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RESEARCH ARTICLE

PERFORMANCE ANALYSIS OF ADAPTIVE BIT LOADING SIPM-OOFDM IN INTENSITY MODULATION AND DIRECT DETECTION TDM- AND TWDM-PON SYSTEMS

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Abstract

Technological advancements over recent decades prompted the development of bandwidth-intensive services, necessitating the deployment of optical fibers in access networks up to the subscriber. To address these increasing demands, innovative transmission techniques, including advanced modulations and architectures, are expected. This study aimed to enhance transmission distance and user capacity in Passive Optical Networks (PON). The Subcarrier Index Power Modulated Optical Orthogonal Frequency Division Multiplexing (SIPM-OOFDM) technique, which conveyed additional information per subcarrier compared to conventional OOFDM, was implemented using MATLAB R2019a. To further improve the capacity performance, an Adaptive Bit Loading SIPM-OOFDM (ABL-SIPM-OOFDM) was implemented. We have modeled an IM/DD link in Optisystem7 and simulated the performance of conventional SIPM-OOFDM and ABL-SIPM-OOFDM in Time Division Multiplexing-PON (TDM-PON) and Time and Wavelength Division Multiplexing-PON (TWDM-PON) systems. The ABL-SIPM-OOFDM is shown to achieve an effective data rate of 18 Gb/s in TDM-PON, compared to 13 Gb/s with conventional SIPM-OOFDM, for a Bit Error Rate (BER) target of 10^{-3} at 20 km of fiber length with power budget supporting 64 users. This represents a 5 Gb/s increase in transmission capacity over the conventional approach.Additionally, in a TWDM-PON setup, the ABL-SIPM-OOFDM achieved an effective data rate of approximately 41 Gb/s over a distance of 40 km, supporting 64 Optical Network Units (ONU with 4 wavelengths each). In conclusion, the proposed ABL-SIPM-OOFDM demonstrated significant potential as a candidate for NG-PON systems, meeting the requirement of a 40 Gb/s downlink data rate for at least 256 users over a fiber distance of 40 km.

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Introduction:-

Over the past five (5) decades we have witnessed an exponential growth of internet demand [1] with the development of new real time technologies such as Internet of Things (IoT), Telephony over IP, videoconference, online gaming, Fintech, ecommerce etc. The trend has even more increased in 2020 because of the coronavirus pandemic that people are facing all over the world. The demand of the final user in terms of transmission throughput and Quality of Service (QoS) skyrocket constantly and necessity of increasing telecommunication infrastructures capacity is becoming obvious. A lot of research is being undertaken with the aim of increasing the throughput and the overall performances of access networks [2]-[5]. Several areas of research are focused on multiplexing techniques, advanced modulation methods, development of high-bandwidth optoelectronic and optical components. Among advanced modulation techniques [5] proposed for optical access networks, OFDM continues to demonstrate its effectiveness. With the advancement of Optical Communications systems, leveraging digital signal processing (DSP) to introduce an additional information-bearing dimension in OOFDM systems, without the need for extra analog optical/electrical hardware—has emerged as a highly advantageous solution. This is the case of Optical OFDM with Index Modulation (OOFDM-IM) that emerged as a promising optical multicarrier technique, gaining attention across all the aforementioned fields [4]. Several variants of OOFDM-IM in Optical Communications have been investigated, including mode index, layer index, and enhanced index, with the aim of improving system performance [6]-[9]. One such approach is known as “Subcarrier Index Power Modulated - Optical Orthogonal Frequency Division Multiplexing (SIPM-OOFDM)” [6], [8]. This technique enhances system performance by introducing an additional information-bearing dimension, based on subcarrier index-power modulation, into conventional OOFDM. As a result, it significantly improves signal transmission capacity without increasing the minimum required Signal-to-Noise Ratio (SNR) or compromising tolerance to chromatic dispersion and nonlinearity.

In classic OFDM systems, the frequency selectivity implies that each subcarrier is differently affected by the channel and consequently the channel performances can highly vary from one subcarrier to another [10], [11]. If the same constellation size is used for all subcarriers, the probability of errors is then dominated by the subcarriers with poor signal to noise ratio (SNR), resulting in poor performances of the overall system. This problem can be solved if the modulation scheme used on a given subcarrier is selected regarding its sub-channel quality [12]. As opposed to conventional OFDM systems, adaptive OFDM adapts to the individual subcarriers SNR, which can significantly improve the performances of the system in terms of BER and throughput. For example, if the subcarriers which present a high probability of error for a given OFDM symbol can be identified and excluded from the transmission, the overall BER can then be improved with in exchange a small loss of performances in terms of throughput. But this loss due to the exclusion of a subcarrier can be further compensated by using high order modulation format on subcarriers with good SNR values. In this context, many adaptive modulation algorithms are developed [10]- [17], the most known among them being Adaptive Bit Loading (ABL), Adaptive Power Loading (APL) and Adaptive Bit and Power loading (ABPL). These algorithms can easily be implemented using the well-known Water-filling principle. About ABL algorithms [10]- [15], different modulation formats are used on each subcarrier with an identical electrical power for all of them. For APL algorithms [16], electrical power is adapted on each subcarrier using the same modulation format on all subcarriers [17]. Finally, for ABPL algorithms [18], the electrical power as well as the modulation format are adapted on each subcarrier [19]. All these algorithms can be used to maximize the achievable throughput for a fixed BER and a fixed power budget or for minimizing the overall system BER for a fixed throughput to improve the power budget of the system [10]- [19].

