Chapter 1
Introduction

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Abstract In this introductory chapter, the physical limits and prospects of the present optical fiber communication systems as well as EXAT initiative and 3M technologies are briefly described. Then, the demands from future applications, namely ultra-realistic communications, and wireless communication networks, such as 5G technologies are described. Lastly, the state-of-the-art terrestrial optical transmission systems and optical submarine cable systems are summarized.

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1.1 Physical Limits and Prospects of Optical Communication Systems

Figure 1.1 shows the evolution of transmission capacity per fiber of commercial optical fiber communication systems over the last four decades since 80s and future projections toward the next two decades. It is seen that the transmission capacity has been increasing constantly at an annual increase rate of about 1.5 dB per year, which has been enabled by various great inventions and breakthrough technologies. These include ultra-low-loss single-mode optical fibers, longitudinally single-mode laser-diodes, single-mode connection technologies (optical connecters, fusion splicing), Erbium-doped fiber amplifiers (EDFAs), WDM (wavelength division multiplexing) technologies with arrayed waveguide gratings (AWGs) and digital coherent technologies. However, it has been pointed out since the turn of the century that optical communication systems are rapidly approaching their capacity limit [1, 2] of around 100 Tbit/s per fiber [3–14], due to three major physical limiting factors, i.e., optical nonlinear effects in optical fibers, bandwidths of optical amplifiers as well as a destructive phenomenon called fiber fuse [15, 16]. Fiber fuse is described in detail in Chapter 7.

Figure 1.2 depicts how the total transmission capacity per fiber is determined by a product of spectral efficiency (SE), i.e., bit/s/Hz and a signal bandwidth. Firstly, the SE is governed by "Shannon limit" shown as a solid curve in Fig. 1.2a, but is further affected by signal distortions caused by various optical nonlinear effects in optical fibers, leading to a practical curve with a maximum peak called "nonlinear Shannon limit" shown as a dotted curve, an example of which is shown in the same figure. These nonlinear effects include self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM) and stimulated Raman scattering, etc.,

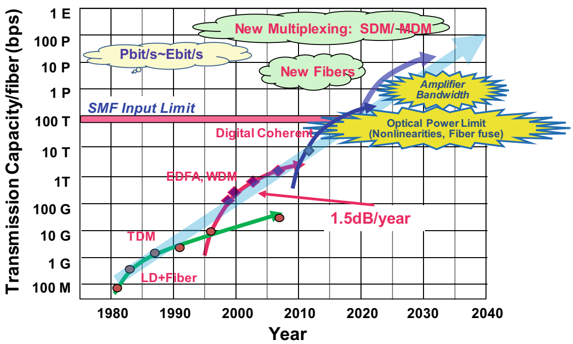


Fig. 1.1 Evolution of transmission capacity per fiber of commercial optical fiber communication systems over the last four decades and the projection for the next two decades. LD: laser diode, EDFA: erbium-doped fiber amplifier, TDM: time division multiplexing, WDM: wavelength division multiplexing, SDM: space-division multiplexing, MDM: mode-division multiplexing, SMF: single-mode fiber (Reprinted with permission from [17]. ©2017 IEICE)

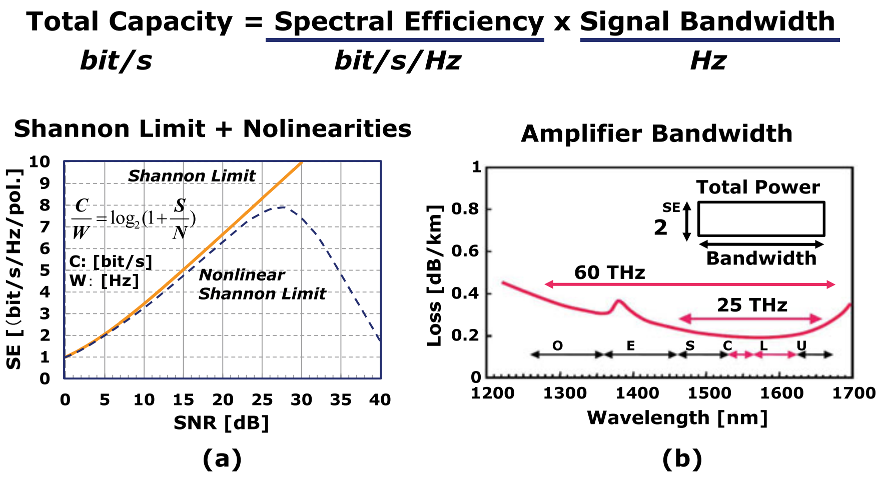


Fig. 1.2 Total capacity and its limiting factors

which are generated by high-power signals in optical fibers. The signal bandwidth given by the amplifier bandwidths is also limited up to around 40 nm per band in the case of rare-earth doped fiber amplifiers and around 100 nm for Raman amplifiers. The total amplifier bandwidth of the low-loss 1.5 μm bands including C-band (1530–1565 nm), L band (1565–1625 nm) and S-band (1460–1530 nm) amounts to 25 THz or combining all the other communication bands, i.e., O-band (1260–1360 nm), E-band (1360–1460 nm), U-band (1625–1675 nm), to around 60 THz. This would result in the maximum potential capacity of around 250 Tbit/s, or 600 Tbit/s, respectively per core if we assume an SE of 5 bit/s/Hz per polarization for all the bands. The ultimate capacity is, however, limited by the maximum allowable optical powers into the fiber, i.e., the fiber fuse propagation threshold optical powers, defined as those at which the fiber fuse stops once it has started. It should also be noted that distributed Raman amplification systems requiring pumping powers of several hundred mW up to W pause a big challenge where their pump powers combined with the signal powers are approaching the fiber fuse propagation threshold power of around 1.4 W for standard single-mode fibers and 1.2 W for dispersion-shifted fibers.

1.2 EXAT Initiative and 3M Technologies

1.2.1 EXAT Initiative

A study group named "EXAT (**EX**tremely **A**dvanced **T**ransmission) Initiative" was organized and initiated in January, 2008 by the National Institute of Information and Communications Technology (NICT), Japan, with 25 members from Japanese industries, academia, and national institutes in order to identify the ultimate limits of the present optical communication systems and to invent new breakthrough technologies which enable to substantially increase the transmission capacity well over Pbit/s per fiber [4, 7, 9, 11, 12, 14, 17]. They focused on identifying ultimate physical limitations of the present optical fiber communication systems, i.e., the maximum optical power that can be transmitted safely in optical fibers, the optical amplification bandwidths, as well as those of optical submarine cables systems, the capacity of which is limited by the electrical power consumed by the optical repeaters. As new R&D directions, the initiative proposed the use of a "space" as the last degree of freedom for multiplexing and the urgent need to develop new optical fibers (multi-core fibers (MCFs) [18–20], few-mode fibers (FMFs)) and both combined [21] as well as new multiplexing schemes, namely space-division multiplexing (SDM) and mode-division multiplexing (MDM), as depicted in Fig. 1.1. It should be pointed out that MCFs and MDM were initially proposed nearly four decades ago as a means to realize high-density optical cables primarily for subscriber lines [22, 23] and a new multiplexing scheme [24] compatible with time division multiplexing (TDM) and WDM, respectively.

After its first investigation period was over in 2008, an international symposium EXAT 2008, the first of its kind in the field of SDM was held in Tokyo in November 2008, where the initiative reported its first study on new optical fibers and related SDM technologies with a clear message that there is an urgent need of developing them in order to overcome the rapidly approaching limit of the optical communication systems. In its second term in 2009, EXAT Initiative discussed specific technological proposals toward the creation of national projects. Technical reports of each term were incorporated into a Japanese book entitled "Innovations in Optical Fiber Communications Technologies" published in 2012. The NICT EXAT then evolved to a new Institute of Electronics, Information and Communication Engineers (IEICE) EXAT study group in 2010, which has continued its vigorous activities, organizing 20 + international workshops, symposia, including EXAT 2013 (Sapporo), EXAT 2015 (Kyoto), EXAT 2017 (Nara), EXAT 2019 (Ise) and EXAT 2021 (virtual).

EXAT Initiative has also led to the creation of a series of pioneering national projects on SDM technologies, such as i-FREE (Innovative Optical Fiber Technologies: 2010–2012), i-ACTION (Innovative Optical Communication Infrastructure: 2011–2015), and i-FREE^2 (Innovative Optical Fiber and Communication Technology for Exa-bit Era with SDM: 2013–2018) which will be described in detail in Chapter 8. Recently, new projects SDM-PN (R&D of Space-Division Multiplexing Photonic Node: 2016–2020), i-FAST (R&D on Innovative Optical Fiber and Communication Technologies Toward Standardization: 2018–2022) and OCEANS (R&D on high-capacity multi-core fiber transmission systems: 2018–2022) were initiated and are ongoing. Furthermore, an EU-Japan coordinated R&D project SAFARI (**S**calable **A**nd **F**lexible optical **A**rchitecture for **R**econfigurable **I**nfrastructure: 2013–2017) was created as the first internationally collaborative project between Japanese EXAT and the European partners, commissioned by the Ministry of Internal Affairs and Communications (MIC) of Japan and European Commission Horizon 2020. These national projects have been leading the SDM technologies in the world, creating many world records such as 1-Pbit/s transmission (2012 [25], 2017 [26]), 1-Ebit/s·km transmission (2013) [27, 28], 2-Pbit/s (2015) [29, 30] and 10-Pbit/s transmission (2017) [31].

1.2.2 3M Technologies

As described in the preceding sections, EXAT Initiative explored new optical fibers making use of "space" dimension, namely MCFs and FMFs or multi-mode fibers (MMFs) as depicted in Fig. 1.3. MCFs have the propagation mode in each core either coupled with those in other cores or un-coupled. FMFs/MMFs, on the other hand, have different modes in a core, which normally couple with each other over some distances and thus multiple-input, multiple-output (MIMO) processing is usually required to separate different modes at the receiver side.

In developing SDM technologies, EXAT Initiative identified three major fundamental research topics, namely "Mutil-core Fiber," "Multi-mode Control" and "Multi-level Modulation," which we call "3M technologies" as depicted in Fig. 1.4 where a factor of 10 in each category should enable a factor of 1000 increase in capacity [4, 11, 17]. In fact, 32-core [26]/37 core [32]/38 core fiber [33] as well as 45-mode [34] transmission has already been demonstrated.

