Subcarrier-Enabled Record Field Trial Demonstration in a Dispersion Uncompensated Ultra-Long Transpacific Cable

Sumudu Edirisinghe[1], Siddharth Varughese[1], Domaniç Lavery[2], Pierre Mertz[1], and Han Sun[2]
[1]*Infinera Corporation, 9005 Junction Drive, Annapolis Junction, MD 20701 USA*
[2]*Infinera Canada Inc., 555 Legget Drive, Ottawa, ON K2K 2X3*
sedirisinghe@infinera.com

Abstract: A record real-time transmission is demonstrated over an 18,008 km dispersion uncompensated subsea cable, enabled by subcarrier-based EEPN mitigation and FEC. Numerical analysis supports the field trial's real-time measurements, quantifying the benefit of subcarrier modulation. ©2024 The Author(s)

1. Introduction

With the aim of increasing subsea cable capacity, subsea transmission systems have begun the transition from high spectral efficiency to high power efficiency [1]. While these space division multiplexed (SDM) cable systems optimize cost per bit, they present new challenges for both system design and transceiver development.

From the transceiver's perspective, the reduced signal to noise ratio (SNR) is particularly problematic in ultra-long cables, where the SNR may already be close to the commissioning threshold (i.e., the FEC limit plus some margin in either SNR or Q factor). Furthermore, due to relatively low launch powers, future capacity upgrades cannot rely on novel nonlinearity compensation techniques. A second, but equally significant, issue in ultra-long, dispersion uncompensated links is equalization enhanced phase noise (EEPN); the interaction between digital chromatic dispersion compensation (CDC) and laser phase noise. EEPN is generated in any uncompensated link with coherent receivers and digital signal processing (DSP). However, for ultra-long, SDM cables, EEPN further degrades SNR; compounding to an already challenging SNR issue.

Here, we report on the field trial of a real-time coherent transponder in a loopback configuration over 18,008 km of a transpacific subsea cable system (Fig. 1). This cable is power feed (PFE)-limited, and thus operates in a quasi-linear regime. We show experimentally, supported by numerical simulations, how digital subcarriers (DSCs) sufficiently mitigate EEPN as compared to a single carrier system, and how modern ASICs have the capability to upgrade such a system. While there have been a few published laboratory demonstrations at comparable transmission distances [2¬4], we believe this is the first field demonstration using real-time transponders.

2. Chromatic Dispersion Compensation

Staggering developments in DSP and ASICs have enabled modern optical transceivers to implement CD compensation in the digital domain. It is typically implemented in the frequency domain [5] with half the CD being pre-compensated at the transmitter and the remaining half being post-compensated at the receiver. Digital CD compensation has allowed for the deployment of high-capacity dispersion unmanaged submarine cables as CD introduces walk-off between different wavelengths and reduces the effects of fiber nonlinearity on the modulated signal [6]. However, the application of CD compensation in the digital domain introduces two challenges in ultra-long links employing high baudrate optical transceivers.

Firstly, real-time implementation of the digital CD compensation circuit uses fixed point filters with finite lengths, which can only compensate for a certain amount of CD. If the CD-induced intersymbol interference (ISI) is longer than the designed filter length, significant penalties are incurred. The length of the filter is directly proportional to the square of the signal bandwidth [7]. Therefore, compensating for large CD (>300,000 ps/nm) in high baudrate signals (>50 GBaud) can be computationally expensive and power intensive.

Secondly, CD compensation in the digital domain introduces EEPN into the optical signal [8]. Owing to the non-commutability of laser phase noise and CD, the application of CD filters spreads the laser phase noise over the

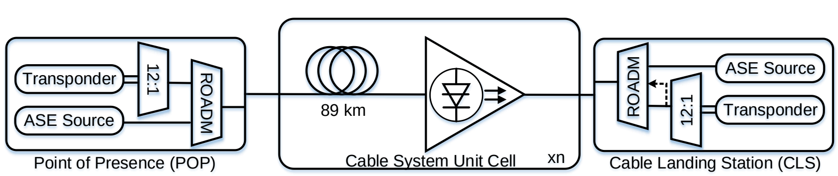


Fig. 1: A simplified schematic of the field trial setup. A loopback (depicted by dashed line) was used at the CLS to emulate the ultra-long link described in this work. Cable system unit cell shows a nominal 89 km span length, though some spans have a slightly reduced span length (see Field trial configuration section).

