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Advantages of Spectrally Efficient Frequency Division Multiplexing Over Orthogonal Frequency Division Multiplexing

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Abstract*: An analysis on Spectrally Efficient Frequency Division Multiplexing (SEFDM) is contrast with Orthogonal Frequency Division Multiplexing (OFDM) considering the impact on Peak to Average Power Ratio (PAPR) and nonlinearities within fibre. With respect to OFDM the sub-carriers in SEFDM signals are compressed adjacent to each other at a rate of frequency lesser than the symbol rate. At the receiver end we have utilized the Sphere Decoder which is used to recover the data to remunerate the Interference created by the compressed signals (ICI) faced in the system. This research shows the advantages by using SEFDM and evaluates its achievement. PAPR. when compared with OFDM, while effects of non-linear fibres are considered. The use of various formats of modulation going from 4-QAM to 32-QAM, shows that the SEFDM signals have a noteworthy increment in the transmission length with respect to ordinary signals.

***Keywords*: Spectrally efficient frequency division multiplexing (SEFDM), orthogonal frequency division multiplexing (OFDM), optical fibre communication.**

I. INTRODUCTION

In our day to day life, optical fiber frameworks convey a large portion of the Internet information and structure the significant part of the correspondence foundation. The effectiveness of data capacity i.e. bandwidth usage [1] is a known key parameter of optical fiber framework. The spectral proficiency in optical frameworks is right now restricted because of fiber Kerr impacts, where signal debasement is all the more frequently and critical, for frameworks having higher transmission data transfer capacities, close channel separating or higher adjustment designs. We have reviewed the results of OFDM and SEFDM different modulation formats and calculated the PAPR results to compare them. In wireless communications, Multiple sub-carriers present in orthogonal frequency division multiplexing (OFDM) is generally utilized, which has been explored in super channel transmission in optical communications to gain spectral capacity i.e. bandwidth similar to Nyquist spaced wavelength division multiplexing (WDM) [2].

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For same optical bandwidth, OFDM and Nyquist spaced WDM system have equal error rate in bits (BER) and transmission efficiency. To improve the spectral efficiency, two approaches can be used. Using higher formats by considering given data transfer capacity and the other one is to possess less transmission capacity by lessening the sub carrier separating lesser than the rate of symbol, in this manner, at the cost of loss of orthogonality. This paper reports a near investigation of the two methodologies (higher-format modulation and the distance between sub-carriers lesser than the rate of symbol) for optical framework experiencing non-linearities of fiber Kerr. The issue in the main methodology is the cost and complication in the nature of creating modulation formats of a higher order, and in the subsequent methodology is the Interferences created by the carriers (ICI) produced due to the compression of sub-carriers adjacent to each other at a frequency rate lesser than the symbol rate [3]. On embracing non-orthogonal multicarrier signals with sub-carrier separating not as much as the rate of symbol, multicarrier frameworks can compress the data and increase bandwidth. This is known as spectrally efficient frequency division multiplexing (SEFDM). The work clarified above shows the benefit of SEFDM in sparing range when contrasted with OFDM for a similar order of modulation, additionally, SEFDM has more advantages when contrasted with OFDM of high modulation order with similar spectral efficiency. In any case, no examination for looking at the effect of performance and non-linear properties of SEFDM and OFDM is accounted for.

II. SPECTRALLY EFFICIENT FREQUENCY DIVISION MULTIPLEXING

The stream of modulated SEFDM symbols are carried by SEFDM, where each SEFDM signal carries the Quadrature Amplitude modulated symbols of N complexity. These symbols of N complexity are inflected on every individual sub-carrier each. This SEFDM signal can be written as

$$x(t) = \frac{1}{\sqrt{T}} \sum_{l=-\infty}^{\infty} \sum_{n=0}^{N-1} S_{l,n} exp\left[\frac{j2\pi n\alpha(t-lT)}{T}\right]$$

here the bandwidth compression factor is α which is:

$$\alpha = \Delta f \,.\, T,$$

where Δ f shows the difference in frequency of any two contiguous subcarriers, the period of single SEFDM symbol is T, for normalization the scaling limit taken is 1/√ T, here N represents the total sum of sub carriers and $S_{l,n}$ represents the modulated complex QAM symbol at the nth sub-carrier at the lth symbol of SEFDM.

