WELCOME TO 400GB/S & 1TB/S ERA FOR HIGH SPECTRAL EFFICIENCY UNDERSEA SYSTEMS

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Abstract: Coherent detection associated with digital signal processing has been shown recently to be a key enabler of 40Gb/s and 100Gb/s deployment over undersea systems. Increasing spectral efficiency of 100Gb/s systems and providing a channel rate of 200Gb/s or more are key targets for future systems. Some techniques targeting transport of 200Gb/s, 400Gb/s or 1Tb/s channels over transoceanic distances are presented.

1 INTRODUCTION

Polarization division multiplexing (PDM) associated with binary phase shift keying (BPSK) has been shown to be particularly effective for the upgrade of dispersion managed systems using NZDSF and +D/-D fibers [1]. For new builds, advanced undersea systems are now being deployed using only +D fiber with PDM quadrature phase shift keying (QPSK) and advanced forward error correction code. Using QPSK instead of BPSK doubles the number of bits carried by each symbol, and thus the spectral efficiency (SE), although there is a trade-off with the achievable reach [2].

In this paper, we present our view of the evolution of undersea systems in the near future. More complex multi-level modulation formats, e.g. quadrature amplitude modulation (QAM) formats, could increase system spectral efficiency [3] [4] [5]. For instance, 16QAM carries 4 bits per polarization, doubling capacity per symbol compared to QPSK, while 8QAM carries 3 bits per polarization. Our analyses presented in this paper quantify the reach and margins provided by these solutions.

Increasing channel count is also a key to raising total undersea cable capacity. Here, advanced pulse shaping techniques, called root raised cosine (RRC) with narrow roll-off factor, are presented as a means to reduce channel spectral width to be close to the modulation speed (in GHz) in order to pack channels very densely.

Both techniques are combined to increase spectral efficiency and thus cable capacity to be close to fundamental limits. In order to support new client rates such as 400Gb/s and 1Tb/s, two or more wavelengths, densely packed within a superchannel, are used.

2 200GB/S PDM-QPSK WITH INCREASED SYMBOL RATE

In order to reach 200Gb/s over ultra long haul distances, we investigated the impact of increasing the symbol rate of a QPSK signal from 28Gbaud up to 56Gbaud. [6] Doubling the symbol rate induces a signal spectrum twice as wide. Channel spacing has thus been doubled from the standard 50GHz to 100GHz. The same transmission line based on Erbium doped fiber amplifier (EDFA) and span of EX2000 fiber has been used in both cases. The experimental results were in line with theoretical expectations [7], with similar performance being observed.

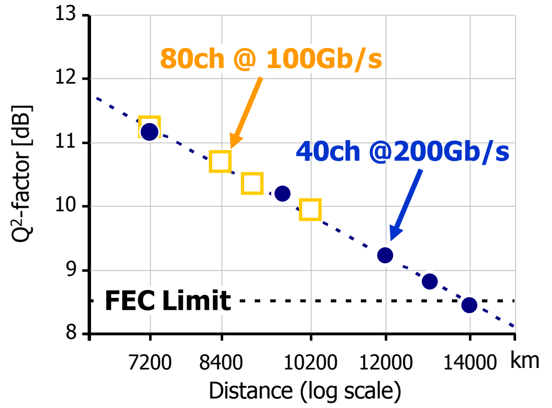

Fig. 1 : Transmission quality (Q²-factor) as a function of transmission reach for 100Gb/s and 200Gb/s

At 200Gb/s, all measured channels exhibited Q²-factor above the FEC limit, indicating an error free transmission at 12,000km distance.

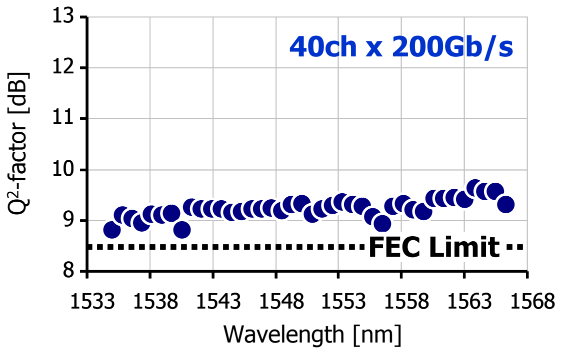

Fig. 2 : Transmission quality (Q²-factor) of forty 200Gb/s channels at 12,000km reach

In order to further improve performance, digital non linear compensation can also be implemented.

