Performance Analysis of High Speed Bit-Interleaving Time-Division Multiplexing Passive Optical Networks (TDM-PONs)

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Abstract. Time-division multiplexing passive optical networks (TDM-PONs) considered as a good solution for a high bit rate and flexible bandwidth system. In this paper, the simulation of a new bit-interleaving TDM transmitter has carried out. The proposed scheme of downstream TDM-PON based on single Mach–Zehnder modulators (MZM) and single laser diode to carry an electrical multiplexed data providing cost effective, high-transmitted power and easy implementation system. The TDM-PON technique has seen widespread since the beginning of this century, especially with FTTH where flexible bandwidth and high bit rate are required. Hence, the simulation of 10, 25, 40, and 50 Gbps TDM-PON have been presented in three scenarios based on two downstream transmitter schemes of FTTH. Those scenarios have carried out the standard single-mode fiber (SSMF) and the free-space optic (FSO) as transmission media, and the single mode dispersion compensating fiber (DCF) and Fiber Bragg Gratings (FBG) as dispersion compensators. The results show that the electrical multiplexed scheme of TDM transmitter provides better performance with the comparison of the traditional optical TDM transmitter in different scenarios with different bit rates.

Keywords. Time-division multiplexing passive optical networks (TDM-PON), bit interleaving PON (Bi-PON) dispersion compensating fiber (DCF), Fiber Bragg Gratings (FBG), Free Space Optics (FSO).

1. Introduction

A good quality access to services become the purpose objective of each operator, the optical networks system can ensuring a good performance for such a system of large number of users. TDM-PON (e.g. GPON and EPON up to 10G PONs) have been widely deployed around the world to provide the needed transmission capacity. The capacity demand growing led to need of future generations of the TDM-PON based on 25 Gbps or higher e.g. IEEE P802.3ca standard that suggested to be implemented by using TDM-PON 25 or 50 Gbps for a single wavelength (as of this writing, the IEEE P802.3ca standard is not published yet)[1]. TDM-PON is a technique that combine multiple user’s data rate channels into a single wavelength channel of a high bit rate and time based multiplexing. This multiplexing technique provides many advantages like management effort reduction, less complexity of end node equipment, power consumption, non-linear effect overcome, and cost [2]. However, as new applications (like IPTV, video on demand and High Definition online video game) turn into being more popular, the bandwidth demand is rapidly growing, which is pushing to increase the limited capacity of the traditional TDM-PON, because the capacity is shared for all users by a single
wavelength (e.g. 1:256 split ratio). So a higher capacity system is required to satisfy future optical access networks. There are some challenges to initiate high speed transceivers in a TDM-PON include: the dispersion effects, time synchronization and the simultaneous additional bit rate demand [3].

In a communication system, higher data rate transmission is always a goal for the researcher. R. Kaur and Anjali have proposed a TDM-PON system providing flexible bandwidth and higher bit rate with two types of modulation format. Modified duobinary return to zero (MDRZ) and return to zero (RZ) were carried out there, the comparison results of Q-factor value between these technologies show that TDM-PON system with MDRZ without using repeater has more transmission distance than the system with RZ technology. Where the transmission distance of an acceptable bit error rate (BER) is only up to 300 km in the RZ TDM-PON [4].

D. Veen and V. Houtsma experimentally reported a 25 and 50 Gbps TDM-PON with different modulation formats in 2016 [5]. A bi-directional 25G/50G TDM-PON system was experimentally tested by the same researcher (D. Veen and V. Houtsma) in 2017. They have used a single carrier 25 Gbps for the upstream and 50 Gbps for the downstream using a commercial 25G APD receiver with duobinary, where a simple 3x3 fiber splitter has used for the coherent detection scheme of a NRZ On-Off-Keyed (OOK) signal [6].

In this paper, to the best of our knowledge, a new TDM-PON transmitter scheme has proposed as a convenient system to the fiber-to-the-home (FTTH) downstream as well as fiber-to-the-building (FTTB) or fiber-to-the-distribution point (FTTdp) upstream and downstream. In addition, this paper demonstrates a comparison between different bit rates of two architectures at the transmitter side in the optical line terminal (OLT) FTTH network linked either SSMF or FSO. The results obtained by Optisystem 7.

2. TIME-DIVISION MULTIPLEXING PASSIVE OPTICAL NETWORK (TDM-PON) SYSTEM

Two methods are used for TDM-PON: the first involves packet interleaving while the second one involves bit interleaving.

