THE FUTURE IS NOW - MAXIMIZING SPECTRAL EFFICIENCY AND CAPACITY USING MODERN COHERENT TRANSPONDER TECHNIQUES

Neal S. Bergano, Georg Mohs, and Alexei Pilipetskii
Email: nbergano@subcom.com

TE SubCom, 250 Industrial Way West, Eatontown, NJ 07724

Abstract: Our industry is in the midst of a technology paradigm shift rivaled only by the switch from electro-optic repeaters to erbium-doped fiber amplifiers. The evolution of transponder technology from direct detection to coherent techniques has already allowed a 5-10x increase in capacity that can be offered on new transoceanic length cables. Our system research laboratories now leverage the signal processing techniques that will allow the next leap in capacity. In this paper we discuss these areas of forward looking research that may enable the next generation undersea systems and the capacity to alter future networks and applications.

1. INTRODUCTION

State-of-the-art undersea cable systems can exploit the full 40nm (or 5THz) transmission bandwidth of Erbium-doped fiber-amplifiers to transmit data over transoceanic distances [1]. TE SubCom's transponders using dual-polarization QPSK modulation allow newly built systems to operate at spectral efficiencies of 2 to 3bits/sec/Hz; thus, achieving a total capacity of 10-15Tb/s per fiber pair. In our system research laboratories we have already demonstrated the next 2-3x in capacity increase above and beyond the first generation of coherent technology. We believe that the capacity of undersea systems will continue to increase with anticipated improvements in coherent transponders and potentially disruptive technologies in fibers and optical amplifiers. In this paper we will explore what capacities will be possible in the next generation of undersea cable systems.

2. SPECTRAL EFFICIENCY LIMITS USING QPSK

The Optical Internetworking Forum's (OIF) original 100G physical layer proposal used dual-polarization QPSK at 50GHz channel spacing yielding 2bits/sec/Hz spectral efficiency [2]. Theoretically this format should be able to operate up to a spectral efficiency of ~4bits/sec/Hz (less the FEC overhead) before large transmission penalty sets in. We explored the operation of the QPSK format in the range 2-4bits/sec/Hz spectral efficiencies. Figure 1 shows the measured and simulated Optical Signal-to-Noise Ratio (OSNR) required for a 100G channel to achieve a Q-factor of 10dB as a function of channel spacing [3]. The "knee" in the curve occurs at the so-called "Nyquist" spacing, where the channel spacing is equal to the symbol rate. Using 7% FEC overhead a spectral efficiency of ~3.6bits/sec/Hz was achieved at low OSNR penalty.

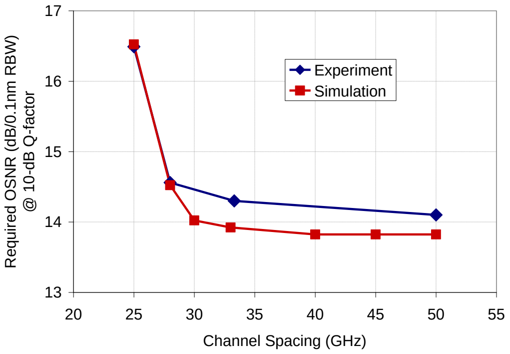

Figure 1 - Required OSNR (in 0.1nm RBW) for 10dB Q-factor vs. channel spacing

Using this Nyquist spacing we performed a wide-bandwidth transmission experiment where we transmitted 112x100G channels over 9,360km spaced at 28GHz giving a spectral efficiency of 3.6bits/sec/Hz. Figure 2 shows the performance across all channels with more than 2dB of margin above the FEC threshold. In this body of work we also introduced the concept of spectrally constrained transmission formats (for large spectral efficiency) in concert with multi-symbol detection (to reduce inter-symbol interference) [4]. Using these techniques we also showed that it was possible to reduce the channel spacing below the Nyquist spacing, with anticipated large transmission penalty.

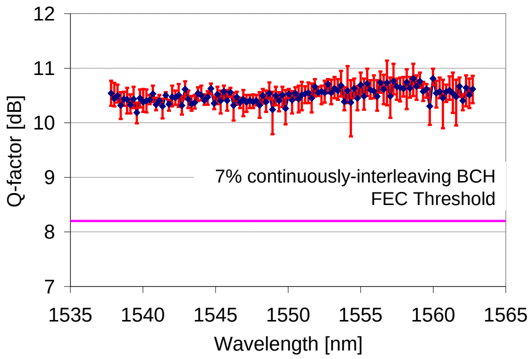

Figure 2 – Q-factor vs. wavelength for 112x100Gb/s over 9,360km

3. MOVING BEYOND QPSK

A higher order modulation format is needed to move beyond QPSK's ~4bits/sec/Hz spectral efficiency limit [5, 6, 7]. Many in the industry have been studying Quadrature Amplitude Modulation (or QAM) to achieve higher spectral efficiency. Using a similar argument as in figure 1, 16QAM for example should be able to operate at twice the spectral efficiency of QPSK, or about 6.7bits/sec/Hz assuming 20% FEC overhead. One potential problem making the transition from QPSK to higher-order QAM is the inherent increase in OSNR required to maintain constant bit error ratio (BER) performance. Figure 3 shows this characteristic for several QAM formats.

