Experimental Characterization of Power Efficiency for Power-Limited SDM Submarine Transmission Systems

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Abstract We examine fiber capacity per unit amplifier pump power relevant to power-constrained spatial-division-multiplexing submarine systems via extensive amplified transmission experiments and modeling. Our results suggest the utility of amplifier pump powers as low as 20 mW and output powers as low as 6.5 dBm.

Introduction

In order to meet increasing demands for trans-oceanic submarine system capacity, there have been significant recent efforts to deploy more cables with higher capacities[1]. Given the fixed-power-supply nature of submarine cables, significant attention has been focused on maximizing information transmission power efficiency[2]-[5]. This has led to arguments that cable capacity is increased for a given power supply limit by reducing optical amplifier output powers and thus channel signal-to-noise ratios (SNRs) at the receiver, while increasing the fiber pair count in the cable[6]-[12]. This spatial-division-multiplexing (SDM) approach follows from Shannon's capacity formula, in which capacity scales logarithmically with SNR but linearly with the number of spatial paths (i.e., fibers) over which signal power is divided. A recent study considering fundamental amplifier physics and optimizing channel launch power spectra confirmed that capacity is maximized by reducing amplifier output powers[13]. Sinkin *et al.* demonstrated the existence of maximum power efficiency governed by a signal droop effect in constant-output-power amplifier systems[4],[5], a concept that has been expanded and modified to accommodate other noise sources[14]-[16]. Sinkin *et al.* presented the first experimental measurements of power efficiency for an exemplary C+L-band system[4],[5].

In this paper, we follow on the earlier experiments with extensive transmission measurements to evaluate power efficiency expressed in terms of fiber capacity per unit power consumption. We present measurements taken over a wide range of transmission distances and power consumption levels. The optical channels carry 48 Gbaud polarization-multiplexed 16-ary quadrature amplitude modulation (PM-16QAM) or quadrature phase shift keying (PM-QPSK) signals, and we assess capacity by measurement of generalized mutual information (GMI). The power efficiency results are in excellent agreement with theoretical modeling predictions. We present examples estimating total submarine cable capacities and the corresponding number of fiber pairs.

Experimental Set-up

The experimental configuration is shown schematically in Fig. 1. A total of 80 channels were modulated with 48 Gbaud PM-16QAM or PM-QPSK signals on a 50 GHz grid in the C-band. For most experiments, the format was 16QAM. A wavelength-tunable test channel laser with linewidth ~100 kHz was modulated by one dual-polarization (DP) I-Q modulator, while the other 79 channels were modulated by another single-polarization I-Q modulator. A four-channel arbitrary waveform generator (AWG) with bandwidth ~42 GHz and sampling rate of 120 GSa/s created the electrical signals that drove the I-Q modulators to create optical signals having root-raised-cosine (RRC) pulse shaping with roll-off factor of 0.02. All four AWG channels drove the DP I-Q modulator for the test channel, while two of the negative-polarity AWG outputs created a single-polarization signal for the other 79 channels. That 79-channel set was polarization multiplexed by splitting, polarization rotating to orthogonal states, delaying one stream, and then re-combining. All 80 channels were combined and amplified before launch into a re-circulating loop system.

The transmission system in the loop was comprised of six spans of optical fiber (Corning® Vascade® EX3000 fiber) with an average span length of 60.3 km. The fiber effective area was 153 μm^2 and the average span loss was 9.6 dB, including connectors and splices. The first five spans in the loop were followed by erbium-doped fiber amplifiers (EDFAs) built from 6 m of EDF, a single forward-propagating 980 nm

