Breaking the Transmission Barriers in Ultra-broadband High-capacity Optical Fiber Transmission Systems

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Abstract: The limitations and practicalities in design of ultra-high-capacity optical transmission systems with transmission bandwidth beyond C+L EDFA are described, together with a deep theoretical understanding of each noise source contribution limiting the overall data throughput.

1. Introduction

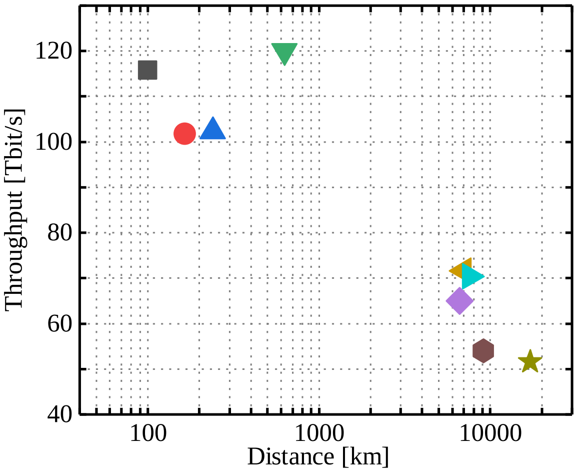

Fig. 1. Records data throughput versus distance.

Recent years have seen several landmark transmission results using single mode fibre (SMF) [1] [2] [3] [4] [5] [6] [7] [8]. Advanced methods and concepts employed in the forefront spectrally efficient coherent optical fiber transmission systems, such as probabilistic and geometrical shaping, adaptive digital nonlinear compensation and per channel adaptive code rated combined with advanced high speed electronics, large-effective area / low-loss transmission fibers, and broadband hybrid distributed Raman-EDFA amplifier, have resulted in experimental SMF capacity increases as highlighted in Fig.1. The trans-Atlantic and trans-Pacific record data throughput to date is 70.46 Tbit/s over 7,600 km [1] and 51.5 Tbit/s over 17,107 km [2]. Theses records have been empowered by the combination of coded modulation with hybrid probabilistic and geometrical constellation shaping with multi-stage nonlinearity compensation including digital back-propagation, fast LMS equalizer and generalized filter, together with a per channel adaptive-rate decoding. Despite the advantages of using low noise hybrid distributed Raman-EDFA amplifier (HRE) as demonstrated in [3] most of theses records throughput in trans-Atlantic and trans-Pacific distance was achieved by using C+L band EDFA. On the other hand, the records throughout in short, metropolitan transmission distance have been achieved mainly by using amplification techniques that goes beyond C+L band EDFAs. In [4], a continuous-band 100 nm semiconductor optical amplifier (SOA) enabled a potential SMF capacity of 115.9 Tbit/s over 100 km. Although the bandwidth is notable, SOAs have a relatively high noise figure compared with distributed Raman amplifiers, so the system performance decreases rapidly with distance. High data throughput in [5] [6] and [7] was achieved by using continuous 90 nm hybrid distributed Raman-EDFA amplifier, with the world record SMF data throughput of 120 Tbit/s over 630 km demonstrated in [7].

Recently, it was demonstrated that transceiver constrained-SNR imposes a significant reduction in throughput for medium transmission links [9]. In this paper we further investigate the impact of transceiver constrained-SNR, limiting the overall transmission system performance. In particularly, the reduction in received SNR due to transceiver noise contribution is studied from short to trans-Atlantic distance.

