IMPROVED SUPERCHANNEL SPECTRAL EFFICIENCY ON A TRANSATLANTIC LINK USING REAL TIME DUAL-CARRIER FEC GAIN SHARING

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Abstract: Coherent optical carriers on a dispersion managed subsea link with a zero-dispersion wavelength (ZDW) can have high nonlinearities near zero dispersion of the transmission spectrum. Independent carriers will thus experience a large variation in Q performance vs wavelength near the ZDW, and some may fall below the commissioning limit for a system. By pairing the best carriers with the worst carriers in a superchannel using a single modulation format and dual-carrier SD-FEC gain sharing, weak channels can be pulled above the commissioning limit, delivering improved spectral efficiency. In addition, modeling shows that total system capacity can be increased by using FEC gain sharing in systems with widely varying channel performance.
The experiment was performed with a real time DSP on a dispersion-managed transatlantic link. The robustness of this technique is demonstrated by lowering the power of the worst carrier well below its single carrier FEC limit, down to the paired subcarrier FEC limit. The rest of the DSP processing for this carrier remains stable even in this highly nonlinear and low OSNR environment.

1. INTRODUCTION

Hybrid modulation formats are an effective way of increasing the capacity of optical fiber links by increasing the granularity of the capacity per carrier[1]. However, the variable rate per carrier may lead to operational complexities when provisioning fixed rate clients or migrating capacity from carrier to carrier.

Multi carrier joint digital signal processing (DSP) has also been gaining interest as a technique to enable higher capacity superchannels[2] with dual-carrier FEC gain sharing being an effective strategy to increase the capacity of superchannels in submarine cables[3].

In this paper, we demonstrate this strategy using production line cards containing multi-carrier photonic integrated circuits (PICs) combined with multi-carrier coherent ASICs[4]. The test was performed over a dispersion managed transatlantic fiber cable containing a high nonlinear region near the center of the repeater bandwidth at the zero-dispersion wavelength.

We validate the robustness of gain sharing by impairing the worse performing carrier to below its single carrier FEC limit. The spectral efficiency for the superchannel with fixed rate carriers is compared to what could be achieved using hybrid modutations

2. FEC GAIN SHARING

By having a single DSP capable of processing two carriers, the FEC can be designed such that it can process the bit streams from both carriers as a single bit stream. The individual carriers' pre-FEC errors can be averaged to calculate the shared

FEC threshold. The carrier with lower performance is thus improved by the carrier with higher performance.

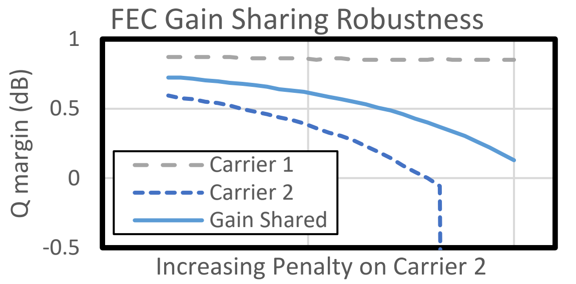

Figure 1: Two sweeps are performed increasing the penalty on Carrier 2. The first is with the FECs run individually, shown in the dashed curved. The second is with a gain shared FEC shown in the solid curve.

The robustness of FEC gain sharing is ensured by having deep interleaving between the two carriers. It is verified in Figure 1 comparing individual FEC vs gain shared FEC while degrading a single carrier. Although carrier 2 is below margin with an individual FEC, it stays above margin when gain shared to carrier 1.

3. TRANS-ATLANTIC CABLE

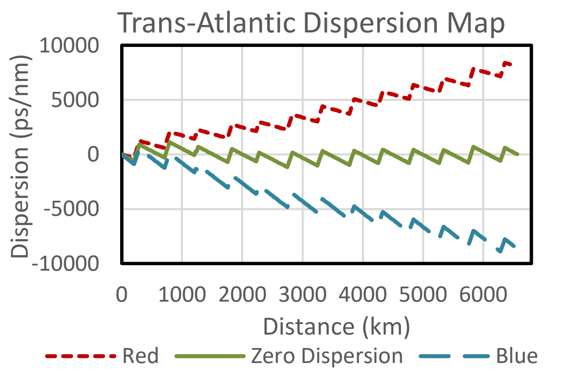

Figure 2: Dispersioned management for OOK designed trans-Atlantic cable. The center of the repeater bandwidth is designed to have zero dispersion, which induces high nonlinearities for coherent carriers.

