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Research Article

A Viable Passive Optical Network Design for Ultrahigh Definition TV Distribution

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International Telecommunication Union (ITU) has recently standardized ultrahigh definition television (UHD-TV) with a resolution 16 times more than the current high definition TV. An increase in the efficiency of video source coding or in the capacity of transmission channels will be needed to deliver such programs by passive optical network (PON). In this paper, a high capacity integrated PON infrastructure is proposed to overlay ultrahigh definition television by a complete passive coexistence of 10G-PON (XG-PON) and single carrier directly modulated, duo-binary 40G-PON (XLG-PON) signal. The simulation results show error-free transmission performance and further distribution to 32 optical network units (ONUs) on broadcast basis with negligible power penalty over 20 km of bidirectional standard single mode fiber.

1. Introduction

Service providers and telecom operators are very keen to offer triple-play (video, voice, and data) service on single common broadband passive optical network (PON) infrastructure. The present cost model for optical access only reflects the broadband connections to end users but it is obvious that this fiber setup should be used to distribute the other services such as wireless access and HDTV signals. It is very important to share the high installation cost of fibers between diversified revenue streams. Therefore, the engineering and legal liability to install the fiber network must be supported by as many services as possible [1, 2]. Internet protocol television (IPTV) is becoming a common service for many IP service providers, especially for live television and for video on demand (VOD) [3]. IPTV not only provides the access to the channel programs as does the traditional TV, it also provides interactivity with the network. Moreover, it provides end-to-end service quality compared to internet video that works on "best effort" fashion with no end-to-end service management and quality of service considerations. However, the next challenge for IPTV providers is to enhance the bandwidth capacity to deliver contents in stereoscopic video, which has gained popularity for 3D vision films [4]. At present, the major concern with the IPTV service is the delay in channel selection for live broadcast TV. The channel change response time (CCRT) is defined as the time delay between a viewer asking for a channel change by pressing some buttons on a remote control unit and the display of the selected channel on the TV screen [5]. The CCRT is affected by network operations such as admission control, multicast distribution at routers, and video processing (decoding and buffering) at network elements. Network delay is the time interval that the first video frame of a requested channel arrived after the internet group management protocol (IGMP) leave/join process completed [6, 7]. Therefore, the multicast approach is causing a delay delivery of live IPTV contents. The other considerable delay is caused by computational complexity and quantization effects of decoding process at the set-top box. The H.264/MPEG-4 encoding process is employed to reduce the size of TV channel to make it adaptable for low bandwidth systems. Normally, a high definition television application compressed at a constant bit rate of 12 Mbit/s [8]. The set-top box (STB) is a device that connects to a television and

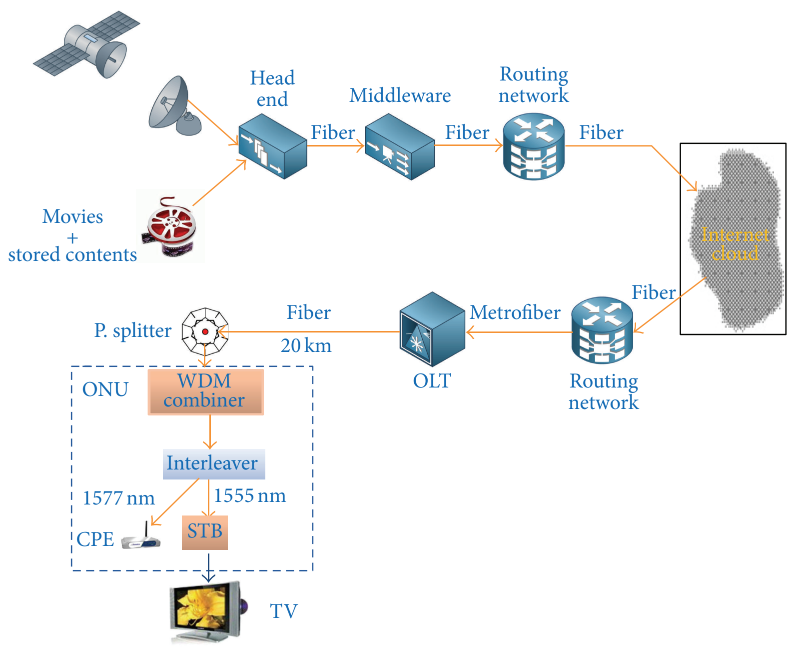

FIGURE 1: The principle diagram of typical setup of IPTV distribution.

