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Technical Features and Approaches on Optical Access Networks for Various Applications

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SUMMARY This paper describes optical access networks focusing on passive optical network (PON) technologies from a technical point of view. Optical access networks have been applied to fiber-to-the-home as a driving force of broadband services and their use will continue growing in the near future. They will be applied as an aggregate component of broadband wireless networks. This paper also addresses solutions for their application.

key words: *optical access network, PON, broadband service, mobile backhaul, mobile fronthaul*

1. Introduction

Internet use has been popularized worldwide, and it is expected that broadband services enabling high-speed transmission over the Internet will result in improved economies. In Japan, economical and “ultra-broadband” services, i.e., Fiber-To-The-Home (FTTH), have been enabled by the deployment of optical access networks based on Passive Optical Network (PON) technology. Toward this deployment, industry and academia have discussed several aspects. The Technical Committee on Communication Systems of the Institute of Electronics, Information and Communication Engineers (IEICE) has shown strong leadership in such discussions [1].

On the other hand, the development of broadband wireless technologies has been growing rapidly. In particular, the 5G mobile system provides similar services to optical access capabilities. Therefore, in the near future, optical access networks can be positioned as an aggregate system component of broadband wireless systems and provide direct access to users. Therefore, it is necessary for optical access networks to be compatible with broadband wireless systems.

This paper summarizes past and present PON technologies, discusses future services using PONs focusing on collaboration with the 5G mobile system, and mentions possible solutions for such services.

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2. Worldwide Trends in Broadband Services

This section surveys the trends of Internet and broadband service popularity, indicates future trend directions, and then provides a technical discussion. The Internet has been popularized in both developed and developing countries. The International Telecommunication Union (ITU) reports that the average penetration ratio is expected to be almost 50% in 2016 [2]. In developed countries, the penetration ratio will reach more than 80% in 2016. The Internet has become an important tool in the daily social life of individuals and in business. However, in developing countries, although the penetration ratio is about 35%, it is expected that Internet subscriptions are shared with several users in public spaces and schools.

As the next step, broadband services with high-speed transmission are expected to provide high-speed Web access and high-quality real-time video streaming services. In Japan, especially, highly economical broadband services are available. The broadband commercial price per megabit in various countries [3] is shown in Fig. 1. The popularity of broadband services as reported by [2] is also shown in Fig. 1. It can be concluded that Japan is a worldwide leader in the provision of economical broadband services.

The deployment of broadband services includes two approaches: wireless communication technologies for “broadband services” and optical communication technologies for “ultra-broadband services” [3]. From a transmission rate point of view, ultra-broadband services have been one step ahead of broadband services. In the near future, 5G mo-

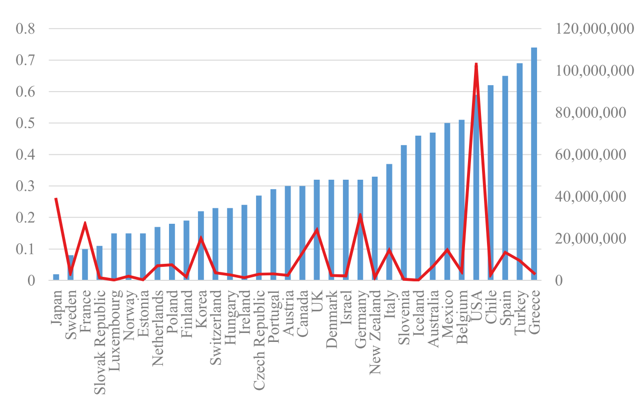


Fig. 1 Service prices and popularity of broadband services in countries.

bile systems will be able to provide subscribers with giga-class transmission services similar to those of current ultra-broadband services. Therefore, new technologies are required for 10 G and higher bit-rate services for optical communication, especially optical access technologies.

3. Overview of PON Technology

PONs have been researched and developed since the 1990s in an attempt to develop economical optical access networks. In the past, as optical access networks have a point-to-point optical fiber between a central office and subscribers, the related costs were high, and their deployment was limited to business applications. However, since PONs can enable point-to-multipoint connections using passive optical splitters, their use is feasible for low cost systems and has expanded from business applications to general consumer applications. It is concluded that PONs have played a primary role in contributing to the increasing popularity of broadband services, i.e., ultra-broadband services on the Internet. Many articles on the overview, strategic deployment, and standardization of PONs have been published [4]–[6]. Especially, the Full Services Access Network (FSAN) group [7] has clarified PON technical feasibility, accelerated standardization including interoperability and implementation, and promoted trials. Ref. [8] introduces the activities of the FSAN initiative.

