# SLTE MODULATION FORMATS FOR LONG HAUL TRANSMISSION

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**Abstract:** The invention of new modulation formats and advanced FEC algorithms has enabled data transmission over transoceanic distances with improved spectral efficiency, receiver sensitivity, and tolerance to transmission distortion effects. Coded modulation and time-hybrid modulation offer the capability to implement variable spectral efficiency, which can be used to optimize the overall cable capacity by taking advantage of variations in OSNR versus wavelength. In this paper, we discuss recent experiments using these next generation modulation formats and FEC algorithms, and the resulting implementation issues.

## 1. Introduction

The application of advanced digital signal processing to the field of optical fiber transmission has enabled the rapid deployment of 100 Gb/s coherent systems. Initial deployments with BPSK and QPSK modulation formats resulted in systems with up to 3 bits/s/Hz spectral efficiency and overall fiber pair capacity up to 15 Tb/s. However, further capacity increases over trans-oceanic distances are required.

New modulation formats and advanced FEC algorithms have been developed to achieve the necessary improvements in total capacity and spectral efficiency. Coded Modulation [1] and Time Hybrid Modulation [2] have improved receiver OSNR sensitivity (OSNR error decoding threshold) and tolerance to transmission distortion effects. Both formats can provide variable spectral efficiency (VSE) while operating at a uniform line baud rate. Time hybrid modulation implements VSE by varying the constellation size (bits/symbol). Coded modulation implements VSE by either changing the constellation size or by varying the redundancy in mapping the bits into symbols.

The total capacity of a fiber pair equipped with VSE-capable line cards can be maximized by optimizing the spectral efficiency of each linecard based on the performance of the transmission line. It is well known that receive OSNR can vary across the spectrum, for example due to fiber loss and amplifier noise figure variations. In a recent experiment over a "C+L" transmission path, the spectral efficiencies of the C-band and L-band channels were separately optimized [3]. Another practical example where VSE is very useful is a fiber pair with OADM bands that are routed to multiple landing sites over dramatically different distances. The spectral efficiency of channels on each OADM path can then be independently optimized for the appropriate path length.

Recent product introductions from multiple vendors have implemented VSE with a 50 Gb/s capacity increment, using modulation formats including BPSK, QPSK, 8-QAM and 16-QAM to cover the capacity range from 50 Gb/s to 200 Gb/s. Future product offerings may reduce this step size to 25 Gb/s, using either coded modulation [4] [5] or time hybrid modulation.

## 2. Coded Modulation

In Coded Modulation, error-correction coded binary bits are symbol mapped into higher-order modulation formats. Symbol mapping can also be done on higher dimensionality (e.g. 4-D), and it is referred to as multi-dimensional coded modulation. In any QAM modulation, the basic two dimensions are the in-phase and quadrature components. One way to achieve 4-D is by mapping the symbols on both polarizations simultaneously, 2-D on X-polarization and 2-D of Y-polarization. Alternatively, in order to have linear scaling, time slots can be used to increase dimensionality. For example, a sequence of two symbols is 4-D, and a sequence of three symbols is 6-D. The minimum Euclidean distance between the set of multiple symbols (symbol sequence) can be increased by moving part of the data redundancy from the FEC encoder into the symbol encoder/mapping. Research on coded modulation initial focused on suitable four dimensional (4-D) constellations, but has increased to 6 and 8 dimensional constellations.

Coded Modulation uses the constellation design and symbol mapping to vary the number of information bits per symbol. This allows Coded Modulation to implement variable transmission rates for VSE, while keeping the line baud rate constant. Coded Modulation can also be used to eliminate phase ambiguity to avoid cycle slips in coherent detection, thus enabling absolute phase operation [6].

Coded modulation has been demonstrated over legacy "dispersion-managed" fiber pairs with low accumulated dispersion, and over newer "D+" fiber pairs with high accumulated dispersion. For example, coded modulation was used to transmit PDM-QPSK over 6,370 km of dispersion managed NZDSF using absolute phase [7]. The experiment was done using a loop with 45 km spans as shown in Figure 1. The figure also shows the accumulated dispersion.