Furthermore, multiplexing techniques are also known to improve the optical access networks performances [20]. The most used multiplexing techniques for Passive Optical Networks are [21]: Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM) and recently Time and Wavelength Division Multiplexing (TWDM) [22]. TDM operates on the principle of sharing a single wavelength among multiple users. Its main drawback is that all Optical Network Unit (ONU) devices must operate at the system's maximum throughput, which significantly exceeds the actual data rate required by individual users. Wavelength Division Multiplexing (WDM), on the other hand, assigns a unique wavelength to each user. Its main disadvantage lies in its complexity, particularly in ensuring flexibility and efficient bandwidth sharing among multiple users. Time and Wavelength Division Multiplexing (TWDM) combines the strengths of TDM and WDM and has recently been standardized by the International Telecommunication Union (ITU) as a leading candidate for Next-Generation Passive Optical Networks (NG-PON) [22]. It offers significant advancements, including extended transmission distances, higher throughput, and the ability to support a larger number of users within the network. As the demand for high-speed broadband continues to grow, NG-PON2 leverages TWDM to achieve high capacity. In this context, SIPM-OOFDM could serve as a valuable complement by delivering higher data rates and optimizing channel utilization.

Considering all the above, and to the best of our knowledge, this paper is the first to explore the performance of the ABL algorithm with SIPM-OOFDM modulation in an Intensity-Modulation/Direct-Detection (IM/DD) TWDM-PON architecture. The study is structured as follows: in section II, a comprehensive explanation of the ABL-SIPM-OOFDM operating principles is provided, along with a detailed description of the simulation setup and parameters. Finally, the results obtained are analyzed and discussed in section III, followed by the conclusion.

Materials and Methods:-

The aim of this section is to present the operating principle of the proposed Adaptive Bit Loading SIPM-OOFDM (ABL-SIPM-OOFDM) technique and the methodology employed to effectively conduct this study.

SIPM-OOFDM Operating Principle

The operating principle of the SIPM-OOFDM technique is similar to that of conventional OOFDM, with modifications to the data-encoding and decoding functions at both the transmitter and receiver [9]. Also, the receiver introduces a subcarrier power threshold determination step prior to the equalization process. At the transmitter, as illustrated in Fig. 1-A, the encoding process begins with an incoming Pseudo Random Binary Sequence (PRBS). When a bit "1 (or 0)" is encountered, the corresponding subcarrier power is set high (or low) level, as shown in Fig. 1-B. The following 3 (or 2) bits of the PRBS sequence are then encoded using 8PSK (or QPSK) and the corresponding symbol is assigned to the subcarrier.

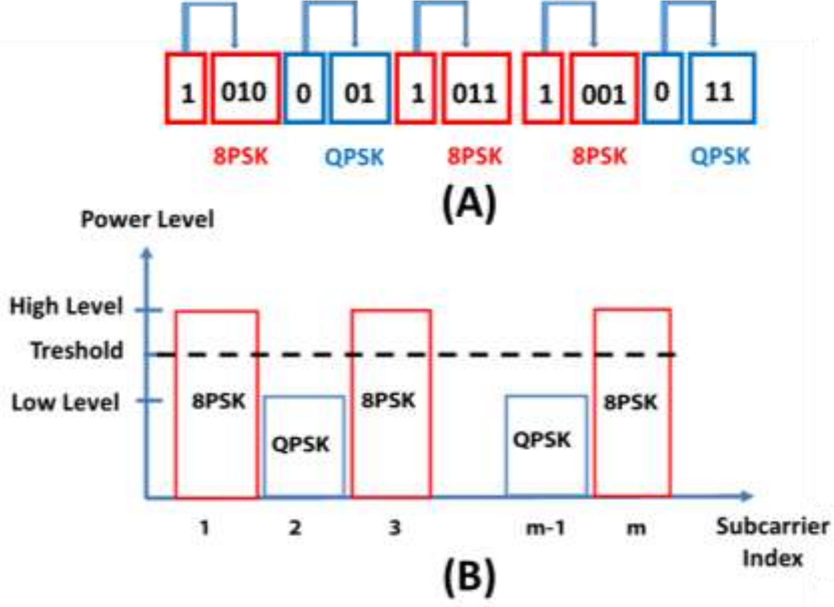

Fig 1:- (A) SIPM-OOFDM data-encoding process at the transmitter. (B) A schematic diagram illustrating the encoding of a subcarrier with a specific power level at the transmitter using QPSK and 8PSK. A power threshold line is also depicted, delineating the boundary between the QPSK and 8PSK power levels.

