Performance limitations of 40 Gb/s SSB MB-OFDM metropolitan networks induced by phase-to-intensity conversion of laser phase noise

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Abstract—Multi-band (MB) orthogonal frequency division multiplexing (OFDM) signals have recently been proposed to be used in optical metropolitan (metro) networks. MB-OFDM signals transmission provides increased bandwidth allocation flexibility, high spectral efficiency, higher capacity provisioning granularity and high tolerance to linear fibre distortion effects. Metro network implementation cost restriction can be meet by employing direct-detection (DD) OFDM. However, although DD-OFDM presents robustness against phase fluctuations, fibre chromatic dispersion (CD) causes phase-to-intensity conversion of laser phase noise, leading to performance degradation in DD-OFDM systems.

The objective of this work is to evaluate through numerical simulation the maximum laser linewidth and maximum reach of a 40 Gb/s single sideband (SSB) MB-OFDM metro ring limited by laser phase noise.

In this work, the transmission of MB-OFDM signals employing virtual carriers is studied. For a 3-band MB-OFDM system with laser linewidths as high as 5 MHz, it is demonstrated that the penalty of the required optical signal-to-noise ratio (OSNR) to achieve a bit error rate (BER) of $10^{-3}$ after a fibre span of 500 km does not exceeds 1 dB. The results considering a real network show that, using a Gaussian BS, it is possible to transpose 5 fibre spans of 40 km with a maximum laser linewidth of 10 kHz for BER $<10^{-3}$. A highly selective 2nd-order super Gaussian BS is also evaluated and it is shown that the MB-OFDM signal can travel through more than 7 spans of 40 km for laser linewidths up to 100 kHz.

Index Terms—Metro networks, orthogonal frequency division multiplexing, multi-band, direct detection, laser phase noise, phase-to-intensity noise conversion.

I. INTRODUCTION

U

ually, telecommunication networks are stratified in core, metro and access networks. The core or backbone network deals with long-haul transmissions, covering vast distances. It provides connectivity to metro networks and carries large traffic. Access networks are the connection to end-users, support a wide diversity of protocols and cover the last 10 km to 35 km of the overall network.

Metro networks are responsible for delivering traffic from core to access networks and vice-versa, but also between different access networks. Designed to serve large and densely populated areas, metro networks typically extend between 200 km and 300 km, depending on the region geography [1]–[3].

The metro network must aggregate different types of traffic coming from the access layer. Therefore, flexibility, scalability, dynamic reconfiguration and transparency are key features [4]. Also, since the metro network infrastructure is shared among fewer people than core networks, it requires cost-effective solutions [4].

The most common metro networks present a ring topology [1], [5], as shown in figure 1. An optical network is composed by nodes linked by optical fibre, generally the standard single mode fibre (SSMF) [2], [8]. The nodes connect the metro network to the access or core networks and typically the distance between two adjacent nodes (a span) ranges from 5 km to 100 km [2], [9].

Fig. 1: Metro network with five nodes in a typical ring configuration.

Since bandwidth demand continues to grow exponentially, there is little alternative but to develop new solutions that allow us to maximize existing systems and networks. Subsequently, wavelength division multiplexing (WDM) role is increasingly significant as metro networks tend to adopt optical transparency. As dense WDM (DWDM) is deployed extensively in metro networks, the use of a large number of wavelengths and unpredictable bandwidth demand have led to the development of reconfigurable OADMs (ROADMs), allowing wavelength rearrangement through software control [10].

Moving towards all or predominantly optical environments enables several advantages. The most significant ad-
MB-OFDM considers the transmission of multiple narrow and independent OFDM bands in each wavelength. This implementation presents many advantages. The sharp shape of the OFDM spectrum allows achieving high spectral efficiency by reducing the spacing between bands [4]. With the use of parallel lower-speed bands, electrical bandwidth requirements can be reduced [11]. Furthermore employing DD makes MB-OFDM a very cost-effective solution for metro networks.

High spectral efficiency and resilience against linear fibre effects led OFDM systems to be widely implemented in optical communications [13]–[18]. Interest in optical OFDM is also supported by recent advances in microelectronic technologies, such as the analogue-to-digital converter (ADC), digital-to-analogue converter (DAC) and digital signal processing (DSP) [18].