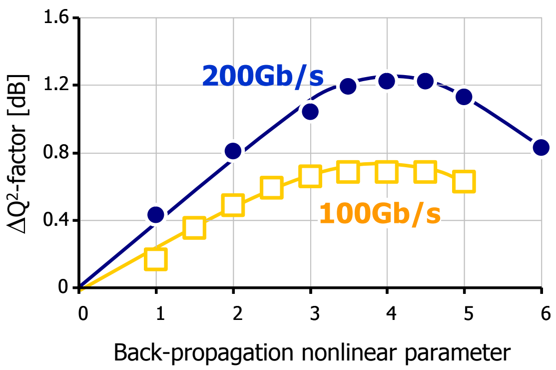

Fig. 3 : Performance improvement achieved using digital non linear compensation

Digital back-propagation compensates the non-linear distortions at each of the 240 spans (or even four times per span for 200Gb/s to have similar chromatic dispersion impact per non-linear step). Here, only single channel non-linear distortions are compensated. As expected, a larger gain is observed for 200Gb/s channel than for 100Gb/s as non-linear compensation is done over a spectrum twice as broad. Nevertheless, this gain has to be compared with the additional complexity required in the DSP. Chromatic dispersion compensation has to be performed 240 times versus a single one in a standard receiver. Even if each of the 240 small steps required has a lower complexity than full chromatic dispersion compensation, the overall complexity is increased by more than one order of magnitude, making the use of such a technique questionable for future undersea coherent transponders.

3 1TB/S SUPERCHANNEL BASED ON FOUR WAVELENGTHS CARRYING 250GB/S EACH RELYING ON 16QAM

In coming years, 1 Terabit Ethernet is a probable successor of 100Gbit/s Ethernet. It is likely that the transport of such a high bit rate will require multi-channels or "superchannel" methods. Here, a possible implementation of a 1Tb/s superchannel is presented using only four wavelengths carrying each 250Gb/s [8].

Compared to state-of-the-art 100Gb/s relying on QPSK modulation and symbol rates between 30 and 32Gbaud to support advanced soft decision FEC, we increased both the symbol rate to 40Gbaud and the modulation complexity by using 16QAM, as shown in Fig. 4, while keeping a wavelength spacing of 50GHz.

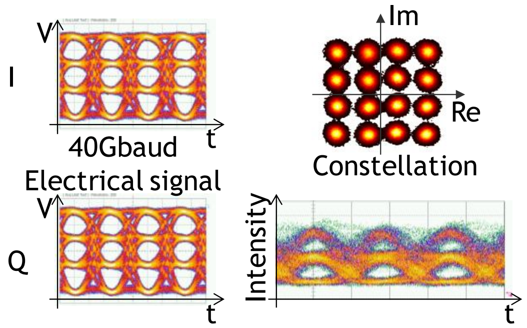

Fig. 4 : Left : Four level electrical signals; Top Right : 16QAM constellation diagram; Bottom Right : Eye diagram of 16QAM signal

By combining four wavelengths, 1Tb/s superchannels were formed and 22Tb/s were transported error free over 2,400km. In Fig. 5, it can be observed that performance in the lower part of C-Band exhibits margins 1dB lower than for wavelength above 1539nm because of non-optimized gain equalization in this region.

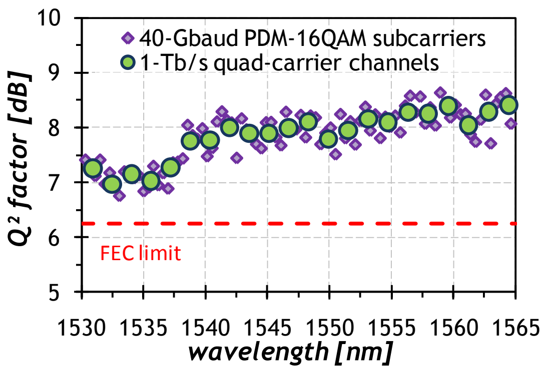

Fig. 5 : Transmission quality (Q²-factor) of twenty two 1Tb/s superchannels, each composed of four wavelengths, over 2,400km

4 ADVANCED PULSE SHAPING AND 8QAM MODULATION

In order to compare the performance of QPSK, 8QAM and 16QAM, a transmitter operating at 28Gbaud, based on 56GSamples/s digital to analog convertor (DAC) was used [9]. We first evaluated the noise sensitivity of the three modulation formats in a back-to-back configuration by using the set-up described in Fig. 6. Specific pulse shaping was applied by digital signal processing (DSP) to reduce spectral width to 1.1 times the symbol rate.

