Ultrahigh-speed Transmission Technology for Future High-capacity Transport Networks

Yutaka Miyamoto, Shuichi Yoshino, and Akira Okada

Abstract

Ultrahigh-speed transmission technologies in radio and optical fiber transport systems are essential to accommodate the ever-increasing demand for bandwidth in future network infrastructure. Advanced digital modulation/demodulation techniques as well as ultrahigh-speed front-end integration technologies are optimized to fully exploit the characteristics of different types of transmission media such as air and optical fiber, considering novel degrees of freedom such as space division multiplexing. This article introduces state of the art research and development that achieves ultrahigh-speed communications at speeds of over 1 Tbit/s per carrier (over a hundred times the current speed) in both optical fiber transmission and radio transmission.

Keywords: transmission, digital modulation/demodulation, parametric optical amplification

1. High-capacity transport networks and applications of ultrahigh-speed communications

Common broadband network services such as video streaming and electronic commerce (e-commerce) are now available all over the world via personal computers (PCs) and smartphones in daily life. The novel transmission technologies have thus become essential for future network infrastructure in order to achieve further network service evolutions. The fifth-generation (5G) mobile communications service will start in fiscal year 2019, and broadband communications at a line rate up to 20 Gbit/s with low latency will be expected to support emerging new services such as self-driving vehicles and factory automation. Furthermore, it is expected that the application of new technologies such as machine learning and artificial intelligence will facilitate the emergence of new applications such as detailed weather forecasting and preventive medicine, thanks to the Internet of Things technology achieved through recent advances in cost-effective low-power semiconductor integrated circuits used in sensor technology. We believe that future transport networks will have to support the creation of such new application services supporting our daily life.

The application area of ultrahigh-speed transmission technology in today's high-capacity transport networks is shown in **Fig. 1**. In radio transmission, significant advances in digital modulation/demodulation techniques have been made in fixed microwave transmission systems, and these had been used to support long-haul core networks until the commercial installation of optical fiber transmission systems began in the 1980s [1]. Further advances have been made in these fixed microwave transmission system technologies to enable economical link systems in areas where it is difficult to install a wired cable transport system.

In addition, dramatic technological advances have been made in mobile communications, achieving high-speed wireless local area networks and mobile phones in the last quarter of a century. Today, wireless access services using PCs and smartphones (4G) with a throughput of at least 1 Gbit/s have spread throughout the world. Furthermore, next-generation 5G systems will offer faster wireless access with the high reliability and low latency required for self-driving

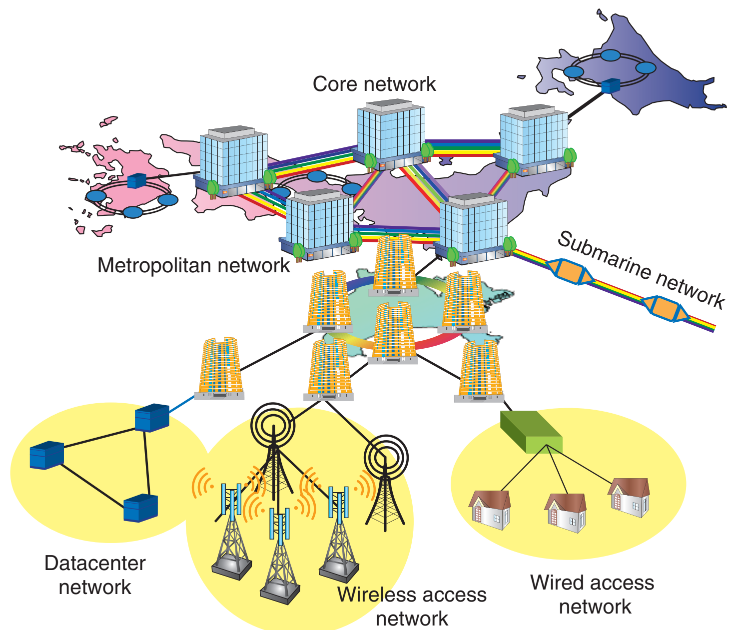

Fig. 1. Application area of ultrahigh-speed transmission technology.

vehicles and factory automation.

