Bandwidth Variable Transponders Based on OFDM Technology for Elastic Optical Networks

Michela Svaluto Moreolo\textsuperscript{1}, Josep M. Fàbrega\textsuperscript{1}, Laia Nadal\textsuperscript{1}, F. Javier Vilechez\textsuperscript{1}, Gabriel Junyent\textsuperscript{1,2}
\textsuperscript{1}Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Av. C. F. Gauss 7; 08860 Castelldefels (Spain)
Tel: (+34) 93 645 29 00, e-mail: michela.svaluto@cttc.es
\textsuperscript{2}Universitat Politècnica de Catalunya (UPC-BarcelonaTech), Jordi Girona, 1-3; 08034 Barcelona (Spain)

ABSTRACT
In this paper, the flexible features of bandwidth variable transponders based on OFDM technology are investigated. The limiting factors due to the subsystem components and the trade-off between cost-effectiveness, capacity and reach are taken into account for designing this fundamental building block of elastic optical networks. Advanced functionalities, including sliceability, are discussed. Performance is analysed by means of numerical simulations. Furthermore, the experimental results, achieved within the EOS platform (Experimental platform for Optical OFDM Systems) of the ADRENALINE testbed, are presented.

Keywords: Optical OFDM, Bandwidth Variable Transponders, Elastic Optical Networks, Flexi-grid.

1. INTRODUCTION
The bandwidth variable transponder (BVT) is a key element of an elastic optical network (EON). The ability of generating elastic optical paths is enabled by its flexibility in terms of variable parameters/attributes, such as the modulation format, the data rate, the number of subcarriers and the bandwidth occupancy. Software-defined BVTs allow reconfiguring the transmission scheme with a suitable selection of these flexible parameters, for an optimal resource usage in a flexi-grid network. In fact, networks are evolving towards the SLICE (spectrum sliced optical path network) architecture, where variable groups of basic fixed-size slots (e.g. 12.5 GHz or 6.25 GHz) are dynamically allocated according to the data rate request and the optical path condition [1]. Unlike the standard fixed spectrum grid, SLICE allows providing an efficient utilization of the optical spectrum with finer grid granularity, according to the client demand.

The orthogonal frequency division multiplexing (OFDM) has been identified as one of the key enabling technology for EON [1], [2]. In fact, advanced modulation parameters and flexible functionalities are introduced when the BVT is based on this technology. Specifically, given the unique subwavelength granularity offered by the OFDM, adaptive modulation, bit and power loading schemes and subcarriers selection/suppression can also be included as advanced BVT features. This means that, according to the channel condition, transmission impairments and bit rate request, different subcarriers are selected to support the proper modulation format with the suitable power profile, trading robustness against spectral efficiency for rate and distance adaptive transmission, managed by the control plane [2].

Here, low-complexity digital signal processing based on the fast Hartley transform (FHT) is proposed for cost-effective direct detection (DD) and simplified coherent OFDM-based BVT solutions, targeting flexi-grid metro/regional and national/core networks, respectively. Limiting factors, such as peak-to-average power ratio (PAPR), available bandwidth and linearity of the subsystem components are taken into account in the BVT design. The advanced flexible/elastic functionalities are analysed by numerical simulations and experiments, which have been performed within our platform for optical OFDM systems.

2. ELASTIC BVT BASED ON LOW-COMPLEXITY DSP
We propose bit rate and bandwidth variable transponders based on the FHT, which allows a fast and low-complexity digital signal processing (DSP) using only real-valued calculation. The transmitter (Tx) and receiver (Rx) DSP is detailed in Fig. 1. The input data are mapped with one dimensional (1D) modulation formats (BPSK, M-PAM). For implementing non-uniform bit loading (BL), according to the intrinsic Hermitian property of the FHT, mirror-symmetric subcarriers are mapped into the same modulation format. Half-length training symbols (TS) are used for a simplified channel estimation requiring only real algebra [3]. Thanks to the FHT self-inverse property, the inverse transform is calculated with the same routine as the direct FHT. A cyclic prefix (CP) is added to the FHT-modulated digital signal, which is then serialized and converted to analog by a single digital-to-analog converter (DAC).

In order to limit the high OFDM peak-to-average power ratio, symmetrically clipping is applied to the digital signal. In our design, an optimal clipping level for the considered modulation formats has been selected, according to previous theoretical study and extensive simulations [4]. Furthermore, the TS sequences have been optimized to present minimum PAPR. The clipping and quantization noise can be further reduced by applying distortionless PAPR reduction techniques, which have low-complexity thanks to the FHT properties [4].

At the receiver side, the signal is analog-to-digital converted (ADC) and demodulated: after serial to parallel conversion (S/P), the CP is removed, then FHT processing, equalization and demapping are performed.
Figure 1. Bandwidth variable transmitter and receiver (BVTx and BVRx) with FHT processing for DD-OFDM: schematic and experimental set-up; in the insets, electrical and optical spectra.

