Optical Fibre Capacity Optimisation via Continuous Bandwidth Amplification and Geometric Shaping

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***Abstract*—The maximum data throughput in a single mode optical fibre is a function of both the signal bandwidth and the wavelength-dependent signal-to-noise ratio (SNR). In this paper, we investigate the use of hybrid discrete Raman & rare-earth doped fibre amplifiers to enable wide-band signal gain, without spectral gaps between amplification bands. We describe the widest continuous coherent transmission bandwidth experimentally demonstrated to date of 16.83 THz, achieved by simultaneously using the S-, C- and L-bands. The variation of fibre parameters over this bandwidth, together with the hybrid amplification method result in a significant SNR wavelength-dependence. To cope with this, the signal was optimised for each SNR, wavelength and transmission band. By using a system-tailored set of geometrically shaped constellations, we demonstrate the transmission of 660×25 GBd channels over 40 km, resulting in a record single mode fibre net throughput of 178.08 Tbit/s.**

***Index Terms*—Broadband transmission system, high order modulation format, geometric shaping.**

I. Introduction

SEVERAL milestones in the achievable data throughput in single mode optical fibres (SMF) [1]–[10] have been reported over the past few years. Fig. 1 shows these record results demonstrated using a range of different amplification techniques. These include distributed Raman amplification, erbium doped fibre amplifiers (EDFA), semiconductor optical amplifiers (SOA), and combinations thereof. Aside from [7], where a capacity of 74 Tbit/s over 6300 km was achieved using a hybrid distributed Raman/EDFA (HRE) amplification scheme, all trans-Atlantic (> 6000 km) and trans-Pacific (> 9000 km) record data rates to date have been reached by using C+L band EDFAs [10]. Despite HRE schemes having a lower noise figure compared with EDFAs, this amplification technology is not as power efficient as EDFA systems, which makes it less attractive for long-haul submarine systems that are electrical power feed constrained. In these long-distance transmission systems, advanced coded modulation schemes and nonlinearity compensation algorithms were used to increase both the throughput and reach. In contrast, record capacities over short transmission distances have mainly used amplification technologies that extend beyond C+L-band EDFAs. In [2], an SOA with a 100 nm gain bandwidth demonstrated the potential for an SMF capacity of 115.9 Tbit/s over a 100 km transmission distance. The relatively high noise figure of SOAs versus, for example, EDFAs means they are generally considered unsuitable for repeatered transmission systems. Nevertheless, by combining an SOA with distributed backward Raman amplification, 107 Tbit/s transmission over 300 km (3×100 km) was reported in [4]. A yet greater data rate of 120 Tbit/s over 630 km (9×70 km) was shown by using hybrid distributed Raman-EDFA amplifiers with a continuous 91 nm gain bandwidth [5].

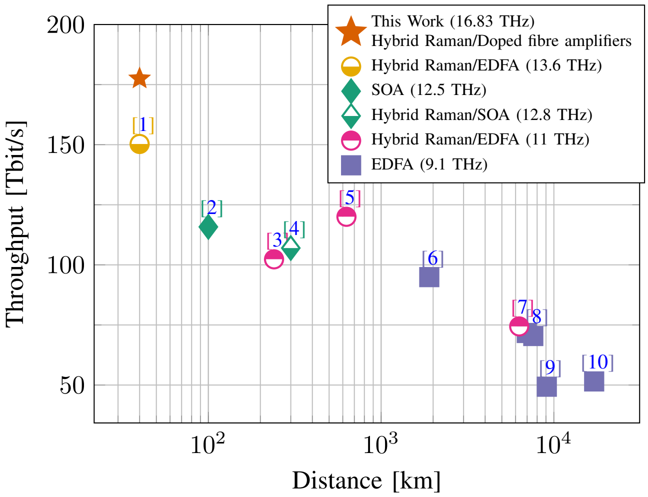

Fig. 1. Record data throughput versus distance for single mode fibre. The transmission bandwidth indicated in each case is for the usable spectrum, not including spectral gaps between amplifier gain bandwidths.

