Transmission of OFDM-UWB Radio Signals along FTTH Networks using Chirp-Managed Lasers

Pedro Luís Benito Canêlhas

Abstract—Orthogonal Frequency Division Multiplexing Ultra-Wideband (OFDM-UWB) radio signals have been proposed to support advanced multimedia-based applications because of their inherent high capacity and the advantage of being already standardized. In this context, the distribution of OFDM-UWB radio signals in long-reach fiber-to-the-home (FTTH) networks using chirp-managed lasers (CML) is a cost-effective solution to extend the coverage of these signals in future wireless personal area networks. Through numerical simulation, this paper analyzes the feasibility of the distribution of OFDM-UWB radio signals in long-reach FTTH networks using CML. The performance degradation of the transmission of an OFDM-UWB signal is assessed in terms of the bit error ratio (BER) and for a minimum quality of BER = 10^{-9}, the CML-based transmission achieves an improvement of 10 km in the maximum transmission distance compared to the use of directly modulated laser (DML).

Index Terms—Chirp-managed laser, directly-modulated laser, fiber-to-the-home networks, orthogonal frequency-division multiplexing, ultra-wideband.

I. INTRODUCTION

Ultra-Wideband (UWB) signals, approved by the U.S. Federal Communications Commission (FCC), have been proposed to be used in wireless personal area networks (WPANs) due to their features such as high bit-rate over short-range broadcasting, low self-interference, tolerance to multi-path fading, low probability of interception and the possibility of coexistence with other deployed wireless technologies [1].

Although FCC has not regulated an UWB transmission scheme, a possible approach for the implementation of UWB technology is based on a multi-carrier technique. It consists in dividing the standardized UWB frequency band from 3.1 to 10.6 GHz into several smaller subbands [2]. Within each sub-band, Orthogonal Frequency Division Multiplexing (OFDM) has been proposed for data modulation [3], leading to OFDM-UWB signals. The OFDM-UWB solution shows flexibility to provide multiple access, tolerance to multi-path fading and inter-symbol interference.

Optical fiber provides an efficient solution for the transmission of UWB signals due to its low cost, wide bandwidth and low loss. The distribution of OFDM-UWB radio signals over fiber-to-the-home (FTTH) networks has been proposed in [4],[5]. This approach presents several advantages: FTTH networks provide enough bandwidth to distribute a large number of UWB signals and no transmodulation and frequency up-conversion is required for a fiber-to-wireless conversion at the subscriber premises.

One of the most attractive architectures of fiber-to-the-home networks is the passive optical network (PON). PON consists in a network shared among many customers which increases its cost-effectiveness. Research attention has been recently focused on new types of optically amplified long-reach (100 km) PONs (LR-PONs) [6]. These LR-PONs would replace the separate metro and access portions of the network with a single, integrated, all-optical communication system.

Currently, external modulation schemes have been adopted for optical transmitters. The use of external modulation is very inconvenient in FTTH networks where cost-effectiveness is a key issue. In this context, the use of directly-modulated laser (DML) as optical transmitter becomes a means to overcome cost issue due to their potential low cost. The adoption of the DML is a promising solution due to its compact size, low power consumption and high optical output power characteristics.

The transmission of OFDM-UWB signals over single mode fiber 5 km length using directly modulated lasers has been experimentally demonstrated [7] and the performance degradation of OFDM-UWB transmission over fiber has been experimentally investigated and theoretically analyzed for a maximum distance of 40 km in [8]. In this paper, a DML-based optical link is established with a maximum length of 100 km. It was shown that direct modulation is limited by laser bandwidth, linewidth, stability, and relative intensity noise (RIN) [9]. In [10] was shown that RIN significantly degrades the OFDM-UWB over fiber system, particularly for the higher frequency UWB channels.

The DML current modulation gives rise to frequency chirp: the intensity modulation is accompanied by frequency modulation [11]. This results in a broad spectrum that severely limits the transmission distance due to the effect of chromatic dispersion. However, through a tuned optical spectrum reshaper filter (OSR) placed after the DML, bandwidth and chirp reductions are achieved. This filter performs frequency modulation (FM) to intensity modulation (IM) conversion, leading to a signal more robust to the dispersion of the fiber. The grouping of the DML and the OSR composes the chirp-managed laser (CML) as presented in [12]. The CML technique has been demonstrated in 10 Gbps transmission over 200 km single mode fiber without dispersion compensation [13]. The CML transmitter is a highly practical solution to meet simultaneously the size, power, capacity and cost requirements of the optical links in FTTH networks.

