Implementation of Optical Orthogonal Frequency Division Multiplexing through Polymer Optical Fibers

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***Abstract* — This work presents the transmission of an Orthogonal Frequency Division Multiplexing (OFDM) signal through a multimode step-index polymer optical fiber (SI-POF), which is going to directly modulate three different LEDs. This modulation scheme can be an interesting approach to increase the spectral efficiency of the system, since the channel presents a low bandwidth. Additionally, this technique also compensates the dispersion effects introduced by the fiber which are mainly dominated by intermodal dispersion. The transmissions performed in this work were based on direct modulation of the LEDs and the non-coherent detection of the PIN photodiode. Bit rates of $26.6\ \mathrm{Mbit/s}$ with a link with 35 meters and a bandwidth of $5.7\ \mathrm{MHz}$ and bitrates of $19.3\ \mathrm{Mbit/s}$ with a link of 100 meters and a bandwidth of $4\ \mathrm{MHz}$ are shown.**

***Index* Terms—OFDM, LED, SI-POF, FFT, Spectral Efficiency, Optical Communications.**

I. Introduction

GLOBALLY, the average number of devices and connections per capita will grow from 2.3 in 2016 to 3.5 by 2021 [1]. By that time, wired devices will account for 27 percent of Internet traffic, and Wi-Fi and mobile devices will account for 73 percent of Internet traffic. In 2016, wired devices accounted for less than half of Internet traffic, at 38 percent. With this increase of devices per capita and global internet traffic it emerges the need of higher data rates, and with the consequently technology evolution associated with the glass optical fibers (GOF) in long distances, it emerged the need of technologies which could develop the same role over short distances [2], such as indoor and intra-vehicular networks. The polymer optical fiber (POF) technologies remained unused since its development in 1968, and only recently have been found application as a high-capacity transmission medium, due to the improvements in their transparency and bandwidth [3], and their price reduction in transmission and reception equipment. The outstanding obstacles to overcome in POFs are still their attenuation and dispersion values, which limits the bit rates and the connection lengths. With the promise of improving the capacity and spectral efficiency of the POF systems, several modulation schemes such as Orthogonal Frequency Division Multiplexing (OFDM) can be a good option to overcome its limitations at a low cost.

OFDM allows the reduction of the channel dispersive effects through the parallel information transmission with a set of orthogonal subcarriers. The spectrum of the individual subcarriers mutually overlaps, allowing to have a higher occupation of the system available bandwidth, comparing to the classical Frequency Division Multiplexing (FDM) [4]. The insertion of a guard interval helps to eliminate the inter-symbol interference at the transmission, and the cyclic prefix is essential for the synchronization at the reception. OFDM presents the great advantage of permitting the substitution of N modulators and filters for the digital processing through the direct and inverse discrete Fourier Transform fast computing algorithms.

The technique presented in this work shows some differences relating to the wireless OFDM, which is well known and dominates the wireless communication systems. The use of Hermitian Symmetry leads to the creation of a purely real signal, which is going to directly modulate the LED and is going to be transmitted through the polymer optical fiber, and at the reception a PIN photodiode is responsible for the non-coherent signal detection.

II. Background on LED-based Optical OFDM Transmissions

An optical system is essentially composed by three components: the transmitter, the optical transmission channel and the receiver. The transmitter is responsible for converting the electric signal into an optical one and sending it to the transmission channel which is, in this work, the polymer optical fiber. After the transmission channel has forwarded the signal to the receiver, the receiver converts it back into an electric signal. The goal is to make the received signal as similar as possible to the transmitted signal.

There are a large number of noise sources in optical systems. However, in short-range data communication, the components most responsible for the noise insertion are the transmitter and receiver components, such as light emitting diodes and photodiodes, respectively.

Modal dispersion is the biggest cause of dispersion and the primary source of inter-symbol interference (ISI) in POFs. The information-carrying capacity of an optical fiber is determined by its impulse response, hence its bandwidth is determined by the modal properties of the fiber: to its large core, some of the optical signal rays may travel a direct route, whereas others in a zigzag trajectory, as they bounce off the cladding. These alternate paths cause the different modes to arrive separately at the receiving point, and therefore the impulse response expands. For a very high data transmission, the duration of the symbols is very short, and the time dispersion is generally much greater than the symbol rate, hence introducing the phenomenon called ISI (because of the frequency-selective fading), and the received signals can add destructively resulting in signal fading and a significant reduction of the received SNR (Signal to Noise Ratio). This fading is very difficult to compensate because its characteristics are random and may not be easy to predict.

The change of the signal form by propagation along the fiber can be explained by signal theory and its impulse response:

$$s_1(t) = s_0(t) * h(t) + n(t), \qquad (1)$$

where $s_0(t)$ and $s_1(t)$ are the signals at the beginning and at the end of the fiber, respectively, and $n(t)$ is the imposed Additive White Gaussian Noise (AWGN), mainly related with the receiver. The operator $*$ stands for a convolution. The impulse response $h(t)$ of the fiber is approximately Gaussian [6] and it can be expressed as

$$h(t) = \frac{\exp(-(t/\Delta t)^2)}{\sqrt{\pi}\Delta t} \qquad (2)$$

Another important process to consider when the optical signal travels along an optical fiber is attenuation. The power of the optical signal decreases when propagating through the fiber. Figure 1 shows the spectral attenuation curve of a standard SI-POF.

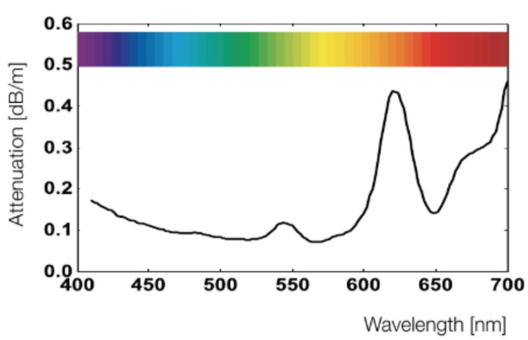

Figure 1. Attenuation curve of a standard SI-POF [5].

