Experimental Validation of an Elastic Low-Complex OFDM-Based BVT for Flexi-Grid Metro Networks

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Abstract *Cost-effective rate/bandwidth variable transponder (BVT) based on DSB DD-OFDM using low-complexity DSP is proposed for flexi-grid MAN. Elastic capabilities are experimentally evaluated, for transmitting 12.5GHz channels at variable rate between 5Gb/s and 10Gb/s along optical path from 45km to 195km.*

Introduction

Flexi-grid technologies allow using 12.5GHz spectrum slots or even 6.25GHz. This granularity is proposed to improve efficient utilization of optical spectrum when creating super-channels for high-rate connections. However, the reduction of channel width enables the creation of low bit rate connections, which may be used in metro area networks (MAN). Typically, metro architectures are composed of two main levels of aggregation: i) First level of aggregation (named Multi-Tenant Unit (MTU)), in charge of collecting traffic from the OLTs; ii) Second level of aggregation (named Access level), that aggregates the traffic from the MTUs mainly through direct fiber connections (i.e. dark fiber). Nowadays, the IP functionality (i.e. traffic classification, routing, authentication, etc.) is implemented in the Broadband Remote Access Servers (BRAS), which are usually located at the second level of aggregation. Therefore, they are distributed in many sites along the regional area covered by the MAN, causing a high CapEx impact.

Lately, main network operators are expanding their photonic mesh to the regional networks, so BRASes could be co-located in fewer locations reducing investment. For this metro scenario, transmission techniques for core networks are not necessary, but a more cost-effective solution must be considered.

In this paper, we propose a cost-effective elastic OFDM BVT using direct detection (DD) for rate and distance adaptive transmission in flexi-grid metro networks and experimentally validate it in the ADRENALINE testbed[1]. The rate/bandwidth can be varied by software with fine granularity, selecting the suitable modulation format and number of OFDM subcarriers. As a constraint, we assume that the optical spectrum occupancy is limited to two frequency slots of 6.25GHz, in order to consider 12.5GHz channels. Thanks to the subwavelength granularity of OFDM, BVT elastic features also include adaptive bit loading (BL), so that, according to the channel condition, the subcarriers with lower signal to noise ratio (SNR) carry data mapped with the most robust modulation format.

The proposed BVT can be the fundamental building block for future sliceable BVT[2,3], where e.g. an array of sub-transmitters with 10Gb/s capacity each, generates OFDM signals with tunable optical carriers that can be aggregated to be routed as variable data flows towards different nodes[4]. A proof of concept of this advanced elastic feature is also provided.

Elastic BVT and experimental setup

The elastic BVT is based on low-complexity digital signal processing (DSP) using the fast Hartley transform (FHT). Only real algebra and M-PAM format are required to obtain the same spectral efficiency and performance as FFT-based DD OFDM systems using M^2-QAM[5]. DD is more robust to dispersion impairments when combined with optical single-side band (SSB) modulation. However, SSB requires a guard

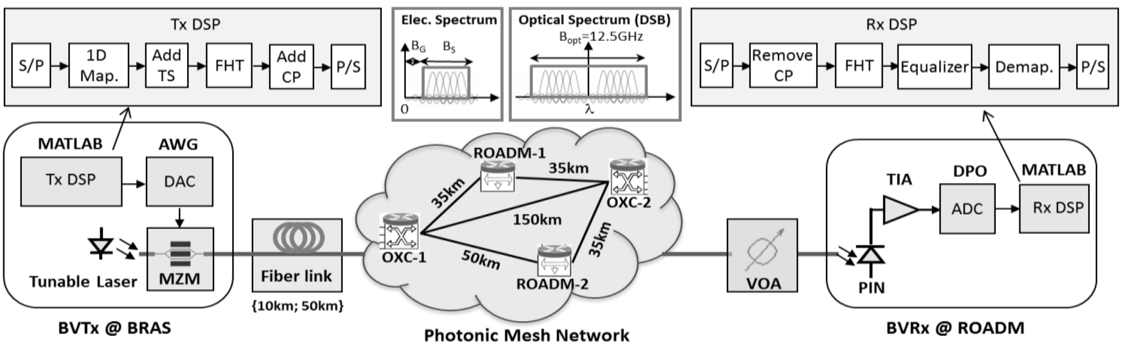

Fig. 1: BVT schematic and experimental set-up.

band equal to the electrical OFDM signal bandwidth for correct photodetection. Furthermore, an optical filter is needed for one sideband suppression, reducing the receiver sensitivity. Alternatively, double-side band (DSB) modulation can be implemented, as it requires a simpler and lower-cost transponder design[5]. It has been demonstrated that using an external Mach-Zehnder modulator (MZM) biased at the quadrature point the required guard band can be reduced enhancing the spectral efficiency[5] However, this scheme is more affected by the chromatic dispersion (CD), in fact, self-cancellation between carriers of the two sidebands of the DSB spectrum can occur, limiting the achievable reach. A more robust DSB transmission can be obtained by reducing the spectral occupancy of the OFDM signal, so that the carriers of the two sidebands experiment lower power fading, induced by the CD, according to formula (2) in[6]. This way the same spectral efficiency as SSB modulation can be achieved. In this work, in order to use cost-effective laser with linewidth of the order of MHz, a guard band (B_G) of 500MHz is considered.