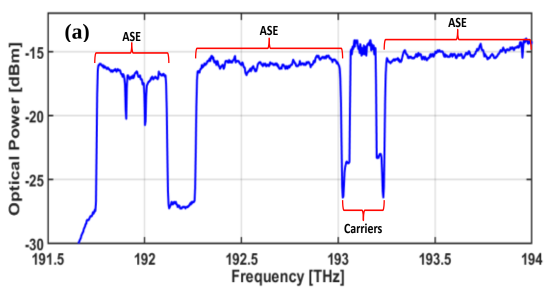
filter memory. The resulting noise manifests itself as timing jitter and degrades the signal performance. Since EEPN is a function of the total compensated dispersion and signal bandwidth, it can be a major performance limiter in high baudrate transceivers on ultra-long links.

Digital subcarriers allow one to circumvent both these challenges by reducing the effective baudrate. If a single carrier signal uses a filter of length L to compensate for CD, a signal employing N_{sc} subcarriers would need N_{sc} filters of length L/N_{sc}^2, thereby reducing the combined complexity of the filters by a factor of N_{sc}. Additionally, such a signal would experience a reduced EEPN by a factor of N_{sc}. Therefore, DSCs are critical to enable high performance transceivers in ultralong links.

3. Field trial configuration

The field trial was performed on the longest segment of a trans-Pacific cable system connecting the point of presence (POP) in Australia and the cable landing station (CLS) in Hawaii, USA, Fig. 1. The segment is 9,004 km long and consists of 108 spans of span loss ~16dB, chromatic dispersion ~20.7 ps/nm/km and mean attenuation 0.179 dB/km at 1550 nm and a repeater output power of 19 dBm (TOP). To create the ultra-long link for this work measuring 18,008 km, an optical loopback was created at the CLS.

The bidirectional setup consisted of a dual wavelength 800 Gb/s real-time transceiver (details in [5]), a 12:1 colorless multiplexer/demultiplexer (mux/demux), a wavelength selective switch (WSS) based ROADM, and an ASE source, Fig. 2(a). Each wavelength in the transceiver consisted of 8 DSCs. At the POP and CLS, the transceiver was coupled to the cable system's wetplant through the colorless mux/demux and ROADM to emulate real subsea field deployments. The ASE source provided spectral occupancy for constant power subsea repeaters. Also note that live traffic was being transmitted on this fiber during the field trial in the frequency range 194.25 THz to 195.75 THz. The test channels were placed in the spectrum where the accumulated dispersion was at its highest.



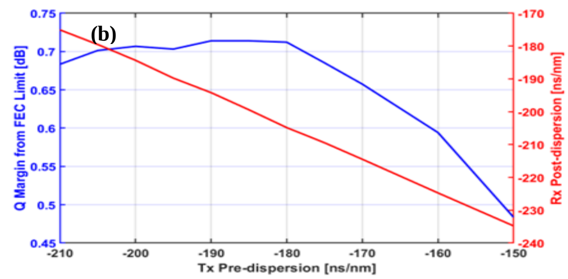


Fig. 2: (a) Transmitted spectrum showing the real-time channels under test (carriers), and the ASE loading and (b) Optimization of Q-factor for various amounts of transmit-side CD pre-compensation. Total compensated CD for this link was ~385,000 ps/nm. The amount of receive-side CD post-compensation (right axis) was the difference between the total dispersion and the transmit side dispersion.

4. Results

Owing to the length of the system and limited SNR, the field trial investigated probabilistically shaped (PS)-64QAM at a pre-FEC spectral efficiency of 2-2.25 bit/s/Hz/pol. All investigated signals carried either 200 Gb/s or 250 Gb/s client traffic in either Ethernet mode (63 GBaud) or OTN mode (66 GBaud). Various DSP parameters were optimized on the link for performance. Figure 2(b) shows one such optimization where the division of CD pre- and post-compensation was varied to maximize pre-FEC Q. Total compensated CD was ~385,000 ps/nm at 191.9 THz (1562 nm) and the best performance was achieved when the CD was almost equally split between Tx and Rx.

The signal was swept across the available cable passband to assess total capacity. Figure 3(a) shows the performance of 200G and 250G signals at 191.9 THz (1563.04 nm) and 193.1 THz (1552.52 nm) in Ethernet mode (63 GBaud). For reference, the performance of 200G signal transmitted over 9,004 km is also provided which is the original system without the loopback. The cable system operates in the quasilinear regime, as is evident from Fig. 3(a), where the peak performance (in terms of Q-factor) was not achieved even after the launch power of the channel under test was increased by 2 dB. This is very similar to how SDM cables perform [1]. For the 9,004 km link, a generous Q margin of >3 dB was achieved. In the loopback mode, PS-64QAM achieved >0.5 dB Q margin with a flat PSD (i.e., 0 dB relative launch power) for 200G line rates.