Extending the transmission bandwidth to S-band wavelengths resulted in the highest single mode fibre capacity experimentally shown to date of 150.3 Tbit/s, transmitted over 40 km [1] This experiment [1] used a distributed backward Raman amplification scheme for the S-band and EDFAs for C- and L-bands; with the transmitted signal occupying a total bandwidth of approximately 109 nm (13.625 THz). However, the gain bandwidth was not continuous, with approximately 17 and 5 nm spectral gaps between S/C- and C/L-bands, respectively. This reduces the spectral efficiency and diminishes the benefit of transmitting signals in multiple fibre transmission

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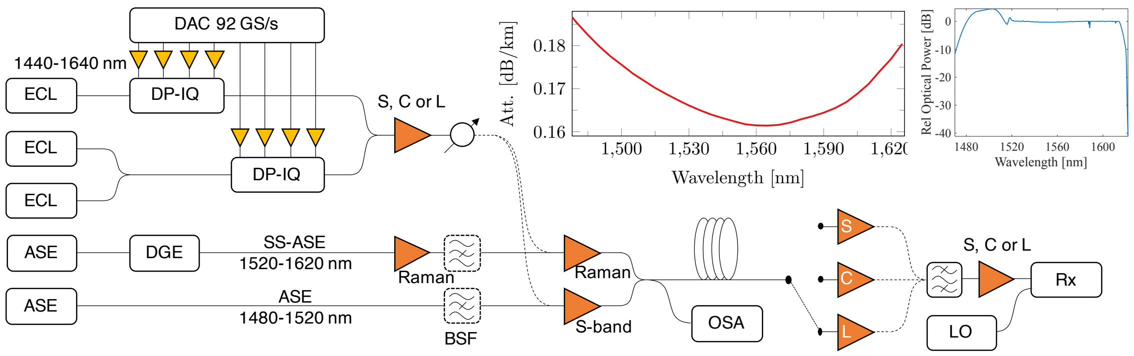

Fig. 2. Schematic of the transmission experiment. Inset: optical fibre attenuation profile and signal spectrum before launching into the optical fibre (the modulated channels are centered at 1588 nm). Key: Dynamic Gain Equaliser (DGE), Spectrally Shaped Amplified Spontaneous Emission Noise (SS-ASE), Bandstop Filter (BSF).

windows.

In this paper, we describe the use of a combination of discrete Raman amplifiers with a continuous gain bandwidth of 1520.00–1619.67 nm, together with a thulium doped fibre amplifier (TDFA), 1484.86–1520.00 nm gain bandwidth, to demonstrate the widest continuous coherent transmission bandwidth of 16.83 THz reported to date in a single fibre core. The use of the combination of amplifier technologies led to a wavelength-dependent SNR variation. To increase the overall data throughput, we therefore designed and implemented new, geometrically-shaped (GS) constellations, tailored for the SNR of each wavelength, maximising the achievable information rate (AIR) of each individual channel. Pilot-based digital signal processing was used, and the AIR was estimated by deducting the pilot overhead (OH) from the per channel generalised mutual information (GMI), assuming an additive white Gaussian noise (AWGN) auxiliary channel [11, Eq. (53)]. The overall net throughput of 178.08 Tbit/s reported represents a record data rate for single core, single mode optical fibre transmission.

II. Experimental transmission set up

The experimental configuration is shown in Fig. 2. Three tuneable external cavity lasers (ECL), spaced by 25.5 GHz, were connected to two independent dual-polarisation IQ optical modulators, each driven by 92 GS/s digital-to-analogue converters (DAC) to generate three odd/even channels. A digital root-raised cosine (RRC) filter (0.01 roll-off) was used to spectrally shape the signals. The channels were generated at carrier frequencies which were tuned across the range 1484.86–1619.67 nm, allowing the measurement of 660$\times$25 GBd dual-polarisation signals. The modulated channels were amplified using TDFA, C/L band EDFA and/or discrete Raman amplifiers, as appropriate for the wavelength of the channel under test. The three channels were combined with wideband amplified spontaneous emission (ASE) noise, which emulated co-propagating channels, followed by a band stop filter (BSF) for creating a spectral gap at the location where the modulated channels were inserted. The validity of using ASE noise to emulate aggressor channels was verified in [12], showing that this technique provides a conservative measure of system performance.The modulated channel power was adjusted to be the same as the surrounding ASE. The ASE noise, generated by a pair of discrete Raman amplifiers to achieve a total output power of 21.5 dBm over the entire bandwidth (from 1520.00–1619.67 nm), was coupled with ASE noise generated by TDFAs with a noise bandwidth of 40 nm (from 1470–1520.00 nm) and a total output power of 19 dBm. Note that due to a sharp decrease on the responsivity of the balanced photo-detectors at lower wavelengths the lowest wavelength received was 1484.86 nm.

