Technologies for Optical Transceivers and Optical Nodes to Increase Transmission Capacity to 100 Tbps

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Enhancing the capacity of optical communication networks is essential to achieving a hyper-connected world in which people, information, and things are connected and to enabling continued development of information and communications technologies (ICT) such as the Internet of Things (IoT), big data, artificial intelligence, and 5G mobile communications. In particular, increasing optical fiber transmission capacity to more than 100 Tbps by 2020 or shortly thereafter is needed to handle the ever-increasing volume of digital data traffic. Since conventional technologies are getting close to the transmission limit, technological breakthroughs enabling higher capacity must be made. Given this requirement, we are researching and developing key technologies for optical transceivers and optical nodes that will enable transmission capacity to be increased. In this paper, we introduce our recent advances in optical modulation and demodulation technologies for sending and receiving large-capacity signals and in optical node technologies for achieving energy-saving broadband optical signal switching.

1. Introduction

The amount of data traffic exchanged in networks keeps increasing exponentially. For instance, the total download traffic through major Japanese domestic Internet exchanges is increasing by an annual rate of 1.2 to 1.5.[1] Triggers for recent traffic increases include the growth of cloud-type network services and an explosion of mobile traffic from common mobile devices such as smartphones and tablets. Furthermore, 5G mobile communications, which will start operations in 2020, will contribute to the traffic increase even further.

Optical fiber communication systems for backbone networks have evolved to fulfill such increasing communication demand for decades. Novel technologies, such as time-division multiplexing (TDM), wavelength-division multiplexing (WDM), and digital coherent transmission, have been introduced to achieve the required capacity increase while keeping costs low, reliability high, and power consumption low (**Figure 1**).[2] A transmission capacity of the order of 100 Tbps per fiber is predicted to be required to meet further increasing demands around 2020. The simple improvement of conventional sets of technologies, however, does not bring this level of capacity enhancement because of several practical limits. Thus, the development of a set of novel technologies that can break through the technological barriers is required.

Current backbone networks mainly consist of optical transceivers, optical fiber transmission lines, optical nodes, and electrical switching nodes such as L2 switches and/or packet routers, as shown in **Figure 2**. Fujitsu provides network solutions as commercial products such as the FUJITSU Network 1FINITY series.[3] In regard to the speed of optical transceivers, 100 Gbps

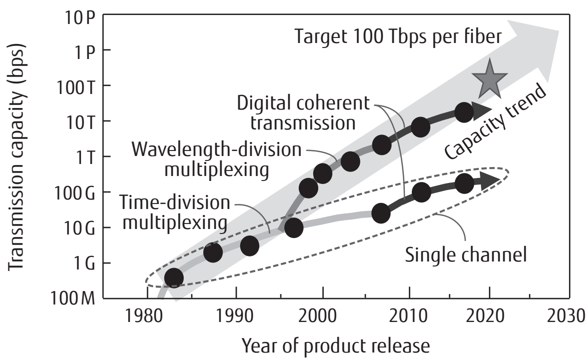

Figure 1
Transmission-capacity trend of optical fiber communication systems.

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per wavelength channel predominates, and 200 Gbps per wavelength channel is also offered for a higher-order multi-level modulation format. Low-loss (≤0.2 dB/km) transmission lines based on silica optical fiber with optical amplifiers support long-haul communication.

In conventional optical networks, routing control for large-volume traffic is mainly achieved by using electrical switches. The power consumption of electrical switching nodes will become a more serious issue as traffic capacity is increased more, so quasi-static optical path switching based on wavelength channels has been introduced to reduce power consumption at the nodes. Dynamic optical path switching technologies[4)–6)] are used to reduce the load on the nodes even further and thus reduce power consumption even more. Electrical switches, however, remain mainstream components because optical path switching technologies have various technical issues to be addressed before they can be commercialized.

In this paper, we first review the issues to be addressed toward the achievement of 100-Tbps transmission capacity. We then introduce recent research progress on optical modulation and demodulation technologies for sending and receiving large-capacity signals and on optical node technologies for achieving network-wide energy saving, as examples to solve the problems.