This encoding procedure ensures that all subcarriers remain active and that each subcarrier is set at a specific power level, enabling it to carry an additional information bit. At the receiver, the decoding process starts with the subcarrier power threshold decision function located between the Fast Fourrier Transform (FFT) and channel equalization. This function calculates the optimum power threshold for each subcarrier by using a training sequence (TS) periodically inserted into the user data sequence at the transmitter. The power thresholds derived from each TS are averaged over time and utilized to recover the information bit encoded in the subcarrier index-power dimension. The subcarrier power threshold is also used to determine the modulation format of the signal carried by the subcarrier. After the power threshold decision process, the same training sequence is employed for channel equalization, ensuring accurate decoding of the information bits encoded in each subcarrier. This approach maintains all subcarriers in an active state, optimizes their power levels for additional data transmission, and incorporates robust decoding mechanisms to enhance the overall performance of the system.

ABL-SIPM-OOFDM Operating Principle

As shown in Figure 2, the ABL-SIPM-OOFDM architecture is very similar to that of the conventional SIPM-OOFDM, with the primary difference being the additional block highlighted in the yellow circle. This block is responsible for evaluating channel quality prior to transmission. The process begins with a training sequence, modulated using SIPM-OOFDM, which is transmitted over the channel to assess its quality. At the receiver, the SNR of each subcarrier is measured [23], allowing for the determination of the optimal number of bits to allocate to each active index subcarrier as in equation (1). Once the bit distribution is established, the actual PRBS input is modulated using SIPM-OOFDM and transmitted through the channel according to the previously determined bit allocation $\boldsymbol{b_k}$ with $\boldsymbol{k = 1, 2, \ldots, N}$.

$$\mathbf{b_k} = \frac{\mathbf{1}}{\mathbf{2}}\log_2\left(1 + \frac{\mathbf{SNR_k}}{\Gamma}\right) \tag{1}$$

$\boldsymbol{\Gamma}$ corresponds to the gap between the SNR required to achieve the maximum Shannon capacity and the $\boldsymbol{SNR_k}$ needed to ensure a specific Symbol Error Rate (SER), as expressed in (2):

$$\boldsymbol{\Gamma} = \frac{\left[Q^{-1}(\mathbf{SER/2})\right]^2}{2\pi^2} \text{ avec } \mathbf{Q(x)} = \frac{\mathbf{1}}{\sqrt{\mathbf{2\pi}}}\int_{\mathbf{x}}^{\infty} \mathbf{e}^{-\frac{\mathbf{u^2}}{2}}\mathbf{du} \tag{2}$$

Sometimes, the number of bits $\mathbf{b_k}$ to be allocated per subcarrier may be a decimal value. In such cases, it is rounded down to the nearest integer. If $\mathbf{b_k}$ is less than 2, the corresponding subcarrier is deactivated. However, if $\mathbf{b_k}$ is between 2 and 3, the subcarrier is activated and modulated by QPSK. Beyond 4, the number of bits per subcarrier $\mathbf{b_k}$ is fixed at 4, and the corresponding subcarrier is activated with 16PSK modulation. Hence, as in SIPM-OOFDM, the ABL-SIPM-OOFDM technique allocates different power levels (low and high) to subcarriers modulated with QPSK and 8PSK, respectively.

Methodology and Simulation Setup

Figure 2 presents the block diagram of the simulated IM/DD TDM-PON system, incorporating both SIPM-OFDM and ABL-SIPM-OFDM implementations. The optical link features a 1915 LMA DFB laser, modulated by an OFDM signal generated with MATLAB, which is then transmitted through a Single-Mode Fiber (SMF) and detected by a PIN photodiode at the receiver.

The OFDM signal processing, including modulation and demodulation, is modeled with MATLAB 2019a, while the optical link is simulated using OptiSystem7. A Variable Optical Attenuator (VOA) block is included to emulate the optical splitter loss typical in a TDM-PON setup. All simulation parameters are taken from reference [23], along with those presented in Table 1.

Table 1:- Parameters Setup.