OFDM systems are composed by radio frequency (RF) transmitters and receivers. Thus, to accomplish optical transmission, the OFDM transmitter is followed by a optical-electrical (EO) converter and the OFDM receiver is preceded by a electrical-optical (OE) converter. Depending on how the OE conversion is performed the system is classified as either coherent optical OFDM (CO-OFDM), when the received signal is mixed with a locally generated optical carrier, or as DD-OFDM, when the signal is transmitted with the optical carrier [13]–[18].

A DD-OFDM implementation uses a simpler receiver with a single photodetector and without a local laser, thus cheaper. However, it requires more optical power in order to transmit the optical carrier and it has less spectral efficiency since some optical frequencies are left unused as a guard band between the optical carrier and the OFDM subcarriers to avoid mixing products interference. Nevertheless, DD-OFDM is preferable for metro and access networks where cost is the primary concern [13], [18], [19].

Recently, a 100 Gb/s DD MB-OFDM superchannel system with virtual carriers was proposed for long-haul networks [20]. The system described in [20] uses dual carriers at both superchannel sides to assist DD. This MB-OFDM system is quite challenging to implement in flexible metro networks due to the huge receiver front-end bandwidth requirements and the need for a dual-band optical filter to assist detection. One way to avoid using a dual-band optical filter and simultaneously reduce the required receiver bandwidth is to use a single virtual carrier close to each OFDM band to assist the band detection [4], [21], [22].

The MB-OFDM system considered in this work is supported in the recently proposed metro networks based on SSB MB-OFDM signals (MORFEUS) [4], [21], which employ virtual carriers to assist DD. MORFEUS proposal addresses the future requirements of metro networks such as high flexibility, scalability, dynamic reconfigurability and transparency.

The MORFEUS solution presents some challenges. The capacity and number of bands of the MB-OFDM signal is determined by the cost restriction of electrical components in metro networks. The increased complexity caused by band insertion and extraction blocks and their impact on the system performance still needs to be investigated. The reduced selectivity of the optical filters used in extraction leads to inter-band crosstalk. Inefficient band blocking results in intra-band crosstalk between an extracted band and the newly inserted band.

Additionally, DD also presents some drawbacks. Particularly, significant performance limitations are imposed by phase noise and wavelength drift of laser sources. Although DD systems are robust to phase impairments, due to fibre CD, phase noise is converted into intensity noise degrading the MB-OFDM signal. While phase noise effects have been widely studied in CO-OFDM systems [23], [24], [26]–[29], the impact of laser phase noise on the DD-OFDM system performance has only been analysed for long-haul networks transmitting a single band [30]. Thus, it is quite important to evaluate the performance of metro networks employing DD limited by the finite linewidth of laser source (which results mainly from phase noise), particularly when transmitting SSB MB-OFDM signals.

The main objectives of this work are to assess (i) the degradation induced by the conversion of the laser phase noise to intensity noise realized by the fibre dispersion in 40 Gb/s SSB MB-OFDM metro networks and (ii) the maximum laser linewidth and maximum reach of the 40 Gb/s DD MB-OFDM metro ring limited by laser phase noise. In order to achieve the proposed objectives, a numerical simulator was developed in MATLAB.

The rest of this paper is organized as follows. In section II, the MB-OFDM system model is provided. Section III describes the laser phase noise and its effects. In section IV, numerical results and analysis of the system performance in the presence of laser phase noise are given. Finally, section V concludes this paper.

II. MB-OFDM System Model

The classical multi-carrier modulation (MCM) system, e. g. frequency-division multiplexing (FDM), is based on non-overlapped band-limited signals. A MCM system can be implemented using a large number of oscillators and filters at both transmitter and receiver which, in turn, leads to channel spacing becoming multiple times the symbol rate, greatly reducing the signal spectral efficiency [31]. Alternatively, OFDM signals use overlapped subcarriers to increase spectral efficiency but in an orthogonal way, with each subcarrier orthogonal to every other subcarrier, and so preventing inter-carrier interference (ICI).
A. The OFDM signal

Considering that a OFDM transmitted signal has a set of subcarriers, each one bearing information symbols, then that signal can be expressed as a time-domain sum of all subcarriers [31], given by

\[ s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=-\infty}^{N_{sc}} c_{ki} s_k(t - iT_s) \]  

where \( c_{ki} \) is the information symbol at the \( k \)-th subcarrier of the \( i \)-th OFDM symbol, \( s_k(t) \) is the waveform of the \( k \)-th subcarrier, \( N_{sc} \) is the number of subcarriers and \( T_s \) is the OFDM symbol duration.

