New Generation Optical Infrastructure Technologies: "EXAT Initiative" Towards 2020 and Beyond

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Abstract
Research effort of most advanced optical infrastructure technologies named "EXAT: Extremely Advanced Transmission" towards the next few decades and beyond are described, enabling well over Peta bit/s per fiber link capacity and Exa-class network throughput.

Introduction
For the last twenty years, the optical communication technologies have seen an increase in transmission capacity per fiber by three orders of magnitudes, achieving several Tbit/s transmission. If the data traffic continues to increase with 40 %~70 % per year, a capacity increase by three to five orders of magnitudes should be anticipated for the next twenty years. This means that in twenty years, the backbone transmission capacity should support well over Pbit/s per fiber and the core network should support Ebit/s throughput where at home, Tbit/s access handling 3D super-high definition videos will be a reality.

At NICT (the National Institute of Information and Communications Technology, Japan), a collaborative study group called "EXAT (**EX**tremely **A**dvanced **T**ransmission) Initiative" was organized in January 2008, gathering researchers from industries, academia, and national institutes in order to develop break-through technologies which enable this giant leap [1]. In the Initiative, we have focused on identifying ultimate physical limitations, i.e., the amount of optical power (bit/s rate) that can be transmitted safely in transmission optical fibers, the optical bandwidth for optical amplification, and the capacity of optical submarine cables systems now limited by the electrical power supplied to the optical amplifier repeaters [2]. In this paper, these physical limiting factors are firstly identified followed by proposals of "EXAT" technologies to go beyond these limits and to create new generation optical infrastructure for the next few decades.

Physical Limiting Factors
Link capacity per fiber is a good measure of optical network capacity and is rapidly approaching its limit as shown in Fig.1. Three major physical limiting factors should be considered for future global optical communication infrastructure as mentioned above.

Although optical fibers have been installed around the globe for more than twenty years, their design principle was established way back in the late 70's and the early 80's when no one ever thought of how much optical power (photons per second, i.e., bit/s) could be transmitted without nonlinear interactions and safely without fiber damage for a long distance in an optical fiber. As a result, as the optical transmission power abruptly increased by two orders of magnitudes in the 90's with newly invented optical fiber amplifiers and WDM (Wavelength-division Multiplexing) technologies, nonlinear interactions (noise) due to various optical nonlinear effects and a more destructive phenomenon of "fiber fuse" [3] causing a permanent thermo-chemical damage to the fiber cores propagating for a long distance have become eminent and persistent problems.

In addition, recently developed distributed Raman amplifier systems requiring pumping powers of several hundred mW up to W pause a big challenge on how to further increase the capacity where its total input optical powers are approaching the fiber fuse propagation threshold power of around 1.2~1.5 W [4]. It should be anticipated that the maximum capacity of practical systems limited by the fiber fuse phenomenon would be around 100 Tbit/s per fiber assuming a substantial improvement in optical amplifier NFs (noise figures) and more power-efficient modulation schemes, which is only 1.5 orders of magnitudes larger than those of the present Tbit/s systems.

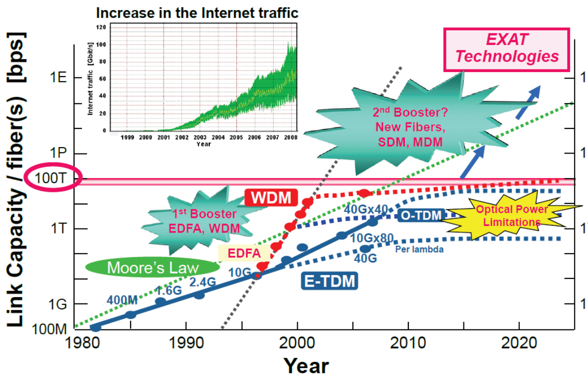

Fig. 1. Progress in optical transmission capacity and EXAT technologies: SDM (Space-division Multiplexing), MDM (Mode-division Multiplexing).