In this paper, the transmission of OFDM-UWB radio signals in CML-based FTTH networks is investigated, using numerical simulation. The main parameters that influence the performance degradation of the OFDM-UWB signals distribution in FTTH networks are identified and optimized. The main transmission impairments - loss and dispersion - are discussed and
the maximum transmission distance for a required minimum quality is assessed.

This paper is structured as follows. In section II, OFDM-UWB radio signals are presented and their time and frequency characteristics analyzed. Section III describes the architecture of the FTTH network adopted for OFDM-UWB signal distribution and each of its components. The methods for evaluating the performance of the network are detailed in section IV and, in section V, the effects of the non-linear operation of clipping accomplished at the transmitter are analyzed. In section VI, the results of the optimization of parameters that influence the performance of the system are presented and analyzed and section VII presents the transmission performance of OFDM-UWB signals in the optimized FTTH network. Section VIII draws the main conclusions of this work.

II. OFDM-UWB RADIO SIGNALS

As mentioned in the Introduction, the UWB multi-carrier approach using OFDM is followed in this paper. It consists in dividing the UWB frequency band into subbands that are 528 MHz wide [2],[14]. A part of the information to be transmitted may be given to each subband. The quadrature phase-shift keying (QPSK) modulation format is used to generate the symbols from the bit sequence to be transmitted [15]. Each symbol modulates one of the 128 subcarriers in the OFDM-UWB subband resulting in a signal rate per subband of 640 Mbit·s⁻¹.

The IFFT/FFT approach for obtaining the OFDM-UWB signal reduces significantly the implementation complexity of the OFDM-UWB transmitter and receiver as described in [16]. Figure 1 shows the block diagrams of the OFDM transmitter (OFDM-UWB TX) and receiver (OFDM-UWB RX). In the OFDM-UWB TX, the information bit sequence is mapped into a symbol stream with QPSK format. Afterwards, the inverse fast Fourier transform (IFFT) is calculated to the symbol sequence and afterwards each subcarrier modulates a carrier with frequency \( f_{RF} \), according to the desired UWB subband.

The OFDM-UWB RX performs backwardly the same operations as the transmitter with the insertion of an equalizer after the fast Fourier transform (FFT) block. The equalization is used to compensate for the amplitude and phase distortion induced by the transmission system and its transfer function is estimated from 12 pilot carriers information of the OFDM signal received. The estimated transfer function of the channel is calculated by using a polynomial of degree 2.

For the reduction of the influence of the aliasing components resulting from the digital-to-analog conversion (DAC) at the OFDM-UWB TX, a 6th-order Bessel low-pass (LP) filter with an optimized bandwidth of 315 MHz (given in [17]) is used. At the OFDM-UWB RX, after the mixing with the RF carriers, similar LP filters reduce the noise power added to the system. This filter bandwidth reduces the distortion within each subband caused by the filter not having a totally flat passband. It also reduces the crosstalk between subbands and out-of-subband noise which comes from the slow transition between the passband and stopband.

One of the major drawbacks of the OFDM signals is mentioned as the high peak-to-average power ratio (PAPR) [18]. Several values of PAPR were calculated when a deBruijn bit sequence of length \( 2^{l_{seq}} \) is mapped into QPSK symbols that modulate each OFDM subcarrier. For a given deBruijn sequence of length \( 2^{l_{seq}} \), the PAPR value was computed for sequences resulting from circular shifting of the original deBruijn bit sequence \( 2^{l_{seq}} \) times. Figure 2 shows the PAPR mean, maximum and minimum for different values of \( l_{seq} \) using the first subband. It is observed that, for a longer deBruijn bit sequence, the PAPR mean value increases. The maximum value found was 16.5 dB but the graph from figure 2 suggests higher PAPR values for longer deBruijn bit sequences.

The OFDM-UWB symbol sequences used in this work comes from the deBruijn sequence of \( l_{seq} = 11 \) with the highest PAPR found. The PAPR of each OFDM-UWB signal depends on which and how many subbands are used. An OFDM-UWB signal with a high peak is more likely to be distorted by the optical transmitter and, therefore, it represents, possibly, the worst case scenario for the optical network. Table I shows the PAPR mean and maximum values for different subbands used. For a single-subband transmission, the PAPR value is independent of the subband used. For multiple-subband transmission, it is observed that the PAPR value increases with the number of subbands assigned.