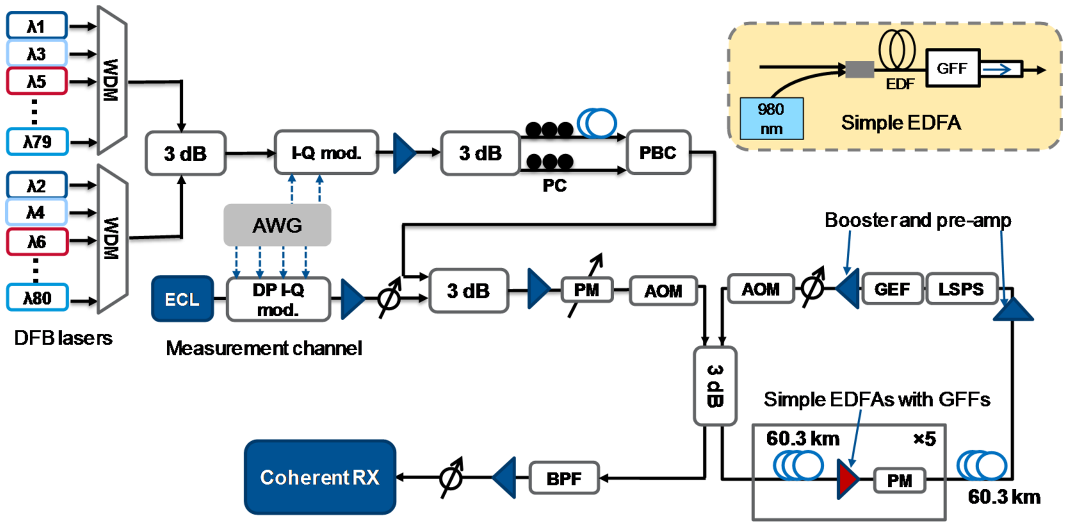

Fig. 1: Schematic diagram of experimental set-up. AWG: arbitrary waveform generator, ECL: external cavity laser, PBC: polarization beam combiner, AOM: acousto-optic modulator, PM: power monitor, BPF: band-pass filter.

pump laser, 980/1550 nm WDM, and a gain-flattening filter (GFF) including output isolator. An inline power monitor followed each EDFA. The GFFs were designed to match the EDFA gain spectrum for a gain of approximately 10 dB, corresponding to the span losses. These simple EDFAs were operated with pump powers set to produce a given total output power. The sixth span was followed by a commercial two-stage EDFA in which a loop-synchronous polarization scrambler (LSPS) and tunable gain equalization filter (GEF) were included in the mid-stage. This two-stage amplifier was not adjusted for different launch conditions. At the output of the loop, the channel under test was selected by a band-pass filter (BPF) and directed into a coherent optical receiver. The electrical output signals were sampled by a pair of 65 GHz bandwidth oscilloscopes with a sampling rate of 160 GSa/s. The waveforms were processed offline using blind digital signal processing algorithms, and GMI was estimated from the recovered signal constellations.

Experimental results

We collected measurement data as a function of transmission distance and EDFA output power. The output powers as indicated by the power monitors and corresponding average pump powers used are given in Table 1. For each output power level, we measured the GMI of 10 equally spaced and representative channels across the full 80-channel plan, for loop numbers in multiples of 5. For the maximum studied EDFA output power of 15 dBm, the transmission distance extended to more than 18000 km, but was shorter for lower output power levels. The results for PM-16QAM transmission measurements are summarized in Fig. 2 in terms of average spectral efficiency (SE) computed for symbol rate R_{sym} and channel spacing Δf as $SE = GMI \cdot R_{sym} / \Delta f$.

Tab. 1: Channel, EDFA output, and pump powers

Channel power (dBm)	EDFA output power (dBm)	Average pump power (mW)
-15	4	14
-14	5	16
-12.5	6.5	20
-10.5	8.5	27
-8.5	10.5	40
-6.5	12.5	60
-5	14	80
-4	15	100

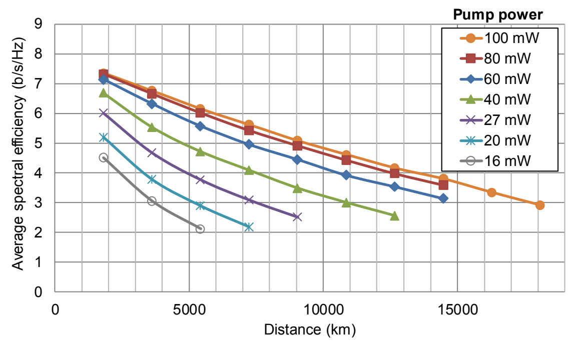

Fig. 2: Average SE vs. distance for different pump powers.

All 80 optical channels were measured for the case of 10.5 dBm EDFA output power and 40 mW average pump power for a subset range of transmission distances. The average spectral efficiency results for all 80 channels were essentially identical to the results found for the 10-channel measurements, providing confidence in the accuracy of the latter data. Results for the 80-channel SE values are given in Fig. 3a for three different link distances.

We next calculated a metric of power efficiency (capacity per unit power consumption) for the range of output powers and link distances. The power efficiency (PE) metric is fiber capacity divided by pump power of a single EDFA, since pump power is directly related to electrical power, as might be facilitated by pump farming[17]. Capacity is given by the average SE multiplied by the 4 THz bandwidth. Results for all PM-16QAM measurements are given in Fig. 3b down to average pump power of 16 mW, illustrating that lower output and pump powers can produce significantly higher power efficiency, depending on link length. Lower pump powers enable higher fiber counts for a fixed power supply. In Fig. 4, we show the measured results at 5430 km and 7240 km against modeling predictions. We included experimental data obtained for QPSK signals at the lowest output power levels, where the model predicts higher capacity and capacity per unit power for QPSK than 16QAM. At 7240 km, one other QPSK data point was also taken at a higher pump power (60 mW) to test model validity. The model employed the generalized signal droop effect[14]-[16] and included accurate measured implementation penalty, or gap-to-GMI, data for both signal formats, as well as optical-to-optical conversion efficiency in the EDFAs. The level of agreement between the measured capacity/power data and the model predictions is excellent and within 10% or better for the range of powers tested.

