

Flexible Transmission Enabled by Novel M^2 -QAM Formats with Record Distance - Spectral Efficiency Tuneability

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Abstract: We propose a variable M^2 -QAM format and coding scheme and demonstrate record distance - spectral efficiency tuneability by 6.4 bit/s/Hz and $\Delta L \approx 18x$, respectively, at 400 and 600 Gb/s per carrier and report record terrestrial reach for high spectral efficient up to 256QAM. © 2018 The Author(s)

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1. Introduction

The ongoing growth in optical transmission capacities leads to relentless pursue of higher data rates per wavelength. To meet the demand, transponders need to generate signals of higher spectral efficiency (SE) for better use of the fiber infrastructure, signals of higher integrity for longer transmission reach, and provide improved flexibility to address a variety of different lengths and system conditions in the field. Recently, we demonstrated for the first time 1 Tb/s on a single carrier bearing PDM-64QAM at 100 GBaud using high speed converters based on SiGe technology [1]. CMOS based transponders enable bitrates of up to 600 Gb/s using either pragmatic QAM up to 64QAM [2] or probabilistic constellation shaping (PCS) [3]. However, a further increase of the bitrate needs improvements of both the electrical bandwidth and the effective resolution (effective number of bits – ENOB) of the converters.

The growth in modulation order comes with an increase in the OSNR requirements, which typically translates to a reduction in reach. The adaptation of the modulation format to the targeted transmission distance requires variability of the delivered bitrate or SE. There are three known methods to do so, having varying bitrate tunability. First, one can employ ‘conventional’ pragmatic (2^{2n})-QAM formats that are selected based on the final SNR of the link [3]. These have very coarse granularity, exhibiting jumps in required OSNR by as much as 6 dB to maintain system performance. The second method is to use a temporal mixture of the latter formats called ‘time-domain hybrid’ (TDH) modulation [4]. TDH offers improvements in the bitrate tunability and is coding-wise easy to implement but is less practical for the receiver DSP unit. Finally, a recently proposed and demonstrated method is to use a fixed QAM constellation of large size and shape the probability of occurrence of its constituent symbols, known as PCS. This method allows for very fine bitrate granularity, at the expense of a more complex coder-decoder [5,6]. All aforementioned approaches allow adjusting the spectral efficiency and the bitrate to the targeted application or to the available transmission channel. Its tuneability is limited by the ENOB, the transponder bandwidth and the available OSNR.

In this paper, we propose another alternative method for bitrate variable transmission systems, where we apply for the first time non-pragmatic M^2 -QAM and pragmatic 2^{2n} -QAM formats from 16QAM up to 256QAM. We implemented a variable system at 400 Gb/s and 600 Gb/s with an adjustable trade-off between SE and reach and demonstrate extreme reach and SE variations at both bitrates using a novel G.654.E terrestrial transmission system.

2. Generation of non-pragmatic QAM

In this section we present the method to generate non-pragmatic M^2 -QAM formats of various orders. We will focus on the number of levels per real-imaginary axis that are not prime numbers, more specifically, on $M=6$ (36QAM), 10 (100QAM), 12 (144QAM) and 14 (196QAM). We will also compare these to pragmatic 2^{2n} -QAM formats with 4 (16QAM), 8 (64QAM) and 16 levels (256QAM). M^2 -QAM formats provide multiple advantages. Firstly, they allow independent signal processing of I and Q component, unlike 2^{2n+1} -QAM formats. Secondly, the same DSP algorithms of low complexity can be applied for all formats (e.g. frequency offset compensation). Thirdly, M^2 -QAM formats have low peak to average power ratios (PAPR) at modulator output, unlike PCS formats. The system relies on a state of the art modulator and mapping scheme for all formats. The schematic of the transmitter for pragmatic and non-pragmatic QAM formats is shown in Fig. 1. The symbol mapping and coding of non-pragmatic formats are very similar to that for PCS-formats [7]. The binary input data $2n$ are partly converted into M -level data from a simple base conversion. A base conversion from base-2 to base- B causes a rate loss R_L , defined by Eq. (1)

$$R_L = \frac{B^l - 2^{\lfloor \log_2(B^l) \rfloor}}{2^{\lfloor \log_2(B^l) \rfloor}} \times 100\% \quad (1)$$

where $l = 1, 2, 3, 4, \dots$. The rate loss can be very little, depending on the value l . Defining $k = \lfloor \log_2(B^l) \rfloor$, we show in Table 1 values of k and l for which $R_L < 2\%$. Non-pragmatic QAM formats have real and imaginary axis varying over 6, 10, 12, or 14 levels that can be decomposed as 2×3 , 2×5 , $2^2 \times 3$ and 2×7 . For instance, generating 6-level symbols is done by generating

