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Performance Analysis of Subcarrier Index Modulation OFDM in a DWDM-FSO Link

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Abstract— Free Space Optics (FSO) is a wireless optical communication system using light to establish high-capacity links between points without the need for physical cables. However, its susceptibility to atmospheric conditions such as fog, rain, and turbulence presents challenges to signal quality maintenance. To address this, Dense Wavelength Division Multiplexing (DWDM), traditionally employed in fiber optics, is leveraged to optimize bandwidth utilization and scalability in high-capacity communications. The integration of DWDM into FSO systems offers redundancy and resilience against signal degradation induced by atmospheric conditions. To the best of our knowledge, this is the first time a paper explores the performance of the Subcarrier Index Modulation Orthogonal Frequency Division Multiplexing (SIM-OFDM) technique within a DWDM-FSO system. The objective is to reinforce FSO link robustness and improve transmission rates. Through a comparative analysis with conventional OFDM in an Additive White Gaussian Noise (AWGN) channel, the study reveals a notable Signal-to-Noise Ratio (SNR) gain of at least 3dB with enhanced SIM-OFDM (ESIM-OFDM). Simulations, conducted with realistic parameters within the DWDM-FSO architecture, demonstrate that ESIM-OFDM modulation enables a transmission range of 2 km with an aggregated rate of 10.1 Gb/s. These results underscore the potential of SIM-OFDM in enhancing FSO system performance through the integration of DWDM technology. The proposed ESIM-OFDM DWDM-FSO scenario could represent a highly interesting solution for establishing 5G Backhaul links.

Keywords— SIM-OFDM; FSO, DWDM; AWGN; BER

I. Introduction

In recent years, there has been significant evolution in transmission systems, particularly in wireless communication. Researchers have extensively studied wireless communication to achieve high-quality communication with ever-increasing transmission rates. This has led to the emergence of Free Space Optics (FSO) links [1]-[7]. The fundamental principle of FSO transmission is similar to that of fiber optic communication, but with modulated data transmitted through an unguided channel instead of an optical fiber (Cf. Fig. 1). The narrow transmission beam width of FSO communication requires Line Of Sight (LOS) communication, necessitating direct visibility between the transmitter and receiver without obstruction [3], [5]. FSO transmission operates in the visible and infrared (IR) spectrum and offers significant advantages over traditional radiofrequency (RF) communication [6]. It provides a high bandwidth allowing for high transmission rates and ease of deployment [7]. Also, there is no need for digging during the installation and no licensing is required [4]. Moreover, FSO deployment costs are much lower compared to fiber optic deployment and installation can be completed more rapidly [2]. The security aspect of FSO communication is enhanced as intercepting and detecting the laser beam is difficult. However, despite these advantages, FSO links encounter two major challenges: geometric attenuation and atmospheric attenuation (rain, snow, fog, dust, etc.), resulting in absorption, scattering, and scintillation phenomena [6]- [7]. Therefore, it is crucial to develop techniques and methods to overcome these obstacles to fully capitalize on the benefits offered by FSO, given the increasing demand for subscriber bandwidth. Orthogonal Frequency Division Multiplexing (OFDM) is a modulation technique that can be used to mitigate the effects of atmospheric attenuation and other challenges in FSO transmission [8]. By leveraging OFDM's resilience to fading, robustness against interference, adaptive modulation capabilities, channel equalization techniques, and spectral efficiency, FSO links can achieve reliable and high-throughput communication even in challenging atmospheric conditions [9]-[10]. Furthermore, Dense Wavelength Division Multiplexing (DWDM) technology offers significant bandwidth enhancement by allowing multiple optical signals to be transmitted simultaneously over a single optical fiber [11]. Its integration into FSO transmission systems can bring numerous benefits, including increased capacity, improved flexibility, long-distance transmission capabilities, redundancy, resilience and interoperability with fiber networks [4], [7], [13]-[13]. The literature has extensively explored the application of OFDM techniques in FSO or hybrid DWDM-FSO links, focusing on aspects such as data transmission and range [14]-[15]. Among recent variants of OFDM techniques, Subcarrier Index Modulation Orthogonal Frequency Division Multiplexing (SIM-OFDM) has garnered attention for its ability to introduce additional modulation capabilities through subcarrier indexing, thereby enhancing robustness and spectral efficiency in wireless communication systems [16]. Due to its promising advantages, numerous studies have investigated SIM-OFDM, including its evolution and applications [17]-[30]. However, to the best of our knowledge, this study represents the first attempt to analyze the performance of SIM-OFDM specifically in a DWDM-FSO context.

