49.2-Tbit/s WDM Transmission Over 2x93-km Field-Deployed Fiber

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Abstract: We present 40 channel WDM transmission experiments over one and two spans of 93-km field-deployed SSMF achieving net capacities of 51.5-Tbit/s and 49.2-Tbit/s for PCS-256-QAM with 7.5 bits entropy and 45.9-Tbit/s and 45.1-Tbit/s for 64-QAM transmission, respectively.
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1. Introduction

The demand for higher data rates in near future will be driven by the 5G rollout incorporating massive MIMO antenna arrays and video streaming, which already amounts most of the overall internet traffic today, or even a combination of both. Both will require moving datacenters towards the edge cloud as the user experience highly depends on providing low latency. The content distribution between these datacenters in quasi real-time requires high throughput over optical fibers for the data center interconnects with typical distances of ~80-100 km.
This leads to a paradigm change for the optical transmission, because the OSNR reduction due to fiber transmission is no longer the limiting factor for these short distances. On the other hand, high transmission capacities and high usage of the available spectral bandwidth is mandatory. This trend can be seen in recently reported results of ultra-wideband transmission experiments [1,2]. In [1] 150-Tbit/s was demonstrated over 272 WDM channels in S-, C- and L-band. In [2] ultra-wideband SOAs enabled a useable transmission bandwidth of 100 nm supporting a transmission capacity of 115-Tbit/s in 250 WDM channels. Using only the C-band, the highest reported transmission demonstration was 41-Tbit/s applying 96 GBd in a 100 GHz WDM grid [3]. It was achieved based on ultra-densely spaced WDM with a very high bandwidth utilization of up to 98% for obtaining spectral efficiencies of more than 10 bits/s/Hz. In transmission experiments over field deployed fiber the highest capacities were 38.4-Tbit/s [4] and 41.5-Tbit/s [5], both with more than 90% bandwidth utilization. However, such high bandwidth utilizations neglect drifts of the laser's center frequency, which can be ± 2 GHz over lifetime, or deviations of the center frequency of filters and filtering penalties for multiplexing and demultiplexing.
We recently reported in [6] a new WDM transmission record of 50.8-Tbit/s in the C-band over field-deployed fiber with 11.29 bits/s/Hz spectral efficiency for 100 GBd PCS-256-QAM with 7.7 bits entropy. The approach is based on 100 GBd channels in a 112.5 GHz WDM grid with bandwidth utilization of 89%, but given the high symbol rate, the tolerances against the above-mentioned effects are highly increased and the number of WDM channels is only 40.
In this paper we present further WDM transmission results of this field trial for 100 GBd PCS-256-QAM with 7.5 bits entropy and regular 64-QAM over one and two spans of 93-km field deployed SSMF. Improvements in the timing alignment of the experimental setup enabled WDM capacities of 49.2-Tbit/s at 10.94 bits/s/Hz spectral efficiency for PCS-256-QAM and 45.1-Tbit/s at 10 bits/s/Hz spectral efficiency for 64-QAM transmission over 2x93-km SSMF, respectively.

2. Experimental Setup

A schematic of the setup for this experiment is shown in Fig. 1. The 100 GBd data signal for the channel under test (CUT) is generated by a 2-channel SiGe DAC sampling at 100 GSa/s, amplified and applied to a single-polarization $LiNbO_3$ IQ-modulator fed by a CW light from a tunable external cavity laser (ECL). Polarization multiplexing is emulated by delaying half of the signal by 54-ns before recombining on orthogonal polarizations. The transmitter DSP consists of a linear digital pre-emphasis filter compensating for the combined frequency responses of the DAC and driver amplifier for each channel. The loading channels are generated by a 120-GSa/s CMOS DAC, which is configured to deliver a 100-GBaud QAM signal with root-raised cosine pulse shaping (0.01 roll-off) to a driver amplifier and a single-polarization $LiNbO_3$ IQ-modulator also followed by a polarization emulator. For temporal decorrelation of the loading channels, 5 km of SSMF is inserted, delaying neighboring channels by ~7.5 symbols.

