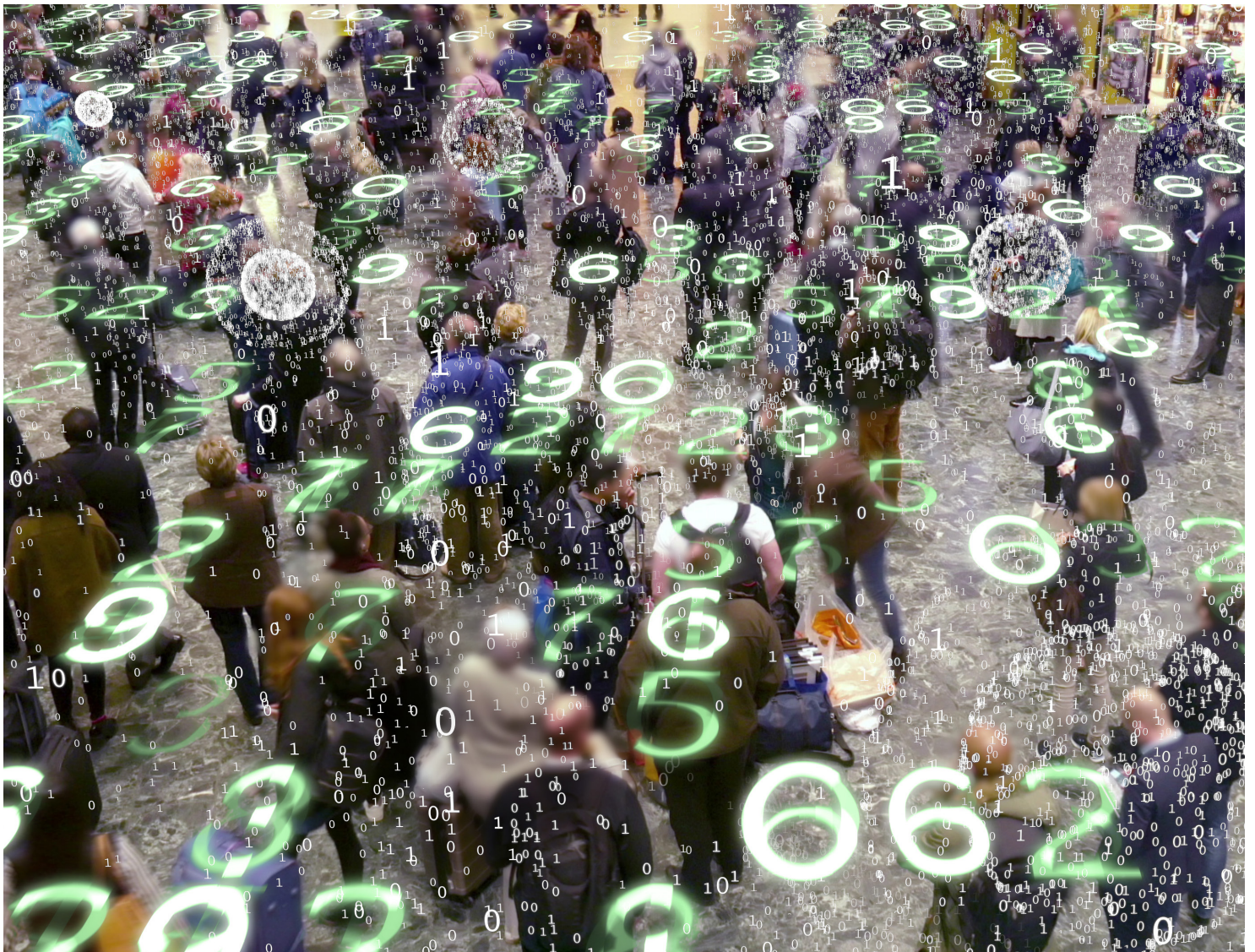


White Paper

Reaching for Shannon's Limit



One of the ultimate challenges and opportunities for the optical networking industry has revolved around achieving Shannon's limit (or capacity), a theoretical maximum rate at which error-free data can be transmitted over a bandwidth-limited and "noisy" channel. In pursuit of higher transmission capacity, the race is always on to develop higher-order and sophisticated modulation techniques, improved and complex constellation shaping, and highly reliable FEC coding schemes applicable to specific use cases that are more tolerant to "noise" introduced by various impairments in optical transceivers, fiber and line systems components. This paper presents a deeper analysis of constellation shaping technique that is more tolerant to fiber non-linearity in the context of relevant use cases for improved optical network design and performance.

Noise and propagation impairments in optical networks come from various sources (See Figure 1). These affect optical performance quite differently depending on the fiber type and its characteristics, including data rate, channel spacing, optical signal power and WDM components (e.g. transceiver, amplifiers). Though linear impairments are commonly compensated for by today's DSPs, non-linear (NL) penalties are more complex, as they primarily come from the interaction of the physical nature of fiber with signal intensity (Kerr Effect). For example, self-phase modulation (SPM) has a higher penalty at lower rates (100 – 200G) as compared to cross-phases modulation (XPM) that affects higher rates (400 – 600G) to a greater degree. NL compensation (NLC) techniques can be implemented and applied in the transmitter and/or receiver with varying degrees of implementation complexity for applicable use cases, with some improvements expected in all use cases (metro, long haul, submarine) except short distance DCI.