The concept of OFDM modulation is to transmit data over different subcarriers at the same time and hence an OFDM symbol consists of a window of time where each subcarrier transmits one symbol. In OFDM modulation, the subcarriers must be orthogonal, i.e., the cross-correlation between two subcarriers must be zero. Assuming that the available bandwidth is represented by B, the number of carriers is $N = B/\Delta f$, where Δf represents the width of each subcarrier. If Δf is small enough, the frequency response of the channel $C(f)$ is approximately constant across each sub-band, and each sub-channel is nearly ideal. This solution suggests a multicarrier modulation (MCM) and it provides transmission rates close to the channel capacity. The carrier period in the OFDM system is $T = NT_{symbol}$ (where T_{symbol} is the symbol period of the single-carrier system). Increasing the number of carriers N reduces de data rate of each individual carrier and therefore the carrier period T is much longer than the time duration of the channel time dispersion. Accordingly, ISI affects all frequencies in the signal equally and it can be estimated and compensated with simple equalization (reception) techniques [7,8]. OFDM systems are implemented using a combination of Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) blocks that are mathematically equivalent to Discrete Fourier Transform and Inverse Discrete Fourier Transform, respectively, but more efficient to implement. An OFDM system maps the source symbols (with QAM, for instance) at the transmitter as though they are in the frequency domain. By using higher order modulation formats (more points on the constellation) it is possible to transmit more bits per symbol. However, since the range between 0 and 360 degrees will be divided into more regions, and those regions get smaller, the points are closer together and they are therefore more susceptible to noise and data errors, increasing the BER. Hermitian Symmetry is applied in this work because an optical system was used, and the signal sent to the LED has to be real-valued. Hermitian symmetry exploits a property of the discrete Fourier transform (DFT), specifically that the DFT of a real-valued signal has Hermitian symmetry. Therefore, to have a real output of the IFFT, an OFDM system with N subcarriers must hold to the conditions expressed in:

$$\begin{aligned} X_{N-k} &= X_k^* \\ X_{N/2} &= X_0 \end{aligned} \qquad (3)$$

X_k is the complex value of the subcarrier with index $k \in [1,2,\ldots,N/2-1]$. This can be achieved by mapping $N/2$ complex symbols to subcarriers of 0 to $N/2-1$ and assigning the respective conjugate value to the subcarriers of $N/2$ to $N-1$, at the cost of having only half subcarriers to carry data, obtaining the following relationship between the number of subcarriers carrying information N_{sc} and the number of subcarriers needed before the Hermitian Symmetry N_{HS}.

$$N_{sc} = \frac{N_{HS}}{2} - 1 \qquad (4)$$

To reduce the algorithm's complexity, it is necessary that the number of subcarriers is a power of two. If it is not the case, it can be extended with zeros, and this process is called zero padding. Therefore, the number of zero padding subcarriers can be defined as:

$$N_{ZP} = N_{IFFT} - N_{HS} \tag{5}$$

The IFFT is responsible for multiplexing an input signal onto a set of orthogonal carriers and it is applied to the sequence of the mapped symbols, converting information in the frequency domain to time domain. Any type of non-ideal transmission channel is going to cause the symbols to suffer dispersion, (creating interference between the transmitted blocks). This is solved with a guard interval insertion in the output of the IFFT, called cyclic prefix (CP), which consists in a section of all zero samples transmitted in front of each block, increasing the extension of the symbol from T_u to $T_s = T_u + T_g$, being T_g the guard interval. After inserting the CP, the signal is submitted to a parallel-to-serial conversion and then it is converted to an analogue signal using a DAC. After that, the signal is ready to be transmitted in the channel. When the OFDM signal reaches the receiver, its process is the same of the transmitter but backwardly: the signal is converted to digital using an ADC, the data are converted to parallel, the CPs are removed, and the signal is then demodulated using the FFT and the QAM demodulator, with the addition of a single-tap equalizer block next to the FFT and the removal of the Hermitian Symmetry next to the equalizer. The equalizer uses training symbols to estimate the channel characteristic, to compensate the distortion caused by the transmission channel. Ideally, the output of the FFT would be the original symbols that were sent to the IFFT.

For each subchannel it is associated the complex signal

$$s_c(t) = A_c(t)e^{j[2\pi f_c t + \emptyset_c(t)]} \tag{6}$$

$A_c(t)$ is the amplitude and $\emptyset_c(t)$ is the phase of the subcarrier, which vary for each symbol. For quadrature phase-shift keying (QPSK or 4-QAM), the amplitude is constant, and the phase takes on one of four possible values per symbol. The transmitted bandpass signal is the real part of $s_c(t)$. In OFDM, the transmitted complex baseband signal for each subcarrier is

$$s(t) = \sum_{k=0}^{N-1} A_k(t)e^{j[2\pi f_k t + \emptyset_k(t)]}, \tag{7}$$

where f_k is the center frequency of the kth subcarrier and N is the number of information subcarriers. If the phase and the amplitude of the transmitted signal do not change over a symbol period, the amplitude and phase dependence on time can be disregarded and the equation can be rewritten by:

$$s(t) = \sum_{k=0}^{N-1} A_k e^{j\left[\frac{2\pi k}{T}t + \emptyset_k\right]} \tag{8}$$

Time can be expressed by $t = nT_s = \frac{nT}{N}$. So, in discrete time format each subcarrier is:

$$s(nT_s) = \sum_{k=0}^{N-1} A_k e^{j\emptyset_k} e^{\frac{j2\pi kn}{N}} \tag{9}$$

Figure 2 shows a block diagram of the implemented OFDM system.

