Achievable Rates of Space-Division Multiplexed Submarine Links Subject to Nonlinearities and Power Feed Constraints

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Abstract

We study the achievable rates of submarine fiber systems in the high-dimensional design space of variables including span length, launch power, number of spatial channels, and power feed current. We identify the regimes in which nonlinearities or PFE constraints become dominant, and demonstrate that optimized system design evolves toward the linear regime as the system scales to a high number of spatial channels. We calculate the bit rate achievable by uniform and probabilistically shaped M-ary Quadrature Amplitude Modulation constellations to identify potential capacity-achieving implementations.

Key words:

Optical communications, submarine transmission, power feed constraints

Introduction

Submarine fiber systems carry nearly 95% of the data traffic between different countries and continents. The capability to support such massive traffic volume is enabled by space-division multiplexing (SDM). In current submarine systems, SDM is realized as a bundle of single-mode fibers (SMFs).

In long-haul systems, typically the bit rate is limited by amplified spontaneous emission (ASE) noise at low power levels, and by fiber nonlinear interference (NLI) at high power levels. Further limitations arise in modern submarine systems, as a large number of spatial channels are required to maximize the bit rate subject to power feed equipment (PFE) constraints. We apply multi-dimensional optimization to obtain the rate-maximizing design, considering NLI and PFE constraints.

This work was performed in collaboration with the company PadTec S/A and researchers from Stanford University. Our results were published in the Optical Fiber Communication Conference [1] and in the Journal of Lightwave Technology [2] and were also the subject of an article on Unicamp website [3].

Results and Discussion

We consider a submarine cable composed of n_{fp} standard single-mode fiber (SMF) pairs. Each SMF is assumed to support n_{ch} wavelength channels of equal rate, bandwidth and launch power P_{ch} . Signals are amplified by n_r repeaters.

We address the design of submarine links as an optimization problem with the following heuristic objective function:

$$\max_{n_r, n_{ch}, P_{ch}, I} 2n_{fp}n_{ch}C - pn_r$$

where I is the power feed current, C is the mutual information between the input and the output signals, which depends only on the signal-to-noise ratio (SNR), and p is a penalty factor to ensure the uniqueness of the solution. This problem is subject to constraints on the power feed voltage and current, the span length and the number of channels.

Figure 1 shows the results of the optimization problem for

M-QAM constellations and their theoretical upper bound, the Shannon capacity.

Figure 1: Achievable bit rate and spectral efficiency of the optimum design of a submarine link containing 6 fiber pairs. In the figure, PS stands for probabilistic shaping.

Conclusions

The achievable bit rate of submarine systems is limited due to NLI and PFE constraints. The optimum regime of operation depends on the span length, launch power, number of spatial channels, and power feed current. The results for a submarine cable with 6 fiber pairs indicate that the transmission rate of links longer than 7,000 km is already limited by PFE constraints. Capacity analyses show that using PS-64-QAM transmission for links longer than 8,000 km, and PS-256-QAM for links between 1,000 km and 8,000 km, are sufficient to approach the Shannon limit.

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