III. FTTH NETWORK FOR THE DISTRIBUTION OF OFDM-UWB RADIO SIGNALS

FTTH networks are based on existing passive optical networks (PON). A PON-based FTTH network consists of an optical line terminal (OLT) at the central node of the service provider and a number of optical network units (ONUs) near end users. A PON is a point-to-multipoint network which reduces the amount of fiber used.
In figure 3, the block diagram of the LR-PON networks is shown. As observed, the central node generates and multiplexes the OFDM-UWB signal making use of dense wavelength division multiplexing (DWDM). This technology is used for the transport of several optical carrier signals onto a single optical fiber of 80 km (as presented in [6]) from the central node until the local exchange. The erbium-doped fiber amplifier (EDFA) at the central node is used to compensate for the multiplexer losses and imposes a defined mean optical power before the fiber transmission. At the local exchange, the EDFA compensates for the losses inflicted by the fiber transmission, splices, connectors, demultiplexer and power splitter. Then, the optical signal is demultiplexed and distributed to N subscribers by a N-splitter. Depending on the geographic location of each subscriber, the optical path between the local exchange and the premises of the subscriber may have a length between 0 and 20 km.

Since the goal of this paper is to evaluate the impact of the FTTH network on the OFDM-UWB signal transmission, from this point on, the discussion will be focused on an individual wavelength channel. The multiplexers/demultiplexers represented in figure 3 are replaced by the equivalent components of the single-wavelength point view. The equivalent FTTH network model, which neglects the crosstalk between different wavelengths, is represented in figure 4.

### A. Central Node

The OFDM-UWB signal generated modulates the intensity of the optical carrier frequency of the transmitter. This means that the transmitting signal must be positive and real. The signal obtained by an OFDM-UWB TX has both positive and negative values, therefore, a conversion of its mean and amplitude should be applied in order to meet the optical transmitter input restrictions.

As observed in figure 4, the $g$ and $I$ parameters set the peak-to-peak and bias current of the current signal that, afterwards, is limited by the clipper that fits the range of the current to the linear operating region of the DML (18~100 mA). The current levels have a strong influence on the performance of the system and, therefore, should be optimized.

The DML used is a Multiple Quantum Wells (MQW) and it is operating at the wavelength of 1550.2 nm. The DML model considers the effects originated from the assemblage of the laser. These effects are represented by a first order low-pass filter with a bandwidth of 6 GHz. The bandwidth of the DML modulation depends on the bias input current: for the bias current of 20 mA and 60 mA, the bandwidth at -3 dB is 10 GHz and 25 GHz, respectively. The overall bandwidth of the DML is the result of the effects of its assemblage and the input bias current. Due to the bandwidth limitation of the DML, the transmission of OFDM-UWB signals is accomplished only for the first four UWB subbands ($f_{RF} = 3.43$ GHz; 3.96 GHz; 4.49 GHz; 5.02 GHz).

The region of linear operation of the DML is limited by the threshold current (18 mA) and the maximum current before it presents multi-mode emission (100 mA).

The OSR filter limits the frequency chirp generated by the DML making the optical signal more resilient to the fiber dispersion effects. This OSR is a 1st order Gaussian filter with a -3 dB bandwidth of $\nu_g$ and central frequency of $\nu_c$. For an optimal chirp control, these parameters of the OSR are optimized.

The optical filter placed after the CML is the equivalent model of the multiplexer (MUX) from the single-wavelength point of view. This filter has the same characteristics as the one that simulates the demultiplexer (DEMUX) at the local exchange. The optical filter at the local exchange narrows the optical noise spectrum. Based on the outcome of [17], it is adopted a 2nd order super-Gaussian filter with an optimized bandwidth of 35 GHz.

For the compensation of the power losses induced by the OSR, an erbium-doped fiber amplifier (EDFA) sets the mean power of the optical signal at the output of the central node to a defined level $P_{CN}$. Thus, the OFDM-UWB optical signals at the fiber input have the same mean power independently of

### TABLE I

PAPR MEAN, MAXIMUM AND MINIMUM VALUES FOR DIFFERENT SUBBANDS USED.

<table>
<thead>
<tr>
<th>Subbands used</th>
<th>mean{PAPR}</th>
<th>max{PAPR}</th>
<th>min{PAPR}</th>
</tr>
</thead>
<tbody>
<tr>
<td>{1}</td>
<td>13.90</td>
<td>15.48</td>
<td>12.24</td>
</tr>
<tr>
<td>{2}</td>
<td>13.91</td>
<td>15.49</td>
<td>12.32</td>
</tr>
<tr>
<td>{3}</td>
<td>13.91</td>
<td>15.50</td>
<td>12.29</td>
</tr>
<tr>
<td>{4}</td>
<td>13.90</td>
<td>15.49</td>
<td>12.33</td>
</tr>
<tr>
<td>{1,2}</td>
<td>16.67</td>
<td>18.45</td>
<td>14.97</td>
</tr>
<tr>
<td>{1,3}</td>
<td>16.61</td>
<td>18.32</td>
<td>14.92</td>
</tr>
<tr>
<td>{1,2,3}</td>
<td>18.36</td>
<td>20.16</td>
<td>16.70</td>
</tr>
<tr>
<td>{1,2,3,4}</td>
<td>19.56</td>
<td>21.30</td>
<td>17.94</td>
</tr>
</tbody>
</table>

![Fig. 2](image-url)  
**Fig. 2.** Mean, maximum and minimum values of the PAPR for a 2<sup>l</sup>-<i>q</i> deBruijn sequence using QPSK mapped in an OFDM-UWB signal using subband 1.