The experimental set-up is shown in Fig. 1. The DSP at the transmitter/receiver is performed off-line using Matlab software. A stream of randomly generated data is mapped into 1D constellation (BPSK or/and 4PAM) and modulated by an FHT with N=64 subcarriers. The real-valued OFDM digital signal is loaded into an arbitrary waveform generator (AWG), which generates an analog signal at 12GS/s. The analog OFDM signal modulates an external MZM biased at the quadrature point ($0.5V_\pi$) and driven by a tunable laser source at λ=1550.12nm.

The maximum electrical signal bandwidth (B_S) is 5GHz and the total electrical bandwidth, including the guard band, is $B_T=B_G+B_S$=5.5GHz. The resulting DSB optical spectrum is B_{opt}=11GHz, which perfectly fit within a 12.5GHz flexi-grid channel, as shown in the inset of Fig.1. At the receiver side, the transmitted signal is detected by a PIN photodiode. The data is captured by a real-time oscilloscope (DPO) at a sampling rate of 50GS/s and then down-converted, demodulated, equalized and demapped off-line with Matlab. 8 half-length training symbols (TS) are considered for low complex equalization[5]; they are inserted each 512 OFDM frames resulting in an overhead of 1.56%. A 10% cyclic prefix (CP) is also considered. In order to assume a target bit error rate (BER) of 10^{-3}, a forward error correction (FEC) with 7% overhead is taken into account. Thus, the resulting total overhead is 19.54%. For sensitivity measurements, a variable optical attenuator (VOA) is used.

The fiber link is a SSMF (G.652), whose length is varied in order to emulate different BRAS locations (e.g. 10km or 50km). The ADRENALINE testbed represents a 4-nodes mesh metro network. Specifically, it consists of two optical cross-connects (OXCs) and two reconfigurable add-drop multiplexers (ROADMs), connected with links of 35km, 50km and 150km, as indicated in Fig. 1. In the set-up, we assume that the rate/bandwidth variable transmitter (BVTx) is located at the BRAS and the receiver (BVRx) at the ROADM.

Performance evaluation

We assess the performance of the proposed BVT by varying the modulation format and bit loading scheme. We analyze two modulation formats (BPSK and 4PAM) at 5GBaud/s (B_S=5GHz), giving 5Gb/s and 10Gb/s, respectively. Fine bit rate selection is achieved using bit loading (BL). An 8Gb/s connection is obtained by mapping the 40% of the subcarriers with BPSK and the 60% to 4PAM. This target rate is also obtained by reducing the electrical signal bandwidth to 4GHz and using only 4PAM format. In all the experiments, the BER is measured by error counting up to 1000 errors. First, we analyze the back-to-back (B2B) case.

Fig. 2 shows the experimental BER curves (black lines with markers) versus the receiver power, compared to the simulated ones (gray lines). It can be observed that the BPSK curves at 5Gb/s are in good agreement. The measured sensitivity at 10^{-3} BER is -14dBm, the numerical result is -14.1dBm. When using multilevel modulation, the experimental curves present approximately 0.5dB of penalty (at the target BER) with respect to the corresponding numerical curves. The measured received power at 10^{-3} BER is -10.1dBm and -10.6dBm for the 4PAM format at 10Gb/s and 8Gb/s; the BL scheme at 8Gb/s shows better performance, requiring -10.9dBm of receiver power.

Then, we validate the BVT in the experimental set-up described in Fig.1. The optical OFDM

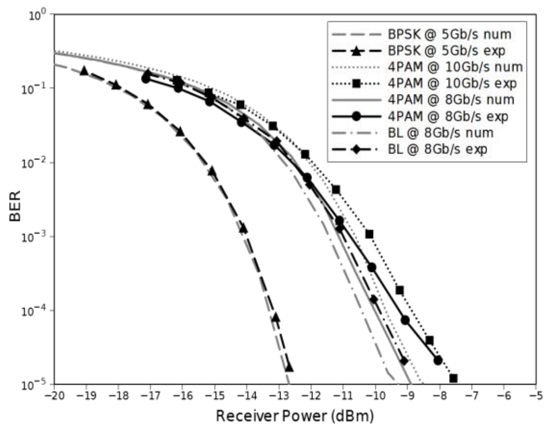

Fig. 2: B2B performance for variable BVT formats.

