# Experimental Assessment of Filter Narrowing Effect for Low Bandwidth Connections in EON

Laura Martín, Josep M. Fàbrega, Michela Svaluto Moreolo, *Senior Member, IEEE*, F. J. Vílchez, and Laia Nadal

***Abstract*— In this letter, we experimentally analyze the filter narrowing effect for low bandwidth connections in the context of the flexi-grid paradigm for optical aggregation networks. First of all, we characterize the concatenation of up to 12 filters by means of a high resolution optical spectral analyzer. Then, we set up the programmable filters with the obtained characterization, in order to emulate the filter concatenation impairments. The studied filters have nominal bandwidths of 12.5 GHz, 25 GHz, and 50 GHz. The two potential candidates analyzed are intensity modulation/direct detection on–off keying and direct detection orthogonal frequency division multiplexing (OFDM) with uniform and bit loading. Results show a significant signal degradation for filter bandwidths of 12.5 GHz with respect to 25 GHz and 50 GHz, considering a net bit rate of 10 Gb/s. We also conclude that for future entire flexi-paradigm, OFDM is an appropriate candidate.**

***Index Terms*— Filter narrowing effect, direct detection (DD), orthogonal frequency division multiplexing (OFDM), intensity modulation (IM), on-off keying (OOK).**

## I. Introduction

THE future adoption of Elastic Optical Networks (EON) due to the increased in traffic demand by the advent of technologies, as Internet of Things or 5G, sets further requirements on the flexibility and scalability, making the conventional fixed-grid to evolve towards a flexi-grid networks [1], [2]. The adoption of flexi-grid networks implies that multiple optical channels with different bandwidths can coexist in the same fiber. This granularity enables the reduction of the channel width for low bit rate connections [2]. As a result, the flexibility of the network improves and CAPital EXpenditure (CapEx) is reduced.

International Telecommunication Union (ITU) has standardized a flexible Wavelength Division Multiplexing (WDM) grid, with a view to making the use of variable bandwidths in steps of 12.5 GHz possible [3]. As a consequence, programmable filters, using proper technologies as Liquid Crystal on Silicon (LCoS) [4], are employed for flexible optical spectrum allocation, avoiding the restrictions of typical 50 or 100 GHz channel spacing of fixed-grid. Adopting the flexi-grid paradigm [1] implies that the signal goes through several nodes with their corresponding filtering elements. When the optical signal traverses these nodes, the resulting signal bandwidth can be distorted, affecting the signal performance. Indeed, the major impact is for bandwidths of 12.5 GHz and 25 GHz with respect to 37.5 GHz [2], [4].

Although this effect, known as filter narrowing effect, based mainly on Arrayed Waveguide Grating (AWG) mux/demux and Micro-Electro-Mechanical Systems (MEMS) switches or Reconfigurable Optical Add-Drop Multiplexer (ROADM) nodes have been widely studied for architectures as in [5], it is also relevant in the context of future flexi-grid networks, where a cascade of filtering elements are envisioned [6]. In the present letter, we experimentally analyze the signal distortion due to the filter narrowing effect for low bandwidth connections. To this end, we first characterize the concatenation of 2 up to 12 filters (2 filters per node) and, after that, we analyze the filter narrowing effect on two different schemes. The first uses an Intensity Modulation/Direct detection (IM/DD) On-Off Keying (OOK) transmission at 10.7 Gb/s gross data rate. Its main disadvantage is that it requires dispersion compensation modules at the networks nodes. Since this system is used in deployed legacy optical networks, it is used as a reference. The second option is the optical Orthogonal Frequency Division Multiplexing (OFDM) transmission. This system is particularly interesting in the context of flexi-grid paradigm due to its spectral manipulation capabilities and its bit rate scalability [7]. Within all possible options that OFDM provides, we consider DD, due to its greater simplicity and cost-effectiveness, and Single Side Band (SSB) transmission, since it allows higher robustness against Chromatic Dispersion (CD) for longer reach transmission [8]. In fact, in [2] the authors propose this OFDM scheme for a flexi-grid metro network scenario, which implies going through several nodes. We have considered a gross bit rate of 12.22 Gb/s, and an intermediate frequency for the upconversion of 9.17 GHz.

In this letter, we experimentally compare the filter narrowing effect for low bandwidth connections, considering the OOK and OFDM transmission schemes, for Back to Back (B2B) configuration.