A dynamic gain equaliser (DGE) with a continuous 100 nm bandwidth was used to spectrally shape the ASE noise generated by the discrete Raman amplifiers with wavelength bandwidth between 1520 and 1620 nm. The S-band ASE noise was not shaped as a gain equaliser for this wavelength range was not available for the experiment; however, an S/C band WDM splitter was placed after the S-band ASE noise source, producing a sharp roll-off of the ASE at approximately 1520.00 nm. The combined ASE noise and modulated channels occupied a total usable bandwidth of 16.83 THz (134.81 nm) with a total output power of 20.4 dBm.

A 40 km Corning® SMF - 28® ULL fibre span with 0.16 dB/km attenuation at C-band, and an additional 0.4 dB loss on the fibre output due to splicing and connectorisation, was used as the transmission span. Its fibre attenuation vs wavelength is shown inset Fig. 2. A TDFA, EDFA or discrete Raman amplifier was used to compensate the fibre loss, depending on the spectral range. A TDFA with 7 dB NF was used for wavelength channels between 1484.86 - 1519.8 nm. For channels spaced in the 1520 - 1529 nm and 1608 - 1619.67 nm ranges a discrete Raman amplifier with average noise figure of 9 dB was used. C and L-band EDFAs with 5.5 and 6 dB NF, respectively, were used to amplify the remaining bandwidth of 1529.2 - 1607.8 nm. At the receiver side, the signal was filtered by using an optical band pass filter (BPF) and amplified before being sent to the coherent receiver. Due to the limited number of TDFAs available, two cascaded SOAs were used to boost the S-band signal power to the receiver. The optical coherent receiver was composed of a polarisation and phase diverse optical hybrid and four balanced photodiodes with a bandwidth of 65 GHz. A digital-storage oscilloscope (DSO) with a bandwidth of 110 GHz digitised the received 25 GBd signal at a sampling rate of 256 GS/s.

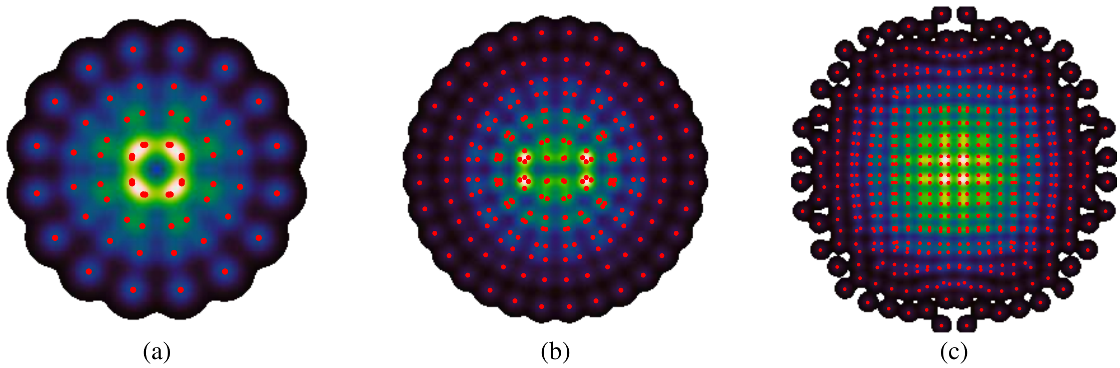

Fig. 3. Constellation diagrams of: GS-64QAM for an SNR of 12 dB (a), GS-256QAM for an SNR of 16 dB (b), and GS-1024QAM for an SNR of 20 dB (c). The pink markers illustrate the generated constellation diagram. Constellation coordinates and bit-to-symbol mappings are available for download at [15].