2.1. Packet interleaving (Packet-by-Packet transmission)

The packet interleaving TDM-PON, where number of bits grouped together and targeted to a particular optical network unit (ONU), has used for downstream by both two bodies standard (IEEE and FSAN/ITU-T) of PONs, where data is sending to various users by a single downstream optical carrier in assigned slots form, as in Figure (1). While the upstream packets of TDM system are sent from an ONU in an individual time slot at the splitter, which requires careful synchronization at the ONUs, as shown in the Figure (2). To ensure collision-free transmission the data of each ONU should be sent at the right time instant. Practically there is a different relative distance between the ONUs and the OLT. Hence, the using of ranging protocols are essential, round-trip time (RTT) can be used to sense this distance. In the OLT, a burst mode receiver is required, which can handle different levels of the amplitude of the received packets (this amplitude fluctuation due to the path loss experienced difference). Initially, with time division multiple access PONs (TDMA-PONs), as the ONUs are sharing the capacity of OLT, this capacity of each ONU decreases with an increase in the ONUs number. However, modern TDMA-PONs can adjust each optical network terminal (ONT) bandwidth dynamically depending on the demand of the customer.
2.2. Bit interleaving (Bit-by-Bit transmission)

In the bit interleaving PON (Bi-PON) all information bits are reorganized in a form of bit-interleaved style according to the targeted ONUs in a regular structure frame, where each ONU can extract its own information easily in a simple periodic style. Bi-PON has reduced the number of functional blocks, which are necessary to operate at full line transmit. Hence, significantly lower dynamic power consumption will be required in a Bi-PON ONU [7].

An Optical power source, as illustrated in Figure (3), generates the periodic pulse train of Bi-PON, and by using a splitter to split this pulse stream to K of pulses, then data encoded signals will modulate over those light pulses by external modulator. Optical delay of it will delay each pulse train. If framing pulses are used, at that point, the interpulse width is \( \tau = T/(n + 1) \) since \( n + 1 \) pulses should be transmitted in each bit period.
3. DISPERSION COMPENSATION TECHNIQUES

Dispersion compensation is a critical point in the high capacity systems. Narrow time slot between the ONU’s pulses makes the TDM-PON very sensitive to the dispersion effect. Hence, two dispersion compensation techniques will discuss where those techniques are implemented in such a system to enhance its tolerance and performance. The first one based on alternating fiber that has negative dispersion value of the first used one, named dispersion-compensation fiber (DCF) or negative-dispersion fiber (NDF). The second technique using Fiber Bragg Gratings (FBG) filter to inverse the dispersion.

3.1. Dispersion compensation using single mode dispersion compensating fiber (DCF)

The dispersion compensation using negative-dispersion fiber known as dispersion compensating fiber (DCF), the Figure (4) illustrates the chromatic dispersion characteristic where a null accumulated dispersion is achieved by inserting a suitable length of DCF with the standard single-mode fiber (SSMF). The DCF length is much less than SSMF length because of the often large absolute negative dispersion of DCF (around −300 ps nm$^{-1}$ km$^{-1}$). Hence, zero overall dispersion will be acquired at the wavelength of 1.55 μm on the transmission channel [8].

![Figure 4. Dispersion compensation by using dispersion-compensating fiber (DCF)](image)

There are three algorithms are possible for dispersion compensation schemes using DCF: pre-compensation algorithm where the DCF is placed before the SSMF, the second algorithm is post-compensation where SSMF is placed before the DCF, and the last one is the mixed compensation algorithm where the DCF placed in both before and after the SSMF. By comparison, the mixed compensation method gives the best performances [9].

3.2. Dispersion compensation using Fiber Bragg Gratings (FBG)

The use of the fiber Bragg gratings have seen significant growth in modern optical communications systems. The operation of the FBG depending on facilitating reflections of different wavelengths, where at each interface between the Bragg regions a portion of the power of signal is reflected back, the principle FBG operation shown in the Figure (5). The total reflection can increase to be about 100% reflection of a wavelength and passing all others if the spaces between those regions are arranged in such a way to make the partial reflections be constructively in phase [7]. As a cost effective passive optical component with low insertion losses the FBG has used as a dispersion compensation in the fiber optical transmission systems.
4. SYSTEM DISCRPTION

The proposed designs of four ONUs TDM-PON will be evaluated for different bit rates and optical media lengths. Two methods have been used in the OLT of the system for downstream (the OLT is a transmitter). The first one, as shown in Figure (6), consist of a laser diode (wavelength of 1552nm, line width 100 KHz and 5 dBm power), power splitter to divide the optical signal, four external modulators, and four optical delays with time delay of \( \frac{i}{K \times \text{bit rate}} \) where \( i = 0, 1, \ldots, K-1 \) to make each destination data able to be transmitted at a specific time slot. The second system is a new multiplexer which proposed to enhance the transmitted power and reduce the optical components, connectors and optical fibers inside the OLT, where four electrical delays have used with a combiner then a single modulator and single unshared light source will modulate the multiplexed signal, as shown in Figures (7). Both TDM-PON systems consist of a pseudo-random bit sequence (PRBS) generator and a return to zero (RZ) pulse generator used to generate the data of each user.