In Japanese academic societies, the Technical Committee on Communication Systems of the IEICE has initiated a discussion on PONs. Since the late 1990s, it has organized special sessions in IEICE general conferences and society conferences and created the Communication System WorkShop (CSWS) to discuss the latest topics facilitating the progress of PON development. This committee was also responsible for the planning of the special IEICE journal issues published in December 2000 and March 2005.

3.1 Requirements of Optical Access Networks and Suitability of PONs

The optical network is responsible for the transport and multiplexing of IP traffic flows from/to end users without bottlenecks and the low-cost system deployment including equipment, installation, and operation The positioning of an optical network is shown in Fig. 2. It provides avoidance of bottleneck in IP flows as shown in dot-lines in Fig. 2.

As shown in Fig. 2, since optical splitters are installed at many locations on a transmission line to share optical fibers with multiple users, the optical network is configured as a flexible star topology. PON technologies comply with the requirements of optical access networks for topology and communication control as explained in the following key technology points of view. Therefore, PONs can effectively perform as a low-cost optical access network.

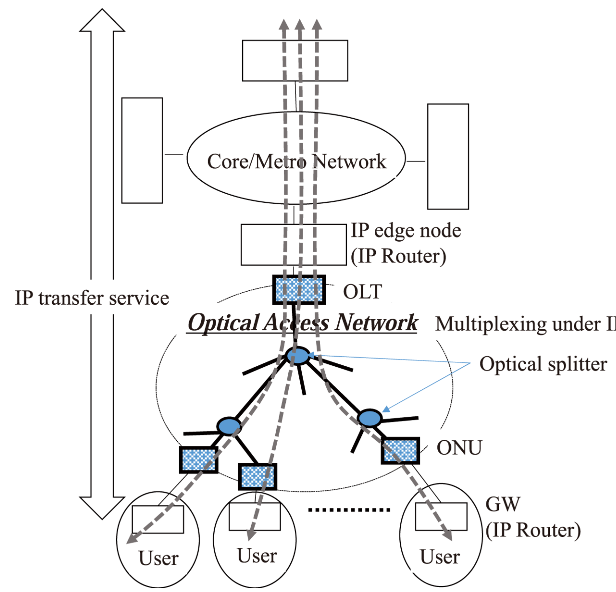


Fig. 2 Network configuration focusing on optical access network.

3.2 Classification of PONs and Key Technologies

PONs are categorized into several types depending on the requirements of communication services over optical access networks. This section provides an overview of PONs based on the technical features of the various classifications.

PONs are roughly classified as having either a “shared bandwidth architecture” or “dedicated bandwidth architecture.” PONs are physically configured as point-to-multipoint using the passive optical splitters described in Sect. 3.1. However, the architectures are classified by assignment of logical resources, such as wavelength and frequencies. In the shared bandwidth architecture, upstream and downstream traffic flows each have one or several wavelengths. Upstream traffic flowing from users on a wavelength are multiplexed by bandwidth assignment mechanisms, while downstream encrypted traffic flow is broadcast to users. In the dedicated bandwidth architecture, resources are allocated to every user; a user can use the allocated wavelength or frequency independent of other users. These architectures are summarized by relationship between total transmission rate and the number of required wavelength or frequency as shown in Fig. 3. Time Division Multiplexing PON (TDM-PON) provides multiplexing of upstream traffic in one wavelength. It has many options as shown in lower side in Fig. 3. Time and Wavelength Division Multiplexing PON (TWDM-PON) is realized by combination of several TDM-PON. Wavelength Division Multiplexing PON (WDM-PON) and Frequency Division Multiplexing PON (FDM-PON) assign wavelength and frequency to each ONU, respectively. Therefore, the number of required wavelength and frequency depend on the number of branches.

Next, we discuss the key technologies of each architecture. A PON key technology map is shown in Fig. 4.

