16 Tbit/s Real-time Unrepeated Transmission over 420 km G.654E Fiber

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Abstract *We report a real-time demonstration of 16-Tbit/s DWDM system in 420-km un-repeated transmission link, which is a new distance and capacity record of single span transmission system. It shows 48-nm ultra-wide DWDM system by collaboration of extended C-band EDFA, RGU, and distributed Raman amplifier.*

Introduction

As internet services well develops, it is playing an important role in our daily life, which builds up information link among people and items. Optical fiber transmission plays a role of back-bone in communication networks, which takes advantage of the ultra-wide band of optical fiber and optical amplifier. The majority of the back-bone systems are continental basis, the rests are sub-marine. Most of them are using repeated optical amplifiers to extend transmission distance [1]. Although it is commercialized and cost effective to implement optical amplifier in the majority scenarios of optical transmission systems, there is still some cases which are difficult to deploy repeated optical amplifiers, such as offshore island, desert, and depopulated zooms. Thus, un-repeated transmission scheme is required to recover these specific scenarios those have ultra-large span loss and pure passive fiber link [2].

In un-repeated link, all active things are placed at the two ends of the link, including two directional pump lasers, pre and post EDFAs. The link is composed of optical fiber and remote gain unit (RGU), which are used as optical gain medium by optical stimulated amplification. Distributed Raman pump laser is basic solution in the un-repeated link, which can co-work with RGU for obtaining more gain in the fiber link to extend transmission distance. In order to further improve the transmission distance, additional fiber is dedicated to deliver pump light to RGU to enhance pump power in gain medium for larger optical gain concern [3].

Although the transmission distance of single channel un-repeated transmission system can reach more than 600 km [4], it is quite challenging to un-repeated WDM system push transmission distance to 400km and beyond, due to complicated cross channel effect, multi-channel gain and flatness. It is not cost-effective to transmit only single channel in a fiber link in commercial networks. In [5], 409.6-km un-repeated transmission with 15-Tb/s capacity by

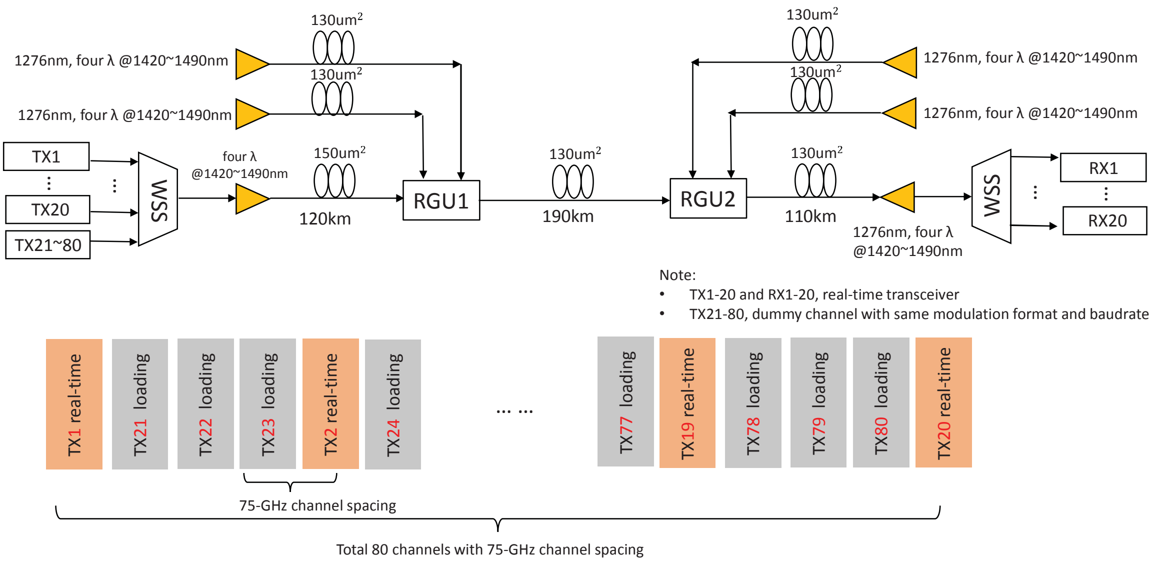

Fig. 1: System setup of 420-km un-repeated transmission.

using 150 channels in C+L band has been reported, whose spectral efficiency is 2 bit/s/Hz. In order to increase the total system capacity, 16QAM [6] is used to place 200G signal in 33-GHz channel spacing, however, the transmission distance is reduced to 345 km. In [6], it is verified that smaller channel spacing causes higher system penalty due to larger cross channel effect. In brief, un-repeated system has features of high nonlinearity and large system noise. Thus, lower modulation format is preferred, which has larger linear and nonlinear noise tolerance.