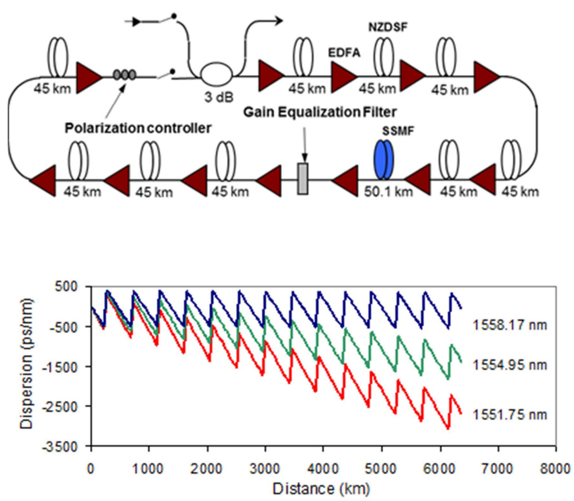


**Figure 1. Experimental configuration with a 45 km span length, 28 nm bandwidth EDFAs, and NZDSF fiber spans.**

The experimental results are shown in Figure 2. The performance improves for wavelengths away from $\lambda_0$ at 1558.17 nm. The approximately 2 dB benefit of absolute phase (solid diamonds) compared to differential coding (open diamonds) is also shown at 1558.17 nm.

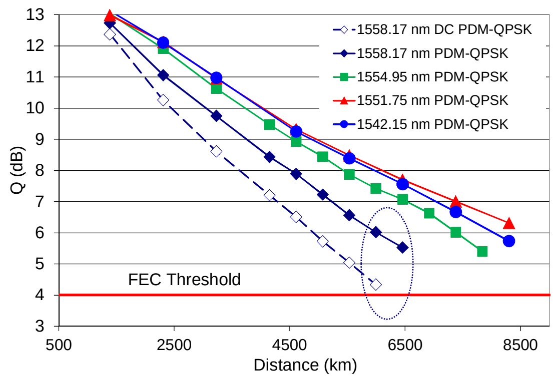


**Figure 2. Q-factor vs. Distance at optimal OSNR**

In another example an 8-dimensional modulation format showed a 1.0 dB improvement over PDM-BPSK for 5,000 km transmission in a dispersion managed system [4]. In this experiment, the received data was decoded with offline processing.

Coded modulation is also useful for newer systems with high accumulated dispersion. A capacity of 54 Tb/s was transmitted over 9,150 km using an optimized hybrid Raman-EDFA system with a total continuous bandwidth of approximately 73 nm [3] [8]. In this experiment, variable spectral efficiency was used to compensate for the variation in system nonlinear OSNR performance. The resulting spectral efficiency was 5.40 bits/s/Hz for the most nonlinear portion of the C band, and 6.08 bits/s/Hz for the remaining portion of the C-band and all of the L band, as shown in Figure 3.

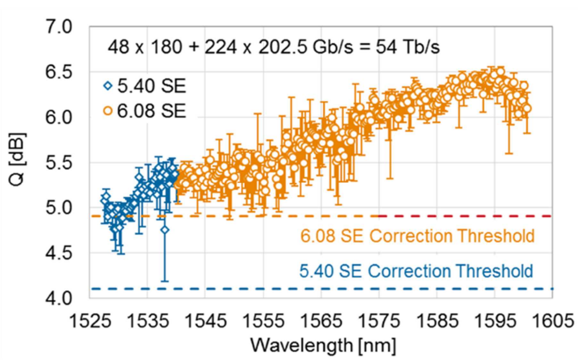


**Figure 3. Performance after 9,150 km**

Current work on coded modulation is focused on improving receiver sensitivity at very low signal-to-noise ratio (SNR) in the presence of strong nonlinear distortions. It is expected that coded modulation will be used in the next generation of DSP chips to improve performance for legacy systems, and to provide increased granularity in spectral efficiency.

## 3. Time Hybrid Modulation

Time Hybrid Modulation utilizes a frame of symbols from a combination of two different modulation formats to implement variable spectral efficiency (VSE). The total frame of $(M = M_1 + M_2)$ symbols consists of $M_1$ symbols in the first format followed by $M_2$ symbols in the second format. The VSE is implemented by changing the ratio between $M_1$ and $M_2$. For an example with PDM QPSK and PDM 16-QAM symbols, the resulting capacity is equivalent to PDM 8-QAM when each format is used for 50% of the frame.

The performance of Time Hybrid modulation depends on the number of symbols in each frame and the relative power ratio of the two modulation formats. Simulation results show that for a mix of QPSK and 16-QAM symbols optimization of the frame size and power levels, it is possible to obtain the same performance as the standard 8-QAM modulation format [2].

Successful transmission of 495 Gb/s over 12,000 km with a spectral efficiency of 4.125 bits/s/Hz has been demonstrated using a combination of PDM QPSK and PDM 8-QAM [9]. The transmission signal consisted of ten subcarriers operating at 10 Gbaud each. Each frame was 128 symbols, with 77 symbols of 8-QAM and 44 symbols of QPSK, with 3 extra training symbols for carrier phase recovery. The 8-QAM symbols are uniformly distributed within each frame, with a sequence of two 8-QAM symbols followed by one QPSK symbol. For ease of processing, the Euclidean distances for the 8-QAM and QPSK symbols are designed to be identical, resulting in an 8-QAM-like constellation with unequal constellation occupation probability.