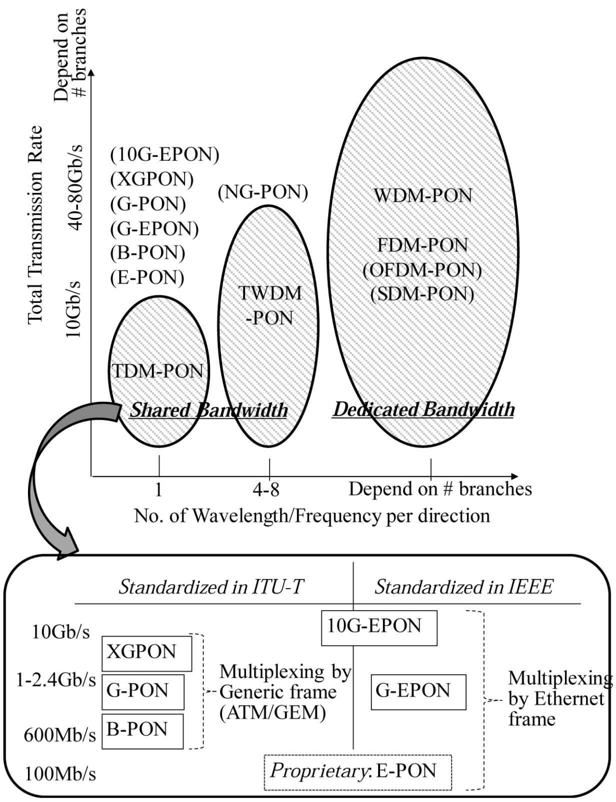


Fig. 3 Overview of PON architectures.

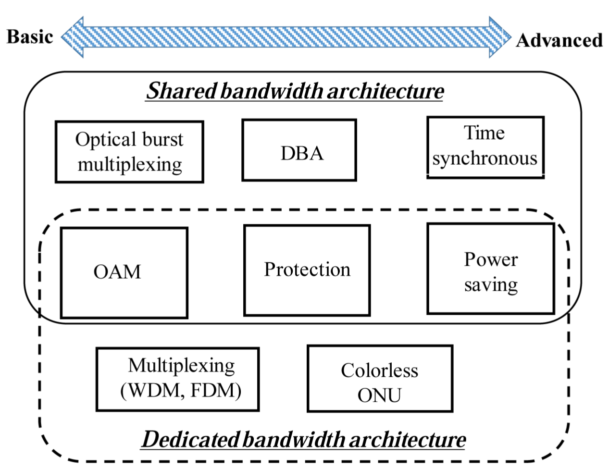


Fig. 4 Technology map of PON.

Common technologies of both architectures are PON protection, power saving, and operation, administration, and maintenance (OAM).

Several types of shared bandwidth architecture have been standardized and deployed commercially [9] and are categorized as either generic frame, e.g., asynchronous transfer mode (ATM) and gigabit encapsulation mode (GEM),-based or Ethernet-based. The synchronous digital hierarchy (SDH) base includes broadband PON (B-PON), gigabit PON (G-PON), and 10-gigabit-capable PON (XG-PON) standardized in ITU-T SG15. The Ethernet base includes

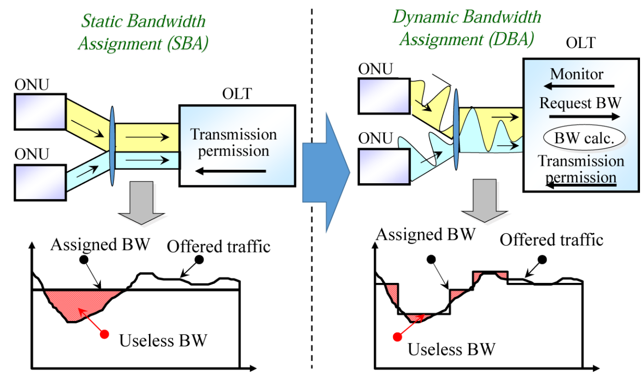


Fig. 5 Operation of DBA and non-DBA for assigned bandwidth in each ONU.