The optical bandwidth for optical amplification would also be a major limiting factor for long-haul transmission systems and networks. Presently, low-loss 1.5 μm bands of C-band (1530 nm-1565 nm) or L-band (1565 nm-1625 nm) with each amplifier bandwidth of about 40 nm (5 THz) are currently being used for long haul transmission. Since the total amplifier bandwidth including S-band (1460 nm-1530 nm) should be estimated to be around 120 nm (15 THz), the maximum long-haul capacity would amount to around 150 Tbit/s, assuming 10 bit/s/Hz frequency utilization efficiency. Although this value could further be increased by utilizing broadband Raman amplification and/or 1.3 µm bands, the optical power limitation from the fiber fuse should limit the ultimate capacity in the present systems.

Optical submarine cable systems are definitely the basis of global broadband connections. Since the cable capacity is limited by its high pressure-proof cable design and electrical powers supplied to the optical repeaters from lands, the present maximum capacity per cable remains to be about 10 Tbit/s (10 Gbit/s, 128 WDM, eight fiber pairs).

EXAT Technologies

Fig. 2 depicts three distinctive key technologies of EXAT, namely, "Multi-core Fiber", "Multi-mode Control", and "Multi-level Modulation" technologies, what is called "3M" technologies.

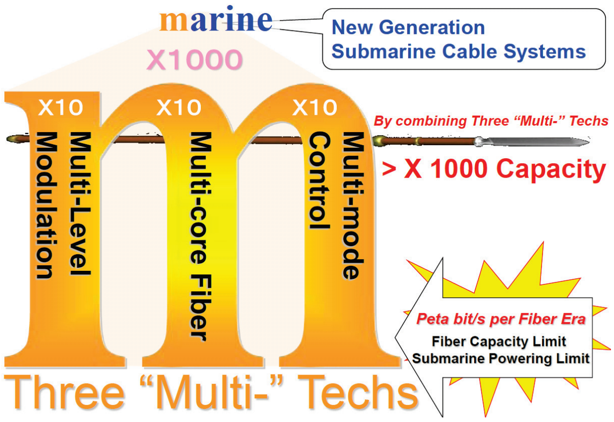

Fig. 2. Three "Multi-" (3M) Technologies to achieve >1000 x capacity and throughput.

Three major research areas are being studied at EXAT Initiative based on the 3M technologies.

1. New generation optical fiber technology

New transmission optical fibers capable of transmitting well over Pbit/s information per fiber along with optical connectors, splicing, and cabling technologies are being studied. These include power-proof multi-core optical fibers, multi-mode fibers, PCF (Photonic Crystal Fiber), and PBGF (Photonic Bandgap Fiber) for SDM (Space-division Multiplexing) and MDM (Mode-division Multiplexing). Remote detection and halting schemes of fiber fuse phenomenon have also been developed [5].

2. Novel transmission and optical node technologies

Novel multiplexing/transmission schemes and node architecture beyond TDM (Time-division Multiplexing) and WDM utilizing spatial (transverse) modes and spatial coherence of light are being studied. These include super multi-level modulation, SDM/MDM and MIMO (Multi-input Multi-output) processing with multi-core/multi-mode fibers [6] [7] along with corresponding optical amplifiers, MUX/DEMUXs, and optical signal processing technologies. Ebit/s class multi-granularity optical node architecture has also been proposed [8].

3. Optical submarine cable system technology

Novel transmitters/receivers, transmission line technologies (ultra-low loss, low nonlinearity optical fibers, low-noise optical amplifiers) to achieve a capacity-distance product of Ebit/s km (100 Tbit/s per fiber, 10,000 km) are being studied.

Conclusions

"EXAT: Extremely Advanced Transmission" towards the next few decades and beyond are briefly described which will enable well over Peta bit/s per fiber link capacity and Exa-class network throughput. The proposed three "Multi-" (3M) technologies will play a vital role in realizing a giant leap in both transmission and network capacity.

Acknowledgement

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