2. Transmission System Design

Fundamental limits of an optical communication system are imposed by a combination of noise from the transceiver subsystem, optical amplifier and optical fibre nonlinearity. An upper bound on the achievable SNR in coherent optical communication systems is set by the noise introduced by the transceiver subsystems [10]. Significant sources of transceiver noise include quantisation noise due to the finite resolution of digital-to-analog converters (DAC) and analog-to-digital converters (ADC) as well as noise from the linear electrical amplifiers. During transmission, the achievable SNR is further limited by amplified spontaneous emission noise (ASE) from optical amplifiers in the transmission line and by nonlinear signal distortion, inherent to transmission through silica optical fibres. Therefore, to investigate the individual noise source contribution of each transmitted channel, and the overall system performance, a basic SNR model is used. After coherent detection and electronic dispersion compensation, the received signal-to-noise ratio can be calculated as $\mathrm{SNR}_{\mathrm{Total}} = \frac{P}{\kappa P + NP_{\mathrm{ASE}} + NP_{\mathrm{NLI}}}$, with $\kappa = 1/\mathrm{SNR}_{\mathrm{TRX}}$, were $\mathrm{SNR}_{\mathrm{TRX}}$ is the maximum SNR that can be achieved in a given transceiver subsystem, and it can be measured in a back-to-back configuration, N is the number of spans, P_{ASE} is the accumulated ASE noise power and P_{NLI} is the nonlinear noise power. The transmission system considered in work is an 312x35 GBd dual polarization 256-*ary* quadrature amplitude modulation (DP-256QAM). The transmission link is comprise by spans with 70 km of SMF and hybrid distributed Raman-EDFA amplifier (HRE). Detailed experimental setup description of this system under investigation can be found in [7]. The theoretical calculation of P_{ASE} and P_{NLi} was performed using the inter-channel stimulated Raman scattering (ISRS) GN-model [11] and the accuracy of this system modeling compared to the experimental measurements is shown in [12].

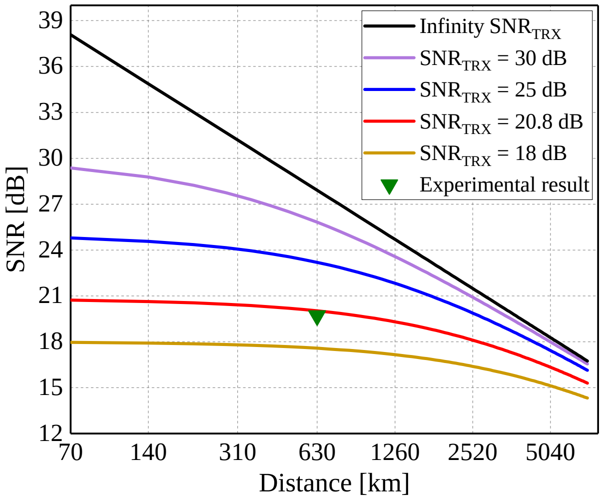

Fig. 2. Received SNR versus distance for different transceiver constrained-SNR.

The plot in Fig. 2 shows the impact of different transceiver-constrained performance ($\mathrm{SNR}_{\mathrm{TRX}}$) on the received $\mathrm{SNR}_{\mathrm{Total}}$ over different transmission distances. The green marker is the mean SNR of the 312 channels measured experimentally after 630 km (full set of results can be found in [7]). This particular experimental system, with a transceiver $\mathrm{SNR}_{\mathrm{TRX}}$ of 20.8 dB has been well modeled with an offset of the model prediction of only 0.4 dB, with a mean $\mathrm{SNR}_{\mathrm{Total}}$ of 19.3 dB experimentally measured. The black line illustrates the model prediction of the receiver $\mathrm{SNR}_{\mathrm{Total}}$ when the transceiver subsystem is ideal ($\mathrm{SNR}_{\mathrm{TRX}} = \infty$). The model predicts that for an ideal transceiver subsystem, the received $\mathrm{SNR}_{\mathrm{Total}}$ after 630 km would be 27.9 dB; 8.6 dB higher compared to the system with a $\mathrm{SNR}_{\mathrm{TRX}}$ of 20.8 dB. Similar gains in transmission distance can also be observed. For instance, for an ideal transceiver, the model predicts a received $\mathrm{SNR}_{\mathrm{Total}}$ of 19.3 dB after transmission distance of 3430 km; more than 5-fold increase in distance compared with the system under investigation, that exhibit a $\mathrm{SNR}_{\mathrm{TRX}}$ of 20.8 dB.

As expected, as the transmission distance increases the impact of transceiver limited SNR becomes less significant and the system performance becomes dominated by the nonlinear distortion. High quality signal generation and reception are crucial to improve signal quality and maximize data throughput in medium- and long-haul transmission links.

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