an external source of signal, performs encoding/decoding, and provides the content which is then displayed on the television screen. It also works as a minirouter and completes the interactive functions directly through the IP packets interactive mode (HTTP, RTSP, IGMP).

The 8K UHDTV systems are expected to become available till 2017–2020 in South Korea and Japan [9]. The substantial improvement in the efficiency of video source coding or quite noticeable increase in the capacity of transmission channels will be required to deliver such programs by PON [10]. A highly complex source encoder will be required to reduce the 3 Gbit/s data rate of UHD-TV into 10–20 Mbit/s range. It may require either quite complicated processing at the set-top box or compromise on some quality features of UHD-TV. The complex processing at the set-top box will result in adding delay in channel selection. Therefore, a large bandwidth system is required to simplify the work of source encoding so that 50–100 MB/channel will easily be supported by future PON networks. Furthermore, the increase in bandwidth will also allow broadcasting of all live TV channels at the same time to reduce the channel latency problem of present multicast propagation. IPTV over GPON and GEPON is proposed [11, 12] but it is based on multicasting and legacy TV transmission.

On the other hand, the coexistence of 10G-PON and single wavelength 40G-PON is not previously proposed. A prototype network is introduced for TWDM PON on Huawei based system with intensity modulator and offline processing [13, 14], where a coexistence of 10 G and 40G PON systems are indicated, but this 40G-PON is comprised of four wavelengths of 10 G data rate as per the proposed standardization of NG-PON2. Moreover, this system is just presenting the combined propagation of XG-PON and XLG-PON, whereas their generation is by two complete different modules. In [15], some features of XG-PON1 (10G-PON) and NG-PON2 (40G-PON) are compared but the options for implementations of NG-PON2 or coexistence generation and transmission were not discussed.

In this paper, to the best of our knowledge, a novel coexistent 10G-PON and single wavelength 40G-PON with entirely passive and optical plant are demonstrated to achieve high bandwidth for overlay of UHD-IPTV. After this brief introduction, Section 2 describes the simulation setup and working principle of the architecture of our proposed scheme, Section 3 presents simulation results and analysis of these results and finally Section 4 summarizes the paper.

2. Simulation Setup and Working Principle

A typical optical transport network layout for the delivery of IPTV services is presented in Figure 1. Live television content from sources such as satellite, analog off the air, or direct feeds from broadcasters are aggregated at the head end. The middleware provides management functions, channel mapping, electronic program data, content (both music and video) on demand (COD), online games, and internet connectivity [16, 17]. This content is then distributed over the core transport network to the central offices (CO) located in metropolitans/cities. The CO further connected to optical line terminals (OLTs) through metro area fibers. To achieve very high bandwidth for delivery of UHD-IPTV, a proposed schematic architecture of coexistent XG-PON and single carrier XLG-PON is shown in Figure 2. In this scheme, an optical line terminal (OLT) connected to the remote node (RN) by 20 km of standard single mood fiber to deliver multimedia services to 32 ONUs. The OLT consists of an optical duobinary XLG-PON downstream transmitter