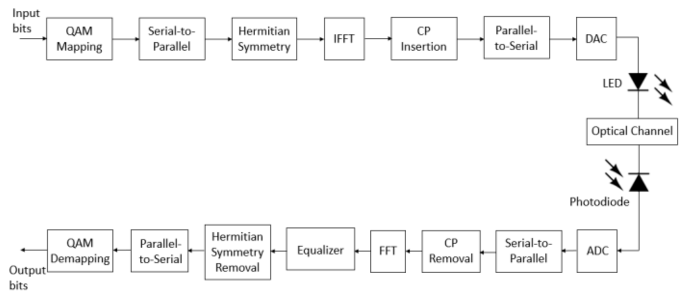

Figure 2. Block diagram of an OFDM system.

At the receiver, the equalizer is used to compensate the channel effects. The transmission channel causes signal distortion and, furthermore, it does not affect all the signal frequencies at the same way. Training symbols are commonly used to obtain the equalization function. This approach consists in sending, at the transmitter side, some training symbols, which are symbols which do not carry information. These symbols are only sent so that the receiver can know how the channel is affecting each different frequency. To make this possible, the receiver must know what the training symbols are and their position, so that when the received symbols arrive it can compare the training symbols received with the ones transmitted, knowing automatically how the transmission channel is affecting each one of the signal frequencies. By doing this, it is possible for the equalizer to respond to the channel by applying the inverse operation to each one of the signal frequencies, making it possible to recover the symbols sent by the transmitter. For a sequence of training symbols TS, the channel frequency response H_E is expressed as:

$$H_E = \frac{s_{TS}}{S_{TS}}, \tag{10}$$

where s_{TS} is the received training sequence, and S_{TS} is the generated training sequence. This transfer function has all the information about the transmission effects in the frequency domain and is enough to relate all the amplitude and phase differences of each subcarrier. To compensate these effects, the equalizer uses H_E^{-1} as the transfer function to mitigate all the distortions present in the transmission channel. The equalizer transfer function G_E is given by:

$$G_E = \frac{1}{H_E} = \frac{S_{TS}}{s_{TS}} \tag{11}$$

Although the training symbols decrease the system capacity in terms of information data, they are crucial for having a robust system.

After the symbols are demapped, the bit error rate (BER) is calculated to evaluate the system's performance. The definition of bit error rate can be translated into a simple formula:

$$BER = \frac{number\ of\ errors}{total\ number\ of\ bits\ sent} \tag{12}$$

Because of the introduction of forward error correction (FEC) techniques, in which a percentage of the total bits is repeated to add redundancy to the signal, it is nowadays possible to meet the required quality standards with a BER of 3.8×10^{-3}, and to validate the results in this project a BER below that limit is required [9].

III. Computational Simulations

The transmission channel of this work can be represented as an additive white Gaussian noise (AWGN) channel and the most responsible component for this effect is the photodiode. The system also suffers from fading due to the dispersion of the signal in the POF, as mentioned before. Therefore, there was created the system described in Figure 2, and for the transmission channel, *Matlab* functions were used to insert the AWGN and it was created the fiber model to estimate the impulse response of the channel. The concept was to use equation (1) to perform a convolution between the signal and the frequency response of the equation (2), and then it was inserted the AWGN based on the SNR.

The simulations were used to test the results obtained in the experimental part of this work. Therefore, the same parameters of section IV were used, for 35 and 100 meters of fiber. To simulate the 35 meters transmission, 2700 samples were transmitted with a simulation time of $10.92\ \mu s$ and 256 total subcarriers were used. For the 100 meters transmission simulation, 7650 samples were transmitted with a simulation time of $30.81\ \mu s$ and 512 total subcarriers were used. Figure 3 shows the generated channel frequency response, which was obtained using equation (2), and the estimated channel frequency response, which was obtained using equation (10), and they were created with *Matlab*. From Figure 4 to Figure 6 there are presented the constellation diagrams of the received signal for 4-QAM, 16-QAM and 64-QAM, simulating the transmission over 35 meters of fiber, created with *Matlab*. Figure 7 shows the diagram of the obtained BER versus E_b/N_o for 4-QAM, 16-QAM and 64-QAM, for 35 meters of fiber.

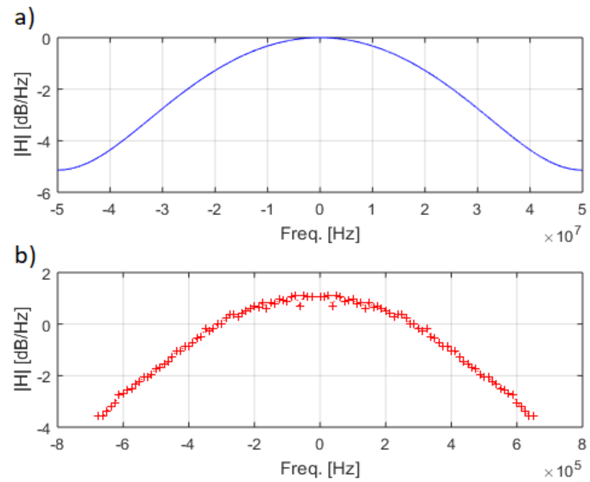

Figure 3. a) The generated frequency response of the channel for 35 meters of fiber and for a E_b/N_o of 5 dB; b) The estimated frequency response for 35 meters of fiber and for a E_b/N_o of 5 dB.

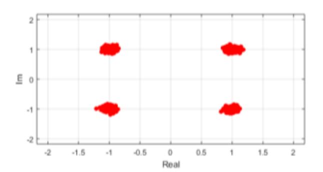

Figure 4. Received constellation diagram for 35 meters of fiber, for 4-QAM and for a E_b/N_o of 5 dB.