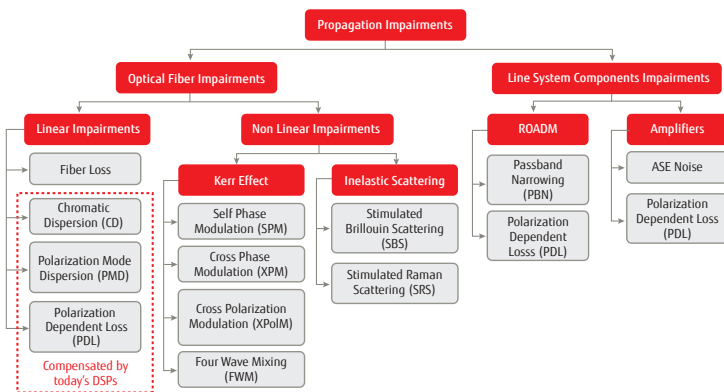


Figure 1: Propagation impairments in optical networks

In general, modulation or baud or symbol rate defines the sample rate of symbols, a higher modulation rate results in higher data rates at the expense of reduced sensitivity at the receiver, thus limiting achievable reach due to higher bit error rates (BER). The receiver has to work more precisely to detect a symbol from a larger set due to higher order modulation, as they start to show up much closer to each other. An increase in order of modulation format also incurs linearly incremental susceptibility to fiber nonlinearities, which is where constellation shaping (CS) can help tremendously in bridging the SNR gap to Shannon's limit, as shown in Figure 2.

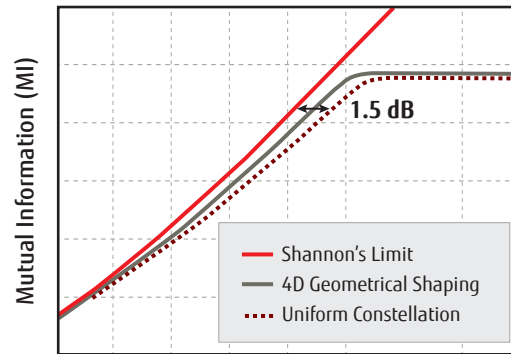
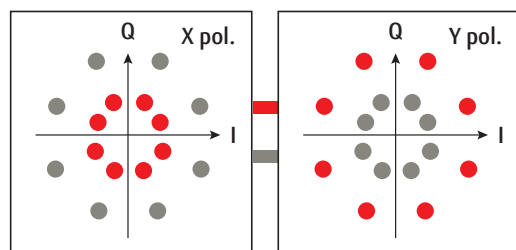


Figure 2: SNR Improvement with 4D Constellation Shaping

Constellation shaping is about how symbols are mapped (or positioned) into a constellation pattern with an objective to achieve larger Euclidean distance (ED) between constellation points (the farther apart points are, the less prone they are to NL noise). They can also be transmitted and received with constant and lower power, making it easier for the receiver to make a correct decision about their precise location, resulting in better OSNR, lower BER and longer reach. Power efficiency (the energy per bit for a given minimum Euclidean distance between constellation points) is also improved by CS that has larger ED.

4D geometrical constellation shaping (used in 4D constant modulus modulation formats, e.g. 2A8PSK) provides better linear and nonlinear performance by arranging the constellation with large Euclidean distances, using X and Y polarization dimensions. Due to the 4D constant modulus characteristics, the power of combined X and Y polarizations is constant at each time slot. This suppresses SPM and XPM very effectively.

In a quadrature modulation format, like 16QAM, there are four different levels of amplitude and two phases (shifted by 90°). The placement of symbols, however, are non-uniform, as two polarizations can be at the same amplitude at any given time, with smaller ED, resulting in large power variations in each time slot. In the case of 4D-2A8PSK (See Figure 3), each polarization (X and Y) has eight phases (8PSK) and two levels of amplitude (denoted by 2 radii $r_2 > r_1$ in each polarization), but only one radius is chosen in each polarization (if r_1 is picked in X, then r_2 is picked in Y). The combination of polarization provides 4D space with 256 possible combinations or constellation points (8 bits per 4D space, $B[0], B[1], \dots B[7]$).



Example of 4D-2A8PSK 3bits/Symbol

Figure 3: 4D-2A8PSK constellation

To further enhance optical performance at the receiver, optimum constellation points can be selected and used. For example, 5b4D-2A8PSK format has a spectral efficiency of 5 bits/symbol by using 5bits $B[0]..B[4]$ as information bits and $B[5]..B[7]$ as parity bits (for better detection). In one study, the effect of modulation format on high fiber nonlinearity was evaluated by a nonlinear transmission simulation conducted using a 2000 km dispersion managed link consisting of 25 spans of 80 km nonzero dispersion shifted fiber (NZDSF) at a rate of 34 Gb/s per channel. Results found that 5b4D-2A8PSK has the higher maximum span loss budget by 1.8 dB over 32SP-16QAM.¹

4D geometrical constellation modulation formats perform better in higher non-linear impairment conditions, especially against SPM and XPM, and can provide longer reach compared to conventional modulation formats. This constellation shaping technique adds to the toolbox available to coherent optical DSPs and system vendors. It allows them to differentiate their products for optimal performance in terms of improved reach and capacity, and narrows the gap as close to Shannon's limit as possible.

References

- [1] Keisuke Kojima, Toshiaki Koike-Akino, Tsuyoshi Yoshida, David S. Millar and Kieran Parsons (December 20th 2017). Nonlinearity-Tolerant Modulation Formats for Coherent Optical Communications, Selected Topics on Optical Fiber Technologies and Applications, Fei Xu and Chengbo Mou, IntechOpen, DOI: 10.5772/intechopen.73031. Available from: <https://www.intechopen.com/books/selected-topics-on-optical-fiber-technologies-and-applications/nonlinearity-tolerant-modulation-formats-for-coherent-optical-communications>

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