## II. Filter Transfer Function Characterization

The optical signal is expected to go throught a high number of filters in an optical network. So here, we study the case of filters with nominal bandwidths of 12.5 GHz that corresponds

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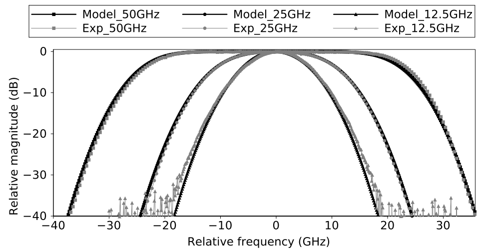
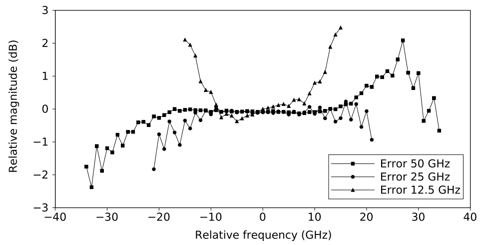
The authors are with the Centre Tecnològic de Telecomunicacions de Cataluya, ONS Department, 08860 Castelldefels, Spain (e-mail: lmartin@cttc.es; jmfabrega@cttc.es; msvaluto@cttc.es; jvilchez@cttc.es; lnadal@cttc.es@cttc.es).




(a)




(b)

Fig. 1. (a) Model fitting of the experimental filter characterization for bandwidths of 12.5 GHz, 25 GHz and 50 GHz. (b) Relative error between the model and the experimental filter characterization for bandwidths of 12.5 GHz, 25 GHz and 50 GHz.

to the ITU elementary slot, 25 GHz that correspond to two ITU elementary slots and 50 GHz that correspond to the typical fixed-grid frequency slot [3]. Similarly to [2], we consider a node architecture with two filters per node. So, as first stage, we characterize each of these filters and their concatenation in steps of 2 up to 12 filters [2].

To do this, we characterize the programmable filters according to the model of [9]. After that, we carry out the estimation of the concatenation of up to 12 filters in steps of 2 filters by means of a high resolution Optical Spectral Analyzer (OSA). Then, we set up the programmable filters with the obtained characterization. Finally, we compare the filter models with the experimental characterization.

Fig. 1 (a) shows the transfer functions of the characterized filters and the modeled filters. There, we can observe that the model is perfectly matching all the experimental characterization for relative magnitudes values down to $-25$ dB. This is also reflected in Fig. 1 (b) where the relative error between the model and the experimental filter characterization is illustrated. It can be observed that the maximum error is $-0.37$ dB for a frequency within $\pm 6.25$ GHz for the 12.5 GHz nominal bandwidth filter. For the 25 GHz bandwidth filter, the maximum error is 0.33 dB within $\pm 12.5$ GHz and, similarly, for the 50 GHz bandwidth filter this error is 1.15 dB within $\pm 25$ GHz.

In Fig. 2 [a–c] the transfer functions of the characterized filters for the above-mentioned nominal bandwidths in steps of 2 filters up to 12 are shown. It can be observed that at increasing of the number of concatenated filters, the narrowing of the filter bandwidth is more pronounced. In fact, the difference between the concatenation of 2 and 12 filters in terms of bandwidth reduction is 10 GHz (from 50 GHz to 40 GHz) for the 50 GHz nominal bandwidth filter and 12 GHz (from 24.5 GHz to 12.5 GHz) for the 25 GHz nominal bandwidth filter at $-6$ dB of the relative magnitude. A zoom from the area of interest of the 50 GHz and 25 GHz nominal bandwidth filters transfer function is illustrated in Fig. 2 b.1) and b.2). In the case of the 12.5 GHz nominal bandwidth filter, where we only consider the concatenation of 2 filters, the resulting bandwidth is 5 GHz.

As we will see in the upcoming sections, the Bit Error Rate (BER) characteristic will be affected by the nominal bandwidth filters, the filter narrowing effect due to the concatenation of the filters and hence the spectral characteristics of the signal.

## III. Experimental Setup

The experimental setups for the OOK and OFDM transmission schemes are illustrated in Fig. 2. The optical domain part of the experimental setups is common for both alternatives. Specifically, the OOK or OFDM electrical signal is converted to the optical domain by a Mach-Zehnder Modulator (MZM) biased near to the null point for DD OFDM or quadrature point for OOK. A laser centered at 1550.12 nm with 13.99 dBm output power is used. In order to achieve SSB transmission after the MZM and only for the DD OFDM alternative, the signal is optically filtered with a filter of 25 GHz bandwidth resulting in an optical bandwidth of 12.22 GHz, including 6.11 GHz of guard band. Then, for both alternatives, the optical signal traverses the cascade of filters modeled by the programmable filter. After that, a Variable Optical Attenuator (VOA) and an Erbium Doped Fiber Amplifier (EDFA) are used to vary the Optical Signal to Noise Ratio (OSNR) at the receiver. Additionally, an Amplified Spontaneous Emission (ASE) filter of 50 GHz bandwidth and an OSA are added before the photodetection.