An ultrahigh-speed optical fiber transmission system was first installed in NTT's core network in the 1980s, and remarkable progress has been made over the last 40 years. Today, optical fiber is widely used for transoceanic systems over 10,000 km, long-haul national backbone networks, metropolitan networks, and access networks. Optical fiber transmission systems have also become indispensable recently for increasing the capacity of networks such as datacenter (DC) networks and mobile backhauls. Optical fiber transmission systems have so far mostly used single-mode fiber (SMF) as a transmission medium. SMF is designed to have only one optical waveguide (core) per fiber supporting a single waveguide mode. Recent long-haul core networks support a capacity in excess of 10 Tbit/s per fiber by using 100-channel wavelength division multiplexing (WDM) of 100-Gbit/s channels [2]. Furthermore, low-power optical communications with a compact configuration and a channel capacity over 200 Gbit/s have recently been introduced in DC interconnection networks [3].

2. Technical challenges in ultrahigh-speed communications technology

This section describes the common technical challenges in introducing ultrahigh-speed communications technologies in both radio transmission systems and optical fiber transmission systems. The system capacity C of a communications system is generally expressed by the following equation according to Shannon's well-known theorem:

$$C = N \cdot B \cdot log\,(1 + SNR),$$

where N represents the number of multiplexed channels, B represents the signal bandwidth, and SNR represents the signal-to-noise ratio. There are three major approaches to improving the system capacity C of a communications system as expressed by this equation:

Approach 1: Increase the symbol rate by expanding the signal bandwidth B of each channel.

Approach 2: Improve the SNR by reducing noise in the system and/or increasing the signal power, or by adopting a digital modulation technique such as quadrature amplitude modulation (QAM)* that is more efficient than binary modulation.

Approach 3: Improve the channel capacity by using a frequency or spatial degree of freedom to achieve higher multiplicity (increasing N).

* QAM: A highly efficient digital modulation scheme whereby the amplitude and phase of a signal's electrical field are modulated to multiple signal levels.