A typically used function set is the windowed discrete tones [31], given by

\[ s_k(t) = \Pi(t) e^{j2\pi f_k t} \]  

where \( f_k \) is the frequency of the \( k \)-th subcarrier and \( \Pi(t) \) is the pulse shaping function given by

\[ \Pi(t) = \begin{cases} 1, & \text{if } 0 < t \leq T_s \\ 0, & \text{if } t \leq 0, \ t > T_s \end{cases} \]  

The OFDM signal’s orthogonality can be verified if the following condition [31] is fulfilled

\[ f_k - f_l = \frac{m}{T_s}, \ m \in \mathbb{N}. \]  

In OFDM, a large number of subcarriers (\( N_{sc} \)) is required in order to the transmission channel appears flat to each subcarrier and therefore recover the subcarriers with minimum signal processing complexity [18]. Nevertheless, a large number of subcarriers leads to an extremely complex architecture involving many oscillators and filters. Another way to generate the orthogonal subcarriers is to make use of the discrete Fourier transform (DFT), applying the inverse DFT (IDFT) to implement OFDM modulation and DFT for demodulation. Focusing on only one OFDM symbol, \( (i = 0) \), and assuming a sampling period of \( \frac{2}{N_{sc}} \), then, from equation (1), the \( m \)-th sample of the transmitted signal becomes

\[ s_m = \sum_{k=1}^{N_{sc}} c_k \cdot e^{j2\pi f_k \frac{mT}{N_{sc}}}, \ m = 0, 1, \ldots, N_{sc} - 1. \]  

Using the orthogonality condition presented in equation (4) and the convention [18] that the frequency of the \( k \)-th subcarrier is given by

\[ f_k = \frac{k - 1}{T_s} \]  

then, equation (5) can be rewritten as

\[ s_m = \sum_{k=1}^{N_{sc}} c_k \cdot e^{j2\pi i \frac{k-1}{N_{sc}} m} = \text{IDFT}\{c_k\} \]  

where IDFT\{x\} stands for the IDFT of \( x \).

B. OFDM transmission system

The structure of a generic OFDM communication system based on a DFT architecture is depicted in figure 2. Both the transmitter and receiver process the signal digitally, while transmission is done in the analogical domain. The fast Fourier transform (FFT) and inverse FFT (IFFT) are used as practical versions of the DFT and IDFT, respectively. At the transmitter side, binary data is mapped into symbols accordingly to a digital modulation scheme. In this case, data is mapped using QAM.

![Fig. 2: Block diagram of DFT-based OFDM transmitter and receiver.](Image)

The resulting sequence of QAM symbols must be converted to a suitable input for the IFFT. This operation is performed in the serial-to-parallel (S/P) block, where a sequential input is divided in multiple \( N_{sc} \) parallel streams. The IFFT modulates the mapped symbols into subcarriers of a OFDM symbol. After the \( N_{sc} \)-point IFFT, a cyclic prefix (CP) is added to the beginning of the OFDM symbol [32].

The OFDM symbol is lined up through a parallel-to-serial (P/S) process. DSP facilitates the OFDM implementation but requires digital-analogue conversion. Therefore, the signal must be converted to analogue by a DAC which turns discrete samples used in the digital domain into a continuous analogue waveform. Also, the signal is filtered by a low-pass filter (LPF) to eliminate excessive bandwidth, due to aliasing [31].

The resulting signal is up-converted by an in-phase/quadrature (I/Q) modulator. Taking advantage of the real (in-phase) and imaginary (quadrature) signal components, the modulator up-converts the signal from a baseband frequency into a passband one used for transmission.

