Limitations of inter-ring OFDM-band transfer imposed by laser phase noise

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Abstract
Throughout the past years, the use of multi-band orthogonal frequency division multiplexing (MB-OFDM) signals in optical fibre telecommunications systems has been proposed. MB-OFDM presents various advantages such as increased bandwidth allocation flexibility, high spectral efficiency, higher capacity provisioning granularity and high tolerance to linear fibre distortion effects.

Given these advantages, MB-OFDM appears as a good solution for transparent metropolitan networks. However, in transparent metropolitan networks, the successive filtering in consecutive nodes has been identified as the main limiting factor of the number of transparent nodes that can be traversed with good performance. For this reason, the focus of this work is the number of transparent nodes that can be traversed with good performance limited by the successive filtering. A MB-OFDM signal using radio frequency (RF) tones to assist the direct detection is proposed and evaluated.

Keywords: multi-band orthogonal frequency division multiplexing (MB-OFDM), metropolitan networks, direct detection

I. INTRODUCTION

Metropolitan Area Networks (MANs) must have high flexibility, transparency and dynamic reconfiguration. With the MB-OFDM concept, MANs gain higher granularity because OFDM bands can be dropped and added in each network node in the optical domain. In the receiver, the optical detection is employed with direct detection, due to its cost-effectiveness. In order to do so, the optical signal needs a carrier so it is possible to recover the information. In this work RF tone assisted MB-OFDM is used, where a RF tone is added to the end of each OFDM band. This RF tone aims at assisting the O/E conversion and with this solution, the optical carrier is no longer necessary for the photodetection. Also, the RF tone assisted MB-OFDM signal increases the spectral efficiency which in turn reduced the cost of the network.

Laser phase noise constitutes a major source of distortion in optical communications.

In the receiver, direct detection is employed and so, the block that performs O/E conversion is the PIN. The PIN is immune to phase noise. In fact, the phase noise is only relevant due to the phenomenon of phase-to-intensity noise conversion that occurs when the optical signal with phase noise goes through an element with complex impulsive response, as it is an optical filter for example. To demodulate a MB-OFDM signal, the OFDM bands need to be demodulated separately and for that, an optical filter called band selector is used. This filter is what enables the phase-to-intensity noise conversion.

When dropping the OFDM bands from one MAN to another, an optical filter is also used. If the OFDM bands are transferred more than once, an optical filter is used for every transfer from one MAN to another. This increases the impact of laser phase noise on the performance of the system. Therefore, it becomes a necessity to study and quantify the decrease in performance induced by this effect.

II. BACKGROUND

An OFDM signal is one that, like Frequency Division Multiplexing (FDM), divides the frequency band into several channels in order to allow multiple transmissions at the same time. However, the big advantage of OFDM is that, unlike FDM, does not need a frequency guard interval. Consequently, the bandwidth occupied in OFDM systems is reduced leading to higher spectral efficiency.

The main principle of OFDM is that, at the central frequency at which one subcarrier is transmitted, the amplitude of the other subcarriers is null. This means that the subcarriers are orthogonal to each other and thus allowing for subcarrier overlapping without causing Inter-Carrier Interference (ICI).

II-A. MB-OFDM system

The OFDM scheme proposes the use of multiple subcarriers instead of only one subcarrier. Combining that with a scheme with multiple bands, MB-OFDM approach consists in dividing the channel spectrum in fine separable and independent sub-bands where each sub-band is composed of several subcarriers. In metro networks, which use WDM, each wavelength comprises one MB-OFDM signal, as illustrated in figure 1.

![Fig. 1. Representation of the spectrum of two MB-OFDM signals each with 5 OFDM bands.](image-url)
When compared to other encoding methods, MB-OFDM requires a narrower bandwidth thus increasing spectral efficiency and reducing system complexity as well as power consumption, [1]. The multi-band approach also allows for more flexible channels with higher granularity [1].

II-B. Optical Detection

In optical OFDM the detection can be implemented in one of two ways: Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) or Direct Detection Optical Orthogonal Frequency Division Multiplexing (DDO-OFDM). CO-OFDM was first introduced by Shieh and Athaudage [2] as a way to achieve a superior performance in receiver sensitivity, spectral efficiency and robustness against polarization dispersion at the cost of a higher complexity [3]. In 2008, Yamada [4] proposed and demonstrated a no-guard interval CO-OFDM, eliminating the need for a CP and improving even further the spectral efficiency.