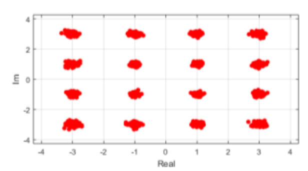

Figure 5. Received constellation diagram for 35 meters of fiber, for 16-QAM and for a E_b/N_o of 5 dB.

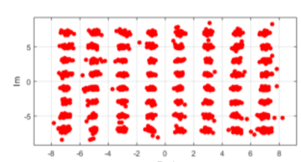

Figure 6. Received constellation diagram for 35 meters of fiber, for 64-QAM and for a E_b/N_o of 5 dB.

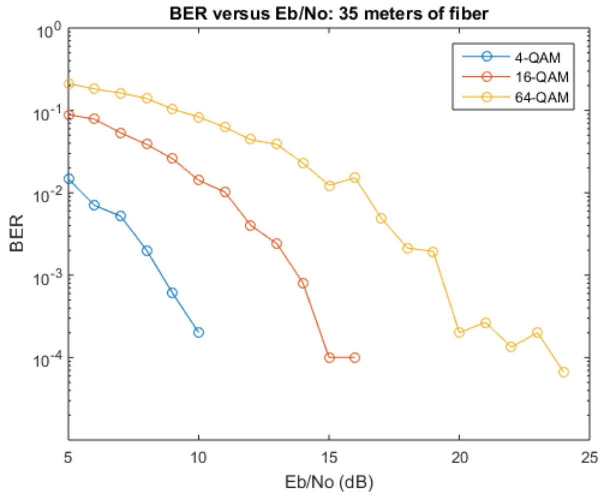

Figure 7. Diagram of the obtained BER versus E_b/N_o for 4-QAM (blue), 16-QAM (red) and 64-QAM (yellow), for 35 meters of fiber.

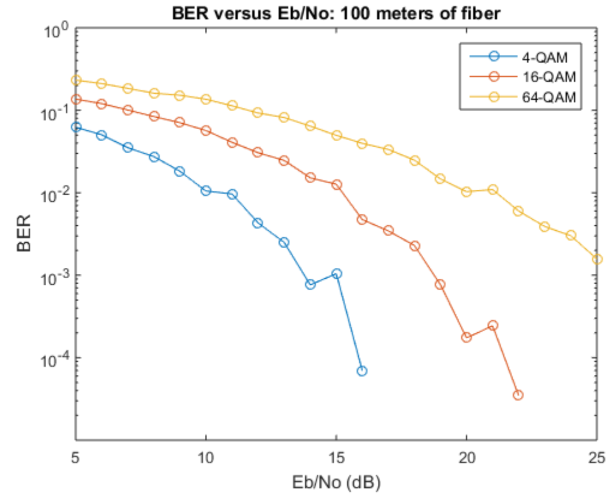

Figure 11. Diagram of the obtained BER versus E_b/N_o for 4-QAM (blue), 16-QAM (red) and 64-QAM (yellow), for 100 meters of fiber.

From Figure 8 to Figure 10 there are presented the constellation diagrams of the received signal for 4-QAM, 16-QAM and 64-QAM, simulating the transmission over 35 meters of fiber, created with *Matlab*. Figure 11 shows the diagram of the obtained BER versus E_b/N_o for 4-QAM, 16-QAM and 64-QAM, for 35 meters of fiber.

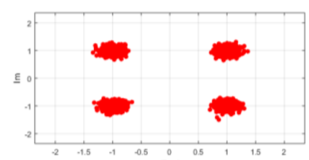

Figure 8. Received constellation diagram for 100 meters of fiber, for 4-QAM and for a E_b/N_o of 5 dB.

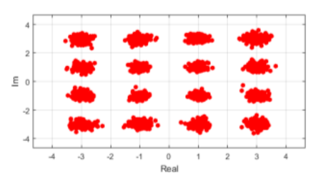

Figure 9. Received constellation diagram for 100 meters of fiber, for 16-QAM and for a E_b/N_o of 5 dB.

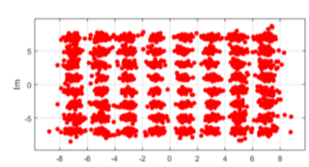

Figure 10. Received constellation diagram for 100 meters of fiber, for 64-QAM and for a E_b/N_o of 5 dB.

Comparing the simulation results presented above, with 35 meters of fiber the BER is lower than with 100 meters of fiber because the dispersion in the fiber is also lower. One can also note that for higher levels of QAM modulation the BER is lower because each symbol carries less energy and the symbols are closer to each other in the constellation, increasing the probability of obtaining an error bit. Likewise, with the increase of the fiber distance and in the QAM modulation level there is an increase in the transmission rate, which increases the SNR.

IV. Experimental Implementation

The experimental setup was based on the block diagram of Figure 2. The transmission of the OFDM signal through the POF was divided in three blocks. The first one was to create the signal using a *Matlab* script according to the parameters chosen for this work (number of information subcarriers, available bandwidth, cyclic prefix duration and the level of QAM-mapping). In the second block, the signal was used to directly modulate the LED using a DAC and then it propagates in the POF, being converted to the electrical domain through a PIN photodiode. An ADC converts the received signal into a digital signal and, at the final part, the signal is demodulated also with *Matlab* and the evaluation parameters BER is calculated. For the transmitter, three different LEDs were used in order to decrease the costs of the work: IF-E92B which has a blue optical signal, operating at 470 nm peak wavelength, IF-E93 which has a green optical signal, operating at 522 nm, and IF-E96E, which has a red optical signal, operating at 650 nm, all from *Industrial Fiber Optics*. For the receiver, it was used the PIN photodiode IF-D91, also from *Industrial Fiber Optics*. The DAC and ADC used for the experiment was *Analog Discovery* and for the transmission channel there were used two different lengths of POF, 35 and 100 meters, HFBR-EUS100Z from *Broadcom*

Limited. Figure 12 shows the photograph of the implemented system with 100 meters of fiber.

