# ADVANCES IN SUBMARINE LINE TERMINATING EQUIPMENT (SLTE): PRESENT STATUS AND FUTURE DIRECTIONS

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**Abstract**: Advances in SLTE, primarily the introduction of Coherent Technology, has been largely responsible for the tremendous increases in submarine system capacity that we have experienced over the past decade. Coherent Submarine Line Terminating Equipment (SLTE) transponders have allowed the transition from 10 Gb/s channels to 100 Gb/s channels and now 400 Gb/s channels, at near Nyquist channel spacing. The virtually unlimited dispersion compensation ability of coherent has also enabled the adoption of large area, positive dispersion fibers.

## 1. INTRODUCTION

We have witnessed a revolution in submarine systems over the past 20 years. System capacity has increased by 50 times while the cost per bit of transmission has decreased over 20,000 times. (referenced to 10 Gb/s NRZ/RZ SLTE in the early 2000s).

It can be argued that SLTE has been the driver behind these impressive advances. This is especially true because of the introduction and rapid acceptance of coherent based SLTE transponders 10 years ago. The adoption of large area, positive dispersion fibers is also responsible for these gains, but the use of these fibers are entirely enabled by the nearly unlimited chromatic dispersion (CD) compensation ability of coherent SLTE.

## 2. INCREASING CAPACITY IN SUBMARINE SYSTEMS VIA SLTE

There are four main axes for SLTE that have been leveraged to increase the capacities of submarine systems: coherent dual-polarization constellations, increasing symbol rates, subcarrier optimization, and advanced coding techniques. These are shown schematically in Figure 1.

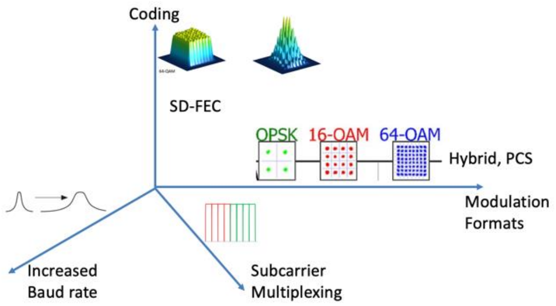


**Figure 1: Four optimization axes of SLTE techniques for increasing capacity.**

The suite of available coherent constellations have exploded in complexity and creativity since the first coherent SLTE transponders. The first generation of coherent transponders focussed on 3 main constellation format choices (QPSK, 8QAM, 16QAM), while modern day transponders now offer on the order of 30+ discrete modes to choose from, using techniques such as probabilistic constellation shaping (PCS) hybrid constellations, and multi-dimensional coding (4D or 8D). [1] These are no longer able to be described by common square constellation shapes but are rather characterized by capacity per wave at a given baud rate and spectral occupancy.

Increases in baud rate has played a significant role in the cost per bit optimization of coherent SLTE. Early coherent solutions had baud rates on the order of 30-35 Gbaud, while today they are available with baud rates on the order of 70-90+ Gbaud. [1] High baud rate SLTE enables higher capacity in a single wavelength, occupying more optical spectrum per wavelength, therefore requiring fewer transponders to fill a fiber pair. This lower quantity of transponders per fiber pair brings with it the promise of decreased cost, power and space per Tb/s, as well as a benefit in decreased operational complexity.

Increased baud rate in SLTE transmission, with all of the advantages noted above, run counter to the idea that transmission penalties in fiber are optimized at lower baud rate, as shown in Figure 2. [2] The use of digital subcarriers in high baud transmission can offer the best of both worlds. Subcarriers in principal can be coded with different mixtures of constellations within high baud rate waves. Extremely robust clock recovery has been demonstrated by associating the clock recovery tone with an inner subcarrier, allowing tighter packing of channels and thus offering improved spectral efficiency. Digitally shaped Nyquist carriers with small alpha factors have also been demonstrated via locking a group of wavelengths to a common wavelocker, and hence reducing the inter-wavelength guard bands, similarly improving the overall spectral efficiency. Subcarriers have also been shown to exhibit an increased nonlinear tolerance in transmission. [3]

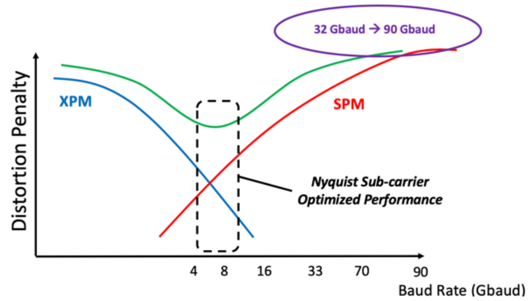


**Figure 2: Optimum baud rates for transmission.**

Coding is the fourth main axis in SLTE optimization. Advances in SD-FEC have been impressive, with net coding gains of 12-13 dB being currently available. The emergence of PCS is an additional method of providing additional coding overhead. Optimization of transmission with PCS based constellations has shown that the optimal results are obtained with a lower FEC overhead (on the order of 20%). [4] It will be interesting to further understand the optimization of coding approaches and whether a common approach emerges. Current SD-FEC implementations already account for 25-35% of the entire gate count of the DSP, so this will surely factor in.

