Experimental Analysis of 8-QAM Constellations for Adaptive Optical OFDM Systems

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***Abstract*—In this letter, we numerically and experimentally evaluate the influence of adopting different 8-QAM constellations. The performance of flexible/adaptive direct detection (DD) optical orthogonal frequency division multiplexing (OFDM) transmission systems has been evaluated in the back-to-back (B2B) configuration. Metro/regional network scenario is also considered using the 4-node photonic mesh network of the ADRENALINE testbed. Specifically, different optical paths of the network ranging from 50 km to 185 km are analyzed to asses the optimal 8-QAM format, which maximizes the system performance. Additionally, single side band (SSB) modulation is implemented in order to enhance the robustness against the chromatic dispersion (CD). The effect of CD on the format selection is investigated targeting different data rates using the implemented loading algorithm.**

***Index Terms*—Bit/power loading, OFDM, SSB, modulation format.**

I. Introduction

METRO networks are evolving towards more elastic and scalable infrastructures in order to efficiently deal with the exponential growth of the traffic demand [1]. Hence, orthogonal frequency division multiplexing (OFDM) technology can be implemented enabling data rate/bandwidth scalability and super-/sub-wavelength granularity [2]. Specifically, system adaptability can be achieved by loading the subcarriers with different number of bits and suitable powers according to the optical channel [3]. At the increase of the optical path length, chromatic dispersion (CD) and fiber nonlinearities limit OFDM transmission [4]. By implementing direct-detection (DD) system, cost-effectiveness is enhanced, while CD effect can be mitigated by using single side band (SSB) modulation [4]. In order to further increase the tolerance against fiber impairments, low-order modulation formats ($<$ 16-QAM) are widely assigned to different subcarriers according to the bit/power loading algorithm [3]. Among the candidates, 8-QAM is the one that presents many possible signal constellations with different performance, when distinct symbol distances and amplitudes are considered [6], [7]. Hence, the selection of a suitable 8-QAM format becomes crucial in order to maximize either system performance or data rate in adaptive optical OFDM systems equipped with flexible programmable transceivers [8].

In this letter, we numerically and experimentally evaluate the performance of several 8-QAM constellations in SSB DD optical OFDM systems targeting metro/regional networks. With this aim, the optimal format selection is investigated, implementing either uniform (8-ary) or arbitrarily bit/power loading on the OFDM subcarriers generated in the electrical domain by means of digital signal processing (DSP). This allows to dynamically reconfigure the transceivers according to the network condition. In particular, optical back-to-back (B2B) configuration and different optical paths of the ADRENALINE photonic mesh network have been analyzed [9], [10]. The impact of the 8-QAM constellations on the achieved data rate is also evaluated when different percentages of this format are assigned to the subcarriers in relation with the loading algorithm. The rest of this letter is organized as follows, the system model is described in section II. In section III, the numerical and experimental analysis are presented. Finally, conclusions are drawn.

II. System model

The proposed adaptive SSB DD OFDM system is described in Fig. 1. At the transmitter (Tx) DSP block of Fig. 1, a randomly generated data stream is parallelized and mapped into 8-QAM constellation, in the case of uniform loading. Circular, star, rectangular and square 8-QAM formats have been considered (see Figs. 3 (d)-(g)) [7]. BPSK and M-QAM formats (being M a power of 2, ranging from 2 to 256) are used, when bit/power loading is applied with the Levin-Campello margin adaptive algorithm [3]. After the mapping, training symbols (TS) are added in order to equalize data at the receiver side. An inverse fast Fourier transform (IFFT) of 512 points is performed with half of the subcarriers set to zero to create a guard-interval, as required in SSB transmission. Then, a cyclic prefix (CP) is added to the signal, which is serialized and symmetrically clipped with a 9 dB clipping level [3]. The resulting data is upconverted to a radio frequency in order to transmit a real OFDM signal. A pre-emphasis digital filter is applied to compensate the system performance degradation due to the limited bandwidth of the digital-to-analog converter (DAC). The DAC impulse response is modeled as a 2nd order Gaussian filter, based on the characterization of a commercial high-speed DAC. For optical modulation, an external push-pull single drive Mach-Zehnder modulator (MZM) biased near the null point is considered. The laser driving the MZM is modeled as a standard continuous wave laser. An optical filter