While time hybrid modulation offers maximum flexibility in VSE granularity, there is a transmission performance penalty relative to Coded Modulation. Figure 4 illustrates a comparison between conventional QPSK, 8-QAM or 16-QAM and the two VSE technologies. Coded Modulation is shown implemented with a 16-QAM constellation at 30 Gbaud. Time Hybrid Modulation is implemented with a combination of (QPSK, 8-QAM) for 125 Gb/s, and (8-QAM, 16-QAM) for 175 Gb/s. The Coded Modulation results in a performance improvement over both conventional QAM and time Hybrid Modulation, ranges from a few tenths of a dB for QPSK to 0.7 dB for 8-QAM. This comparison does not include implementation issues related of the complexity of the two techniques.

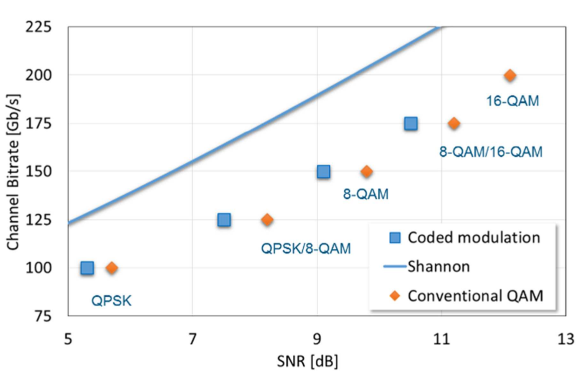


**Figure 4. Performance of Coded Modulation, Time Hybrid Modulation, and Conventional QAM.**

## 4. Forward Error Correction

Forward Error Correction (FEC) with net coding gain (NCG) greater than 11 dB has been a major enabling technology for high spectral efficiency transmission systems. FEC can also be used to achieve VSE by utilizing variable FEC overheads together with a large constant-size modulation constellation [10]. In some cases, this technique may achieve superior results in approaching the Shannon limit when compared to coded modulation, but lacks the improved tolerance of transmission distortion effects. Moreover, the hardware complexity of including multiple FEC overheads may be prohibitive in products, especially when including larger number of possible bit rates on the same line card.

On transmission fiber pairs with OSNR variation versus wavelength, line cards with modulation-based VSE capabilities can adjust the data rate to match the actual channel OSNR. A FEC-based approach is referred to as "joint-FEC coding", where FEC coding is implemented over two channel wavelengths [11]. The FEC decoder algorithm operates on the average BER over the two channels, so that pairing one high performance and one low performance channel boosts the overall BER and allows the poorer channel to operate at a higher data rate.

## 5. Advanced Digital Signal Processing

The techniques discussed above require increased DSP hardware complexity, and can impose tradeoffs between the achievable

VSE granularity and FEC performance. For Coded Modulation, the required complexity can vary with the dimensionality of the data format, the required receiver sensitivity, and the acceptable latency. For FEC, increasing the decoding iterations can improve the FEC threshold, but also increase the DSP complexity. Looking at the 6-D coded modulation in [3] as an example of DSP complexity, the FEC threshold is determined by iterations within and between the MAP decoder and LDPC decoder.

Coded Modulation utilizes fast equalization techniques to improve tolerance to transmission impairments. The resulting complexity of the equalizer and modulation decoder can be limited by reusing DSP blocks for different spectral efficiencies. This is not the case for time-hybrid modulation formats, where the equalization algorithm needs to be modified for different spectral efficiencies based on constellation sizes.

## 6. Discussion

System owners are already anticipating that advanced modulation formats and improved FEC algorithms will be incorporated in the design of new systems, and are asking for systems to be designed for higher line rates. For example, trans-Atlantic systems are now being designed with higher output power repeaters.

A significant issue for practical usage of VSE is the resulting non-standard data rates. For example, a channel operated with PDM 8-QAM at a line rate of 30 Gbaud has a capacity of 150 Gb/s. This capacity must then be mapped into standard client interfaces, whether 10 Gb/s, 100 Gb/s or a multiplexed flex Ethernet interface using 25 Gb/s or 50 Gb/s.

An additional client interface design issue is how to distribute the framer and cross connect functions. Building these functions into the next generation of DSPs adds to the complexity of the chip, but can also reduce the overall linecard cost by eliminating an additional FPGA or framer chip. The move to 17 nm chip process technology should provide sufficient gates to implement the new modulation formats and FEC algorithms, as well as the framer and cross connect functions. These chips should be reaching the market in 2017.

## 7. Conclusions

Extensive research has developed new modulation formats and FEC algorithms for optimizing linecard spectral efficiency and total fiber capacity. These techniques are currently being implemented in the next generation of DSP chips, allowing the undersea cable industry to continue increasing the total capacity of both existing systems and new cables.

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