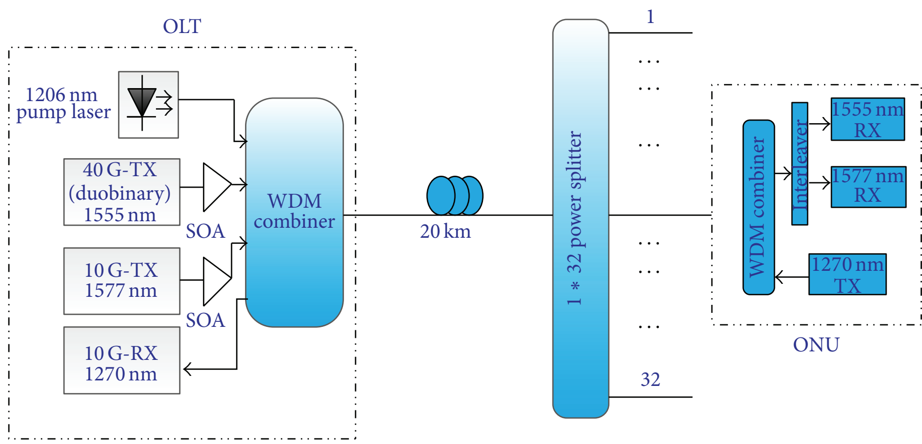

Figure 2: The schematic diagram used for coexistence generation and transmission of XG-PON and XLG-PON.

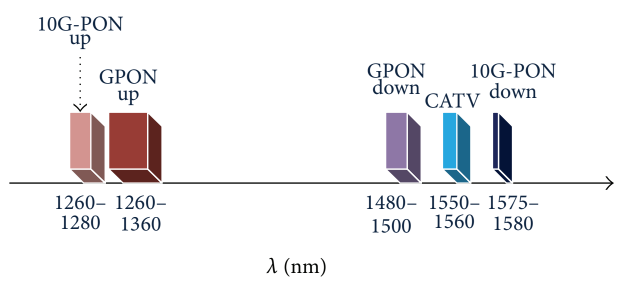

Figure 3: ITU bandwidth specifications for GPON and XG-PON.

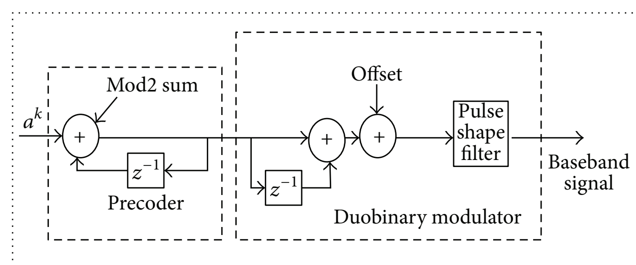

Figure 4: Duobinary modulation encoding schematic diagram.

at 1555 nm, a distributed feedback laser (DFB) at 1577 nm as XG-PON downstream transmitter, and avalanche photo diode (APD) as XG-PON upstream receiver. A pump laser is also added at OLT to boost XG-PON upstream signal to avoid the insertion of amplifier at subscriber end. The pump laser is coupled into the feeder fiber to provide the distributed Raman gain for upstream XG-PON signal band (1260–1280 nm) at wavelength 1206 nm. The choice of wavelengths is made to ensure compatibility with the wavelength band specifications for XG-PON and GPON signals as defined in ITU-T standards [18, 19], also depicted in Figure 3.

For high-speed optical 40 Gbit/s XLG-PON link, chromatic dispersion (CD) limits the transmission distance to a few kilometers without dispersion compensation [20]. In this setup, a three-level intensity duobinary modulation is applied to reduce the impacts of chromatic dispersion for XLG-PON to avoid the need for dispersion compensation modules in access network. A duobinary coding process is illustrated in Figure 4. The power spectral density of duobinary signals is more concentrated around the optical carrier resulting in reduced bandwidth requirements for the system that helps to increase CD tolerance about three times more than nonreturn to zero (NRZ) [21]. The duobinary data can be generated at the transmitter by sending NRZ data through a "delay and add" filter, which has a z-transform of $1 + z^{-1}$ and can be approximated by a low-pass filter [22]. The precoder involves a delay of $2T_b$ seconds:

$$c_k = a_k - a_{k-2}. \tag{1}$$

We get an overall frequency response of

$$H(f) = \begin{Bmatrix} 2j\sin(2\pi f T_b)\exp(-j2\pi f T_b) \longrightarrow |f| \leq \dfrac{1}{2T_b} \\ 0 \longrightarrow \text{eleswhere} \end{Bmatrix}. \tag{2}$$

