Evaluation of the Link Budget Increase using Error-Tolerant TCPs for Optical Communication in Nonlinear Regime on 200G PM-16QAM Real-time Signal Demodulation

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Abstract *We evaluated TCP/IP data transfer throughput using real-time 200G PM-16QAM signal over 75km SMF in the nonlinear regime. We show the validity of TCP/IP with an additional 0.2 dB increase in link budget in the nonlinear regime compared to 0.3 dB in the linear regime.*

Introduction

Recently, content providers on the Internet own optical cables to enlarge the volume and improve the cost-efficiency of their services. This variety of owners has brought a diversity of policies regarding the capacity, quality, and reliability of optical communication[1],[2]. This opens opportunities to the adaptation of technologies in optical networks to increase capacity or reduce margins, such as TCP, which has been mainly used in the Internet and wireless networks so far.

Therefore, we are investigating the low-margin optical cable design concept[3],[4] utilizing Ultra-high-speed TCPs[5]-[7] (UHS-TCPs), allowing post FEC errors to increase total throughput. UHS-TCPs have significant robustness against signal errors to cover high-order QAMs which require higher SNR to enable higher capacity. Notably, we aim to realize higher capacity error-tolerant services as the alternative to the current error-free services, as illustrated in Fig.1, which does not include nonlinearities caused by fibre transmission.

UHS-TCP is used in wireless applications mostly, where nonlinear transmission impairments are out of scope. In the optical domain, we have analyzed the performance of our concept[3] including real-time communication tests, changing ASE noise power[4], but limiting the test to the linear domain as the first step of validation of our concept. As a mandatory step, we are aiming at validating our concept with long-haul WDM transmission.

In this paper, we discuss the performance degradation of optical communications by the nonlinear effects based on the GN-model[8]. Then, we evaluate the use of UHS-TCP with real-time demodulated 200G PM-16QAM after 75 km SMF transmission with two adjacent dummy channels. We compare the link budget increase offered by the use of UHS-TCP in the linear and nonlinear domains.

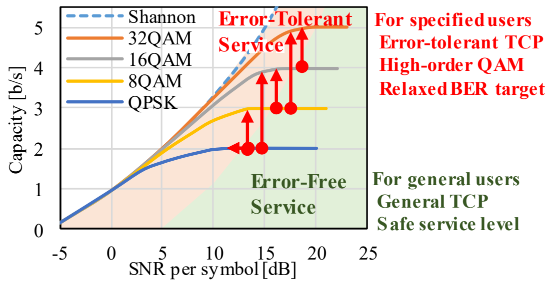


Fig. 1: Error-tolerant service ideas in linear regime.

SNR under nonlinear noise

The signal-to-noise ratio of optical wavelength channel i is modeled as[8]-[10]:

$$SNR_i = \frac{p_i}{n_{ASE,i} + n_{NLI,i}} \quad (1)$$

where p_i is the launch power, $n_{ASE,i}$ is the noise of Erbium Doped Fibre Amplifier (EDFA), and n_{NLI} is the nonlinear noise. $n_{ASE,i}$ is expressed as follows:

$$n_{ASE,i} = N_s \times 10^{\frac{NF}{10}} \times h \times v \times R \times 10^{\frac{A_{span}}{10}} \quad (2)$$

where N_s is the number of spans in the cable system, NF is the amplifier noise figure (dB), h is Planck's constant, v is the frequency of the optical carrier, R is the symbol rate (Baud), A_{span} denotes the signal attenuation between two amplifiers.

The power of the nonlinear noise of wavelength channel i interfered by another channel j is expressed as follows:

$$n_{NLI,i} = N_s p_i \sum_j X(\Delta f) p_j^2 \quad (3)$$

p_j is the launch power wave channel j. $X(\Delta f)$ is a single span nonlinear efficiency factor calculated with the spectrum difference between wave channel i and j , as $\Delta f = f_i - f_j$.

We show examples of SNR by the model in Fig. 2. For instance, investigating with the GN model and 100 km span parameters, a decrease of SNR margin by 1 dB taking advantage of a low-margin design using TCP would enable a 200 km reach extension for a 2,000 km terrestrial system and an 800 km increase for a 7,000 km submarine system. This illustrates the potential benefits of low-margin systems.

As shown in Fig. 2 (b), decreasing the number of optical amplifiers, *i.e.* increasing the span-length is attractive for cost-efficiency but it decreases the generalized SNR as it increases nonlinearities. Indeed using 100 km span compared to the optimal span length of 25 km reduces the number of amplifiers by 75% but it reduces the SNR of 5,000 km cable by 17 dB.

Thus, the GN model enables estimations of the potential benefits of UHS-TCP, however, there remains a doubt on the tolerance of this scheme to the nonlinear impairments, which are considered in a Gaussian approximation and considered inside a generalized SNR. Therefore, we conducted further experimental evaluations in real-time with a signal transmitted over fibre in the nonlinear regime.