3-level symbols {1,3,5} and multiplying each by either +1 or -1. From Table 1, blocks of 19 bits from the incoming bit stream are taken to generate 12 3-level symbols. This process of block bits to M -level symbol generation (Base conversion) is repeated continuously, and is depicted by the first box in Fig. 1. To maintain the delivered bitrate, the symbol rate should be increased by $1+R_L$, which is not problematic for $R_L < 0.02$. Afterwards, each $B=3$ level symbol is respectively linearly re-mapped to bits using a binary reflected Gray code of $C = \lceil \log_2(B) \rceil = 2$ bits ($2^C = 4$ possibilities). This new bit stream, in addition to further bits from the original stream, is subsequently FEC encoded. The parities and the further bits (12 in sum) are used as ± 1 multiplier for the 3-level symbols generating 12 '6-level' symbols. These 6 levels are taken to drive the DAC and the E/O modulator. This scheme is repeated four times, once per independent dimension of the polarization multiplexed QAM format. At the receiver, inverse blocks to those presented in Fig. 1. are applied to regenerate the binary stream from each dimension of the received non-pragmatic QAM formats.

3. Transponder

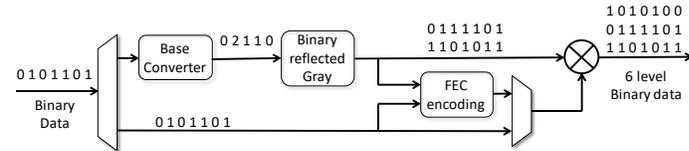


Fig. 1: Transmitter architecture of M^2QAM system.

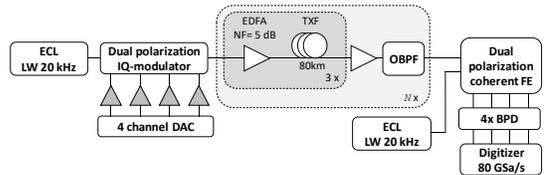


Fig. 2: Optical transmission system.

The lab transmitter consists of a 28 nm CMOS quad-channel DAC coupled to a 4-channel driver amplifier and a dual polarization IQ-modulator (cf. Fig. 2.). The 3-dB bandwidth of the driver modulator combined is ≈ 35 GHz. An external cavity laser (ECL) with ≈ 20 kHz linewidth is used as the optical carrier. The converters are operated at 80 GSa/s and their responses are entirely compensated up to Nyquist using a digital FIR filter, excluding higher orders of distortions.

At the receiver (RX) we superimpose the signal with a local oscillator (ECL) using a dual polarization 90° -hybrid followed by balanced photodiodes. The analog voltages are digitized with a 33-GHz bandwidth 80 GSa/s real time scope.

Pre-calculated random sequences with 180.000 symbols for each modulation format are loaded into the memory of the DACs and sent out repeatedly. The received sequences are stored and post-processed using offline digital signal processing (DSP). The symbol rate is varied from 32 GBaud to 64 GBaud. We target bitrates of 400 Gb/s and 600 Gb/s by adjusting the symbol rate and the SE (cf. Tab.2.). The SE limit is upper bounded mainly by the ENOB of the converters (DAC and analog to digital converter – ADC) and the OSNR of the transmission link. Lower SE, requiring larger symbol rates, are bounded mainly by the electrical bandwidth of the transponder, in particular by the real-time scope in our testbed.

For this demonstration, we employed a new terrestrial fiber (Corning® TXF™ fiber [8]) of larger effective area and chromatic dispersion, complying to the ITU-T G.654.E standard. The effective area A_{eff} is $125 \mu\text{m}^2$ and the average chromatic dispersion is ~ 21 ps/nm/km at 1550 nm. Furthermore, this fiber exhibits a lower attenuation of 0.168 dB/km at 1550 nm.

System experiments

In this experiment, the EDFAs inside the loop are spaced 80 km apart and have a noise figure (NF) of ~ 5 dB (cf. Fig. 2.). Using back-to-back (B2B) measurements, we determined the gap between mutual information and the entropy of the TX signal for all formats (cf. Tab. 2. and Fig. 3.). At 400 Gb/s, transmission up to 256QAM has been found to be feasible. The implementation penalty measured by variable OSNR B2B experiments is as low as 1.8 dB in required OSNR at the FEC threshold versus theory, while at 16QAM the implementation penalty is 0.8 dB. The difference in sensitivity (required OSNR at FEC threshold) between both formats is 9.0 dB. At an increased target bitrate of 600 Gb/s, the implementation penalties allow for modulation up to the order of 144QAM, while the highest symbol rate you can operate at is 64 GBaud due to the electrical bandwidth bounds. We first assessed the optimum launch power for the TXF fiber (cf. Fig. 4.). We observe a good matching between launch power increase and symbol rate increase. Operating at 64 GBaud allows for an increase in launch power by ~ 3 dBm compared to 32 GBaud.