## 3. COHERENT CORRECTION OF TRANSMISSION IMPAIRENTS

The transmission impairments of CD and polarization mode dispersion (PMD) scale rapidly with symbol rate and have previously hindered the adoption of SLTE transponders with baud rates greater than ~10 Gbaud. However, the adoption of coherent electronic dispersion compensation presented the ability to correct nearly unlimited amounts of CD. SLTE transponders are now available that correct >400,000 ps/nm, enabling optimized designs for submarine links in excess of 15,000 km. Likewise, PMD tolerances have increased from a few ps to over 100 ps, essentially erasing this parameter from the list of limiting factors on the already low PMD environment in submarine cables.

In older dispersion managed cables, and in some modern day D+ cable designs, transmission performance is ultimately limited by the nonlinear impairments accumulated in long distance submarine systems. However, progress in nonlinear compensation (NLC) has enabled SLTE transponders to operate effectively in the nonlinear regime, with gains of 0.5 to 0.8 dB being reported. [1] Higher gains require more complex NLC algorithms, such as full nonlinear backpropagation, dramatically increasing the complexity and number of DSP gates required. The recent emergence of Spatial Division Multiplexing (SDM) in submarine cable designs limits the region of operation to a significantly more linear regime, with future designs trending ever further in this direction, and will no doubt influence future implementations of NLC.

## 4. SUBMARINE TRANSMISSION FIELD TRIALS

Recent trials on live submarine systems have demonstrated the recent advances in coherent SLTE. Given the convergence of SLTE performance close to the impending Shannon limit, live trials on demanding submarine links are preferred to optimize and demonstrate SLTE performance. Trials on an empty fiber pair are also preferred because both the primary and looped back transmission distances can be tested.

PCS based SLTE transmission, using offline processing, was first demonstrated on the AEC trans-Atlantic link. The record setting spectral efficiencies of 7.46 b/sHz and 5.68 b/s/Hz were obtained on the one way and round-trip distances respectively. [5] A trial on the 10,500 km SEABRAS-1 system demonstrated a spectral efficiency of 4.66 b/s/Hz with a real time ASIC. [6] Several successful field trials have also been demonstrated on the trans-Atlantic MAREA system. A capacity of 26.2 Tb/s, spectral efficiency of 6.22 b/s/Hz) was demonstrated with commercially available SLTE. [7] A second trial demonstrated a spectral efficiency of 4.61 b/s/Hz on MAREA. [8]

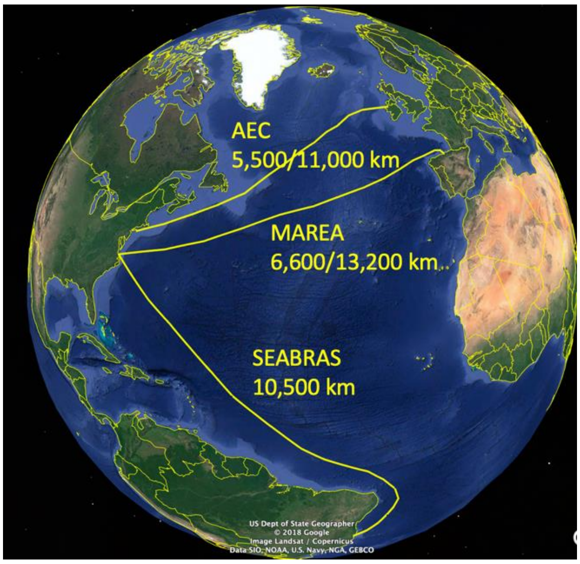


**Figure 3: Cables used for referenced submarine transmission trials**

## 5. FUTURE DIRECTIONS IN SLTE

As impressive as the SLTE advancements in recent years have been, and the dramatic increase in submarine capacities they have enabled, SLTE performance is quickly approaching the fundamental Shannon limit, which dictates the maximum spectral efficiency that can be achieved within a given bandwidth in the presence of noise. As we approach Shannon in the current submarine cable design regimes, each subsequent generation of SLTE offers decreasing incremental capacity improvements. This trend may result in a shift away from the rip & replace model adopted in recent years when cable capacities were significantly increased with each new generation, making it no longer economically viable to do so. This will impact strategies around margin and aging requirements, new cable build cycles, and overall cost per bit build costs required to sustain the bandwidth demand curve being experienced today.

As SLTE technologies converge towards an increasingly narrow gap to the Shannon limit, it is likely that advances and innovations in SLTE over the next several years will focus on pragmatic metrics such as cost, power and space per Tb/s. The emergence of SDM as a means to increase total cable capacity in future submarine systems [9] will likely shift the performance focus of SLTE advancements to optimizations in the linear operation of lower OSNR regimes. In parallel, the trend of increasing fiber count in SDM designs will also drive both the full fill capacities and quantities of SLTE transponders required by a factor of 2-5x or more.

## 6. REFERENCES

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