For a lower cost network, DDO-OFDM is more appropriate. It requires less components at both receiver and transmitter sides, allowing to be more cost-effective.

In DDO-OFDM, the optical carrier is sent along with the OFDM signal and at the receiver side, the signal is detected with only one photodiode. The output signal of the photodetector, as illustrated in figure 2(b), comprises three terms: a Direct Current (DC) component (caused by the carrier-carrier beat), a fundamental term containing OFDM subcarriers (signal-carrier beat) and a second order non-linear product (signal-signal beat). The first DC term is removed using a DC block and the latter, non-linear term often referred to as signal-to-signal beat interference (SSBI), should also be removed. The second linear term is the OFDM signal to be recovered. If the signal spectrum is located near the optical carrier frequency, the second order terms are located in the same frequency range as the electrical OFDM signal, leading to performance degradation.

This detection technique has a major problem of power fading in Double Sideband (DSB) transmission, since fibre dispersion moves the two sidebands generated to a different phase. When the sidebands are photodetected, they will beat with one another, which can lead to destructive interference, originating power fading. To overcome this power fading problem, Single Sideband (SSB) transmission should be used in direct detection systems.

DDO-OFDM is more sensitive to noise and is less power efficient than CO-OFDM since some of the power is lost in the optical carrier that bears no information. However, in opposition to CO-OFDM, a detection laser in the receiver is not required so the problem of OFDM being sensitive to phase noise and frequency offset is reduced.

II-C. Laser Phase Noise

In optical communications, the optical signal is originated by a laser, a coherent light source. Coherent implies that all the light waves emitted from the laser are in phase with each other. This is possible since it is a common trigger that stimulates the emission events that provide the light. However, the laser sources used are not always as coherent as desirable leading to phase noise distortion. In order to overcome this problem, the signal emitted from the source (laser) must be thoroughly studied and mathematically described specially in terms of phase and how fluctuations in phase might affect the signal that arrives at the receiver.

The instantaneous phase of a laser is a random walk or a Brownian motion [5]. To quantify the instantaneous phase, the electric field of the laser must be taken into account and so it is necessary to use extremely complex equations. For that reason, a simpler way to approach the problem of phase noise distortion will be explained and phase noise will be studied through frequency noise.

Given a phase noise \( \phi_n(t) \), frequency noise \( \dot{\phi}_n(t) \) can be defined as [6]

\[
\dot{\phi}_n(t) = \frac{1}{2\pi} \frac{d\phi_n(t)}{dt} \quad (1)
\]

Defining \( \dot{\phi}_n(t) \) as above, it becomes clear that it accounts for the fluctuations on the instantaneous frequency of an oscillating signal. As these fluctuations are random, \( \phi(t) \) is a random variable with Power Spectral Density (PSD) directly related to the linewidth of the laser, \( \Delta \nu_L \) [5]

\[
S_{\dot{\phi}_n}(t) = \frac{\Delta \nu_L}{2\pi} \quad (2)
\]

and given that the PSD is constant with variable frequency, this is a white Gaussian stochastic process with the following characteristics [6]

\[
E[\phi_n(t)] = 0 \quad (3)
\]

\[
E[\dot{\phi}_n(t)\dot{\phi}_n(t-\tau)] = S_{\dot{\phi}_n}(t)\delta(\tau) \quad (4)
\]

\[
\sigma^2 = \int S_{\dot{\phi}_n}(t)df_{sim} \quad (5)
\]

where \( E[\dot{\phi}_n(t)] \) denotes the mean value, \( E[\dot{\phi}_n(t)\dot{\phi}_n(t-\tau)] \) the autocorrelation, \( \sigma^2 \) is the variance, \( \delta(\tau) \) is the delta dirac function and \( df_{sim} \) is the simulation bandwidth.