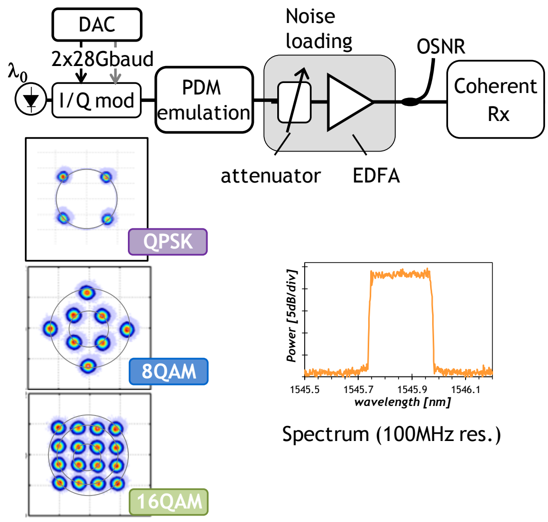

Fig. 6 : 28Gbaud programmable transmitter generating QPSK, 8QAM and 16QAM with a compact spectrum shape

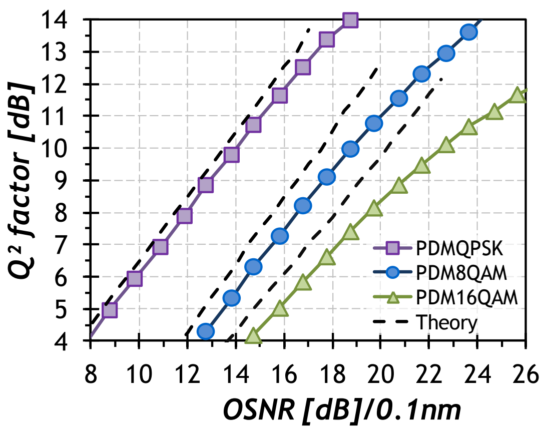

Fig. 7 : Measured OSNR sensitivity for QPSK, 8QAM and 16QAM, each modulated at 28Gbaud

The OSNR sensitivity is shown in Fig. 7. Different bit rates are transported, 100Gb/s for QPSK, 150Gb/s for 8QAM and 200Gb/s for 16QAM, assuming 12% overhead for protocol and FEC. The 100Gb/s PDM-QPSK signal requires an OSNR of about ~14dB for 9.8dB Q²-factor performance (corresponding to 10-3 BER), less than 0.5dB away from the theory. The 150Gb/s PDM-8QAM and the 200Gb/s PDM-16QAM signals are in turn further away from theory and an error floor is observed.

A WDM signal was then sent into a high performance recirculating loop consisting of twelve spans. Each span was composed of Corning EX3000 fiber followed by Corning EX2000 fiber. Channel spacing was fixed at 33GHz for all formats.

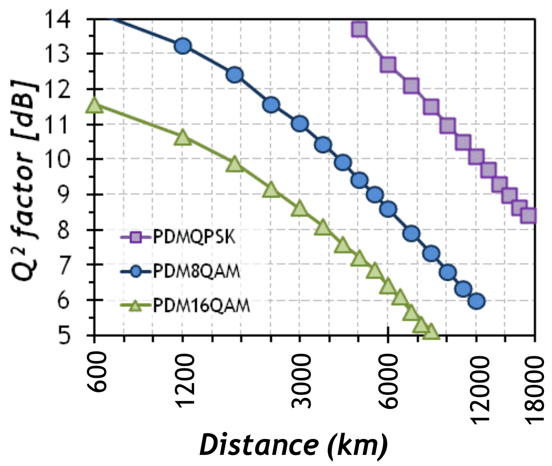

Fig. 8 : Transmission quality as a function of transmission reach for QPSK, 8QAM and 16QAM, each modulated at 28Gbaud.

The transmission quality, expressed by the Q^2-factor, decreases with the distance for all formats but starts from different values, as shown in Fig. 8. At 6,000km, a Q^2-factor around 12.7dB is measured for QPSK, 8.5dB for 8QAM and 6.5dB for 16QAM. Looking at a Q^2-factor of 8.5dB, it can be seen that 18,000km can be crossed with QPSK, while the distance reduces to 6,000km with 8QAM and is limited to 3,000km with 16QAM.