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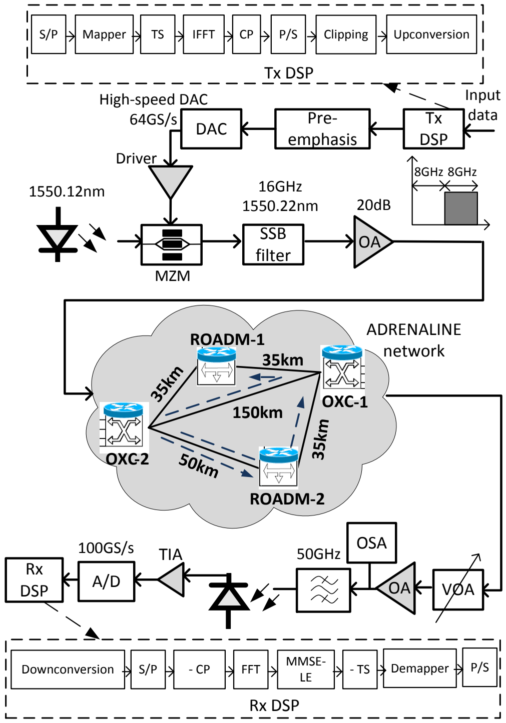

Fig. 1. System model and experimental set-up.

is used to generate an optical SSB signal. At the receiver side, the transmitted signal is detected with a PIN photodiode, analog-to-digital (A/D) converted and synchronized. Finally, downconversion, parallelization, CP removal, FFT processing, equalization, TS removal, demapping and serialization are performed at the receiver (Rx) DSP block. Zero-forcing (ZF) equalizer is commonly used in OFDM systems to retrieve the original transmitted data [11]. However, when circular 8-QAM constellation is considered, the received data can not be equalized, as the constellation has a symbol in the origin. To overcome this problem, minimum mean-square error linear equalization (MMSE-LE) is used [11]. It offers a wider variety of possible 8-QAM constellations to be implemented without increasing system complexity requirements. In fact, according to [11], both equalizers present the same computational complexity and in some cases MMSE-LE outperforms ZF.

III. Numerical and experimental analysis

The proposed system of Fig. 1 is numerically analyzed using Python software and considering an optical B2B configuration. Different 8-QAM constellations are implemented in order to determine the optimal format selection, which maximizes the system performance. To this extend, all the subcarriers are mapped with 8-QAM format (uniform loading) using different constellations, which are indicated with crosses in Figs. 3 (d)-(g). A data stream of 153600×20 bits is transmitted at 24 Gb/s occupying an optical bandwidth of 16GHz (as seen in the inset of Fig. 4). The optical channel is emulated with a variable optical attenuator (VOA). A target bit error rate (BER) of $3 \cdot 10^{-3}$ and a total overhead of 13.4% have been considered including the overheads due to 1.9% CP, 4% TS and 7% HD-FEC [12]. The BER is calculated using error counting. The

Fig. 2. Picture of the experimental set-up.

optical signal-to-noise ratio (OSNR) is defined within 0.1 nm. The numerical B2B BER performance vs OSNR can be seen in Fig. 3 (a). Circular 8-QAM format, which has the highest number of different levels in the quadrature component, outperforms the other three analyzed constellations, as shown in the figure. The target BER can be achieved with 11.5 dB OSNR (2 dB less OSNR than with rectangular 8-QAM).

As a next step, an experimental analysis of the different constellations for the adaptive SSB OFDM system is performed. The set-up and a picture of it can be seen in Fig. 1 and Fig. 2, respectively. Tx, pre-emphasis and Rx modules are the same used in simulation. To perform digital-to-analog conversion a commercial 13 GHz DAC working at 64 GS/s is used. A tuneable laser centered at 1550.12 nm with 5 dBm output power is considered. Then, the optical signal, generated with the MZM, is filtered with a 16 GHz SSB optical filter and optically amplified to transmit at a constant power of -1 dBm. A VOA and an optical amplifier (OA), working at constant power mode, are used to perform OSNR measurements. They are properly varied to fix a constant power at the PIN input. Additionally, a 50 GHz optical band pass filter for noise rejection and an optical spectrum analyzer (OSA) are included. Finally, a real-time 20 GHz oscilloscope at a sampling rate of 100 GS/s is used for A/D conversion.

