Octary QAM as Capacity Extension for Coherent UDWDM PON

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Abstract *Optical 8-QAM generation for coherent PONs with a low-complexity and flexible SOA+EAM modulator is experimentally demonstrated. 8-QAM transmission for 3Gb/s per-user bandwidth over 100km and its compatibility with high split and a channel spacing of 3GHz is verified.*

Introduction

Triple-play services have become reality and services such as 3DTV-on-demand are about to inundate the web. At its cusp of evolution, mature TDM-based equipment dominates market penetration through the E/GPON standards. Further capacity extension has been demonstrated by means of hybrid WDM/TDM architectures[1] as well as higher sustainable per-user bandwidth using advanced modulation techniques such as OFDM,[2] which however do not scale well with high guaranteed data rates and high loss budgets, respectively. Next-generation optical access in form of NG-PON2 and beyond will require a disruptive approach on how the network and the subsystems thereof are perceived. A shift from electrical TDM towards optical WDM can be a promising solution: Ultra-dense WDM-PONs with coherent detection are able to provide a very high user count together with high symmetrical per-customer bandwidth through its potentially much better spectral efficiency and compatible loss budget. Recently, NSN has demonstrated real-time downstream reception of 0.3 Gb/s in a back-to-back configuration over a loss budget of 50 dB, using electrical DPSK modulation at a channel spacing of 2.8 GHz.[3] What still remains open is how to introduce higher-order optical QAM formats with low-cost off-the-shelf devices, in order to provide an upgrade path towards a higher data rate and/or customer density, e.g. for deployment as FTTB+LAN or business-FTTH. Advanced modulation formats generated by simple semiconductor modulators have been recently proposed for WDM-PONs,[4,5] however, without optimization for ultra-dense channel allocation or higher-order QAM.

In this work, we demonstrate for the first time the cost-efficient generation of optical 8-QAM with a SOA+EAM transmitter and evaluate its performance for a long reach 100 km coherent PON with ultra-dense channel spacing of 3 GHz.

Flexible QAM Generation with SOA/EAM

The multi-format QAM (upstream) transmitter is designed as SOA+EAM and provides a cost-effective, integrable and amplified solution with small form-factor. While the SOA serves as optical phase modulator, the EAM modulates the intensity of the seed light injected by a local oscillator.[5] In this way, multi-level formats can be effectively supported with the capability of adjusting on-demand the relative rotation between inner and outer constellation points, e.g. to avoid a star-QAM configuration. The SOA and EAM sections were fed with de-correlated 2^{11}-1 PRBS streams, forming the required quaternary and binary electrical driving signals with 110 mA_{pp} and 0.9 V_{pp}, respectively. A slight pre-distortion was applied to the quaternary SOA drive to cope for its nonlinear gain-current relation. The symbol rate was 1 Gbaud and limited by the 1.2 GHz modulation bandwidth of the SOA, however, high-bandwidth SOAs for 10 Gbaud modulation have been demonstrated.[6] The optical seed of the EAM was 0 dBm at 1551.2 nm and the output OSNR of the ONT

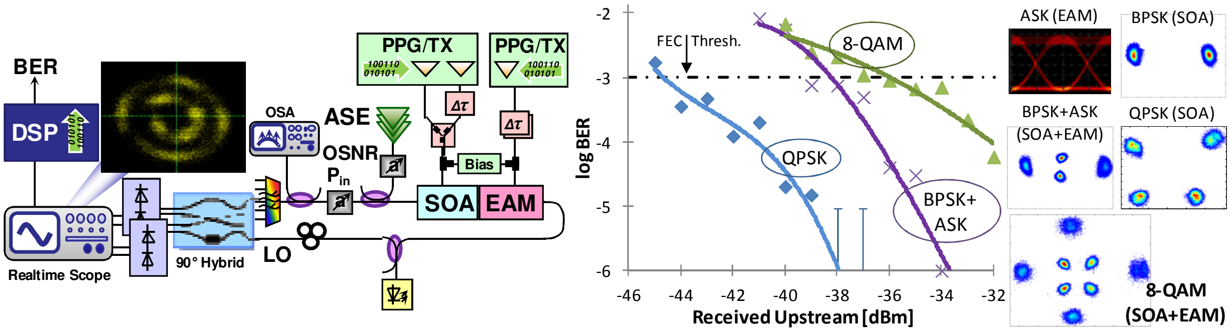

Fig. 1: Characterization of the flexible m-QAM transmitter. BER for QPSK, BPSK+ASK and 8-QAM.

