Record 2.29 Tb/s GS-256QAM Transmission using a Single Receiver

Benedikt Geiger(1,2), Eric Sillekens(1), Filipe Ferreira(1), Robert Killey(1), Lidia Galdino(1), Polina Bayvel(1)

(1) Optical Networks Group, Department of Electronic & Electrical Engineering,
University College London (UCL), London WC1E 7JE, UK, b.geiger@ucl.ac.uk
(2) Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany

Abstract

8 x 26 GBd DP-GS256QAM super-channel with a net data rate of 2.29 Tb/s was received after 75 km transmission using a single 211-GHz optical receiver. The use of digital pre-distortion and tailored geometric constellation shaping led to an improvement of 1.2 bit/4D-sym in the achievable information rate.

Introduction

The internet traffic has grown exponentially over recent years and this trend is expected to continue in the next decade[1]. Increasing digitalisation will lead to numerous high-data applications including self-driving cars and edge computing, with data center interconnect (DCI) links, and metropolitan and core networks being required to carry increasingly high data rates in the future.

Satisfying this growth requires high-capacity optical transmission systems, with increases in both the signal bandwidth and the SNR enabling higher order modulation formats. Most recent record experiments used a single carrier, generated in one of two ways: (i) Using a single digital-to-analogue converter (DAC)[2]–[7] achieving up to 130 GBd and 1.78 Tb/s[7], limited by its frequency roll-off or (ii) Using multiple DACs[8],[9] achieving up 176.2 GBd and 1.35 Tb/s[8], limited in SNR and, therefore, spectral efficiency due to hardware imperfections[8]. A multi-carrier architecture[10],[11], where a super-channel consisting of multiple sub-carriers is transmitted but received with a single coherent receiver, has the advantage of relaxing the transmitter frequency roll-off requirements, allowing the use of the full receiver bandwidth.

In this paper, we demonstrate the transmission of 8 x 26 GBd DP-GS-256QAM sub-carriers which are received with a single 211-GHz optical-bandwidth receiver. Due to electrical bandwidth constraints on our transmitter, a multi-carrier approach was chosen to investigate the receiver performance. The combination of digital pre-distortion (DPD) to compensate for the transmitter frequency roll-off and non-linearities, pilot-aided digital signal processing (DSP), geometric constellation shaping (GS), and forward error correction (FEC), tailored to each individual sub-carrier enabled the demonstration of a record net bitrate of 2.29 Tb/s 75 km long transmission, a 29% increase compared to the previously reported DCI transceiver record of 1.78 Tb/s[7] and a doubling of the last reported super-channel experiment[11].

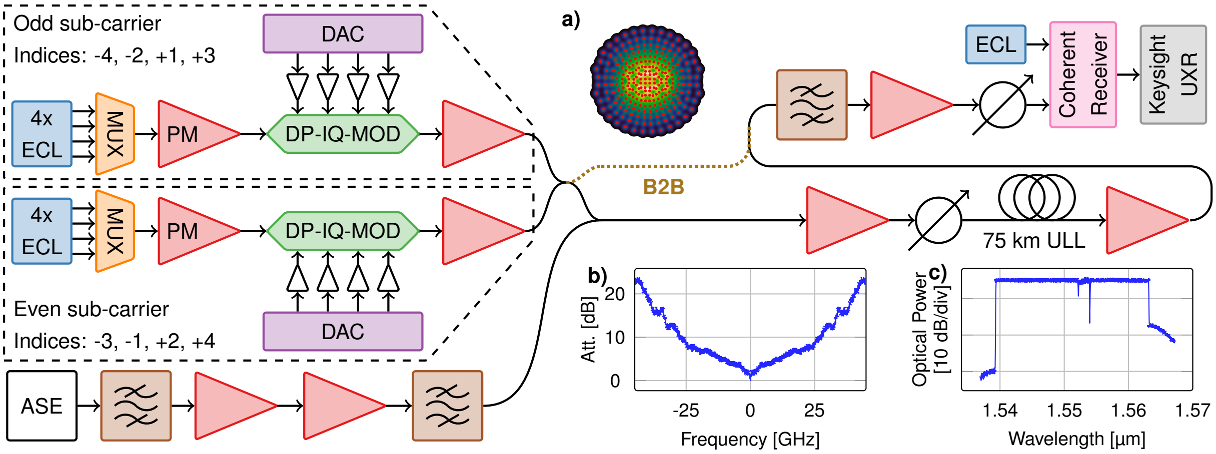

Fig. 1: Experimental setup. **(a)** GS-256QAM for an signal-to-noise ratio (SNR) of 22 dB. **(b)** Frequency dependent attenuation of the transmitter. **(c)** Spectrum of the 14 super-channel WDM signal.

