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Performances of OFDM/OQPSK Modulation for Optical High Speed Transmission in Long Haul Fiber over 1600 Km

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Abstract- Orthogonal Frequency Division Multiplex (OFDM) is a high-speed transmission technique widely studied in wireless networks. Its potential presents it as an ideal solution for high-speed transmission in optical fiber networks. This study presents the OFDM modulation associated with Offset Quadrature Phase Shift Keying (OQPSK) filtered using a filter banks for an optical transmission at the rate of 10 GB/s over 1600 Km in a single mode fiber (SMF). The simulations are performed in the VPI Photonics software environment. The results show that the filtered OFDM/OQPSK provides better transmission performance than the Classical OFDM/QPSK firstly because it does not require equalization to certain distances; secondly distances are greater than those achieved with the conventional OFDM in similar studies. In this study the bandwidth is maximized because we do not use the cyclic prefix (CP). Moreover the complexity of transmitters and receivers is reduced, which shows OFDM/OQPSK as an effective solution to combat the effects of the chromatic dispersion (CD), the polarization mode dispersion (PMD), the inter-symbol interference (ISI) and nonlinearities.

Index Terms: ber, high-speed, OFDM, OQPSK, optical fiber.

I. INTRODUCTION

OFDM multicarrier modulation techniques have been used to transmit information using various channel transmission networks such as Wi-Fi (IEEE 802.11) or new mobile networks [1], [2]. Application to optical fiber networks is new and raises new issues as the transmission channel has different characteristics [3], [4]. Techniques related to the conventional OFDM like the implementation of an appropriate channel coding (COFDM) is used to improve the performance of OFDM on an optical medium. COFDM has been studied in our previous works [5], [6]. New solutions that can save the cyclic prefix, OFDM/OQPSK, are based on a prototype function which is better localized in time and frequency domain. Another approach is related to the use of OQPSK modulation with a filter banks to perform a good signal processing which can achieve a better performance than the classical OFDM with cyclic prefix.

In fact, the idea of using filtered OFDM/OQPSK by a filter banks is based on the fact that OFDM is a common choice that can now be replaced or supplemented by Filter Bank-based Multicarrier (FBMC) techniques which have some very interesting characteristics, like the results showed by M. Bellanger [7], [8]. Then, it seems to us as a good idea to investigate the combination of the two techniques where an OFDM/OQPSK signal is filtered by a filter banks.

Filter Banks Multicarrier approach can be seen as an evolution and an extension of the FFT approach of the OFDM. In order to keep the same size as the FFT used in OFDM, we implemented a polyphase structure.

In this context, we used to modulate subcarriers by QPSK for the generation of the OFDM baseband signal before applying the OQPSK and filter banks process.

Performance tests of the transmission chain were carried out on the basis of the Error Vector Magnitude (EVM), the Q factor (Qeff) and Bit Error Rate (BER). All these tests were performed according to the Optical Signal to Noise Ratio (OSNR).

II. MATERIAL AND METHODOLOGY

a) OFDM/OQPSK data structure

The principle of the OFDM is based on the division of the transmitted signal into many sub-carriers, which makes it less sensitive to frequency selectivity, and by the extension of the OFDM symbol duration using a Cyclic Prefix (CP) of sufficient length to avoid ISI. The OFDM signal is in baseband time domain [3]:

$$S_{OFDM}(t)=\sum_{i=-\infty}^{+\infty}\sum_{k=-N_{SC}/2+1}^{k=N_{SC}/2}C_{ki}\Pi(t-iT_S)e^{j2\pi f_k(t-iT_S)} \qquad (1)$$

$$S_k(t-iT_S)=\Pi(t-iT_S)e^{j2\pi f_k(t-iT_S)} \qquad (2)$$

$$f_k=\frac{k-1}{t_S} \quad \Pi(t)=\begin{cases}1, & (-\Delta_G \prec t \le t_S)\\ 0, & (t\le -\Delta_G, t\succ t_S)\end{cases} \qquad (3)$$

where $S_{OFDM}(t)$ is the OFDM signal, Δ_G is the guard interval characterizing the cyclic prefix CP and $\Pi(t)$ the rectangular function taking into account the guard interval. C_{ki} is the *i-th* information symbol of the *k-th* subcarrier, $S_k(t)$ is the waveform of the *k-th* subcarrier, N_{SC} is the number of carriers, f_k is the frequency of the

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k-th subcarrier, T_S is the symbol period, t_s is the observation period of the OFDM symbol.