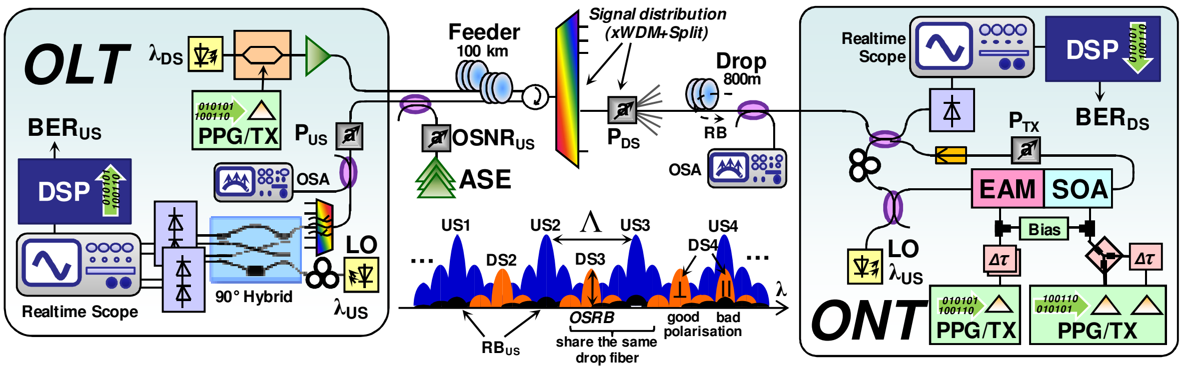

Fig. 2: Coherent PON test-bed and UDWDM allocation. The SOA+EAM transmitter is used as upstream source.

was 41 dB. A characterization of the flexible ONT transmitter for different amplitude/phase formats is presented in Fig. 1. Self-homodyne reception with a 100 kHz linewidth tunable laser, a silicon-on-insulator 90° hybrid and a balanced photo receiver array was carried out for different power and OSNR levels. The latter is of practical interest as the optical noise emission of several ONTs will accumulate and degrade the delivered upstream OSNR, especially in case of high user count per feeder/tree, such as purely splitter-based ODNs. A 100 GHz filter before the hybrid accounts for the potential WDM split towards a bank of multi-channel receivers. Demodulation was carried out using offline DSP. Format-specific carrier phase recovery schemes based on the ubiquitous Viterbi-Viterbi 4th-power method have been applied.

Though the mixed BPSK+ASK and 8-QAM formats showed penalties with respect to QPSK, the Reed-Solomon (255,223) FEC threshold can be clearly reached. Two-level ASK and BPSK transmission has been verified to perform 2.5 and 6 dB better than QPSK at low BER. The extra penalty for 8-QAM with respect to BPSK+ASK stems from the fact that the former is more sensitive to the ASK-dependent phase modulation index (i.e. achieved phase depth per electrical drive swing), which differed by ~4% between inner and outer 8-QAM rings. Multi-format reception is also verified at a degraded OSNR of 18 dB for 8-QAM, proving viability in case of simultaneous operation of multiple ONTs with an acceptable OSNR degradation of 23 dB, corresponding to a split of 1:128 per tree.

Transmission in a Coherent PON

The flexible m-QAM transmitter was embedded in a transmission test-bed (Fig. 2) to evaluate its applicability as upstream transmitter in coherent PONs. The local oscillator at the ONT receiver was split with a 50/50 coupler and reused as seed light source for the SOA+EAM based QAM modulator. The intensity modulated downstream was received by a single-ended heterodyne receiver and envelope detection with a Hilbert transform. Polarization diversity reception was not applied but could be in principle implemented by photonic integration of a PBS,[3] or by transmitting the downstream within the UDWDM channel at two different intermediate frequencies (IF) and orthogonal state of polarization,[7] as sketched in the inset of Fig. 2 (DS/US4). No extra bandwidth would be required if the worse state of polarization is overlapped with the upstream Rayleigh noise.

The passive ODN had a 100 km standard single-mode feeder fiber, a WDM demultiplexer, an attenuator emulating a power splitter in the feeder, and a 800m drop span. The combination of WDM and power split greatly reduces the PON loss budget with respect to a purely power splitting ODN. An ultra-dense channel allocation can be kept though the wavelength plan and required optical bandwidth for several sub-systems widens slightly due to the presence of stop-bands between the AWG channels. Two scenarios have been investigated, targeting 100 km reach at 640 users and 50 km reach at 1000 users. The parameters and characteristics of these PONs and the signals thereof are listed in Table 1. Although just a pair of full-duplex wavelengths (λ_{DS}, λ_{US}) has been implemented, the low -2 dBm downstream launch infers that no strong non-linearities arise at the feeder fiber. Since just one 100 km fiber stack was available, the dual feeder was replaced by a single fiber and the downstream was turned off during the upstream BER measurements to avoid crosstalk from Rayleigh noise arising at the feeder fiber.