![Fig. 3](image-url)  
**Fig. 3.** Schematic of the FTTH network using DWDM technology with optical amplification.
the input currents of the DML and the characteristics of the OSR.

Standard single-mode fiber (SSMF) is considered for the FTTH system and is characterized by a loss coefficient of $\alpha = 0.21$ dB/km, a dispersion parameter $D$ of 17 ps/(km-nm) and a dispersion-slope parameter $S$ with a value of 0.09 ps/(km-nm$^2$).

### B. Local Exchange

As observed in figure 4, the OFDM-UWB signal is optically amplified at the local exchange. Considering the loss inflicted by the FTTH network, a 30 dB gain in the optical amplifier at the local exchange ($g_{\text{edfa}, \text{LE}} = 1000$) is considered.

After the local exchange, the power splitter divides equally the power by the $N$ subscribers.

### C. Receiver

The optical-to-electrical conversion is performed by a photodetector PIN with a responsivity of 1 A/W. The receiving filter before the OFDM-UWB receiver is a $5^{th}$-order Bessel low-pass filter with a bandwidth of 10 GHz. This filter performs a signal conversion from current to voltage and limits the noise generated by the optical amplification. The OFDM-UWB RX demodulates and decodes the received electrical OFDM-UWB signal.

### IV. PERFORMANCE EVALUATION METHODS

In this work, the error vector magnitude (EVM) is adopted as a measure of the distortion inflicted by the system. The EVM is a common figure of merit that evaluates the quality of a digital transmission. Its value expresses the difference between the value of the actual received symbol and the expected complex voltage/current value of the demodulated symbol. The EVM is usually adopted as a general performance of the system. Nevertheless, since it does not take into account the noise generated by the system, it is just a measure of the distortion inflicted on the signal at the OFDM receiver input.

The semi-analytical Gaussian approach (SAGA) allows evaluating the bit error ratio (BER) of each OFDM subcarrier in direct detection optical communication systems through numerical simulation [19]. The SAGA method is a powerful tool for the optimization of the network under analysis and its estimates have shown excellent agreements with the MC simulation. It takes into account the distortion induced by the components of the system (e.g. filter shapes) and considers the optical noise from amplified spontaneous emission (ASE) of the EDFA, and electrical noise generated at the receiver.

The noise field affecting each subcarrier is assumed zero mean additive white Gaussian noise with a power density given by the sum of the power spectral density (PSD) of the electrical noise and the PSD of the noise originated at the EDFAs.

The noise from ASE has a power spectral density per polarization mode defined by

$$S_{\text{ASE}} = h\nu_0n_{\text{sp}}(g_{\text{edfa}} - 1)$$

where $h$ is Planck’s constant, $n_{\text{sp}} = 1.26$ is the spontaneous emission noise factor and $\nu_0$ is the optical carrier frequency.

The PSD of electrical noise is given by

$$S_c = \frac{4k_BT}{R_0}f_{n,e}$$

where $k_B$ is the Boltzmann constant, $T$ is the room temperature (290 K), $R_0$ is the polarization resistor of the photodetector (50 $\Omega$) and $f_{n,e}$ is the noise factor that represents the influence of the active elements of the receiver. In order to obtain a PSD of $2.5 \times 10^{-23}$ A$^2$/Hz, $f_{n,e}$ has a value of 11 dB.

### V. EFFECT OF THE CLIPPING OPERATION IN OFDM-UWB SIGNALS

The clipping operation accomplished before the electro-optical conversion fits the OFDM-UWB current signal into the linear operating region of the laser. Although it causes an increase of distortion, a benefit that comes from removing the peaks of the signal is the reduction of the PAPR.

In this section, the distortion inflicted by the clipper is assessed in terms of the EVM. A multi-subband OFDM-UWB signal sequence transmitting simultaneously in the first 4 subbands with a PAPR of 21 dB is considered: the current at the clipper input is defined by a mean of 60 mA and a peak-to-peak current of 80 mA so that the multi-subband OFDM-UWB signal fits to the whole linear operating region of the laser (18~100 mA).