2.1 Cost-effective BVT design for flexible-grid metro networks

For a cost-effective BVT design, the optical modulation is performed by a Mach-Zehnder modulator (MZM) biased at the quadrature point and driven by a tunable laser source (TLS). The DD receiver consists of a simple PIN photodiode with a transimpedance amplifier (TIA) and requires a single analog-to-digital converter (ADC), as indicated in Fig. 1. For sensitivity measurements, a variable optical attenuator (VOA) is used. In our experimental platform for optical OFDM systems (EOS) within the ADRENALINE testbed [5], off-line DSP is performed by using Matlab code. The analog signal is generated by an arbitrary waveform generator (AWG) with sampling speed up to 24GSa/s. The optical OFDM signal is transmitted over an optical fiber, which can be a simple fiber span or a lightpath set-up in the ADRENALINE testbed, which represents a 4-nodes mesh optical network [6]. The photodetected analog signal is captured by a real-time oscilloscope (DPO) at 50GSa/s for further off-line Matlab processing.

As the proposed cost-effective solution is based on double side band (DSB) modulation and DD, the achievable reach is limited due to the power fading induced by the chromatic dispersion (CD) [7]. Single-side band (SSB) transmission is more robust to dispersion impairments. However, a guard band ($B_G$) equal to the electrical OFDM signal bandwidth ($B_S$) is required for correct photodetection and an optical filter is needed. In [3], we have experimentally demonstrated that, using an external Mach-Zehnder modulator (MZM) biased at the quadrature point, the guard band can be reduced up to 89%, at the expense of the receiver sensitivity. A fixed modulation format (BPSK) has been used and the bit rate varied with the signal bandwidth $B_S$ from 5GHz to 9GHz. Optical bandwidth occupancy of $B_{op}=20GHz$ has been considered for DSB transmission with variable rate up to 9Gb/s and 25km of standard single mode fiber (SSMF). Performance is reported in Fig. 2a. A target bit error rate (BER) of $10^{-3}$ is considered, assuming a forward error correction (FEC) of 7% overhead. For longer optical paths, the spectral occupancy of the optical OFDM signal must be reduced in order to mitigate the self-cancellation between the carriers at the two sidebands [7]. The spectral efficiency can be enhanced by minimizing the guard band and using higher 1D modulation formats, such as 4PAM. The bandwidth and bit rate can be varied at the DSP level by software, selecting the suitable modulation format and number of OFDM subcarriers. The rate can be adapted with fine granularity by using BL. Adaptive strategies can be adopted, according to the channel condition, so that data mapped with the most robust modulation format are supported by the subcarriers with lower signal to noise ratio. To further improve the achievable reach at a certain rate, power loading schemes can be also implemented.

In order to minimize the guard band and consider a low-cost laser with linewidth of the order of MHz, we analyse the sensitivity performance of the system of Fig. 1 for 4PAM format and 80km of fiber span. Compared to the case of 100kHz linewidth and $B_G=1GHz$, better performance is achieved with a laser of 1MHz linewidth and 500GHz guard band, as shown in Fig. 2b. Thus, we assume the parameter $B_G=500MHz$ as optimal.

Figure 2. (a) Sensitivity performance at $10^{-3}$ BER and fixed BPSK format with variable bit rate and guard band. In the insets, B2B spectra after PD at 5Gb/s ($B_G=B_S=5GHz$) and 8Gb/s ($B_G=8GHz, B_S=2GHz$); (b) Guard band optimization: BER performance varying the laser linewidth; (c) Experimental (black lines) and numerical (gray lines) B2B performance of BVT at variable rate.
In a flexi-grid scenario, the reduction of channel width enables the creation of low bit rate connections, which may be used in metro area networks. Thus, we consider 12.5GHz channels, where the maximum optical spectrum occupancy $B_{max}$ of the OFDM signal corresponds to two frequency slots of 6.25GHz. We analyse variable bit rate from 5Gb/s to 10 Gb/s, obtained with different modulation formats and BL schemes: a) 5Gb/s using BPSK with $B_s=5GHz$ and $B_{opt}=1GHz$; b) 10Gb/s using 4PAM with $B_s=5GHz$ and $B_{opt}=11GHz$; c) 8Gb/s using 4PAM with $B_s=4GHz$ and $B_{opt}=9GHz$; d) 8Gb/s using adaptive BL with 40% of BPSK and 60% of 4PAM, for $B_s=5GHz$ and $B_{opt}=11GHz$. The back-to-back (B2B) performance is shown in Fig. 2c. The numerical and experimental BER curves are in good agreement for BPSK format. For 4PAM and BL, the receiver power measured at $10^{-3}$ BER has a penalty of about 0.5dB with respect to the numerical value. Preliminary results, for connections set-up in the 4-nodes optical network of the ADRENALINE testbed, have shown that, at the increase of the path length, bandwidth reduction gives more robust transmission than adaptive BL for the same rate. Additionally, numerical simulations demonstrate that, by suitably varying the OFDM signal bandwidth and/or selecting the BL scheme (including also 8PAM format), a net data rate of 10Gb/s (considering a total overhead of about 20%, taking into account CP, TS and FEC) can be transmitted, within 12.5GHz channels, up to 120km connections [8]. Therefore, the proposed BVT can be suitable for flexi-grid metro networks.