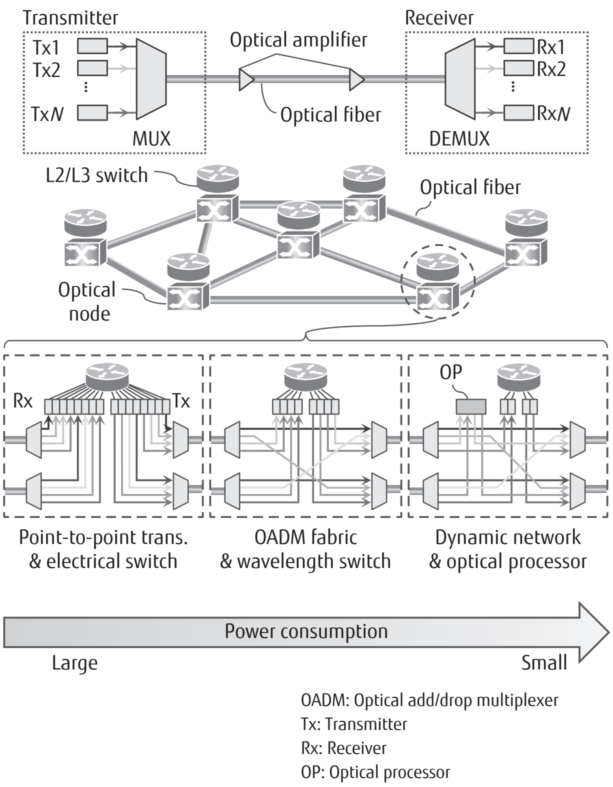

Figure 2
Schematic of current backbone networks.

2. Issues to be addressed

Figure 3 shows the relationship between maximum transmission capacity and transmission distance as given by the Shannon limit under the assumptions of 100-km spans of optical fiber with an attenuation coefficient of 0.2 dB/km, optical repeaters with noise figures of 3, 5, or 7 dB, and 80 or 240 wavelength channels at 50 GHz over the C-band (spanning from 1,530 nm to 1,565 nm in wavelength) or the C+L-band (spanning from 1,530 nm to 1,635 nm). For instance, a typical optical transmission system with 100-Gbps optical transceivers per wavelength channel can provide 10-Tbps transmission throughput per optical fiber after WDM with 50-GHz spacing over the C-band.

Typical 100-Gbps optical transceivers in core networks use quadrature phase shift keying (QPSK) modulation. To achieve even higher capacities with higher-order modulation, new technologies must be considered. However, the higher-order multi-level modulation format requires a higher signal to noise

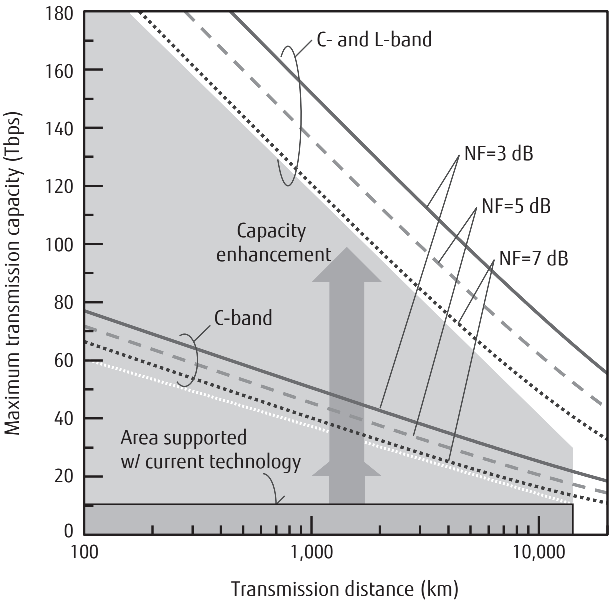

Figure 3
Relationship between maximum transmission capacity and transmission distance.

ratio (SNR), and thus the transmission capacity to be achieved with a single optical fiber is restricted to a shorter distance.

If we have to rely on an increase in modulation order alone to achieve a 10-fold increase in per-fiber capacity, a modulation order as high as 2^{20} (=1,024,576) will be necessary, which is way too high for practical implementation. It is also difficult to achieve 10-times-larger capacity by expanding the transmission wavelength bandwidth since the most practical and efficient optical amplifiers, i.e., erbium-doped fiber amplifiers, are available only for the C- and L-bands. Therefore, higher-order multi-level modulation technology and broadband amplification technology should be combined in an appropriate manner for achievement of optimal 100-Tbps transmission capacity, such as three-times-wider wavelength bandwidth spanning the C- and L-bands, modulation order increase for three-times-higher spectral efficiency [64-level quadrature amplitude modulation (QAM)], and 20% tighter wavelength channel spacing for WDM.