![Figure 6](image-url)
Figure 7. The schematic block diagram of TDM-PON with one MZM, the transmission media is FSO.

At the receiving side, the optical signal that has passed through a specific channel goes to an optical power splitter to be divided for many copies; each one of those signal copies has entered into an ONU subsystem detector to extract the original information. In the de-multiplexing operation, a time delay and clock-recovery should be used to receive the custom signal for this user, as in Figure (8). Subsequently, by PIN diode photodetector (dark current 5 nA, responsivity of 1 A/W and thermal noise 1.8e-024 W/Hz) the optical signal will be converted to an electrical signal with the help of a low pass filter (LPF) of cut-off frequency 0.75*Bit rate.

Figure 8. The schematic block diagram of ONU subsystem.

Finally, a 3R-Regenerator will be used to generate the original bit sequence of the data, and the modulated electrical signal of the RZ pulse generator to be used for BER analysis, which measures Q-factor value and BER. Where the Q-factor can evaluate the qualitative-performance of a receiver. The Q-factor can be calculated by:

\[
Q = \frac{i_{H}-\gamma_{opt}}{\sigma_{iH}} = \frac{\gamma_{opt}-i_{L}}{\sigma_{IL}} \quad (1)
\]

\[
Q = \frac{i_{H}-i_{L}}{\sigma_{iH}+\sigma_{IL}} \quad (2)
\]

\[
BER = erf c(Q) \quad (3)
\]

Where \(\gamma_{opt}\) optimal value of the decision level, \(i_{H}\) and \(i_{L}\) are the current corresponding to the optical power level on the photodetector for both log.1 and log. 0 levels.
In this paper, to evaluate the proposed TDM-PON system performance three scenarios have used for the channel. The first scenario is an SSMF of the attenuation coefficient of 0.2 dB/km, dispersion 16.75 ps/nm/km, non-linearity refractive 2.6e-20 m2/W and dispersion slop 0.075 ps/nm2/km with using FBG filter as a dispersion compensator and without using an amplifier, as in Figure (6). The second scenario is long optical fiber distance consists of a sequence of SSMF/DCF/SSMF with appropriate lengths that ensure almost zero chromatic dispersion, as in Figure (9). To reach a long distance optical power amplifiers must be used to compensate the power dissipated by the fiber. In this work, erbium dopped fiber amplifiers (EDFAs) of 4 dB noise figure and 22 dB gain have been used. The DCF of attenuation coefficient of 0.5 dB/km and dispersion (DDCF) of -170 ps/nm/km have used in this work. Where the total compensation of the dispersion (DT) should be equal to zero for a certain length of the DCF (LDCF), to compute this length the following expression can be used [10].

\[ D_T = D_{\text{SMF}}L_{\text{SMF}} + D_{\text{DCF}}L_{\text{DCF}} = 0 \]  
\[ L_{\text{DCF}} = -\frac{D_{\text{SMF}}L_{\text{SMF}}}{D_{\text{DCF}}} \]

Where \( L_{\text{SMF}} \) and \( D_{\text{SMF}} \) are the length and the dispersion of the SMF respectively.

![Figure 9. The schematic block diagram of long reach TDM-PON over 440 Km, dispersion compensation based on DCF](image)

The third scenario of the optical transmission media is the FSO as in Figure (7), where there no dispersion occurs and large attenuation relative with the atmospheric conditions like haze, rain, hot and dry which are dramatically effect on the power received as it clear in the equation (6). More losses can also increase the attenuation of FSO channel due to mispointing, scintillation and other perturbations can be defined as additional losses [11]. However FSO system provides good advantages, like the initiation cost, deployment time and low maintenance cost, making it a good alternative solution for the last mile connection where using an optical fiber cable is difficult [12].

\[ P_{\text{Received}} = P_{\text{Transmitted}} \frac{d_R^2}{(d_T + \theta R)^2} 10^{-aR/10} \]  

Where \( d_R \) is the receiver aperture diameter, \( d_T \) transmitter aperture diameter, \( \theta \) beam divergence (mrad), \( a \) atmospheric attenuation (dB/km) and \( R \) is the range in km.
5. RESULTS AND DISCUSSION

To evaluate the performance of the proposed dispersion compensators of TDM-PON system, a comparison of dispersion compensation based on FBG and DCF by eye diagrams are considered as shown in Figures (10) and (11), with same parameters of transmitters, channels (SSMF range of 110 Km without amplifier) and receivers. It can noted that the RZ TDM-PON system with dispersion compensation based on DCF gives better performance than the RZ TDM-PON system with dispersion compensation based on FBG because eye in Figure (11) has the larger eye opening. In the eye diagram, the more open the eye is, the easier the distinction between ones and zeroes of the received bits. In other words, as the received pulses are more distorted in either phase or amplitude the eye will appear more closed.