Parameters	**Values**
IFFT/FFT Size of $\boldsymbol{N}$	32 ~ 256
Number of Useful Subcarriers	15 ~ 127
Number of Pilot Symbols	11
PRBS Sequence Length	65536
Emitted Optical Power	10 dBm
Receiver PIN Sensitivity	-20 dBm
Thermal Noise	10^{-18} W/Hz
SMF attenuation	0.2 dB/km
Chromatic Dispersion	17 ps/nm/km
Nonlinearity Coefficient	2.6×10^{-20} m²/W
TWDM Wavelengths : λ_1 , λ_2 , λ_3 and λ_4	1553 nm, 1553.8 nm, 1554.6 nm and 1555.4 nm
Mux/Demux Losses	3 dB

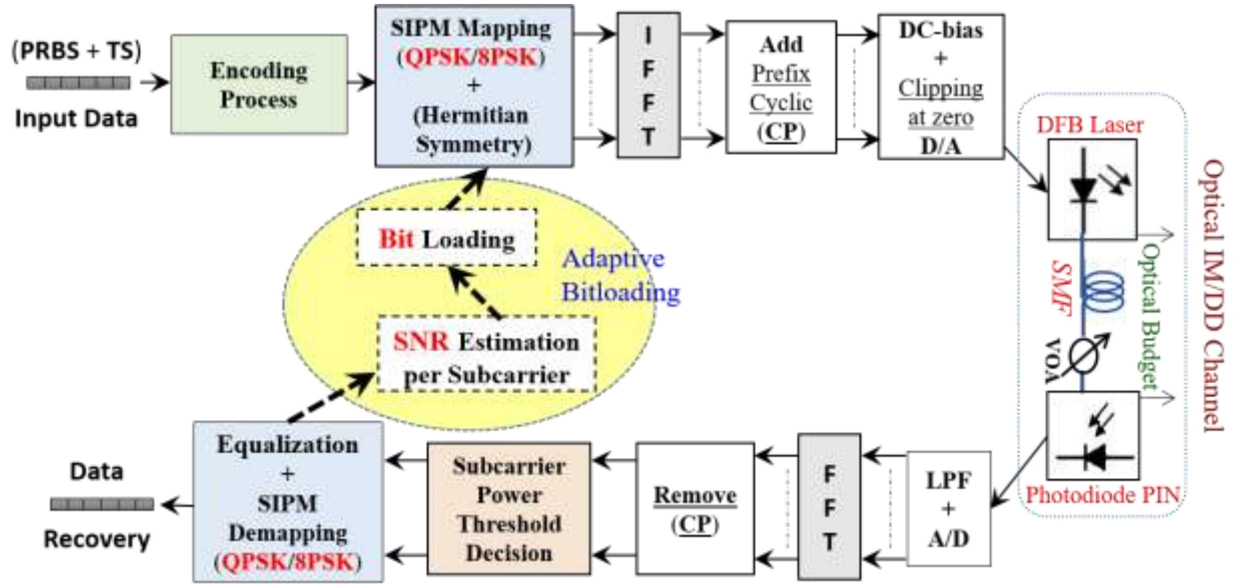

Fig 2:- Block Diagram of the IM/DD SIPM-OOFDM link with the Adaptive Bit Loading (ABL) highlighted by Yellow Circle implemented in a TDM-PON Systems.

Various performance metrics are employed in the literature to compare modulation schemes in optical communication systems. A widely used metric is the signal-to-noise ratio (SNR), which evaluates performance based on the ratio of optical power to the standard deviation of zero-mean noise power in the system. Another commonly used metric is the optical energy-per-bit to single-sided noise power spectral density ratio, $E_{b(Opt)}/N_0$, which also provides a measure of performance. Notably, an increase in $E_{b(Opt)}/N_0$ corresponds to an increase in SNR. In this study, we adopt $E_{b(Opt)}/N_0$ to evaluate and compare the BER performance under an AWGN channel as in [8] and [23].