gigabit Ethernet PON (G-EPON) and 10 Gb/s Ethernet PON (10G-EPON) standardized in IEEE 802.3 and P1904. Then, 10G-EPON has been also standardized in ITU-T SG15. The basic mechanisms of the these types are same, and both multiplex information on a time line requires media access control and optical burst multiplexing on one wavelength. PON systems using this technology are referred to as "TDM-PON." This media access control (MAC) assigns bandwidth to every user for upstream traffic flow and is referred to as "dynamic bandwidth assignment" (DBA) [10]. This mechanism provides a statistical soft guarantee to ensure the quality of user communication. Optical burst multiplexing technology provides multiplexing data on optical splitters with little overhead. DBA operation, illustrated in Fig. 5, compares the assigned bandwidth of the DBA and non-DBA (static bandwidth allocation) cases. If DBA is supported by a PON system, users can transfer information on upstream traffic flows according to their demands. In short, as shown in Fig. 5, if the ONU requires much bandwidth, it can use surplus bandwidth of other ONUs. On the other hand, if the ONU does not require bandwidth, it can give this bandwidth to other ONU. These mechanisms lead to minimize useless bandwidth. However, the DBA method faces two critical problems. One is the mechanism for assignment of bandwidth in optical line terminal (OLT). This mechanism is implanted in ASIC or high-performance CPUs to provide suitable bandwidth assignment for enhanced accuracy and reaction speed. Another problem is the control cycle for monitoring user requests and user assignment bandwidth. If the control cycle is short, bandwidth can be assigned to users with high accuracy. However, the network bandwidth for this control cycle has to be reserved. If the control cycle is long, the assignment accuracy decreases. Therefore, the relationship between the control cycle and the required bandwidth is a trade-off. Optimized points must be specified in network designs.

In the shared bandwidth architecture, transmission technologies of upstream traffic flows tend to create bottlenecks. Currently, systems with transmission rates from 1 Gb/s to 1.2 Gb/s, e.g., G-EPON and G-PON, have been deployed due to the driving force of FTTH promotion. To extend the bandwidth, systems such as XG-PON based on Generic frame and 10G-EPON based on the Ethernet have been researched and developed. However, it is reasonable that upstream traffic flow using optical burst multiplexing is less than 2.4 Gb/s or 10 Gb/s from the point of view of an optical device's cost. To solve this problem for enhancement of capacity, the combination of four or eight wavelengths has been proposed in ITU-T as NG-PON. This architecture is a combination of TDM and WDM and is referred to as "TWDM-PON" and can offer more than 10 Gb/s upstream traffic flow.

In dedicated bandwidth architecture, wavelengths or frequencies are assigned to users independently, without burst multiplexing on upstream traffic flows. This architecture provides a hard guarantee of available bandwidth for user communication and is feasible to provide symmetrical communication with identical bandwidths for both upstream and downstream traffic flow. This architecture has been researched and includes WDM-PON, which allocates wavelengths for every user, and FDM-PON, which allocates frequencies for every user. Enhanced mechanisms of FDM-PON include Orthogonal Frequency Division Multiplexing PON (OFDM-PON) and Subcarrier Digital Modulation PON (SDM-PON) [11]. However, since this architecture manages the allocation of wavelengths and frequencies poorly, it is deployed for services with few points and a large bandwidth per point than mass users, e.g., FTTH. For example, it can be applied to base stations of 5G mobile devices and super-high video definition systems for public viewing.

3.3 Applied Services Using PON Technology

PONs have been applied to FTTH for general consumers using shared bandwidth architecture. Currently, G-PON and/or G-EPON have been deployed worldwide. XG-PON, 10G-EPON and/or TWDM-PON will be deployed in the near future to support broadband traffic. However, it will be applied to various configurations as shown in Fig. 6 in addition to FTTH. In the case of fiber-to-the-building (FTTB), the optical fibers of PON are terminated at the entrance to a

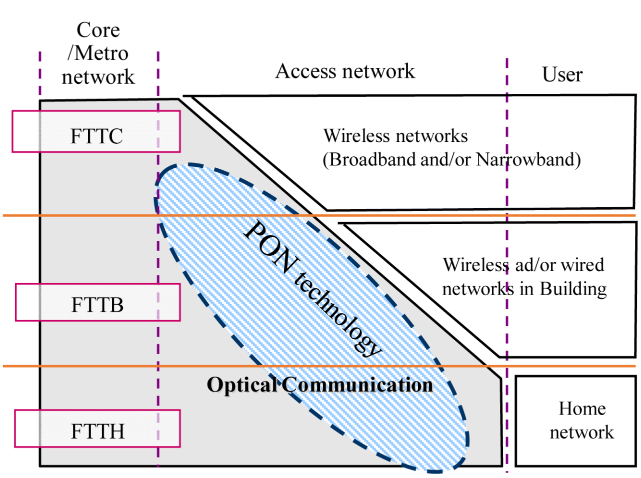


Fig. 6 PON configurations.