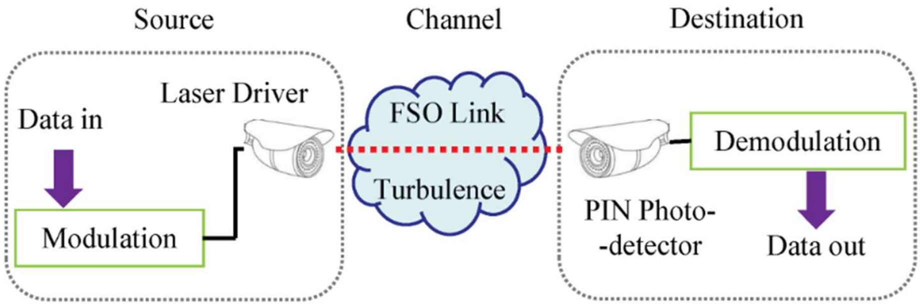

Fig. 1. Overview of an FSO Link over atmosphere.

This document is organized as follows: Section II introduces the principle of SIM-OFDM and its enhanced version. The materials and methodology used are presented in Section III. Section IV presents the results obtained and discussion. Then, Section V concludes the paper.

II. Overview of SIM-OFDM Technique

SIM-OFDM is a cutting-edge technique in the field of wireless communication, particularly suited for scenarios demanding high spectral efficiency and robustness against channel impairments [16]-[23]. It uses the concept of Subcarrier Index Modulation (SIM), which introduces an additional degree of freedom in the modulation process. Unlike traditional OFDM, where each subcarrier carries information independently, SIM-OFDM employs the indices of the active subcarriers to convey additional data symbols [16]. This means that in addition to transmitting information through the amplitude and phase of the subcarriers, SIM-OFDM also uses the presence or absence of subcarriers to encode supplementary information.

Fig. 2 illustrates the operational principle of SIM-OFDM modulation. From an incoming binary sequence of $N_{IFFT}\left(\frac{log_2(M)}{2}+1\right)$ bits, two blocks BOOK and BQAM are formed. The first N_{IFFT} bits are referred to as BOOK block and the remaining $N_{IFFT}\frac{log_2(M)}{2}$ bits form the BQAM block. Each BOOK block is analyzed to find the majority bit value, which corresponds to the bit (either 1 or 0) that occurs most frequently within the BOOK frame. All the subcarriers within an OFDM symbol, whose positions align with this majority bit value, are categorized as "active," and the others, are designated as "inactive" (Cf. Fig. 2). The aforementioned inactive subcarriers are not modulated. To encode the BQAM block, the first $\frac{N_{IFFT}}{2}$ active subcarriers are allocated with amplitudes corresponding to the employed QAM symbols. The remaining active subcarriers are assigned the average energy of the QAM constellation and designated for signaling the majority bit value to the receiver. A specific subcarrier can also be reserved to transmit the majority bit value with a sufficiently high SNR [19].

Fig. 3 presents the block diagram of the SIM-OFDM receiver. At the output of the Fast Fourier transform (FFT) and equalization step, each subcarrier is analyzed. When the power of a subcarrier exceeds a predetermined threshold (which is set to be less than the minimum power of the used QAM constellation), it is classified as "active". Otherwise, it is considered as "*inactive*". Then, each BOOK block is recovered based on the identified subcarrier states and known majority bit value. After that, the first $\frac{\boldsymbol{N_{IFFT}}}{\mathbf{2}}$ "*active*" subcarriers are demodulated regarding to the M-QAM constellation to recover the BQAM block [16]-[17]. An incorrect detection of a subcarrier state not only results in the incorrect demodulation of the M-QAM symbol it encodes, but also leads to the incorrect demodulation of all subsequent QAM symbols. This occurs because an erroneous detection of a subcarrier state alters the order in BQAM and misaligns all subsequent bits within that section of the frame. This effect significantly impacts the Bit Error Rate (BER) performance. Clearly, to demodulate a M-QAM symbol accurately, it is essential not only to detect its subcarrier as active but also to accurately detect any preceding subcarriers (active or inactive).