To determine the maximum transmission distances, we first simulated the FEC thresholds for the different formats. We

Tab. 1: Details on base conversion.

B	k	l	Rate loss
3	12	19	1.36%
5	28	65	0.97%
7	31	87	1.96%

Tab. 2: Details of formats for 400 Gb/s and 600 Gb/s.

Mod.- format	M^2 Factor.	Capacity [bit/channel use]	Symbol rate [GBaud]	
			400 Gb/s	600 Gb/s
16QAM	4^2	6.2	64	
36QAM	$(2 \times 3)^2$	8.0	49	
64QAM	8^2	9.4	43	64
100QAM	$(2 \times 5)^2$	10.4	38.5	57.8
144QAM	$(4 \times 3)^2$	11.2	35.7	53.5
196QAM	$(2 \times 7)^2$	11.8	33.6	
256QAM	16^2	12.5	32	

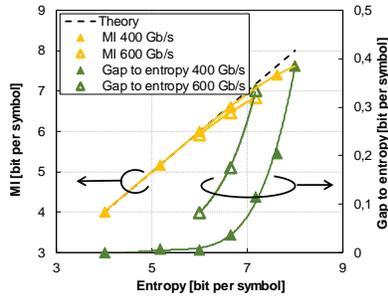


Fig. 3: Mutual information versus entropy for B2B at maximum OSNR (35 dB).

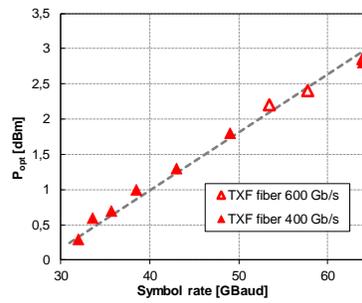


Fig. 4: Optimum launch power for TXF fiber versus symbol rate.

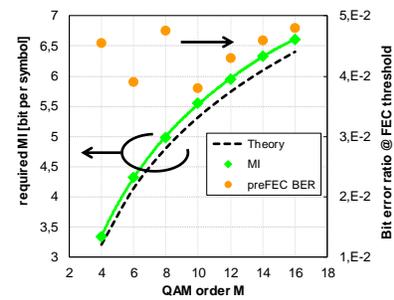


Fig. 5: Required MI and preFEC BER for successful decoding vs. QAM order M.

performed FEC decoding of simulated data using the family of spatially coupled (SC) LDPC codes with 25% overhead described and tested in [9,10]. Fig. 5. shows the required MI for successful decoding. The non-pragmatic M^2 -QAM formats show almost the same gap to theory compared to pragmatic 2^{2n} -QAM formats without any degradation.

From the required MI with an additional 5% margin, we determined the maximum transmission distances over TXF fiber for all combinations of format–SE (cf. Fig. 6.). BER-free operation has been confirmed after successful FEC decoding with zero post FEC errors. At 400 Gb/s, the proposed M^2 -QAM formats and system allows for varying the SE by as much as 6.4 bit/s/Hz and the maximum reach by a factor of 18. This factor is in good agreement with the B2B sensitivity difference of 9 dB and the additional optimum launch power difference of 3 dB. Furthermore, we demonstrate 400 Gb/s 256QAM transmission over a remarkable distance of 354 km. At 600 Gb/s the maximum reach is reduced by ~24% versus 400 Gb/s at respective SE except for the 144QAM format, where the increased implementation penalty leads to a greater degradation and shorted reach.

Conclusions

In conclusion, we proposed a variable transmission system using non-pragmatic and pragmatic M^2 -QAM constellations targeting spectral efficiency adjustments with fine granularity. M^2 -QAM formats offer good compromise between (de-)coding complexity and system tunability for high speed transponders. We demonstrated high flexibility for a wide range of SEs and demonstrated up to 256QAM transmission at 400 Gb/s over terrestrial links with transmission distances of 350 km. A record range in variability of spectral efficiency ($\Delta_{SE} > 6$ bit/s/Hz) and transmission reach (~18x) allows for adaptation from short Metro networks to long-haul distances on a terrestrial G.654.E fiber.

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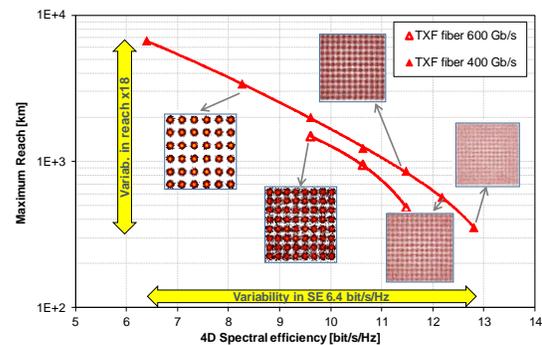


Fig. 6: Transmission reach versus 4D spectral efficiency for 400 Gb/s and 600 Gb/s formats.