The modified duobinary coder consists of the impulse response of two sinc pulses that are time-displaced by $2T_b$ seconds with each other:

$$h(t) = \frac{2T_b^2 \sin(\pi(t/T_b))}{\pi t(2T_b - t)}. \tag{3}$$

To eliminate the possibility of error propagation, data can be precoded propositionally:

$$d_k = b_k \oplus d_{k-2}. \tag{4}$$

A 10 GHz low-pass filter is used to generate 40 Gbps duobinary signal in this simulation setup. The distributed feedback laser diodes (DFB LDs) is modulated at 10 Gbit/s (2^{31-1})

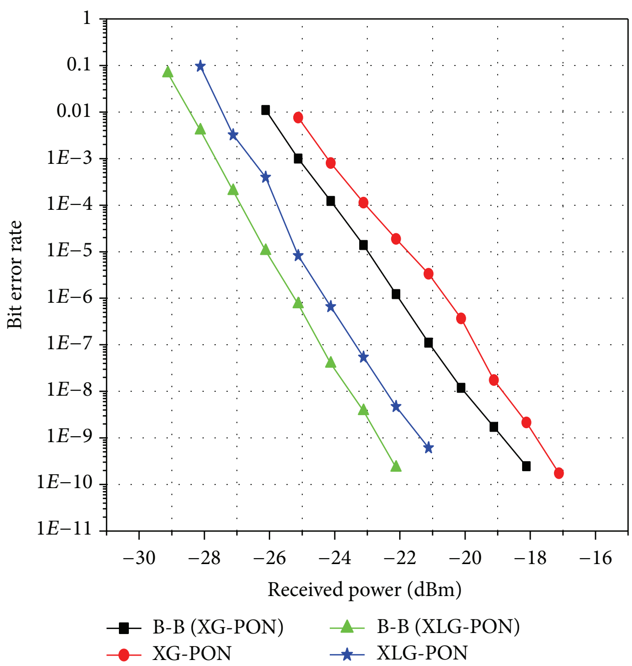

Figure 5: Downstream bit error rate as a function of received power back to back signal and after 20 km propagation of XG-PON and XLG-PON.

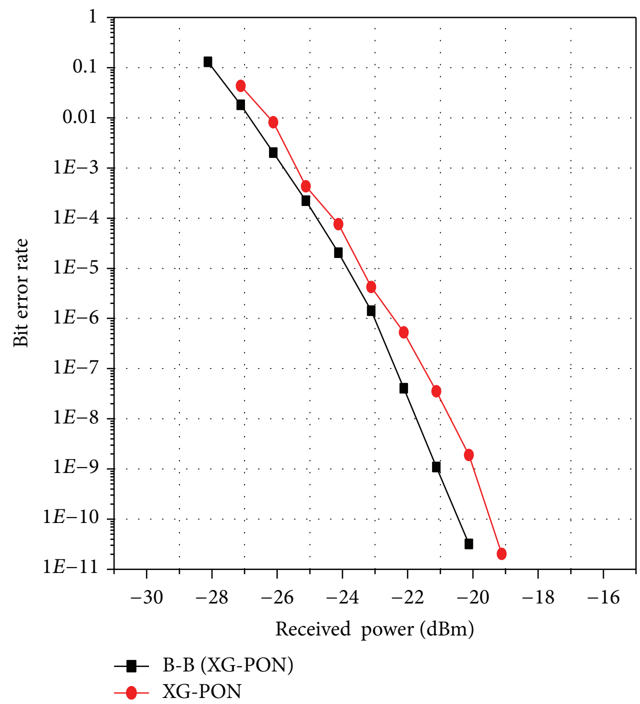

Figure 6: Upstream bit error rate as a function of received power for back to back and 20 km propagation of XG-PON.