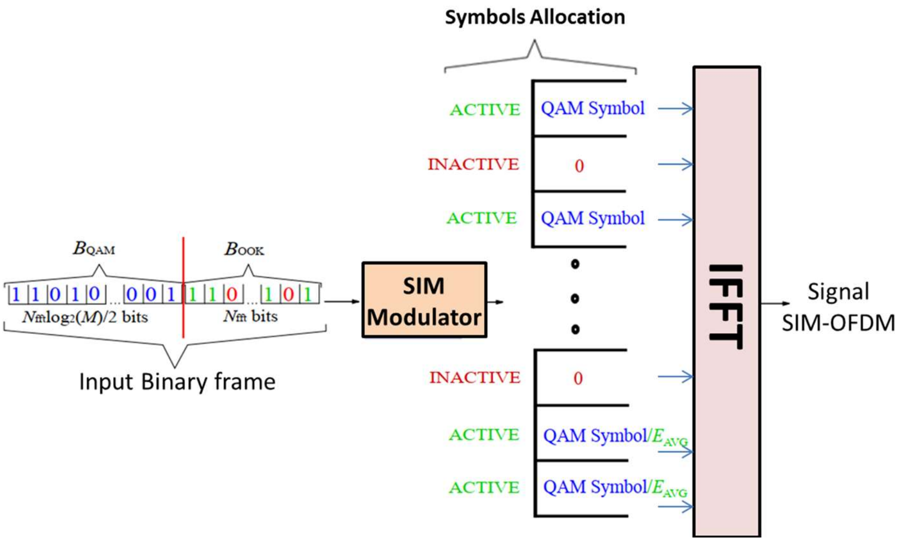

Fig. 2. Principle of SIM-OFDM modulation.

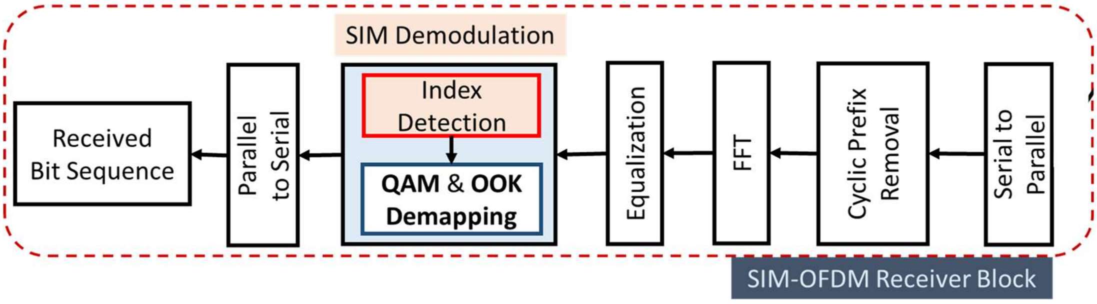

Fig. 3. Block diagram of SIM-OFDM receiver.

To address this issue, an enhanced version of SIM-OFDM was proposed [17]. The operational principle of ESIM-OFDM modulation is similar to that of the previous SIM-OFDM, except that for every encountered bit of BOOK, a pair of subcarriers is assigned to transmit the QAM symbol (Cf. Fig. 4). Therefore, when encountering a bit 1 in BOOK, the QAM symbol is assigned to the first subcarrier and 0 to the second subcarrier. Otherwise, the opposite order is applied when encountering a bit 0 in BOOK.