Figure 12. Implemented system with 100 meters of fiber.

The LED must operate in the quasi-linear segment of its characteristic, through DCO-OFDM. Therefore, the DC characteristics of the LEDs were measured with the power supply PS613, from *Velleman*, and the multimeter 75-MY64, from *Vitecom*, to measure its forward current. Analyzing the obtained results, it was chosen for an applied voltage from 3.0 V to 3.8 V, from 1.7 V to 2.1 V and from 3.0 V to 3.8 V, for the green, red and blue LED, respectively.

To determine the bandwidth of the system a sinusoid signal generated using *Waveforms*, which is a software developed by *Digilent*, was injected into the LEDs and the amplitude of the output signal was measured for different frequencies, using the 35 and 100 meters of fiber length. Table I shows the determined -3dB bandwidth of the system with the three LEDs and with 35 and 100 meters of fiber.

TABLE I
$-3dB$ SYSTEM'S BANDWIDTH

LED	35 meters	100 meters
Blue	4.6 MHz	4 MHz
Red	5.7 MHz	4.1 MHz
Green	4.8 MHz	4.4 MHz

The OFDM parameters were chosen to compensate for the dispersion introduced by the POF. The number of data subcarriers, before Hermitian Symmetry is applied, can therefore be obtained as:

$$N_{HS} = \frac{B}{\Delta f} = B.T_u \quad (13)$$

The parameters of the OFDM system for the two fiber lengths are represented in Table II.

TABLE II
PROJECTED PARAMETERS FOR THE OFDM SYSTEM

Parameters	35 m fiber	100 m fiber
Δt	$0.91\ \mu s$	$2.57\ \mu s$
T_g	$2\Delta t = 1.82\ \mu s$	$2\Delta t = 5.14\ \mu s$
T_u	$10\Delta t = 9.10\ \mu s$	$10\Delta t = 25.67\ \mu s$
T_s	$10.92\ \mu s$	$30.81\ \mu s$
Δf	110 kHz	38.97 kHz
N_{HS}	110	308
N_{IFFT}	256	512
N_{sc}	$\frac{N_{HS}}{2} - 1 = 54$	$\frac{N_{HS}}{2} - 1 = 153$

For the parameters described, different levels of QAM-mapping were used: 4-QAM, 16-QAM and 64-QAM. The sampling frequency of the DAC and ADC must be, accordingly to the Nyquist Theorem, at least two times the available bandwidth. Thus, the sampling frequency was chosen to be 100 MHz. After the first part is performed in *Matlab*, as shown in Figure 13, the signal is sent to the DAC, travels through the different lengths of optical fiber, and then the demodulation process starts, as it can be described in Figure 14.

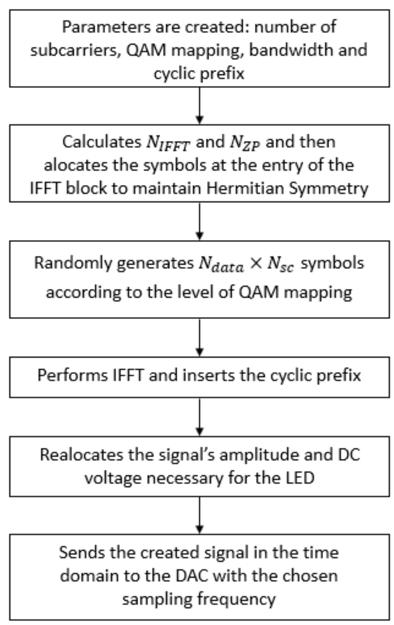

Figure 13. Diagram of the modulation process in *Matlab*.

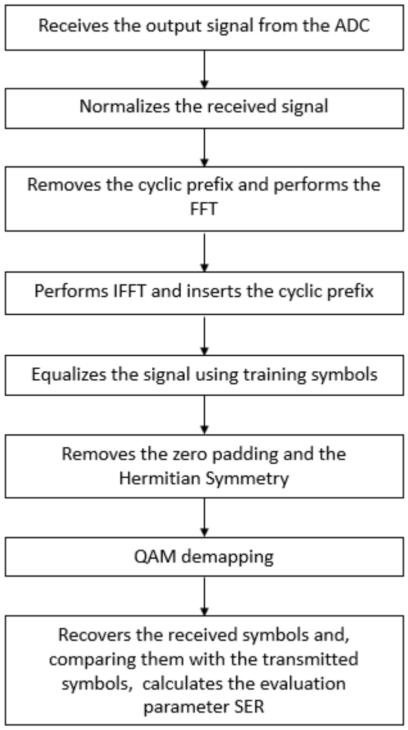

Figure 14. Diagram of the demodulation process in *Matlab*.

V. Results and Analysis

2700 samples were transmitted over 35 meters of fiber, with a simulation time of 10.92 μs and 256 total subcarriers were used. With 2700 samples transmitted and 162 of them used for the equalizer, for 4-QAM, 16-QAM and 64-QAM, the total number of bits sent was 5394, 10788 and 21576, respectively. Figure 15 shows the transmitted OFDM symbol for 4-QAM, and Figure 16, Figure 17 and Figure 18 show the received symbols after 35 m SI-POF, for 4-QAM, 16-QAM and 64-QAM, respectively.