While higher-order multi-level modulation is a key technology for transmission capacity enhancement, it imposes a stringent requirement on the SNR through the system. Furthermore, the nonlinear response of the transmission line and/or opto-electrical circuits in transceivers causes severe distortion. Compensation for the distortion[7),8)] is required to achieve such large-capacity transmission.

If we look at the entire network, a 10-times transmission capacity increase means a 10-times increment in electrical switching, for which the power consumption of the network explodes. In 100-Tbps-era networks, it is important to reduce the load on the electrical switching nodes since advances in complementary metal oxide semiconductor (CMOS) processing technology, which has brought about huge power savings for several decades is predicted to soon end. Optical switching is expected to replace electrical switching due to its broader bandwidth. However, the problem of wavelength contention, where optical signals with the same wavelength cannot be simultaneously routed through the same outbound optical fiber, could be a critical issue in the deployment of optical switching nodes.[6)]

3. Higher-order multi-level modulation technology

We are developing dual-polarization (DP) 64QAM technology, which has three times higher spectral efficiency, to achieve 100-Tbps transmission capacity.

In general, higher-order multi-level modulation formats such as DP-64QAM require higher linearity for optical transceiver components. However, such components tend to be costly and large. We have thus developed an optical transceiver architecture that equalizes the distortion that occurs in an optical transmitter [**Figure 4(a)**].

In the proposed architecture, the receiver effectively equalizes the distortion by using a specially designed pilot signal, which is multiplexed with the data signal from the transmitter and is free from the effects of signal distortion accumulated along the transmission line. Since the conventional receiver performs carrier phase recovery after equalization for the transmission line, it is difficult to equalize large distortion in a conventional receiver. The proposed architecture, on the other hand, is capable of handling larger distortion since the carrier phase recovery and the equalization for transmitter distortion are performed before

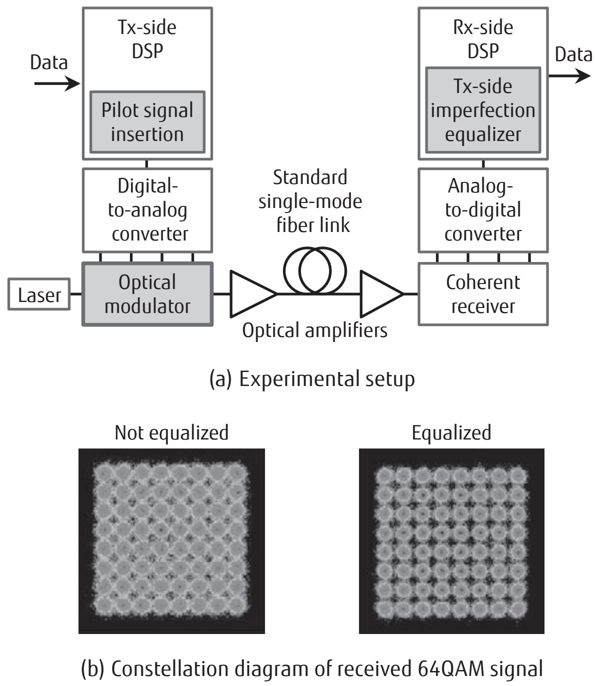

Figure 4
Transmission test of DP-64QAM signal with proposed transmitter distortion equalization.

equalization for the transmission line [**Figure 4(b)**].

Transmission of a DP-64QAM signal through a 160-km unrepeated single-mode fiber (SMF) link was achieved by applying the proposed architecture.[8] The distortion equalization technology enables transmission using a higher-order multi-level modulation like DP-64QAM while using a lower accuracy component. Thus, a larger-capacity optical transmission system with lower cost and a smaller size is expected to be achieved.

4. Wavelength conversion technology for optical nodes

We are developing optical signal processing technologies for power efficient optical networks by replacing electrical processing with optical processing. One promising example is wavelength conversion for resolving the wavelength contention.

Figure 5 shows three wavelength conversion technologies. The one using electrical signals [Figure 5(a)] has two problems. One is increased processing latency due to mutual conversion of electrical and optical signals. The other is increased electricity consumption due to an increase in the number of multiplexed wavelengths because one conversion circuit is required for each wavelength. Although conversion using nonlinear optical effects [Figure 5(b)] reduces power consumption,[9] an optical filter is needed to remove only the wavelength of the signal prior to conversion, making it difficult to handle signals with a variety of wavelengths.