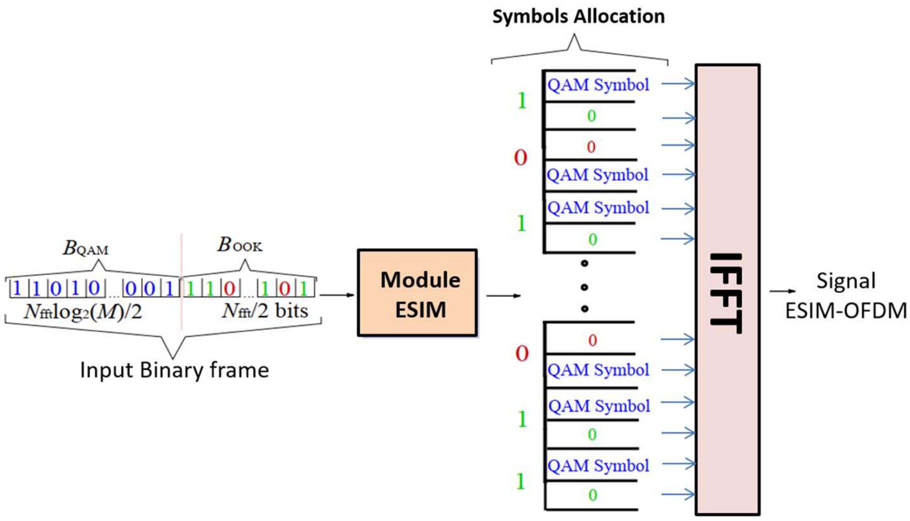

Fig. 4. Principle of ESIM-OFDM modulation.

III. Materials and Methods

In this section, we outline the methodology employed for implementing the SIM-OFDM techniques within a DWDM-FSO link.

3.1 Implementation in an AWGN channel link

In this study, we compare the performance of both SIM-OFDM and ESIM-OFDM techniques in a noisy channel to determine the most suitable one for implementation in the DWDM-FSO system.

Fig. 5 illustrates the simulated link of (E) SIM-OFDM technique in an AWGN channel. After applying OFDM modulation, whether using SIM or ESIM technique, to a given binary sequence, the resulting signal is transmitted through an AWGN channel before being demodulated at the reception. T hen, the BER is estimated using (1), where Q(x) represents the Q-function given by (2), and EVM denotes the error vector magnitude computed as illustrated in (3) using TABLE I. The simulation parameters used for the implementation of SIM/ESIM-OFDM techniques are listed in **Erreur ! Source du renvoi introuvable.**

$$BER \approx \frac{2\left(1-\frac{1}{L}\right)}{log_2(L)} Q\left[\sqrt{\left[\frac{3log_2(L)}{L^2-1}\right] \cdot \frac{2}{log_2(M)[EVM^2]}}\right] \quad (1)$$

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{+\infty} e^{-\frac{t^2}{2}} dt \quad (2)$$

$$L = \sqrt{M} \text{ and } EVM = \sqrt{\frac{\sum_{n=1}^{N_{ST}} |S_n - S_{0,n}|^2}{\sum_{n=1}^{N_{ST}} |S_{0,n}|^2}} \quad (3)$$

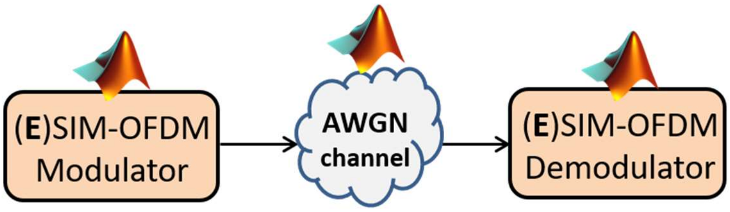

Fig. 5. Simulated OFDM techniques within AWGN channel..

TABLE I. VARIBALE NOMENCLATURE

Variables	Designations
M	Constellation size
N_{FFT}	Number of subcarriers of FFT
L	Number of levels on each M-QAM dimension
λ_i	i^{th} Wavelength of Mux/Demux
Eb/No	Energy-per-bit per noise ratio, dB
n	Index of the transmitted or received QAM symbols.
N_{ST}	Total number of emitted or received QAM symbols
$S_{0,n}$	n^{th} emitted QAM symbol
S_n	n^{th} received QAM symbol
$E_{b(elec)}/No$	Electrical energy-per-bit to noise ratio, dB.