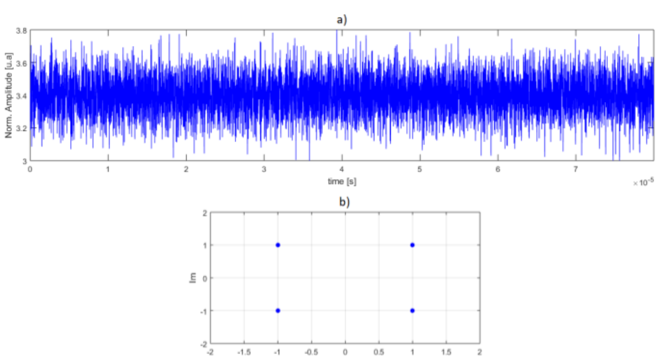

Figure 15. a) Transmitted OFDM symbol in the time domain for 4-QAM, 35 meters of fiber and for the blue LED; b) QAM constellation diagram of the transmitted signal for 4-QAM, 35 meters of fiber and for the blue LED.

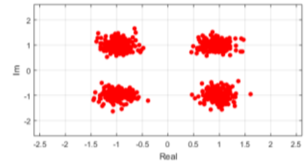

Figure 16. QAM constellation diagram of the received signal for 4-QAM and 35 meters of fiber, for a received optical power of -16.92 dBm.

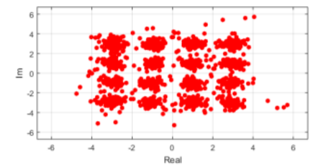

Figure 17. QAM constellation diagram of the received signal for 16-QAM and 35 meters of fiber, for a received optical power of -17.30 dBm.

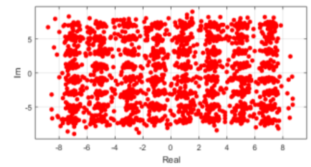

Figure 18. QAM constellation diagram of the received signal for 16-QAM and 35 meters of fiber, for a received optical power of -17.33 dBm.

Comparing the constellation diagrams of the received signal between 4-QAM, 16-QAM and 64-QAM one can see that for higher modulation levels the closer the QAM symbols are, increasing the probability of error. The constellations are not rotated, however the symbols are horizontally dislocated, which is an effect of the fiber dispersion. The noise in the received constellation diagrams is higher for higher QAM modulation levels, as it was expected.

The best results achieved with the transmission over 35 meters of fiber were a BER of 2.0×10^{-4} for 4-QAM, with the three LEDs, a BER of 1.0×10^{-4} for 16-QAM and with the red LED, and a BER of 5.5×10^{-4} for 64-QAM and also with the red LED. For some of the obtained results zero erroneous bits were reported, which means that only one erroneous bit could be detected in the total received bits (which represents one percent), obtaining the measured BER. The curves of the obtained BER versus the optical power at the receiver for each LED are presented in Figure 19, Figure 20 and Figure 21, for each level of QAM modulation.

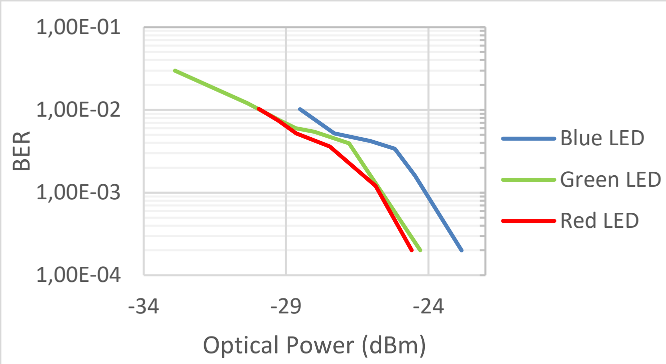

Figure 19. BER versus optical power at the receiver for 4-QAM, for 35 meters of fiber.

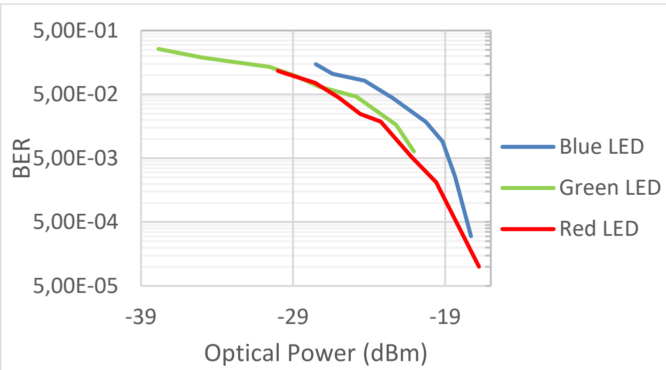

Figure 20. BER versus optical power at the receiver for 16-QAM, for 35 meters of fiber.

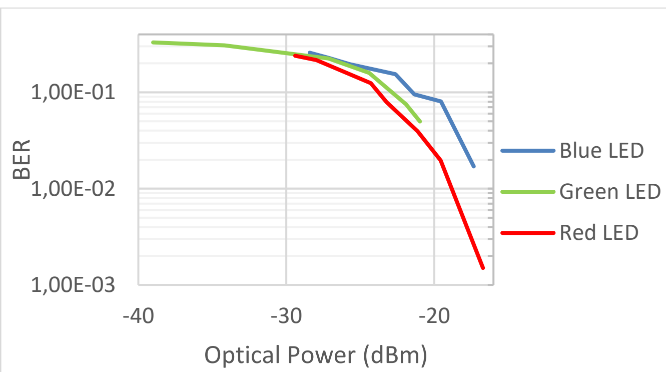

Figure 21. BER versus optical power at the receiver for 64-QAM, for 35 meters of fiber.

The blue LED shows to have the highest BER at the same optical power, and this results are expected as the system with the blue LED presents the lowest available bandwidth. Figure 22 and Figure 23 show the lowest obtained BER and spectral efficiency, respectively, for the three LEDs and for different QAM level modulations.