The first experimental assessment is performed considering the optical B2B configuration and the obtained results can be seen in Fig. 3 (b). Comparing Figs. 3 (a) and (b), it can be observed that the experimental curves are in good agreement with the obtained numerical results. In particular, the maximum OSNR difference for $3 \cdot 10^{-3}$ BER is about 0.1 dB and it occurs using the rectangular 8-QAM constellation. Despite the limited bandwidth of the DAC, all the subcarriers present similar SNR value thanks to the preemphasis filtering process, as shown in Fig. 3 (c). The received experimental optical B2B constellations are depicted in Figs. 3 (d)-(g). Since circular 8-QAM constellation maximizes the system performance in the B2B case, we have experimentally assessed its performance over the ADRENALINE network, which is considered for representing a 4-nodes metro network (see Fig. 1) [10]. Single and 2 hop paths of 50 km, 85 km and 185 km of single mode

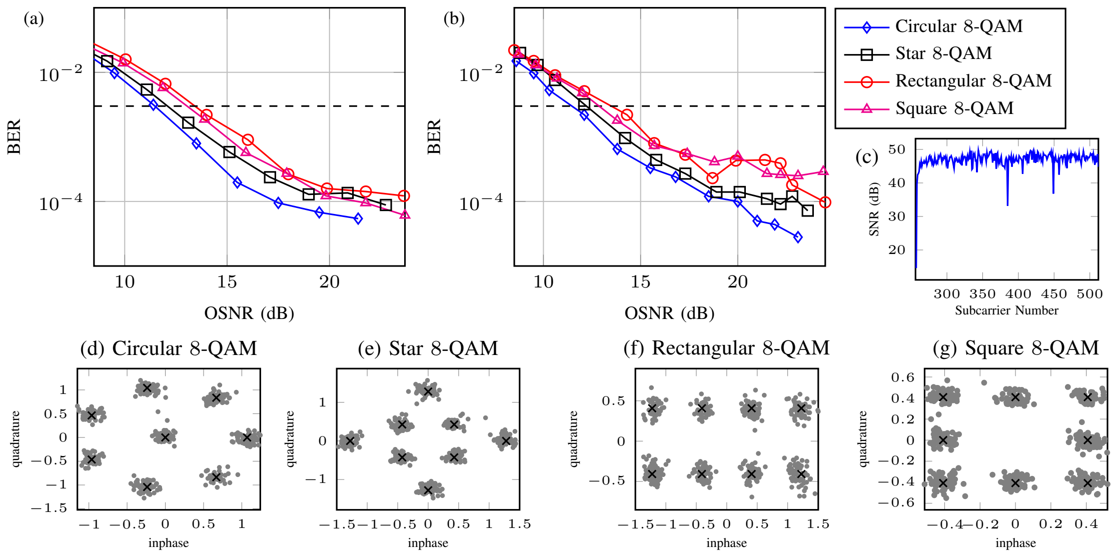

Fig. 3. (a) Numerical and (b) experimental optical B2B BER curves at 24 Gb/s. In (c) experimental optical B2B SNR estimation at 15.3 dB OSNR. In (d)-(g) 8-QAM transmitted (x) and experimental optical B2B normalized received constellations at 25 dB OSNR.

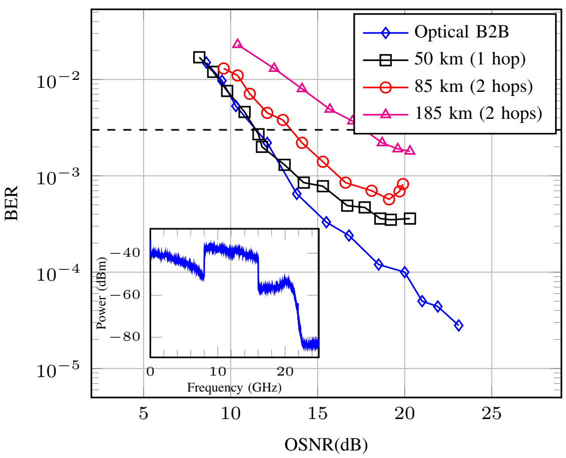

Fig. 4. Performance of circular 8-QAM for different paths. In the inset, photodetected spectrum after 85 km at 15.3 dB OSNR.

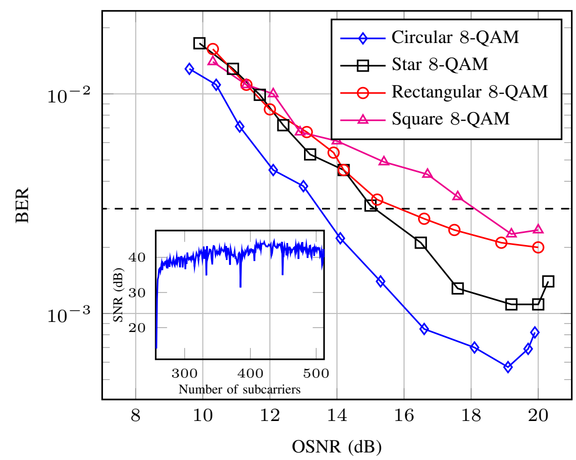

Fig. 5. System performance at 24 Gb/s after 85 km optical path. In the inset, SNR estimation after 85 km at 15.3 dB OSNR.