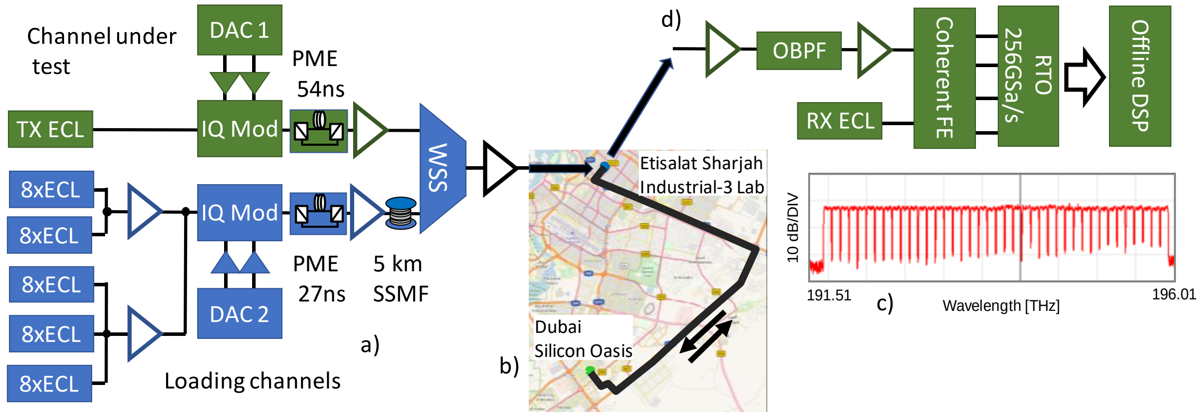

Fig. 1 Experimental setup of 40-channel WDM field trial. a) WDM transmitter, b) Map of 93-km deployed fiber loop in the Dubai area c) Optical WDM Spectrum, d) Receiver.

The WDM channels are on a 112.5 GHz frequency grid. The CUT and WDM loading channels are combined by a wavelength-selective switch (WSS) that also performs bulk channel power equalization to get a flat optical spectrum, as seen in the OSA trace of Fig. 1 c). The WSS simultaneously applies an optical pre-emphasis to the CUT. WDM EDFAs set the power launched into the field-deployed fiber spans in the network of Etisalat in the Dubai area. The G.652 SSMF fiber spans have a length of 93-km, a span loss of ~20 dB, and are configured as a loop-back between Dubai and Sharjah. At the receiver, Fig. 1 d), the signal is pre-amplified before a tunable bandpass filter (OBPF) selects the CUT. The coherent receiver uses a standard ECL serving as local oscillator (LO) and a coherent frontend consisting of a dual polarization hybrid and balanced photodiodes having ~100 GHz of bandwidth are used for o/e conversion. The electrical signals are digitized by a 256-GSa/s real-time oscilloscope. Digital signal processing is done off-line.

For flexible transmission and fine tuning of the spectral efficiency probabilistic constellation shaping (PCS) is applied, offering a shaping gain of ~1 dB in required OSNR versus standard QAM [7,8]. In the receiver DSP, we resample the signals to 2 Sample/symbol, filter and compensate for chromatic dispersion. A 2×2 MIMO equalizer, updated by a multi-modulus algorithm (MMA) to separate the two polarizations follows an intradyne frequency offset and phase offset compensation stage. A final post-equalizer mitigated residual signal distortions. Finally, the information rates are calculated and forward error correction (FEC) was performed. To determine the maximum net bit- rate, a family of 130 optimized spatially coupled (SC) LDPC codes with variable overheads were used for FEC as described and tested in [8]. Successful decoding at the lowest overhead gave the maximum net bit rate. Each WDM channel transmitted was decoded separately and the results were averaged per channel.

3. Experimental Results

Compared to [6] we achieved an improved system performance by more accurate timing alignment. For 64-QAM we found a GMI of 5.9 bits/symbol/polarization at maximum OSNR in back-to-back configuration and we also extracted the system's maximum SNR of 21.5 dB from this measurement. The system's maximum SNR is mainly limited by the noise and nonlinearity of the transmitter's components.

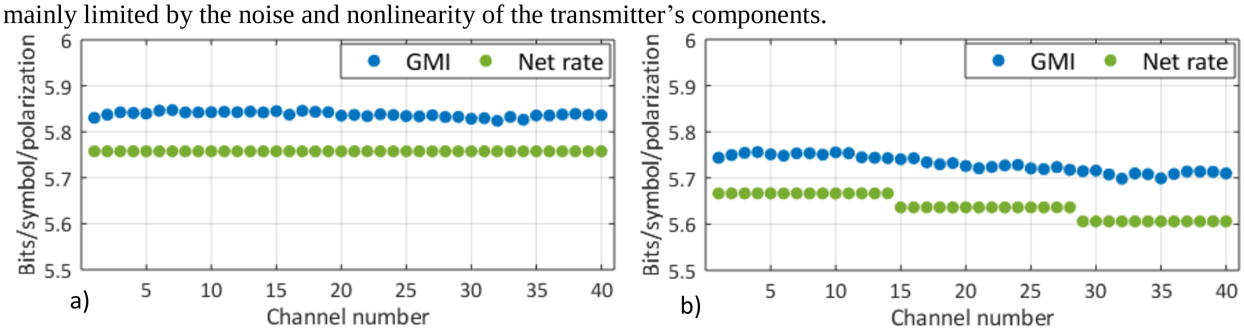

Fig. 2. GMI and Net rate vs. channel number for 64-QAM, a) 93-km, b) 2x93-km WDM transmission