Experimental Setup

The experimental setup is shown in Fig. 1. A super-channel consisting of 8 (4 x odd- and even-) sub-carriers with a spacing of 26.5 GHz was generated by free running external cavity lasers (ECL) with $<$100 kHz linewidth, multiplexed and amplified by a polarisation maintaining (PM) erbium doped fiber amplifier (EDFA). The sub-carriers were modulated with 26 GBd, RRC spectrally shaped (roll-off: 0.01) GS-256QAM by Oclaro (now Lumentum) dual-polarisation (DP) IQ modulators with a typical 3-dB bandwidth of 40 GHz. The modulators were driven by Keysight arbitrary waveform generators (AWG), with analogue bandwidth of 32 GHz, a sampling rate of 92 GSa/s, and 5 effective number of bits (ENOB). The outputs of the modulators were amplified by EDFAs and combined into a super-channel with a super-channel symbol rate of 8 x 26 GBd.

A spectrally-shaped amplified spontaneous emission (SS-ASE) noise source covering the band 1539 nm to 1563 nm was used to emulate C-band interfering channels[12]. The minimum and maximum wavelengths were limited by the EDFA bandwidth. A notch was carved into the SS-ASE, where the super-channel-under-test was placed, with its power controlled to ensure it had same spectral density as the SS-ASE noise (Fig. 1c).

Both back-to-back (B2B) operation as well as transmission over fibre were investigated. The 75 km link used the Corning® SMF-28® ULL optical fibre, with a total attenuation of 12.2 dB including splicing and connection losses.

At the receiver, a waveshaper was used to filter out the super-channel, which was then amplified by an EDFA and attenuated by a variable optical attenuator (VOA) to reduce signal-signal beating. A $>$100-GHz coherent receiver was used to convert the optical signal into the electrical domain. Finally, the signal was digitised using a 100-GHz Keysight UXR oscilloscope with a sampling rate of 256 GSa/s and ENOB value of 5.

To increase the achievable information rate (AIR), a pilot-aided DSP chain following[13] was used. The pilot sequence length 2^{10} and pilot insertion rate 2^6 maximising the AIR were found in a parameter sweep, leading to a pilot-overhead of 3.1%. The AIR was assessed assuming ideal FEC, i.e., we calculated the generalised mutual information (GMI)[14] and subtracted the overhead associated with the pilot symbols. The net bitrate was determined by FEC decoding the data using the family of DVB-S2 low density parity check (LDPC) codes to obtain a bit error rate (BER) below 1e-5 and assuming the use of an outer BCH (30832,30592) code to obtain a BER below 1e-15[10].

Experimental Results

The overarching goal of this work was to understand the throughput limitations of a single receiver. We investigated the impact of the number of 26 GBd sub-carriers and the resultant super-channel bandwidth on the SNR, since the throughput is mainly limited by the receiver performance in a multi-carrier, super-channel architecture. For this experiment, the setup was in optical B2B and the carriers were modulated with 1024-QAM. Table 1 shows the measured SNR of positive centre sub-carrier (+1) as a function of the number of sub-carriers, with a maximum SNR of 30.1 dB, achieved for only one carrier. In fact, this is close to the fundamental quantisation noise limit of the AWG and oscilloscope with an ENOB of 5. We observed that the SNR decreased by approximately 3 dB with each doubling of the number of carriers. Since the EDFA at the receiver is operated in saturation, the optical signal power into the coherent receiver and, therefore, the electrical signal power into the UXR are independent of the number of sub-carriers. Since the quantisation noise is constant but the electrical signal power per carrier is halved every time the number of carriers is doubled, a SNR degradation of 3 dB can be observed. Note that if optical signal power into the coherent front-end was higher, the SNR would decrease due to stronger signal-signal beating.

The AIR improvement achieved using DPD and GS were quantified in the B2B case, since both methods showed an significant data rate increase in[4],[7],[13]. Firstly, we mitigated the transmitter impairments using a DPD method consisting of a linear filter, to obtain a flat spectrum at the output of the transmitter, in combination with an arcsine with a parameter sweep optimised clipping voltage to compensate for transceiver nonlinearities such as the IQ-modulator transfer function[15]. The frequency roll-off of the transmitter

Tab. 1: SNR of sub-carrier no. +1 as a function of the number of sub-carriers and resultant super-channel bandwidth.