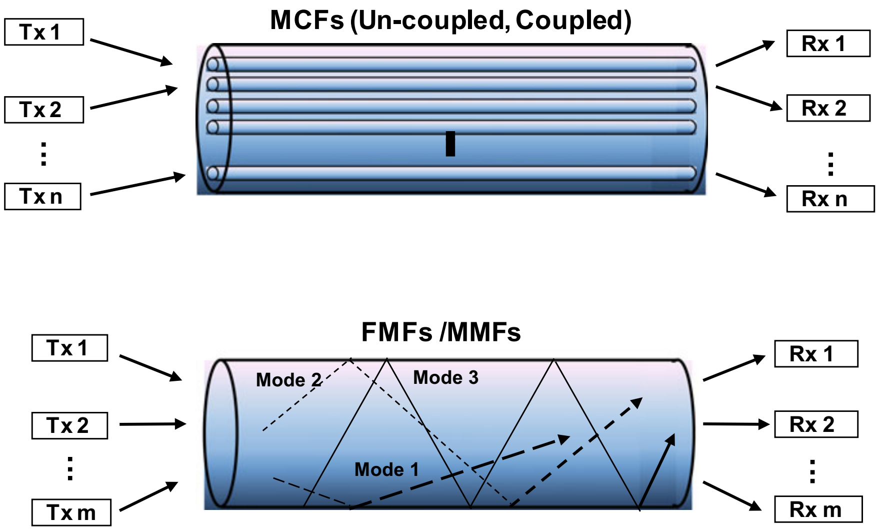


Fig. 1.3 Schematics of multi-core fibers (MCFs) and few-mode fibers (FMFs) or multi-mode fibers (MMFs) (Reprinted with permission from [17]. ©2017 IEICE)

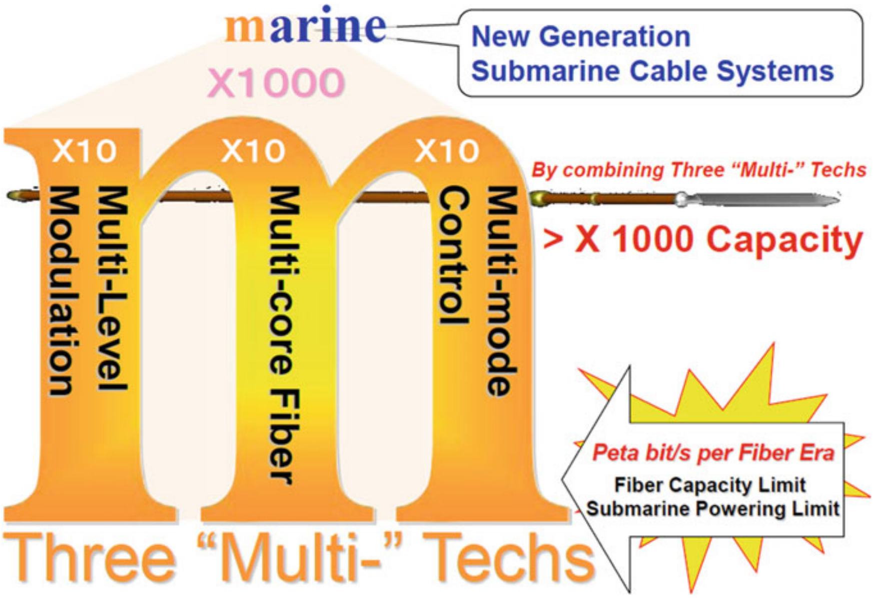


Fig. 1.4 3M technologies (Reprinted with permission from [17]. ©2017 IEICE)

Recently, few-mode, multi-core fibers (FM-MCFs) have been developed to further increase the transmission capacity and used to achieve up to 10-Pbit/s transmission [29, 31, 33, 35]. The major SDM components to be developed are SDM fibers, SDM multiplexers/demultiplexers (SDM-MUXs/DEMUXs), SDM optical amplifiers, optical connectors/splicing as depicted in Fig. 1.5. Important characteristics of the passive components are naturally low insertion loss, low core-/mode-dependent loss, low crosstalk among modes/cores and wide-bandwidths to support as many WDM/SDM channels as possible. SDM optical amplifiers require low core-/mode-/wavelength-dependent gain, wide-bandwidths with high gain and low NFs. All these components will be described in detail in the following chapters.

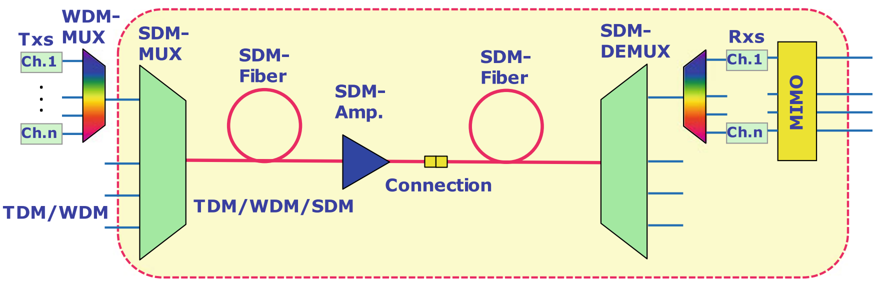


Fig. 1.5 Basic optical components for SDM technologies. Tx: transmitter, Rx: receiver (Reprinted with permission from [17]. ©2017 IEICE)

1.3 Requirements for Future Applications

1.3.1 Ultra-Realistic Communication

To confront various societal issues such as global warming or the aging of the population, a great deal of attention is being paid to ultra-realistic communication, which makes viewers feel as if they were somewhere else without actually leaving their own locations. If meetings could be conducted so that actual face-to-face discussions were held even though the participants were far apart, no energy need be consumed for travel and if there were a system that made it possible for people with physical impairments to take part in social activities, society could make the best use of the knowledge and skills of the elderly.

Although teleconferencing systems already exist, they certainly feel as if the meeting is being conducted through a screen and there is a considerable sense of discomfort compared with a face-to-face meeting. This sense of discomfort would be eliminated if ultra-realistic communication technology was implemented by delivering advanced video conveying the sensations of immersiveness, extremely fine detail, or three-dimensionality; 3D sound imparting even the presence of people nearby or the environmental sounds of a room; or sensations that make it feel as if something in a distant location were close at hand.

This section will introduce ultra-high definition video or 3D video, which are the core technologies of ultra-realistic communication, and will describe the requirements of an optical communication system for transmitting them.

1.3.1.1 Evolution of Video and Their Corresponding Transmission Capacities

The history of the evolution of video, especially television broadcasting, is a history of increasing realism. Figure 1.6 shows the history of this progress from photographs to black and white television, from black and white to color, and from Standard

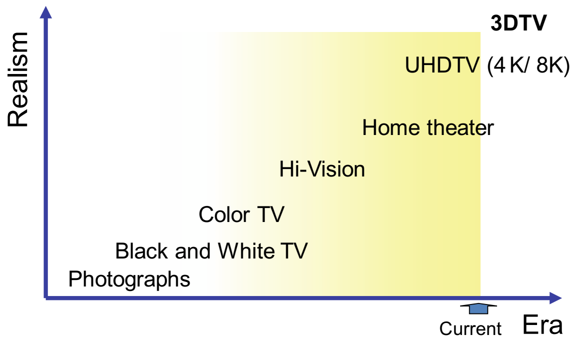


Fig. 1.6 History and future of TV broadcasting advancing toward ultra-realism

Definition TV (SDTV) with 500 or 600 scan lines to High-Definition Television: commonly called Hi-Vision (HDTV) with 1080 scan lines. The marketing of large flat screen TVs for projecting Hi-Vision quality images contributed to this progress. Recently, home theaters with screen sizes of 70 inches or more have become quite popular.

In addition, 4 K Ultra-High Definition (UHD) and 8 K UHD television, which aim to increase high-definition standards even further, were steadily implemented as the latest TV, and research is being conducted on 3D television as the next-generation TV after that.

(1) UHDTV (4 K/8 K)

I have installed a home theater in my home which combines a full HDTV projector and a 90 inch screen so that I can enjoy watching Hi-Vision broadcasts that make me feel as if I were actually present in the scene being broadcast. However, since I am viewing this in the narrow environment of a 6 tatami mat room (approximately 99 square feet), I am unable to maintain the optimum HDTV viewing distance (3 times the screen height) and must watch the picture from too close a distance. Screen display degradation due to the scan line structure or digital compression is conspicuous in full-impact scenes. This increases my desire to be able to view a high-quality picture even when viewing the screen from a close distance.

Ultra-HDTV (UHDTV), which aims to increase high definition standards even further, is an attempt to achieve this goal. Other common names for this technology are 4 K UHDTV and 8 K UHDTV. Specifications for these technologies have already been standardized by the International Telecommunication Union (ITU) [36] and started broadcasting from 2018.

4 K UHDTV is a video system with double the number of scan lines of HDTV at 2160 lines and double the number of horizontal pixels at 3840. Since the number of horizontal pixels is approximately 4000, this has “4 K” in its name. The color reproduction capability is also greater than that of HDTV. Displays and cameras that satisfy 4 K specifications are already on the market. Test terrestrial broadcasts of 4 K UHDTV were conducted in Korea in 2012, and experimental satellite broadcasts were started in Japan in 2014. In June 2014, the FIFA World Cup from Brazil was broadcast in Japan in 4 K video.

Research and development of 8 K UHDTV, which is also known as Super Hi-Vision television, has been conducted with NHK Science and Technology Research Laboratories playing the leading role. Super Hi-Vision television has 4320 vertical scan lines and 7680 horizontal pixels, which are each 4 times those of Hi-Vision television, as shown in Fig. 1.7. The optimum viewing distance for this kind of extremely detailed video can be viewed from a distance much closer to the screen (0.75 times the screen height). The angle of view with which the viewer observes the screen at that time is 100°. The relationship between the visual field and the size of the image projected on the retina indicates that the angle of view of Super Hi-Vision television is almost equivalent to the size of the induced visual field that affects the

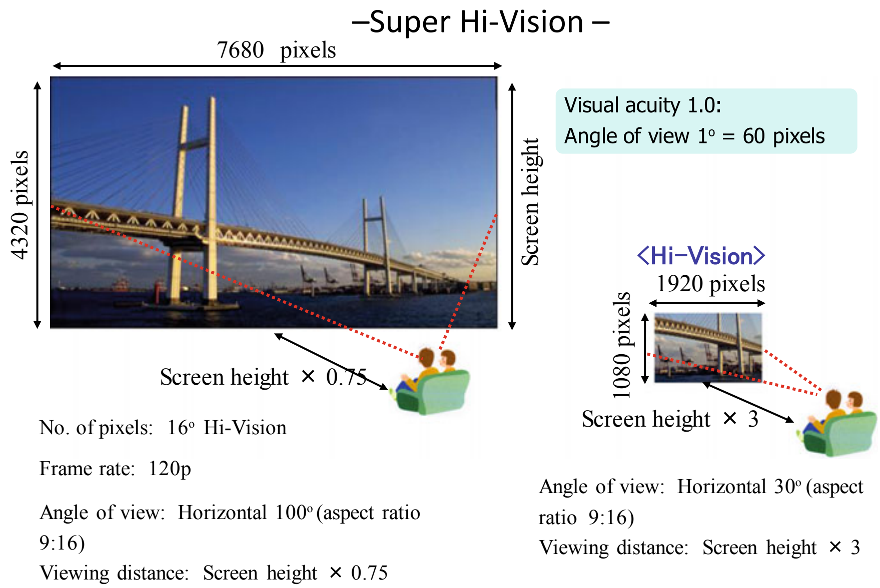


Fig. 1.7 8 K UHDTV

sense of orientation. In other words, a large screen UHD video system can greatly bring about an enhanced sense of reality in which viewers instinctively move their bodies due to motion of the image on the screen. NHK Science and Technology Research Laboratories performed subjective evaluation experiments concerning the visual field angle of view and the sense of reality and obtained results indicating that the sense of reality is saturated for horizontal visual field angles of view ranging from 80 to 100° [37]. In addition, as the screen size increases, motion resolution must also increase. Therefore, 8 K UHDTV also includes standards that increase the number of images per second (frame rate) from the normal 60–120. The color reproduction capability is also greater than that of HDTV as it is for 4 K UHDTV. In addition to this kind of high-definition video, a 22.2 channel multi-channel surround sound system is also provided as part of the Hi-Vision broadcasting service.