Upstream transmission over 100 km can be achieved for both, 3 Gb/s 8-QAM and 2 Gb/s QPSK with FEC (Fig. 3). Frequency offset compensation using a novel phase-entropy algorithm had to be used after transmission,[8] as the standard phase-increment approaches failed to provide sufficient accuracy in the presence of significant constellation impairments. There is a small penalty of 1.6 dB for 8-QAM with respect to its back-to-back characterization. The upstream launch of 0 dBm leads to compatible loss budgets of 34.4 and 39.8 dB for QPSK and 8-QAM, respectively. The achieved upstream

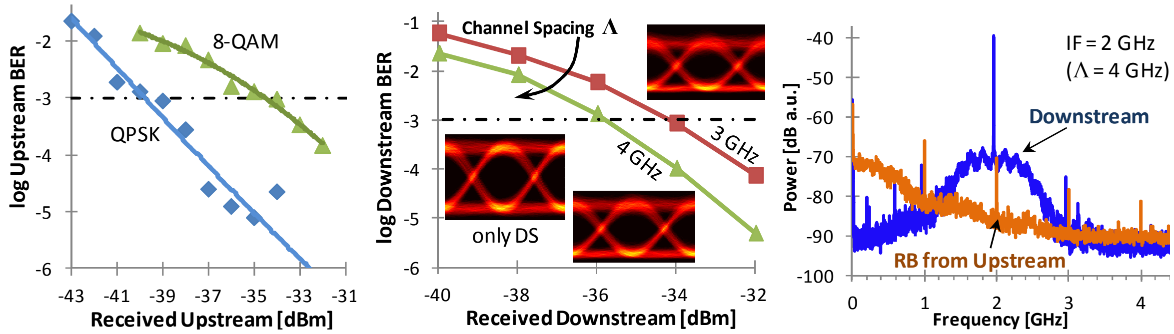

Fig. 3: BER after 100 km transmission for up- and downstream as function of Λ, and spectra at ONT receiver.

performance over 100 km confirms the feasibility of 8-QAM for both scenarios (Table 1).

A broad optical upstream spectrum could be inferred when using a (R)SOA as optical m-QAM modulator. As sketched in Fig. 2, this can be critical for the downstream (DS3) reception, where Rayleigh noise from the local upstream channel (US3) is causing a strong crosstalk at the shared drop fiber. The backscattered light of the neighboring upstream channel (US2) is negligible as it does not arise at the local drop span. At the same time a narrow UDWDM channel spacing Λ is required to keep the optical bandwidth of all sub-systems such as tunable laser or SOA+EAM below a certain value, e.g. 40 nm. The feasibility of the proposed QAM transmitter is therefore assessed in terms of compatible Λ, by experimentally measuring the downstream BER while launching the spectrally overlapped upstream with 0 dBm. Fig. 3 shows the spectra for the received downstream and the backscattered upstream, and the resulting downstream BER as function of Λ, defined as twice the detuning between down- and upstream (i.e. 2·IF for heterodyne detection). Note that a NRZ downstream at 1 Gb/s and a 8-QAM upstream at 3 Gb/s were used for this investigation, reflecting a worst case where dynamic bandwidth allocation is applied and a spectrally broad upstream penetrates a narrow and weak downstream signal.

The downstream BER confirms that a channel spacing as small as 3 GHz can be supported in case of an 800m drop span. Moreover, the obtained reception sensitivity allows loss budgets compatible with both scenarios in combination with a downstream launch of less than -2 dBm per UDWDM channel (Table 1). Carrier-suppression and single-sideband modulation for the downstream, not implemented for the sake of simplicity, can further improve the reception sensitivity and Λ. The obtained spacing is also compatible with the requirement of keeping the optical response of several components within a 40 nm bandwidth, which would translate to a maximum allowed Λ of 4 and 5.7 GHz for scenarios 1 and 2, respectively. Scaling down to a symmetrical 1 Gb/s data rate, even a sub-3GHz spacing is possible. This validates that SOA+EAMs are a viable solution for ultra-dense QAM transmission for residential-FTTH and can also provide a solution to introduce higher rate business-FTTH.

Tab. 1: Compatible loss budget for down-/upstream.

Parameter	*Scenario 1* 50km reach, 1000 user-ch.		*Scenario 2* 100km reach, 640 user-ch.	
	QPSK	**8-QAM**	**QPSK**	**8-QAM**
PON budget*	29.4 dB		33.6 dB	
Λ for 40nm BW	< 4 GHz		< 5.7 GHz	
chosen Λ	3 GHz	3 GHz	4 GHz	4 GHz
DS/US launch	-3 / 0 dBm		-2 / 0 dBm	
Deliv.US OSNR	26 dB		32 dB	
DS budget [dB]	31.1		33.8	
US budget [dB]	39.8	34.4	39.8	34.4

*ODN Scenario 1: 100 GHz AWG + 1:32 split/tree
ODN Scenario 2: 50 GHz AWG + 1:8 split/tree

Conclusions

Higher-order 8-QAM has been experimentally demonstrated in coherent PONs with 3 Gb/s per-user data rate, exploiting a low-cost SOA+EAM. Operation at a narrow 3GHz channel spacing under conditions of a high user count and extended reach was validated.

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