Performance evaluation and enhancement of dense wavelength division multiplexing passive optical network DWDM-PON cross-seeding system with Rayleigh backscattering mitigation

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Performance Evaluation and Enhancement of Dense Wavelength Division Multiplexing Passive Optical Network DWDM-PON Cross Seeding System with Rayleigh Backscattering Mitigation

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ABSTRACT. In this paper, a dense wavelength division multiplexing passive optical network (DWDM-PON) using cross seeding system is designed and evaluated. This system utilizes 16 channels with low channel spacing of 12.5 GHz. Upstream (US) capacity is enhanced to 2.5 Gb/s over 25 km single mode fiber (SMF) transmission. This optical network has a downstream (DS) capacity of 10 Gb/s. A noteworthy average bit error rate (BER) of $10^{-13}$ is achieved during system evaluation process. A successful mitigation for Rayleigh backscattering (RB) is achieved comparing to conventional bidirectional wavelength division multiplexing passive optical network (WDM-PON).

Keywords: BER, Cross Seeding, DWDM, PON, RB.

1. INTRODUCTION

Today, standard time division multiplexing (TDM) passive optical network (PON) is used in many countries. TDM-PON splits the optical power over a limited number of users based on synchronized time slot in which all the users share the same bandwidth. With the increase of demands for advanced multimedia applications, TDM-PON becomes insufficient enough for the high data rate that required for each user [1]. To meet the rapid growth in bandwidth requirements wavelength division multiplexing-passive optical network (WDM-PON) is the best choice in the near future next generation network, which achieves the full usage of bandwidth by assigning for each user its own wavelength which creates a virtual connection between the central office (CO) and the user terminal. As a result, a high bit rate can be reached to each user [2]. A dense wavelength division multiplexing passive optical network (DWDM-PON) is considered as the future of ultra-capacity networks that essentially increase number of channels by decreasing the channel spacing. Optical network also requires remarkable low cost optical network unit (ONU) colorless operation [3]. Also, an efficient utilization of the wavelength is another important requirement [4].

To meet low cost ONU colorless operation, several techniques, devices and architectures are proposed, tested and evaluated. A famous technique to meet these requirements is reflective transmitters using 1) injection-locked Fabry-Perot lasers (FP-L) [5], 2) reflective semiconductor optical amplifier (RSOA) [6], 3) semiconductor optical amplifier (SOA) with a reflective electro-absorption modulator (R-EAM) [7]. However, reflective transmitter that utilizes FP-L requires polarization and temperature control, which adds complexity [5]. These techniques that use RSOAs suffer from limited bit rate ~ 1.25 Gb/s due to internal noises and nonlinearities [8]. Finally, any colorless ONU that uses SOA R-EAM, suffers from chromatic dispersion and high interference in the signal due to the wide bandwidth of R-EAM [9]. As a result, the reflected transmitter technique generates a large level of the RB which affects the signal received at CO [10].

Through this paper, an RB mitigation DWDM-PON with cross seeding architecture is simulated, tested and evaluated using OptiSystem simulator. The future of channel spacing in ITU-T G.694.1 Standard for DWDM (i.e. 12.5 GHz) is
successfully achieved with a reasonable channel interference [4]. Enhancing the network channels capacity with high effective wavelength utilization, improving US and DS bit rate, minimizing active components and maintaining remarkable BER performance with low cost ONU are the main the targets of this work.

The remaining of this paper is classified as follows: basic cross seeding system’s design, architecture and operation principle are demonstrated in Section 2. Detailed system architecture and parameters are presented in Section 3. In Section 4, tracing, testing and system evaluation are carried. Section 5 is a comparison of the obtained results in our work with related recent works. The main conclusions are introduced in Section 6.

2. SYSTEM DESIGN, ARCHITECTURE AND OPERATION PRINCIPLE

The proposed high capacity DWDM-PON system based on the modified cross seeding architecture is shown in Fig. 1. The basic system structure, operation description and design enhancements for this work are illustrated. The optical line terminal (OLT) can be divided into four stages as illustrated in Fig. 1:

- Stage 1 represents the input light source, which consists of eight continuous wave (CW) light sources. They have wavelength spacing 25 GHz combines together to be forced into stage 2.

- At stage 2, the optical light sources are utilized to generate subcarriers by using double sideband optical carrier suppression technique (DSB-OCS) [11]. In our work, the DSB-OCS technique is used to increase the system capacity to a record of eight light sources with 16 subcarriers (i.e. channels) by decreasing channel spacing to 12.5 GHz. Each sideband (i.e. subcarrier) acts as centralized light source (CLS) to be remodulated as US signal. Generally, DSB-OCS has a high receiver sensitivity with small power penalty [12]. Also, in this stage, EDFA is used.

- The subcarriers are demultiplexed as odd and even subcarriers to be ready for the transmission through the two-bidirectional feed fiber 1 (FF1) and feed fiber 2 (FF2), respectively. This part of operation takes place at stage 3. In our work, this function in this stage is done with much lower complexity compared to related literatures that utilize cross seeding technique [13], [14], without affecting the performance as will be described later in Section 4.