While developing prototype equipment such as 8 K cameras, editing systems, transmission devices, broadcasting media (satellite broadcasting, terrestrial broadcasting and broadband networks) and display devices, transmission trials have already been performed. NHK provided public viewings of prototype broadcasts of the 2012 London Olympics at several locations throughout Japan. In addition, experimental broadcasting began in 2016 and actual broadcasting in 2018.

The amount of information (uncompressed signal) carried by Super Hi-Vision television is approximately 144 G bit per second (bps). This number can be calculated from (12 bits per pixel) × (4320 × 7680 pixels) × (120 frames) × (3 primary colors). The amount of information for HDTV, however, is approximately 1.5 Gbps.

Currently, HDTV (Hi-Vision) is being broadcast in Japan by both terrestrial and satellite digital broadcasters, but due to bandwidth constraints, MPEG 2 is being used to compress the signals to approximately 15 Mbps for terrestrial broadcasts and to approximately 20 Mbps for satellite broadcasts (using a compression ratio of approximately 1/100). The compression standards that have been determined for Super Hi-Vision television use High-Efficiency Video Coding (HEVC) [38], which has greater compression efficiency than MPEG 2, so that the drop in image quality is visually permissible even when compressed to approximately 100 Mbps (using a compression ratio of approximately 1/1000).

(2) 3D television (3DTV)

The ultimate video service for ultra-realistic imaging techniques is 3D television, and research and development of 3DTV is being conducted by various organizations including the National Institute of Information and Communications Technologies (NICT). A 3D imaging system can be constructed by understanding the mechanism by which people perceive an external three-dimensional space from two-dimensional images projected on their retinas. Physiological cues that cause us to perceive stereopsis are listed below.

- Binocular parallax: Difference according to the distances to the subject in the images projected on the left and right eyes
- Convergence: The angle determined by both eyes focusing on the object (the eyes will cross when viewing a nearby object)
- Accommodation: Focal adjustment of the eye lens according to the distance to the object
- Motion parallax: Difference in how objects appear due to changes in their relative motion or degree of overlap

In addition to these, there are also graphic clues such as contours and shadows (psychological cues) that enable us to perceive objects three-dimensionally.

The simplest 3D video system for stimulating perception of stereopsis uses the binocular parallax method. In other words, the stereoscopic method presents separate images for the left and right eyes simultaneously on one screen and apportions those images, respectively, to the left and right eyes by using some means such as special glasses. In 2010, Hollywood studios began making many stereoscopic 3D movies which were shown in digital theaters throughout the world. However, although some TV sets that were manufactured for home use also had features that enabled stereoscopic 3D images to be viewed, they did not become very popular because relatively little content was created and because of the following drawbacks of the stereoscopic method. First, special glasses are typically worn to properly view images created by the stereoscopic method, and since the position of the display surface differs from the position where the 3D image is reproduced, the resulting eye adjustments for convergence and accommodation are unbalanced, which often results in eyestrain. In addition, stereopsis can become disrupted when there are more sudden scene changes than can be followed by changes in binocular parallax.

Recently, a great deal of research has been conducted concerning methods of reproducing three-dimensional space in natural light. Some examples include a multi-view autostereoscopic display method in which numerous viewpoints are strictly arranged in a fixed alignment [39], a light field method that uses a lens array, etc., to create light in various directions [40] and an electronic holography method that reproduces light with light-wave precision based on the theory of holography [41].

The amount of information for the stereoscopic method is twice the amount of image information for one eye because there are left and right images. For the multi-view method, this increases to a multiple corresponding to the number of views. For example, the large screen glasses-free (multiview) 3D display on which we are currently conducting research at NICT uses an ultra-multiview autostereoscopic 3D imaging method in which several hundred Hi-Vision picture-quality projectors are arranged horizontally, and the amount of information in this case is approximately 300–500 Gbps. Figure 1.8 shows the 200-inch, approximately 200-view horizontal parallax, large screen ultra-multiview autostereoscopic display that we developed [42]. The theoretical value for a system with specifications of a 50-inch screen, 30° field of view (range in which stereopsis is possible), Hi-Vision picture quality using the holographic method for generating the most ideal 3D images is 600 Tbps.

The Moving Picture Experts Group (MPEG), which determines international standards for video encoding, discussed encoding for compressing these kinds of multi-viewpoint images with massive amounts of data and created Multiview Video Coding (MVC) as the video compression standard for multiview images. This standard encodes data by treating the multiview data as a single base view and some residual non-base views. It uses interview prediction, which references frames contained in

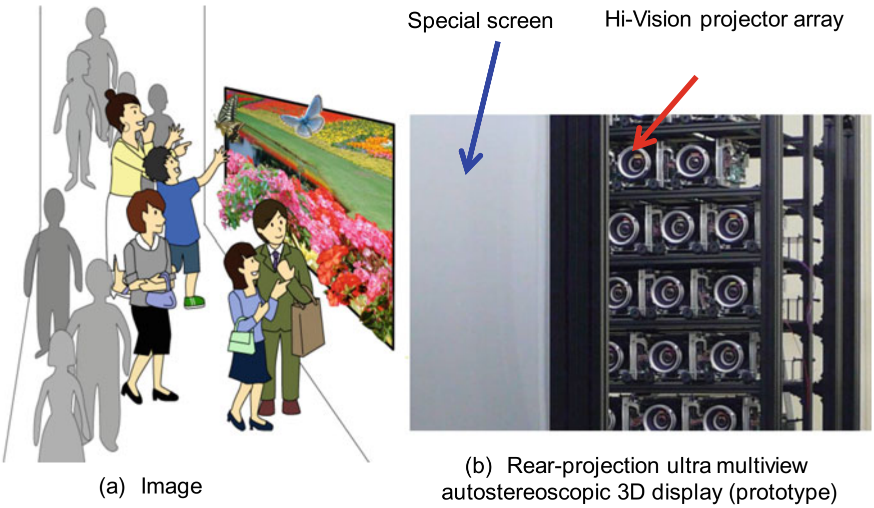


Fig. 1.8 Ultra-multiview autostereoscopic 3D display developed by NICT

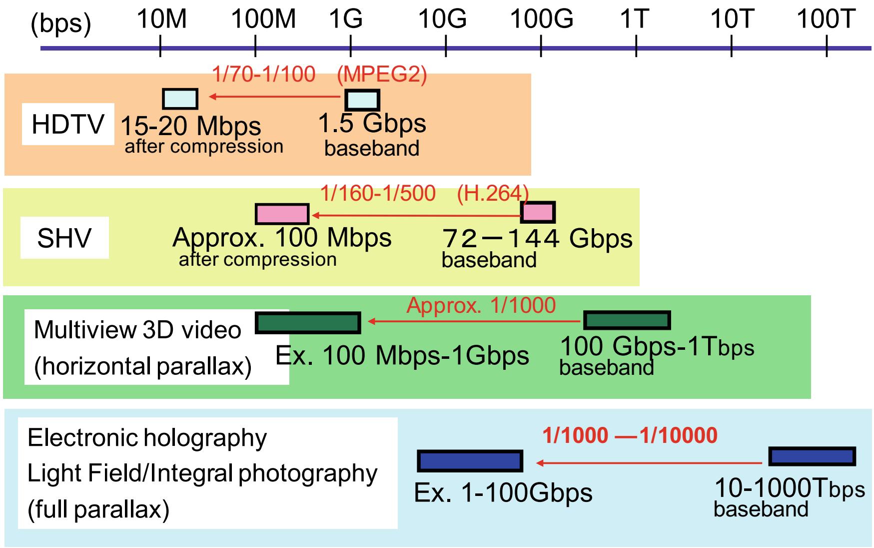


Fig. 1.9 Expected amounts of information before and after compression for various types of video methods

the other view to encode the non-base view. The non-base view can be compressed approximately half as much as the base view.

MPEG was also examining 3D-AVC and 3D-HEVC as separate encoding methods for compressing 3D images. These methods simultaneously encode multiview images and depth data by using interrelations between them. Since 3D image information is based on the projection of an object in 3D space, it makes sense to encode the multiview images and depth data simultaneously. Not only are the compression capabilities of 3D-AVC and 3D-HEVC highly efficient, but the decoder can also generate images at various viewpoints depending on the display system at the decoder side.

Since hologram images or multiview images and depth data are used for 3D video information as described above, it is advantageous that the compression efficiency of these methods theoretically is relatively high for increasing amounts of data. The ultra-realistic multiview 3D imaging methods or holographic methods that NICT will be developing in the future will probably require a transmission capacity of several Gbps to several dozen Gbps per content (Fig. 1.9).

1.3.1.2 Ubiquitous Video

Recently, surveillance cameras have been installed all over for security purposes. Public vehicles such as buses and taxis have also been equipped with cameras. These are connected to closed networks, and each of them is used independently.

On the other hand, live video cam images are publically available from Web pages to inform viewers of traffic conditions, how crowded sightseeing spots are, and how much snow has fallen at ski slopes. Bird's-eye views like those of Google Earth are also available.

Mutually connecting this kind of video, which is flowing throughout the world, to a network and collectively delivering or recording it together with metadata from various types of sensors such as position information, sound, temperature or CO_2 measuring instruments will make it possible for almost any location to be viewed together with data that changes from moment to moment, including even video from the past, at any time from various angles. This is the so-called Internet of Things (IoT) including video information. Of course, policies must be devised for privacy protection, but this certainly can be implemented technically. We have coined the term "ubiquitous video" for this kind of wireless sensor network centered on video. These videos and metadata will be the input information for ultra-realistic video communication.

Implementation of ubiquitous video can give rise to new public services or businesses. For example, this surely can be useful for disaster prevention, security, and elder care, and also can be used to implement monitoring of environment changes (environmental logging), trip navigation, and even life-logging by videoing oneself.

Not only will video be distributed by these kinds of ubiquitous video services, but ordinary Internet users also will continue to distribute video in email attachments and blogs. Although Asymmetric Digital Subscriber Line (ADSL) networks had previously been popular, they were based on the premise that much less information would be uploaded than downloaded. However, networks from now on must guarantee that the amount of uploaded information can also be transmitted.

1.3.1.3 Requirements for Optical Communication Networks

The "killer application" for optical communication networks will surely be video information. To stably distribute the high-capacity video information of the future including UHDTV or 3DTV or to make practical use of video information anywhere throughout the world, the next-generation optical transmission network must satisfy the following conditions.

- Ultra-fast broadband: Able to distribute UHD, 3D video information at rates of several Gbps to several dozen Gbps.
- Low latency: Latency on the order of several dozen milliseconds. Able to provide stress-free interaction, remote control, and negotiation between transmission and reception terminals.
- Variation-free latency: Latency must not differ due to differences in transmission channels or audio and video media.
- Balanced upstream/downstream transmission speeds: Uploading of video information will also increase in the future.