TABLE II. SIMULATION PARAMETERS FOR SIM/ESIM-OFDM

Parameters	Values
FFT size	512
Number of OFDM symbols	1024

Parameters	Values
Number of Pilot Symbols	22
Cyclic Prefix Size	16
QAM Constellation	4, 16, 64, 256
Emitted optical power	1 W

3.2 Simulation in a realistic FSO system link

In FSO systems, the Non-Return-to-Zero (NRZ) encoder is generally the most widely used modulation. In this part of the study, only the ESIM-OFDM technique is considered for OFDM modulation. Initially, a Hermitian Symmetry [31] is applied for its implementation within FSO consideration. We begin by comparing the use of NRZ and ESIM-OFDM in a single-wavelength FSO scenario (Fig. 6-a), followed by selecting the optimal modulation scheme based on data rate and range criteria for performance analysis in a hybrid DWDM-FSO scenario (Fig. 6-b). For the study, a 4QAM constellation and realistic FSO parameters are employed, as shown by TABLE III.

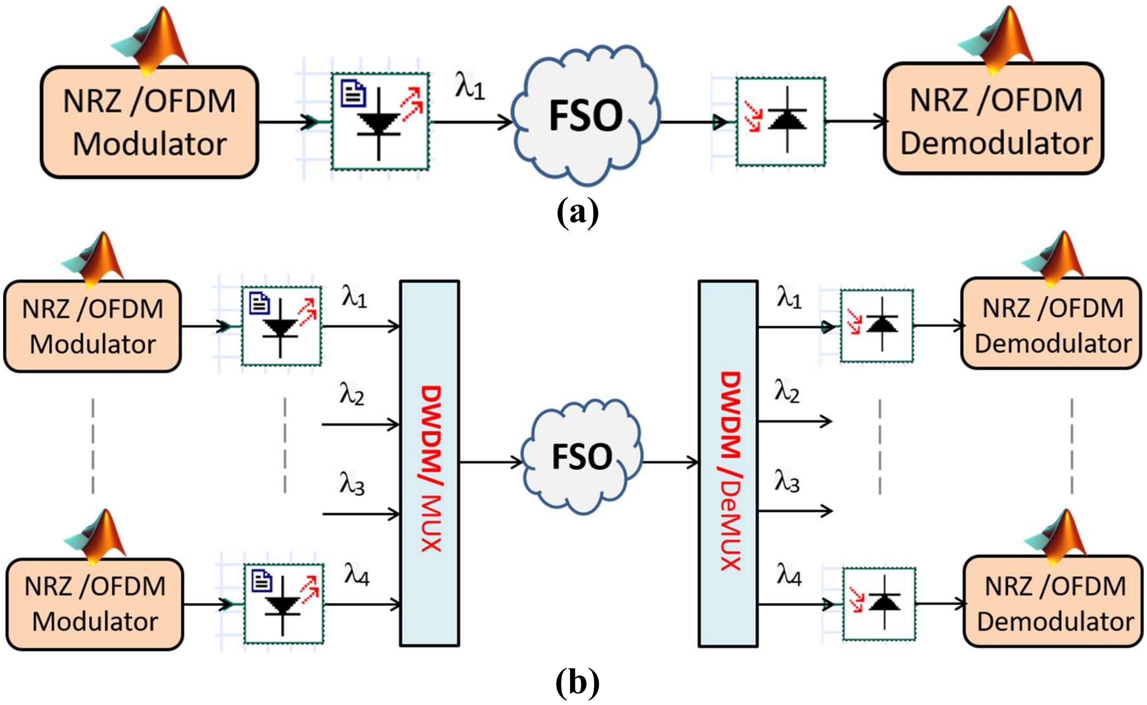

Fig. 6. Simulated : (a) FSO link, (b) DWDM-FSO link.