- Then, each odd and even subcarrier is modulated by on-off key (OOK) modulation at stage 4. OOK is the simplest modulation format and relatively inexpensive. For this reason, it is used to meet the ONU requirement as mentioned before. The transmitter (Tx) consists of a CW laser source with a frequency of 193.025 THz and an output power of 8 dBm. It is externally modulated at 10 Gb/s with a non-return to-zero (NRZ) pseudorandom binary sequence in a Mach–Zehnder modulator (MZM) with a 30 dB extinction ratio. NRZ format has been widely implemented, mainly because of its signal bandwidth and its relatively easy generation [15]. Stage 4 contains also a receiver (Rx) of the US signal. A PIN photodetector is used with low pass filter (LPF) to demodulate the US signal. The PIN specifications are 10 nA dark current and 1 A/W responsivity. The same Tx and Rx will be used again in stage 7. The odd DS signals are multiplexed to be transmitted through FF1. Similarly, it is repeated for even DS signal over FF2.

- Stage 5 represents the core of cross seeding technique that mitigates the RB. This is done through transmitting the odd DS signals after remodulation (i.e. stages 6, 7) as a US stream through FF2 as indicated in Fig. 1. The same procedure will be applied to even DS signals but with passing through FF1 after re-modulation. Recall that transmission through conventional full duplex bidirectional techniques suffers from huge level of RB [16] that forces researchers to find solution as indicated in Section 1.

- Finally, at stage 6, the RN consists of two multiplexers (MUX) and two demultiplexers (DeMUX). The MUX and DeMUX are simpler and lower cost than the array waveguide grating (AWG) which is a complex component that consists of coupler and fiber grating [17]. Txs and Rxs are used for demodulation/re-modulation in stage 7 after the received signal is split by 20:80 coupler. The 20% of the signal power is used to extract the DS information by using the same receiver structure mentioned in stage 4. The remaining 80% of the signal power is used for re-modulation the US by OOK and its structure is mentioned in stage 4. Saving AWGs, internal feed fiber and RSOA is a merit for this work design compared to any related literatures that utilize cross seeding technique [13], [14].
Fig. 1 The system architecture. DeMUX: demultiplexer, MUX: multiplexer, Tx.: transmitter, Rx.: receiver.

3. EXTENDED SYSTEM ARCHITECTURE AND PARAMETERS

The proposed cross seeding based DWDM-PON system is presented with more details in Fig. 2. The stages that are presented in Fig. 1 are re-introduced with specifications in Fig. 2. The specifications with their corresponding values are listed in Table 1. Points (a, b, c, d, e, f and g) indicated in Fig. 2 are used to trace, test and evaluate the proposed design as will be provided in Section 4.

Table 1. Parameters of Each Component in DWDM-PON.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Value(s)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW Laser</td>
<td>First frequency</td>
<td>193.025</td>
<td>THz</td>
</tr>
<tr>
<td>Sine Generator</td>
<td>Wavelength spacing</td>
<td>25</td>
<td>GHz</td>
</tr>
<tr>
<td></td>
<td>Launching power</td>
<td>8</td>
<td>dBm</td>
</tr>
<tr>
<td>OLT Transmitter</td>
<td>Frequency</td>
<td>6.25</td>
<td>GHz</td>
</tr>
<tr>
<td>Bidirectional</td>
<td>DS Bit rate</td>
<td>10</td>
<td>Gb/s</td>
</tr>
<tr>
<td>Optical fiber</td>
<td>Length</td>
<td>25</td>
<td>km</td>
</tr>
<tr>
<td>ONU Transmitter</td>
<td>Attenuation</td>
<td>0.2</td>
<td>dB/km</td>
</tr>
<tr>
<td></td>
<td>US Bit rate</td>
<td>2.5</td>
<td>Gb/s</td>
</tr>
</tbody>
</table>
Fig. 2 Simulation setup of DWDM-PON. MZM: Mach Zehnder Modulator, EDFA: Erbium Doped Fiber Amplifier, NRZ: Non-Return to Zero, IM: Intensity Modulator, LPF: Low Pass Filter.

4. RESULTS AND DISCUSSION

To verify this work's goals, the system tracing and evaluation are presented in this section by using OptiSystem simulator. Figures 3 (a)-(g) represent the optical spectra for signals while processing through the proposed cross seeding system as indicated (with corresponding points) in Fig. 2.

Figure 3 (a) represents 16 DS channels with channel spacing of 12.5 GHz starting from (λ1-1 corresponding to 193.019 THz) to (λ8-2 corresponding to 193.206 THz). These channels resulted from the eight CW light source each with 8 dBm after being forced to MZM with 6.25 GHz sine wave generator as indicated in point (a) Fig. 2.

After being demultiplexed, even and odd DS channels are modulated through IM with NRZ format each with 10 Gb/s. Finally, these channels are applied to DS MUX to provide the cross seeding odd and even spectra ready to be transmitted through FF1 and FF2, respectively. These spectra are presented in Figs. 3 (b) and (c) and are considered as corresponding to system signals trace at point (b) and (c) in Fig. 2.