Also, a performance comparison between SIPM-OOFDM and ABL-SIPM-OOFDM is conducted within an IM/DD TDM-PON link. For a fair comparison, the effective data rate as a function of transmission distance was evaluated with a BER target of 10^{-3}. The effective data rate is considered in this study to evaluate the actual usable throughput that a user can experience in the context of PON applications. The SNR distribution and bit allocation were analyzed to confirm the positive contribution of ABL-SIPM-OFDM compared to the conventional SIPM-OFDM method in terms of data rate enhancement. To further address our objective of enhancing the data rate in access optical networks, we simulated a four-wavelength (04) TWDM-PON link based with the proposed ABL-SIPM-OFDM scheme, as illustrated by Figure 3. In this architecture, four (04) ABL-SIPM-OOFDM signals are generated using Matlab and used to directly modulate DFB laser sources with wavelengths λ_1, λ_2, λ_3 and λ_4, as detailed in Table 1. The resulting optical signals are wavelength-division multiplexed (WDM) and transmitted through a single-mode fiber (SMF). The optical signal is then shared by 64 Optical Network Units (ONUs) via a 1x64 optical splitter. Each ONU consists of a corresponding demultiplexer for the four wavelengths, followed by a photodiode for each simulated wavelength, and an ABL-SIPM-OOFDM demodulator implemented in MATLAB. The simulation evaluates performance in terms of effective data rate as a function of transmission distance, under a target bit error rate (BER) of 10^{-3} and a 64-ONU splitting ratio (Demux/WDM), with four wavelengths assigned to each ONU. The BER performance is computed [24] using the mean value derived from relation (3), considering equation (4) with $\boldsymbol{EVM_k}$ the Error Vector Magnitude, $\boldsymbol{S_k}$ and $\boldsymbol{S_{0,k}}$ respectively the received and emitted M-PSK symbols for $k = 1, 2, \ldots, N$.

$$\mathbf{BER_k} \approx \frac{\mathbf{1}}{\boldsymbol{b_k}} \boldsymbol{erfc}\left[\sqrt{\boldsymbol{SNR_k}}\right] \times \sin\left(\frac{\boldsymbol{\pi}}{\mathbf{2}^{\boldsymbol{b_k}}}\right) \tag{3}$$

$$\boldsymbol{SNR_k} \approx \frac{\mathbf{1}}{[\boldsymbol{EVM_k}]^{\mathbf{2}}} \quad \text{where } \mathbf{EVM_k} = \sqrt{\frac{\frac{1}{N}\sum_{k=1}^{N}\left|S_k - S_{0,k}\right|^2}{\frac{1}{N}\sum_{k=1}^{N}\left|S_{0,k}\right|^2}} \tag{4}$$

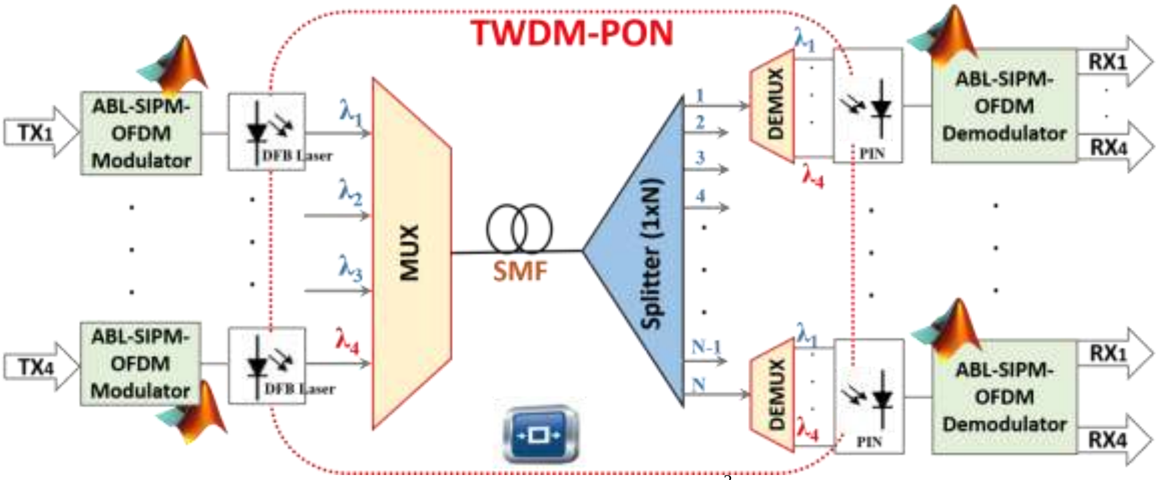

Fig 3:- Simulated TWDM-PON Architecture for a Target BER of 10^{-3} with the proposed ABL-SIPM-OOFDM.

In the following section, we present the results based on the methodology and then proceed with the discussion.

Results and Discussion:-

Figure 4 presents the BER performance as a function of $E_{b(Opt)}/N_0$ in an AWGN channel using SIPM-OOFDM, compared with the conventional OOFDM using QPSK, 8PSK and 16PSK modulation formats. The total optical power is fixed to unity as [8]. It can be seen that the BER improves as $E_{b(Opt)}/N_0$ increases. This can be explained by the fact that as the $E_{b(Opt)}/N_0$ increases, the SNR becomes high and the transmitted signal becomes less affected by channel noise, resulting in more accurate symbol transmission. As shown by authors in [8], it can be observed that SIPM-OOFDM exhibits a BER behaviour similar to that of 8PSK-OOFDM. For a specific BER value, a small SNR gap exists (≤ 0.9 dB) between SIPM-OFDM and 8PSK-OOFDM. This can be attributed to error propagation caused by incorrect subcarrier power threshold decisions. The results in Figure 2 indicate that the additional subcarrier index-power information dimension in OOFDM does not significantly compromise the signal SNR at any given BER target. This motivates us to explore its implementation in a realistic optical IM/DD channel link.

