Vision for Next Generation Undersea Optical Fibers and Cable Designs

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Abstract *In the on-going quest for higher capacity undersea transmission systems, significantly higher capacities can be achieved with existing field-proven, highly reliable cable designs by using advanced fibers that are ultra-low loss, bend insensitive, and more compact. The introduction of multi-core fiber in the future would continue this trend.*

Introduction

Throughout the history of undersea optical communications, system capacity increases were primarily achieved through increased capacity per fiber pair using higher bit rate transmission formats [1]. As capacities increased into the 100's of Gb/s per fiber pair, more electrical power was needed for the submerged repeaters to amplify the higher power optical signals [2]. This need to supply more power to the repeaters on the sea bottom drove toward lower electrical resistance cables, a costly endeavor. In addition, to reduce non-linear optical impairments, these high-power systems used premium fiber with the lowest attenuation and largest effective area, again somewhat costly.

Recently a more efficient undersea system design approach has been adopted. In order to use optical power more efficiently, increase capacity, and achieve reduced cost per bit, the undersea industry is progressing to a Space Division Multiplexing (SDM) approach with single mode fibers utilizing less power per fiber pair with higher overall larger fiber count [3-8].

This more linear SDM approach has allowed the use of moderate effective area fibers (80-130 μm^2), which have been designed to minimize micro-bending loss, allowing for higher fiber packing densities within existing cable structures. Since the optical power is lower in each fiber pair, the system power can be shared among more repeater optical pumps [9] to improve power utilization efficiency and reliability. This paper examines the current direction in overall optimization of cable and fiber solutions that can achieve $\gtrsim$1Pb/s overall cable capacity for all but the longest transmission distances with existing, field-proven and highly reliable cable designs.

Field-Proven Cable Designs

Reliability is paramount in undersea systems, and field-proven cable designs ensure long term reliable operation.

The long haul undersea industry has used highly reliable and mechanically stable cable structures for decades. Typical cable structures shown in Fig. 1 are comprised of fibers buffered in gel at the center of the cable. In some cases this central core structure is contained by an extruded plastic tube or a thin steel tube. This central optical core structure is protected by a secure, hydrostatic pressure-resistent vault consisting of either 8 steel wires forming a locking circular arch or by a thick-walled, three-piece segmented steel tube. Additional strength is provided by a surrounding layer of wires. Typically, a welded copper tubular sheath is formed around these strength wires for electrical conductivity, over which a polyethylene insulating layer is extruded to finish the deep water Light Weight (LW) cable structure. This cable design structure has been fully field-proven through decades of undersea system deployments.

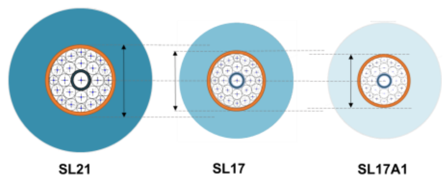

Figure 1. SubCom's Field-Proven SL Cables

Options for Next Generation Capacity Increases

System capacity is a function of the number of fibers in a cable, transmission bandwidth, and achieveable spectral efficiency per fiber pair, thus increasing the number of optical paths/fibers in a cable is critical. A larger number of optical paths also leverages the power efficiency of the SDM system design approach.

Cable size is a major factor that defines the fiber count. For repeatered long haul systems, typical LW cable outer diameters range from ~17 mm to 21 mm. Larger outer diameter cables are typically more costly in materials, and also in installation, since additional shiploads and transits may be required to install a specific route. Here, for simplicity, we study the capacities of three SubCom cables ranging from smallest to largest: SL17-A1, SL17 and SL21 with electrical conductivities of 1.3, 1.0 and 0.7 ohms/km, respectively. We study capacities for higher fiber packing densities and more compact fibers, as well as provide an initial estimation for multi-core fibers.