We propose using an optical circuit configuration independent of the wavelength of the input optical signal and modulation format [Figure 5(c)] to achieve wavelength conversion of DP-WDM signals. Wavelength conversion of optical signals with a throughput of over 1 Tbps was experimentally demonstrated using the proposed scheme.[11), note)]

The proposed wavelength conversion scheme manipulates the wavelength and polarization of the optical signal simultaneously. Therefore, the optical signal prior to conversion can be removed with a polarizer instead of the optical filter used in conventional technologies. The polarization-division multiplexed signal can be controlled using a polarization diversity configuration, in which the split horizontal and vertical polarization components are combined after operating in parallel. Furthermore, the proposed scheme enables arbitrary wavelength conversion by controlling the wavelength spacing of the pump lights without having to adjust the transmittance of the optical filters.

For the wavelength conversion of large-capacity

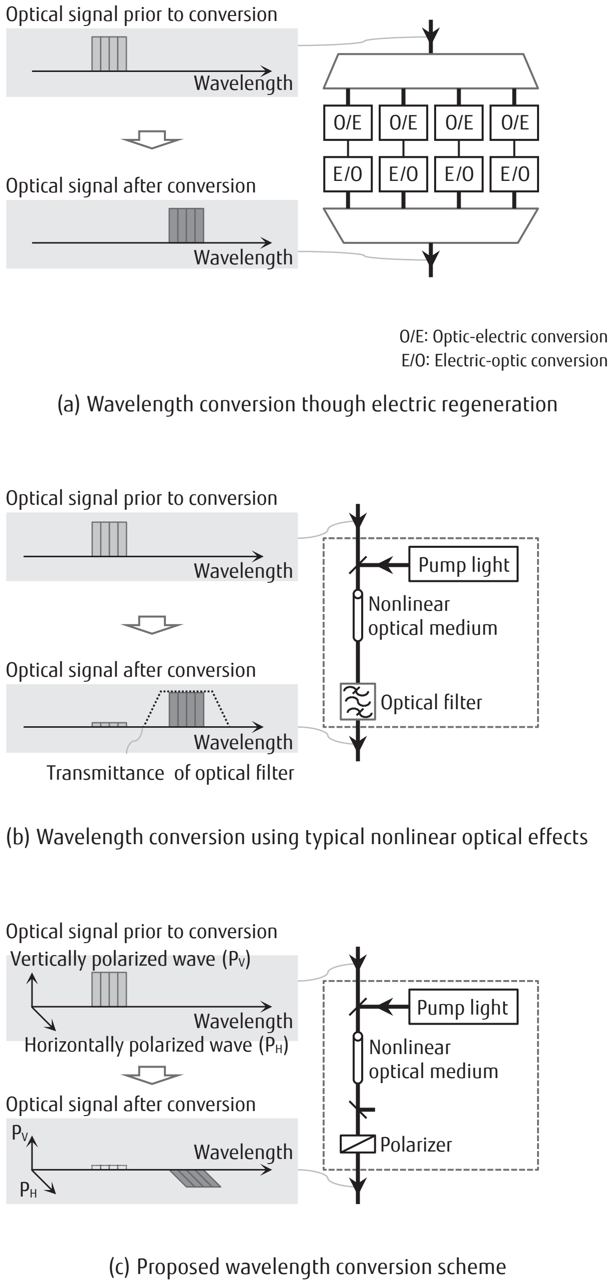

Figure 5
Wavelength conversion technologies.

note) This experimental demonstration was performed in collaboration with the Fraunhofer Heinrich Hertz Institute.

optical signals (1 Tbps and more), for example, ten converters are required if conversion through electrical signals is used. In contrast, the proposed scheme can achieve simultaneous conversion with only one converter. It thus performs an equivalent function while consuming less power than previously required. In addition, because there are no restrictions on the wavelengths before or after conversion, this scheme can contribute to the creation of next-generation optical networks in which the configuration of the network can be flexibly modified.

5. Conclusion

In this paper, we discussed the issues that must be addressed in order to achieve 100-Tbps transmission capacity, which will be required for near-future optical networks, and introduced some of our recent research targeting these issues.

The proposed distortion compensation technology is promising for achieving higher-order modulation transceivers with a lower cost and smaller size. The proposed wavelength conversion technology to resolve wavelength contention is expected to reduce the power consumption of optical nodes in future flexible networks.

Integration of these technologies along with broadband optical amplifier technologies will contribute to achieving a large-capacity optical network infrastructure. Furthermore, it will accelerate the evolution of information and communications technologies (ICT) for various services based on the Internet of Things, 5G mobile communication, and distributed computing.

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