With frequency noise defined, it is now possible to obtain laser phase noise through equation 1. In the continuous time domain [6]

\[
\phi_n(t) = 2\pi \int_0^t \dot{\phi}_n(t')dt' \quad (6)
\]
In the discrete time domain with \( t_i = i \Delta t \) and \( N_{T_i} = \frac{t_i}{\Delta t} \):

\[
\phi_n(t_i) = 2\pi \sum_{n=1}^{N_{T_i}} \phi_n(t_n) \cdot \Delta t
\]

(7)

Observing the latter equation, it is also possible to obtain \( \phi_n(t_i) \) in a recursive way. The increment from \( t = (i-1)\Delta t \) to \( t = i\Delta t \) is \( 2\pi \phi_n(t_i) \cdot \Delta t \). For this reason,

\[
\phi_n(t_i) = \phi_n(t_{i-1}) + 2\pi \phi_n(t_i) \cdot \Delta t
\]

(8)

III. IMPLEMENTATION

III-A. System Architecture

This work studies a MB-OFDM system with DDO-OFDM architecture that consists of a transmitter, one or more metropolitan rings and a receiver.

The MB-OFDM signal is generated in the transmitter. Each electrical OFDM band is generated separately and then the OFDM bands are frequency multiplexed to compose the MB-OFDM signal. With this method, each OFDM band has a different central frequency, hence avoiding interference between bands and allowing the posterior selection and demodulation of each individual band.

The MB-OFDM signal is then injected in the metropolitan ring through a MORFEUS node.

A MORFEUS node, proposed in [7], consists of a Reconfigurable Optical Add-Drop Multiplexer (ROADM), MORFEUS Insertion Blocks (MIBs) and MORFEUS Extraction Blocks (MEBs). The MIBs and MEBs are the blocks responsible for allowing the manipulation of single OFDM bands in the optical domain, as required in a transparent network.

The input signal of the MORFEUS node enters the ROADM where it is wavelength-demultiplexed. In a given wavelength, the MEB extracts the OFDM band to be dropped. A band blocker blocks the dropped band and feeds the signal without the dropped band to the MIB. The MIB is responsible for inserting one OFDM band in the MB-OFDM signal passing through the node. The bands dropped by the MEB go through a switch and are routed to another metro ring, routed to the access network or delivered to the client.

In order to have several optical channels, the metro ring uses WDM. So, one optical channel is attributed to the MB-OFDM signal and the signal is injected in the network. However, before the signal is launched into the MAN, first it needs to be converted from the electrical to the optical domain. For this operation, it was elected a Dual-Parallel Mach-Zehnder Modulator (DP-MZM).

A DP-MZM is an E/O converter composed of two branches, each one containing an inner Mach-Zehnder Modulator (MZM). The output signals of each MZM are then combined by a phase shifter, using a bias voltage \( V_b(t) \) to obtain the output optical signal of the DP-MZM, \( E_{out}(t) \). A MZM is an external modulator, where a continuous wave laser provides the optical power which is then modulated according to the input MB-OFDM signal.

The signal then goes through a transparent network, the metropolitan ring, and eventually arrives at the node where it is transferred to another metro ring or extracted and demodulated.

At this point, one or more bands are dropped. To drop an OFDM band, the MB-OFDM signal passes through a band selector that selects the band to be dropped. The MB-OFDM signal also goes through a band blocker that leaves an empty slot in the frequencies where the dropped band previously was.

In the case that the dropped OFDM band is extracted, after the band selector the band is O/E converted. In this work, the O/E converter is a PIN which is described by equation 9.

\[
I(t) = R_{\lambda}|E(t)|^2 = I_{DC} + I_{SSBI} + I_{sig}(t)
\]

(9)

The output of the PIN is an electric signal containing the original OFDM band. However, it also has SSBI that does not allow proper demodulation and, for that reason, an SSBI mitigation process is applied.

Lastly, the signal is forwarded to the receiver where it is demodulated.

III-B. MB-OFDM signal with virtual carriers

In [8], a OFDM system where a RF tone is added at the edge subcarrier of the OFDM signal is proposed. The purpose of that RF tone is to assist the signal extraction at the O/E conversion. The RF tone is an electrical carrier that is generated simultaneously with the OFDM band.

In this work, this concept is applied to a MB-OFDM signal. Given that each band is one OFDM signal, at the end of each OFDM band, a RF tone is added with a small gap between the band and the RF tone. In this situation, the optical filter only needs to have one passing band which selects both the band and the RF tone, therefore eliminating the heavy requirements described above. The RF tone is named virtual carrier.

For this system, two concepts must be defined: Virtual-carrier to Band Gap (VBG) and Virtual-carrier to Band Power Ratio (VBPR).