We always set the launch power to 21 dBm (5 dBm per channel) for the WDM transmission experiments. When transmitting the 40 channel 64-QAM WDM signal over 93-km SSMF the reduction of OSNR only leads to 1 dB reduction in the SNR, because the 27.4 dB SNR of the link is still much larger than the system's maximum SNR. The average GMI is reduced to 5.84 bits/symbol/polarization as shown in Fig. 2 a) and after FEC decoding we achieve a WDM net capacity of ~45.93-Tbit/s and a spectral efficiency of 10.21 bits/s/Hz.

For the two-span transmission experiments we inserted a gain equalizer between the two spans to compensate for the power profile of the used WDM EDFAs. After transmission over 2x93 km of SSMF we again observed a 1 dB SNR reduction with respect to single span transmission and the link SNR still being 25.3 dB. The average GMI is 5.73 bits/symbol/polarization, see Fig. 2 b), and the net capacity after FEC decoding is 45.1-Tbit/s at 10.02 bits/s/Hz spectral efficiency. Steps in the Net rate in Fig. 2 b) are due the granularity of the applied SC-LDPC codes.

For comparison, we increased the capacity by switching to PCS-256-QAM with 7.5 bits entropy, for which the GMI is 6.86 bits/symbol/polarization in back-to-back configuration. After 93-km SSMF transmission we observe a performance variation over the WDM spectrum in achieved GMI, which is 6.62 bits/symbol/polarization in average, and Net rate which due to the higher SNR requirements is more pronounced as for 64-QAM transmission and is caused by the EDFA's power profile. After FEC decoding, the resulting net capacity amounts 51.5-Tbit/s at 11.44 bits/s/Hz spectral efficiency, as shown in Fig. 3 a).

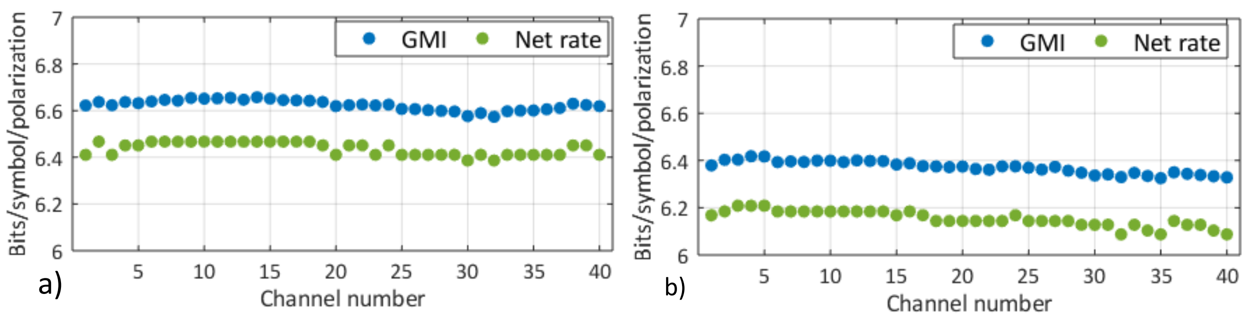

Fig. 3 GMI and Net rate vs. channel number for PCS-256-QAM entropy 7.5 bits, a) 93-km, b) 2x93-km WDM transmission

When transmitting over 2x93-km SSMF we observe a GMI of 6.37 bits/symbol/polarization which again shows reduction by ~0.25, see Fig. 3 b), showing that the OSNR reduction has a more impact. The WDM net capacity is reduced to 49.23-Tbit/s at 10.94 bits/s/Hz spectral efficiency. Also, the average difference between GMI and Net rate increases from ~0.19 to ~0.23 bits/symbol/polarization when doubling the transmission distance.

4. Conclusion

We presented results of 40 channel full C-band WDM transmission experiments at 100 GBd symbol rate over field deployed SSMF in Etisalat's network. For PCS-256-QAM with 7.5 bits entropy transmission of 51.5-Tbit/s WDM capacity at 11.44 bit/s/Hz spectral efficiency over 93-km and 49.2-Tbit/s at 10.94 bits/s/Hz over 2x93-km, respectively, is demonstrated. Transmission of 64-QAM resulted in 45.93-Tbit/s WDM capacity at 10.2 bit/s/Hz spectral efficiency over 93-km and 45.1-Tbit/s at 10 bits/s/Hz over 2x93-km, respectively.

5. References

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