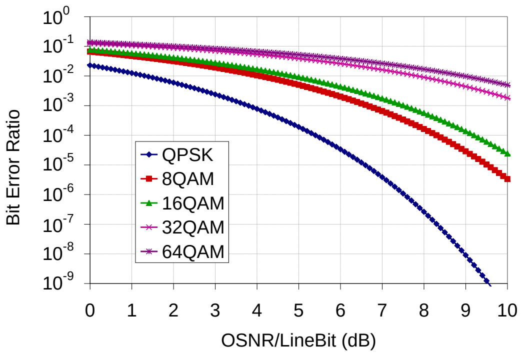

Figure 3 – BER vs. OSNR per bit for different formats

Using 16QAM requires ~3.6dB greater OSNR per information bit to achieve the same BER performance in the neighborhood of 10^{-2} BER with respect to QPSK. This added penalty makes it challenging to move beyond the capacity given by QPSK.

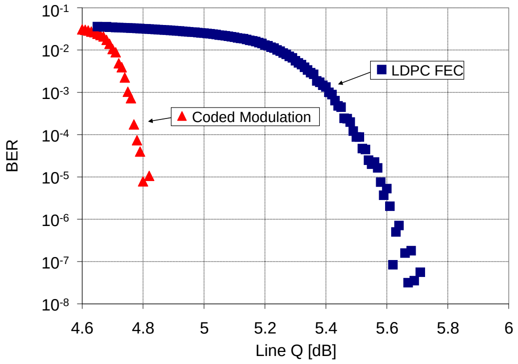

Figure 4 – FEC "waterfall" curve and receiver BICM-ID decoder schematic

To address this challenge, we used the 16QAM format in combination with an error correcting code in order to reduce the required OSNR for large spectral efficiency modulation formats. Further signal processing steps included a maximum a posteriori (MAP) detection algorithm with a single parity check code. This "coded modulation" [8] allowed us to achieve an FEC "waterfall curve" as shown in figure 4, where the output BER was very low for input Q's ~4.9dB.

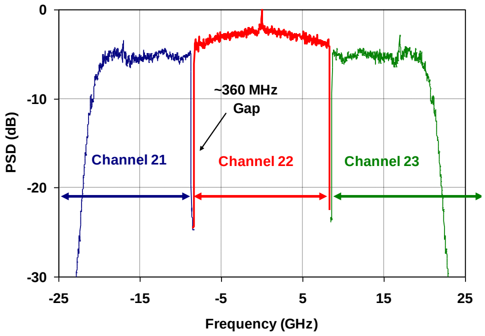

Figure 5 - Spectrum of three adjacent “rectangular” channels

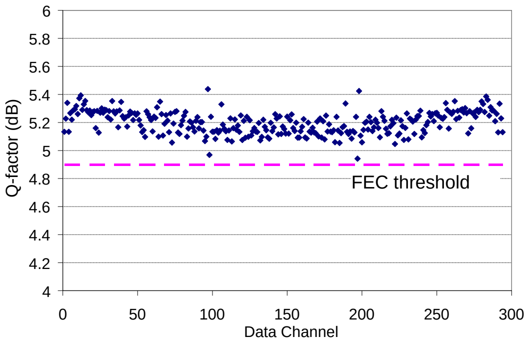

Figure 6 – Q-factor vs wavelength for 294×104 Gb/s over 7,230 km

In addition to these receiver techniques, digital signal processing can be applied at the transmitter to “engineer” the transmitted spectrum to achieve maximum spectral efficiency [9]. Using a digital to analogue converter at the transmitter makes it possible to design the transmitted spectrum of a signal to be approximately rectangular; thus, minimizing channel cross-talk. For example, the center red part of figure 5 shows the spectrum of a 100G channel “shaped” at the transmitter to have a rectangular spectrum so that neighboring channels can be placed very close, without overlapping. Here the channel separation between 100G channels is only 360MHz, and the transmitted spectrum was shaped to be nearly flat. In this example the gap between WDM channels is simply a practical limitation of the setting accuracy of the lasers used in the transmitter.

The usefulness of these techniques has been demonstrated with a transoceanic length transmission experiment where we transmitted 30.58Tb/s data (294×104Gb/s) channels over 7,230km in 40nm bandwidth with 6.1bits/sec/Hz spectral efficiency (figure 6) [10]. This gave a record 221Pb/s•km capacity-distance product. Here we note that the spectral efficiency achieved is 3 times larger than the 2bits/sec/Hz spectral efficiency given by the first generation of coherent transponders.