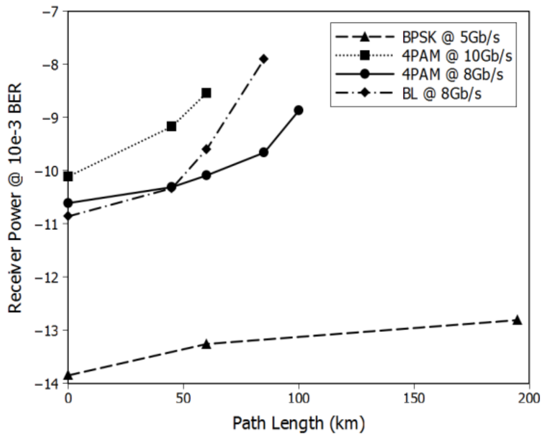

Fig. 3: BVT performance at different optical paths.

signal is routed towards one of the network ROADM through optical paths of 2 hops (via OXC-1). Connections of 45km, 60km, 85km and 100km are tested. Results in terms of receiver sensitivity at 10^{-3} BER are shown in Fig. 3. For all the analyzed cases, the measured optical SNR (OSNR) ranges between 36.21dB and 36.93dB. Therefore, we can assume that the system is not limited by the optical noise, due to the network amplifiers. BPSK is the most robust modulation format. Thus, it is also successfully transmitted to ROADM-2 through a 3 hops path (via OXC-1 and OXC-2) of length 195km. Compared to the sensitivity (at the target BER) required for the 2 hops path of length 60km (-13.26dBm), a penalty of only 0.45dB is measured. 4PAM format, with the same bandwidth occupancy, doubles the spectral efficiency at expense of the receiver sensitivity and the achievable reach. The required receiver power for a BER of 10^{-3} is -8.54dBm, considering a path of 60km with 2 hops.

For distance-adaptive transmission assessment, we analyze the connections at 8Gb/s. As the subcarriers at the edge of the signal present lower SNR (due to channel impairments), they are loaded with BPSK symbols. We compare this adaptive BL scheme at 8Gb/s (B_{opt}=11GHz), with uniform 4PAM format and reduced bandwidth occupancy (B_{opt}=9GHz). The BL scheme has better performance up to a reach of 45km (2 hops). For longer path, in order to cope with the accumulated CD, it is convenient to obtain the same bit rate by reducing the signal bandwidth and select the same modulation format (4PAM) for all the subcarriers. This connection can be successfully established through an optical path with 2 hops of length 100km, requiring a receiver sensitivity of -8.87dBm. The longest 2 hops path supporting adaptive BL at 8Gb/s is 85km; a BER of 10^{-3} is achieved with a receiver power of -7.9dBm. This results in a penalty of 1.76dB compared to the sensitivity of 4PAM format at the same bit rate.

Furthermore, the proposed BVT can be used as the building block of a sliceable BVT. In order to prove this capability, the set-up in Fig. 4 is implemented. Two data flows, consisting of two optical OFDM signals at half of the maximum rate capacity of the BVT, are generated using two tunable laser (TL) sources at λ_1=1550.12nm and λ_2=1550.92nm. BPSK format and electrical bandwidth of 5GHz are selected at the transmitter DSP. As the modulation is performed by a single MZM, two identical signals at 5Gb/s with optical bandwidth of 11GHz are obtained. After passing the first hop (10km), at the OXC-1, they are sent towards ROADM-1 and ROADM-2, through the link of 35km and 50km, respectively. Both signals have been correctly detected. For a BER of 10^{-3}, the measured receiver power at ROADM-1 (signal at λ_2) is -13.1dBm and the OSNR is 34.7dB. At ROADM-2 (signal at λ_1), the receiver power is -13.35dBm and the OSNR is 35.43dB.

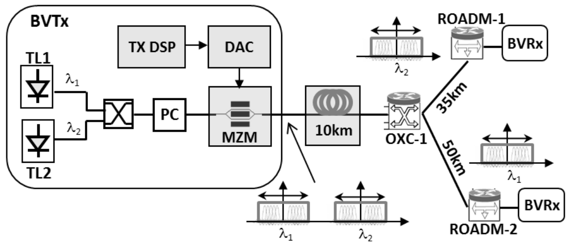

Fig. 4: Set-up for sliceable BVT proof of concept.

Conclusions

Elastic BVT based on OFDM with DSB and DD can be a suitable cost-effective solution for flexi-grid metro networks. The modulation format and bandwidth occupancy (within 12.5GHz channel) are selected at the DSP by software. Distance-adaptive connections at variable rates from 5Gb/s to 10Gb/s are tested. BPSK at 5Gb/s is supported up to 195km (3hops). By reducing the signal spectrum with 4PAM format, more robust transmission than using adaptive bit loading is obtained at 8Gb/s up to 100km and 2 hops. To provide higher capacity and flexibility, the BVT can be used as a building block for future sliceable transponder.

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