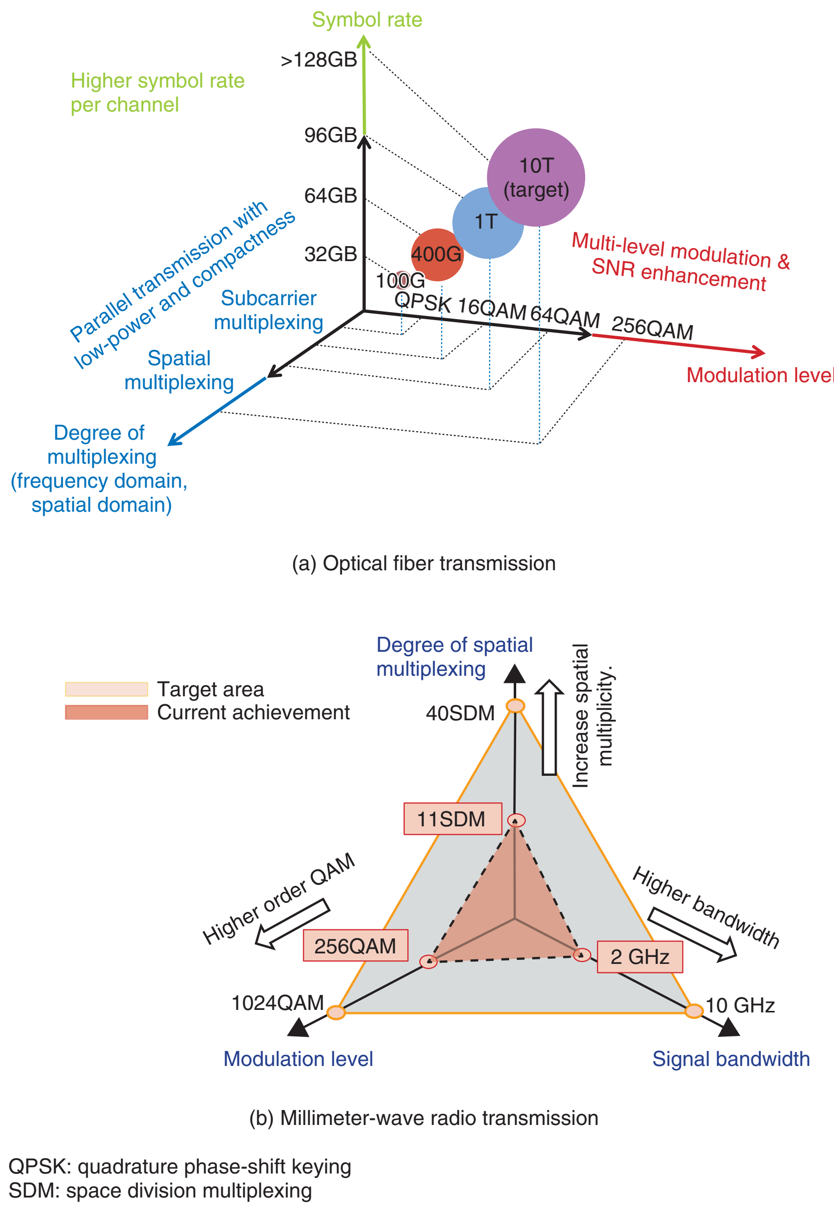

Fig. 2. Three approaches in ultrahigh-speed communications.

To increase the channel speed in both wireless and optical fiber communications, it is very important to choose the right combination of the feasible above-mentioned approaches considering their application area and the maturity of the technologies.

The future technical trends of the abovementioned approaches in line-of-sight millimeter-wave radio transmission and optical fiber transmission are shown in **Fig. 2**. In the case of using single-channel polarization-division multiplexed (PDM) quadrature phase-shift keying (QPSK) (Approach 1 only) to realize channel capacities over 1 Tbit/s, it is necessary to achieve a symbol rate of at least 300 Gbaud. However, it is very difficult to achieve such a high symbol rate over 300 Gbaud using the latest front-end devices and digital signal processing (DSP) circuits with analog-to-digital converter (ADC) circuits and digital-to-analog converter (DAC) circuits. We therefore need to reduce the required symbol rate by adopting higher-order QAM and/or by using subcarrier multiplexing in the frequency or spatial domain.