The compression factor of bandwidth is α and therefore the percentage of bandwidth saved is equal to $[1-\alpha] \times 100$ percent. Generally, in OFDM signals the value of α is equal to 1 and the value of α in SEFDM is less than 1. The given Figure 1 below shows the frequency vs amplitude of both the signals. It can be observed that the signals of SEFDM has a lesser and narrower bandwidth due to the non-orthogonal sub-carriers being relatively closer to each other, compared to the OFDM signal with similar parameters that is the total sum of sub-carriers and bandwidth of modulation for each sub-carrier, at the cost of ICI formed by itself in the process. In SEFDM the sub-carriers are relatively closer to each other while compared to OFDM which leads to the compressed signal data capacity. To compare fairly with the same bandwidth occupied by the signal, more sub-carriers have to be packed closely. The data rate can be improved to a level which is equal in modulation formats of higher order

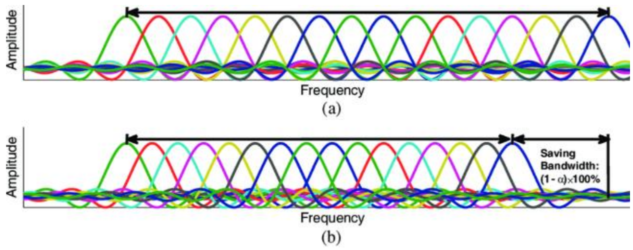

Figure. 1. Amplitude vs Frequency, 16-overlapped sub-carriers in (a) OFDM and (b) SEFDM. Each Colours represent another sub-carrier and shows compression and overlapping of signals orthogonally and the non-orthogonal in (a) and (b) respectfully

TABLE 1
4-QAM and 8-QAM Specifications in Dual-Polarization of OFDM and SEFDM (α = 0.667)

Scheme	Sub carriers	BW- (data capacity)	Rate of symbol	Rate of bits
4-QAM,OFDM	12	25 GHz	25 Gsym/s	~95 Gbits/s
8-QAM,OFDM	12	25 GHz	25 Gsym/s	~142 Gbits/s
4-QAM,SEFDM	17	25 GHz	37 Gsym/s	~142 Gbits/s

TABLE 2
16-QAM and 32-QAM Specifications of Dual-Polarization OFDM and SEFDM (α = 0.81)

Scheme	Sub carriers	BW- (data capacity)	Rate of symbol	Rate of bits
16-QAM,OFDM	12	25 GHz	25 Gsym/s	~192 Gbits/s
32-QAM,OFDM	12	25 GHz	25 Gsym/s	~240 Gbits/s
16-QAM,SEFDM	17	25 GHz	32 Gsym/s	~240 Gbits/s

In 4QAM SEFDM signal modulation, the closely adjacent sub-carriers are seen in Table 1. The FFT is of size 32 in all framework where sum of data sub-carriers is unique in the framework. It can be seen that the 4QAM modulated signals can pack five sub-carriers more than OFDM. The higher symbol rate is achieved even though the signal bandwidth is equal for all frameworks.

Therefore, bit rate for both 8-QAM in OFDM and 4-QAM signals in SEFDM are equal. From the table we can conclude that the modulation of high order can be substituted by modulation of lower order. To increase the framework capacity by double, dual-polarization signal transmission scheme can be considered in the optical fibre frameworks. In modulation of high order as in 16-QAM, the compression limit of bandwidth and extra sub-carrier are set accordingly as needed and can be seen in Table 2. The system modification shows the rate of bits in a 32QAM of OFDM and 16QAM of SEFDM as similar.

III. COMPARISON OF PEAK TO AVERAGE POWER RATIO BETWEEN SEFDM AND OFDM

In MATLAB, we have evaluated the Peak to Average Power Ratio (PAPR) [4] of both the signals. We have determined that, for given set of same parameters the Spectrally Efficient Frequency Division Multiplexing have significantly lower Peak to Average Power Ratio (PAPR) to that of OFDM (Orthogonal Frequency Division Multiplexing).

