High spectral efficiency real-time 500-Gb/s/carrier transmission over field-installed G.654.E fiber link using forward and backward distributed Raman amplification

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Abstract: Transmission distance of 1234.2 km with high spectral efficiency of 5.71 b/s/Hz over terrestrial G.654.E fiber links is achieved for 500-Gb/s/carrier signals using EDFAs with forward and backward DRAs compliant with laser power safety requirements.

1. Introduction

High-speed and large-capacity backbone networks are in high demand with the rapid increment of network traffic. To cope with increasing data traffic, high-speed technologies beyond 100 Gb/s, exploring digital signal processing (DSP) and digital coherent techniques, have greatly increased the transmission capacity of optical communication systems. For example, in [1] and [2] described DSP application-specific integrated circuits (ASICs) that supported polarization-division multiplexed (PDM) quadrature amplitude modulation (QAM) formats with the modulation orders of ~16. Figure 1 shows recent field experiments using DSP-ASIC-integrated real-time optical transponders over terrestrial links [1, 3, 4, 5, 6, 7, 8, 9, 11]. To expand transmission distance possible with high-order QAM signals demands very high optical signal-to-noise ratio (OSNR) and low fiber nonlinearity. Accordingly, large-core pure-silica-core fiber has been deployed in terrestrial links (ITU-T G.654.E, effective area (A_{eff}): 110 μm2) [3, 4]. In these experiments on G.654.E transmission, only erbium-doped fiber amplifiers (EDFAs) were used to compensate for losses of the optical fiber links. As the modulation order must be higher than 32 to realize a capacity of 500 Gb/s/carrier with the symbol rate of ~64 GBaud, distributed Raman amplifier (DRA) should be considered to improve the OSNR of transmission links. We demonstrated 500 Gb/s/carrier transmission over 1122 km with frequency grid of 100 GHz, i.e., spectral efficiency of 5.0 b/s/Hz with EDFA and backward DRA [11]. To increase the transmission capacity, the frequency grid should be set on narrower flexible grid. Unfortunately, narrow frequency grid spacing causes a degradation of signal quality.

We demonstrate, using forward DRA with terrestrial G.654.E links for the first time, net data-rate 500 Gb/s PDM-32QAM signaling with spectral efficiency of 5.71 b/s/Hz over 1234.2 km (11 spans × 112.2 km) of field-deployed G.654.E fiber with EDFA and backward/forward DRA. The forward DRA used to extend the transmission distance even if the signal quality degrades doe to the narrow frequency grid. All of DRA comply with laser power safety requirements. The total pump power of each DRA is several hundreds of milliwatts. These high powers constitute a severe eye hazards, especially in field environments [12]. The signals are generated and detected with our newly developed transponder that integrates a DSP-ASIC based on 16-nm complementary metal oxide-semiconductor (CMOS) technology [10]. This transmission distances of 1234.2km with net data-rate of 500 Gb/s/carrier is, to the best of our knowledge, the longest in field experiments achieved with DSP-ASIC-integrated real-time optical transponders with high spectral efficiency of 5.71 b/s/Hz.

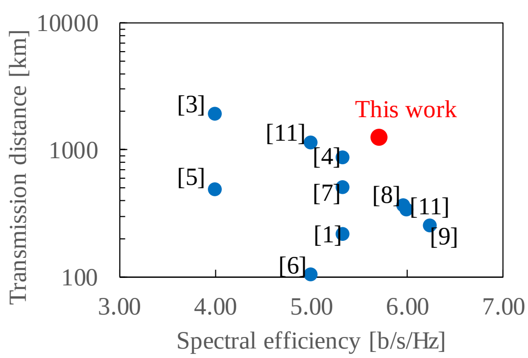

Fig.1 Recent field experiments on terrestrial links using DSP-ASIC-integrated real-time optical transponder.