An example of the latest digital coherent optical

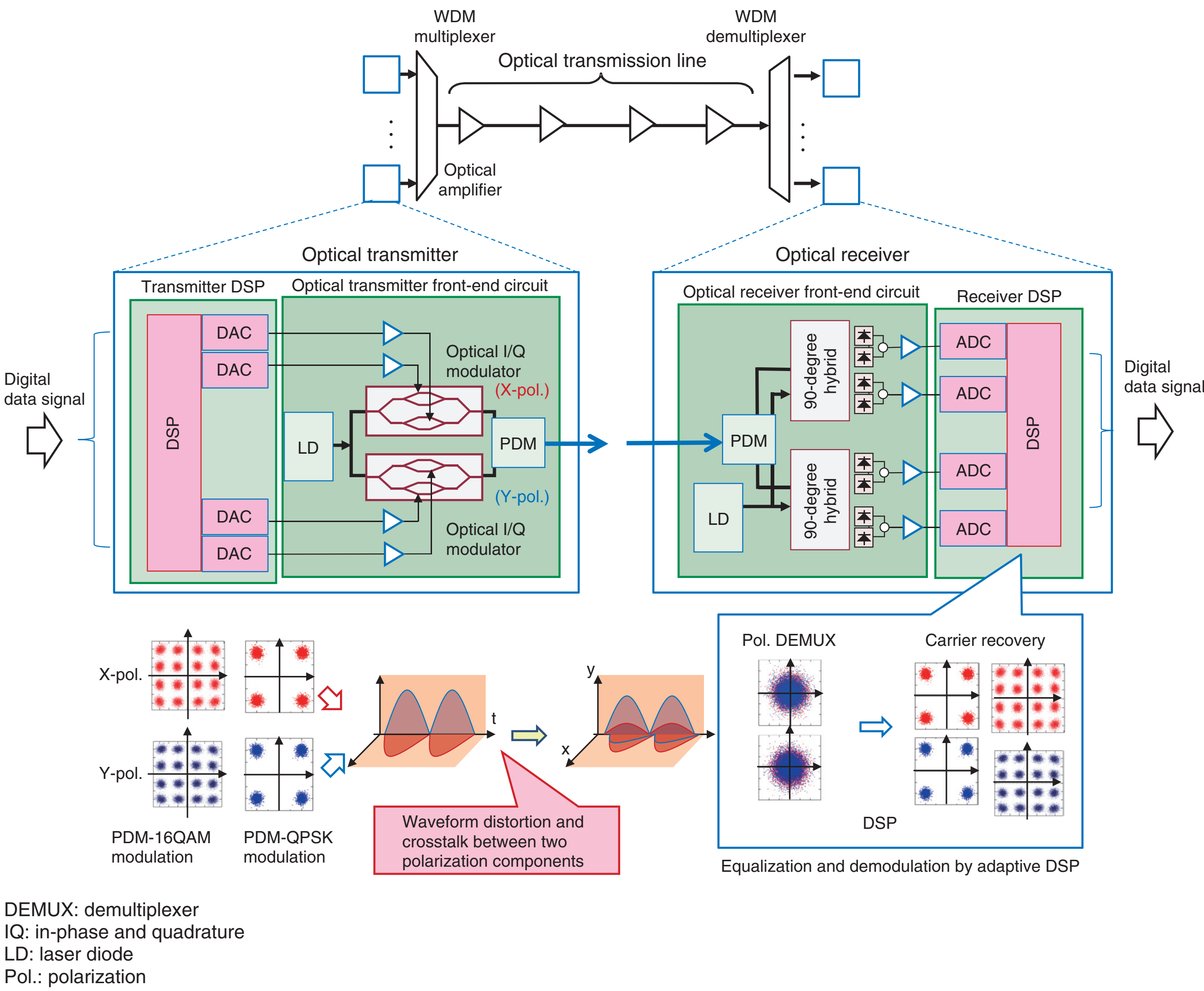

Fig. 3. Example configuration of digital coherent optical transceiver circuit in an optical fiber transport system.

transceiver circuit configuration in an optical fiber transmission system is illustrated in **Fig. 3** [2, 3]. In this system, each channel is modulated in PDM-QPSK format, and approximately 100 channels of 100-Gbit/s optical signals are wavelength-division-multiplexed to form a 10-Tbit/s aggregate capacity signal and transmitted through an optical inline amplified link over 1000 km.

Here, the optical transmitter consists of a transmitter DSP circuit and an optical transmitter front-end circuit. Each polarization component from a continuous-wave signal laser diode (LD) is independently modulated in QPSK format at a symbol rate of the order of 32 Gbaud, and 100-Gbit/s PDM-QPSK signals (approximately 64 Gbit/s per polarization in gross capacity with error-correcting coding at a coding rate of $R = 5/6$) can be generated. If the modulation scheme is adaptively changed to 16QAM, it is possible to double the channel capacity to 200 Gbit/s at the same symbol rate.

Similarly, the optical receiver consists of a receiver DSP circuit and an optical receiver front-end circuit. An intradyne reception of PDM-QPSK signals is performed using a wavelength-tunable local oscillating LD that has a frequency offset within a few gigahertz. Four lanes of received electrical tributary signals are fed to ADCs, and linear waveform distortions of transmitted signals after the optical fiber transmission are digitally equalized to demodulate the QPSK (or 16QAM) signals. Finally, the error correcting