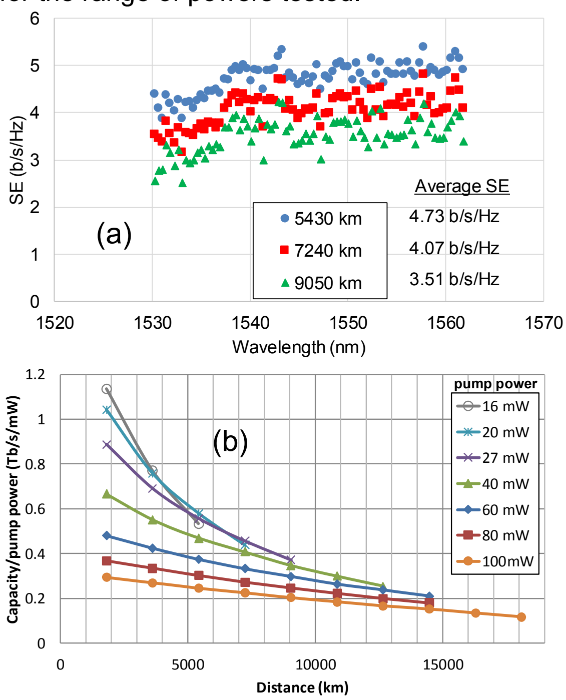

Fig. 3: (a) SE of all 80 channels for 40 mW pump power, 10.5 dBm output power at 5430 km, 7240 km, and 9050 km. (b) Power efficiency vs. distance for PM-16QAM signals.

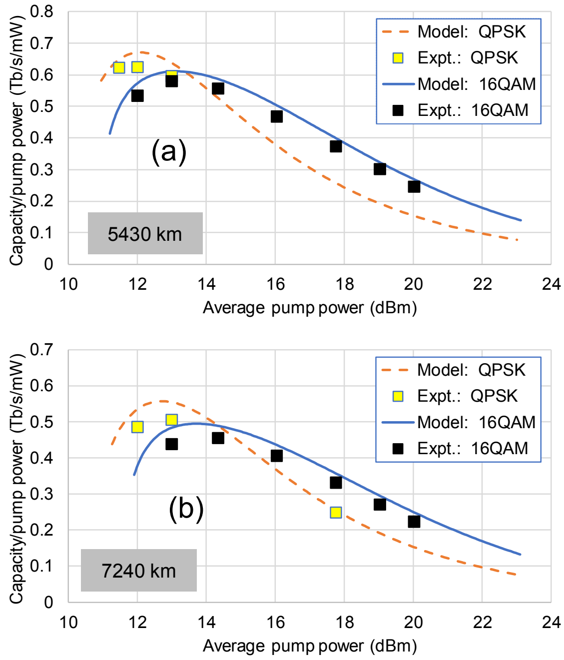

Fig. 4: Measured power efficiency data vs. pump power (pump power on x-axis in units of dBm for ease of visualization) with model predictions for (a) 5430 km and (b) 7240 km.

Summary and discussion

We have built and tested a system to investigate submarine transmission in the regime of fixed electrical power supply by operating simple EDFAs with different output and pump power conditions to evaluate fiber capacity per unit of power consumption. The range of EDFA output powers investigated extends from 15 dBm down to 4 dBm for 80-channel systems, with corresponding pump powers of 100 mW to 14 mW. The measured results agree very well with predictions based on a generalized signal droop model and show clearly that operating at lower channel, EDFA output, and pump powers can significantly increase the power efficiency in terms of capacity per unit pump power. As examples of cable capacities predicted by the measured and modeled data, 10.5 dBm EDFA output power (40 mW pump power) may be expected to allow approximately 650 Tb/s capacity over 38 fiber pairs at 7240 km, and more than 200 Tb/s capacity over 17 fiber pairs at 10860 km, under the same realistic power supply and electrical-to-optical conversion efficiency assumptions [9]. An EDFA output power of 6.5 dBm (20 mW pump power) at 7240 km could in principle support 1 Pb/s total cable capacity over approximately 95 fiber pairs.

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