TECHNOLOGY FOR C+L UNDERSEA SYSTEMS

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Abstract: C+L technology makes possible undersea systems with higher total capacity and lower cost per Tb/s than C-only systems. C+L transmission experiments have demonstrated 9100 km transmission of 49.3 Tb/s per fiber using C+L amplifiers. Practical system designs can support 24 Tb/s per fiber pair over 12,500 km and higher capacities on shorter systems. All supporting technologies have been or soon will be qualified for use in wet plant equipment and in the required terminal equipment. This paper reviews system architecture, transmission results, and progress in developing the system elements and system designs using C+L technology in undersea systems.

1. INTRODUCTION

Transmission capacity for undersea systems to be deployed in the next few years can be increased with more fibers, higher spectral efficiency, and more optical bandwidth. This paper describes the potential and the value of adding capacity using Er-Doped Fiber Amplifiers (EDFA) to design undersea systems that support transmission in the C and L bands. Recent experimental results confirming this advantage will be reviewed. All required technologies have been demonstrated and commercial components and subsystems have completed or can complete qualification in 2016. The high efficiency of the EDFA allows systems with more than 120 Tb/s total capacity to operate with wet plant powered from a single end over more than 9,000 km, for higher availability in the event of a system shunt fault.

2. C+L TRANSMISSION SYSTEM ARCHITECTURE

C+L system design supports twice the optical bandwidth of C-only systems. Figure 1 shows the architecture. Optical powers for the two bands are separated at each repeater, amplified in separate EDFAs, and combined again before transmission via cabled fiber to the next repeater. Separating and combining bands at each amplifier adds cost to the repeaters, but this cost is more than offset by reduced number of fibers needed in a C+L system to realize the equivalent total bandwidth in a C-only system.

This architecture can support 240 channels on a 37.5 GHz channel grid, and repeaters can support at least eight fiber pairs. In most C-only systems, we cannot take advantage of all the pump power available from qualified 980 nm pump lasers, because operating the pumps at full power drives channels into regions of strong penalty from nonlinearity in the transmission fiber. This has been a motivating factor in work on space division multiplexed transmission technology (SDM), leading to demonstration of high capacity in transmission experiments with multi-core fiber [1]. Like SDM, C+L systems make better use of the total available signal power by reducing nonlinear penalties per channel, and even higher pump powers can be used in C+L systems to increase repeater spacing or higher system capacity using higher order modulation formats. More pump lasers per fiber pair and pump lasers qualified for operation at higher power can be used in C+L systems to increase capacity and/or repeater spacing.

Fiber and cable design for C+L systems is essentially the same as fiber and cable design for C-only systems. Lower loss and higher effective area are key factors for achieving highest capacity over very long systems for both C-only and C+L systems.

Terminal equipment supports client interfaces to the data channels, optical mux and demux of the data channels and optical loading for unused portions of the spectrum. Coherent transponders for C-band can support L-band with modest changes in optics, and advances in modulation formats and FEC do not depend on wavelength.

Monitoring the health of the wet plant in C+L systems can be implemented using the same principles used for C-only systems: passive optical loop gain measurements or active monitoring via parameter queries to the repeaters.

Although none of the C+L building blocks are new to the industry, C+L undersea systems have not been commercially attractive because, until recently, capacity needed for new systems could be realized at lower cost with C-only systems. The growing demand for international transmission capacity is making it commercially viable to move to C+L. Alternatives to EDFA-based C+L systems for higher capacity wet plant are too inefficient in their use of electrical and optical power or too early in their development to support application in the near term. In particular, system architectures using Raman amplification to support more than 40 nm transmission bandwidth require much higher pump power and electrical power than C+L systems, resulting in reduced reach for high capacity systems, especially those requiring continued operation when powered from one end to a shunt fault near the other end of the wet plant.

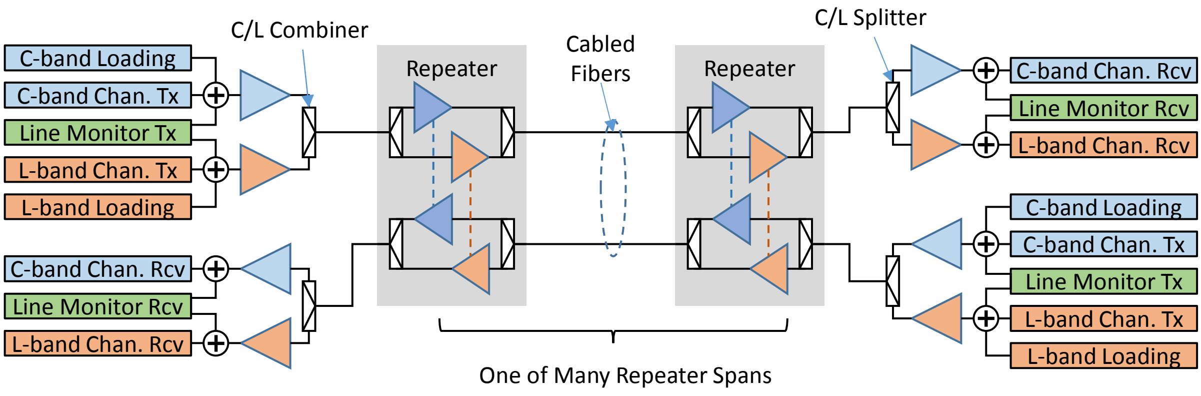

Figure 1. Optical architecture of one fiber pair through a C+L Undersea System.