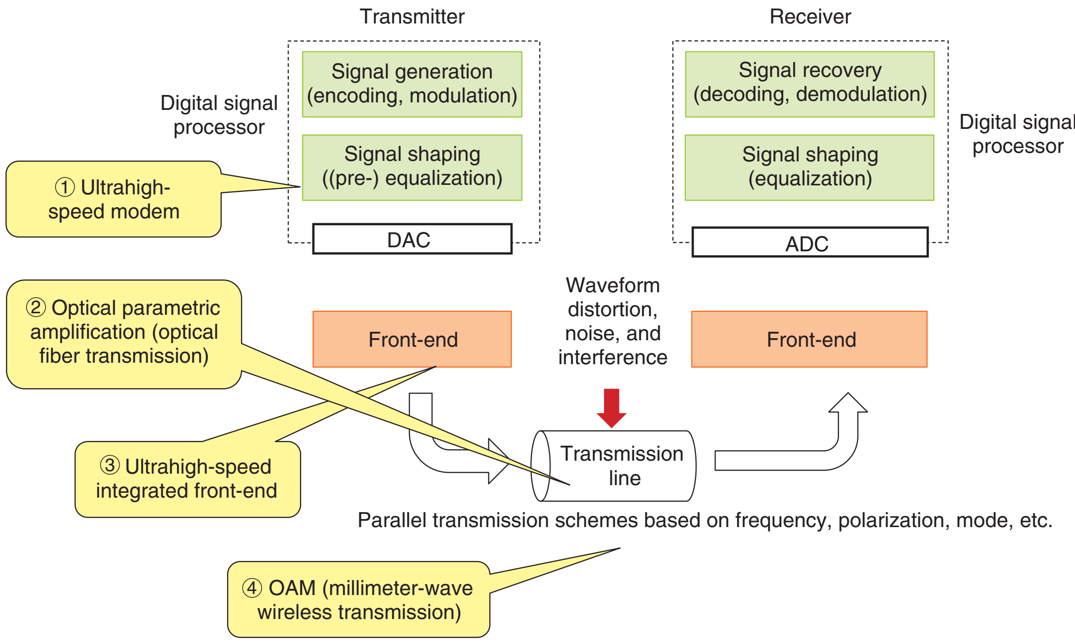

Fig. 4. Key technologies to achieve future ultrahigh speeds for millimeter-wave radio transmission and optical fiber transmission.

code recovers the original data bit stream. In this case, the throughput in the DSP circuit exceeds 2 Tbit/s (≈8×2×(6/5)×100 Gbit/s) between the DSP circuit part and the DAC/ADC circuit part, when the channel capacity is 100 Gbit/s assuming 8-bit quantization, a sampling rate of two samples per symbol, and an error correction coding rate of $R = 5/6$.

In order to implement a compact and cost-effective DSP circuit, it is preferable to integrate the DAC/ADC circuit part and the DSP circuit part on a single-chip large-scale integrated (LSI) circuit. Furthermore, it is essential to suppress the skew of the four parallel broadband analog electrical signals (in-phase and quadrature signal components for each of the X- and Y-polarization planes) between the DSP-ASIC (application-specific integrated circuit) and optical front-end circuits for high-quality digital modulation and demodulation.

3. Fundamental technologies for ultrahigh-speed communications infrastructure

The Feature Articles in this issue focus on the four fundamental technologies of ultrahigh-speed transmission to achieve a capacity of 1 Tbit/s (**Fig. 4**), and they introduce the current status and future prospects of these technologies.

3.1 Ultrahigh-speed digital modulation/demodulation circuit technology

The ultrahigh-speed transmission technology used in digital modulation and demodulation circuits has common technical issues for both optical fiber transmission systems and radio transmission systems. The article "Ultrahigh-speed Optical Communications Technology Combining Digital Signal Processing and Circuit Technology" [4] discusses the latest achievements relating to the required functions of ultrahigh-speed digital modulation/demodulation circuits with capacities of over 1 Tbit/s per wavelength, especially in optical fiber transmission systems. In general, higher-order QAM digital modulation and demodulation require a higher SNR and more precise DSP calibration techniques for simple and stable operation. Here, we discuss the effectiveness of a novel coded modulation that makes full use of the features of higher-order QAM digital modulation.

3.2 Low-noise high-power parametric amplifier relay technology

Low-noise high-power parametric amplification technology is promising for reducing system noise, as needed for higher-order QAM signal transmission. Optical signal processing based on the parametric amplification greatly reduces the required complexity of DSP for high-speed higher-order QAM signal transmission.