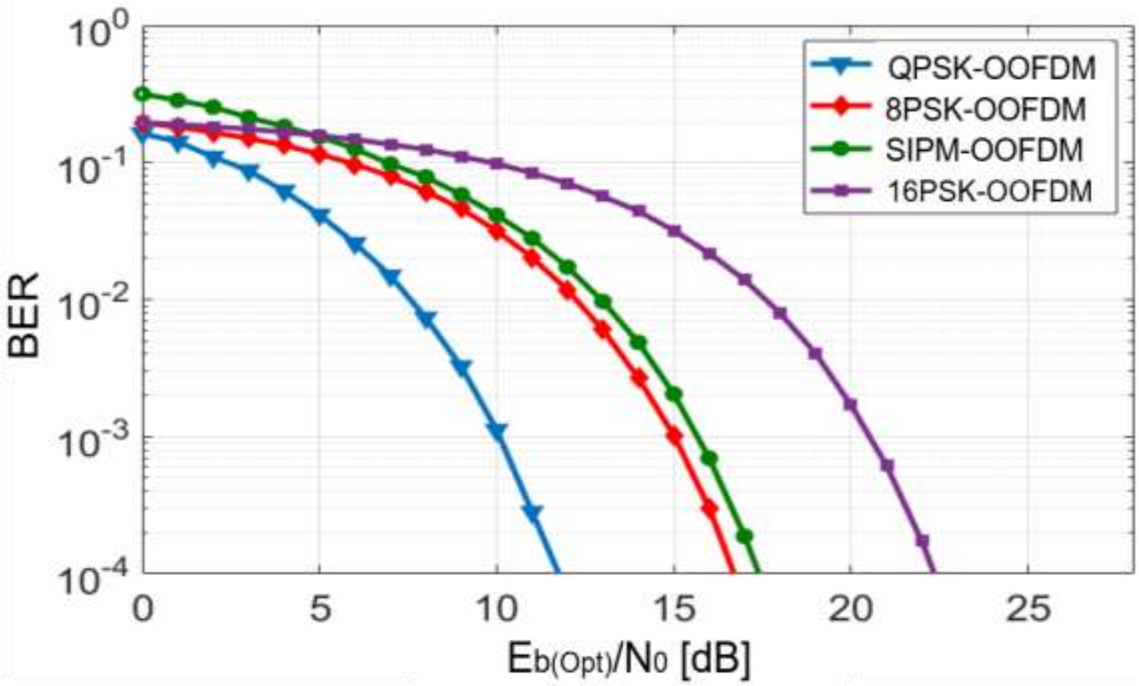

Fig 4:- BER performance of SIPM-OOFDM vs QPSK/8PSK/16PSK-OOFDM as a function of $E_{b(Opt)}/N_0$ in an AWGN channel.

Figure 5 shows the channel response of the simulated IM/DD TDM-PON link from Figure 2, with N=32 at a fixed transmission distance of 20 km. It can be observed that the obtained channel response shows frequency selectivity, with peaks and valleys in the SNR across the subcarriers. This suggests that not all subcarriers behave the same in terms of SNR and, therefore, cannot carry the same number of bits according to equation (1).

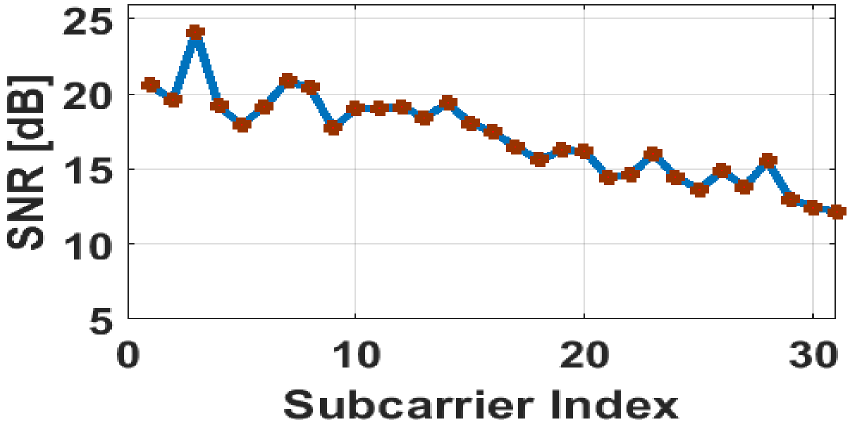

Fig 5:- Channel response of the simulated optical link in terms of Signal-to-Noise-Ratio per Subcarrier.