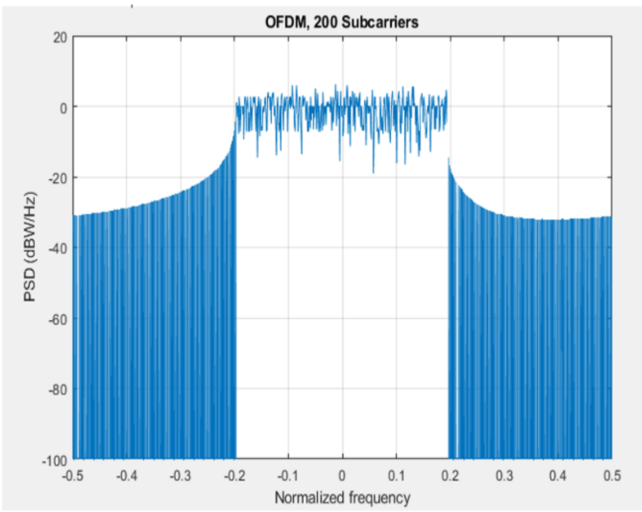

Figure. 2a. Simulation of OFDM with 200 Subcarriers

In the Figure 2a, we first simulated the OFDM using the set of parameters (sub-band size, number of sub-bands, sub-band offsets, filter length, slope attenuation, bits per sub-Carrier i.e. 4:16 QAM we have used) and we have calculated the PAPR for OFDM.

And using these set of parameters for SEFDM we have also calculated PAPR for SEFDM as shown in Figure 2b. Notice that these 200 sub-carriers are placed in the same signal bandwidth as we have normalized the frequency.

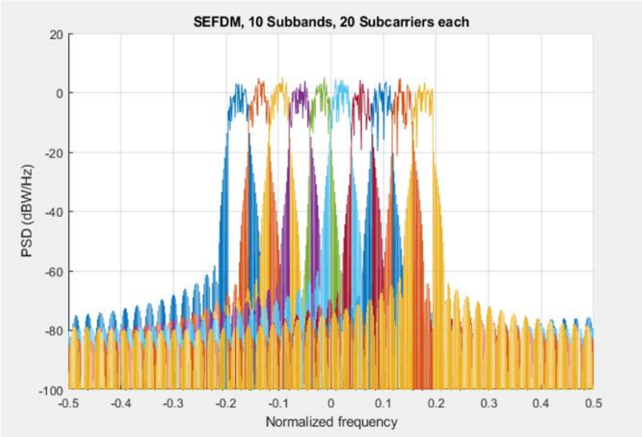

Fig. 2b. SEFDM Simulation with 200 Subcarriers

IV. SPHERE DECODING AT SIGNAL DETECTION

Detection linear in nature takes place initially and then decoding by hard decision of OFDM signals, which develops to ideal potential. But the non-orthogonal signals of SEFDM, demands the complex methods like detection using non-linear methods. In between subcarriers, the loss of orthogonality causes severe damage of the signals by ICI, which leads to high possibility of the rate of error if a detector linear in nature is utilized. Having a goal to reduce the rate of error, for SEFDM, the optimal detection algorithm was proposed called Maximum Likelihood (ML).

The motive of ML is, finding every possible sequence of symbols transmitted for every SEFDM symbol (e.g. QAM). It estimates the received symbols in SEFDM in Euclidean form. In a given symbol which is received, the best solution is one among the Euclidean norm which is small. The challenge is that the ML complexity increases tremendously with increase in total sum of subcarriers or modulation scheme order. In order to decrease these high complex levels, present in ML detection with least error rates, a new and unique complexity reduction technique, known as Sphere Decoder (SD) [5] and was suggested mainly in MIMO (Multi Input Multi Output) systems, which was later modified and utilized in retracing the complexity SEFDM signals. The main principle of a Sphere Decoder [6] is to perform better than the ML and its able to do that by finding the best optimal solution possible, with the smallest Euclidean norm and in the already defined sphere space limited by a radius of sphere initially. The infinite space of ML used in searching is furthermore than the already defined space of searching, therefore the sphere decoder attains closer to ideal performance and decreases complexity at the receiver. Figure 3 shows the diagram of tree which demonstrated how the algorithm of SD works. Every individual circle of the tree is called a node and shows a constellation's point. The total sum of branches present for each node and the constellation's size are equal. ML identifies every node with ease both reserved and abandoned. On the other hand, SD only detects node with in pre-set sphere at Fig.3. At every node, the total points which are inside the boundary of the sphere space are kept while the left over are abandoned with every predecessor node. The transition occurring forwardly from top level to bottom level shows the decision of only one symbol and the backward occurring transition shows the discard of every node and its every child node.