- Smooth access switching: Must be able to execute distributed server transfer and area control without interruption. Must be able to allow smooth channel surfing. Must be able to support changes in the viewing environment (e.g., a viewer may want to continue viewing content that had been viewed through a wired connection from a separate wireless device).
- Plug and play: Video information is expected to be generated by various methods in the future. To support this information with flexibility, any kind of information must be able to be sent and received just by plugging in to a network.
- Robust and highly stable: Must be stable as the core information distribution infrastructure. Must be resilient and durable even during disasters. An unstable network when charges for content are widespread cannot be a core infrastructure.
- Highly reliable and secure: Content must not be easily falsified. Copyrights must be diligently protected. Privacy must be safeguarded.
- Energy conservation: Network and terminals both must operate with low-power requirements.

Conclusions

In this section, we described future video technologies and their transmission capacities as well as requirements for optical communication networks. To increase a sense of realism, information will have to be delivered with as much fidelity as possible. To accomplish this, the some information may have to be delivered directly without compression encoding. Other information such as audio, tactile and vestibular sensation information may also have to be delivered in addition to video information. Delays will not be permitted for interactions with other parties. In this sense, even higher speeds and greater capacities are desirable.

1.3.2 Optical Network Technologies for Wireless Communication Network

Optical networks continue to play an important role in wireless communication systems, especially to link base stations to the core network in the radio access network (RAN).

Two RAN architectures have been developed to accommodate base stations: distributed RAN (D-RAN) and centralized RAN (C-RAN). In the D-RAN architecture, as shown in Fig. 1.10a, base stations are connected to the core network via an IP/Ethernet-based network and connected to other base stations via switches or routers. The link between the base stations and the core network is called the mobile backhaul (MBH). The data rate of MBH from base stations roughly equals that of mobile data traffic. Latency between base stations is categorized as non-ideal backhaul, and latency should be decreased to provide higher system performance. Commercial IP and Ethernet services are currently used as the transmission medium for MBH.

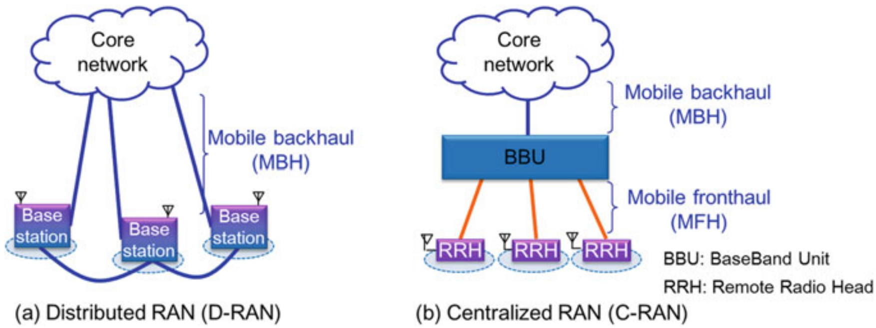


Fig. 1.10 RAN architectures

In the C-RAN architecture, as shown in Fig. 1.10b, the baseband function of base stations are concentrated and remote antennas need offer only transmit and receive functions. The C-RAN configuration realizes advanced cooperation between the cells covered by each base station. In the C-RAN architecture, the link between baseband unit (BBU) and remote radio head (RRH) is called the mobile fronthaul (MFH) and is based on digital radio over fiber (DRoF) for low-cost optics and waveform transparency. Common public radio interface (CPRI) is the de facto standard for MFH transmission [43]. CPRI transmission is based on IQ data transmission and requires high bandwidth (1 Gbit/s for single antenna 20 MHz radio bandwidth transmission). The number of antennas, frequency bands and MIMO layers are increased until the required bandwidth is satisfied. The BBU-RRH response is a severe problem. Since the response time of hybrid automatic repeat request (HARQ) is set to 8 ms, the latency limit for CPRI transmission is about 300 μs in general [44] and the transmission distance is limited to 10–20 km.

Moreover, accurate frequency and time synchronization are required for proper operation of baseband units [45]. The frequency accuracy of 50–200 ppb is required for proper frequency radio transmission. Time accuracy is required for time division duplex (TDD) transmission control, and heterogeneous network (HetNet) operation, etc., and required accuracy is about 1 μs.

1.3.2.1 Prospects of 5G Mobile Communication System

Mobile communication services have demonstrated significant growth over the last few decades. Currently, many operators worldwide have already deployed Long-Term Evolution (LTE) and LTE-Advanced, i.e., fourth generation mobile communications system (4G) to offer faster access with lower latency and higher efficiency than its predecessors, 3G and 3.5G. Given these trends, there is inexorable demand for new mobile communications systems with even further enhance capabilities, namely 5G. Several organizations have established worldwide to study 5G networks, such as the 5G Infrastructure Public Private Partnership (5G-PPP) in Europe [46], IMT-2020 (5G) promotion Group in China [47], 5G Forum in Korea and 5G Mobile Communications Promotion Forum (5GMF) in Japan [48].

The radio access network (RAN) of 5G assumes that small cells will be laid over macro-cells [49]. The small cells offer wide-bandwidth and super high-speed transmission using higher frequency bands from super high frequency (SHF) to extremely high frequency (EHF) in small coverage area, while the macro-cells provide coverage and mobility. 5G RAN will also support extension so that existing small cells as well as various future small cells are accommodated flexibly and appropriately by the networks, and cell selection and radio resource assignment can be performed according to each user's moving situation, service requirements, etc.

The assumed targets of 5G network are as follows:

1. Augmented system capacity is 1000 times higher traffic volume than around 2010 when LTE service started,
2. Supporting the connection of one hundred times more devices than LTE,
3. Higher data rate deployments, e.g.,> 10 Gbit/s,
4. User-plane latency of less than 1 ms over the RAN, (currently 5 ms in LTE).

To meet these 5G targets, we need to address spectrum efficiency, spectrum extension and network densification.

Figure 1.11 shows an assumed 5G RAN [50]. It uses the multi-layered cell architecture with the cooperation of all layer radio access technologies (RATs) to achieve high data throughput and high availability everywhere. As shown in Fig. 1.11, each macro-cell is overlaid by many small cells. The small cells are used for high capacity, while the macro-cell provides coverage and user mobility. Especially in high traffic density areas, small cells should be deployed densely with the cell radius of several

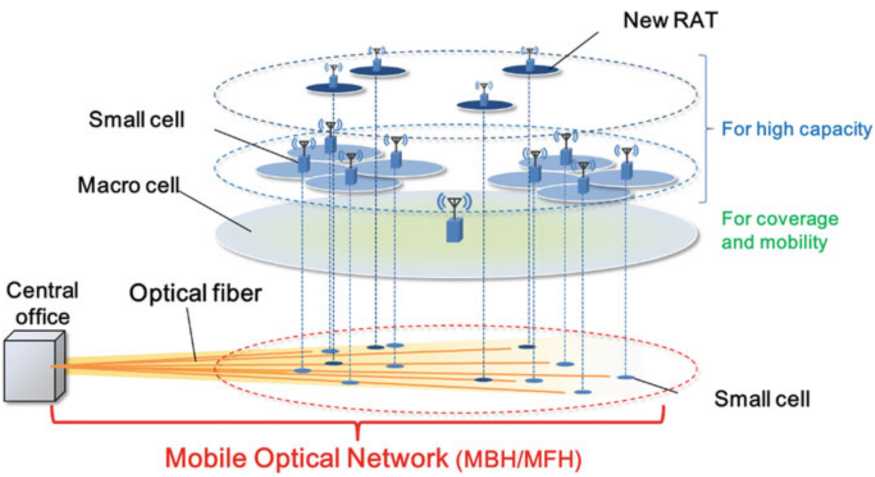


Fig. 1.11 5G RAN

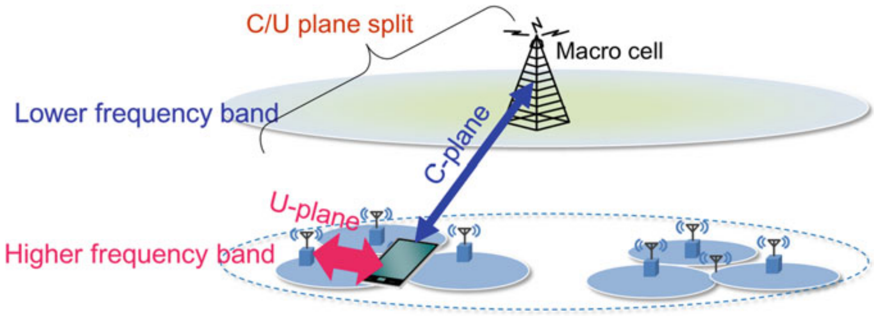


Fig. 1.12 C/U plane split

tens of meters. The RATs of these new small cells are not the same as those of conventional small cells so RAT enhancement is also needed for 5G RAN.

With regard to RAT enhancement, higher order modulation schemes such as 256-QAM and high-frequency utilization schemes such as non-orthogonal multiple access (NOMA) have been studied [51, 52].

To permit the new RATs to offer higher throughput, it is preferable to use of higher frequency bands, such as Super High Frequency (SHF) band, i.e., 3–30 GHz, and Extremely High Frequency (EHF) band, i.e., 30–300 GHz, with large bandwidth (> 100 MHz). Radio waves in the high-frequency range have exceptionally strong line of sight performance so interference between cells is very small. Moreover, higher order MIMO with many antennas can be realized with small antenna size, and this will enhance cell capacity. Therefore, 10-Gbit/s class capacity per cell per RAT can be achieved [53].

For high user mobility, the frequency of handover between macro- and small cells and between small cells will be raised, and control traffic between base station and core network will be increased. Moreover, HetNet operation between macro- and small cells also requires control bandwidth for high mobility. To reduce the control traffic, splitting the control and user planes (C/U plane split), see Fig. 1.12, is a useful technique [50]. The C-plane traffic is transmitted over the macro-cell network, and high connectivity is assured. The high capacity of the U-plane is achieved by small cells, and handover and HetNet operation in a macro-cell area is controlled by the macro-base station. Radio resource management for efficient traffic accommodation is also controlled by the macro-base station. In this case, cooperation between macro- and small cells is very important, and low latency and high-capacity connections between macro- and small base stations are critical.

1.3.2.2 Challenges Imposed by Optical Access Technology for 5G Network

Optical access technology, especially the passive optical network (PON), has been widely deployed in the form of fiber-to-the-home (FTTH) service. In a PON system, one fiber is shared with multiple subscribers and this enables broadband services at low cost. Gigabit class FTTH services are widely offered using the gigabit PON (G-PON) system standardized by ITU-T or the gigabit Ethernet PON (GE-PON) by IEEE. These PON systems are based on the time division multiplexing (TDM) technique. TDM-PON is a cost-effective solution to accommodate small cell clusters; however, there are many technical issues to resolve, such as latency and bandwidth. It is also important for the next optical networks to support the flexible configuration of small cell clusters. Securing the cooperation of mobile and optical networks is one key to resolve these issues, and in the following, some challenges are briefly introduced.