TABLE III. SIMULATION PARAMETERS IN FSO TRANSMISSION

Parameters	Values
Emitter optical power	10 dBm
Signal bandwidth	5 GHz
Mux/Demux Channel bandwidth	10 GHz

Parameters	Values
Wavelength window	1550 nm with $\Delta\lambda$=0.8 nm
Insertion loss (Mux/Demux)	1,5 dB
Beam divergence	0.1 mrad
Transmitter Aperture	5 cm
Receiver Aperture	7.5 cm
FSO channel attenuation	3.5 dB/km
FSO range	0 ~ 6 km
Propagation delay	6 ps/km
Transmitter/Receiver FSO attenuation	1 dB
FSO Additional losses	0.5 dB
Photodiode responsivity	0.8 A/W
Photodiode dark current	10 nA
Photodiode thermal noise	10^{-21} W/Hz

IV. Results and Discussion

The following section presents the obtained results and analysis.

4.1 Performance of SIM-OFDM and ESIM-OFDM over AWGN channel

In this subsection, we first present the validation results of the implementation of SIM-OFDM and ESIM-OFDM techniques in an AWGN channel. Since the evaluation of modulation techniques in an AWGN channel is often done by assessing the BER as a function of the electrical signal-to-noise ratio $E_{b(elec)}/N_0$, we have followed the same approach for the SIM-OFDM and ESIM-OFDM techniques. Fig. 7 shows the evolution of the conventional SIM-OFDM (without Hermitian symmetry) BER as a function of the electrical energy-per-bit to noise ratio for different QAM formats and threshold values (expressed as a percentage of the minimum power of the symbols in the employed QAM constellation).

Considering threshold values ranging from 25% to 75%, the analysis of Fig. 7 reveals that, regardless of the $E_{b(elec)}/N_0$, the BER improves for thresholds close to 50%. With 75% threshold value, the BER performances are better than at 25%. This suggests that achieving better performance in SIM-OFDM is strongly linked to the choice of the threshold value used at the receiver. To face this issue, a correct threshold value is required. For that, an optimal solution would be the implementation of an artificial intelligence model.

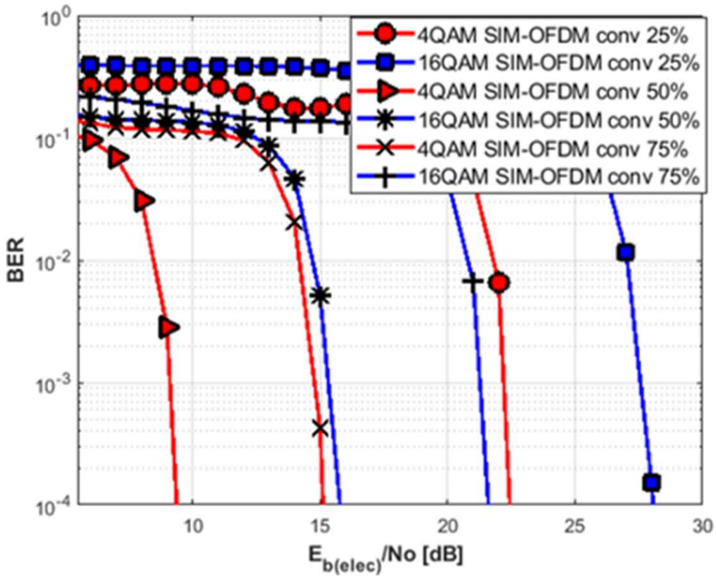

Fig. 7. BER against $E_{b(elec)}/N_0$, for improved SIM-OFDM over AWGN channel for different threshold values and QAM constellations.

Fig. 8 depicts the performance achieved under the same conditions (AWGN channel) for ESIM-OFDM compared to conventional OFDM. The analysis of Fig. 8 reveals a better BER performance compared to SIM-OFDM. This is justified by the fact that in ESIM-OFDM, QAM demodulation is facilitated by a simple comparison of the amplitude of symbols carried by every successive pair of subcarriers. Furthermore, comparing the performance of ESIM-OFDM with conventional OFDM shows a gain in $E_{b(elec)}/N_0$ of at least 3 dB for all QAM. This means that to achieve identical BER performance at a fixed QAM, only half the energy is required in ESIM-OFDM compared to conventional OFDM. In light of these results, ESIM-OFDM would be a suitable candidate for FSO systems deployment.