At the receiver end, the reverse process must be done in order to obtain the original data. Firstly, the analogue received signal is down-converted by an I/Q demodulator. The next step is a digital conversion using a ADC enabling
DSP. The ADC samples a received waveform in such way that with an ideal channel the ADC output should be equal to the DAC input.

The digital OFDM signal received is separated in \( N_{sc} + CP \) streams by a S/P block and the CP is removed. We now have a suitable input for the \( N_{sc} \)-point FFT. The FFT demodulates the OFDM subcarriers into QAM symbols. The received QAM symbols must be equalized and afterwards those symbols are demapped through a decision process where the original binary data is expected at the output of the demapper.

C. SSB MB-OFDM transmission system

In metro networks using DD, after photodetection, the fibre CD accumulation induces high power fading in double sideband (DSB) signals [33]. A possible solution to overcome CD-induced power fading is to transmit SSB signals [4] at the expense of reducing the available bandwidth of the OFDM signal. Using SSB signals, that can be generated at the optical transmitter, instead of resorting to optical dispersion compensation allows network upgrading without modifying equipments installed between transmitter and receiver.

SSB OFDM transmitters generally reserve a frequency gap between the optical carrier and the OFDM signal. The gap bandwidth is usually similar to the OFDM signal bandwidth [17], [20], [22], [35]–[37]. This gap serves to accommodate the distortion induced by signal-signal beat interference (SSBI) resulting from the DD process, as detailed in subsection II-C3. However, this leads to a spectrally inefficient system.

The inclusion of a virtual carrier (RF tone) close to each OFDM band allows reducing the frequency gap and, thus, increasing the spectral efficiency. The main limitation of this technique is the additional distortion of the OFDM signal caused by the SSBI. Nevertheless, such distortion can be diminished either by increasing the power of the virtual carrier compared to the power of its corresponding OFDM band or by using DSP algorithms at the receiver side to reconstruct and remove the SSBI term from the photo-detected signal [8], [38], [39].

Figure 3 presents a scheme of the optical SSB MB-OFDM system employing virtual carriers (VCs). As shown in figure 3, the MB-OFDM transmitter is composed by OFDM transmitters, one for each band, where virtual carriers are electrically generated and added to the OFDM bands. Additionally, the MB-OFDM transmitter is responsible to convert the generated signal into an optical SSB signal. The MB-OFDM signal is transmitted along a SSMF span and the necessary signal amplification is assured by erbium-doped fibre amplifiers (EDFAs). At the MB-OFDM receiver, the desired band is filtered from the MB signal by a band selector (BS). The MB-OFDM receiver also includes a DD-based OE converter, a digital SSBI removal block and a OFDM receiver.

1) Virtual carrier-assisted transmission: The virtual carrier enables to separately detected each OFDM band

![Fig. 3: Scheme of the optical SSB MB-OFDM system employing DD and virtual carriers to assist detection.](image)

[21]. The BS in the optical receiver selects both the OFDM band and the virtual carrier and, after photo-detection, the resulting direct current (DC) component is removed from the signal.

Figure 4 illustrates the spectral occupancy of a (SSB) MB-OFDM signal with virtual carriers in the electrical domain. In figure 4, \( R_{OFDM} \) is the bandwidth of a OFDM band considering that all bands have the same bandwidth, \( f_{c,n} \) and \( f_{vc,n} \) are the central frequency and the frequency of the virtual carrier, respectively, of the \( n \)-th OFDM band. Additionally, figure 4 identifies the virtual carrier-to-band gap (VBG), the band gap (BG) and band spacing, \( \Delta f_c \), which is the spacing between central frequencies of adjacent bands.