Low latency transmission is very important for the mobile optical network. In downstream TDM-PON, the latency of network equipment is estimated to be several tens of microseconds and 20 km fiber length (100 μs latency) is possible for MFH. In the upstream, due to the dynamic bandwidth allocation (DBA) algorithm, the latency is more than 1 ms, which is too large to support MFH transmission. One approach to reducing DBA latency is using a fixed bandwidth allocation (FBA) scheme. By using FBA, no control signal between OLT and ONU for bandwidth allocation is transmitted, which reduces the latency to several tens of microseconds. However, with FBA operation, the bandwidth of each connection is fixed and efficient bandwidth usage based on statistical multiplexing cannot be achieved.

Recently, a new bandwidth allocation scheme for upstream PON based on mobile bandwidth allocation has been proposed [54]. In the LTE system, the base station allocates uplink bandwidth for each user terminal and also passes scheduling information to UE with 4 ms timing advance. Therefore, as shown in Fig. 1.13, the required upstream bandwidth of the PON can be calculated using scheduling information of the mobile system, and grant data reaches each ONU before uplink signal reception. Thus, the latency of TDM-PON is minimized and total latency, excluding fiber delay, should theoretically be of order of several tens of microseconds. Some measured results of a prototype are shown in Fig. 1.14. Latency under 30 μs is achieved with the proposed scheme. To implement this method, an interface of scheduling information should be placed in the base station.

There are two ways to handle the huge service demands placed on MBH and MFH of 5G RAN, expansion of transmission bandwidth and data bandwidth reduction.

With regard to bandwidth expansion, NG-PON2 can provide 40-Gbit/s class bandwidth, which is enough for current MBH and MFH. However, much higher bandwidth will be needed in future given the vision of 10-Gbit/s class user bandwidth. Digital coherent detection with high level modulation can be used to enhance capacity per wavelength. However, in optical access, cost is a very important factor, and the development of low cost digital coherent systems is critical. WDM-based bandwidth

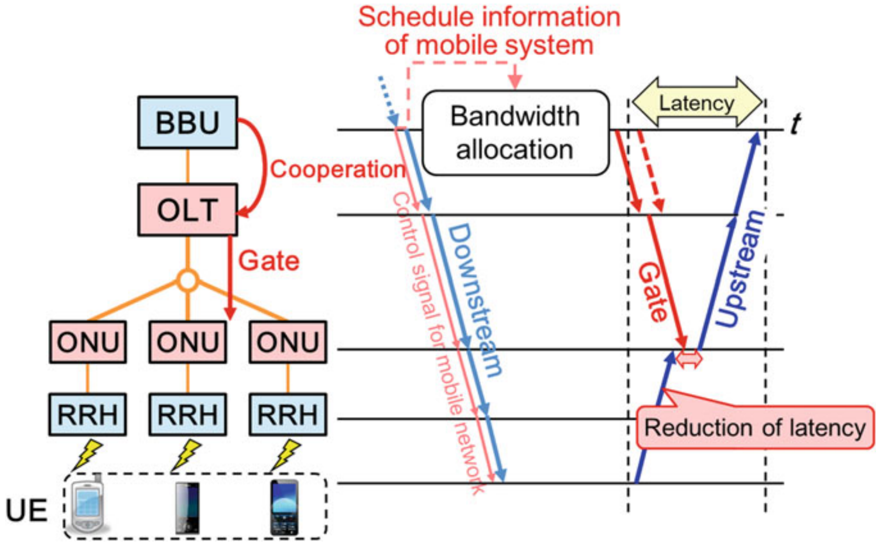


Fig. 1.13 Mobile optical network with TDM-PON

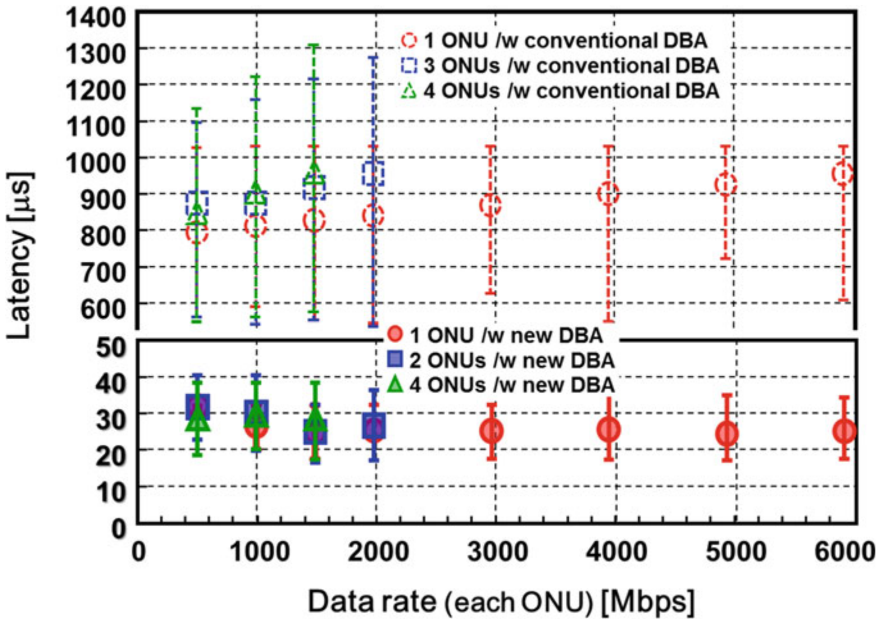


Fig. 1.14 Measured latency with conventional DBA and DBA using schedule information of mobile system (Reprinted with permission from [54]. ©2014 Authors)

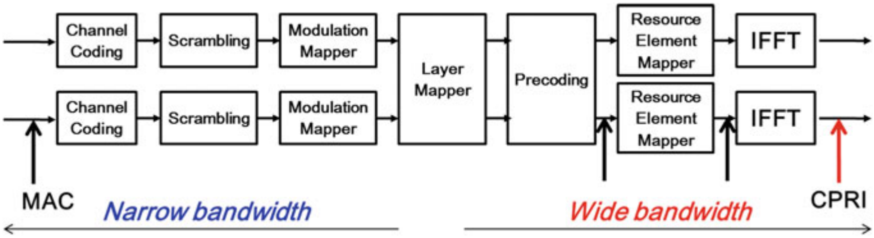


Fig. 1.15 BBU-RRH separation point

expansion is also available, and wavelength allocation for WDM overlay has been discussed in NG-PON2/ITU-T [55, 56].

Bandwidth reduction is very useful for MFH. In the recent CPRI specification [43], a new line coding (64b/66b coding) that offers less redundancy than conventional coding (8b/10b coding) and sampling rate reduced transmission have been proposed. More antennas or bands can be accommodated on the same CPRI link. IQ data compression is also useful. Currently, many compression schemes have been proposed that mainly use sampling rate reduction and quantization bit width reduction; compression ratios of under 1/2 can be realized [57, 58]. However, these methods are lossy compression for low latency and high compression rates, and some distortion in IQ data seems inevitable. In the latest proposals, distortion is set to low enough that signal quality degradation is insignificant ($< 1\%$ EVM degradation); however, more accurate transmission of IQ data and high dynamic range is needed for enhanced RAT (256 QAM and NOMA), and the merit of data compression seems to be problematic.

Another approach to bandwidth reduction in MFH is changing the BBU-RRH separation point in the physical layer (Fig. 1.15). Higher sublayer separation reduces the required bandwidth to the mobile data rate [59]. Pre-IFFT data transmission also reduces bandwidth drastically [60, 61]. The MFH data rate of these techniques dynamically changes with the mobile traffic, and in TDM-PON systems, statistical multiplexing gain can be expected. Therefore, a combination of these methods and DBA using scheduling information of the mobile system is very effective for future MFH. These methods need tight integration of the base stations and TDM-PON system, and if the mobile operator is not the FTTH operator, development of an effective control interface between systems is very important.

Conclusions

In the 5G RAN for 2020 and beyond, the role of small cells is very important, and to support the efficient and cost-effective operation of 5G RAN, cooperation of mobile and optical access networks is essential. To accommodate small cell clusters, the TDM-PON-based optical network is useful for its flexibility and cost effectiveness in terms of CAPEX and OPEX, but further enhancement to meet 5G RAN requirements is needed.

1.4 State-of-the-Art Terrestrial Optical Transmission

1.4.1 Expansion of Broadband Services in Japan

There has been a rapid expansion of broadband services in Japan in recent years, spurred by the development of diverse services that use the Internet. According to statistics published by the Ministry of Internal Affairs and Communications, the total number of broadband subscribers in Japan exceeded 40 million and the download traffic of broadband service subscribers reached 19.0 Tbit/s as of May 2020 (Fig. 1.16 and Fig. 1.17) [62]. Fiber to the home (FTTH) has taken over the lead from ADSL in Japan, and Japan now has the highest penetration of optical access services of any

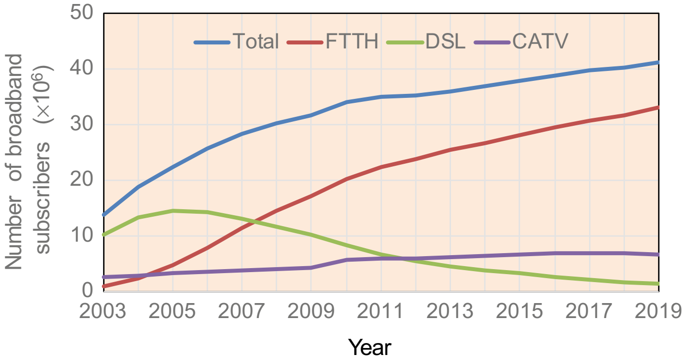


Fig. 1.16 Expansion of the broadband infrastructure

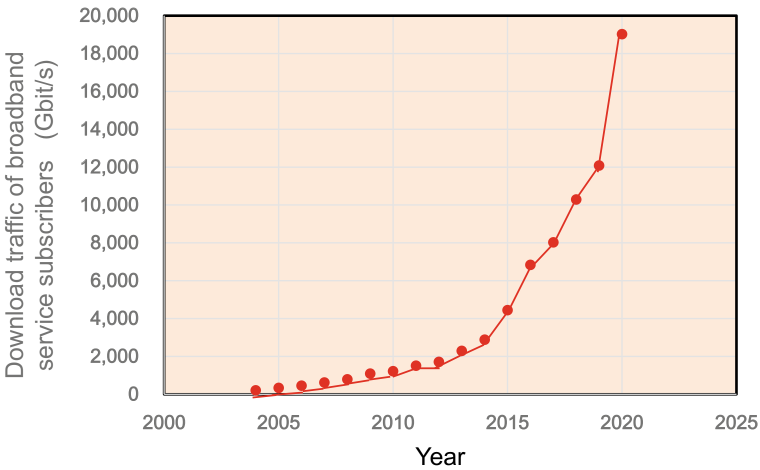


Fig. 1.17 Increase in Internet traffic

country in the world. Furthermore, the data traffic volume on the core network, which carries the high-volume multiplexed access network signals, has been increasing annually by a factor of from 1.3 to 1.4. Research and development on access networks and photonic transport networks that can handle high-volume traffic is indispensable for the growth and further development of the future broadband society. In this section, we introduce the current state of optical access technology and high-capacity optical transmission technology.