For the OOK case, the signal is generated by an Arbitrary Waveform Generator (AWG) as a pseudorandom binary sequence of $2^{15}-1$ bits at 10.7 Gb/s with 7% Hard Decision-Forward Error Correction (HD-FEC) overhead. The total signal bandwidth is 10.7 GHz. At the receiver, the signal is converted into the electrical domain by means of a PIN and captured with a real-time oscilloscope, which is also used to analyze the eye pattern and estimate the BER. The received signal spectrum is shown in Fig. 2 d).

For the DD OFDM case, the Digital Signal Processing (DSP) transmitter and receiver have been performed offline using Python software. $2^{16}$ bits are randomly generated running at a net data rate of 10 Gb/s and HD-FEC coding scheme with 7% overhead is assumed. Next, the bit sequence is parallelized and Quadrature Phase-Shift Keying (QPSK) encoded, and 4 Training Symbols (TS) are inserted. After that, the signal is modulated into 512 carriers using the Inverse Fourier Fast Transform (IFFT). Finally the Cyclic Prefix (CP) is added (1.9% overhead). The resulting OFDM symbol is serialized and clipped. The signal bandwidth results in 6.11 GHz. Then, the signal is upconverted to the intermediate frequency. The next step is the conversion from digital to analog domain by means of a Digital to Analog Converter (DAC). Due to the limited bandwidth of the DAC, after the DSP transmitter, a preemphasis digital filter is used to compensate the system performance degradation. At the receiver, the signal is photodetected by a PIN and captured by a 100 GS/s real-time oscilloscope. The received signal spectrum is shown in Fig. 2 e). Then, the resulting digital signal is downconverted and parallelized,

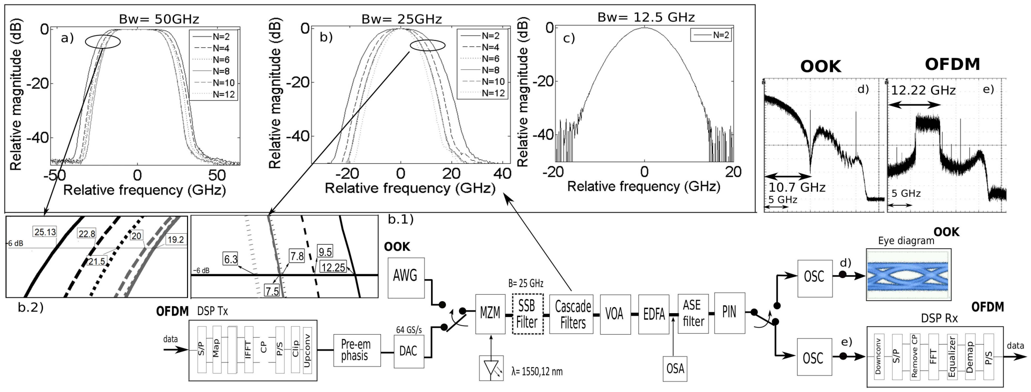
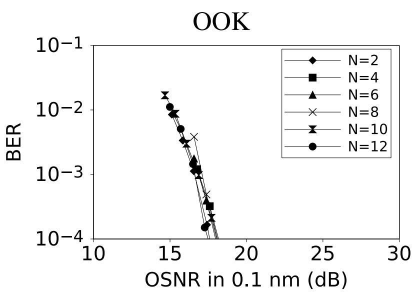
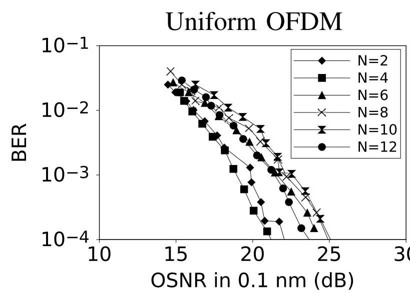


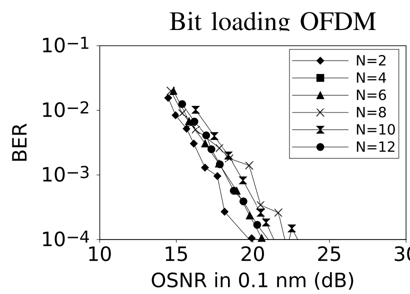

Fig. 2. Experimental setup for OOK and DD OFDM approach. Cascade filters characterized by the OSA for nominal bandwidths of 50 GHz a), 25 GHz b) and 12.5 GHz c). Received spectra after the oscilloscope for OOK d) and OFDM e) alternatives.



