent Gigabit services over FTTH may provide market motivation, and NG-PON2 may accelerate the cost reduction of tunable optics. Therefore, the time for WDM PON may come sooner than expected.

III. A BRIEF REVIEW OF HOME NETWORKING STANDARDS

Advancement of FTTH technology enables gigabit services to the home. IEEE 10G EPON provides 10Gbps symmetric shared bandwidth to 32 or more customers, and ITU-T NG-PON2 can provide 40Gbps aggregated capacities. However, the physical media for home networking are age old, and some can date back to 1880s. The most common media for home networking today are twisted pair phone lines, power lines and coax cables—or, air with Wi-Fi. Although these are different media, they share the same limitations:

- Limited spectrum
- Limited bandwidth
- Vulnerable to RF interference
- Vulnerable to EMI
- Low PHY and MAC efficiencies
- Complexity at PHY & MAC layers

A. Twisted pair phone line

The application of twisted pair phone lines can be dated back as early as the 1880s when the telephone was invented. Although twisted pair phone lines are still used in copper access networks for POTS phone services and data services with XDSL technologies, they were rarely used for home networking until G.hn [8] was recently published. G.hn is a new home networking standard published by ITU-T in 2010. The main application of G.hn is for home networking with twisted pair phone lines, although it has variations for coax cables and power lines. The G.hn twisted pair version supports PHY rates up to 900Mbps with 500Mbps MAC rates.

B. Power line

Power Line Communication (PLC) has been used in the power industry for many years for internal communications. Only in recent years with HomePlug AV [9] has PLC been used for home networking. The HomePlug AV standard published in 2005 supports 200Mbps PHY rates with 80Mbps MAC rates. The newer HomePlug AV2 [10] specification published in 2012 supports 750Mbps PHY rates in Single Input Single Output (SISO) mode with MAC rates up to 300Mbps. HomePlug AV2 also supports Multiple Input Multiple Output (MIMO) mode with PHY rates up to 1.5Gbps.

C. Coax cable

Coax cable has been the main physical medium in home networking for video and data services since the mid 1990s when the Internet became popular. Multimedia over Coax Alliance (MoCA) published MoCA 1.0 [11] in 2006 and MoCA 2.0 [12] in 2010. MoCA 2.0 base mode supports 700Mbps PHY rates with 400 Mbps MAC rates. MoCA 2.0 extended mode supports up to 1.4Gbps PHY rates with 800Mbps MAC rates.

Table 1 shows a comparison of wire line based home networking standards. It is interesting to note that the PHY rates of home networking standards in Table 1 are 1.8 times to 2.5 times higher than the corresponding MAC rates.

Table 1. Comparison of home networking standards

Media	Standard	PHY rate	MAC rate
Twisted pair	G.HN	900 Mbps	500 Mbps
Coax	MOCA 2.0 base	700 Mbps	400 Mbps
	MOCA 2.0 Extended	1.4 Gbps	800 Mbps
Power line	HomePlugAV	200 Mbps	80 Mbps
	HomePlug AV2 (SISO)	750 Mbps	300 Mbps

We can see from Table 1 that a commonality between these home-networking standards is that they have rather low PHY efficiency. The excessive PHY overheads come from several sources. All these copper-based PHYs have to operate with various EMI and RF noise sources, and therefore strong FECs are needed. This adds relatively large overhead. Since copper-based media have limited bandwidth, advanced modulation, such as OFDM, is used that add additional overhead for channel estimation, pilot tones, channel bonding, etc.

Coaxial cables are shielded media that are less vulnerable to RF noise. Needless to say, MoCA still has rather low PHY efficiency. There are many contributing factors, one is the complexity associated with the Multi-Point-to-Multi-Point topology. MoCA has a MP2MP architecture using coax cables. For a meshed MP2MP coax network using RF power splitters, some connections only experience splitting loss while other connections experience isolation loss that is normally >25dB. Take a 1X2 RF splitter for example, as shown in Fig. 5, connection A-B has a 3 dB splitting loss. In contrast, connection B-C has >25dB isolation loss since it has to cross port B and port C. Therefore, the transmitter for link BC has to have higher burst power than that of link BA. This high power transmission will cause strong reflections that behave as noise.

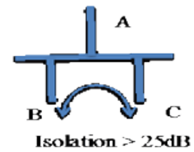

Fig. 5. Links across 1X2 RF splitter in MoCA architecture

Low PHY layer overhead is essential for media that have limited bandwidth, such as twisted pair phone line, PLC and coax cable. However, the home networking standards with all these media have rather high PHY overhead. The excessive PHY overhead further limits copper-based media for Gigabit Smart Home networking applications.

D. Air

For Wi-Fi based home networking, air or vacuum (better be air) can be considered the physical medium. The capacity of Wi-Fi for home networking is essentially limited by the available RF spectrum.

IV. FIBER IN THE HOME WITH POF

The FTTH technologies continuously evolve to higher bandwidths; Gigabit services to the home gateway are available today. The Smart Home requires high bandwidth connectivity in the home, driven by services such as cloud, 4K video, multi-room DVR, high speed Internet, Internet of Things, etc. The old home network physical media have become the bottleneck. The copper-based home networking media and standards have limitations on bandwidth and low PHY efficiency. The capacity of Wi-Fi home networking is limited by the available RF spectrum and by regulations. FITH is the natural and inevitable path to extend FTTH bandwidth within homes.