pseudorandom binary sequence (PRBS) using pattern generator (PG) to operate at 1577 nm used as the XG-PON downstream transmitter. The chirp $\Delta v(t)$ of a directly modulated laser (DML) is related to the laser output optical power $P(t)$ through the expression [23]

$$\Delta v(t) = \frac{\alpha}{4\pi}\left(\frac{d}{dt}[\ln(P(t))] + \kappa P(t)\right), \tag{5}$$

where α is the line-width improvement factor and κ is the adiabatic chirp coefficient. The output power $P(t)$ is interrelated to the photon density $S(t)$ through the relation

$$P(t) = \frac{V\eta hv}{2\Gamma\tau_P} S(t). \tag{6}$$

The photon density $S(t)$ is calculated by the small signal, single mode laser rate equations in this simple form

$$\begin{aligned}
\frac{dS(t)}{dt} &= \frac{\Gamma g_0 (N(t) - N_0)}{1 + \varepsilon S(t)} S(t) - \frac{S(t)}{\tau_P} + \frac{\Gamma \beta N(t)}{\tau_C}, \\
\frac{dN(t)}{dt} &= \frac{I(t)}{eV} - \frac{N(t)}{\tau_c} - \frac{g_0 (N(t) - N_0)}{1 + \varepsilon S(t)} S(t), \\
\frac{d\phi}{dt} &= \frac{\alpha}{2}\left[\Gamma g_0 (N(t) - N_0) - \frac{1}{\tau_P}\right],
\end{aligned} \tag{7}$$

where $I(t)$ is the current waveform injected in the active layer, $N(t)$ is the carrier density, v is the optical frequency, h is the Plank's constant, η is the differential quantum efficiency, Γ is the confinement factor, N_0 is the carrier density at transparency, β is the fraction of spontaneous emission noise coupled into the lasing mode, g_0 is the differential gain coefficient, ε is the nonlinear gain compression factor, τ_p is the photon lifetime, τ_c is the carrier lifetime, and V is the volume of the active layer. One has

$$\kappa = \frac{2\Gamma}{\eta h v V}\varepsilon. \tag{8}$$

Hence, to compensate the losses at high data rates, two low-cost semiconductor optical amplifiers (SOAs) for XG-PON and XLG-PON are integrated with downstream (DS) transmitters at the OLT into the feeder fiber to boost down signal powers, respectively. A WDM combiner is employed to combine the XG-PON and XLG-PON downstream signals along with Raman pump laser. After 20 km propagation, a 1 $\simeq$ 32 power splitter is used to serve 32 ONUs on power sharing basis in downstream. A built-in fiber Bragg grating (FBG) in WDM combiner is able to filter out undesired Raman ASE noise outside of the US signal bands to improve the transmission performance and mitigate the Raleigh back scattering impacts [24, 25]. At optical network unit (ONU), an optical interleaver is used to separate the optical power of UHD-TV overlaid XLG-PON from XG-PON signal. Two Bessel filters of order one and bandwidth of 10 GHz at central wavelengths of 1555 nm and 1577 nm, respectively, are applied to reduce the noise before bit error rate estimation. After photo detection, XLG-PON signal is brought to the television set using a set-top box (STB) that decrypts the signal and assembles the packet information into a viewable program to further convert IP packets into TV contents.