In this paper, we propose to use 80 real-time 200G PDM-QPSK signals with 75-GHz channel spacing by using extended C-band amplification solution to achieve 16 Tbit/s (200Gbit/s x 80Chs) WDM system in a 420-km un-repeated transmission link. The total net system capacity is 16 Tbit/s with 2.67 b/s/Hz spectral efficiency, which is a new spectral efficiency record for 400-km+ single span system. And the extended C-band solution is based on single EDFA and single WSS, which is different with C+L solution that requires separated EDFA and WSS for C and L band signals.

System Setup

Fig. 1 shows the system setup of this work, which is composed of real-time transceivers and un-repeated single span fiber link. This real-time DWDM system has 20 real-time coherent transceivers with 200-Gb/s net speed, which is configured to PM-QPSK format. Moreover, 60 loading channels are modulated by two individual transceivers, which have same modulation format and baud rate as the real-time channels. The 20 real-time channels are uniformly located in the 80-channel WDM system with 3x75-GHz channel spacing. Between two neighbouring real-time channels, there are 3 loading channels with 75-GHz grid. Thus the whole WDM system has 80 channels with 75-GHz grid and 16 Tb/s payload. A single coherent transceiver is comprised by 100-kHz continous wave laser, 64-Gbaud commercial linear driver, optical modulator, integrated coherent receiver, and real-time ASIC chip. In the transmitter DSP, FEC, symbol mapping, pulse shaping, bandwidth pre-compensation, skew compensation are used to generate PDM-QPSK signal. At the receiver DSP, resampling, CD compensation, frequency offset compensation, polarization de-multiplexing, phase estimation, and FEC are employed to recover signal. The whole optical module is packed into an MSA module. The 3-dB bandwidth of generated single channel optical signal is about 68 GHz, which is placed into 75-GHz DWDM channel by using WSS. Before the 80-channel WDM signal is launched into fiber link, it is boosted to ~20 dbm. In order to provide wide band gain for the 80-channel WDM signal, the single span link is jointly designed with link optical amplification scheme. The whole link of this experiment contains three separate sub-spans, being connected by two RGUs. Four additional parallel fibers are used to deliver pump light to RGUs in forward and backward directions separately. In each pump light fiber, one 3-th order and four 1-st Raman wavelengths are used to provide sufficient pump power to RGUs. The whole link uses large area ultra low loss G.654E fiber that has 130-um^2 effective core area except the first fiber span (120 km), which selects 150-um^2 effective core area fiber for fiber nonlinearity concern. It is proved that hybrid fiber link is an effective way to mitigate nonlinearity. At the receiver end, WSS is used to drop the individual channels to corresponding receivers for demodulation and decoding.

Results and Discussions

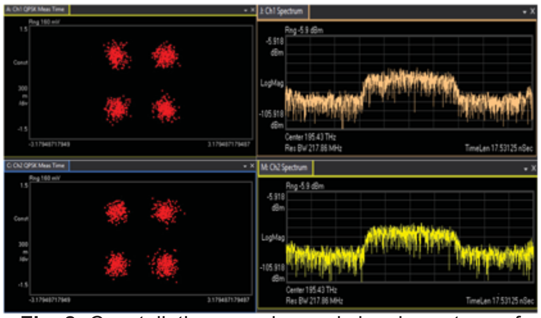

Fig. 2: Constellation mapping and signal spectrum of two polarization of real-time signal.