In the context of OFDM/OQPSK, we don't use the cyclic prefix, so $\Delta_G = 0$. The signal at the output of the optical receiver is:

$$r(t) = e^{j(\omega_{off} t + \Delta\phi)} . r_0(t) \qquad (4)$$

$$r_0(t) = S_{OFDM}(t) * h(t) \qquad (5)$$

with $\omega_{Off} = \omega_{LD1} - \omega_{LD2}$ and $\Delta\phi = \phi_{LD1} - \phi_{LD2}$; ω_{LD1} and ϕ_{LD1} are respectively frequency and phase angular of the transmitter laser. ω_{LD2} and ϕ_{LD2} are respectively frequency and phase angular of the receiver laser. The symbol * represents the convolution product and *h(t)* is the impulse response of the optical fiber channel (SMF fiber).

OFDM has many variants and especially the one where the Cyclic Prefix is suppressed and adding an extension of the FFT approach, like FBMC. There are mainly three FBMC techniques that have been studied in the literature: Offset Quadrature Amplitude Modulation (OQAM), Cosine Modulated multi Tone (CMT), and Filtered Multi Tone (FMT). The term 'offset' refers to the time shift of half the inverse of the sub-channel spacing between the real part and the imaginary part of a complex symbol. Our goal is to address OQPSK which is a variant using QPSK modulation.

Contrary to OFDM, which transmits complex-valued symbols at a given symbol rate, OQPSK transmits real-valued symbols by introducing a half symbol space delay between the in-phase and quadrature components of QPSK symbols, it is possible to achieve a baud-rate spacing between adjacent subcarrier channels and recover the information symbol, free of ISI and Inter-Carrier Interference (ICI). The OQPSK transmitter structure used is the one presented in Figure 1. In the Receiver in Figure 2, the inverted process is achieved using an analysis filter bank.

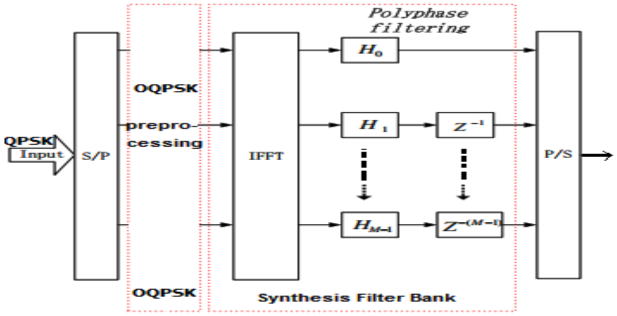


Figure 1 : OQPSK transmitter

H_0, H_1,… H_{M-1} are the prototype filter coefficients. The prototype filter design is based on the Nyquist criterion where the global Nyquist filter is generally split into two parts, a half-Nyquist filter in the transmitter and a half-Nyquist filter in the receiver.

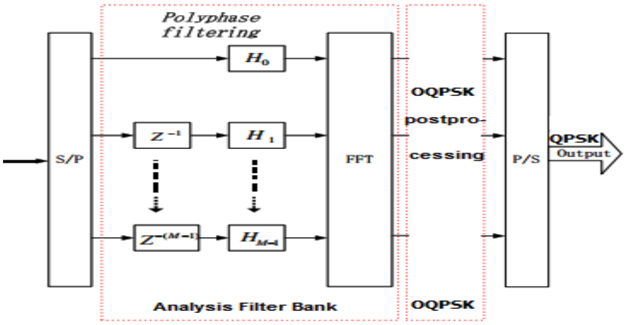


Figure 2 : OQPSK receiver

The analysis and synthesis filter banks can be expressed as functions of the prototype filter *P*[m].The symmetry condition is satisfied by the squares of the frequency coefficients of the filter [9].

$$P[m] = \bar{P}[0] + 2\sum_{k=1}^{K-1} (-1)^k \bar{P}[k] \cos\left(\frac{2\pi k}{KM}(m+1)\right) \qquad (6)$$

With m =0,1,…, KM-2, the prototype filter length is L = KM±1 with M the number of subchannels and K the overlapping factor.