2. Experimental setup

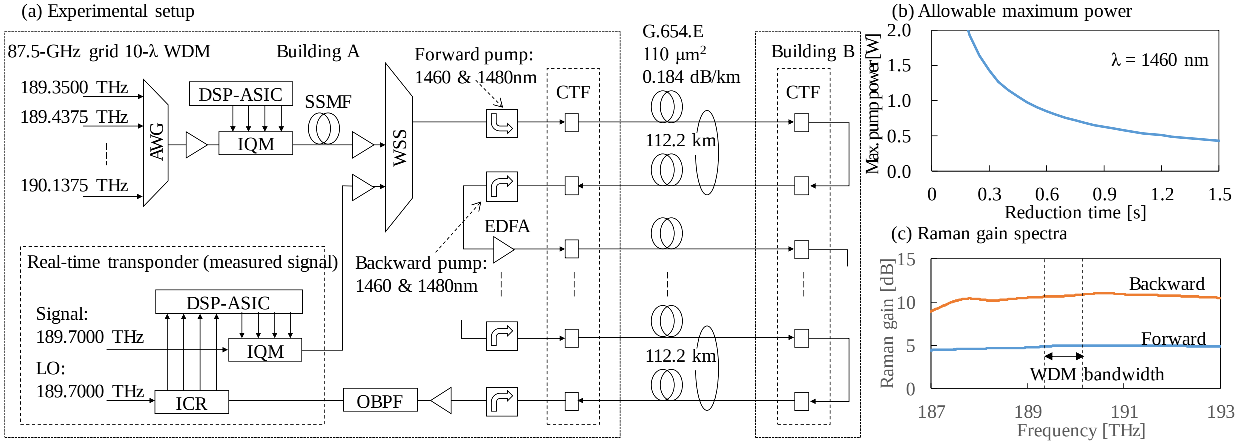

Fig. 2. (a) Setup for field experiments over G.654.E link, (b)Allowable maximum power as function of auto power reduction time , and (c) Raman gain spectra.

Figure 2 (a) shows the setup for our field experiments using NTT Group's terrestrial links. The experimental equipment was placed at building A; building B was only for directly looping back the transmission lines. Our newly developed optical transponder consists of a DSP-ASIC based on 16-nm CMOS technology [10], inphase quadrature modulator (IQM), and intradyne coherent receiver (ICR). The measured signal was generated in the optical transponder; the electrical signals output from the DSP-ASIC were modulated by the IQM in the optical frontend with the optical carrier output from a local oscillator (LO). The carrier frequency of the measured signal was set to 189.7000 THz. The ten 87.5-GHz-spaced optical carriers with frequencies from 189.3500 to 190.1375 THz were modulated by an IQM using electrical signals from a DSP-ASIC after being multiplexed by an arrayed waveguide grating (AWG). The wavelength-division multiplexing (WDM) signal was input into an 11-km standard single mode fiber (SSMF) for signal decorrelation. The measured and WDM signals were multiplexed by a wavelength selective switch (WSS). The WDM signal was input into field-deployed G.654.E (A_{eff}: 110 μm^2) fiber between buildings A and B. In building B, the transmission lines were connected using only patch fiber cables. The average optical loss of the transmission link was 20.7 dB per 112.2-km span (0.184 dB/km) at 1580 nm; this include fusion splice points of the field-deployed fiber, cable termination frames (CTFs), and intra-building fibers. After WDM signal transmission over each 112.2-km span, the optical loss was compensated by an EDFA and backward DRA with and without forward DRA; pump lasers operated at 1460 and 1480 nm, respectively. Fig.2 (b) shows allowable maximum power of DRA as function of auto power reduction time. We set total pump power of 800 mW for backward DRA, and 500mW for forward DRA. As shown in Fig. 2 (c), we confirmed that flat Raman gain was attained in the WDM signal bandwidth (BW). By adequately designing the pump wavelength, flat Raman gain spectra could be achieved in field-deployed G.654.E fiber transmission. One of the WDM signals was filtered by an optical band-pass filter (OBPF) after transmitting the field-deployed optical fiber link and measured. It was coherently detected by an ICR with the optical LO. Finally, the received signal was equalized, demodulated, and decoded in the DSP-ASIC.