Figure 10. Eye diagram of RZ TDM-PON system with 25 Gpbs, SSMF range of 110 Km without amplifier, and FBG as dispersion compensator.

Figure 11. Eye diagram of RZ TDM-PON system with 25 Gpbs, SSMF/DCF/SSMF range of 110 Km without amplifier, and DCF as dispersion compensator.
Figure (12) illustrates the relation between the Q-factor performance versus optical fiber distance of the first scenario of the channel, where four users linked to the OLT by SSMF without any amplifier and using FBG filter as a dispersion compensator. Two type of transmitter have been used in the OLT (downstream), the first has used four MZM as an external modulator to modulate data toward four users while the second one used only single MZM for all those users as it mention above. This Figure shows that the first system (TDM-PON with transmitter of 4MZM) gives lower performance than the second system with 1MZM at 10 Gbps where the launched power is higher even that same laser diode with power of 5 dBm has used for both systems. In this second system different bit rates were also evaluated as shown in Figure (12), the signal of 25 Gbps per line (100 Gbps TDM) stays above the acceptable level for about 92 Km without amplifier which gives better performance than 40 Gbps, while the 50 Gbps was the worst where low Q-factor even with short distances. From the results in this graphical representation it can be noted that the increase of the bit rate leads to reduce the Q-factor at the same fiber length.

![Figure 12. Comparison Q factor Performance versus optical fiber distance for different bit rate and both TDM-PON proposed systems with FBG (four users)](image)

Figure (13) illustrates the relation between the Q-factor Performance versus optical fiber distance of the second scenario, where four ONUs linked to the OLT by long range of SSMF with EDFA amplifier of 4 dB noise figure and 22 dB gain and with using DCF as a dispersion compensator. Also in this scenario, the TDM-PON of transmitter of one MZM gives better performance than the system that used single laser and individual MZM per user at the same distance and bit rate. It can be noted from this figure that the high bit rate signals do not reach long distances despite the existence of dispersion compensator, where this steep drop in the Q-factor with the comparison to the performance of 10 Gbps TDM-PON due to the effect of dispersion is more in a high bit rate systems.
Figure 13. Comparison Q factor Performance versus optical fiber distance for different bit rate and both TDM-PON proposed systems with DCF and EDFA (with four users)

In the result FSO system, as shown in Figure (14), it can be noted that the increase of the bit rate does less Q-factor decrement than SSMF system because in the FSO system the light travels through the atmosphere instead of fiber so there is no dispersion occurs and only an attenuation can affect the light signal. As the attenuation is varying with the climate change, a large variation will occur to the power of received signal, in this simulation a heavy rain attenuation of the FSO link are considered. Also it can noted that the worst case is a 10 Gbps with single laser diode shared to four users and four MZM system where the launched power is less than others, on the contrary the best performance was for 50 Gbps with EDFA amplifier. Hence the authors recommend to use an optical amplifier before transmit the signal through the free space.

Figure 14. Comparison Q factor Performance versus FSO distance under heavy rain for different bit rate and both TDM-PON proposed systems (simulated with four users)
6. CONCLUSION

The worldwide spread of the TDM-PONs with the capacity demand growing and the fact of bit rate increasing that causes a decrease in the Q-factor led to the need to rely on the bit rate higher than 10 Gbps TDM. Hence, 10, 25, 40, 50 Gbps bit-interleaving TDM-PON have been simulated in three scenarios based on two downstream transmitter schemes of FTTH. The proposed scheme of TDM transmitter that use a single MZM and laser diode to carry the data of multiuser, which has cost effective, high-transmitted power and easy implementation system, provides better performance in the TDM-PON linked by SSMF with DCF or FBG as a dispersion compensation and provides much better performance in the FSO system based on different bit rates. The simulation results of the FSO, where there is no dispersion occurs, have shown that the 50 Gbps TDM-PON with EDFA amplifier is better presented than 10, 25 and 40 Gbps without amplifier. In contrast, TDM-PON with the SSMF based on a wavelength of 1550 nm, the 50G TDM showed poor performance even with the addition of an amplifier. Hence, the authors recommend using more complex modulation techniques than RZ and NRZ, more sensitive receiver and using a wavelength within O-band where there is a zero dispersion wavelength (ZDW) for a TDM-PON of 50 Gbps per channel.

7. References

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