The frequency coefficients of the half-Nyquist filter obtained for K=4 are used for the prototype filter in the simulation and are given in Table1.

Table 1: Frequency Domain Prototype Filter Coefficients

K	H0	H1	H2	H3
4	1	0.971960	√2 / 2	0.235147

The *kth* synthesis filter is defined by [10]:

$$g_k[m] = P[m]\exp\left(j\frac{2\pi k}{M}(m - \frac{L_p - 1}{2})\right) \qquad (7)$$

The *kth* analysis filter is simply a time-reversed and complex-conjugated version of the corresponding synthesis filter. So it is as follows:

$$f_k[m] = g_k^*[L_p - 1 - m] \qquad (8)$$

$$f_k[m] = P[m]\exp\left(j\frac{2\pi k}{M}(m - \frac{L_p - 1}{2})\right) \qquad (9)$$

b) Optical transmission chain

The digital optical transmission channel used is illustrated in Figure 3.

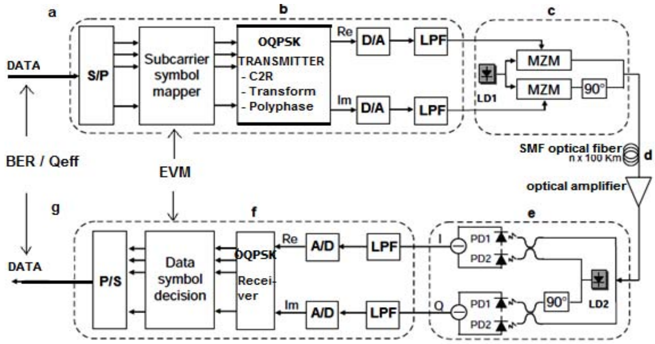


Figure 3 : OFDM/OQPSK optical transmission channel: a- data generation; b-OFDM/OQPSK transmitter; c-RF/Optical converter, d-Optical SMFfiber; e-Optical/RF Converter; f-OFDM/OQPSK Receiver g-data recovering

OFDM optical transmission chain is simulated in VPITransmissionMaker 9.1, [11] and Matlab cosimulation environments. OQPSK modulations are not available in VPITransmissionMaker. So cosimulation with Matlab is used to add specific processing.

The developed processing platform is a universe of interconnected modules where some new galaxies were created. The processing chain used is shown in Figure 4. The simulation model "OFDM for Long-Haul Transmission" available in VPITransmissionMaker was used as a model of inspiration [12].