![Fig. 4: Spectral scheme of a 3-band MB-OFDM signal employing virtual carriers in the electrical domain.](image)

The VBG is defined as the width of the frequency gap between the OFDM band and its corresponding virtual carrier. The VBG should be as small as possible in order to maximize spectral efficiency but, since it coincides with the SSBI accommodation gap, if the VBG is narrower than the bandwidth of the OFDM band then, after photodetection, SSBI overlaps the signal. Assuming that the MB-OFDM receiver completely removes SSBI after photodetection, then the VBG is selected in order to allocate the virtual carrier at a null of the OFDM subcarriers sinc-square spectrum avoiding the out of band side lobes and...
unnecessary degradation. Thus, the VBG can be obtained as follows

$$\text{VBG} = k \frac{R_b}{N_{\text{band}} N_{sc} \log_2 M}, \quad k \in \mathbb{N}. \quad (8)$$

The BG is defined as the width of the frequency gap between two adjacent bands of the MB-OFDM signal. An appropriate BG is necessary to avoid inter-band crosstalk due to the finite selectivity of the BS. The BG value is obtained considering that: (i) the maximum bandwidth for the MB-OFDM signal is 20 GHz [4] and (ii) the band spacing is chosen targeting an even distribution of the OFDM bands along the MB-OFDM signal spectrum. The BG relation to the band spacing is perceived in figure 4 and it is given by

$$\Delta f_c = \text{BG} + B_{\text{OFDM}}. \quad (9)$$

The virtual carrier amplitude depends on the virtual carrier-to-band power ratio (VBPR), which is defined as the ratio between the power of the virtual carrier, $p_{vc}$, and the power of the OFDM band, $p_{\text{band}}$. The VBPR expressed in dB is given by

$$\text{VBPR} = 10 \log_{10} \left( \frac{p_{vc}}{p_{\text{band}}} \right). \quad (10)$$

2) Optical transmitter: An optical transmitter is required to convert the electrical OFDM signal into optical form and launch the resulting optical signal into the optical fibre. In this work, an optical transmitter using external modulation is employed.

The optical SSB signal can be generated by using a conventional optical modulator followed by an optical SSB filter to remove one sideband of the signal or using a dual parallel (DP) Mach-Zehnder modulator (MZM) [40], avoiding the use of an optical SSB filter which presents a limitation for spectral efficiency and system performance due to its finite selectivity. The DP-MZM EO converter is composed by two inner MZMs and an outer MZM.

The DP-MZM allows generating a SSB version of the MB-OFDM signal by applying the electrical signal and its Hilbert transform to the two arms of the DP-MZM [41]. The ideal Hilbert transform transfer function is given by

$$H_H(f) = j \cdot \text{sgn}(f).$$

In a real system, the Hilbert transform is implemented by a hybrid coupler.

Figure 5 shows the spectrum of the optical SSB MB-OFDM signal at the DP-MZM output.

A single OFDM band signal, in a back-to-back implementation, without BS, without any noise addition and neglecting non-linearities of the EO conversion, presents a photo-current at the PIN output given by

$$i_{\text{PIN}}(t) = A_{vc}^2 + 2A_{vc} R\{s_{\text{OFDM}}(t)\} + |s_{\text{OFDM}}(t)|^2 \quad (11)$$

where $A_{vc}$ is the virtual carrier amplitude and $s_{\text{OFDM}}(t)$ is the OFDM band signal, both after the OE conversion.

In equation (11), the first term is a DC component (easily removed with a DC block), the second term is the desired OFDM band signal amplified by a constant value and the third term is the SSBI.

In the developed simulator, SSBI removal is achieved by obtaining the SSBI-induced distortion separately and then removing it from the photo-current signal, as proposed in [42].

III. Laser phase noise

In optical systems, phase noise is caused by fluctuation in the laser source, in this case a continuous wave (CW) laser. An ideal optical source without any modulation is a monochromatic oscillator. Its output electrical field power spectral density (PSD) is a line located at the oscillation frequency and its spectral linewidth is null [43]. Although photon generation in a laser is done through stimulated emission, in a non-ideal situation, there is some spontaneous emission, causing phase fluctuations in lasers. Consequently, the optical source is noisy and can be seen as not monochromatic or incoherent [43]. This means that, even in absence of modulation, the output field PSD is not a line and no longer has null spectral linewidth. In semiconductor lasers, the linewidth is usually large, up to the megahertz range [31].

The phase fluctuation of a laser, $\phi(t)$, which can be quantified by the laser linewidth, $\Delta \nu_L$, is generally mod-
elled by the Wiener process [23]–[28] as follows

$$\phi(t) = 2\pi \int_0^t n(v)dv$$  \hspace{1cm} (12)

where \( n(t) \) is a zero mean random process, known as white Gaussian noise, with a variance of \( \Delta \nu_L/(2\pi) \) [30]. As a result, the phase fluctuation has a normal distribution with zero mean and a variance of \( \Delta \nu_L/(2\pi) \) [30].