The effect of removing a percentage of the bottom half of the current on the EVM of each subband is represented in figure 5. It is observed that the subbands at the edges of the subband group (subbands 1 and 4) present a lower EVM than the subbands in the middle (subbands 2 and 4) due to the interference coming from only one adjacent subband instead of two.

As expected, figure 5 shows that the absence of clipping results in the lowest value of EVM of each subband and as the bottom of the signal begins to be removed, the corresponding EVM increases. For a clipping percentage near 100%, the EVM of each subband shows an abrupt decrease, showing a similar value to the non-clipped signal.

The percentage increase of the removal of the bottom half of the signal causes the growing of power outside the subband group. This power raising comes from intermodulation products at frequencies multiple of the sum or difference between the original used frequencies. The appearance of unwanted frequencies is a consequence of the non-linear operation performed and, as observed in figure 6 for 100% removal, the possible introduction of higher-frequency subbands (namely for subbands 10 and 11) would be affected by clipping noise generated by the first four subbands.

The result of a low EVM for a half-clipped OFDM signal was also obtained previously in [20]. It is explained that for an
OFDM signal with only the odd index subcarriers modulated, half-clipping reduces the amplitude of the subcarriers by exactly one half making all intermodulation products fall on the even subcarriers, reducing the distortion of the signal although half of the signal amplitude was removed. Figure 5 shows that the effect of low distortion for half-clipping an OFDM signal is replicated when modulating both odd and even indexed subcarriers.

VI. OFDM-UWB FTTH SYSTEM OPTIMIZATION

For the optimization process, the optical filters that simulate the MUX and the DEMUX were removed for simplicity, and it was introduced a variable attenuator and an EDFA that compose the noise loader at the PIN input. The loss effects of the fiber ($\alpha = 0$) and the electrical noise are not considered in the process. The noise power at the receiver input is adjusted by the noise loader in order to obtain a defined optical signal-to-noise ratio (OSNR). The OSNR is calculated for a reference optical bandwidth of 0.1 nm.

The values of $g$ and $I$ are set in order to minimize the required OSNR at the PIN input for a BER of $10^{-4}$, calculated using the SAGA method. The optimization was performed simultaneously for both gain $g$ and $I$.

A. Single subband optimization in back-to-back configuration

Figure 7 represents the contour of the required OSNR value as a function of the bias and peak-to-peak current for the system in back-to-back configuration (no fiber transmission) using subband 1. A bias current of 18 mA and peak-to-peak current of 350 mA was the result of the optimization with a required OSNR value of 5.08 dB.

A bias current of 18 mA originates a half-clipped OFDM-UWB current signal. As shown in section V a reduced distortion was obtained although half of the amplitude of the current signal was removed. A half-clipped OFDM-UWB signal defines the optimal bias current value for the single subband transmission.

An optimal peak-to-peak current of 350 mA for back-to-back transmission exceeds the upper limit of the linear operating region of the DML (100 mA). An increase in $g$ and the higher clipping of the peaks of the current signal severely distorts the signal at the clipper output. However, a higher value of $g$ raises the power level of the UWB subband increasing the resilience to the noise added by the EDFA. The optimal $g$ sets the balance between increasing the distortion introduced by the clipper and raising the power level of the UWB subband.

The transmission of single subbands 2, 3 and 4 in the back-to-back configuration show similar optimal current levels: a bias current that leads to a half-clipped signal and a gain $g$ that imposes a peak-to-peak of current before clipping operation of 350 mA. Table II shows the noiseless EVM of the single subband OFDM-UWB signal at the DML input and at the receiver in back-to-back configuration.

B. Single subband optimization with fiber transmission

The bias and peak-to-peak current were optimized for a single subband OFDM-UWB signal in the configuration with fiber transmission with length from 0 to 100 km. Similar results were obtained for the optimal bias and peak-to-peak current compared to the back-to-back configuration.

Figure 8 exhibits the performance degradation in terms of the required OSNR for BER=$10^{-4}$ for the configuration with fiber transmission. It is observed that transmission with a higher degradation was achieved for higher frequency UWB subbands due to the RIN generated by the laser.

The noiseless EVM calculated at the DML input was obtained by demodulating the electrical signal at this point of the network.
TABLE II
NOISELESS EVM OF THE SINGLE SUBBAND OFDM-UWB SIGNAL IN SEVERAL POINTS OF THE SYSTEM IN THE BACK-TO-BACK CONFIGURATION.