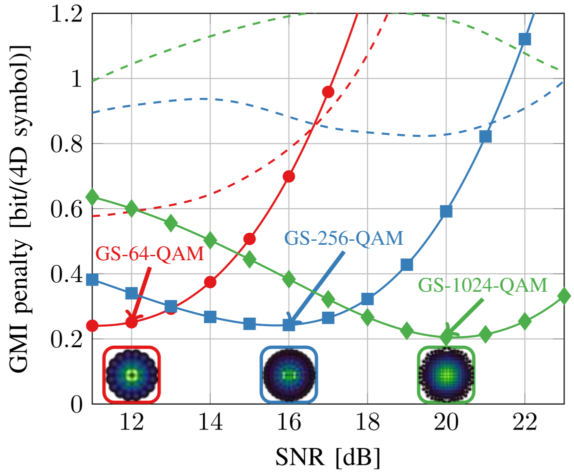

Fig. 4. Gap to AWGN capacity for each modulation format. The target SNRs for which each of the constellations were optimised are indicated by the arrows. Dashed lines show the gap to capacity for square QAM constellations. Constellation coordinates and bit-to-symbol mappings are available at [15].

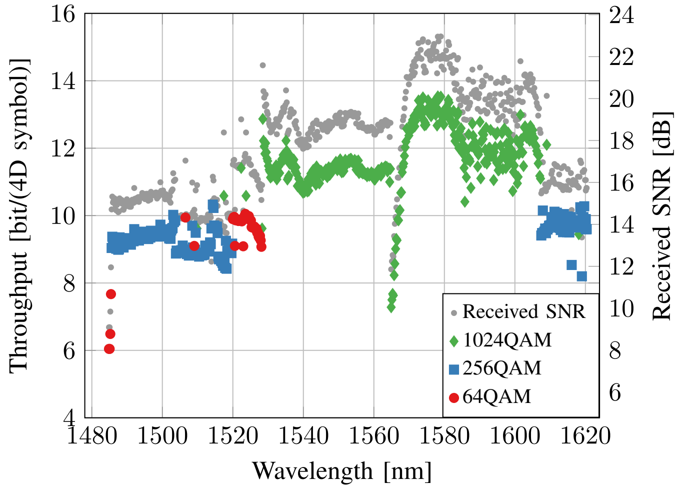

Fig. 5. Per-channel throughput over 2 polarisations after 40 km.

Pilot-based digital signal processing was implemented as described in [13], with QPSK pilot symbols embedded within the data payload instead of using a separate optical pilot tone. This facilitates equalisation and carrier recovery for high-order and/or non-uniform constellations in a standard intradyne configuration, and was key to recovering the information for any designed GS constellation without incurring any SNR penalty. Mersenne twister random integer sequence with 2^{16} length was used for the payload and pilot symbols. The required pilot overhead (OH) was optimised to maximise the overall AIR [13]. Pilot symbols for carrier phase estimation were inserted at a rate of 1/32. The pilot sequence length and the frame length were fixed at 1024 symbols and 65536 symbols, respectively, thus requiring a pilot OH of 4.64%.

III. Geometric Constellation Shaping

The GS formats were designed by using a gradient descent algorithm with a cost function seeking to maximise GMI at the given received SNR (assuming a linear AWGN channel), as per [14]. For the transmission system under test, the received signal SNR varied between 12 dB and 20 dB over the bandwidth due to the combination of the variation of fibre parameters over this wavelength range and the amplifier noise figures and gain profiles. Thus, to maximise the AIR of each channel, GS modulation formats of 64, 256 and 1024 constellation points were designed for a received SNR between 12 and 23 dB. Fig. 3 shows the designed GS-64QAM, GS-256QAM and GS-1024QAM constellations for a received SNR of 12, 16 and 20 dB, respectively. (Here, GS-MQAM is taken to mean *M-ary* constellations, of equal probability, shaped in two dimensions.) The pink markers display the generated constellation diagram. The coordinates of each constellation are available at [15].

Fig. 4 illustrates the AIR gap for each optimised GS constellation to AWGN capacity for received SNR of 12, 16 and 20 dB. The dashed lines show the AIR gap to AWGN capacity for square 64QAM (red), 256QAM (blue) and 1024QAM (green). The red circles show the optimised GS-64QAM constellation for 12 dB SNR, while the blue square and green triangle markers illustrate the optimised GS-256QAM and GS-1024QAM constellations for 16 and 20 dB SNR, respectively.