If a high performance soft decision FEC is assumed and a Q^2-factor of 6dB is considered, transmission reach could be considerably increased for 16QAM at 6,600km while 8QAM could reach 12,000km. Nevertheless, it should be kept in mind that some system margins are always required to ensure the 25 year system life of an undersea system.

Another way to increase cable capacity is to raise the channel count. Widening the EDFA bandwidth is now quite challenging, so reducing the channel spacing is an attractive direction. From communication theory, it is known that the channel spacing can theoretically be reduced to the symbol rate without inter-symbol interference and thus no degradation. Our target was thus to investigate a practical implementation with a very small penalty, relying on root raised cosine pulse shaping with a small roll-off factor.

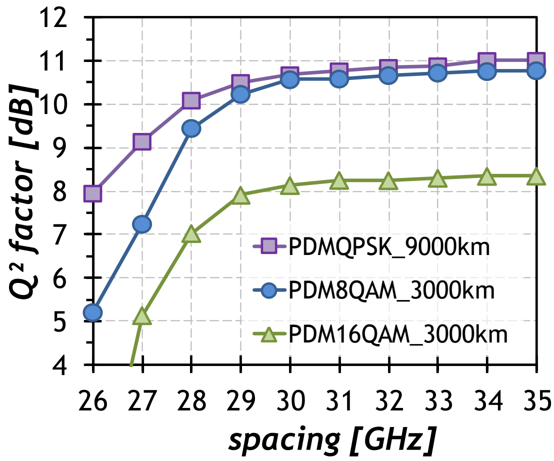

Fig. 9 : Impact of channel spacing on performance for 28Gbaud QPSK, 8QAM and 16QAM

Fig. 9 shows the measured transmission quality for various channel spacings for all three formats using a roll-off factor of 0.1. Almost no penalty was measured when channel spacing was reduced from 35GHz down to 29GHz. When channel spacing was set to 28GHz (i.e. equal to the symbol rate), a penalty of 1dB was observed for QPSK, and slightly more for 8QAM and 16QAM. For channel spacing below 28GHz, complex digital equalization techniques such as maximum likelihood sequence estimation (MLSE) or maximum a posteriori (MAP) could be implemented to reduce the penalty [10].

5 400GB/S SINGLE CHANNEL TRANSMISSION BASED ON 64QAM

One solution to move to 400Gb/s per wavelength requires simultaneously raising the symbol rate to 43Gbaud and increasing the constellation complexity to 64QAM [11]. One key feature demonstrated with this experiment using this high complexity format is a very high spectral efficiency of 8bit/s/Hz, meaning 400Gb/s transport with 50GHz channel spacing.

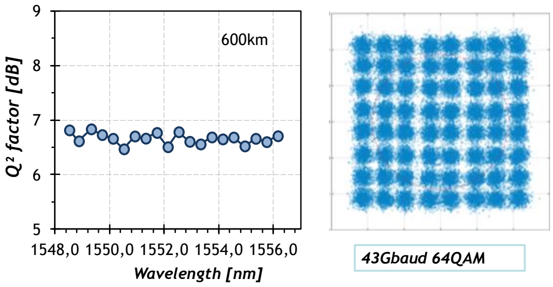

Fig. 10 : Left :Transmission quality measured after 600km. Right : Constellation diagram of 43Gbaud 64QAM

The associated drawback of this very high spectral efficiency is the transmission reach, limited here to only 600km. This reach reduction is in line with the prediction of Shannon's theory, which links spectral efficiency and signal to noise ratio. Fig. 10 shows the performance of the twenty measured channels as well as a measured constellation diagram.

6 CONCLUSION

Current technology based on 100Gb/s with PDM-QPSK modulation and soft-decision FEC is extremely effective to transport data over very long undersea distances. A combination of advanced pulse shaping techniques and QAM formats is required to increase channel bit rate and spectral efficiency beyond today's limit. Moving from QPSK to QAM modulation format significantly reduces the tolerance to linear and non-linear effects, and thus reduces the maximum achievable reach. Use of digital back-propagation to improve transmission reach is questionable when digital signal processing complexity is considered. But improvements in soft decision FEC technologies as well as in transmission fiber characteristics will be welcome to allow propagation over transoceanic distances without compromising system margins. Transport of 400Gb/s and 1Tb/s service over undersea links will therefore almost certainly require multiple sub-carrier, or superchannel, schemes.

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