1.4.2 Optical Access Technology

The leading optical access technology to support FTTH is Passive Optical Network (PON). It realizes point-to-multipoint communication between Optical Line Terminal (OLT) at the central office and a number of Optical Network Units (ONUs) at the subscribers' side via Optical Distribution Network (ODN). The massive FTTH deployment in recent years has been supported by Gigabit Ethernet PON (GE-PON) which was standardized by IEEE in 2004 as a part of the IEEE Standard 802.3 [63]. GE-PON offers symmetric 1-Gbit/s bandwidth which is shared among up to 32 ONUs through the use of Time-Division Multiple Access (TDMA). The TDMA technique not only allows the shared use of the optical fiber and the OLT optics, but also enables the aggregation of the traffic from the number of ONUs. Thus, it realizes a simple and cost-effective access and aggregation network.

As a successor of GE-PON, IEEE standardized 10G-EPON in 2009 [64]. Its downstream bandwidth is 10 Gbit/s while its upstream bandwidths are 1 Gbit/s and 10 Gbit/s in the asymmetric and the symmetric options, respectively. 10G-EPON OLT can accommodate GE-PON ONUs so that a smooth migration from GE-PON to 10G-EPON is realized.

ITU-T standardized Gigabit-capable PON (G-PON) and 10Gigabit-capable PON (XG-PON) in 2004 and 2010, respectively [65, 66]. For further evolution, ITU-T standardized 40 Gigabit-capable PON in 2015, which has been also known as Next-Generation PON2 (NG-PON2) [67]. NG-PON2 adopts the Time- and Wavelength-Division Multiplexing PON (TWDM-PON) as the primal technology, in which 4–8 wavelength pairs are used to realize the 40-Gbit/s aggregated capacity or over. TDMA is used to share the bandwidth in each upstream wavelength among a number of ONUs. NG-PON2 also adopts Point-to-Point WDM PON (PtP WDM-PON) as the secondary technology. The evolution of PON technologies will continue to support the growth of the broadband access services in the long term.

1.4.3 High-Capacity Optical Transmission Technology

Optical transmission technologies have advanced rapidly over the past thirty years in three main technological innovations (Fig. 1.18): time division multiplexing

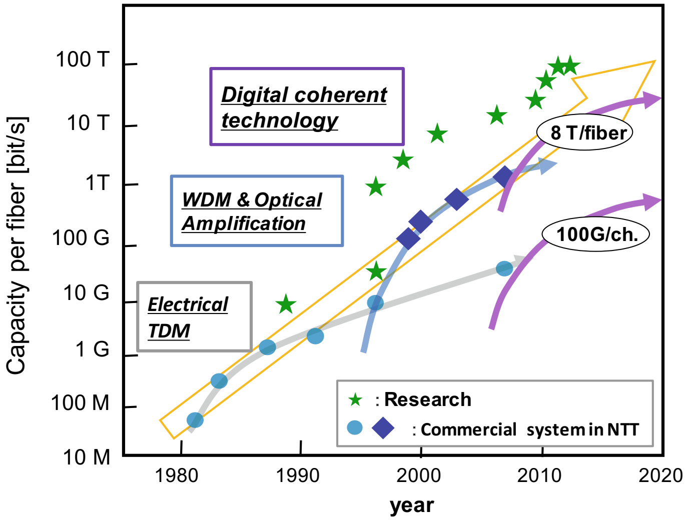


Fig. 1.18 Increase in optical fiber transmission capacity

(TDM) technology based on electrical multiplexing, optical amplification technology/wavelength division multiplexing (WDM) technology, and digital coherent technology. Progress in R&D in the 1980s resulted in a high transmission speed of 10 Gbit/s, and since the 1990s, systems that apply WDM technology to attain terabit-per-second class transmission speeds have been developed [68]. Since 2000, transmission experiments in which capacity up to 100 Tbit/s in the research stage have been reported [68–77].

Ethernet speeds have also been increasing since the 1990s, and 10 GbE has become practical. There has also been development of 100G–class transmission technology, and the appearance of 100G Ethernet as a new client signal has led to continuing discussion of expansion of the OTN. We can expect that Ethernet will continue to drive increases in optical fiber transmission capacity.

The problems associated with such technology include limits on the power input to optical fiber, OSNR, chromatic dispersion and polarization mode dispersion, band restrictions, and nonlinear optical effects. To overcome such problems, research and development on optical amplifier technology, modulation and demodulation technology and ultrafast device technology is important.

The relation between transmission capacity and average optical fiber input power is shown in Fig. 1.19, where the distance per span is 100 km and the signal-to-noise ratio is the same. Increasing the optical power by about 1 W increases the likeliness of damage to the optical fiber or the optical components. One way to avert that problem is to use a Raman amplifier or other distributed amplifier. The optical power of the input signal to the transmission fiber can be reduced by using a hybrid amplifier that includes both an EDFA lumped optical amplifier and a Raman distributed amplifier. The hybrid amplifier prevents damage to the optical fiber and

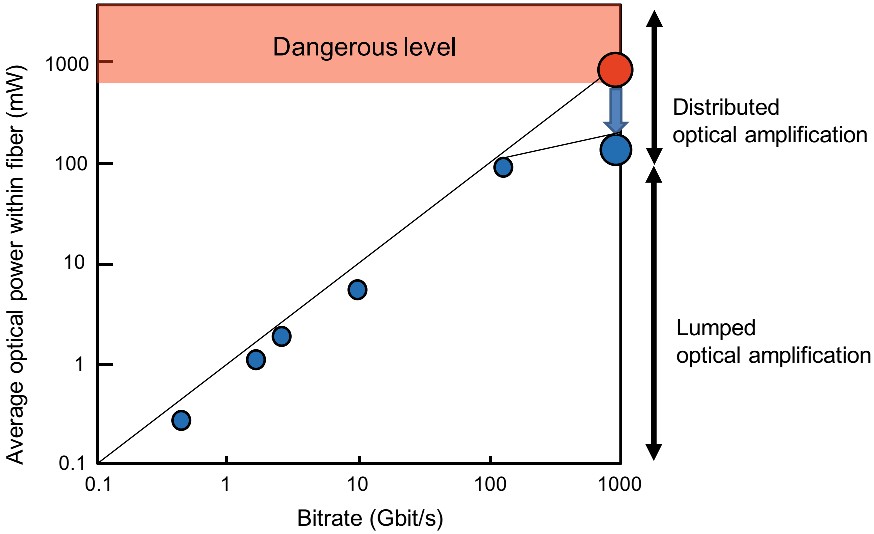


Fig. 1.19 Relationship of transmission capacity and mean optical fiber input power

optical components and reduces the nonlinear optical effect in the transmission path. Studies on increasing bandwidth are also underway, and broadband amplification of 10 THz has been achieved by hybrid amplification using a Raman distributed amplifier and an extended L–band EDFA. That is an increase by a factor of 2.5 compared to the conventional method [75, 77].

Also, incoming signal sensitivity and robustness against wavelength and polarization mode dispersion has increased in recent years, so research and development on phase modulation and demodulation technology and multi-level modulation and demodulation technology has been progressing. RZ–DQPSK modulation, which can increase spectral efficiency by a factor of 2 compared to the conventional OOK scheme, was introduced. Recently, there has been vigorous research on next-generation modulation schemes using polarization-division multiplexing to further improve spectral efficiency.

Digital coherent technology has been attracting attention in recent years, and there are very active works on practical implementation of the research [69–71]. The technology applies ultra-fast digital signal processing achieved through progress in ultra-fast CMOS LSI circuits for highly sensitive coherent detection [70]. Digital coherent technology involves coherent detection using digital signal processing as is done in wireless systems rather than the conventional intensity modulation direct detection, thus enabling coherent detection without physical frequency or phase synchronization of the signal light and the local oscillator light. In addition to greatly increasing receiver sensitivity and spectral efficiency, previously difficult optical fiber dispersion compensation in long-distance transmission can be greatly improved. Digital coherent optical transmission system (Fig. 1.20) is the main method being used in the high-capacity optical transport system for the current core network of

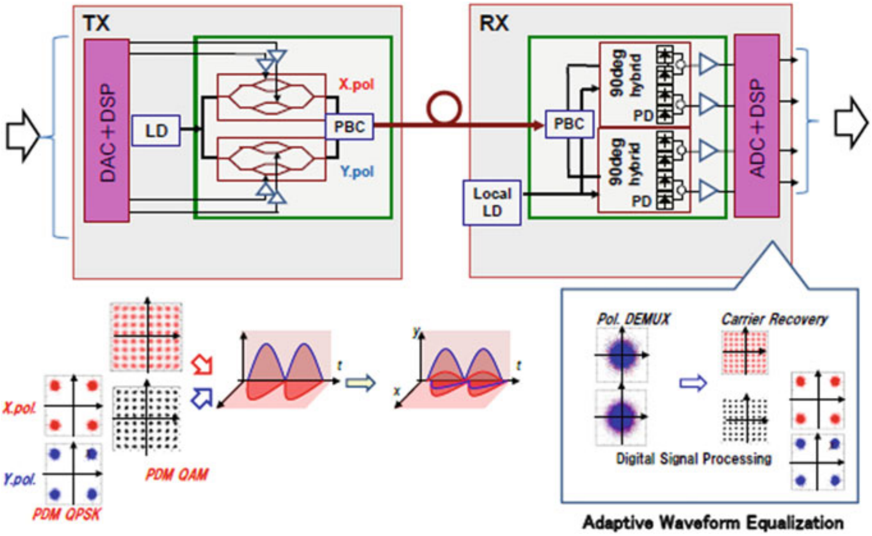


Fig. 1.20 Configuration for digital coherent optical transmission

2020. High-capacity transmission at the 100 Gbit/s per wavelength level has been achieved by using PDM-QPSK to transmit optical signals in optical fibers that have different polarization axes. A practical 10 Tbit/s-class high-capacity optical network using existing optical fiber and 50 GHz channel spacing in the same way as with the conventional wavelength division multiplexing system is possible. With practical digital coherent technology, the main bit rate per wavelength in the core network has shifted from the range between 10 and 40 Gbit/s to 100 Gbit/s. By 2020, continuing reduction of the size and cost of optical transmitter/receiver and miniaturization of digital coherent DSP have lowered power consumption and cost, and 100 Gbit/s per wavelength technology have spread rapidly in the metropolitan network and access network as well.

Conclusion

The total number of broadband subscribers in Japan has increased to over 40 million, and FTTH has recently taken the lead over ADSL. Internet traffic has been increasing by a factor of from 1.3 to 1.4 each year. The evolution of PON technologies has continued to support the growth of the broadband access services. Optical transmission technologies also have advanced rapidly over the past thirty years in three main technological innovations: time division multiplexing (TDM) technology based on electrical multiplexing, optical amplification technology/wavelength division multiplexing (WDM) technology and digital coherent technology. With practical digital coherent technology, the main bit rate per wavelength in the core network have shifted from the range between 10 and 40 Gbit/s to 100 Gbit/s and 400 Gbit/s, and a 19-Tbit/s high-capacity optical network has been achieved. By 2020, 100 Gbit/s per wavelength technology has rapidly come into wide use in metropolitan networks and access networks as well. Implementation of a photonic network that is capable of broadband transport of diverse, huge-volume client signals, including 100 Gigabit Ethernet, is indispensable for the future broadband society. That requires progress in optical access technology and large-capacity optical transmission technology, and future development of these technologies is expected.