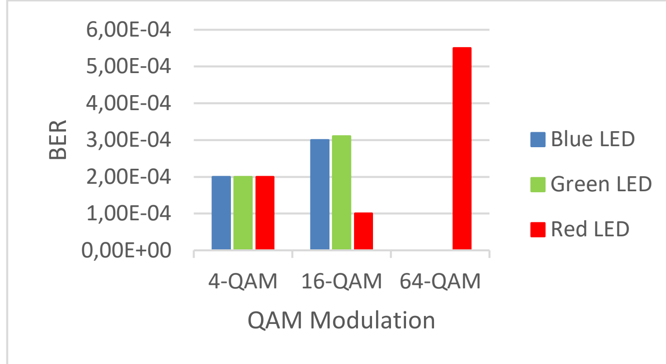

Figure 22. Obtained BER for the three LEDs and for 4-QAM and 16-QAM for 35 meters of fiber.

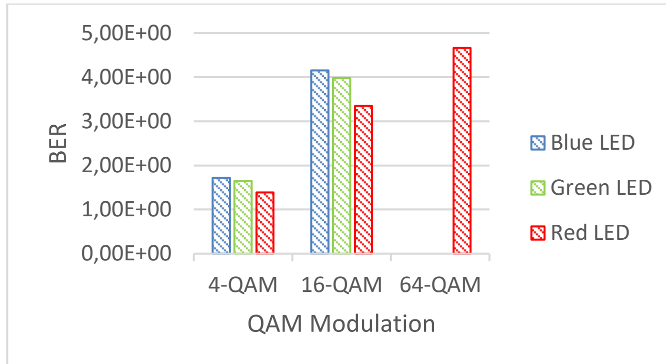

Figure 23. Obtained spectral efficiency S for the three LEDs and for 4-QAM and 16-QAM for 35 meters of fiber.

For the transmission over 100 meters, 7650 samples were transmitted with a simulation time of 30.81 μs and 512 total subcarriers were used. With 7650 samples transmitted and 459 of them used for the equalizer, for 4-QAM, 16-QAM and 64-QAM, the total number of bits sent was 15294, 30588 and 61176, respectively. Figure 24 shows the transmitted OFDM symbol for 4-QAM, and Figure 25 and Figure 26 show the received symbols after 100 m SI-POF, for 4-QAM and 16-QAM, respectively.

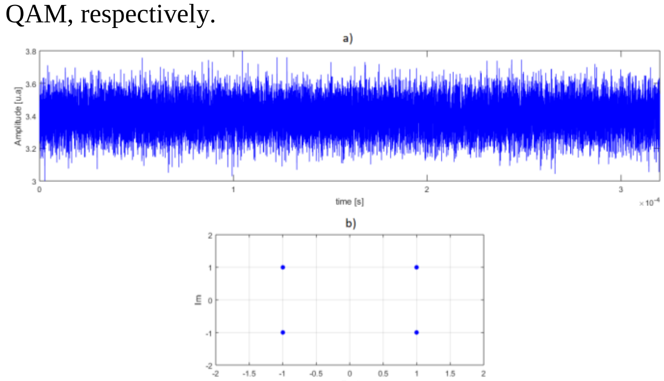

Figure 24. a) Transmitted OFDM symbol in the time domain for 4-QAM, 100 meters of fiber and for the blue LED; b) QAM constellation diagram of the transmitted signal for 4-QAM, 100 meters of fiber and for the blue LED.

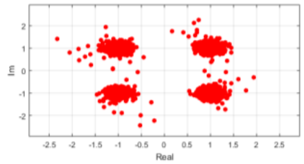

Figure 25. QAM constellation diagram of the received signal for 4-QAM and 100 meters of fiber, for a received optical power of -20.17 dBm.

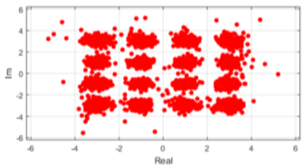

Figure 26. QAM constellation diagram of the received signal for 16-QAM and 100 meters of fiber, for a received optical power of -20.12 dBm.

Comparing the constellation diagrams of the received signal between 4-QAM and 16-QAM it can also be seen that for higher modulation levels the closer the QAM symbols are, increasing the probability or error, and the constellations are also not rotated. The noise in the received constellation diagrams is not higher than for 35 meters of fiber. The curves of the obtained BER versus the optical power at the receiver for each LED are presented in Figure 27, Figure 28 and Figure 29, for each level of QAM modulation and for the transmission over 100 meters of fiber.

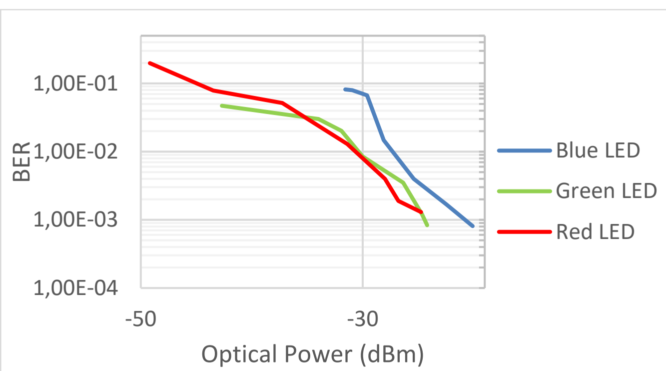

Figure 27. BER versus optical power at the receiver for 4-QAM, for 100 meters of fiber.

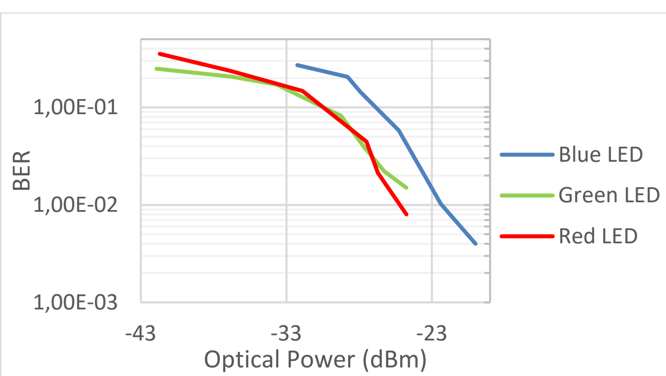

Figure 28. BER versus optical power at the receiver for 16-QAM, for 100 meters of fiber.