Figure 3 (d) represents the spectrum of a chosen odd DS channel spectrum (i.e. λ1-1 corresponding to 193.019 THz as an example for the odd channels) after transmitting 25 km FF1 and demultiplexed at DeMUX 3 (as shown in Fig. 2 at point (d)) before ONU receiver. Figure 3 (f) represents this channel after transmitting back through the retransmitting path (US path) with a record of 2.5 Gb/s (i.e. point (e) in Fig. 2). One needs to remember that, from Fig. 2 the retransmitting path (US path) includes CLS module, MUX, transmitting through FF2 (not FF1 that is used in DS path and that is the core of cross seeding technique that mitigates RB) and finally DeMUX to reach at the receiver (as shown in Fig. 2 at point (e).
Similarly, the DS channel ($\lambda_{1-2}$ corresponding 193.031 THz as an example for the even channels) with DS path in FF2 and US in FF1 resulting in Figs. 3 (e) and (g) corresponds to point f and g in Fig. 2, respectively.

![DS channel diagram](image)

Furthermore, Fig. 4 represents the eye diagrams for selected odd and even channels after the retransmitting path (i.e. point (e) and point (g) in Fig. 2). Figures 4 (a) and (b) represents the eye diagram evaluation for the previously chosen odd and even channels presented in Figs. 3 (f) and (g) (i.e. $\lambda_{1-1}$ and $\lambda_{1-2}$), while Figs. 4 (c) and (d) represent the extra chosen channels (i.e. $\lambda_{8-1}$ and $\lambda_{8-2}$) for verifying the following results.

![Eye diagrams for selected channels](image)
The obtained results indicate that the worst simulated BER through the chosen samples is observed for channel \( \lambda_{1-1} \) of \( 10^{-12} \) which corresponds to a quality factor (Q) of 6.88 while, a remarkable simulated BER of \( 10^{-13} \) which corresponds to a Q of 7.03 is noticed for channel \( \lambda_{1-2} \). An average BER with better than \( 10^{-12} \) can be observed for the remaining channels.

![Eye diagrams for odd and even channels after the retransmitting path](image)

**Fig. 4** Eye diagrams for odd and even channels after the retransmitting path (a) \( \lambda_{1-1} \), (b) \( \lambda_{1-2} \) (c) \( \lambda_{8-1} \), (d) \( \lambda_{8-2} \).

Figure 5 demonstrates the proposed architecture optimization for various distances. According for the simulation results, the BER for US signal is enhanced with increasing the launching optical power. The proposed system can achieve \( 10^{-13} \) BER for US signal at 30 km optical fiber on the trade off the power (12 dBm).
A comparison of BER versus different optical launching powers for both the proposed cross seeding and conventional bidirectional WDM PON are illustrated in Fig. 6. The performance of the two systems are evaluated. One is the proposed DWDM PON with cross seeding connection. The other is the conventional bidirectional connection using 8 channels with 12.5 GHz channel spacing. In the conventional WDM PON, US signals using the same wavelengths of DS. As shown in Fig. 6, the conventional bidirectional WDM PON without RB mitigation has poor BER constant value $10^{-4}$ with increasing the launching power comparing to the proposed DWDM PON. Also, the eye diagram for each system shown in Fig. 6 demonstrates the performance which declare the enhancement of the proposed system.

5. COMPARISON WITH RELATED WORK

Here, we present a comparison between our work and selected recent related studies. This will highlight the proposed DWDM-PON cross seeding system efficiency with different RB mitigation techniques.

Wavelength shift (WS) and optical carrier-suppressed subcarrier-modulation (OCS-SCM) techniques, can efficiently avoid the RB effect and achieve a reasonable level of wavelength utilization by adopting centralized light source [18], [19]. Comparing to the proposed architecture, these techniques suffer from complex modulation techniques, add huge/moderate cost for the colorless ONU and require large channel spacing. Adding a CW light source at remote node (RN) is another approach [20], [21]. This technique satisfies both avoiding RB and low cost ONU, but it does not take wavelength
utilization in consideration [22], [23]. On the contrary in the proposed system, a CLS is used at the OLT with channel spacing 12.5 GHz. Utilizing orthogonal codes and correlation receiving methods can mitigate the RB but it required a processor and more components [24], [25]. The cross seeding method, as designed in [13], [26] provides remarkable RB mitigation, high level of wavelength utilization and low cost colorless ONU. However, these combined merits are associated with adding two feeding fibers and active elements (i.e. EDFA and ROSA) to the network that results in a higher implementing cost.

6. CONCLUSION

This work simulates an enhanced cross seeding based DWDM-PON system with the future channel spacing in ITU-T G.694.1 Standard for DWDM (i.e. 12.5 GHz). A brief review on several RB mitigation/minimization techniques is performed to emerge the merits of cross seeding technique and the cost for applying it. Utilizing this work design enhancement, the proposed DWDM-PON system successfully achieved a record of 16 channels, US capacity of to 2.5 Gb/s over 25 km transmission and a noteworthy average BER of $10^{-12}$. The used system components are minimized comparing to classic and recent literatures that depend on cross seeding technique as RB mitigation method.

REFERENCES