Experiment setup for evaluation of optical transmission with TCP

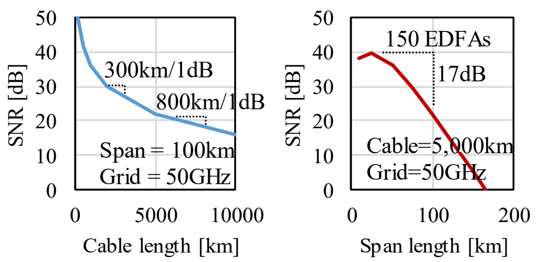
We illustrate the overview of the test setup in Fig. 3. We used a real-time non-commercial 32-GBaud-PM-16-QAM evaluation board (EB) featuring a DSP LSI. The evaluated channel was chosen in the C band. We show the specifications of the test environment in Tab. 1.

We used three PCs as a traffic generator (Sender), network emulator (EMU), and traffic terminator (Receiver). EMU forwards the traffic from Sender to Receiver, adding the emulated propagation delay set according to the investigated transmission distance. Using an optical wave shaper (WS), shaping ASE, we emulated two adjacent channels, which were multiplexed via a fibre coupler (FC) with the central channel featuring the evaluated signal. The optical signal was also tapped to an optical spectrum analyser (OSA). We measured OSNR 43.1 dB/0.1nm at OSA for back-to-back condition without additional ASE. We adjusted the transmission power to the 75 km-fibre using an actively controlled attenuator to keep the OSNR constant during the test. We show an example of a 50 GHz grid spectrum after 75 km propagation in Fig. 4. The received optical power was maintained constant using another attenuator.

Evaluation of link budget and throughput using TCP

As shown in Fig. 5, we measured the BER characteristic of transmissions by single-channel (1WL) and 3 wavelengths on 50 GHz-grid (3WL), changing the power to the 75 km-fibre.

We see the additional link-budget space from the error-free limit (Error-free-limit) to the link-establish limit (Link-limit). The Error-free-limit lies at BER of 1.58×10^{-2} in this test. Indeed, although post FEC error appears, the throughput of UHS-TCP is almost constant; therefore using the link limit enables to increase the link budget with a negligible decrease of throughput. We illustrate the link-budget space of the low-power side (LPS), in the linear regime, and the one of the high-power side (HPS), in the nonlinear regime, in Fig. 6, and the results are also shown in Tab. 2. In the linear regime, the increase of link budget



(a) **(b)**

Fig. 2: Overview of SNR, (a) vs. cable length, (b) vs. span length.

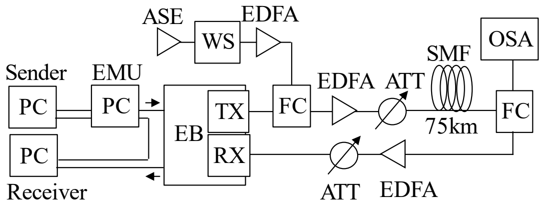


Fig. 3: Test setup.

Evaluation board		PC	
Signal	PM-16QAM	CPU	Xeon W2123
FEC	SD (LDPC)	RAM	64GB
Client IF	100GbE x2	OS	ubuntu 19.03

Tab. 1: Test environment specification.

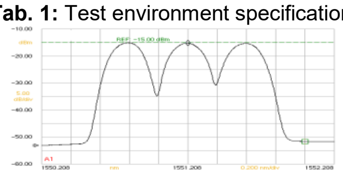


Fig. 4: Spectrum with the emulated side-signals.

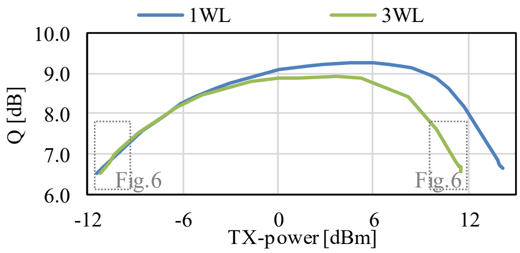


Fig. 5: Q vs. TX-power.

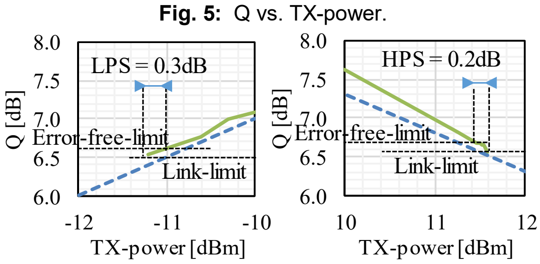


Fig. 6: Measurement of the link-budget space.

Tab. 2: Measured link-budget space.

	LPS [dB]	HPS [dB]
1WL	0.3	0.2
3WL	0.3	0.2

is 0.3 dB, whereas it is 0.2 dB in the nonlinear regime. This difference is consistent with the slopes of the Q curves versus OSNR in the linear and nonlinear regimes around LPS and HPS, as shown by dotted-lines in Fig.6 (dQ/dOSNR of 0.5 and 1 respectively).