<table>
<thead>
<tr>
<th>Single subband used</th>
<th>{1}</th>
<th>{2}</th>
<th>{3}</th>
<th>{4}</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVM [dB] @ OFDM-RX</td>
<td>-18.25</td>
<td>-17.82</td>
<td>-15.57</td>
<td>-14.43</td>
</tr>
</tbody>
</table>

higher fiber length increases the required OSNR value leading to worse performance. This results from the fiber dispersion effects that are stronger for transmission with a higher length.

Figure 9 shows the noiseless EVM of the OFDM-UWB RX signal input as a function of the fiber length. It is observed that higher frequency subbands experience more distortion (at least until a 50 km transmission) and, therefore, show a worse performance.

For this work, the mean power of a subband \((\bar{P}_{sb})\) is defined as the mean power of the signal obtained by filtering the OFDM-UWB RX input by an ideal band-pass filter centered at the frequency center of the subband with a 528 MHz bandwidth. Figure 10 presents the \(\bar{P}_{sb}\) of each single subband as a function of the fiber length. It shows that the \(\bar{P}_{sb}\) decreases with the length of the fiber transmission.

Although the losses induced by the fiber are not introduced in the numerical model of the optical fiber, its dispersion effects influence the power of the UWB subband through chromatic dispersion. The decrease of \(\bar{P}_{sb}\) when the level of added noise by the EDFA is the same, makes the required OSNR increase in order to maintain the BER = 10\(^{-4}\). This leads to the performance degradation shown in figure 8. It can be noticed from figure 8 that the fiber transmission degrades the performance more severely for higher frequency subbands. Figure 10 shows that the \(\bar{P}_{sb}\) of subband 1 decreases 2 dB between the back-to-back configuration and the configuration with 100 km fiber transmission, while \(\bar{P}_{sb}\) of subband 4 decreases 8 dB. A higher decrease of \(\bar{P}_{sb}\) leads to worse performance in terms of the required OSNR.

C. Multi-subband optimization

In this section, the optimization is performed in a similar way to the single-subband case, changing the number of subbands used. The use of multiple subbands raises the interference level between subbands which leads to a higher performance degradation. The optimization was accomplished for subband groups \(\{1,2\}\), \(\{1,2,3\}\) and \(\{1,2,3,4\}\).

Since a required OSNR value for BER=10\(^{-4}\) is computed for each subband, the required OSNR that indicates the performance of the multi-subband transmission corresponds to the one of the subband with the highest OSNR.

As in the single subband optimization, the optimal bias current leads to a half-clipped signal. The peak-to-peak current of multi-subband optimal transmission has a higher value than the single-subband case, due to higher PAPR values of the OFDM-UWB signals using multiple subbands.

As shown in figure 11, the contour of the BER considering an OSNR of 15 dB \(^2\) as a function of the bias and peak-to-peak current for the back-to-back configuration, the optimal current levels stay in a similar region to the single subband case.

Figure 12 shows the performance degradation of multi-subband groups \(\{1,2\}\), \(\{1,2,3\}\) and \(\{1,2,3,4\}\). As expected, due to higher interference from crosstalk and the use of higher frequency subbands, the required OSNR for BER = 10\(^{-4}\) increases with the number of subbands used by the multi-subband OFDM-UWB signal.

For the subband group \(\{1,2\}\) and \(\{1,2,3\}\), the subband with the highest frequency in each group imposes the highest OSNR: for subband group \(\{1,2\}\), subband 2 has the lowest performance, and for \(\{1,2,3\}\), subband 3 imposes the highest OSNR. Worse performance in higher-frequency subbands, results from the stronger distortion inflicted by the components of the network, namely by the DML, and the higher decrease

\(^2\)The optimization was performed by minimizing the required OSNR for \(\text{BER} = 10^{-4}\) but, for the current values considered, the contour of the required OSNR did not fit the limits of the figure. Nevertheless, the contour of the BER shows a similar behaviour.
of the $P_{sb}$ for higher frequencies, as concluded in section VI-B.

For the subband group $\{1,2,3,4\}$, subbands 3 and 4 impose the worst performance: subband 3 experiences a higher level of interference from subbands at the both sides of the frequency spectrum, but the higher frequency subbands have $P_{sb}$ decrease, and are submitted to a higher distortion inflicted by the network, as demonstrated in VI-B. For a configuration with no fiber transmission, subband 4 sets the highest required OSNR. For a transmission with an increasing fiber length, the crosstalk between subbands increase due to the chromatic dispersion effects, making subband 3 the one that imposes the worst performance of the subband group. Figure 13 presents the EVM value of each subband of the OFDM-UWB signal at the receiver. It can be noticed that the EVM of subbands 2 and 3 substantially increases for the 100 km fiber transmission. The level of interference raises significantly due to the crosstalk from both sides of the frequency spectrum which is augmented by the fiber dispersion effects. This makes the subband 3 to impose the worst performance.