As it was said above, the mixing of the photodetection generates a DC component, SSBI and the signal to be recovered. Figure 2 (a) and (b) show an OFDM band with a virtual carrier and the same band after photodetection, respectively. Figure 2(b) shows that the SSBI is located around the DC component. As for the signal to be recovered, when the virtual carrier is placed at the edge subcarrier of the OFDM band in the transmitter, after photodetection the left edge of the band is at the same frequency of the DC component. Consequently, the information band and the SSBI are overlapped. In order for this situation not to occur, a
gap is introduced between the right edge subcarrier and the virtual carrier, depicted in figure 2(a). With this gap, after photodetection the band is spaced from the DC component. The spacing is the same as the spacing between the OFDM band and the virtual carrier, as illustrated in figure 2(b). This gap is called Virtual-Carrier to Band Gap (VBG) and it is measured in Hz.

![Fig. 2. (a) Illustration of a OFDM band of a MB-OFDM signal with a virtual carrier and (b) illustration of the same band after photodetection plus the SSBI representation.](image)

After photodetection, given that the OFDM band is recovered from the signal-carrier beat, it is desirable that the signal-carrier beat has more power than the SSBI, so that the recovery of the signal is more successful and the SSBI impact is mitigated. For this reason, the virtual carrier should have more power than the OFDM band.

\[ V B PR = 10 \log_{10} \frac{p_{VC}}{p_B} \]  

(10)

The ratio between the power of the virtual carrier, \( p_{VC} \), and the power of the band, \( p_B \), measured in dB is named Virtual-Carrier to Band Power Ratio (VBPR).

### III-C. Laser Phase Noise

Laser phase noise constitutes a major source of distortion in optical communications. For optical systems with direct detection, the phase noise is only relevant when the phase-to-intensity noise conversion is taken into account.

In a real situation, ideal lasers do not exist. Consequently, the lasers used for E/O conversion have a certain linewidth. Before the O/E conversion, the MB-OFDM optical signal passes through a band selector which results in phase-to-intensity noise conversion after the PIN.

In the studied system, the phase noise is generated using the method presented in [9].

Figure 3 represents the PSD of the laser phase noise for linewidths of 2 MHz and 8 MHz. The \( e^{j\phi(t)} \) was simulated with 10000 noise runs and the average PSD is represented in figure 3. It is possible to verify that, at -3 dB of the peak, the linewidth corresponds to the one that was intended. These results validate the method used.

![Fig. 3. Representation of the PSD of the laser phase noise for 2 MHz linewidth and 8 MHz linewidth.](image)

After the DP-MZM, a random phase \( \phi(t) \) that represents the random phase fluctuations due to the laser phase noise is generated. Then, the MB-OFDM optical signal is multiplied by \( e^{j\phi(t)} \).

Figure 4 a) and b) illustrate one OFDM band of a MB-OFDM signal after the DP-MZM, without and with phase noise, respectively.

![Fig. 4. PSD of an OFDM band after the DP-MZM for a MB-OFDM system with a VBG width of 27.9 MHz and (a) without phase noise and (b) with phase noise (laser linewidth of 1 MHz).](image)

The main visible difference is in the virtual carrier which, when there is phase noise, is no longer in one single frequency but its power is spread in an interval of frequencies. For this reason, it is also possible to observe (via EVM per subcarrier) that the most degraded subcarriers are the ones closer to the virtual carrier. This effect is mainly due to the spectral spreading of the carrier which overlaps the band.

### IV. RESULTS

#### IV-A. Impact of Phase-to-Intensity Noise Conversion Induced by the Band Selector

When in presence of phase noise, the main visible impact observed in the spectra is the spectral spreading
of the virtual carrier that ceases to be a simple Dirac impulse. This spreading of the virtual carrier overlaps the OFDM information band. This overlap causes the degradation of the system performance. Consequently, it is expected that one way to reduce the interference of the virtual carrier with the band is to increase the VBG. Given that stepping away from the virtual carrier the power of the virtual carrier decreases, increasing the spacing between the OFDM band and the virtual carrier implies that the overlapping of the OFDM band and the virtual carrier causes less interference. However, if the VBG is too high, the bandwidth of the band selector needs to be high also. In this situation, adjacent bands are not adequately suppressed, causing interference and performance degradation.