building. Then, wired networks such as Very high bit rate Digital Subscriber Line (VDSL) or Ethernet are distributed to every user on every floor of the building. Moreover, fiber-to-the-curb (FTTC) will be an attractive configuration. This configuration terminates optical fibers on the way of access networks; then, wireless networks are connected to the termination points of the optical fibers. When the small cells of 5G mobile systems are associated with PONs, this configuration will be an especially promising candidate. Moreover, an Internet of Things (IoT) area network configured by sensor networks can be connected to these termination points if IoT services are deployed using the horizon architecture as a social infrastructure [12]. In these new configurations, shard bandwidth architecture is also deployed initially. However, to increase capacity and enhance services, dedicated bandwidth architecture will be deployed. Especially, traffic aggregation for 5G mobile system in FTTC expects deployment of PON based on dedicated architecture. This point is described in next section. However, concrete specifications on PON based on this architecture will be discussed from many points of view, e.g., some costs and progression of R&D.

4. Application of Optical Access Technology to Future Mobile Networks

The mobile network is expected to be one of the most important applications of optical access technologies in the future. This section describes the architecture and transmission interfaces of optical networks between central offices and small cells in future mobile networks, 5G, focusing on the mobile fronthaul (MFH) transmission interface and discussing the application of optical access technologies in these optical networks.

4.1 Future 5G Mobile Network

Recently, research on 5G following LTE-Advanced (LTE-A) technology is actively advancing. The exemplary features of 5G are a low latency, massive connectivity, and high data rate; the target for the wireless data rate is greater than 10 Gb/s.

One of the key technologies in 5G will be the effective utilization of small cells. Small-cell technologies are already applied to LTE-A, such as HetNet where macro cells and overlaid small cells concertedly work to enhance mobile network capacity. In 5G, further advanced utilization of small cells is expected to achieve much higher data transmission rates. For example, various types of small cells including new radio access technology-based (RAT) cells and high-frequency millimeter-waveband cells employed in multi-layer configurations are being developed as shown in Fig. 7 [13]. Depending on the type of application and user situation, some functions of these small cells, such as handover for mobility management, are totally controlled by utilizing C/U-split technology. These small cells will be deployed in large numbers with high density, especially in

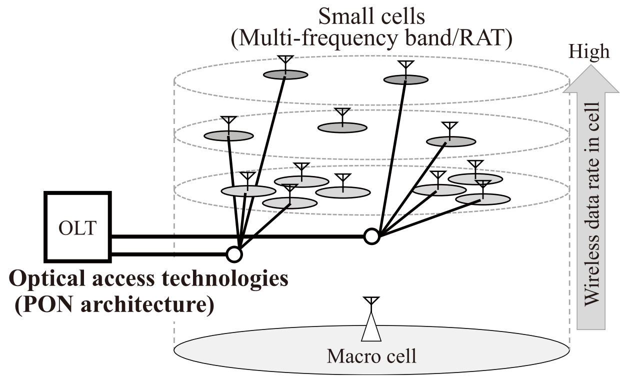


Fig. 7 Application of optical access technologies in future mobile network: PON architecture for small cells.

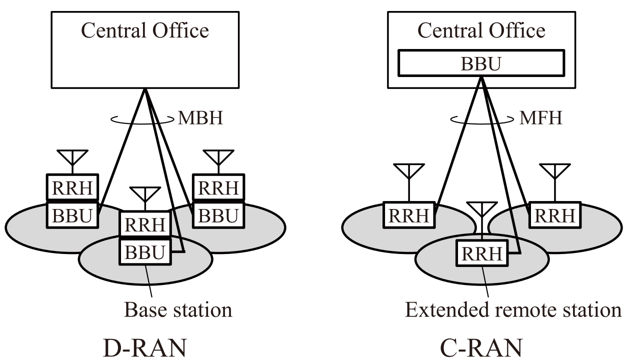


Fig. 8 D-RAN (mobile backhaul) and C-RAN (mobile fronthaul).

high-traffic areas. Therefore, PON architectures to realize low-cost FTTH services can be applied to the optical fiber connections between a central office and many small cells to realize a cost-effective network.