The demonstration was performed on a ~6500km trans-Atlantic cable designed for transmission of 10G on/off keyed (OOK) carriers. The dispersion map in Figure 2 has zero dispersion in the center of the repeater bandwidth which causes high nonlinear penalties in coherent carriers whose dispersion is better compensated in in the Tx and Rx DSP's. The higher dispersion walk-off on the edges of the repeater bandwidth leads to better performance for coherent carriers. In this paper we analyze the performance and optimize capacity for the region near the dispersion zero.

The repeater power on this cable is fixed and designed for OOK carriers, which have a higher optimum power setting versus coherent carriers. It is important to reduce the power spectral density of the active carriers by loading optical power elsewhere in the repeater gain bandwidth.

4. SLTE SETUP

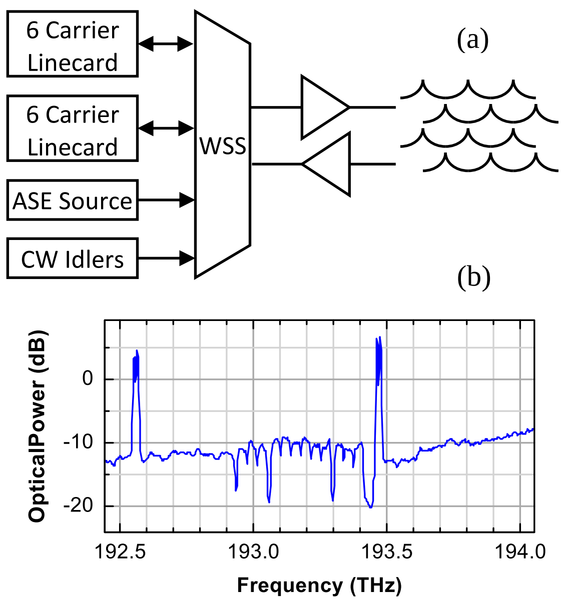

Figure 3: (a) SLTE setup on both sides of transatlantic link consisting of two 6-carrier 33Gbaud linecards, an ASE source and dual pol CW idlers coupled using a WSS. (b) the receive spectrum shows the 6 carriers of the linecard under test surrounded by 3 carriers on either side from the other linecard. The rest of the spectrum is loaded with ASE and dual pol CW idlers.

The Submarine Line Terminal Equipment (SLTE) setup shown in Figure 3a consists of two production line cards with six 33 Gbaud carriers spaced at 37.5 GHz spacing. An ASE source adjusted to the same power spectral density as the carriers is combined with the carriers using a wavelength selective switch (WSS). Since the repeater powers are fixed at the power optimized for legacy 10G OOK traffic, dual pol idlers are used to lower the power spectral density of both the ASE and the carriers by loading both polarizations with high power in a very narrow spectral width to minimize both XPM and XpolM[5]. Both sides of the link have identical equipment setups.

All carriers of the superchannel under test are set to PM-3QAM, which has a capacity of 3 bits per symbol between PM-BPSK and PM-QPSK. It is constructed using the QPSK symbol set, but coded 4 dimensionally to obtain an OSNR tolerance half way between BPSK and QPSK.

5. DEMONSTRATION RESULTS

The zero dispersion frequency is at 193.5 THz, where coherent carriers experience high nonlinearity. Figure 4 trace (a) shows the steep variation of Q caused by the zero dispersion, varying over 1.5 dB within the superchannel width of 225 GHz. If the commissioning limit were 6.7 dB, two of the carriers would have to be converted to run PM-BPSK, for a superchannel capacity of 400G.

The carriers are ordered in such a way that the highest Q carrier is a paired with the lowest Q carrier and so on. The performance achieved by gain sharing the paired channels is shown in the trace (b), where the Q variation across the superchannel becomes negligible. The superchannel capacity is 450G with 6 fixed rate 75G carriers.

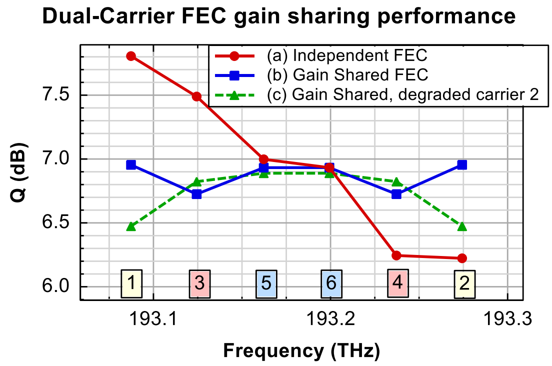

Figure 4: (a) Independent FEC Q measurements showing large Q variations from 7.8 dB to 6.2 dB within a superchannel near the zero dispersion frequency 193.5 THz. (b): FEC gain shared Q measurements of properly ordered carriers. Note the Q's of the paired carriers are identical. (c): Carrier 2 is degraded by lowering its power such that its independent preFEC Q would be below the FEC limit, yet stays well above the FEC limit by being gain shared with carrier 1

Figure 4 trace (c) validates the robustness of FEC gain sharing. As the carrier nearest the zero dispersion frequency is further degraded by lowering its power, such that its independent preFEC Q would be below the FEC limit, its gain shared carrier furthest from the zero dispersion frequency keeps both Q's at 6.4dB, well above the FEC limit. It was also degraded further and the carriers maintained zero post FEC errors until the gain shared Q's were below the FEC limit.