The optimal VBG depends on the number of bands and on the band selector. Since the bandwidth of the hybrid coupler is limited and given that the bands are placed in slots multiple of 3.125 GHz, a higher number of bands results in a smaller bandwidth of each band and a smaller gap between bands, therefore limiting the range of possible values for the VBG. The analysis performed considers only MB-OFDM signals comprising 3 and 6 bands.

For the band selectors, three filter types are tested: rectangular transfer function-shaped filter, Gaussian filter and 2nd order super-Gaussian filter.

As it was said previously, when in presence of laser phase noise, the spectrum of the virtual carrier broadens. The broadening of the virtual carrier is quantified by the linewidth associated with each laser. As the linewidth increases, so does the broadening of the spectrum of the virtual carrier. Consequently, increasing the linewidth leads to the degradation of the performance. For this reason, the tests are performed not only for different values of VBG but also for different values of laser linewidth. The EVM is determined for each pair of linewidth and VBG.

These tests are performed for 6 different systems that result from the 2 possibilities of number of bands and the 3 types of band selector. The purpose is to find the VBG for each linewidth and for each of the six cases that leads to the lowest EVM.

Figure 5 shows the EVM for a signal with 3 bands and for each of the band selector types considered. The EVM presented is the one that corresponds to the worst band for every pair of VBG and linewidth.

Figure 5 shows that the performance obtained with the Gaussian band selector is worst than the performance obtained with the super-Gaussian band selector. Figure 5(a) shows that, contrarily to what was expected, increasing the VBG does not improve the performance of the system. In fact, the optimal VBG should be less than 250 MHz. This is due to the fact that increasing the VBG increases the bandwidth of the band selector and, given the poorer selectivity of the Gaussian filter, the inter-band crosstalk also increases. However, figures 5(b) and 5(c) show that it is advantageous to increase the VBG as the optimal VBG is between 250 and 420 MHz. Given the higher selectivity of the rectangular transfer function-shaped and the super-Gaussian filters, the effects of inter-band crosstalk are only present for higher VBGs than in the case with the Gaussian filter. So, in figures 5(b) and 5(c), it is possible to see what was expected before the tests. The increase of VBG leads to performance improvement due to less interference caused by the overlapping of the band with the spectral spreading of the virtual carrier.

Figure 6 shows the EVM for a signal with 6 bands and for each of the band selector types considered.

The overall behaviour of the system with a MB-OFDM signal with 6 bands, shown in figure 6, is similar to the one for a MB-OFDM signal with 3 bands. However, due to the fact that the gap between OFDM bands is half the gap for a signal with 3 bands, the optimal VBGs are smaller than for a MB-OFDM signal with 3 bands.

The VBG width chosen to be used in the next studies is 27.9 MHz. Analysing both figures 5 and 6, it can be
(a) Gaussian band selector

(b) Super-Gaussian band selector

(c) Rectangular band selector

Fig. 6. EVM in dB as a function of the VBG and the laser linewidth for a signal with 6 bands and: (a) Gaussian band selector, (b) super-Gaussian band selector and (c) rectangular band selector.

seen that the value of 27.9 MHz is within the optimal regions in three of the six cases. In the other three cases, the penalty of choosing this value instead of the optimal one is at most 0.5 dB in EVM. Taken into account the spectral efficiency, the VBG should be as small as possible and given that this penalty of 0.5 dB in EVM is very reduced, the VBG width of 27.9 MHz was maintained.

IV-B. OFDM Band Transfer Between Metropolitan Rings

There are some challenges when transferring one OFDM band from one metropolitan ring to another. First, each metro ring has a different laser noise and optical noise. The noise from each ring overlaps and interferes with the bands. Secondly, the optical filters used for the drop operation are not rectangular transfer function-shaped filters so, there is always some in-band distortion and also some inter-band crosstalk.

The studied situation involves two metropolitan rings, A and B, as depicted in figure 7. In ring A, there is a MB-OFDM signal A with 3 or 6 bands. In ring B, there is also another MB-OFDM signal B. The two rings are connected by a MORFEUS node.

First, considering a MB-OFDM signal with 3 bands, the studied situation is:

1) The second OFDM band from the MB-OFDM signal A is selected in the MORFEUS node 1 with an optical filter and extracted from signal A
2) Signal B only has the first and third bands, with the second slot empty
3) The dropped OFDM band from signal A is added to the empty slot in signal B, composing the MB-OFDM signal B’

The band transfer realized in other rings follows the procedure described from points 1 to 4.