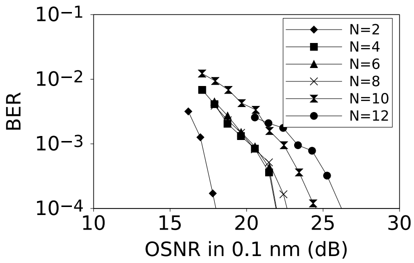

(a) OOK and bandwidth of 50 GHz



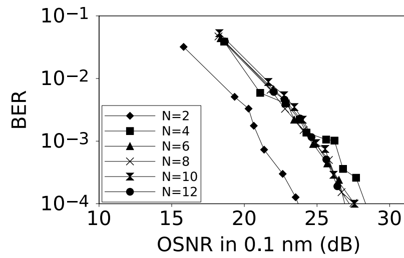

(b) Uniform OFDM and bandwidth of 50 GHz



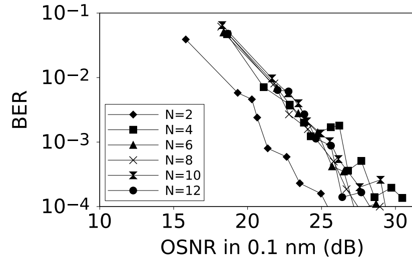

(c) Bit loading OFDM and bandwidth of 50 GHz




(d) OOK and bandwidth of 25 GHz




(e) Uniform OFDM and bandwidth of 25 GHz




(f) Bit loading OFDM and bandwidth of 25 GHz

Fig. 3. BER vs OSNR for the OOK approach (a and d), DD OFDM approach using uniform loading (b and e) and bit loading (c and f) after cascade filters with bandwidths of 50 GHz (a, b, c) and 25 GHz (d, e, f).

the CP is removed, the FFT is implemented, the equalization is performed, and the signal is decoded in order to recover the original bit stream.

In addition, for the DD OFDM system alternative we have also considered bit loading. Adaptive bit assignment is performed according to the channel state information estimated with a probe signal [7]. Bit loading is implemented with a Levin-Campello margin adaptive algorithm, as in [2], set to operate at 10 Gb/s.

## IV. Experimental Results

The performance of the proposed system is assessed in terms of Back-to-Back (B2B) OSNR requirements within 0.1 nm. The target BER is set to $10^{-3}$ assuming the HD-FEC coding scheme [2]. We also define the OSNR penalty as the difference between the OSNR required for the concatenation of 2 filters and 12 filters at target BER.

The 50 GHz case is depicted in Fig. 3 (a), (b), (c) for the OOK and DD OFDM schemes, this last using uniform loading and bit loading. The OOK signal is not affected by the filter narrowing effect for all the examined filtering stages, being 16.7 dB the required OSNR for the target BER. Nevertheless, for the DD OFDM, the OSNR ranges between 18.7 dB and 22.5 dB for uniform loading and between 17.7 dB and 20 dB for bit loading. Therefore, the OSNR penalty results in 3.7 dB for uniform loading and for bit loading it decreases to 2.3 dB approaching to the performance characteristic of the OOK.

When we consider 25 GHz filter for the OOK scheme, the BER characteristics are more scattered than in the previous case, being the OSNR within 17 dB and 23.5 dB as it is shown in Fig. 3 (d). The OSNR requirements for DD OFDM with uniform loading and bit loading are around 21.1 dB for two filtering stages as it is shown in Fig. 3 (e) and (f). However, it can be seen that, after two filtering stages up to 12 filters, the OSNR requirements remain concentrated around 26.5 dB for both. These last results are directly related to the transfer function of the filter concatenation shown in Fig. 2 b) and in Fig. 2 b.1).