# carrier	**BW** [GHz]	**SNR** [dB]
1	26.5	30.1
2	53	26.9
4	106	24.3
8	212	21.2

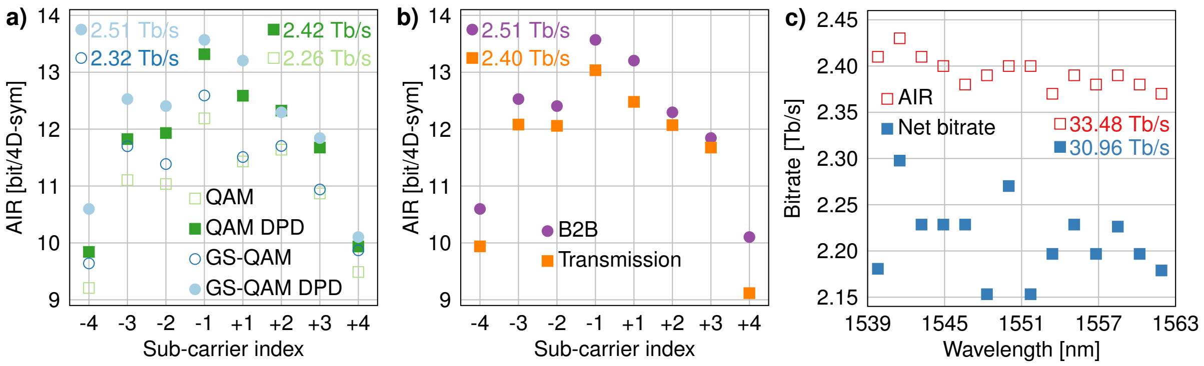

Fig. 2: Experimental results: (a) AIR improvement due to DPD and GS. Filled and unfilled markers refer to with and w/o DPD, respectively. Dots and squares refer to GS-QAM and QAM, respectively. (b) AIR in B2B case and after 75km transmission. (c) Wavelength dependence across the entire C-band. The data points give the wavelength of the LO.

can be seen in Fig 1b. Secondly, a geometrically shaped constellation format was designed, aimed to close the shaping gap to the additive white Gaussian noise (AWGN) capacity and increase the AIR. A gradient descent algorithm was used to find the constellation coordinates (Fig. 1a) which maximised the GMI for a 256-ary constellation, tailored to the AWGN channel with the highest observed SNR[16],[17]. This was 22 dB for the centre sub-carriers. Fig. 2a shows the B2B AIR vs. sub-carrier index with and without DPD and GS. We expected the sub-carriers with the same index, e.g. +1 and -1 to have the same performance but it was noted that the performance strongly depended on whether the carrier was suppressed by the bias controller or not. Overall, DPD and GS enabled a B2B AIR of 2.51 Tb/s, where the DPD contributed 180 Gb/s (0.87 bit/4D-sym) and the GS 70 Gb/s (0.33 bit/4D-sym), on average.

Next, we investigated how transmission over a 75 km SMF link impacted the AIR. We emulated the transmission of 14 super-channels within a bandwidth of 2.97 THz using SS-ASE noise loading. Fig. 1c shows the spectrum of the WDM signal. The launch power of 14 dBm (corresponding to 2.5 dBm and -6.5 dBm per super-channel and per sub-carrier, respectively) maximising the AIR was determined by sweeping the launch power. Fig. 2b compares the AIR between B2B operation and transmission over 75 km SMF. Only a small degradation was observed, compared to the B2B case, because the performance is largely limited by the transceiver SNR rather then the optical signal-to-noise ratio (OSNR), i.e. optical power, for DCI distances[18]. This differs from[11] where a comb was used and the setup was OSNR limited, highlighting the advantage of free-running ECL.

In a final experiment, we swept the position of the super-channel over the C-band and FEC decoded the data to determine the wavelength dependence of the AIR and net bitrate across the entire C-band. Fig. 2c shows both quantities for the 14 super-channels after a 75 km long transmission, where the best super-channel achieved a net bitrate of 2.29 Tb/s. We observed that the AIR bit rate decreased slightly with wavelength, due to the gain tilt in the amplifier in the noise loading stage, leading to 33.5 Tb/s AIR and 30.96 Tb/s net bitrate over the C-band, respectively. The high variance in the net bitrate results from different coding gaps per sub-carrier caused by AIR fluctuations of the sub-carriers and the limited number of DVB-S2 code rates.

Conclusion

We investigated the limits on the data rate of next generation high-speed ultra-wideband transceivers. A world record experimental B2B AIR of 2.51 Tb/s for a single receiver was enabled by the combination of a wideband 211-GHz optical-bandwidth receiver, pilot-based DSP, a multi-carrier approach, DPD, and GS. Additionally, we achieved a world record net bit rate of 2.29 Tb/s after transmission over a 75 km ultra-low-loss fibre, using a single receiver, which represents an increase of 510 Gb/s (29%) compared to the previous DCI transceiver record[7] and a doubling of the previous record multi-carrier experiment[11].

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