If the MB-OFDM signal has 6 OFDM bands, the extracted band from signal A is the third band and the process is similar. For the extraction, it is chosen the band that is expected to represent the situation that leads to the worst performance. In this work, each operation of drop one band from ring A and add that band to ring B is called OFDM band transfer.

When analysing the situation of consecutive drop/add operations performed over the same band, the consecutive filtering by Gaussian or super-Gaussian filters deforms the band with every drop operation. Also, the filtering diminishes the band power and so, before adding the band to the other MB-OFDM signal B, an amplifier was inserted to level the power of the dropped band with the power of the other bands in the MB-OFDM signal B, were it will be inserted.

Figure 8 depicts the OSNR penalty as a function of the number of OFDM band transfers for a MB-OFDM signal with 3 bands and in four situations: no laser phase noise (figure 8(a)), laser linewidth of 10 kHz (figure 8(b)), laser linewidth of 100 kHz (figure 8(c)) and laser linewidth of 1 MHz (figure 8(d)). The OSNR penalty is obtained considering as the reference a MB-OFDM system with 3 bands and no band transfer.

The required OSNR to achieve a BER of $10^{-3}$ in this case is 22.4 dB. The BER is calculated for each band and the OSNR penalty shown corresponds to the value
for the second band which is the one that suffers the consecutive filtering and therefore is the worst band.

The overall appreciation is that the required OSNR remarkably increases with the number of OFDM band transfers. By observing the different situations shown in figure 8, it can be seen that, as the linewidth increases, the number of OFDM band transfers below an OSNR penalty of 5 dB decreases. Also, the behaviour of the system with no laser phase noise, with 10 kHz of laser linewidth and with 100 kHz of laser linewidth is similar. It is only for 1 MHz of linewidth that the performance degrades significantly. For example, considering an OSNR penalty not exceeding 2 dB, it is possible to perform 6 OFDM band transfers without considering laser phase noise and only 3 transfers for a linewidth of 1 MHz.

The OSNR penalty as a function of the number of OFDM band transfers for a MB-OFDM signal with 6 bands is depicted in figure 9. The OSNR penalty is obtained considering as the reference a MB-OFDM system with 6 bands and no band transfer. The required OSNR to achieve a BER of $10^{-3}$ in this case is 22.8 dB. The values of OSNR penalty correspond to the value for the third band which is the band that suffers consecutive band transfer operations (and therefore the band with the worst performance) for a MB-OFDM signal with 6 bands.

The results in figure 9 have a similar behaviour to the one shown in figure 8. However, the number of possible OFDM band transfers for an OSNR penalty not exceeding 5 dB is less than with a MB-OFDM signal with 3 bands for all situations of laser linewidth considered. When the MB-OFDM signal has 6 OFDM bands, the bandwidth of one OFDM band is one half the bandwidth of one OFDM band of a MB-OFDM signal 3 bands. However, the frequency gap between bands for a MB-OFDM signal with 6 bands is also one half the gap between bands for a MB-OFDM signal with 3 bands. Taking this into account, the distortion of the band induced by the band selector is higher, as well as the inter-band crosstalk.

V. CONCLUSIONS

In this work, the performance of a MB-OFDM system with 3 or 6 bands and with the three types of band selectors was assessed when in presence of laser phase noise.

The impact of the phase-to-intensity noise conversion induced by the band selector was assessed. It was seen that the laser linewidth needs to be limited to a few MHz. When the linewidth is higher than approximately 10 MHz, the performance greatly degrades hence not allowing for the proper demodulation of the MB-OFDM signal.

With the VBG and laser linewidth values set, the following tests attempted to recreate a real network, composed by several metro rings connected by MORFEUS nodes. The focus of the study was the drop/add operations in the MORFEUS nodes when transferring OFDM bands from one MAN to another MAN. The OSNR penalty as a function of the number of OFDM band transfers was quantified. It can be seen that the laser linewidth greatly degrades the system’s performance. For example, for a system with a MB-OFDM signal with 3 bands and considering an OSNR penalty not exceeding 2 dB, it is possible to perform 6 OFDM band transfers without considering laser phase noise whereas it is only possible 3 transfers for a linewidth of 1 MHz. For linewidths higher than 1 MHz, it is not even one transfer is possible.

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