The radius of the sphere initially determines all the complexity involved in the decoding process as it identifies the search sphere space's size. The probability of finding an ideal solution reduces with small radius as it reduces and restricts the space used in searching about a node and having a big radius aids in increasing the complex nature effectively. 31 nodes can be seen in Fig.3. Only few nodes are searched while remaining are abandoned. Therefore, we can conclude that the efficiency of sphere decoder is much better than that of ML and it can be seen with increase in formats of modulation or with a large sum of sub-carriers.

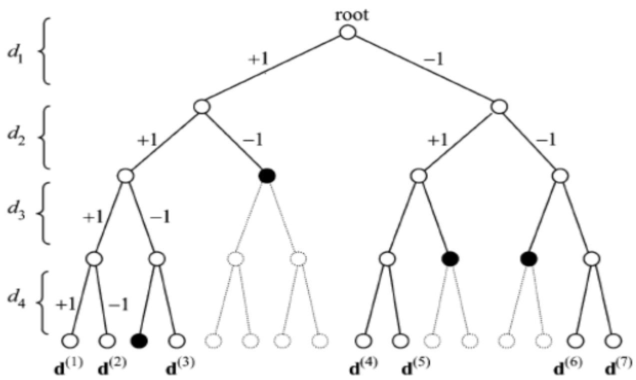

Fig. 3. Example of Tree Diagram SD

V. OPTICAL TRANSMISSION SETUP

Both OFDM and SEFDM and transmission is executed in a double polarization optical fibre, as found in Figure. 4. For a specified polarization, at the transmitter, the stream of bits is initially mapped at the M Quadrature Amplitude Modulated and there after serial and parallel transformation, guard-bands in frequency are located at all the ends of the spectrum of signal for usage of extensive sampling technique. At that point, both of OFDM/SEFDM Inverse Fast Fourier Transform is used in modulating the M Quadrature Amplitude Modulated symbols on individual sub carrier. After serial and parallel transformation, the signal complex which is electrical in nature is mapped on the carrier by utilizing the specifications seen in the Table 2. The similar kind of process is utilized in the 2nd polarization. The symbols produced after the modulation are random to every polarization and independent to each other. By the use of Manakov equation, the Standard Single Mode Fibre (SSMF) is reproduced, utilizing the Fourier strategy of split step with step size of logarithmic conveyance [7]. An Erbium Doped Fibre Amplifier is used towards the last end in every transmission range to make up for fibre losses. Blending of signal with a perfect Lo (Local Oscillator) laser for the execution of angle of phase and polarization different coherent detector at recipient. The digitization of identified signals utilizing perfect convertors like Analog to Digital (ADC). The framework concentrated of this work, doesn't utilize cyclic prefix, and CD (chromatic dispersion) was remunerated with the equalizer of frequency domain [8]. The fibre scattering impacts are linear, it very well may be completely repaid utilizing DSP (Digital Signal Processing) techniques in long distance Optical fibre Frameworks.

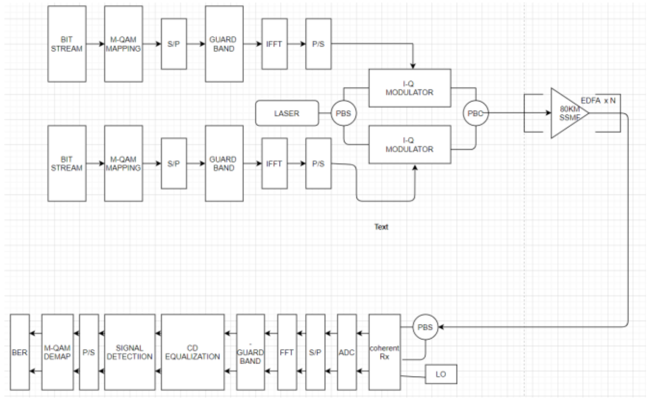

Figure. 4. Systematic diagram of OFDM or SEFDM optical fibre transmission setup. Abbreviations are IQ is In phase & quadrature, S/P is serial to parallel, S/P is parallel to serial, PBS stands for polarization beam splitter, PBC stands for polarization beam combiner, Rx is receiver, ADC stands for Analogue to Digital converter.