Fig.2 shows constellation map and signal spectrum of single channel, which is measured by optical modulation analyzer (OMA). The output of the real-time optical module is connected to OMA directly. The embedded demodulation algorithm in OMA can recover the real-time 200Gb/s PDM-QPSK signal, whose 3-

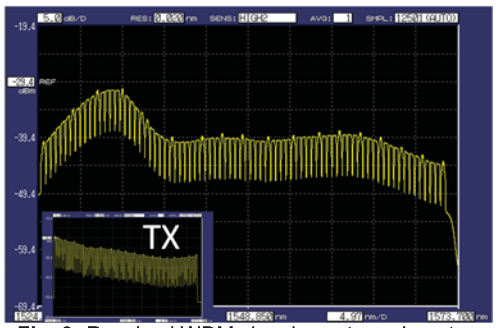

Fig. 3: Received WDM signal spectrum; Inserter: transmitted WDM signal spectrum

dB bandwidth is about 68 GHz as the spectrum shows. The bit error rate (BER) before FEC can reach $1x10^{-7}$ level. Then, we investigate the 80-channel WDM system performance after 420-km transmission. The optical spectrum of the received signal at link end is shown in Fig. 3. It can be found that the flatness of WDM system is about 13 dB, which is caused by uneven Raman gain, but it does not bring significant degradation to the whole WDM system performance. The higher power channel has larger OSNR, but it is with more significant nonlinearity. Thus, linear optical ASE noise and nonlinear noise should be jointly considered. The received BER is a better index to evaluate channel performance, which has direct relationship with ASE noise and nonlinearity. We can fine tune the optical power profile of WDM signal at the transmission side of the link to obtain a flatten BERs of the WDM system. Thus, BER flatteness of the WDM system is considered as key index for power profile optimization of the WDM channels at

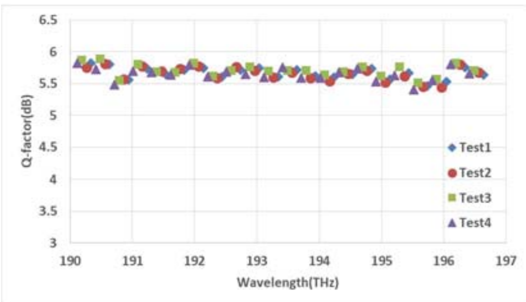

Fig. 4: Q-factor of WDM channels after 420km link

transmitter end. The transmitted WDM signal spectrum is shown by the inserter in Fig.3. Fig. 4 shows the Q-factor of all 80-channels after 420-km transmission. The Q-factor is converted from the BER before FEC decoding. Although the received WDM signal spectrum has poor flatteness, we can get flatten BER profile. Since we have 20 real-time channels, and 60 loading channels, we split the measurement into 4 groups. In each testing group, the real-time channels swap with its neighbor loading channel, such that 4 testing group can cover whole 80 channel. We

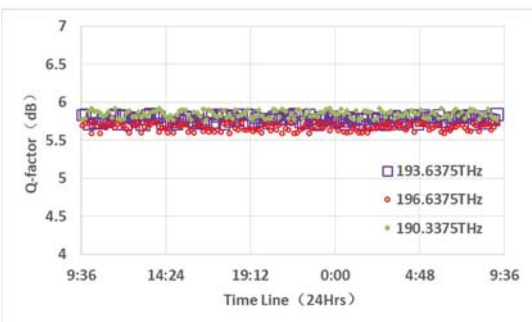

Fig. 5: 24-hours Q-factor monitoring of three channels

also monitor long-time system performance by deriving Q-factor in 24-hours at different channels. In Fig.5, the 24-hours Q-factor variation in three channels is shown, which represents the performance variation in short, medium, and long wavelength regions. The Q-factor is derived by every 10 minutes, which is the average value in the 10-minutes.

Conclusions

In this work, we make successful real-time demonstration of 420-km single span transmission with 16-Tbit/s system capacity in extended C-band (about 48 nm) only, which is a new record of single span system. The deigned dual pump fiber structure and two stage RGU is proved to support ~67-dB single span loss and 48-nm gain bandwidth. Comparing with duplicated EDFA and WSS components in C+L system, the extended C-band system supports the same architecture as normal C-band system, which is more friendly for commercial deployment.

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