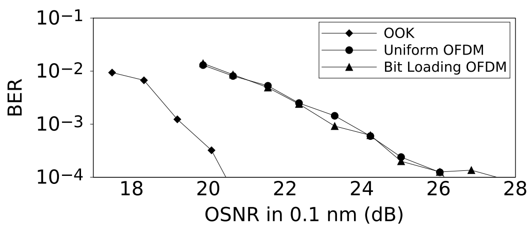



Fig. 4. BER vs OSNR for the OOK approach, the DD OFDM SSB approach using uniform loading and bit loading after 2 filters with bandwidths of 12.5 GHz.

There, we can observe a significant reduction of the bandwidth between the concatenation of 2 filters and the concatenation after 4 up to 12 filters, leading the worsening of the performance characteristic in terms of OSNR. To be more precise, the value of the bandwidth after the concatenation of 2 filters is 24.5 GHz whereas after 4 up to 12 filters the corresponding bandwidth is within 17 GHz and 12.5 GHz. Therefore, it is noted that the OSNR reminds concentrated around 26.5 dB for an effective bandwidth smaller than 17 GHz.

Finally, the case of filter with 12.5 GHz of bandwidth is analyzed. The target BER of $10^{-3}$ can be achieved only after 2 filters. The experimental results are shown in Fig. 4. It can be seen that the OSNR at target BER is 19.3 dB for OOK and around 23 dB for DD OFDM with uniform loading and bit loading.

As it was previously advanced, the bandwidth occupied by the signal is also of great relevance, in order to explain the performance degradation of the BER characteristic, when the effective bandwidth filter is reduced. The optical bandwidth of the signal, when we use the OOK system, is 10.7 GHz. The spectrum of the signal, can be seen in Fig. 2 d). Considering the 50 GHz of nominal bandwidth filter, the minimum value of the effective bandwidth is 40 GHz, and corresponds with the concatenation of 12 filters. Then, the bandwidth is wide enough not to affect the system performance (Fig. 3 (a)). However, using the 25 GHz of nominal bandwidth filter, we can see as the value of the effective bandwidth is close to the bandwidth of the signal, the performance decreases (Fig. 3 (d)). It is the case of the concatenation of 12 filters that corresponds with a effective bandwidth of 12.5 GHz, which is very close to the 10.7 GHz and where the OSNR reaches its maximum value (23.5 dB at target BER).

When we use the OFDM scheme, the signal bandwidth is within 6.11 GHz and 12.22 GHz. The spectrum is shown in Fig. 2 e). For the 50 GHz filter, there is a BER degradation after the concatenation of 4 filters as a consequence of the effective bandwidth reduction below 21 GHz. This reduction can be appreciated in Fig. 2 b.2). The degradation is also due to the spectral signal characteristic. In fact, the OFDM subcarriers loaded with data, are located at the edge of the occupied bandwidth, while the main data content of the OOK signal is located close to the optical carrier. As a result, the BER performance for the OFDM case is more affected. However, using the bit loading we can observe an improvement of the BER giving similar performance as OOK (Fig. 3 (a),(b) and c)). For 25 GHz and 12.5 GHz of nominal bandwidth filter, the decrease of the effective bandwidth due to the similar values of the signal bandwidth, entails a further degradation of the BER performance (Fig. 3 (e) and (f) and Fig. 4). For example, if 2 filters are concatenated using the nominal bandwidth filter of 12.5 GHz, the resulting effective bandwidth is 5 GHz. This value is much smaller than the 12.22 GHz of the OFDM signal bandwidth. Therefore, the performance degradation limits the benefit of applying bit loading.

## V. Conclusions

In this letter, we have studied the filter narrowing effect in the context of the flexi-grid paradigm. Thus, we have considered the legacy OOK and DD OFDM systems with uniform and bit loading. The impact on the system performance increases for the filters with nominal bandwidths of 12.5 GHz with respect to 25 GHz and 50 GHz.

The future migration to the flexi-grid involves that the fixed-grid that, only can provide fixed frequency slots of 50 GHz or 100 GHz, will disappear. So, the solution is envisioned to be efficient with slots of 37.5 GHz, 25 GHz and 12.5 GHz [2]. Although the performance degradation is more accentuated in OFDM than in OOK systems, OFDM is shown to be a feasible candidate since the creation of the generic flexi-grid mesh implies flexibility and adaptability, which fits with the essence of the OFDM principles. In fact, OFDM scheme avoids the need of dispersion compensation modules at the networks nodes that in OOK systems are required. Furthermore, OFDM based on adaptive DSP is considered for the implementation of programmable transceivers for metro/regional EONs enabling software-defined multi-rate, multi-format, multi-reach and multi-flow optical transmission [7].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