2.2 Simplified CO-OFDM for national networks upgrading

A coherent optical OFDM (CO-OFDM) architecture (shown in Fig. 3a) is under investigation for enhancing the reach of the transponder, at the expense of slightly increasing its complexity. Specifically, a constant envelope CO-OFDM (CE-OFDM) system [9] using polarization multiplexing (Pol-Mux) is proposed to increase the spectrum efficiency. The main property of CE-OFDM is its robustness against nonlinearities, as a pure phase modulation (PM) is obtained at the output of the transmitter, resulting in a signal with 0dB PAPR.

A set of preliminary simulations are carried out for evaluating the performance at variable net bit rates. The measured output parameter is the statistical counting of received bits, providing BER performance. The gross bit rate is obtained after adding a total overhead of 38.2%, which takes into account phase noise mitigation (7.8%), TS (0.8%), CP (10%) and soft-decision FEC (20%) for targeting a BER of $2 \times 10^{-2}$. B2B results are shown in Fig. 3b. There it can be observed that for the targeted BER, the OSNR requirement is 2.7dB at 10Gb/s, 7.6dB at 40Gb/s and only 11dB at 100Gb/s. Additionally, for amplified links running at 10Gb/s, a correct reception has been achieved for distances beyond 1000km, making possible to target national-wide networks.

![Figure 3. (a) Pol-Mux coherent BVT scheme. (b) B2B simulation results at different net bit rates.](image)

3. SLICEABLE BVT

Sliceable BVTs are currently under investigation [10]. This advance functionality allows considering the BVT as a set of virtual transponders able to generate a flow of great capacity, which can be suitably sliced as multiple flows direct towards different nodes [11]. Different solutions have been already proposed [11-13].

The BVTs described in Sec. 2 can be also seen as building blocks for designing future sliceable BVT. For example, they can be used to implement an array of subtransmitters generating OFDM signals centred at different optical carriers, according to the wavelength selected at the TLS [13]. Each subtransmitter has a certain capacity (e.g. 10Gb/s), which can be varied with subwavelength granularity, thanks to the OFDM modulation. Furthermore, multi-band OFDM signals can be transmitted (also with DD [14]) to enhance the transponder capacity. The total BVT capacity is given by the contribution of all the rate/bandwidth variable subtransmitters. The aggregated flow can be routed as data flows with less capacity towards different destination nodes, as in the example of Fig. 4a. At the receiver, the data flow is distributed to the subreceivers array and correctly demapped.

Similarly, time-multiplexed data flows can be routed towards different nodes through different optical paths, as shown in Fig. 4b. Bursts of variable duration, supporting different modulation formats, rates and bandwidth occupancy, can share the same wavelength or can be generated varying the tunable laser [12]. In this design, a challenging issue is the amplification of the burst-mode traffic using Erbium doped fiber amplifiers (EDFAs). In fact, the burst pattern can cause variations to the population inversion of the Erbium doped fiber, giving non-negligible gain transients (as shown in the inset at node-2 of Fig. 4b). The transmission performance, in terms of tunability and in the presence of EDF transients giving a 10% overshoot, has been assessed for the BVT of Fig. 1 (described in Sec. 2.1). Experimental results within our platform have shown a correct transmission in the wavelength range between 1535.04nm and 1560.20nm, almost covering the entire C-band [15].
4. CONCLUSIONS

The flexible features of BVT based on OFDM technology allow adaptively adjusting/selecting the bandwidth, modulation format and bit loading scheme, with subwavelength granularity, in elastic optical networks.

We have analysed bit rate and bandwidth variable transponders based on low-complex FHT processing using both direct detection and coherent schemes. Specifically, a cost-effective design has been numerically and experimentally assessed for targeting flexi-grid metro networks and a simplified coherent scheme using phase-modulation is investigated for upgrading national networks to the SLICE architecture. Bit loading schemes and guard band minimizing are proposed for distance adaptive transmission using the former BVT design. For the latter BVT solution, polarization multiplexing, together with an increased overhead, is used for achieving longer distances and higher bit rate. The proposed BVTs can be the building block for designing future sliceable transponders, introducing advanced flexible functionalities and improving the BVT capacity.

ACKNOWLEDGEMENTS

This work was supported by the EU-FP7 IDEALIST project (G. A. 317999), the Spanish MINECO project FARO (TEC2012-38119), the FPI research scholarship grant BES-2010-031072 and the grant PTQ-1108405.

REFERENCES