1.5 State-of-the-Art Optical Submarine Cable Systems

1.5.1 Main Features of Optical Submarine Cable Systems

Today, optical submarine cable systems connect many countries in the world as shown in Fig. 1.21, and as of 2020, 1.2 million kilometers of optical submarine cable have been installed [78]. The role of satellite systems was taken over by submarine cable systems many years ago, and the majority of international telecommunications is carried on optical submarine cable systems currently. Since the continuously growing of the demand for international telecommunications is foreseen, the role of optical submarine cable systems is becoming larger.

A transmission capacity of optical submarine cable systems has drastically increased since 1980s to satisfy huge demands for international telecommunication services. Table 1.1 and Fig. 1.22 show main parameters and the capacity expansion of major transpacific optical submarine cable systems. In transpacific submarine

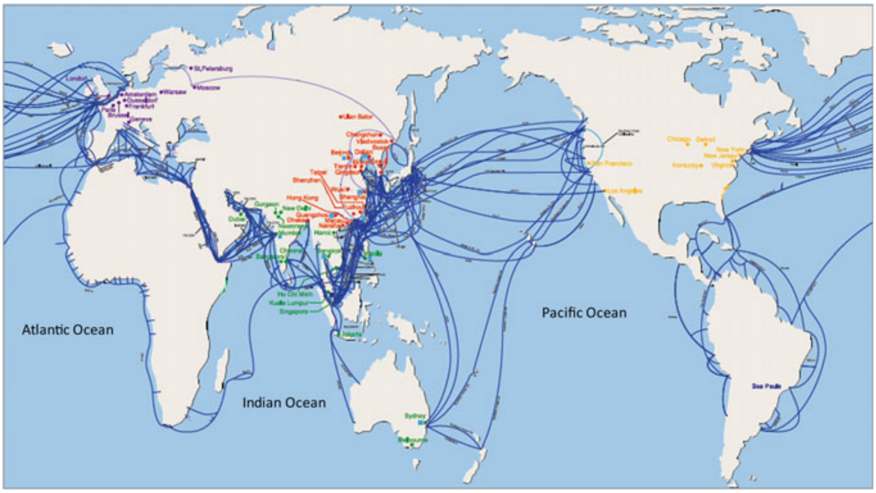


Fig. 1.21 Global network with optical submarine cable systems

Table 1.1 Main parameters of transpacific cable systems

	Ready for service year	Designed fiber capacity (bit/s)	No. of fiber pair	Designed cable capacity (bit/s)	Modulation format	Fiber type	Repeater type
TPC-3	1989	280 M (280 M × 1)	2	560 M	NRZ-OOK	SMF	Digital regenerator
TPC-4	1992	560 M (560 M × 1)	2	1.12G	NRZ-OOK	CSF	Digital regenerator
TPC-5	1996	5G (5G × 1)	2	10G	NRZ-OOK	DSF	Optical amplifier
China-US	1999	20G (2.5G × 8)	4	80G	NRZ-OOK	NZDSF	Optical amplifier
PC1	2000	160G (10G × 16)	4	640G	CRZ-OOK	NZDSF	Optical amplifier
Japan-US	2001	160G (10G × 16)	4	640G	CRZ-OOK	NZDSF	Optical amplifier
VNSL-P (TGN-P)	2002	960G (10G × 96)	8	5.12 T	CRZ-OOK	DMF (+D/−D)	Optical amplifier
Unity	2010	960G (10G × 96)	5	4.8 T	RZ-DPSK	DMF (+D/−D)	Optical amplifier
Faster	2016	10 T (100G × 100)	6	60 T	DP-QPSK	+ D	Optical amplifier

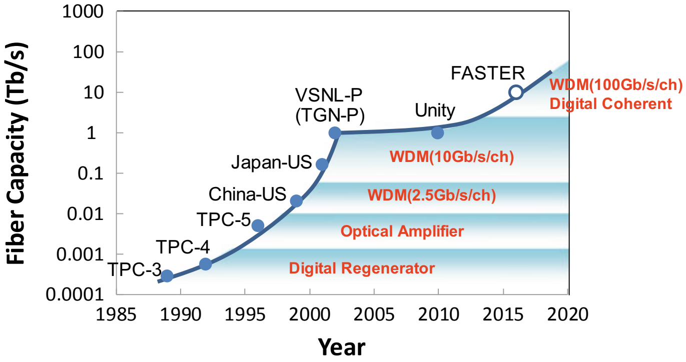


Fig. 1.22 Progress of fiber capacity in transpacific submarine cable systems

cable systems, fiber optic transmission technology was firstly introduced in TPC-3, which was placed into service in 1989. In this system, the digital regenerators were used. In the digital regenerator, the incoming optical signals were converted to electrical signals and then the converted signals were reshaped, retimed and regenerated with high-speed electrical circuits and retransmitted with a local laser. Then, optical amplification technology was introduced in TPC-5CN, which was placed into service in 1996. In China-US cable system, which was placed into service in 1999, wavelength-division-multiplexing (WDM) technology was introduced, and the introduction of WDM accelerated the capacity expansion in optical submarine cable systems. In the earlier generation WDM systems, non-return-to-zero on–off keying (NRZ-OOK) signal with a channel bit rate of 2.5 Gbit/s was used, since it is easy to generate and detect. With introducing chirped return-to-zero on–off keying (CRZ-OOK) signal which is more tolerant against fiber nonlinear effects, the channel bit rate was increased to 10 Gbit/s.

Although the initial designed capacity of transpacific cable shown in Table 1.1 and Fig. 1.22 had not increased drastically from 2003 to 2010, the actual fiber capacity had been upgraded by replacing the transmitter and receiver for higher bit rate by using advanced modulation formats, such as differential phase-shift-keying (DPSK). For example, in 2008, the cable capacity of Japan-US cable was upgraded up to 1.28 Tbit/s, doubling the initial design capacity of 640 Gbit/s.

The submarine cable systems are different from the terrestrial system in many aspects. The main differences are as follows.

- High reliability: system design life over 25 years
- High water pressure resistance: 800 atm
- High tension during laying: 6 t
- Resistance to high voltage: $\pm$ 12 kV
- Fewer fiber pairs in cable: less than 10 pairs
- Large accumulation of optical properties: large accumulation of nonlinear effects, chromatic dispersion and noise generated in optical amplifiers in over 6000 km transmission in transoceanic cable systems.

Since the maximum water depth in transpacific cable systems is around 8000 m, submarine cables and repeaters must have high tolerance against water pressure and tension. When a submarine repeater breaks down, it takes a lot of time to repair or exchange it. Thus, each submarine repeater must have very high reliability to minimize the unavailability of the system. In addition, the number of fiber pairs in submarine cable systems is limited because the provided power-by-power feeding equipment (PFE) at landing points and the size of repeater housing have some limitation. Therefore, it is very important to increase the transmission capacity per fiber.

1.5.2 Main Building Blocks of Optical Submarine Cable Systems

Figure 1.23 shows main components of optical submarine cable systems. They mainly consist of terminal equipment, PFE, optical fiber cable and optical repeaters.

1.5.2.1 Terminal Equipment and PFE

Terminal equipment is installed at the cable station and sends and receives optical signals and supervises the system. The basic functions of transmitter and receiver for submarine cable systems are identical as those for terrestrial systems. In many submarine cable systems, however, the different modulation formats which are more tolerant to fiber nonlinear effects have been utilized. With the increase of the channel bit rate, the modulation format was changed from intensity modulated signals, NRZ-OOK and CRZ-OOK, to phase-modulated signals, RZ-DPSK and quaternary phase-shift keying (QPSK).

In the latest systems with digital coherent transponders, polarization-division multiplexing (PDM) which can double the spectral efficiency is also introduced.

PFE is installed at the cable station to supply a precisely controlled constant direct current of around 1 A to optical repeaters through the optical cable conductor together with sea ground. PFE generates very high voltage of around 10 kV to drive a few hundreds of repeaters in a transoceanic system.

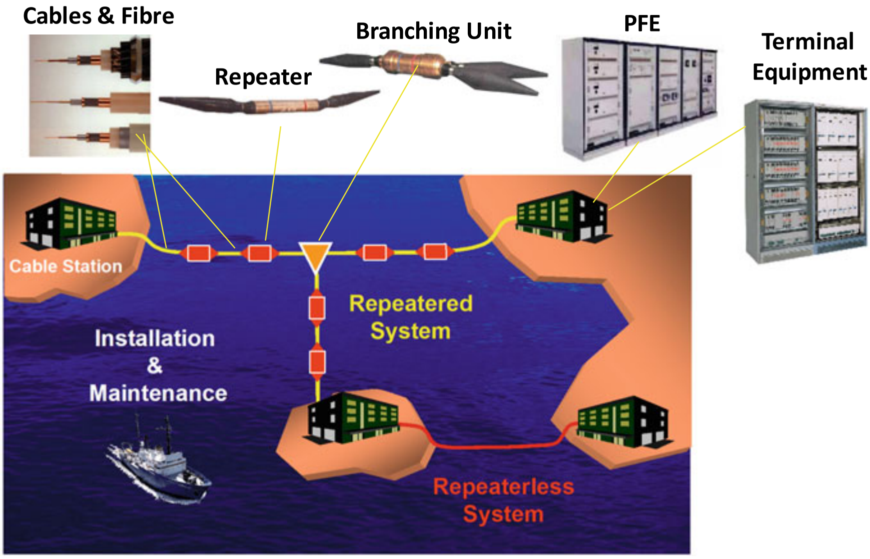


Fig. 1.23 Optical submarine cable system

1.5.2.2 Optical Fiber Cable and Dispersion Management

Optical fiber cables have contained less than ten fiber pairs since their first introduction to submarine cable systems. Recently, the number of fiber pairs is increased to more than 20 in order to increase the cable capacity with the limited supplied power by PFE. The different cable structures are adopted with water depth. The optical fiber cable for deep sea has light structure designed to protect from water pressure. Figure 1.24a shows an example of such cable, which is called lightweight (LW) cable. The optical fiber cable for shallow sea is heavily protected against the cable cut by ships. Figure 1.24b shows the example, which is called double armored (DA) cable. The optical fiber cables mainly consist of an optical fiber unit and power feeding copper conductors which supply electric power to optical repeaters.

In submarine cable systems, new fiber is usually installed when a new system is constructed, which is different from the terrestrial systems where the systems are optimized on the already deployed fiber. Therefore, the optical fiber and dispersion map optimized for each system are utilized in optical submarine cable systems.