POF is the most promising solution for FITH. Compared with Glass Optical Fibers (GOF) such as Single Mode Fiber (SMF) and Multi-mode Fiber (MMF), POF has a large core diameter. For example, Step Index POF (SI-POF) has a core diameter up to 1000um that translates into low cost connectors as well as easy installations and terminations. Fig. 6 illustrates the relative diameters of POF with MMF and their capacities.

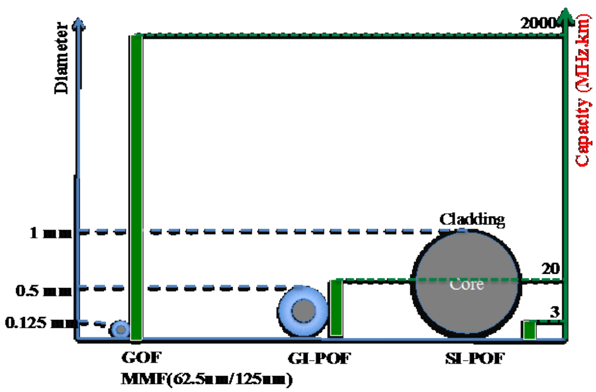

Fig. 5. Comparison of POF with MMF

The low cost POF solution for home networking is also reflected in the low cost light sources for POF transmissions. Unlike GOF, incoherent light sources such as LEDs can be used for POF transmission, which greatly reduces the cost of POF transmitters. The coupling of light sources to POF is much easier than to GOF. Vertical-cavity Surface-emitting laser (VCSEL) arrays can be used with POF for high density P2P links.

The capacity of SI-POF is around 3MHz-km, see Fig. 5. In order to achieve Gigabit rates with 50-100m distances, advanced modulation has to be used. The choice of modulation formats includes QPSK, QAM, OFDM, M-PAM, etc. Among these modulation formats, M-PAM is suitable as a low cost solution with relatively high bit/s/Hz efficiency. M-PAM is a one-dimensional code; it is much less complex than two-dimensional codes such as QAM and OFDM. Another advantage of M-PAM is that it uses low cost Intensity Modulation – Direct Detection (IM-DD) methods for transmission and detection.

The bit error rate (BER) of M-PAM can be expressed as

$$BER = \frac{M-1}{M\log_2 M} erfc\left(\sqrt{\frac{3}{2(M^2-1)}\frac{S}{N}}\right) \quad (1)$$

where M is modulation order and S/N is signal to noise ratio. Assuming BER=10^{-6}, the required S/N for 8-PAM is 26.56 dB.

The theoretical spectral efficiency of M-PAM is $2\log_2(M)$. With the consideration of FEC, the true spectral efficiency be expressed as:

$C_{PAM} = 2\log_2(M)*R$ (2)

where R is the FEC code rate. Take 8-PAM with a FEC code rate at 0.90 for example, the spectral efficiency is:

$C_{PAM} = 2\log_2(8)*0.90 = 5.40$ bit/s/Hz (3)

The Shannon limit is expressed as:

$C_{Shannon} = \log_2(1+ S/N)$ bit/s/Hz. (4)

The low boundary of S/N according to equation (4) can be expressed as

$$10\log_{10}(2^C -1) \quad (5)$$

For spectral efficiency at 5.40 bit/s/Hz, the Shannon limit gives 16.2 dB as the low S/N boundary.

The low cost M-PAM modulation with POF gives sufficient spectral efficiency for Gigabit/s home networking. When transmitting Gigabit/s Ethernet over POF, the PHY efficiency can be increased by changing the 8B/10B Gigabit/s Ethernet line code to more efficient 64B/66B line code. This alone can reduce about 25 percent PHY overhead. Optimizing FEC is another area to improve the efficiency of Gigabit/s Ethernet over POF. LDPC can be used for higher coding gain and lower overhead. In general, Gigabit Ethernet POF (GEPOF) is expected to have lower PHY overhead than that of copper-based solutions for home networking.

IEEE started Gigabit Ethernet over POF standardization in May 2014 under the 802.3 Working Group.

V. FTTH WITH FITH

Fiber in the Home with Gigabit/s Ethernet POF can be used with FTTH to extend Gigabit/s services to home networking devices.

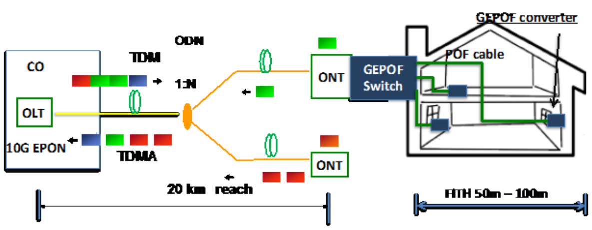

Fig. 6. FTTH + FITH solution

Fig. 6 shows the FTTH + FITH solution [13]. In this scenario a 10G EPON provides up to 10 Gigabit/s connectivity to the ONT at customer premises with Gigabit/s service to the home. A Gigabit POF switch/converter converts the Ethernet frames onto the M-PAM modulated GEPOF links to provide P2P Gigabit/s Ethernet links to the GEPOF converters in the home. At the GEPOF converters 1000BASE T interfaces are provided for Ethernet devices in the home. The GEPOF converters can be powered by DC power, or, they can be powered by Power over Ethernet (POE) from consumer devices.

FITH is a solution where P2P POF cables are terminated at the wall jacks with a 1000BASE T interface to consumer devices via a short CAT5 cable.

VI. CONCLUSION

FITH is a natural and inevitable next step to extend FTTH in order to serve the Smart Home with Gigabit/s and above bandwidths. POF is a promising physical medium for next generation home networking technologies.

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