3. CAPACITY AND REACH FOR C+L TRANSMISSION

Capacity limits for C+L band EDFA-based transmission were explored using a recirculating loop testbed consisting of single-stage C-band and L-band EDFAs with 980 nm forward pumping and gain flattening filters at each amplifier's output (Fig. 2). The C+L EDFAs were equalized to support ~77 nm transmission bandwidth (~9.4 THz) with a 4 nm band gap between bands, dictated by characteristics of the C/L WDM combiners/splitters.

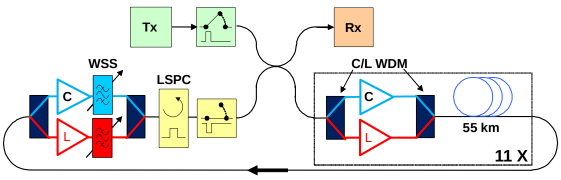

Fig. 2. Circulating loop test bed using C+L EDFAs. LSPC: loop synchronized polarization controller, WSS: wavelength selective switch.

In one set of experiments [2] the total output power of the amplifiers was set to ~20 dBm. Data was transmitted via spectrally shaped, 100 Gb/s, PDM multi-dimensional coded modulation channels at a wavelength spacing commensurate with a spectral efficiency (SE) of 4.93 bits/s/Hz. Total capacity achieved after ~9,100 km distance was 44.1 Tb/s.

In a second experiment [3], higher capacity (49.3 Tb/s) was achieved using higher amplifier output power (~22.2 dBm) and transmitting a mix of PDM 16QAM multi-dimensional coded modulation channels with different spectral efficiencies, 4.86 and 5.40 bits/s/Hz. The mixed channel spectral efficiencies were used to maximize system capacity at a fixed channel spacing and symbol rate. Fig. 3 shows channel BER measurement results expressed as Q-factor and error correction thresholds for each of the modulation formats.

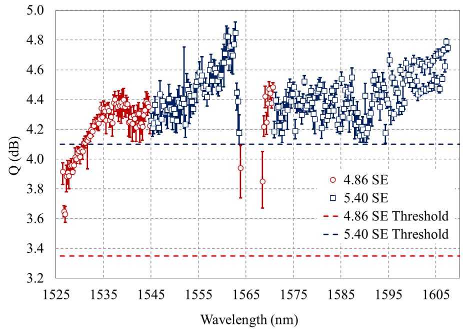

Fig. 3: 49.3 Tb/s with 282 channels after ~9,100 km.

Loop design parameters and key transmission results for the two experiments are shown in Table 1.

Signal Launch Power [dBm]	Capacity per fiber [Tb/s]	# of WDM Ch.	Channel Spacing [GHz]	Span Length [km]	Span Loss [dB]	Fiber A_{eff} [μm^2]	Fiber Loss [dB/km]
20	44.1	441	20.30	55	9.9	152	0.178
22.2	49.3	282	33.33	55	9.9	152	0.178

Table 1: Loop design parameters and key transmission results.

4. STATUS OF TECHNOLOGIES REQUIRED BY C+L SYSTEMS

Essential components for C+L wet and dry plant equipment will complete qualification within 12 months. Key components include higher power pump lasers for repeaters, filters for splitting and combining C and L bands, and cabled transmission fiber. All dry plant functions have been demonstrated in the laboratory with subsystems that translate well into manufactured products.

Higher power pump lasers for repeaters are important for achieving commercial viability of C+L wet plant. C+L transmission nearly doubles the available bandwidth and channel count per fiber, greatly increasing the value of pump power higher than the 500 mW currently available from undersea qualified pumps. At least two suppliers are actively working on qualifying a higher power 980 nm pump laser for undersea applications, and first commercial product is expected in September 2016.

Erbium-doped fiber (EDF) for the L-band is commercially available, and gain flattening filter technology and system gain equalization processes established for C-band systems are also effective for the L-band.

Optical design of wet and dry equipment requires many passive optical components, and the technology used successfully for C-band system also works well for C+L. Parts can be optimized for L-band, but no fundamental changes to design and manufacturing are required.

The L-band transponder functions have been demonstrated with commercial coherent transponder modules built for C-band and modified to replace internal lasers and amplifier functions with external sources. Commercial L-band lasers and EDFAs have been made and the modules for fully integrated L-band transponders are being developed. Optical loading equipment based on broadband noise sources and spectrum control using wavelength selective switches has been demonstrated with commercial equipment; development of equipment suitable for integration into line terminating equipment is underway.

Transmission fiber developed for C-band systems has similarly good optical features (low loss, high dispersion, low PMD) in the L-band, and cabling experiments have shown that established undersea cable manufacturing processes can make cable that does not degrade the fiber characteristics.

For line monitoring of the installed undersea plant, both passive optical loopback and active power detection in conjunction with a repeater command-response function can provide C+L systems with monitoring functions like those used for C-band systems. OTDR measurement capability is implemented using the same methods adopted for C-band systems.

5. CONCLUSIONS

Continued increase in the demand for international capacity has created a window of opportunity for introducing new transmission technology in undersea systems. Adding optical bandwidth using C+L transmission is a low risk, cost effective way to implement higher system capacity in long undersea systems. The system elements are in or through their qualification programs, and the high efficiency of EDFAs, in conjunction with advances in available pump power and continuous improvements in transponder technology make C+L viable as a platform to support capacity demands for the next few years. Building on established technologies reduces risk of system failure and allows for earlier deployment of qualified systems.

6. References

[1] A. Turukhin, *et al.*, “105.1 Tb/s Power-Efficient Transmission over 14,350 km using a 12-Core Fiber” OFC 2016, Anaheim, CA, 2016, paper Th4C.1

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