In a DD-OFDM system, the transmitter’s oscillator is the only phase noise source. Furthermore, due to the power-detection nature of the photo-diode, the laser phase noise will not appear in the converted electrical signal and thus it is harmless to the system performance. However, in optical transmission, the signal accumulates a certain amount of fibre CD and its different subcarriers experience different timing offset [30].

After photo-detection the received signal can be expressed, resorting to equation (11), as follows [30]

$$i_{\text{PIN}}(t) = DC + 2A_{\text{in}}\Re\{s_{\text{OFDM}}(t)e^{j\rho_k(t)}e^{j\theta_k}\} + SSBI.$$  \hspace{1cm} (13)

At the photo-diode output, the desired signal comes multiplied by the converted phase noise (CPN) term, \( e^{j\rho_k(t)} \), where the converted phase fluctuation on the \( k \)-th subcarrier, \( \rho_k(t) \), results from the combination of the laser phase noise and the fibre CD time delay [30]. The desired signal comes also multiplied by \( e^{j\theta_k} \), where \( \theta_k \) is the CD-induced phase rotation on the \( k \)-th subcarrier [30].

The subcarriers symbols of the photo-detected signal with phase noise are not only corrupted by the phase rotation term (PRT), \( e^{j\rho_k(t)}e^{j\theta_k} \), but also by information of the adjacent subcarriers [30]. The latter effect has the appearance of a zero mean Gaussian noise [23], [24], [26], [30], normally known as ICI or loss of orthogonality [27], [29], [30].

Additionally, since signal power is leaking to the PRT and ICI, the presence of phase noise is responsible for power degradation in the received subcarriers.

In coherent-detection systems, symbols phase rotation induced by phase noise is known as common phase error (CPE) [23] and it can be corrected by phase rotation or equalization. The CPN is dependent of the subcarrier frequency and its bandwidth is both independent of the laser linewidth and a function of the time delay [30]. Thus, the CPN bandwidth might range in orders greater than 70 MHz [30] and such a broad spectrum introduces significant ICI. Particularly, PRT differs from CPE because it varies with the subcarrier frequency and therefore is not common to all subcarriers. PRT power is found to increase with fibre length and decrease with the total number of subcarriers, but only affecting the imaginary part of the signal and therefore resulting in a phase rotation [30].

Figure 6 illustrates the described effects of the phase noise on the received QAM symbols. The received QAM symbol, shown in figure 6, suffers from power degradation, thus its vector is shorter than the ideal QAM symbol. PRT effect is represented by a dashed curve indicating the symbol rotation. In figure 6, the QAM symbol scattering due to ICI is illustrated by a circle of possible locations for the received symbol.

Figure 7 shows the received QAM symbols of one OFDM band after a 280 km fibre span, with and without phase noise. The numerical simulator parameters considered for the single OFDM band system are presented in table I.

Tab. I: Parameters of the single OFDM band system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit rate [Gb/s]</td>
<td>14.3</td>
</tr>
<tr>
<td>Bandwidth [GHz]</td>
<td>3.6</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>128</td>
</tr>
<tr>
<td>QAM mapping</td>
<td>16-QAM</td>
</tr>
<tr>
<td>VBG [MHz]</td>
<td>27.9</td>
</tr>
<tr>
<td>VBPR [dB]</td>
<td>6</td>
</tr>
</tbody>
</table>

The selected fibre length corresponds to about the typical maximum length of a metro ring, e.g., a seven-node ring with fibre spans of 40 km between nodes.

The constellation presented in figure 7a) shows the fibre CD-induced rotation. Figure 7b) shows both the constellation rotation and the ICI noisy-like effect of phase noise, now visible due to the combination of phase noise and fibre CD.

IV. PERFORMANCE ANALYSIS

In addition to the parameters presented in table I, the performance analysis of the MB-OFDM system considers the parameters presented in table II.