For high-speed optical signals, small chromatic dispersion is required to keep a waveform. With the small dispersion, however, signals and noise propagate with a same group velocity, resulting in a long interaction length with a phase-matched condition and a degradation of signal performance even in single-channel transmission through four-wave mixing (FWM) between the signal and noise. For WDM signals, nonlinear effects such as FWM and cross-phase modulation (XPM) between WDM signals become the dominant impairment. To prevent this, a dispersion management was introduced. In the dispersion management, the local dispersion is set to be large to reduce the phase matching while the system average dispersion is close to zero by inserting dispersion compensation fiber. In the first-generation WDM submarine cable systems with a channel bit rate of 2.5 Gbit/s, a fiber with a

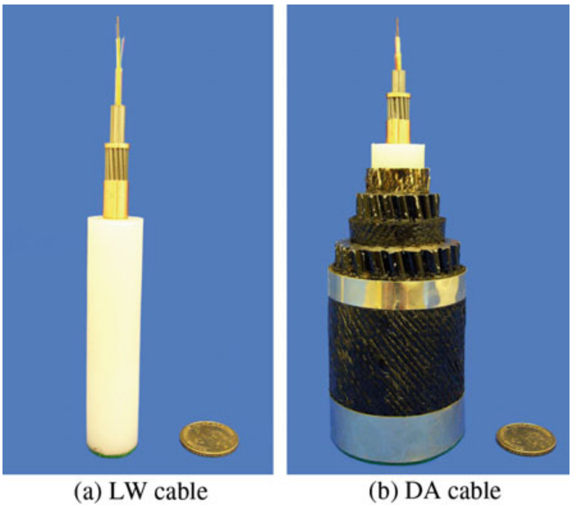


Fig. 1.24 Optical fiber cable for **a** deep sea and **b** shallow sea

large dispersion around 2 ps/nm/km was introduced to reduce inter-channel nonlinear effects. For further reduction of nonlinear effects, new fibers with larger effective area (A_{eff}) around 80 μm^2 or more have been developed for WDM systems with a channel bit rate of 10 Gbit/s. In order to compensate for the accumulated dispersion of the large dispersion fiber, the fiber with opposite-sign chromatic dispersion was inserted periodically as shown in Fig. 1.25a. In this dispersion map, only the second-order dispersion is compensated and the third-order dispersion is not compensated. Therefore, a large amount of dispersion is accumulated at the channels located far away from the system zero dispersion wavelength after long distance transmission. This large accumulated dispersion causes large pulse broadening and overlap with many neighboring pulses. Since the impact of such pulse broadening is more significant in

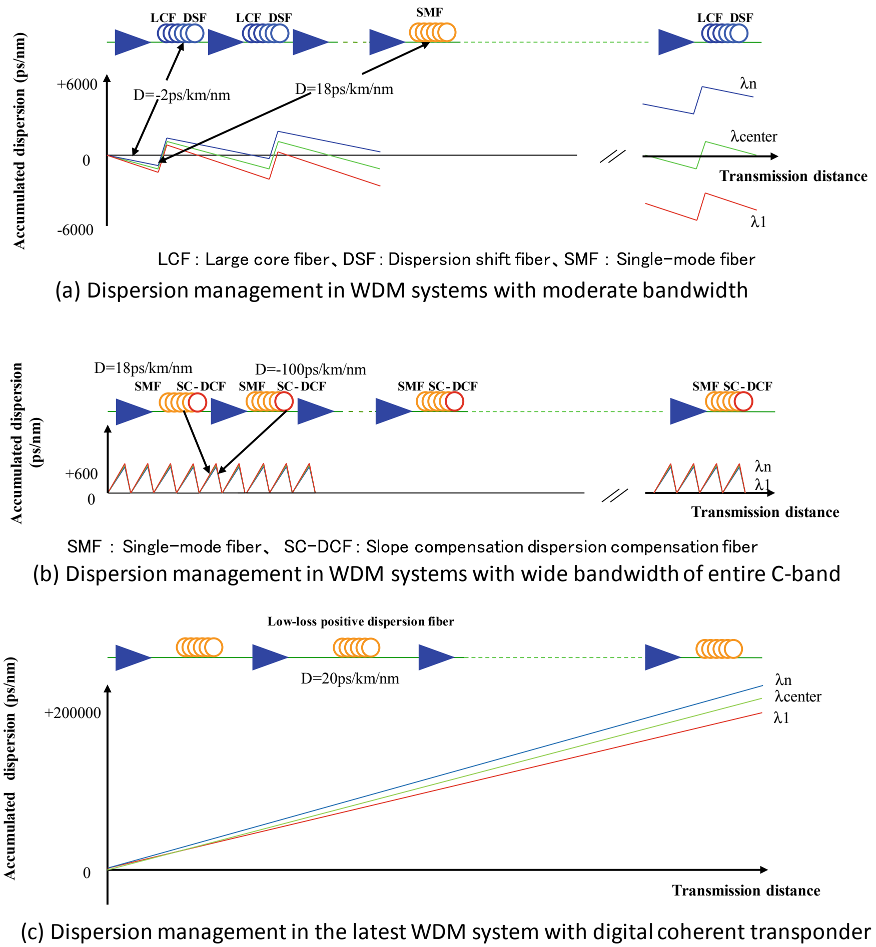


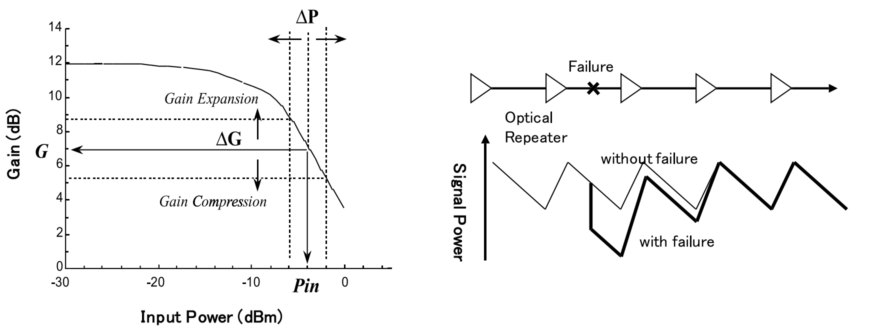
Fig. 1.25 Dispersion management in optical submarine cable systems

WDM systems with higher channel bit rate and wider bandwidth, another dispersion map shown in Fig. 1.25b was introduced in WDM systems with around 1-Tbit/s fiber capacity where the bandwidth was expanded to full C-band around 30 nm. In this dispersion map, each fiber span was constructed with two types of fiber with opposite-sign chromatic dispersion to reduce the span average values of both second- and third-order dispersion. With this configuration, chromatic dispersion characteristic was flattened in around 30 nm bandwidth.

In the latest systems with digital coherent transponders, however, the dispersion management is not utilized. In such systems, the fiber launch power is drastically reduced by using coherent receiver with higher sensitivity and forward error correction (FEC) codes with higher gain. This power reduction together with the use of optical fiber with large dispersion and larger A_{eff} makes the system more linear. Thus, the large amount of accumulated dispersion in the transmission over transoceanic distance can be compensated only at the terminal as shown in Fig. 1.24c and the transmission line is constructed with a single type of fiber, which contributes to reduce the loss of transmission line.

1.5.2.3 Optical Repeater

In the first-generation optical submarine cable systems, digital regenerators, which converted the incoming optical signals to electrical signals, then reshaped, retimed and regenerated the data with high-speed electrical circuits and retransmitted the data with a local laser, was used as repeaters. The regenerator had limitations of its operation speed in electrical circuits, and erbium-doped fiber amplifier (EDFA) was introduced to solve such problems. EDFA has many advantages rather than it can amplify high-speed signals without distortion. One of the advantages of EDFA is its inherent automatic gain control function. Figure 1.26a shows the gain characteristics of EDFA as function of the input power with a constant pump power. When the EDFA is operated in the saturation regime under the nominal operating condition, the EDFA



(a) Gain characteristics of EDFA (b) Signal power recovery in multi-repeater systems

Fig. 1.26 Automatic gain control in EDFA repeaters gain increases by nature and the output power from the EDFA remains constant in the event of the reduction of input power. Figure 1.26b shows the signal power recovery in multi-repeater systems when the loss increases in a span. Owing to the nature of gain-saturated EDFA, the signal power can return to the nominal level after a few optical repeaters with a slight degradation optical signal-to-noise ratio (OSNR). Another advantage of EDFA is that it can amplify multiple signals simultaneously without crosstalk, which enables to introduce WDM in fiber optic communication systems. In submarine cable systems, the repeaters are usually inserted with around 50–100 km spacing, which means more than 100 repeaters are concatenated in transpacific cable systems. Therefore, it is very important to reduce the noise generated in each EDFA as lower as possible. In WDM systems, with wide-bandwidth, the gain equalization is also indispensable to obtain sufficient signal performance with all WDM channels. Usually, the gain equalization is realized with passive gain equalizing filters which are designed to the inverse characteristics of EDFA gain and fiber span loss.

1.5.3 The State-of-the-Art Technologies in Optical Submarine Cable Systems

The transpacific submarine cable system, FASTER, was ready for service in 2016. Table 1.2 summarizes main parameters of FASTER cable system. In FASTER system, the designed system capacity reaches to 60 Tbit/s (10 Tbit/s × 6 fiber pairs) with the state-of-the-art technologies shown in Fig. 1.27.

Table 1.2 FASTER cable system

Partners	KDDI (Japan), China mobile international (China), Chana telecom global (China), Google (USA), Sigtel (Singapore), Global transit, (Malaysia)
System length	about 9000 km
Designed fiber capacity	10 Tbit/s(100 Gbit/s × 100 WDM channels)
No. of fiber pair	6 fiber pairs
Designed cable capacity	60 Tbit/s
Ready for service year	2016

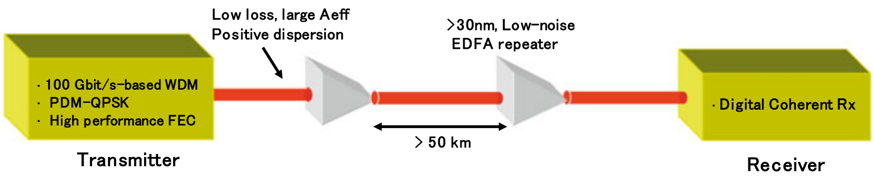


Fig. 1.27 Technologies used in the latest transoceanic submarine cable systems

10-Tbit/s fiber capacity is realized with 100 × 100 Gbit/s WDM transmission, which is enabled with advanced digital signal processing technologies, i.e., digital coherent reception and high-performance FEC. With the latest FEC technology, a net coding gain of higher than 10 dB is achieved with soft-decision FEC. With PDM-QPSK signals, the spectral efficiency reaches to around 2 bit/s/Hz. These technologies used in terminal equipment are similar with those used in the terrestrial systems with channel bit rate of 100 Gbit/s.

The transmission line consists of optical fiber spans whose loss is compensated for by C-band EDFA repeaters with gain bandwidth of larger than 30 nm. The transmission line is constructed with a single type of optical fiber, and the accumulated dispersion is compensated at the receiver in electrical domain. To reduce the nonlinear effects in fiber propagation, the optical fiber with large dispersion around 20 ps/nm/km and large A_{eff} larger than 100 μm^2 is employed. The transmission line with single type of optical fiber has smaller loss, which contribute to obtain a sufficient OSNR after transmission with lower fiber launch power.

The current demand for transpacific traffic can be covered with above-mentioned technologies. In order to expand the fiber capacity furthermore to meet the future explosive traffic demands, the research on disruptive technologies is expected.

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