4.2 Performance analysis in FSO systems

In this subsection, we conduct a comparative study of the performance of 4QAM ESIM-OFDM with the NRZ modulation (often deployed in FSO systems). For this purpose, 0 presents the variation of the BER as a function of distance for different bit rates in a classical FSO transmission. The results obtained shows that for a fixed distance, the BER deteriorates with increasing bit rate, regardless of the modulation technique. At the same time, it degrades with the range of the FSO link regardless of the bit rate.

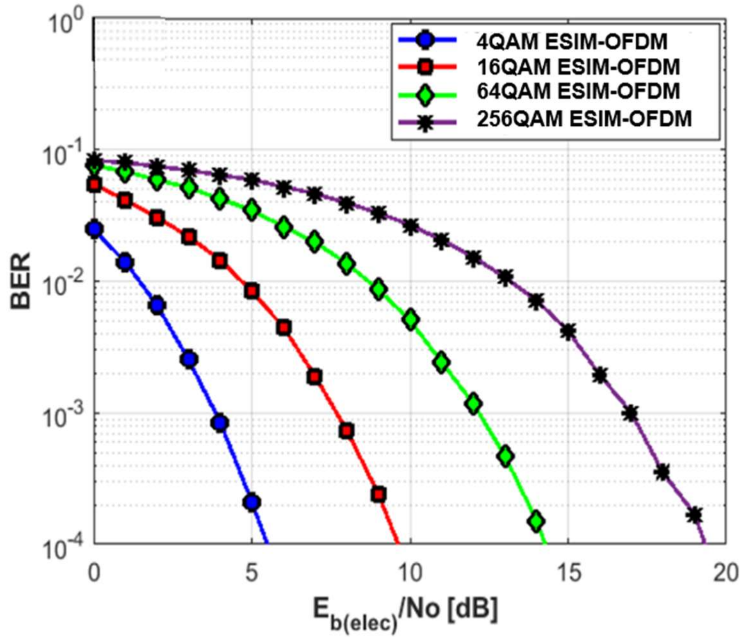

Fig. 8. BER against $E_{b(elec)}/N_0$, for SIM-OFDM versus conventional OFDM over AWGN channel for different QAM onstellations.

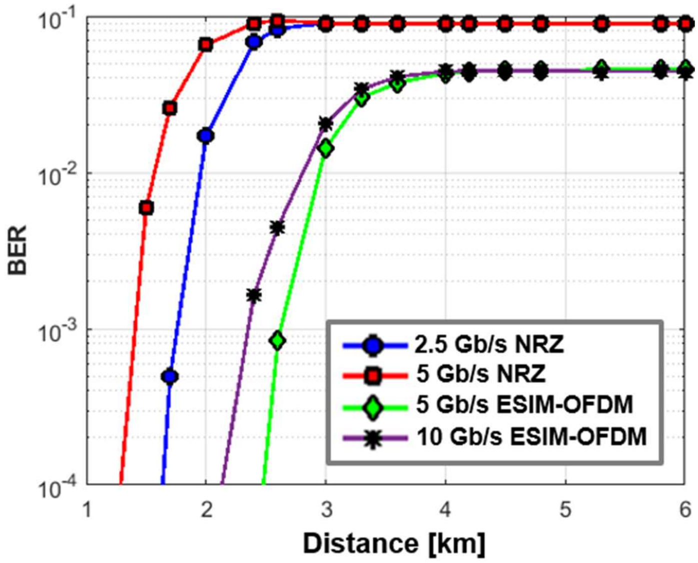

Fig. 9. BER against distance transmission for ESIM-OFDM versus NRZ for different data rates in a single wavelength FSO scenario (according to Fig. 6-a).