4.2 Base Station Architectures: D-RAN and C-RAN

There are two types of base station architecture: distributed radio access network (D-RAN) and centralized RAN (C-RAN) [14]. In the D-RAN architecture, both the baseband unit (BBU) and the RF/PHY functions (remote radio head (RRH)), such as antennas and RF frontend, are deployed together in each base station. In the C-RAN architecture, the BBU and RRH are separated and allocated in a central office and an extended remote station, respectively, as shown in Fig. 8. The networks between the central office and mobile cells of a D-RAN and C-RAN are called mobile backhaul (MBH) and MFH, respectively. The transmission interface depends on the RAN architecture; a packet-based transmission interface, such as Ethernet, is used in MBH networks, and a type of digitized radio-on-fiber-based (DRoF) transmission interface, such as the Common Public Radio Interface (CPRI) [15], is used in MFH networks.

A C-RAN configured as an MFH network, owing to its separated functional allocation architecture, has the following features:

- The configuration of the extended remote stations can be simple and on a small scale, as only RRH is deployed.
- The baseband functions of plural cells can be centralized in a central office.

In the future deployment of 5G small cells, many multi-layer small cells will be flexibly coordinated depending on the type of application and a user's situation, and to achieve this coordination effectively, the utilization of the above-mentioned MFH features is expected.

4.3 Mobile Fronthaul Transmission Interface Research

In the conventional MFH transmission interface (MFH-IF (a) shown in Fig. 9), a type of DRoF-based transmission interface, such as CPRI, is employed. The optical data rate of an MFH network must be approximately 16 times as high as the wireless data rate of the mobile cells [16], whereas regarding the MBH network the optical data rate is expected to be almost the same as the wireless data rate of the mobile cells. On the other hand, in future 5G mobile networks, the introduction of small cells operating at wireless data rates higher than 1 Gb/s is expected, and small cells will be densely deployed in high-traffic areas. Therefore, the application of conventional optical MFH networks to 5G small cells will cause the following problems:

- Since the required optical data rate of the MFH transmission interface exceeds 10 Gb/s, technically mature and widely used optical transmitter/receiver devices with a data rate of 1 Gb/s to 10 Gb/s cannot be employed.
- Even if PON architecture is applied, the cost advantage cannot be fully exploited because the total PON transmission capacity of 10 Gb/s to 40 Gb/s will be occupied by the MFH data traffic of only one or a couple small cells.

To solve the above-mentioned problems, new MFH transmission interfaces are investigated. One approach is data compression of the conventional DRoF-based signal (MFH-IF (b)). The optical data rate of MFH networks can be suppressed approximately 50% by down sampling and non-linear quantizing [16]. Another approach redefines the functional allocation of the BBU/RRH (MFH-IF (c)) [17]; the transmission interface is not based on a DRoF interface, but on packets, by setting a functional split point between the BBU and RRH near the MAC functional layer. With this approach, the required optical data rate of the MFH network is expected to be reduced substantially by the elimination of overhead data induced by the digitizing process. It is notable that whereas the optical data rate of DRoF-based MFH transmission interfaces (a) and (b) will be constant, that of packed-based MFH transmission interface (c) will be variable; since with the DRoF-based MFH transmission interfaces (a) and (b), the digitizing process at constant rate determined by the peak wireless data rate of the mobile cells will be performed independently with actual mobile traffic, and with the packet-based MFH transmission interface (c), MAC frame data or coded bit data, for example, are expected to be transmitted and the optical data rate will vary depending on the actual mobile traffic [17].

The relation between the MFH optical data rate and the wireless data rate of mobile cells is shown in Fig. 9.

The use of analog-transmission-based interfaces in MFH applications has also been studied [18], [19]. In an optical MFH network employing analog-transmission-based interfaces, only a physical media conversion between the optical wave and radio wave is performed in extended remote stations. This means that most of the base station functions, including PHY processing, can be centralized in central offices and the configurations of extended remote stations can be substantially simplified. Therefore, the optical analog-transmission-based MFH has the potential for further flexible and advanced operations to handle a wide range of frequency bands and RATs.