Two different approaches are considered to evaluate the MB-OFDM signal performance degradation due to the combination of phase noise and fibre CD. The first approach consists on a noise loading circuit, where the OSNR is enforced to the system. In this approach the amplified spontaneous emission (ASE) noise is added to

Tab. II: Parameters of the MB-OFDM system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of OFDM bands</td>
<td>3</td>
</tr>
<tr>
<td>Total bit rate [Gb/s]</td>
<td>42.8</td>
</tr>
<tr>
<td>Band spacing [GHz]</td>
<td>6.25</td>
</tr>
<tr>
<td>BS</td>
<td>Gaussian</td>
</tr>
<tr>
<td>BS bandwidth [GHz]</td>
<td>3</td>
</tr>
<tr>
<td>( f_{c,1} ) [GHz]</td>
<td>3.5</td>
</tr>
</tbody>
</table>
In the signal at the BS input and the performance limitations introduced by the network intermediate nodes are neglected (single span). The second approach considers a real network, where the OSNR is not predefined and depends on noise accumulation along the network ring. Contrarily to the noise loading circuit implementation, this approach considers that noise is distributed along the network, at each EDFA the signal accumulates more ASE noise and amplifies both the signal and already existing noise.

The purpose of using a noise loading circuit is to assess the required OSNR value to obtain the target BER of $10^{-3}$. Figure 8 shows, for different laser linewidths, the variation relative to back-to-back (B2B) of the required OSNR ($\Delta$OSNR) as function of the SSMF length.

Although, the maximum length of a metro network is typically around 300 km, figures 8a) and 8b) present results up to 500 km in order to observe the phase-to-intensity noise conversion effect due to the combination of laser phase noise and fibre CD. Nevertheless, the SSMF length by itself does not seem to affect much the system performance and its effect is more significant for laser linewidths above 1 MHz.

Figure 8a) shows that, when employing a Gaussian BS, for a laser linewidth of 5 MHz, the $\Delta$OSNR only reaches 1 dB at 500 km of SSMF. Figure 8b) shows that, using a 2nd-order Gaussian BS, the $\Delta$OSNR for each linewidth is reduced to less than a half in comparison with figure 8a). These results show that, when phase noise is considered, fibre CD is quite less significant to the system performance than the BS. The behaviour of the OSNR penalty variation with the fibre length, shown in figure 8, is in agreement with the study realized in [30].

In order to support the previous results, figure 9 presents the error vector magnitude (EVM) [44] variation along the subcarriers of the OFDM band with worst performance, when employing a Gaussian BS.

In figure 9a) the first and last subcarriers have higher EVM values. This is due to the BS shape and narrow bandwidth, which leads to an EVM variation from -40 dB up to -30 dB, even in a B2B situation without phase noise. Figure 9b) shows that after a 500 km span, fibre CD contributes with an evenly distributed EVM increase across the subcarriers to values between -35 dB and -25 dB. Thus, fibre CD by itself affects less the OFDM band performance than the selectivity of the BS.

Figure 9c) shows the combined effect of the BS and the laser phase noise. In comparison with figure 9a) the EVM across the subcarriers greatly increases, with a maximum difference of approximately 15 dB. This is due to phase-to-intensity conversion of laser phase noise induced by the
Fig. 9: EVM in dB as a function of the subcarriers (a) in B2B, (b) after a fibre span of 500 km, (c) in B2B and with 5 MHz of laser linewidth, (d) after a fibre span of 500 km and with 5 MHz of laser linewidth. A Gaussian filter BS is employed.

BS. Since the aim of this work is mainly to analyse fibre CD-induced phase-to-intensity noise conversion of laser phase noise, further analysis of the BS in the presence of phase noise is out-of-scope of this paper and should appear in other publication. The situation shown in figure 9d) considers the combination of phase noise, a BS and fibre CD. The EVM increases for all subcarriers, reaching a maximum increase of 17 dB in comparison with the situation shown in figure 9a). Comparing with figure 9c) case, fibre CD only contributes with a more even degradation across the subcarriers.

The following simulation results consider the second performance evaluation approach, where the MB-OFDM signal is transmitted between network nodes along SSMF spans of 40 km.