D. Optical spectrum reshaper filter optimization

The optimization of the OSR parameters was performed for the transmission of multi-subband OFDM-UWB signal using subbands $\{1,2,3,4\}$ in a configuration with fiber transmission of length 80 and 100 km. The optimization process was accomplished for the levels of current around the optimal values. Both bandwidth $\nu_g$ and central frequency $\nu_c$ are simultaneously optimized.

Figures 14 and 15 compare the non-managed chirp approach with the introduction of the OSR filter at the DML output, showing the OSNR for BER $= 10^{-4}$ values as a function of the peak-to-peak current with $\bar{I} = 18$ mA.

In terms of the required OSNR for BER $= 10^{-4}$, there is a performance improvement with the use of the OSR: a 3 dB decrease of the required OSNR for BER $= 10^{-4}$ value for the fiber transmission of 80 km and a 5.8 dB decrease for the fiber transmission of 100 km. The optimal bandwidth and central frequency of the OSR place the filter around the UWB subband group $^3$.

$^3$The results obtained for the OSR optimization shown in figure 15 suggest a lower required OSNR for a decreasing peak-to-peak current, however, the required OSNR obtained was unexpectedly high and did not fit the limit of the figure.
Fig. 14. Required OSNR for $\text{BER} = 10^{-4}$ as a function of the peak-to-peak current in 80 km fiber transmission with an optimized OSR and $I = 18 \text{ mA}$.

Fig. 15. Required OSNR for $\text{BER} = 10^{-4}$ as a function of the peak-to-peak current in 100 km fiber transmission with an optimized OSR and $I = 18 \text{ mA}$.

Fig. 16. PSD at the OSR output.

The use of the OSR filter decreases the power outside the subband group as shown in figure 16. It reduces by approximately by 10 dB the DC component (compared to figure 6). Thus, the mean power of the OFDM-UWB signal originated by optimal current levels decreases. This makes the power associated with the UWB subband group higher relative to the mean. The interference from power outside the UWB subband is lower leading to a better performance of the system.

VII. TRANSMISSION PERFORMANCE OF THE MULTI-SUBBAND OFDM-UWB SIGNAL IN THE OPTIMIZED FTTH NETWORK

The outcome of section VI, namely the optimal current levels that modulate the DML and the optimal bandwidth and central frequency that characterize the OSR filter, are adopted for transmission of the multi-subband OFDM-UWB signal using subbands 1, 2, 3 and 4.

The analysis is performed for the power levels of 0, 3 and 5 dBm, at the central node output ($P_{CN}$).

Figures 17, 18 and 19 show the BER as a function of the fiber length of the FTTH network transmitting an OFDM-UWB signal using subband group $\{1,2,3,4\}$ considering $N = 64, 32$ and 16, respectively.

Considering the FTTH configuration with 64 subscribers, the chirp-managed-based transmission does not ensure the minimum quality of $\text{BER} = 10^{-3}$ for $P_{CN} = 0 \text{ dBm}$, but this minimum quality is achieved for the maximum distance of 81 and 90 km for the fiber transmission with $P_{CN}$ of 3 and 5 dBm, respectively. As observed in figure 17, the DML-based transmission only assures a BER not exceeding $10^{-3}$ for the maximum fiber length of 83 km with $P_{CN}$ of 5 dBm. Thus, the CML-based transmission improves the maximum reach of the network that obtains a minimum quality of $\text{BER} = 10^{-3}$, compared to the DML-based transmission, by approximately 1 and 7 km, respectively for $P_{CN}$ of 3 and 5 dBm.

For $N = 32$, as considered in figure 18, the transmission using the DML only assures the minimum quality of $\text{BER} = 10^{-3}$ for the maximum distance of 83 km for $P_{CN}$ of 3 dBm and 89 km for $P_{CN}$ of 5 dBm. The transmission using the CML ensuring the minimum quality of $\text{BER} = 10^{-3}$ is accomplished for a maximum distance of 90 km for $P_{CN}$ of 3 dBm, and 100 km for $P_{CN}$ of 5 dBm. The CML-based transmission with $P_{CN}$ of 0 dBm does not ensure the minimum quality of $\text{BER} = 10^{-4}$. An improvement of 7 and 11 km is achieved for the cases with a $P_{CN}$ of 3 and 5 dBm.