This is explained by the fact that the product [bit rate x distance] is a constant key in communications systems. Indeed, as the transmission distance increases, the distortion caused by atmospheric attenuation compounded with beam divergence intensifies, resulting in deteriorating performance as the data rate increases in the FSO link. It can be also observed that the ESIM-OFDM modulation technique enables achieving a range of at least 2.3 km at 10 Gb/s for a BER target value of 10^{-3}, whereas NRZ only allows ranges of approximately 1.3 km at a similar useful bit rate of 5 Gb/s. For a fair comparison, excluding BOOK transmission, the effective bit rate of ESIM-OFDM at 10 Gb/s would be equivalent to NRZ at 5 Gb/s. Therefore, this demonstrates the robustness of ESIM-OFDM compared to NRZ in FSO transmission context and proves it is a good candidate for free space optics communications.

In the DWDM-FSO link of Fig. 6-b, four (04) optical signals are multiplexed together before propagation through the FSO channel. Thus, when increasing the data rate per each wavelength, the transmitted aggregated data rate also increases. Fig. 10 present the BER obtained as a function of the aggregated data rate obtained in Fig. 6-b. In that case, a 4QAM ESIM-OFDM signal modulates each laser source at the emitter of the DWDM-FSO. Under simulated realistic DWDM-FSO conditions, it is observed that an aggregated data rate of approximately 10.1 Gb/s is achievable for a BER target value of 10^{-3} over a transmission range of 2km. This shows the potential of the ESIM-OFDM DWDM-FSO scenario as a viable solution for interconnection in 5G wireless technology.

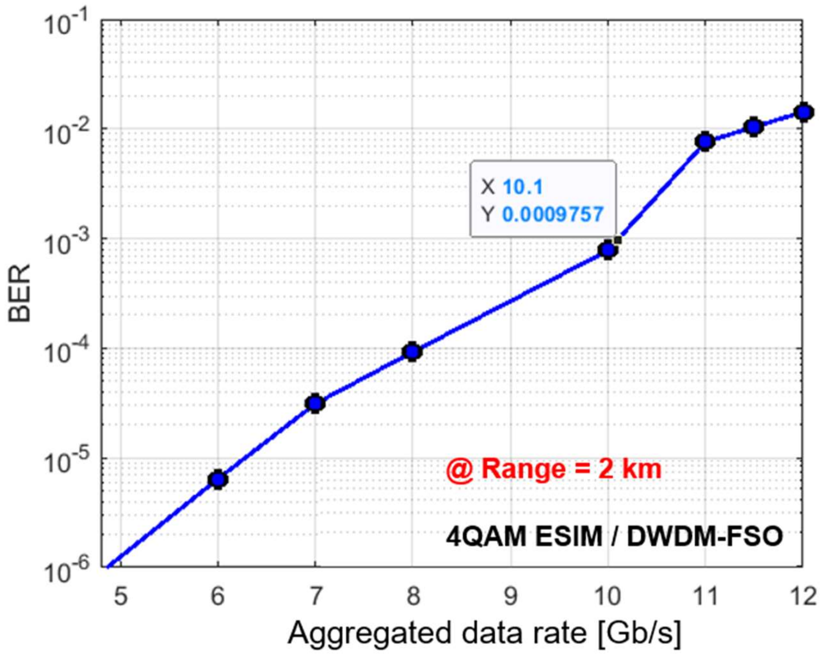

Fig. 10. BER against Aggregated data rate, for 4QAM SIM-OFDM/DWDM-FSO at 2 km transmission.

V. Conclusion

We introduced an overview of Subcarrier Index Modulation OFDM (SIM-OFDM) technique and it deployment in Free Space Optics Communications. After many simulations in AWGN channel and Free Space Optics channels scenarios, we finally showed that the conventional SIM-OFDM transmission performance is strongly linked to the choice of the threshold value used at the receiver side. And then, an Artificial Intelligence (AI) could be an interesting solution to optimize it performance. Also, we found that the Enhanced SIM-OFDM has great potentiality compared to conventional SIM-OFDM to be used in FSO context due to its resilience to fading, robustness against interference and easy demodulation with spectral efficiency. Its implementation in DWDM-FSO could represent a highly interesting solution for establishing 5G Backhaul links or interconnections between telecom sites and DTT (Digital Terrestrial Television) sites, particularly for hard-to-reach or isolated areas. Our future work will focus on the impact of the DWDM channels inputs associated with an AI model for further performance improvement.

VI. Acknowledgment

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