The two samples which are digitized and compensated received samples are operated in a similar manner. Initially every data is converted from serial to parallel multi-carrier (OFDM/SEFDM) symbol streams for the operation of FFT demodulation. After the above process, the guard bands in frequency are taken out to recover and detect the M-QAM symbols by utilizing an either a zero-forcing detector or a SD (Sphere Decoder). The bit stream used in receiver end is obtained after serial to parallel conversion and damping by M-QAM.

TABLE 3
System Parameters

Parameters	Value
Transmission parameters	
Attenuation coefficient	0.2 dB/km
Chromatic dispersion coefficient	17 ps/(nm·km)
Nonlinear coefficient	1.2 /(W·km)
Span length	80 km
SSMF steps per span (logarithmic step size)	1000
EDFA noise figure	4.5 dB
Signal and modulation parameters	
Symbol rate	32 GBaud
Central wavelength (transmitter and LO)	1550 nm
Number of polarizations	2
Number of SEFDM/OFDM sub-carriers	16

Finally, the performance of system is assessed through the estimation of the BER (Bit Error Rate) of 10^5 bits per each polarization either OFDM or SEFDM. The implementation of simulations within an extensive sampling limit equals two. The offset of frequency, angle of phase in the transmitter, LO lasers and delay produced in group between two polarizations of optical systems are dismissed. Transmission framework specifications are defined in Table 3

VI. RESULTS

Binary input/output for the channels which are binary as well as symmetric, where we have applied probability of transition, the R*c* (coding rate) in M-QAM (Quadrature Amplitude Modulation) Optical Fibre, assuming a total rough choice of the code Forward Error Correction (FEC).

Thereby, the SE can be formulated as:

$$\text{Spectral Efficiency} = \frac{1}{\alpha} \,.\, Rc \,.\, Np \,.\, \log_2 M$$

here SE is spectral efficiency that can be gained, M is the size of constellation and N*p* is the value of states of polarization. The values of SE of OFDM and SEFDM are compared in the table 4.

We can identify that it is possible for 4-QAM SEFDM to achieve the same SE as of 8QAM-OFDM, also it shows 1.5 times gain over 4-QAM OFDM. This shows the possibility of replacing higher modulation formats with the lower order.

TABLE 4
Ideal and SE of OFDM and SEFDM

Schemes	Ideal spectral efficiency	Achievable spectral efficiency at BER=3.8x10⁻³
4QAM-OFDM	4 bit/(s·Hz)	3.86 bit/(s·Hz)
8QAM-OFDM	6 bit/(s·Hz)	5.78 bit/(s·Hz)
4QAM-SEFDM (α=0.67)	6 bit/(s·Hz)	5.78 bit/(s·Hz)
16QAM-OFDM	8 bit/(s·Hz)	7.712 bit/(s·Hz)
32QAM-OFDM	10 bit/(s·Hz)	9.64 bit/(s·Hz)
16QAM-SEFDM (α=0.8)	10 bit/(s·Hz)	9.64 bit/(s·Hz)