3. Results

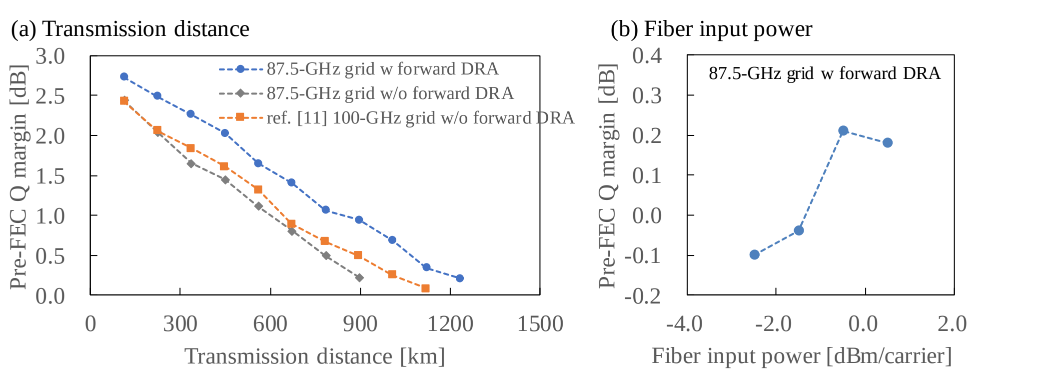

Fig. 3. Experimental results of pre-FEC Q margin of 500-Gb/s transmission using EDFA, backward DRA, with and without forward DRA (a) as function of transmission distance, (b) optimum fiber input power for the transmission distance of 1234.2km with forward DRA.

The net data-rate 500-Gb/s (single-carrier PDM-32QAM) transmission performances at the center carrier frequency of 189.7 THz which is the center of the WDM signals, are shown in Fig. 3 (a). In these experiments, the average fiber input power was -0.5 dBm/carrier with forward DRA, and +2.5 dBm/carrier without forward DRA. The gain of backward DRA was set to 11 dB and that of forward DRA was set to 5 dB for each 112-km span. Note that the pre-forward error correction (FEC) Q margin shown in all of the figures is equivalent to the difference between the pre-FEC Q factor and pre-FEC Q limit; that is, the pre-FEC Q margin of zero corresponds to the pre-FEC Q limit. We observed that the pre-FEC Q margin exceeded zero as shown in Fig. 3 (a), i.e., pre-FEC Q-factor showed better than the pre-FEC Q limit, and confirmed that the post-FEC bit error rate (BER) was error-free at the transmission distance. Thus, we achieved single-carrier 500-Gb/s transmission over 1234.2-km (11 spans × 112.2 km), of field-deployed G.654.E fiber. Also a Q-improvement of 0.72 dB was confirmed with the use of forward DRA compared to that without forward DRA at transmission distance of 897.6km (8 spans × 112.2 km). The orange square plots shows 189.7-THz 500-Gb/s signal with 100-GHz grid using EDFA and backward DRA without forward DRA case [11]. A transmission penalty at distance of 897.6 km (8spans) was 0.27dB by narrowing the frequency grid from 100 GHz to 87.5 GHz. Figure 3 (b) shows pre-FEC Q margin as a function of the 189.7-THz centered signal power for the transmission distance of 1234.2km with forward DRA gain of 5dB and backward DRA gain of 11dB. The optimum fiber input power was -0.5 dBm/carrier, higher powers degraded performance due to the influence of additional nonlinear crosstalk and the transfer of relative intensity noise from the forward DRA pump light.

4. Conclusions

We demonstrated, for the first time, the transmission distance of 1234.2 km for net data-rate 500-Gb/s single-carrier PDM-32QAM signals with spectral efficiency of 5.71 b/s/Hz using our newly developed real-time transponder; 112.2-km spans of field-deployed ITU-T G.654.E fiber were used together with EDFA and backward/forward DRA that complied with laser power safety requirements. The transponder integrates a DSP-ASIC based on 16-nm CMOS technology.

5. Acknowledgments

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6. References

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