It can be seen that, through the combination of different GS-MQAM optimisations, the GMI gap to AWGN capacity can be maintained below 0.3 bit/(4D symbol) for the target

SNRs. For SNRs below 13 dB, the optimised GS-64QAM has a lower GMI penalty in comparison to the higher-order carnality GS constellations. Similarly, for SNRs between 13 and 17.8 dB, GS-256QAM is needed to maintain the GMI gap below 0.3 bit/(4D symbol). For an SNR greater than 17.8 dB, GS-1024QAM should be used. Finally, we also note that the GS constellations exhibit an improvement in GMI compared to the square QAM formats. For instance, the GMI improvement of GS-64QAM compared to 64QAM at 12 dB SNR is 0.34 bit/4D-symbol, while the GMI improvement of GS-256QAM at 16 dB and GS-1024QAM at 20 dB are 0.64 bit/4D-symbol and 0.98 bit/4D-symbol, respectively.

Note that the square 256QAM constellation has a mean GMI gap of 0.9 bit/4D symbol across the range of SNRs considered here. This gap is 0.6 bit/4D symbol higher than the designed GS-MQAM constellation. Therefore, with the use of geometric constellation shaping in this experiment, the data throughput was estimated to be 9.5 Tbit/s higher than would be possible with square 256QAM.

We have also designed GS constellations for all SNR values (in 1 dB steps). We observed that the GMI gap would have been maintained below 0.2 bit/4D symbol for all wavelength channels, compared with a GMI gap below 0.3 bit/4D symbol for 3 optimised constellations. If designed GS constellations for each SNR value were used, only a marginal gain of 1.5 Tbit/s would have been observed.

IV. Performance Analysis

The information rate and SNR are shown in Fig. 5 for all the 660×25 GBd channels received after the 40 km transmission. The per channel throughput, in bit/symbol over both polarisations, was calculated by multiplying the mean AIR, over both polarisations, by the channel symbol rate. As previously noted, the GS modulation formats were tailored to maximise AIR for each value of the received SNR. The mean received SNR was 20.36 dB, with the measured values in the range 9.6–23.0 dB over the entire transmission bandwidth. 99% of channels had SNRs greater than 13 dB. As can be seen in Fig. 5, the lower AIRs (and, thus, SNRs) were in the S-band, due to the lack of a DGE and the use of cascaded SOAs to pre-amplify the received signal. For these channels, optimum performance was generally achieved using 64-*ary* or GS 256-*ary* GS, with an average AIR of 10.79 bit/symbol.

In the C- and L-bands, 1024-*ary* GS constellations were mainly used. Note that, although there was some SNR degradation between the C- and L-bands, 1024-*ary* GS was used for continuity of measurement. It can also be noted that, for channel wavelengths between 1520 and 1529 nm, GS-64QAM was used, despite the fact GS-256QAM provides higher AIR. At these wavelengths, the discrete Raman amplifier used introduced nonlinear distortion to the signal, degrading the received SNR by approximately 7dB compared to the data shown in Fig. 5. After offline DSP processing, which included a nonlinear phase-shift compensation, the nonlinear distortion generated by the DRA was mitigated, improving the received SNR. Therefore, if GS-256QAM had been used, higher throughput could potentially have been achieved for these wavelengths.

Judicious selection of modulation format is key in this experiment. As shown in Fig. 4, using a single GS modulation format would have substantially decreased the throughput, due to an increased gap to capacity at either lower or higher SNRs than the target SNR for GS constellations. Combining the measured per-channel GMI, and deducting the pilot overhead, the achievable information rate for this transmission system is an aggregate throughput of 178.08 Tbit/s.

V. Conclusions

In this work, a record transmission throughput for a single core, single mode optical fibre was demonstrated, using a continuous, ultra-wideband (16.83 THz) transmission window. The latter was enabled using hybrid discrete Raman/doped fibre amplification, which, together with the pilot-based DSP, allowed the use of SNR-tailored geometric constellation shaping. The geometric shaping accounted for approximately 9.5 Tbit/s increase with the overall throughput of 178.08 Tbit/s, over 18% higher than the previous record of 150.3 Tbit/s [1].

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