When the gate length of CMOS (complementary metal oxide semiconductor) LSI circuits is reduced to just a few nanometers (about 10 monolayers of silicon atoms), it is predicted that the conventional scaling law in terms of transistor switching speeds and power consumption (namely Moore's Law) will gradually saturate. To achieve higher channel speeds, this situation will naturally require new system architectures and novel technologies to reduce the amount of DSP and power consumption. In future optical nodes, parametric optical amplifiers will achieve simultaneous coherent optical signal processing of WDM high-speed channels to reduce system noise and the required DSP complexity of waveform distortion compensation of high-speed channels. They are also expected to reduce the system's overall power consumption. The article "Low-noise Amplification and Nonlinearity Mitigation Based on Parametric Repeater Technology" [5] in this issue introduces a low-noise, highly efficient parametric optical amplification system that uses PPLN (periodically-poled Lithium Niobate) crystals developed at NTT's laboratories.

3.3 Ultrahigh-speed optical front-end integration technology

The article "Ultrahigh-speed Optical Front-end Device Technology for Beyond-100-GBaud Optical Transmission Systems" [6] introduces ultrahigh-speed device interconnections between the front-end circuits and DSP circuits. The novel architecture of integrated front-end circuits equipped with an analog multiplexing/demultiplexing function in the front-end circuits can relax the required operation speed of the DAC/ADC in DSP circuits. It also reduces the input and output speed at the front-end module interface to achieve stable interconnections between front-end circuits and DSP circuits. We present the latest performance results of the proposed optical front-end integrated technology for optical fiber communications at symbol rates in excess of 100 Gbaud.

3.4 Ultrahigh-speed technology based on orbital angular momentum mode multiplexing

The article "Toward Terabit-class Wireless Transmission: OAM Multiplexing Technology" [7] introduces novel spatial multiplexing technology for realizing line-of-sight millimeter-wave wireless communications at speeds on the order of 1 Tbit/s. A new spatial degree of freedom based on the orbital angular momentum (OAM) of an electromagnetic field is introduced to increase the spatial multiplicity.

In recent research on optical fiber transmission, mode-multiplexed optical transmission technology using multiple orthogonal waveguide modes was proposed to increase the transmission capacity beyond the physical limit of existing SMF. It has recently been shown that multiple-input multiple-output (MIMO)-DSP technology has great potential to realize long-haul inline amplified transmission over 6000 km [8]. In wireless systems, on the other hand, it is generally impossible to define orthogonal waveguide modes as used in optical fiber, although conventional MIMO spatial multiplexing based on transmission path differences is widely used in commercial wireless communications.

A novel spatial multiplexing scheme using OAM was recently proposed as a way to achieve 100-Gbit/s channel transmission in millimeter-wave wireless communications [9]. This demonstration attracted much attention as a candidate for further increasing the speed of backhaul networks in 5G and post-5G applications. To achieve such high-speed mode-multiplexed transmission systems, it is essential to effectively implement DSP circuits considering the tradeoff between the DSP complexity and reliable dynamic characteristics to accommodate high-speed channel fluctuations in each transmission line (free space, optical fiber, etc.). Further progress in advanced DSP architecture and novel combinations of the abovementioned fundamental technologies are expected.

4. Future prospects

This article introduced the latest ultrahigh-speed communications technologies and future trends to realize a channel capacity over 1 Tbit/s in future transport networks. Further advances are expected in highly efficient DSP technologies for ultrahigh-speed channel transmission with careful consideration of practical DSP complexity economically implemented in single-chip LSI circuits. In millimeter-wave communications, a new degree of freedom offered by the OAM of electromagnetic waves in free space is expected to increase the channel speeds to over 1 Tbit/s. In optical fiber communications, long-haul transmission of high-speed channels beyond 1 Tbit/s will be achieved by using a suitable combination of advanced DSP functions and integrated optical front-end technology. Optical parametric amplifier technology and spatial multiplexing technology are promising for achieving further increases in the channel speed while maintaining the current DSP complexity and power consumption in optical fiber communications. Through continuous efforts in research and development and timely commercialization of these new technologies, terabit-per-second-class signals will be able to be easily handled in future transport networks.

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