4.4 Application of Optical Access Technology in Future Mobile Fronthaul Transmission Interface

The MFH transmission interfaces described in Sect. 4.3 are expected to be applied to small cells depending on the data-rate requirements of each cell. The optical access technology supporting future mobile network depends on the MFH transmission interface and the required optical data rate of the MFH network, which is determined by the wireless data rate of the PON-accommodated small cells as shown in Fig. 9.

The exemplary correspondence relation between the applicable optical access technologies and MFH transmission interfaces is shown in Fig. 10. In terms of the cost-effective utilization of optical networks, the shared bandwidth architecture PON has advantages over the dedicated bandwidth architecture PON, since the former can accommodate a larger number of small cells exploiting time domain multiplexing. With regards to the DRoF-based MFH transmission interfaces (a) and (b), when we define N_{cell} as the number of PON-accommodated small cells for which a cost advantage can be realized, small cells with an MFH data rate (R_o) less than C_λ/N_{cell} will be suitable to be accommodated in shared bandwidth architecture PONs, where C_λ is the transmission capacity per wavelength of the PON system. If we assume that $N_{cell} = 4$, for example, in the cases where TDM-PON or Time Division Multiple Access PON (TDMA-PON) are employed with a C_λ of up to 10 Gb/s [20]–[22], then MFH-IFs (a) and (b) with an optical data rate of under 2.5 Gb/s can be accommodated. This is an exemplary scenario, and if the sum of the R_o of all PON-accommodated cells fits within

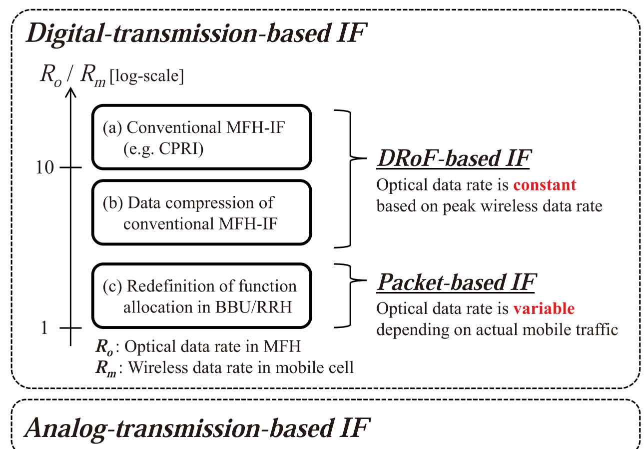
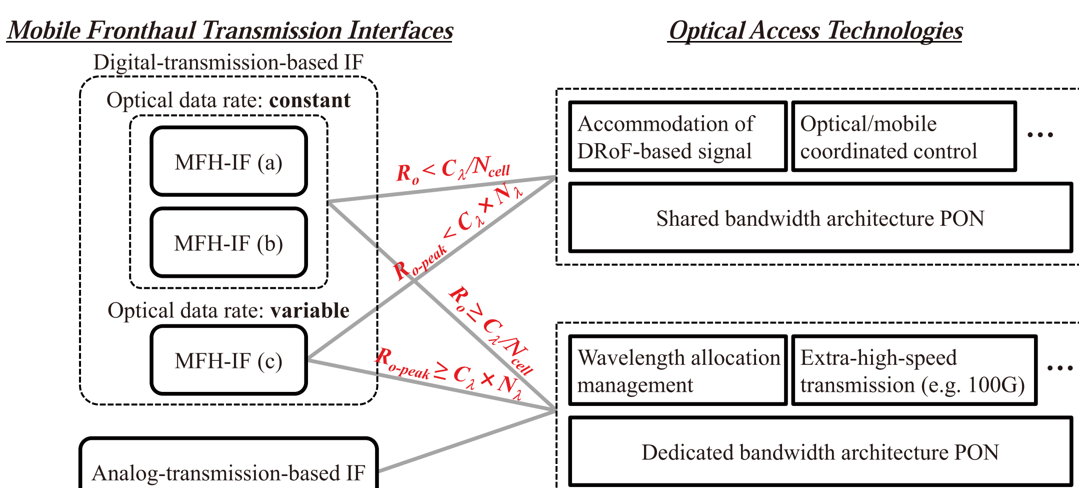


Fig. 9 Digital- and analog-transmission-based MFH interfaces.