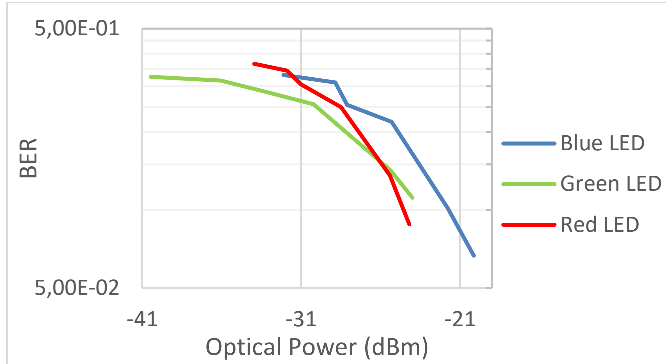

Figure 29. BER versus optical power at the receiver for 64-QAM, for 100 meters of fiber.

The green and red LED shows to have the lowest BER for the same optical power, and the blue LED shows to have the highest BER. Figure 2Figure 30 and Figure 31 show the obtained BER and spectral efficiency, respectively, for the three LEDs and for different QAM level modulations, for 100 meters of fiber.

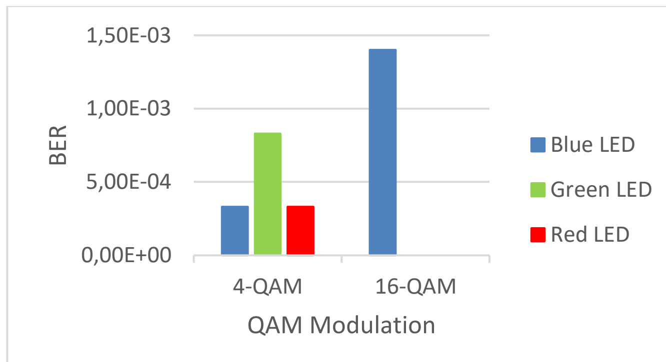

Figure 30. Obtained BER for the three LEDs and for 4-QAM and 16-QAM for 100 meters of fiber.

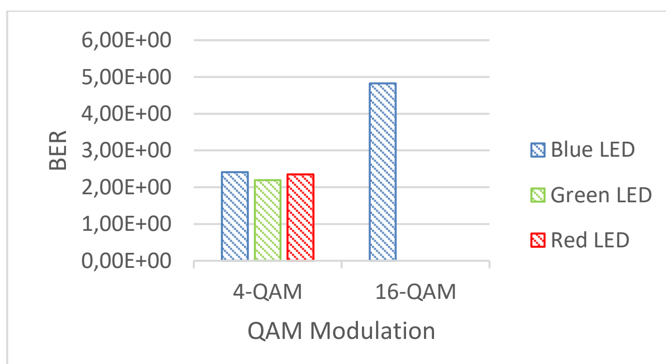

Figure 31. Obtained spectral efficiency S for the three LEDs and for 4-QAM and 16-QAM for 100 meters of fiber.

Comparing the transmission over 35 and 100 meters of fiber it can be observed that the red LED suffers from attenuation the most, because for the 35 meters transmission the optical power at the receiver with the green and blue LED was higher, and for 100 meters transmission the optical power with the red LED reduced to the same optical power as obtained with the green LED. This fact can be confirmed with Figure 1, which indicates that the red optical signal suffers more attenuation through the fiber that green or blue optical signal. For the 35 meters transmission, the transmission rate record for the blue LED was $19.1\ \mathrm{Mb/s}$, with a spectral efficiency of $4.15\ \mathrm{b/s/Hz}$, and the same transmission rate was achieved by the green LED, with a spectral efficiency of $3.98\ \mathrm{b/s/Hz}$. For the red LED a transmission rate of $26.6\ \mathrm{Mb/s}$ with a spectral efficiency of $4.67\ \mathrm{b/s/Hz}$ was accomplished. For the 100 meters transmission, a transmission rate of $9.64\ \mathrm{Mb/s}$ with the green and red LED, with a spectral efficiency of $2.19\ \mathrm{b/s/Hz}$ and $2.35\ \mathrm{b/s/Hz}$, respectively, and a transmission rate of $19.3\ \mathrm{Mb/s}$ with the blue LED, with a spectral efficiency of $4.83\ \mathrm{b/s/Hz}$, were achieved.

VI. CONCLUSIONS

In the transmissions performed, OFDM signals were generated with *Matlab* and then sent to a DAC. The applied offset and peak-to-peak voltage are chosen so that the LEDs and photodiode operate in their linear regimes. The OFDM signal directly modulates the LED and the ADC captures the received signal, at the receiver, and the *Matlab* demodulates it. The obtained results show that the transmissions do not suffer from the effects of the fiber dispersion, because the constellations of the received symbols with 35 and 100 meters of fiber were identical, but they suffer from noise and attenuation, due to the LEDs and photodiode, respectively, and the fiber itself. Transmissions of $26.6\ \mathrm{Mb/s}$ over 35 meters of fiber and $19.3\ \mathrm{Mb/s}$ over 100 meters of fiber with LEDs emitting on wavelengths corresponding to blue, red and green in the visible spectrum and with the non-coherent detection of a PIN photodetector were accomplished. The goal of overcoming the effects of the fiber dispersion was achieved and the transmissions' spectral efficiency has reached $7.19\ \mathrm{b/s/Hz}$ with the red LED and over the 35 meters transmission.

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