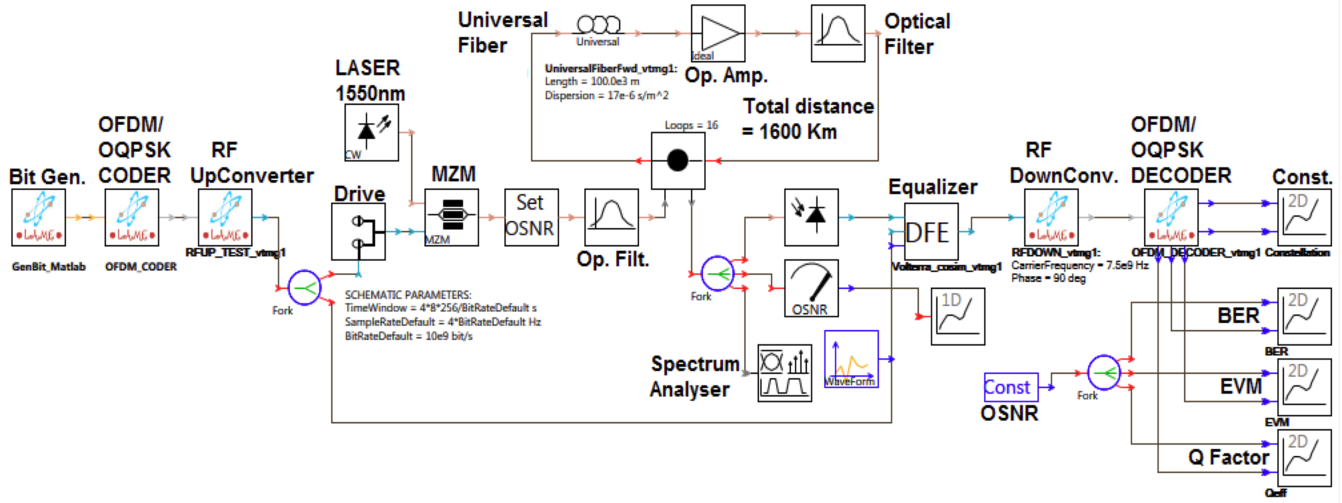


Figure 4 : Scheme of the simulation

New galaxies Bit_Gen for data randomly generation, OFDM_OQPSK_Coder for OFDM/OQPSK coding and RF_Up_Converter for frequency shifts have been implemented in the transmitter side. They have been designed using Matlab in cosimulation with VPITransmissionMaker which provide an interface for that. Figures 5, 6 and 7 show the details galaxies.

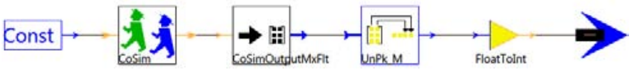
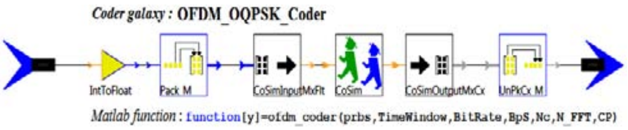


Figure 5 : Bit_Gen galaxy



Matlab function : `function[y]=ofdm_coder(prbs,TimeWindow,BitRate,BpS,Nc,N_FFT,CP)`

Figure 6 : Coder galaxy

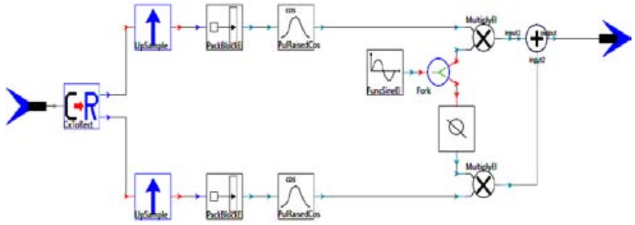


Figure 7 : RF_Up_Converter galaxy

Also new galaxies RF_Down_Converter for frequency shifts and OFDM_OQPSK_Decoder for OFDM/OQPSK decoding have been implemented in the receiver side. They have also been designed using Matlab in cosimulation with VPITransmissionMaker. Figures 8 and 9 show the details galaxies.

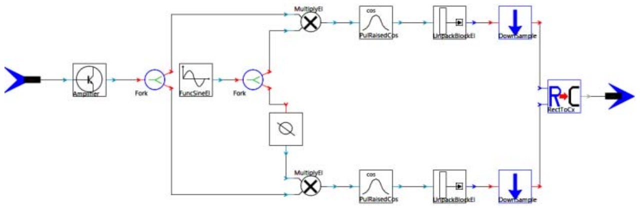


Figure 8 : RF_Down_Converter galaxy

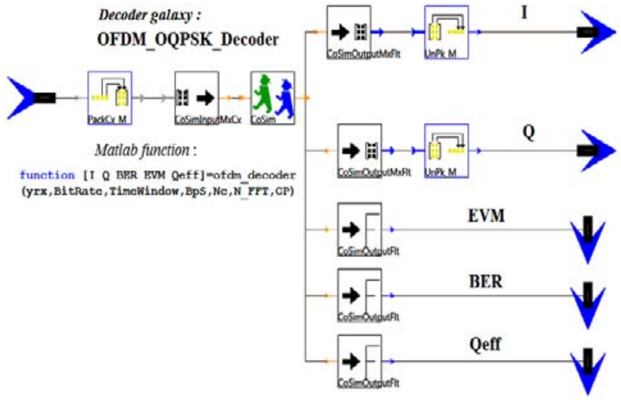


Figure 9 : Decoder galaxy

We monitor the OSNR so as to fix its successive values at the transmitter side which can influence the calculation of BER, modeling the variable effect of imperfections in the optical transmission channel. For this the galaxy Set_OSNR is used. The performances are evaluated using the OSNR measured at the receiver side before the entrance of the signal in the photodiode, by using an OSNR meter.

In order to use the successive values of OSNR in the Decoder galaxy, the OSNR meter uses a variable called OSNR that is also used as the parameter of the Const module in the global transmission chain.