C_λ: Transmission capacity per wavelength of shared bandwidth architecture PON
R_o: Optical data rates in MFH per cell: MFH-IF (a), (b)
$R_{o\text{-}peak}$: Peak optical data rates in MFH per cell: MFH-IF (c)
N_{cell}: Number of PON-accommodated small cells for which cost-advantage can be realized
N_λ: Number of wavelengths that can be used in each cell: MFH-IF (c)

Fig. 10 Exemplary correspondence relation between applicable optical access technologies and MFH transmission interfaces.

the total PON capacity and a cost advantage can be obtained, then small cells with data rates higher than the above condition will also be expected to be partially accommodated.

On the other hand, regarding the packet-based MFH transmission interface (c), since the statistical multiplexing effect described in Sect. 3.2 can be expected between small cells, depending on the fluctuation of actual mobile traffic, the shared bandwidth architecture PON can accommodate small cells with peak data rates ($R_{o\text{-}peak}$) less than $C_\lambda \times N_\lambda$, where N_λ is the number of wavelengths that can be used in each cell of the MFH-IF (c). A value of $C_\lambda \times N_\lambda$ greater than 10 Gb/s can be achieved with NG-PON2-based TWDM-PON technology [22]. Moreover, studies on the 100G-class shared bandwidth architecture PON have been recently initiated, e.g. 100G-EPON [23]. When these technologies are practically realized, small cells with ultra-high wireless data rates of 10 Gb/s and higher are expected to be accommodated in the shared bandwidth architecture of PON with the MFH-IF (c). To achieve accommodation of small cells with shared bandwidth architecture PONs, not only fundamental PON technologies but also technologies that apply TDM-based PON architectures to mobile networks, such as the accommodation of DRoF-based signals in packet-based interfaces [24] and optical/mobile coordinated control of bandwidth allocation for low latency transmission [25], are expected to be established.

On the other hand, the digital-transmission-based MFH-IFs with optical data rates higher than the above-mentioned conditions are expected to be accommodated in the dedicated bandwidth architecture PON as shown in Fig. 10. The accommodation of small cells with dedicated bandwidth architecture PONs also requires additional technologies, such as wavelength allocation management [26], [27] and extra-high-speed transmission rates (e.g. 100 Gb/s) [28]. Additionally, dedicated bandwidth architecture PONs are suitable for use in analog-transmission-based MFH interfaces because these interfaces require transparent optical transmission.

5. Future View of Optical Access Networks

This section describes the evolution scenario of optical access networks focusing on future PON technologies. Two scenarios will be expected as shown in Fig. 11. In short, the extension of physical specifications including transmission rate, reach, and the number of branches and extension of control functions including power saving, OAM, and protection will continue. For example, WDM/TDM-PON with 40km reach and 1024 branches will be researched [29] as one of future targets.

In another scenario, the scope of optical access networks will be extended. Currently, optical access networks provide the traffic multiplexing described in Sect. 3.1. New future responsibilities will be requested in addition to the current scope. The functionalities of OLT will be extended to include the functionality of IP routers and the integration of IP edge nodes. In the mature stages of IoT, fog computing

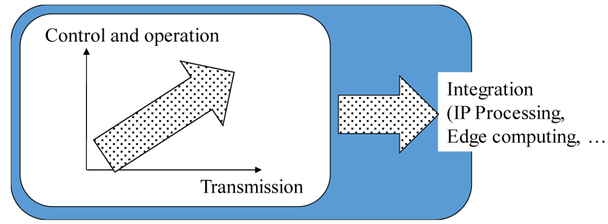


Fig. 11 Future extension of optical access network.

will be introduced [30]. The edge computing function will be implemented in optical access networks because real-time transfer is required and data processing should be performed at points located close to users.

6. Conclusions

This paper described the suitability of PON technologies as the driving force behind the worldwide promotion of FTTH and provided an overview of its technologies and future evolution. Currently, shared bandwidth architecture technology is mature and deployed commercially for FTTH. However, in the near future, when optical access networks cooperate with broadband wireless, especially 5G mobile systems, more optical access network transmission capacity will be required. At this stage, the PON dedicated bandwidth architecture will be also deployed. This paper has clarified problems and offered solutions for the collaboration between PONs and 5G mobile systems. Finally, this paper presented two scenarios for the future extension of PON technology.

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