Higher Fiber Packing Densities

Advancements in fiber designs have led to low bending loss fibers even in Pure Silica Core (PSC) fiber types [10-12]. PSC fiber is quite advantageous as it reduces the number of repeaters needed for a system and thus provides improved power efficiency for the longest systems. Low bend sensitivity fibers of moderate effective area and 250 µm outer diameter, along with precise cable manufacturing techniques, have been used to increase fiber packing density within the core structure without hindering the optical performance of the fibers. Improvements in microbend sensitivity for moderate effective are fibers are shown in Fig. 2.

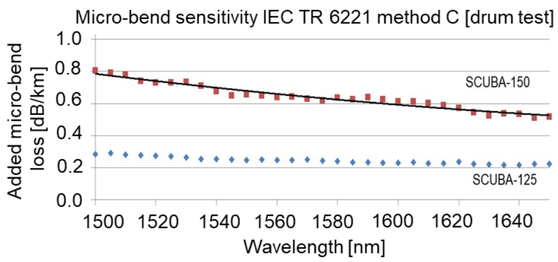

Figure 2. Microbend Sensitivities of 150 µm^2 and 125 µm^2 Fibers of Similar Design (OFS)

Methods of fiber identification have been developed to ensure robust assembly and maintenance processes through the use of up to 24 solid colors, augmented by ring-marking for higher fiber count cables. An example of a SubCom high packing density core structure is shown in Fig. 3.

Figure 3. SubCom High Packing Density Core Structure

SubCom's first SDM system utilized 24 solid-colored, 125 µm^2 fibers in the SL17-A1 cable over a transmission length of ~6000 km. This provided an estimated system capacity of ~250 Tb/s. The limits of higher fiber packing density have not yet been encountered. Cables with 32 fibers (SL17) and 48 fibers (SL21) incorporating ring-marked fibers are currently being manufactured [13].

Figure 4 shows the results of a techno-economic study showing the optimal choice of cable for systems with various transmission distances and cable capacities. This analysis includes factors such as number of fibers, repeater spacing, cable resistance, and SDM index to define the best cost-per-bit system solution. Optimistic margin assumptions and single mode fiber parameters [10] were used in this study. As shown in Figure 4, a 10,000 km transmission path system with ultimate capacity of 350 Tb/s, 500 Tb/s, or 700 Tb/s would optimally use SL17-A1, SL17, or SL21 cable, respectively.

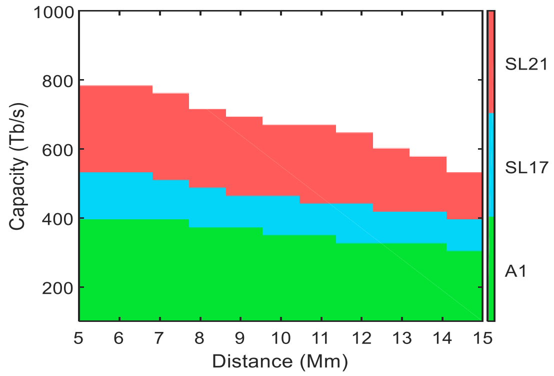

Figure 4. Optimal Cable Choice for 250 µm OD fiber and C-Band Transmission

More Compact Fibers

To increase fiber count in a cable even further, the fiber coating outer diameter can be reduced, making a more compact fiber structure. This approach has been successfully utilized in terrestrial cables. Effort is underway to implement 200 µm outer diameter fibers in undersea cables. The glass outer diameter would remain unchanged and thus fiber strength and prooftest levels would remain the same as today's undersea fibers. While the protective coating is thinner than today's fiber, improvements in fiber handling, such as a full clean room environment with low particle counts and fine surface finishes on all fiber contact areas, ensure full long term reliability.

Figure 5 shows maximum cable capacities with SL21 cable for C-band transmission with 250 µm and 200 µm outer diameter fiber. Compact fiber provides a noticable increase in maximum cable capacity. The advantages of the 200 µm outer diameter fiber diminishes somewhat at longer distances due to a combination of its slightly higher attenuation and system power limitations.