Figure 7 compares the distribution of the Pre-FEC BER of 75 km propagation (3WL) in three cases. We obtained the BER every 2 seconds for 400 seconds.

Case-A: the result near the link-limit in HPS. Post-FEC BER is high due to NLI.

Case-B: the result near the error-free-limit in HPS. Post-FEC BER is low, however not zero.

Case-C: the result near the error-free-limit below HPS. Post-FEC BER is zero.

In Fig. 7, we compare them also to the back-to-back results for the signal, which have similar Post-FEC BER. The distributions of Pre-FEC BER were slightly wider after 75 km transmission as shown in Fig. 7 (b) and (c) due to residual chromatic dispersions and other digital filter variations. However, these differences are negligible when higher BER in the range of 10^{-3} as shown in Fig. 7 (a). Therefore, no significant

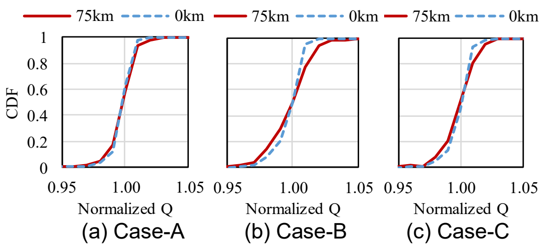


Fig. 7: Pre-FEC BER distribution, 75 km (3WL) and 0 km (1WL w. ASE).

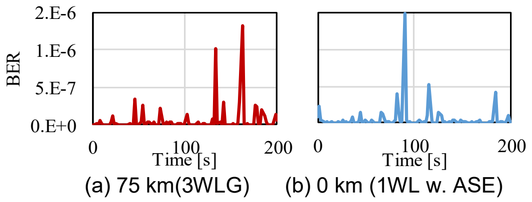


Fig. 8: Post-FEC BER-time history.

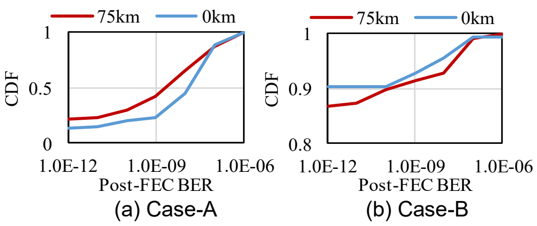


Fig. 9: Post-FEC BER distribution.

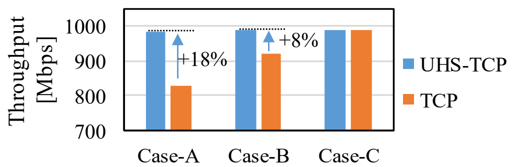


Fig. 10: Throughput by UHS-TCP and TCP (75 km, 3WL).

impact on the TCP throughput is caused by the nonlinear regime in this test. This explains the consistency between LPS and HPS on Tab. 2.

In Fig. 8, we show examples of the Post-FEC BER histories of 75 km and 0 km propagation. They both have spikes in error ratio due to the performance limitation of the FEC and operation around this limit. In Fig. 9, the distributions of the Post-FEC error ratio are compared. Again, after 75 km the distribution of Pre-FEC BER is wider but this difference disappears after the FEC. Therefore, nonlinearity does not impact the behavior of TCP.

We evaluated TCP throughput using the obtained error pattern of the nonlinear scenario. we set the user link speed up to 1 Gbps to see only the effect of BER of optical communication, avoiding packet losses at buffers in PCs. We show the result by UHS-TCP (TCP-FSO[5],[6]) and TCP (Cubic[11]) in Fig. 10. UHS-TCP, which has an improved retransmission scheme and congestion control, had a throughput as high as the user's link speed. The throughput is the data ratio to the application (iperf) which does not include lost data nor redundant data. Thus, with UHS-TCP, link-budget space is available for the data transfer service by UHS-TCP increasing throughput by up to 18%.

In the tests, we see the characteristics of Post-FEC errors by nonlinear noise are similar to the errors by ASE noise in the view of the rough time granularity that end-to-end TCP/IP cares about.

Thus, we confirm that we obtained the budget gain as large as we showed in Fig. 6 and Tab. 2.

Conclusions

We evaluated TCP throughput after 75 km SMF real-time transmission in the nonlinear regime of a 200G PM-16QAM signal with two adjacent channels. We have confirmed in these conditions that UHS-TCP had sufficient robustness against errors occurring when nonlinear effects are dominant. In the test, UHS-TCP allowed an additional 0.2 dB in the nonlinear regime and a 0.3 dB increase in the linear regime. This difference is consistent with the slope of the Q curves in the respective regimes.

We have studied different statistics on appearing errors in linear and nonlinear regimes. Although the distributions seem slightly wider in the nonlinear regime, these differences disappeared around the Post-FEC BER of 10^{-8} around which TCP is used, therefore having no impact on the throughput.

Acknowledgements

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