In order to assess the performance differences between the BS solutions, figure 10 presents the EVM variation in dB per band as a function of the number of spans, without laser linewidth, when employing a Gaussian BS and a 2nd-order super Gaussian BS.

Figure 10 shows that the second and third OFDM bands have similar performance behaviours for both BS implementations. However, using a Gaussian BS, the first OFDM band degradation with the number of spans is much faster, surpassing the other two bands after 5 spans. As detailed in subsection II-C2, the DP-MZM generation of a SSB signal leaves vestiges of the left sideband. Due to the low selectivity of the Gaussian BS, photodetection performs the beat between the vestiges of the left sideband, the desired band and the second band of the right sideband. Together with the aforementioned noise accumulation, that also affects the left sideband, this results in a rapid deterioration of the overall performance.

Figures 11 and 12 show the log_{10}(BER) results as a function the number of spans, for different laser linewidths, when employing a Gaussian BS and a 2nd-order super Gaussian BS, respectively. Phase-to-intensity conversion of laser phase noise due to the BS is also confirmed by the log_{10}(BER) results, since, even in B2B, the MB-OFDM signal is greatly affected by the increase of laser linewidth. Because of the degradation imposed by the combination of the BS and phase noise, for laser linewidth higher than 1 MHz (just 1 kHz in the 2nd-order super Gaussian BS case) the log_{10}(BER) variation with the number of spans become imperceptible.

The simulation results shown in figure 11 allow determining the maximum laser linewidth supported by
the MB-OFDM system and the corresponding maximum reach of the metro ring, when employing a Gaussian BS. According to figure 11, the MB-OFDM signal is able to travel through 5 spans (200 km) before reaching the target BER. This mark is accomplished for laser linewidths up to 10 kHz. For linewidths of 100 kHz or higher the system performance surpasses the target BER even for a single span.

Figure 12 shows that, employing a 2nd-order super Gaussian BS, with a laser linewidth of 10 kHz the MB-OFDM signal crosses a total of 7 spans (280 km) without reaching the target BER. Additionally, figure 12 shows that this theoretical BS solution supports laser linewidths up to 100 kHz (for a laser linewidth of 100 kHz results a $\log_{10}(BER)$ equal to -2.8).

V. CONCLUSIONS

In this work, the transmission of virtual carrier-assisted SSB DD MB-OFDM signals along a metro network impaired by laser phase noise was studied. The impact of the phase-to-intensity noise conversion due to the combined effect of finite laser linewidth with fibre CD and BS was assessed.

The OFDM signal was mathematically defined and the OFDM DFT-based transmission system was described. A virtual carrier-assisted MB-OFDM system employing SSB signals generated by an optical transmitter using a DP-MZM and employing an optical receiver supported by PIN photodetection was presented. Phase noise effects on DD-OFDM systems were identified as power degradation, PRT and ICI.

Results were presented for the implementation of a numerical simulator based on the MB-OFDM metro network system modeled. The MB-OFDM system performance was evaluated by two different figures of merit: the required OSNR to achieve a BER of $10^{-3}$ and the BER value. It was shown that due to phase-to-intensity noise conversion a OSNR increase of 1 dB is necessary for a 5 MHz laser linewidth after a single SSMF span of 500 km. Considering noise amplification and accumulation, it was shown that the MB-OFDM signal can reach 5 SSMF spans with 40 km before reaching a BER = $10^{-3}$, when employing a Gaussian BS, while employing a 2nd-order super Gaussian BS the MB-OFDM signal can travel through at least 7 spans. These results were possible for a maximum laser linewidth of 10 kHz, employing a Gaussian BS, while the 2nd-order super Gaussian BS solution allowed laser linewidths up to 100 kHz.

It can be concluded that for distances within the metro network range, the impact of phase-to-intensity conversion of laser phase noise associated with fibre CD in the system performance is small, at least for laser linewidths up to 5 MHz. However, in this work, it was found that phase-to-intensity noise conversion associated with the BS has a high degrading impact on the system performance. The impact is such that, unless laser linewidths are reduced to values under 100 kHz, even highly selective filters as the 2nd-order super Gaussian are unsuitable BS solutions for DD MB-OFDM metro networks.

REFERENCES