Accounting for appropriate optical guard bands and other deployment constraints, Fig. 3(a) demonstrates that we can transmit 200G and 250G signals over 18,008km under extremely high dispersion. Extrapolation of this results show that 11.4 Tb/s across the cable passband in OTN mode and 11.8 Tb/s in Ethernet mode capacities can be deployed with commercially acceptable Q margin. The cable segment was originally designed with a design capacity of 10 Tb/s per fiber pair in OTN mode in one direction. The higher transmission capacities over double the distance, was made possible owing to the increased range of CD compensation when using subcarriers, recent improvements in forward error correction (FEC), and the inherent tolerance of subcarriers to EEPN.

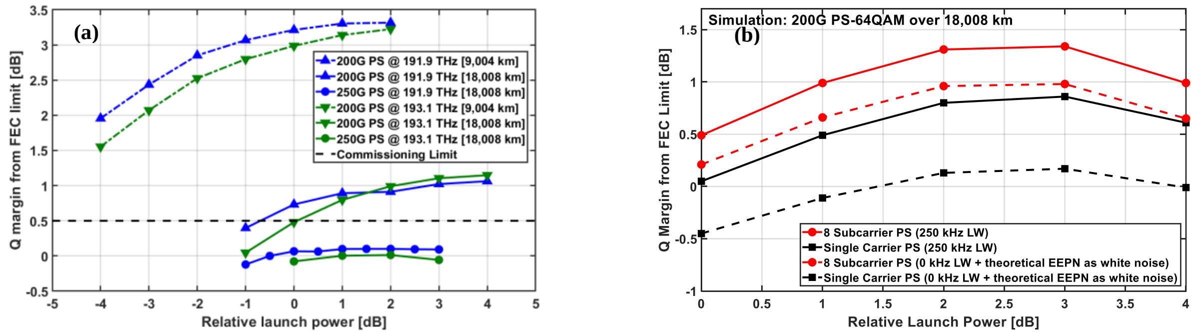


Fig. 3: (a) Q-factor vs relative launch power for 200G and 250G optical carriers employing PS-64QAM formats. For reference, the performance of PS format on the unidirectional link is also shown with the launch power of the channel under test is varied relative to the passband to maximize performance. (b) Numerical simulation comparing single carrier and 8-subcarrier transmission. Dashed lines indicate the numerical simulation results but without laser phase noise, where the theoretical EEPN is added as white noise.

To understand the advantages that subcarriers provide us against EEPN, we simulated the 18,008 km transmission link using the split step Fourier method (SSFM). We first simulated without phase noise; subsequently adding the EEPN as white noise as expected from theory [9]. We then simulated using a combined Tx and Rx laser linewidth of 250 kHz, which is typical for commercial transponders. The carrier phase estimator (CPE) used a pilot-supported blind phase search [9]. The averaging window was independently optimized for both the 8-subcarrier system and the single carrier system. Note we observed a penalty for the single carrier system versus the subcarrier system irrespective of the chosen CPE parameters.

As shown in Fig. 3(b), the subcarriers maintain an advantage over single carrier due to the inherent EEPN tolerance. At higher launch powers, there is also a small nonlinear gain when using subcarriers. (Note that, unlike the field trial, EDFA gain was not limited in simulation, and we could push the signal into the nonlinear regime.) However, the performance difference between single and subcarrier operation is smaller than predicted by theory due to the restorative effect of CPE, which was greater for the single carrier system (this is expected from previous analysis [10]). Nevertheless, the simulations indicate that, at 0 dB relative launch power, the single carrier system would have <0.05 dB margin at the FEC threshold compared to 0.5 dB for the subcarrier system. Therefore, these simulations support our finding that DSCs are a key enabler for future ultra-long, power limited subsea cables.

5. Conclusions

We reported field trial results from an ultra-long transpacific subsea cable. In a loopback configuration, the cable was 18,008 km with a total dispersion up to 385,000 ps/nm. To the best of our knowledge, this is the longest transmission (and highest mitigated dispersion) on a deployed subsea cable with live traffic. Although the results were achieved in part due to the recent availability of high performance FEC in real-time transponders, numerical simulations show that EEPN tolerance of subcarrier modulation further improved SNR versus single carrier systems; confirming a result expected from theory.

6. References

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