fiber have been considered, as indicated in Fig. 4. After single hop 50 km path, 24 Gb/s are transmitted with the same OSNR than in the optical B2B case. A higher OSNR value of 13.5 dB is needed to ensure the target BER after the 85 km path with 2 hops passing through ROADM-2 (see Fig. 1). In this case, particularly high-frequency subcarriers are attenuated due to the transmission over the network. This can be seen in the insets of Figs. 4 and 5, where the photodetected spectrum and the SNR estimation are respectively depicted. Finally, the performance is assessed over the 2 hop path of 185 km (OXC-2→ OXC-1→ ROADM-1) achieving $3 \cdot 10^{-3}$ BER with 17.7 dB OSNR.

Then, we have investigated which is the optimal format selection that maximizes the system performance using either uniform or bit/power loading considering an intermediate path of 85 km with 2 hops. According to Fig. 5, circular 8-QAM format achieves the best performance also in the presence of CD. In this case, a higher OSNR difference of 4.5 dB between circular and square 8-QAM formats is obtained at the target BER, compared with the B2B configuration. Additionally, the robustness of circular 8-QAM against path impairments is also evidenced comparing figures 3 (b) and 5. A 2 dB OSNR penalty is observed at the target BER between the 85 km and the B2B curves, while in case of using square constellation, the penalty is 5 dB. This is mainly due to the greater distance of the symbols of circular 8-QAM in the complex plane, when considering the same average power in all the analyzed formats.

In order to evaluate the benefits of using the optimal format in adaptive systems, different percentages of 8-QAM format are assigned to the subcarriers, by means of the bit/power loading algorithm. This allows achieving different data rates and performances over the 85 km path with 2 hops. Specifically, the constellation selection becomes crucial for maximizing the system performance, when more than 10% of the subcarriers are mapped into 8-QAM format, as seen in

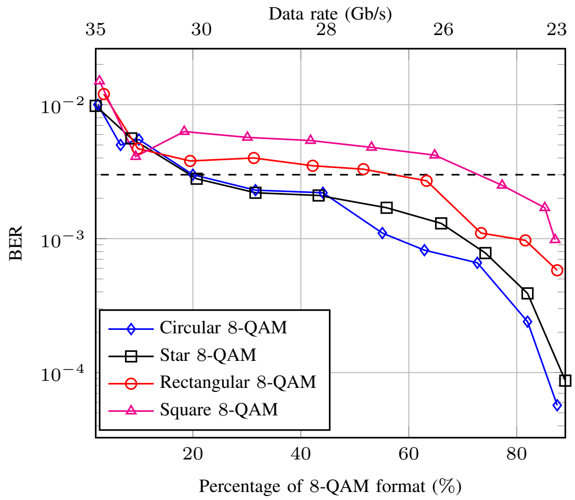

Fig. 6. System performance for 85 km optical path with different percentages of 8-QAM format at 18 dB OSNR.

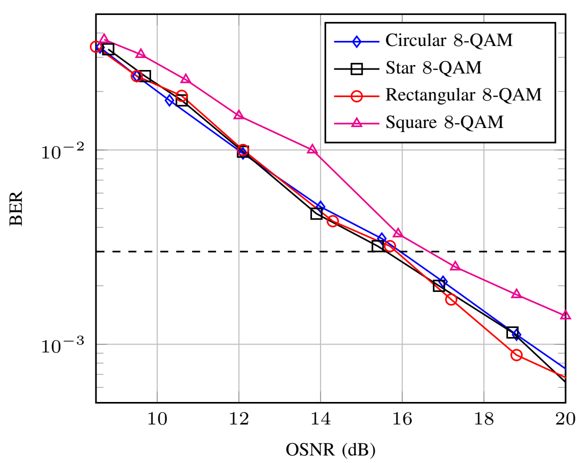

Fig. 7. System performance at 30 Gb/s for the optical B2B configuration using bit/power loading.

