Multicore fiber transmission over transoceanic distances

Alexey Turukhin, Oleg Sinkin, Dmitri Foursa, Maxim Bolshtyansky, and Alexei Pilipetskii

Space-division multiplexing for long-haul submarine transmission increases capacity and improves system power efficiency.

The demand for greater worldwide telecommunication capacity continues to drive research and development efforts in long-haul coherent transmission technologies. Recent transmission experiments have demonstrated that significant improvements to capacity (compared with that achievable in currently deployed long-haul submarine systems) are feasible. These approaches use a variety of technologies, including advanced modulation formats, forward-error correction (FEC), and broadband optical amplification. The use of space-division multiplexing (SDM) offers even greater increases to system capacity and power efficiency (PE).

PE is particularly important in transoceanic transmission systems. Electrical power is typically delivered from the shore-end section of the cable, where high voltages are required to overcome the distribution losses of thousands of kilometers of undersea cable. However, the maximum voltage that can be applied to the cable is limited by the practical considerations put in place by the wet and dry plant designs. These restrictions on cable voltage therefore lead to limitations on the available power per repeater, making PE a significant factor in the design of high-capacity undersea systems.

We have investigated SDM for long-haul submarine transmission with an aim to increase capacity and improve system PE. We have also investigated the limits of capacity achievable with multicore fiber (MCF) and broadband C- and L-band optical amplification technology (i.e., for wavelength ranges of 1530–1560 and 1570–1608nm, respectively).

To experimentally demonstrate a power-efficient transoceanic transmission, we used a 12-core MCF, a power-efficient modulation format, and optimized erbium-doped fiber amplifiers (EDFAs) to achieve an ~22nm transmission bandwidth with an output power of 12dBm. Taken together, these technologies enabled us to demonstrate transmission of a total potential capacity of 105.1Tb/s over 14,352km of 12-core MCF. Furthermore, the total pump power used by the 12 EDFAs in the SDM path is within the 800mW rating of a single pump laser.

Our eight-dimensional (8D) coded modulation (CM) format, based on amplitude-phase shift keying (APSK), is constructed...
from two groups of 4D symbols that are similar, in terms of both constellation shape and number of points, to previously used formats. 11, 12 8D-APSK is a hybrid of a pair of quadrature-phase shift keying (QPSK) symbols and a pair of APSK symbols. An 8D-APSK constellation acquired in back-to-back measurements is shown in Figure 1(b). The polarizion-division-multiplexing 8D-APSK (PDM-8D-APSK) scheme requires an optical signal-to-noise ratio (OSNR) that is ~0.8dB lower than PDM-QPSK for the same FEC overhead and spectral efficiency. This level of receiver sensitivity allows for lower repeater output power and therefore provides better PE.

The transmission path that we used is based on a single 46km spool of 12-core fiber with fan-in/fan-out devices. All 12 cores in our MCF have very similar physical properties (i.e., attenuation, effective area, and dispersion), and the low crosstalk between them allows for the construction of a traditional circulating loop with a single in-loop switch. We used 12 single-mode EDFs to compensate for the loss of each core, as shown in Figure 1(a). The setup includes a loop-specific amplifier, a loop-synchronous polarization controller, and a wavelength-selective switch that performs gain equalization once a loop.

We were able to improve the power efficiency of our single-stage C-band EDFAs by optimizing the width and location of the operating bandwidth. This provides a reduction in gain ripple and makes gain flattening in every amplifier (which adds additional insertion loss and requires more pump power) unnecessary. We obtained Q-factors for each channel from 10 sets of measurements, each containing four million samples, after transmission through 14,352km of MCF: see Figure 2. We processed all data sets independently and decoded them with no errors using our offline digital-signal processing and FEC algorithms.

We found that the results support our claim that the per-core capacity is 8.76Tb/s, corresponding to a 12-core capacity of 105.1Tb/s.13

To investigate the capacity limits that are achievable over transoceanic distances with MCF, a larger optical operating bandwidth is required. In a second experiment,14 we therefore used C- and L-band amplification to demonstrate transmission of 520Tb/s over 8832km. For this demonstration, we combined single-stage C- and L-band amplifiers using band-splitting/combining wavelength-division-multiplexing filters and a 4D CM format (4D-6/8-16APSK). This format achieves a receiver sensitivity improvement of 1.0dB compared to standard 8QAM15 with the same spectral efficiency and 20% FEC overhead. The constellation, recorded in back-to-back measurements, is shown in Figure 3, and transmission results (after traveling through 8832km of fiber) are shown in Figure 4. By transmitting information through 270 channels at 160Gb/s, we achieve a per-core capacity of 43.2Tb/s. This corresponds to a 12-core MCF capacity of 520Tb/s and a capacity-distance product of 4.59Eb/s-km. The difference between the maximum and minimum Q-factors that we obtained from the 10 measurements indicates a good level of system stability.

In summary, we have experimentally demonstrated the feasibility of transoceanic high-capacity transmission over MCF. We have shown that using MCF can simultaneously improve the system capacity and power efficiency of transoceanic transmission systems. In terms of PE, we demonstrated the feasibility of 105.1Tb/s transmission in a 12-core fiber over 14,352km using a power-efficient 8D-APSK modulation format and an optimized

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**Figure 2.** Measured Q-factors for 82 channels after transmission through 14,350km of MCF.

**Figure 3.** A 4D-6/8-16APSK constellation recorded in back-to-back measurements.

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optical system design. By exploring ultimate capacity limits for SDM transoceanic systems, we also demonstrated a potential capacity of 520 Tbps over 8,832 km, with a capacity-distance product of 4.59 Eb/s/Hz using CM, C- and L- band EDFAs, and a 12-core MCF. In the next stage of our work, we plan to further increase the capacity and improve the efficiency of long-haul systems by using cutting-edge technology.

Author Information

Alexey Turukhin, Oleg Sinkin, Dmitri Foursa, Maxim Bolshtyansky, and Alexei Pilipetskii
Department of Transmission Research
TE Subcom
Eatontown, NJ

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