The ability to gain share carriers across the width of the superchannel is accomplished by having 6 fully tunable carriers in a single linecard. The pairing could also be done at larger spectral distances. For example the linecard used for loading is split into two groups of three channels so each pair at a separation of 325 GHz could be FEC gain shared. This separation of frequency improves the tolerance to linear impairments of PMD and PDL[6] as well as nonlinear Q fluctuations.

6. COMPARISON TO HYBRID MODULATION

The carriers on the linecard can have a granularity of 2, 3, 4, 6, and 8 bits per symbol (BPS). In our example with FEC gain sharing all the channels can be set to 3 BPS for a total payload capacity of 450G. With independent FECs, two of the carriers would be set to 2 BPS, losing 50G in capacity.

Transceivers supporting hybrid modulations could also recover the 50G in capacity by having the two bluest carriers set to a BPS of 2.5 and the two reddest carriers set to 3.5 BPS. However, this would result in 3 different capacities per carrier across the 6 carriers. Today's fixed rate clients will make it difficult to utilize these varying capacities, especially when the carriers come from

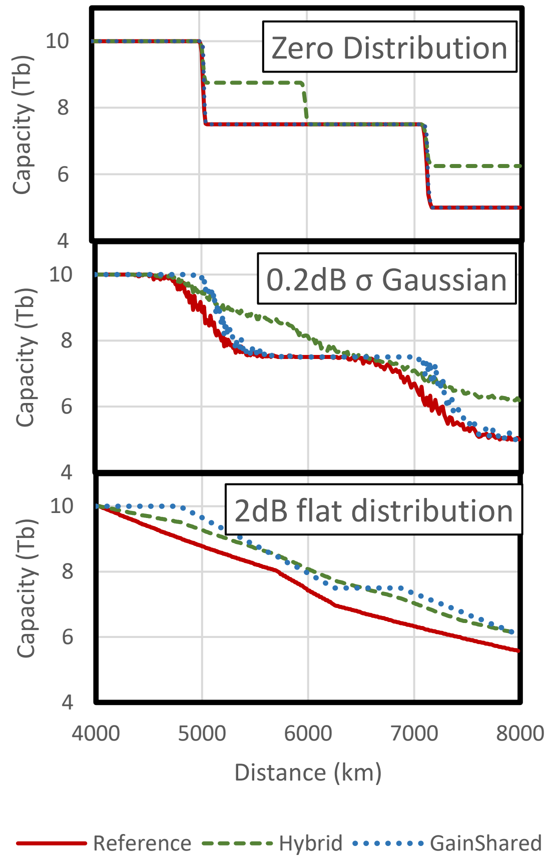

Figure 5: Simulation comparing link capacity of 100 carriers with differing distributions. Reference and Gain Shared have 2, 3, and 4 BPS formats while Hybrid adds 2.5 and 3.5 BPS.

different transceivers. There are also operational complexities when traffic needs to be migrated from carrier to carrier if they each have different payload capacities.
Figure 5 compares link capacities from 100 carriers with QPSK assumed to close 4000 km, 3QAM 6000 km and BPSK 8000 km. With zero distribution, the reference which includes 2, 3, and 4 BPS formats has three different capacities depending on reach. Hybrid formats including 2.5 and 3.5 BPS add two levels of capacity which significantly increase capacity for certain reaches. With no Q spreading, gain sharing does not help capacity. However, when the 100 carriers have a gaussian spread, the capacity vs reach starts to blur. For certain reaches where the average Q values are just above the limit, gain sharing capacities can exceed hybrid capacities, but in general hybrid has more capacity. Finally, when the Q values are uniformly and widely spread, which is more typical of legacy subsea cables, the gain shared capacity exceeds the hybrid capacity for most reaches.

7. CONCLUSION

In this paper, dual-carrier FEC gain sharing has been demonstrated using production linecards on a trans-Atlantic dispersion compensated submarine cable. FEC gain sharing was shown to reduce the 1.5dB Q variation across the 6 channels to a negligible variation allowing all 6 carriers to be set to the same modulation format. For legacy subsea cables, higher capacity is achieved by proper ordering and placement of the superchannel carriers, gaining the capacity advantages of mixed rate formats while keeping the operational efficiencies of fixed rate formats.

8. REFERENCES

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