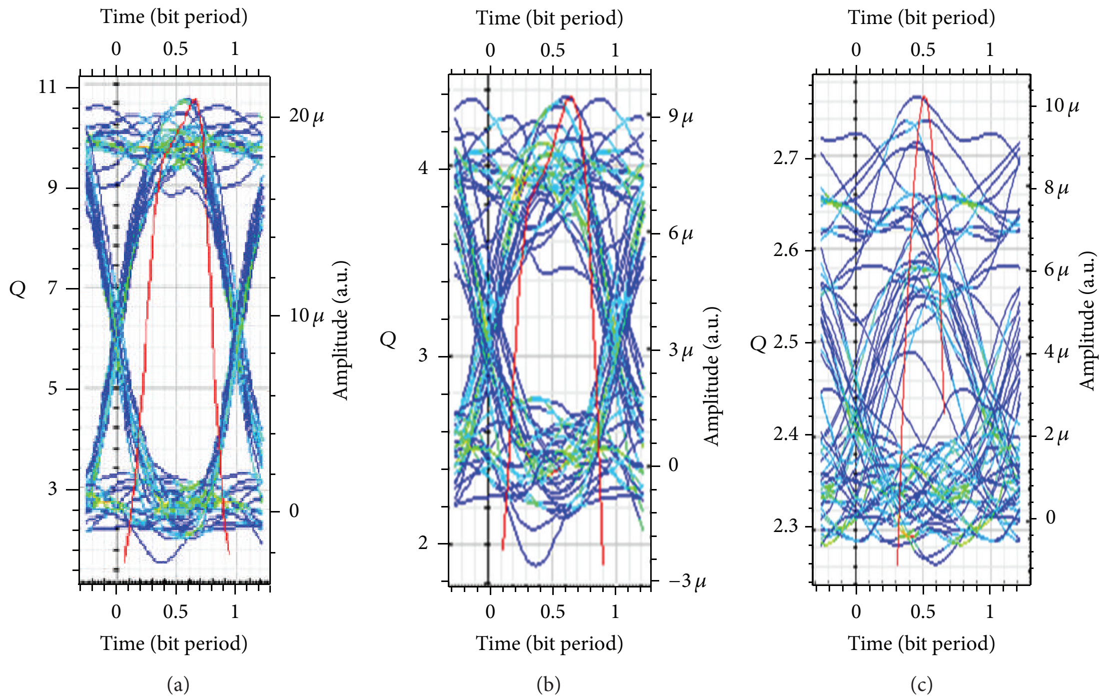

FIGURE 7: Simulated eye diagrams of the data demodulated for (a) DS XG-PON, (b) US XG-PON, and (c) XLG-PON signals after 20 km transmission.

In uplink, an electroabsorption modulated laser at 1270 nm is used as XG-PON upstream transmitter. The upstream EML is modulated at 10 Gbit/s (2^{31-1}) PRBS using a PG with output power 0 dBm at 1270 nm. A 10 G APD with a band-pass filter is used as XG-PON upstream receiver at OLT to receive US signal. Since only passive splitter is used at RN, the outside fiber plant is entirely passive.

3. Simulation Results

The simulation work is performed to testify the coexistence generation and transmission of XG-PON and XLG-PON signals. The power for 1206 nm pump laser was fixed at 500 mW that was optimized to ensure 10G-PON error-free upstream operation. The bit error rate (BER) as a function of received optical power for downstream transmission for XG-PON and XLG-PON signals back to back and 20 km reach with total 1 : 32 split is shown in Figure 5. For 1577 nm downstream, there was about 1 dB power penalty after 20 km transmission with total link loss of 34 dBm, while XLG-PON has shown the power penalty of 1.3 dB with link loss remaining at 37 dBm. In upstream, a power penalty of 1 dB for XG-PON relative to back to back experienced at BER of $1E$-9 after propagating the distance of 20 km is shown in Figure 6, whereas clear eye diagrams after downstream XG-PON and XLG-PON and upstream XG-PON after 20 km traversal are shown in Figure 7. Therefore, it is evident from the above results that an error free transmission has been achieved for both downstream and upstream direction. In this scheme, 1555 nm 40G signal is propagated only in downstream with enough bandwidth to support live broadcast of many hundreds UHD-IPTV channels without involving very reduced compression ratios. The IPTV services like VOD, community TV, time shift television, parent control, electronic program guide that requires backward communication with the network operator and service provider for service selection, termination, and payment information can be accommodated by reserving some bandwidth on upstream 10G-PON. However, this backward communication ability can be easily provided by reserving some bandwidth on upstream 10G-PON. If separate wavelength is dedicated for backward communication, it will not only be a wastage of network resources but also incur a huge extra cost.

4. Conclusion

This coexistence scheme of XLG-PON and XG-PON can be used for the overlay of UHD-IPTV for simultaneous transmission of hundreds of channels at almost unnoticeable delay and quite less processing involved in set-top box. Therefore, it is a bright opportunity to provide the live UHD-TV service with no latency and with all the existing and future auxiliary services of IPTV with minimum cost involved in ONU.

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