An equalization process is added to the global chain to illustrate the impact of equalization in the calculation of *EVM, BER* and *Qeff* factor. For the simulation, we used the new *DFE* equalizer module which implements a Volterra equalization process available in VPITransmissionMaker 9.1.

c) Estimation of the EVM, BER, Qeff factor and OSNR

The EVM is a measure of the quality of the transmission through the quality of the demodulation.

EVM_{RMS} is the value of the root square (Root Mean Square) of the difference between the received symbols and ideals symbols, normalized. It is given by [13]:

$$EVM_{RMS} = \left[\frac{\frac{1}{N}\sum_{r=1}^{N}\left(\left(I_r-\bar{I}_r\right)^2+\left(Q_r-\bar{Q}_r\right)^2\right)}{\frac{1}{N}\sum_{r=1}^{N}\left(I_r^2+Q_r^2\right)}\right]^{1/2} \qquad (10)$$

with $\bar{I}_r$ and $\bar{Q}_r$ the real and imaginary part of the *r-th* received symbol. I_r and Q_r are the real and imaginary part of the *r-th* ideal symbol corresponding to the *r-th* received one. The calculation of EVM_{RMS} is performed in the receiver decoding process.

The Bit Error Rate (BER) is the measuring parameter the best known of the quality of a digital transmission, and represents the ratio between the number of erroneous bits and the total number of bits transmitted. The determination of the BER is based on the following definition:

$$BER = \frac{Number\_of\_errorneous\_Bits}{Number\_of\_Transmitted\_Bits} = \frac{N_{err}}{N} \qquad (11)$$

For a better estimation of BER, we used a Monte Carlo approach, which consists in a stochastic simulation with a large number of random symbols, to estimate the behavior of the system. Therefore, we can estimate that:

$$BER_{MC} = \lim_{N\to+\infty}\left(\frac{N_{err}}{N}\right) \qquad (12)$$

Q factor (*Qeff*) calculation is based on the above *BER* formulas [3]:

$$BER = \frac{1}{2}erfc\left(\frac{Q_{eff}}{\sqrt{2}}\right) \qquad (13)$$

$$Q_{eff} = \sqrt{2}.erfcinv(2*BER) \qquad (14)$$

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^{+\infty} e^{-t^2}dt \qquad (15)$$

with $erfcinv(x)$ the inverted function of the complementary error function $erfc(x)$.

The simulation is performed under the effect of the Chromatic Dispersion (CD) and the Optical Signal to Noise Ratio (OSNR), the ratio of the optical signal power and the noise power:

$$OSNR = \frac{P_S}{P_{Noise}} \qquad (16)$$

with *Ps* the power of the optical signal, P_{Noise} the total power of the noise which models the accumulation of all the noises associated with the optical transmission chain.

III. Results

The simulations helped us to plot the evolution curves of EVM as a function of OSNR. Similarly, the estimations of evolution of the BER and Q factor curves were performed according to the OSNR.

a) Received constellations and spectrums

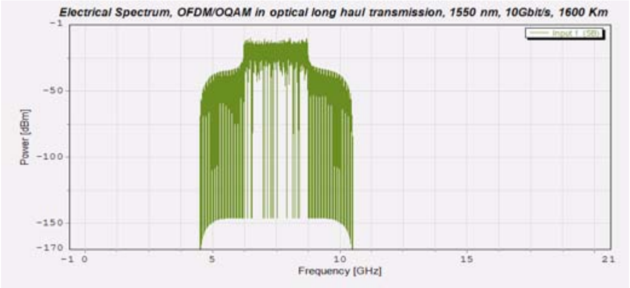


Figure 10 : Electrical spectrum received for OFDM/OQPSK

The electrical spectrum is similar to the one obtained with a OFDM/QPSK transmission

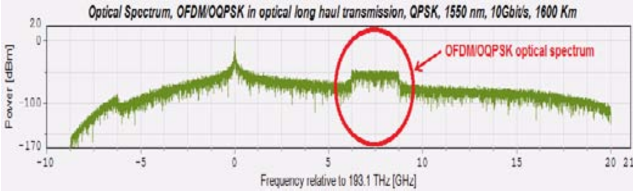


Figure 11 : Optical spectrum received for OFDM/OQPSK

The optical spectrum is also similar to the one obtained with a OFDM/QPSK transmission, due to the use of the same optical components and configuration parameters.