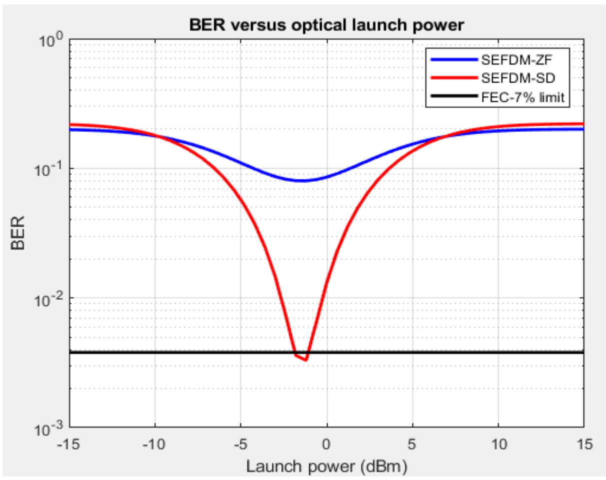

Figure. 5. Bit Error Rate vs ideal launch power signal transmission distance of 7,200 km of two 4QAM-SEFDM (α= 0.667)

In Optics, Communication framework was executed to explore the proficiency of SEFDM signal over fibres considering long haul, contrasted with that of regular OFDM signals. At first, an optical fibre with length of 7,200 kms was assessed. SD was utilized to reproduce 4-QAM SEFDM signals from automatically generated Inter Channel Interference at the recipient, demonstrating significantly better execution over Zero forcing (ZF) detector, that is utilized in OFDM frameworks, as shown in Figure. 5. It is observed that by utilizing SD the FEC limit of BER equals to 03.79 × 10^ (-3) possibly gained, permitting the distance more than 7,200 km fibre. Given the huge out performance comparative with the ZF detection, for the improvement of SEFDM only SD is utilized.

Unlike OFDM, SEFDM is a not an orthogonal signal which develops interference in the middle of the sub carriers.

To avoid this, an interference-cancellation receiver needs to be employed. Since OFDM don't have any self-created ICI, the sphere decoding is of no use to it. It comes to play when signals are affected with ICI only.

To display the upsides of SEFDM on top of OFDM, three frameworks of a similar signal data transmission are tried with 2 diverse modulation formats more than 7,200 kms transmission fibre, are analysed in Figure. 6. (4 & 8) QAM symbols are operated for OFDM, although just 4QAM was operated for SEFDM. From Table 4, to fulfil a similar SE as that of 8-QAM OFDM and 4-QAM SEFDM whose value of α should be 0.667, which brings about 33% bandwidth reduction or 1.5 times improvement in SE.

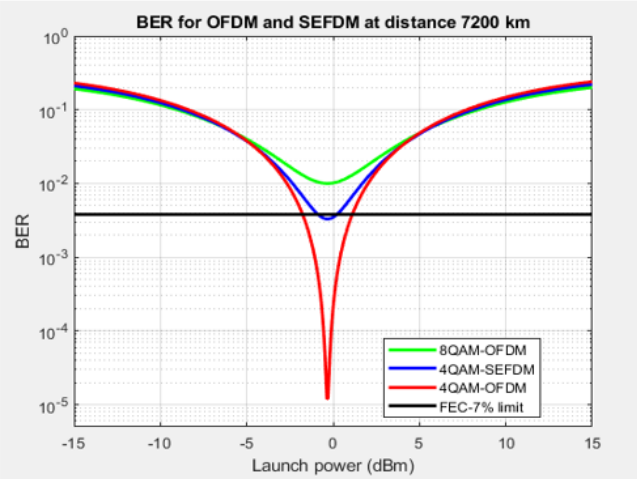

Figure. 6. Bit Error Rate vs ideal launch power signal transferal distance of 7,200 kms.

Although the 4-QAM SEFDM and 8-QAM OFDM have a similar SE and possess a similar transmission capacity, subsequently, the two of them have similar data rate. Accepting equivalent involved bandwidth of signal, the 4--QAM OFDM has less data rate (nearly by half) contrasted with 4-QAM SEFDM and 8-QAM OFDM plans.

We can observe that three bends have about the same ideal launch power as they occupy same data transfer capacity. The examination in Figure. 6 is centred around the 4-QAM SEFDM and the 8-QAM OFDM because of their indistinguishable bandwidth of signal, SE the and rate of data. In view of the previously mentioned outcomes, it is induced that the 4-QAM SEFDM can accomplish 7,200 kms separation while its SE proportionate, the 8-QAM regulated OFDM won't accomplish such separation of transmission. The 4-QAM OFDM brings out perfect execution reason for the way bringing about reduced level impedance.