4. WHAT’S NEXT - THE CLOUDY CRYSTAL BALL

Several physical effects collaborate to make it difficult to increase the spectral efficiency of long-haul transmission systems. We have already talked about the increase of required OSNR for higher-order modulation formats as shown in figure 3. Another difficulty is the nonlinear nature of the transmission line. In the new paradigm of +D fiber spans we have observed that nonlinear penalties scale in such a way that there is an optimum power spectral density independent of spectral efficiency. [11] At first glance this would seem to indicate that it is difficult (or impossible) to make further improvements in capacity. However, we note that optimum power spectral density still depends on fiber parameters such as effective area and attenuation.

To improve fiber performance much beyond the current state-of-the-art may require a fundamental change in fiber design and manufacturing techniques. A possible path to very low loss and more linear fiber might be through photonic band-gap engineering using “air-core” fibers. [12]

Another way to increase cable capacity is to add more optical paths in the same physical cable/repeater space. This might be accomplished by using multi-core single-mode fibers, or perhaps a single core fiber that supports multiple modes. [13]. Clearly, these techniques are not yet ready for deployment. At this point there are no fundamental limitations preventing capacity growth using these techniques; however, there are many engineering and technology challenges that need to first be solved.

5. SUMMARY

It's quite remarkable to witness the growth in capacity given by coherent transponders. Back in the 1960's and 1970's it was understood that fiber optics could potentially make transmission systems with tera-Hertz of bandwidth. However, in those days it could only be hypothesized how to translate this potential into terabits of capacity. Today, some 40+ years later, we finally have a path to exploiting the massive optical bandwidth in undersea fiber optic cables using coherent technology. We now understand how to increase the capacity of an undersea cable system by ten times relative to the most advanced systems from just a few years ago. New techniques being demonstrated in research labs will ensure the continued growth of transmission capacity that can be commissioned on new systems.

6. REFERENCES

[1] J.-X. Cai et al., "Modern Undersea Transmission Technology," Chapter 25 in Optical Fiber Telecommunications VI Elsevier 2013.

[2] J. Berthold, et al., "100G Ultra Long Haul DWDM Framework Document," 2009 OIF document http://www.oiforum.com/public/documents/OIF-FD-100G-DWDM-01.0.pdf.

[3] J.-X. Cai, et al., "112×112Gb/s transmission over 9,360km with channel spacing set to the baud rate (360% spectral efficiency)," Optical Communication (ECOC), 2010 36th European Conference and Exhibition on , vol., no., pp.1-3, 19-23 Sept. 2010.

[4] J.-X. Cai, et al., "Transmission of 96×100G pre-filtered PDM-RZ-QPSK channels with 300% spectral efficiency over 10,608km and 400% spectral efficiency over 4,368km," Optical Fiber Communication (OFC), collocated National Fiber Optic Engineers Conference, 2010 Conference on (OFC/NFOEC), vol., no., pp.1-3, 21-25 March 2010.

[5] S. Zhang; et al., "40×117.6Gb/s PDM-16QAM OFDM transmission over 10,181km with soft-decision LDPC coding and nonlinearity compensation," Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2012 and the National Fiber Optic Engineers Conference, vol., no., pp.1-3, 4-8 March 2012

[6] X. Liu; et al., "Generation and FEC-decoding of a 231.5-Gb/s PDM-OFDM signal with 256-iterative-polar-modulation achieving 11.15-b/s/Hz intrachannel spectral efficiency and 800-km reach," Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2012 and the National Fiber Optic Engineers Conference , vol., no., pp.1-3, 4-8 March 2012.

[7] J.-X. Cai, et al., "25Tb/s transmission over 5,530km using 16QAM at 5.2 b/s/Hz spectral efficiency," Optics Express, Vol. 21, Issue 2, pp. 1555-1560 (2013).

[8] J. Proakis, Digital Communications (4th ed.) McGraw Hill (2001), ISBN 0-07-118183-0.

[9] M. Salsi, et al., “Transmission of 96×100Gb/s with 23% super-FEC overhead over 11,680km, using optical spectral engineering,” Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011 and the National Fiber Optic Engineers Conference, vol., no., pp.1-3, 6-10 March 2011.

[10] H. Zhang, et al., “30.58 Tb/s Transmission over 7,230 km using PDM Half 4D-16QAM Coded Modulation with 6.1 b/s/Hz Spectral Efficiency,” Optical Fiber Communication (OFC), collocated National Fiber Optic Engineers Conference, 2013 Conference on (OFC/NFOEC).

[11] O. V. Sinkin et al., “Scaling of nonlinear impairments in dispersion-uncompensated long-haul transmission,” Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2012 and the National Fiber Optic Engineers Conference, vol., no., pp.1-3, 4-8 March 2012.

[12] N.V. Wheeler et al., “Wide-bandwidth, low-loss, 19-cell hollow core photonic band gap fiber and its potential for low latency data transmission,” Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2012 and the National Fiber Optic Engineers Conference, vol., no., pp.1-3, 4-8 March 2012.

[13] J. Sakaguchi et al., “19-core fiber transmission of 19×100×172-Gb/s SDM-WDM-PDM-QPSK signals at 305Tb/s,” Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2012 and the National Fiber Optic Engineers Conference, vol., no., pp.1-3, 4-8 March 2012.