As it can be noticed in figure 19, for $N = 16$ the transmission using the DML only assures the minimum quality of $\text{BER} = 10^{-9}$ for a maximum transmission length of 80 km with $P_{CN}$ of 3 dBm, and 86 km with $P_{CN}$ of 5 dBm. The CML based transmission ensures the minimum required quality for the transmission length of 87 and 96 km with $P_{CN}$ of 3 and 5 dBm, respectively. For both DML-based and CML-based transmission the minimum quality not exceeding $\text{BER} = 10^{-9}$ is not achieved with $P_{CN}$ of 0 dBm. Thus, an improvement of 7 and 10 km is achieved for $P_{CN}$ of 3 and 5 dBm.

Although the same power level is assigned to both CML and DML-based approaches, the chirp-controlled optical OFDM-UWB signal is more resilient to the fiber transmission. Figures 20 and 21 show the noiseless EVM of the OFDM-UWB signal at the receiver as a function of the fiber length for both DML-based and CML-based transmissions. It can be observed that the chromatic dispersion associated with the fiber transmission has a stronger effect on the DML-based OFDM-UWB signal: there is a higher increase of the EVM value compared to the EVM of the CML-based transmission. The subbands in the middle of the subband group have an EVM increase mainly due to a larger crosstalk coming from subbands at both sides of the spectrum. The distortion coming from crosstalk is enhanced by the higher sensitivity of the non-chirp-controlled OFDM-UWB signal to the fiber dispersion.

Subbands 3 and 4 impose the lowest performance: subband 3 experiences a higher level of interference from subbands at the both sides of the frequency spectrum, but higher frequency
subbands have their $\bar{P}_{sb}$ decrease more due to the fiber dispersion (as seen in section VI) and are submitted to a higher distortion by the DML. For the DML-based transmission, the subband with worst performance varies between 3 and 4. The higher level of crosstalk due to the longer fiber transmission causes the subband with worst performance changing from 4 to 3.

In the CML-based transmission, subband 4 imposes the highest distortion. As observed in figure 20, the fiber dispersion effect does not influence the EVM value as much as in the transmission using the DML. A chirp-controlled OFDM-UWB signal exhibits a higher resilience to the chromatic dispersion of the fiber. Section VI demonstrated that higher frequency subbands experience more distortion by the DML and, in this case, it determines the subband with worst performance.

VIII. CONCLUSION

The final goal of this paper was the analysis and performance optimization of the transmission of OFDM-UWB radio signals in FTTH networks using chirp-managed lasers.

The high PAPR was mentioned as one of the major drawbacks of the OFDM-UWB radio signals. Higher PAPR values were obtained for OFDM-UWB signals originated by longer bit sequences and using more subbands, reaching 21.3 dB subband group $\{1,2,3,4\}$.

The FTTH architecture was presented and each of its components was described. The effect of the non-linear operation of clipping in the OFDM-UWB signal was analysed and it was concluded that a half-clipped OFDM-UWB signal shows a reduced distortion.

The transmission of OFDM-UWB signals in a DML-based system was optimized: the bias and peak-to-peak currents that minimize the required OSNR for BER $= 10^{-4}$ were calculated. The optimal bias current originated a half-clipped OFDM-UWB signal and the optimal peak-to-peak current sets the balance between increasing the distortion introduced by the clipper and raising the power level of the UWB subband.

The performance degradation was analyzed and it was demonstrated that it is imposed by the distortion inflicted by the DML, which is more intense for higher frequency subbands. The larger decrease of $\bar{P}_{sb}$ for higher frequency subbands significantly limits the performance of the system and it was shown that this effect is augmented by the fiber transmission. The higher interference from crosstalk between subbands in multi-subband transmission substantially degrades...
the performance of the system and it is also augmented by the chromatic dispersion of the fiber. A required OSNR of 20 dB for BER = 10^-4 was obtained when transmitting subbands 1, 2, 3 and 4 simultaneously through a configuration with 100 km of fiber transmission. This value is 5 dB higher than the transmission of subbands 1, 2 and 3, and 10 dB higher than the transmission of subbands 1 and 2.

The chirp-managed laser was optimized and an improvement of 5.8 dB in the required OSNR for BER = 10^-4 for the transmission along 100 km of fiber. The method reduces the chirp generated by the DML modulation and raises the subband group power level relative to the unwanted power outside the subband group.

The transmission performance of OFDM-UWB signals along the optimized FTTH network using chirp-managed lasers was investigated. The chirp-managed-based approach for the optical transmitter was compared to the use of the DML, reaching an improvement of 10 km of the maximum transmission distance for the minimum quality of BER = 10^-9. It was concluded that the chirp-controlled OFDM-UWB optical signal is more tolerant to the fiber dispersion, showing a noiseless EVM that is approximately constant with the fiber transmission compared to the EVM of the DML-based transmission.

REFERENCES

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