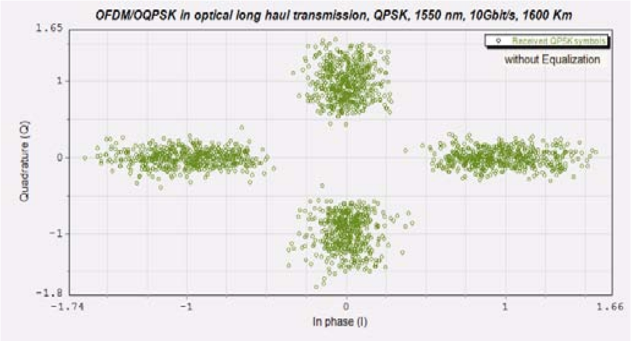


Figure 12 : Constellation received for OFDM/OQSK, without equalization

The constellation received describes the capability of OFDM/OQPSK to be designed for an optical transmission without equalization over a distance of 1600 Km.

b) EVM as a function of OSNR

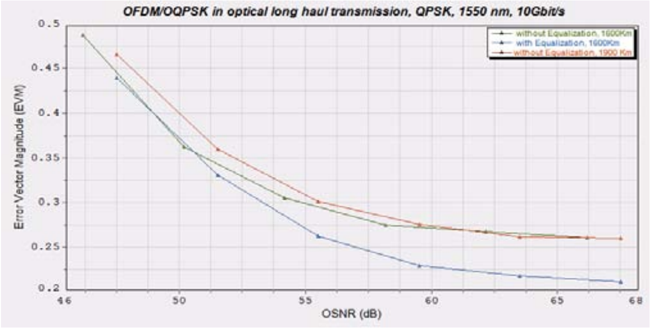


Figure 13 : EVM of OQPSK

Error Vector Magnitude shows the quality of the QPSK demodulation depending on the distance and the equalization process.

c) BER as a function of OSNR

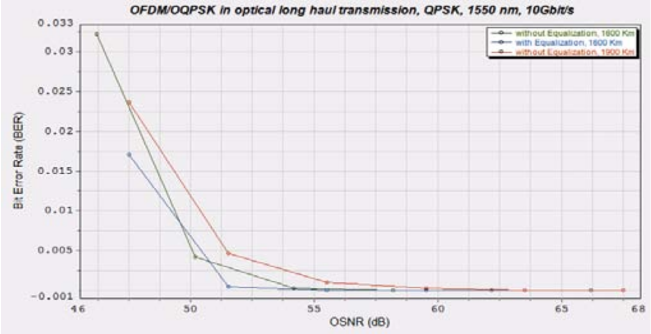


Figure 14 : BER of OQPSK

BER depends on the use of the equalization and also on the distance covered. The simulation gives the better performance over 1600 Km with equalization.

d) Qeff factor as a function of OSNR

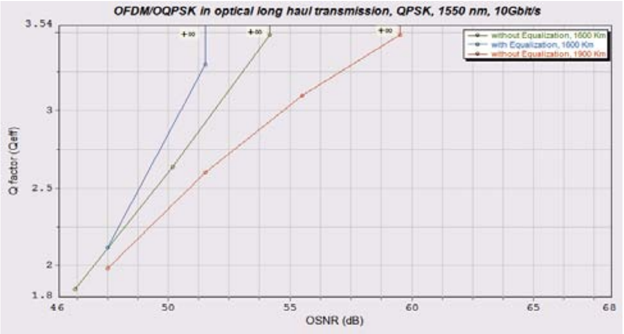


Figure 15 : Qeff of OQPSK

The results show that the Q factor, after some values, became infinite as the better quality is achieved.

IV. Conclusion

OFDM/OQPSK brings a new way of investigation that is being studied in wireless and optical networks. The idea of using variants of OFDM is influenced by the need to strengthen the transmission capacity and the use of new modulation schemes like OQPSK that can be implemented without the use of a cyclic prefix and equalization in some cases.

The simulations showed the superiority of OFDM/OQPSK than standard OFDM with cyclic prefix for optical communications, in term of covering long distance without the need of an equalization process for modulations like QPSK. This can be useful for simple applications with the use of less complex receivers. The equalization process is mandatory for higher level modulation scheme.

Furthermore, the study of FBMC techniques for optical communication is beginning and it opens new ways of research and applications that can be used to maximize the bandwidth with better qualities of transmission for photonics networks.

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