The most elevated transmission separation of 8-QAM OFDM for an objective Bit Error Rate of 03.79 × 10^ (-3) was contemplated and simulated in Figure 7. Their separation is diminished step by step when 5,200 kms is designed for the 8-QAM OFDM framework, the execution curve closely surpasses the Bit Error Rate limit inside ideal launch power being nearer to −1.99 dBm. This demonstrates that most elevated conceivable separation that can be accomplished by 8-QAM modulated OFDM is 5,200 kms. Therefore, contrasted with 4-QAM SEFDM, at a same SE, same BW and data transfer rate, the utilization of 4-QAM SEFDM brings about around 38.5 percent development in distance of the transmission.

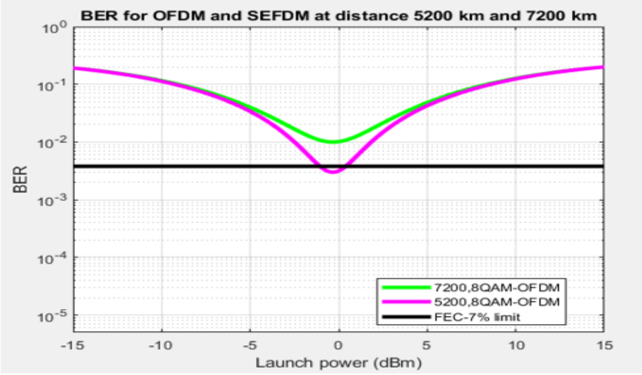

Figure. 7. Bit Error Rate vs ideal launch power signal transferal distance of 5,200 and 7,200 km.

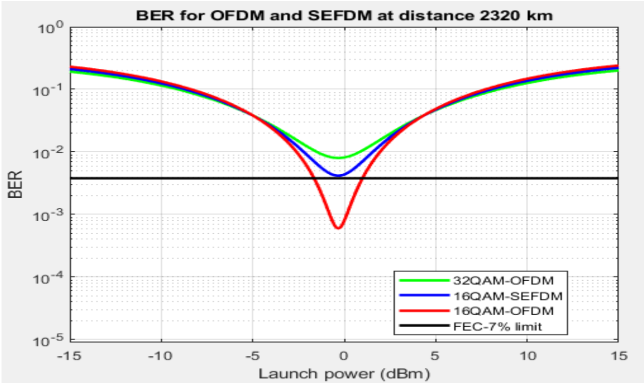

Figure. 8. Bit Error Rate vs ideal launch power signal transmission 2,320 km.

High modulations like (16 and 32) QAM, results seen in Figure 8 and Figure 9 where 3 frameworks are assessed. Figure 8 shows that the 16-QAM SEFDM execution can arrive at 03.79 × 10^ (-3) a good way off of 2,320 kms whereas the 32-QAM OFDM can't accomplish such separation.

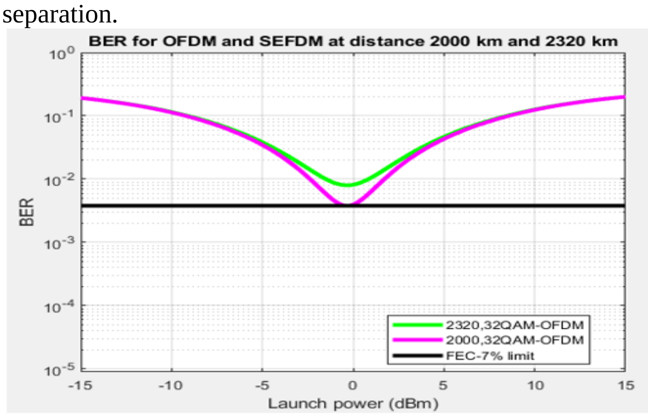

Figure. 9. Bit Error Rate vs ideal launch power signal transmission distance of 2,320 km and 2,000 km.

As both OFDM and SEFDM signals involve a similar transmission capacity, the ideal launch power here is again same. In spite of the fact that, 32-QAM OFDM signal, it can't attain FEC limit. A fascinating detection is that 16-QAM SEFDM framework carries on more awful than 32-QAM OFDM framework at linear and nonlinear frameworks, however it operates much better the 32-QAM OFDM framework all over the ideal power locations. This outcomes in the general out performance of the 16-quadrature amplitude modulated SEFDM. Constellations which have higher density, the SD can't effectively expel the ICI inside SEFDM under presence of powerful noise.