To illustrate this, Figure 6 presents the results obtained when implementing both conventional SIPM-OOFDM and ABL-SIPM-OOFDM over the channel response shown in Figure 5.

The analysis of results in Figure 6 reveals that, when comparing the bit distributions with the channel response showed in Figure 5, the ABL-SIPM-OOFDM bit distribution aligns more closely with the channel response compared to the conventional SIPM-OOFDM. This difference arises because, in conventional SIPM-OOFDM, the modulation format used for each subcarrier is determined without accounting for the channel quality. On the other hand, the ABL-SIPM-OOFDM approach optimally distributes bits across subcarriers based on the channel characteristics. This optimization can enhance the BER at the same data rate compared to the conventional method, as it ensures that subcarriers experiencing higher SNR, transport fewer bits than they can theoretically handle.

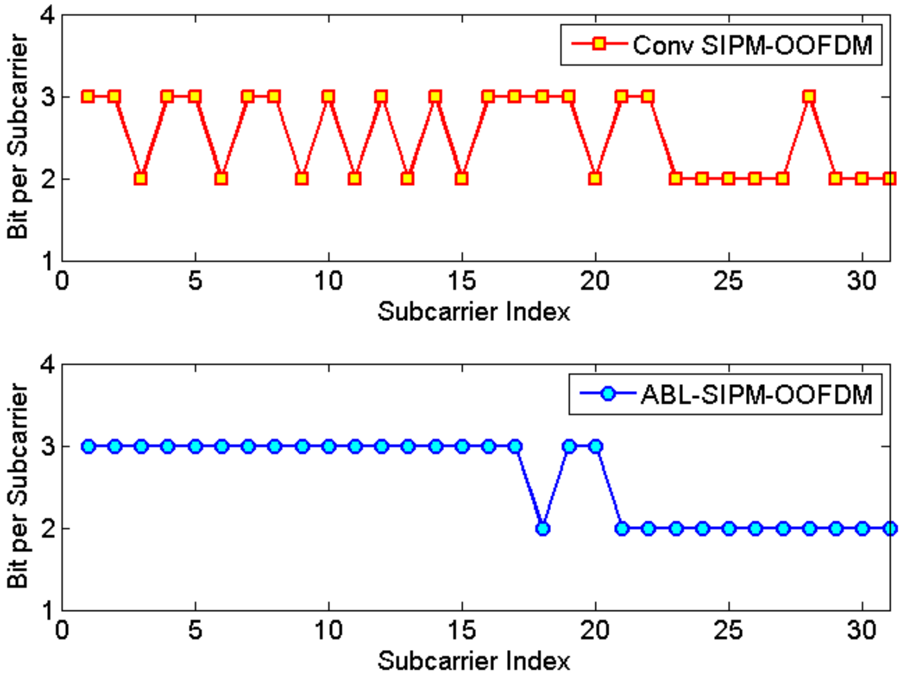

Fig 6:- Bit Allocation obtained when applying both the Conventional SIPM-OOFDM versus proposed ABL-SIPM-OOFDM technique in the simulated IM/DD TDM-PON with 20 km fiber length and for N=32 subcarriers.

Figure 7 provides a fair comparison between conventional SIPM-OOFDM and ABL-SIPM-OOFDM within the simulated IM/DD TDM-PON link, evaluating the effective data rate as a function of transmission distance for a BER target of 10^{-3}.

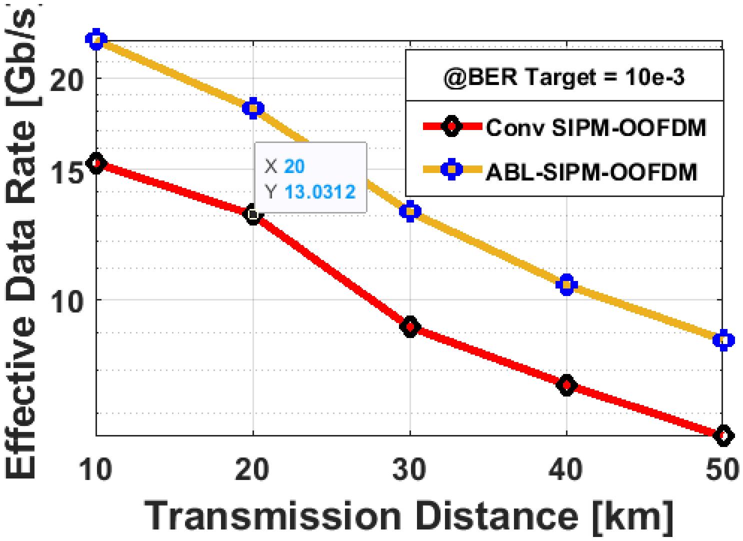

Fig 7:- Effective Data Rate Performance as a function of the Transmission Distance in TDM-PON with the emitting optical power of 10 dBm and OB = 30 dB at a BER Target of 10^{-3} for both Conventional- and ABL-SIPM-OOFDM.