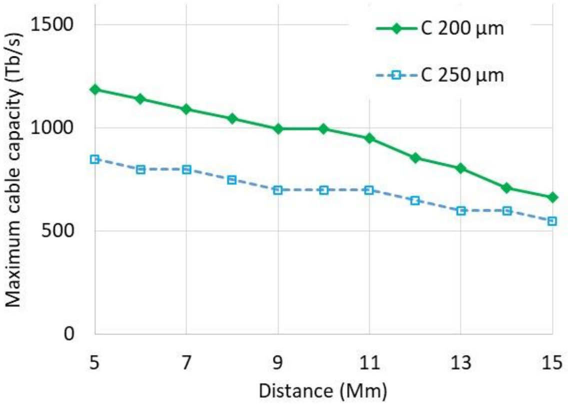

Figure 5. Capacities with Standard 250 µm and Compact 200 µm Outer Diameter Fibers

Further Technical Advancements

An approach to an even more compact fiber is to incorporate multiple waveguide core structures into one 125 µm outer diameter fiber cladding, aptly named multi-core fiber. Photos of two such experimental fibers [14-16] are shown in Figure 6.

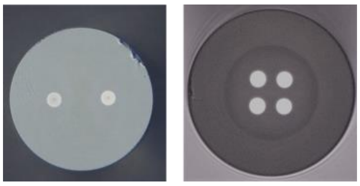

Figure 6. Multi-Core Fibers, Experimental (Sumitomo)

While multi-core fiber is extremely space efficient, it presents numerous technological and economic challenges. From a technology perspective, new optical components will be required, such as fan-in and fan-out devices, which add both optical impairment and cost to the system solution. From an economic perspective, there should be sufficient cost savings so that the developmental and manufacturing expenses for both the fiber and the cable manufacturer to make the approach viable. Higher core-count multi-core fibers may also require transponders with MIMO capability to mitigate crosstalk. Should these hurdles be overcome, an estimation of the maximum SL21 cable capacity in C-band with the 2-core fiber [14] is shown in Figure 7 in comparison with C-band systems utilizing 200 µm outer diameter fibers. Increased capacities are expected for 2-core fiber for all but the very longest system distances, which are affected by the higher attenuation of the multi-core fiber and by limitations of system power. We expect similar maximum capacities to be achieved with C+L technology [17] as well, and even greater if 200 µm diameter fibers are also used.

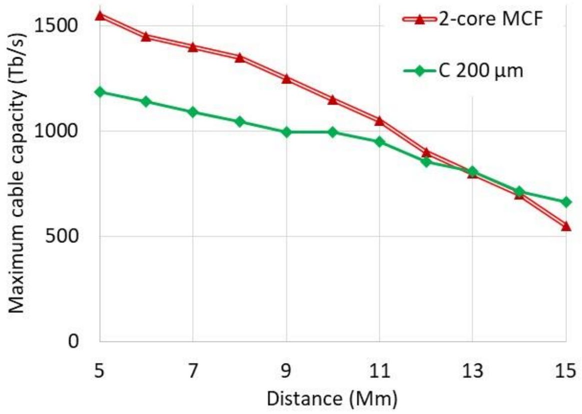

Figure 7. Estimation of Multi-Core Fiber Capacities

Conclusions

SDM system solutions are an efficient means of increasing system capacity with highly reliable, field-proven cable structures, crucial to long term reliable operation. In the near term, advanced compact fiber with low bending sensitivity, and ultra-low loss, can provide >1 Pb/s capacities for most system transmission distances. Adding C+L technology has the potential to achieve even greater system capacities.

The efficacy of multi-core fiber has yet to be demonstrated for undersea systems, noting the complexity of required system components and the developmental and manufacturing cost impacts.

Acknowledgements

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