Figure. 9 shows two frameworks working at two fibre separations. Along these lines, it's clear that maximum reach of 32-QAM OFDM is roughly 2,000 kms. In this, we think about frameworks of equivalent SE's and data rates.

The utilization of SD, which can highly eradicate the effects of ICI created within SEFDM, leads to ideal likelihood execution. Nyquist spaced framework of WDM, where transmission separation is 1,760 kms and data transfer capacity is around 160 Giga Hz. To plan a reasonable examination, a format of modulation 32-QAM is utilized in the FIVE channelled WDM framework and 16-QAM is utilized in the SEFDM framework where the total data transmission of 160 Giga Hz is involved by SEFDM whose α equals to 0.798.

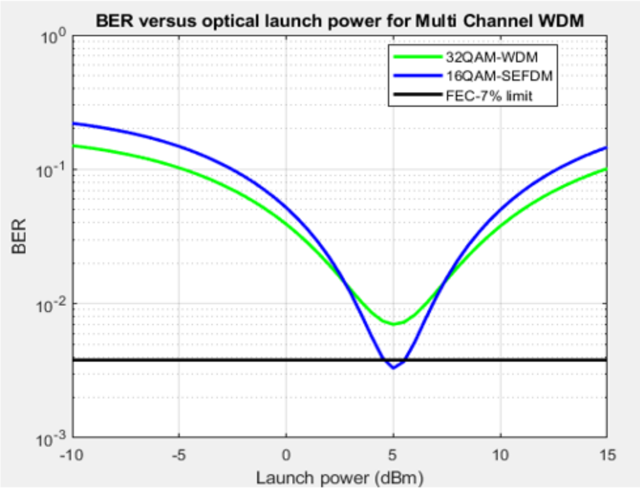

Figure. 10. Bit Error Rate vs ideal launch power for WDM and SEFDM at a transferal separation of 1,760 kms.

Simulated results are shown in Figure 10. The red bend speaks to the average BER execution for five channelled WDM framework (normal BER more than five channels), and the blue bend to the conduct of the transmission of SEFDM framework. It is identified that, for a similar channelling separation, the SEFDM exhibits better execution when contrasted with the five channelled WDM transmission.

SD is a superior arrangement with an execution better than ZF, as it is not advanced in detecting techniques, yet moving toward the ideal execution of ML however with low intricacy.

VII. CONCLUSION

In this paper, we have examined the anticipated execution of OFDM and SEFDM multi carrier frameworks in optical fiber situations where nonlinearities are thought of. In SEFDM, SE can be enhanced by compressing sub carriers closely than OFDM, which lets favorable benefits on top of OFDM when signals traverse over fibers that are nonlinear in nature. Assuming frameworks of equivalent feasible SE and bit rate and for a FEC breaking point of 03.79 × 10^ (-3); the 4-quadrature amplitude modulated SEFDM signal has approximately 38 and ½ percent reach at advantage stretching out transmission separation to 7,200 kms while the 8-quadrature amplitude modulated OFDM signal can just arrive upt0 5,200 kms only. Higher order modulations like, 16-quadrature amplitude modulated SEFDM beats a spectrally identical 32-quadrature amplitude modulated OFDM by 16 percent. This indicates that utilization of SEFDM signals conceivably rise the transmission separation of optical transmission frameworks and that increment is relied upon extremely huge under nonlinearity. Our results that the PAPR of SEFDM is lesser than OFDM, therefore the use of SEFDM have more benefits as it more efficient.

Later on, the utilization of nonlinear remuneration [9] in SEFDM, optical frameworks will be researched further, where the computerized back-spread calculation will be utilized. It has been realized that the SD can't effectively eliminate the ICI in the solid nonlinear system which results to an imperfect activity of SEFDM framework, the use of non -linear fibers utilizing the advanced back propagation is additionally anticipated to enhance the concealment of Inter Channel Interference.

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