It is easy to observe that for each simulated technique, the effective data rate decreases when the transmission distance increases. This occurs because of the combined effects of attenuation loss and chromatic dispersion of the fiber with the chirp in the DFB Laser source. The results indicate that ABL-SIPM-OFDM compared to conventional SIPM-OOFDM offers considerable signal transmission capacity improvement without degrading system power budget and fiber dispersion/nonlinearity tolerances. For example, at a fiber length of 20 km with a power budget supporting 64 ONUs, an effective data rate of 18 Gb/s can be achieved with ABL-SIPM-OOFDM, compared to 13 Gb/s with conventional SIPM-OOFDM, for a BER target of 10^{-3}. This demonstrates a 5 Gb/s increase in transmission capacity when using ABL-SIPM-OOFDM over the conventional approach.

In Figure 8, we present the effective data rate performance of the ABL-SIPM-OOFDM in IM/DD TWDM-PON systems (depicted in Figure 3) as a function of transmission distance, considering a power budget of 30 dB (supporting 64 ONUs with 04 wavelengths each) and a BER target of 10^{-3}. As a result, it is demonstrated that an effective data rate of approximately 41 Gb/s can be achieved over a distance of 40 km.

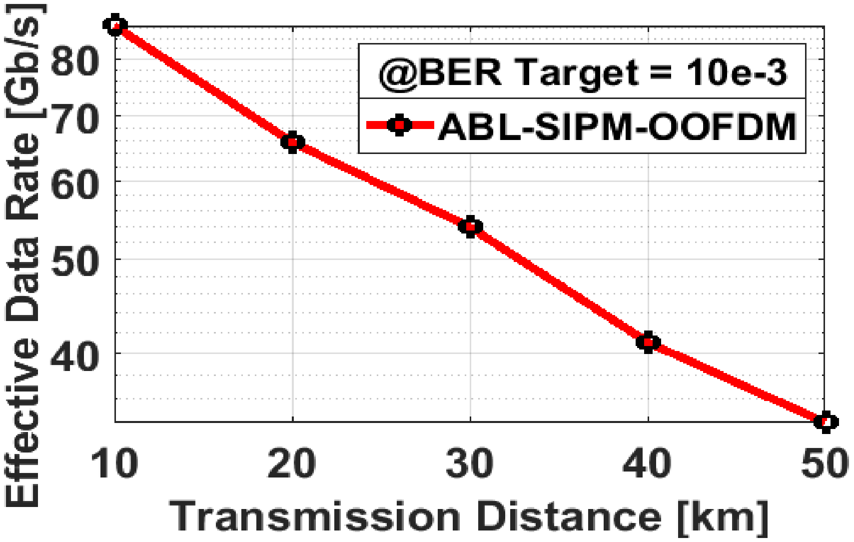

Fig 8:- Effective Data Rate Performance as a function of the Transmission Distance in TWDM-PON Architecture for a Target BER of 10^{-3} with the proposed ABL-SIPM-OOFDM with OB=30 dB.

If a signle wavelength is allocated to each end-user, a useful data rate of about 160 Mb/s per end-user can be provided, supporting a total of 256 users. In conclusion, the proposed ABL-SIPM-OOFDM appears to be a good candidate for NG-PON systems where a 40 Gb/s downlink data rate is needed for at least 256 users over a fiber distance of 40 km.

Conclusion:-

Dans ce papier, nous avons proposé une nouvelle méthode d’optimisation (MET) pour la montée en débit dans les liaisons de réseaux d’accès optiques. Après avoir comparé les performances obtenues avec la méthode (LC), nous avons montré d’une part, que les deux méthodes étudiées permettent de réaliser des débits quasiment-similaires et d’autre part, que la méthode (MET) développée permet d’optimiser le débit pour n’importe quel TEB cible recherché. Ceci ouvre la voie à des perspectives concrètes d’études de complexité de calcul et de consommation d’énergie lorsque l’implémentation est faite avec des DSP et ou FPGA. De plus, l’étude a montré que l’utilisation de convertisseurs DAC/ADC à forte résolution, permet légèrement d’augmenter le débit de la liaison lorsque l’algorithme (MET) est employé.

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