Fig. 6. Circular 8-QAM outperforms rectangular and square constellations from 10% of the mapped subcarriers and star 8-QAM from 45%. Hence, the flexible programmable transceiver can select between 8-ary constellations as well as any modulation format per subcarrier according to the target data rate/performance and complexity requirements. From the figure, it can be seen that a maximum SSB transmission of 30 Gb/s is achieved at the target BER. Figs. 7 and 8 shows the impact of using different 8-QAM formats on the system performance considering bit/power loading at 30 Gb/s in the optical B2B configuration and after the 85 km optical path. Comparing both figures, it can be observed that square 8-QAM is more sensitive to transmission path impairments, showing a 3.6 dB OSNR penalty at the target BER between the two analyzed configurations. Whereas, circular and star constellations present a OSNR penalty of 1.6 dB (2 dB less compared to square). The performance relation between the curves observed in Fig. 8 at 18 dB OSNR, is also maintained in Fig. 6 for 20% subcarriers mapped with 8-QAM.

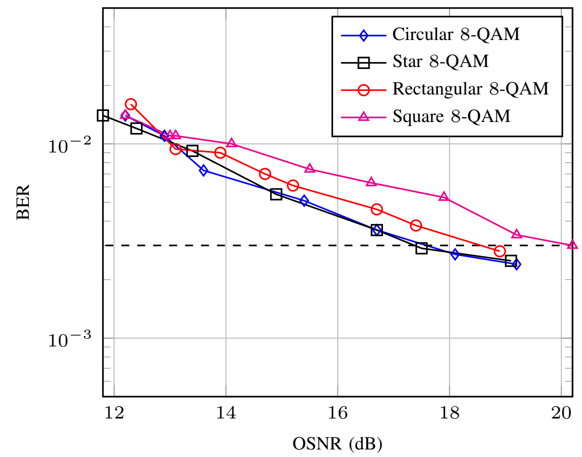

Fig. 8. System performance at 30 Gb/s for 85 km optical path using bit/power loading.

IV. Conclusion

In this letter, it has been numerically and experimentally evaluated the performance of different 8-QAM constellations in optical B2B configuration and after different paths of the ADRENALINE network. Additionally, it has been shown that the choice of 8-QAM constellation impacts on the system performance and on the achieved data rate, when bit/power loading is applied. Particulary, the benefits of using circular 8-QAM, in adaptive systems, are evidenced when more than 10% of the subcarriers are mapped into this format. Depending on the implemented format, MMSE or ZF equalization can be selected. Thus, the proposed transceiver allows flexible constellation/equalization selection, according to the network requirements, in scalable/programmable DD OFDM transmission systems envisioned for future metro networks.

References

[1] O. Gerstel et al.,“Elastic Optical Networking: A New Dawn for the Optical Layer?,” Comm. Mag., Vol. **50**, no.2, p.12, (2012).

[2] J. Armstrong, “OFDM for Optical Communications,” J. Lightw. Technol., Vol. **27**, no.3, pp.189-204, Feb.1, (2009).

[3] L. Nadal et al.,“DMT Modulation with Adaptive Loading for High Bit Rate Transmission Over Directly Detected Optical Channels,” J. Lightw. Technol., Vol. **32**, no.21, p.4143 (2014).

[4] L. Bangjianget et al.,“Comparison of DSB and SSB transmission for OFDM-PON,” J. Opt. Comm. and Netw., Vol. **4**, no.11, pp.94-100, (2012).

[5] B. Schmidt et al.,“Experimental demonstrations of electronic dispersion compensation for long-haul transmission using direct-detection optical OFDM,” J. of Lightw. Technol., Vol. **26**, no. 1, pp. 196-203, (2008).

[6] M. Nolle et al., “Performance Comparison of Different 8QAM Constellations for the Use in Flexible Optical Networks,” Proc. OFC, paper W3B.2, San Francisco, (2014).

[7] J.G.Proakis,“Digital Communications”, McGraw Hill,(2000)

[8] M. Svaluto et al., “SDN-enabled Sliceable BVT Based on Multicarrier Technology for Multi-Flow Rate/Distance and Grid Adaptation,” Proc. ECOC, paper Th.2.1.1, (2015).

[9] M. Svaluto et al.,“Experimental Validation of an Elastic Low-Complex OFDM-Based BVT for Flexi-Grid Metro Networks,” Proc. ECOC, paper We.1.E.5, London, (2013).

[10] R. Munoz et al.,“Dynamic differential delay aware RMSA for elastic multi-path provisioning in GMPLS flexi-grid DWDM networks,” Proc. OFC, paper W3A.2, (2014).

[11] J.M. Cioffi, “Data Transmission Theory,” in Course Text for EE379A-B and EE479, Stanford, CA, USA: Stanford Univ., ch. 4, (2013).

[12] ITU-T recommendation G.975.1 (2004).