Dynamic Resource Control in Optical Access Networks for Diverse Applications

Dissertation

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Short abstract:
The main objective of this dissertation is to develop dynamic network resource control technologies in optical access networks that provide diverse applications cooperating with wireless networks e.g., 5G. In particular, it is expected that the technologies would be applied to network service platforms, providing many kinds of industry-use applications.

Keywords:
Optical access network, Resource control, 5G/Beyond5G, Heterogeneous network, Network abstraction, Traffic modeling, Dynamic bandwidth allocation.

Resume

This dissertation summarizes a methodology for dynamic resource control in optical access networks. Optical access networks are the primary means of economically disseminating FTTH, and the key points in resource control technology are data transfer speed on the Internet and fairness among users. Another application is accommodating mobile base stations for cellular phones, where the number of subscribers is increasing significantly. In this case, it is essential to implement a resource control method that achieves low-latency data transfer. Furthermore, considering future industrial use cases, it is necessary to correspond to various applications with different requirements. In this case, it is imperative to have a resource control method that responds to dynamic changes in requirements. This dissertation proposes a dynamic resource control method that supports these use cases, summarizes the results of verifying its effectiveness, and states that these methods will contribute to expanding the application area of optical access networks.

Chapter 1 summarizes the history of the spread and expansion, overview, and technology trends regarding optical access networks. Also, the basic architecture of mobile networks, such as 5G, is introduced. Then, it describes the progress of resource control technology and its background. A technical overview of optical access networks and technologies related to each chapter is shown as a graphical index of this dissertation.

Chapter 2 summarizes trends in sophistication toward the spread of optical access networks and the expansion of application areas. Progress of PON systems in transmission rate, changes in network usage, and corresponding technologies are described. Case studies and issues for flexible and efficient optical access network systems are clarified. The 2 characteristics are abstracted as typical items in the condition of dynamic changes in requirements of application. Proposed architecture for the issues and its status in international standards are introduced.

In Chapter 3, dynamic bandwidth allocation control technology for 1G and 10G co-existence PON systems is proposed and evaluated. It is assumed that the proposed technology would be applied to FTTH systems, especially for migration from 1G class PON to 10G class PON.

In Chapter 4, optical access network suitable for accommodating mobile communication base stations is introduced. In terms of the technical aspect, resource allocation control technologies that provide low-latency data transfer are developed. A prototype of the allocation method complied with the latency time required for mobile fronthaul is demonstrated.

In Chapter 5, an optical access network supporting resource control of wired and wireless integrated networks is introduced. The integrated networks are assumed to correspond to various applications with different requirements. Verification of a resource control method using network virtualization technology for commonality between heterogeneous networks is performed.

In Chapter 6, a resource control method that responds to dynamic requirements changes is introduced. In the method, traffic monitoring and bandwidth prediction algorithms are developed. Additionally, enhanced responsiveness of resource control by using application information related to changes in application requirements is proposed.

Chapter 7 summarizes this dissertation and discusses future prospects for the research results.

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1. Introduction

1.1. Overview of dissertation

This dissertation is organized by works listed in Achievements. The rest of this dissertation is organized as described in the next paragraph. The challenge of this research is related to uplink resource allocation control in optical access networks, which are representative of Passive Optical Network (PON), and the prerequisite is that various types of data traffic can be distributed via 5G radio access networks. In the environment, the issue is to establish a method and architecture that,

1) make it possible to perform a common resource control and management for heterogeneous networks,

2) make it possible to recognize changes in the status of each application,

3) make it possible to perform a resource allocation according to the changes in the application.

Chapter 2 explains the development and expansion of access networks, including trends in higher speeds and higher capacity and sophistication, industrial use cases, the status of consideration for future application diversification, and standardization trends. Chapter 3 describes the dynamic bandwidth allocation control method for PON, especially the algorithm and verification results for ensuring fairness among subscribers in a mixed 1G/10G system. Chapter 4 summarizes the results of implementation design and verification of a method to achieve low uplink delay, especially regarding the advancement of PON. Chapter 5 summarizes the method for dynamically controlling common network resources, which corresponds to problem 1) above. In Chapter 6, the author proposes a method for predicting the required bandwidth using traffic monitoring to respond to dynamic application state changes, which corresponds to problem 2) above, and a dynamic resource allocation control method, which also corresponds to problem 3). Finally, Chapter 7 provides a summary of this dissertation. A list of results related to this dissertation is given in 'Achievements.'

Figure 1.1 illustrates the structure overview of this dissertation. The figure includes essential technologies regarding optical access networks. There are 3 columns representing the physical, logical, and virtual/abstracted layers. Each layer consists of technologies that solve the issues in the layer. The physical layer technologies mainly solve issues regarding high speed and large capacity. The technologies are also used for the operation and management of equipment. The logical layer technologies are applied for high functionality and performance. The virtual/abstracted layer technologies provide high usability of the systems, including optical access networks. The physical layer technologies are essential, and the author developed technologies related to the layer, e.g., clock and data recovery (CDR) and forward error correction (FEC) in the past time. However, the technologies featured in this dissertation are related to the logical layer and virtual/abstracted layer, especially technologies in the yellow box.

The logical layer consists of dynamic resource allocation, time synchronization, protection, power saving, etc. Dynamic bandwidth allocation (DBA) is one of the most essential technologies that affect the performance of optical access network systems. The virtual/abstracted layer consists of network resource control, heterogeneous networking, network softwarization, network orchestration, etc. Network resource control is one of the most fundamental technologies for not only optical access networks but also all transport networks, which is indispensable for controlling multiple different networks.

In Chapter 2 of this dissertation, trends regarding all the technologies are presented. In Chapter 3, enhancement of DBA for FTTH is presented. In Chapter 4, heterogeneous networking technologies between optical and wireless networks are developed. In Chapter 5, dynamic control methods of network resources, including common architecture for a variety of networks, are presented. In Chapter 6, several studies regarding dynamic resource control cooperating with traffic monitoring and application are summarized.

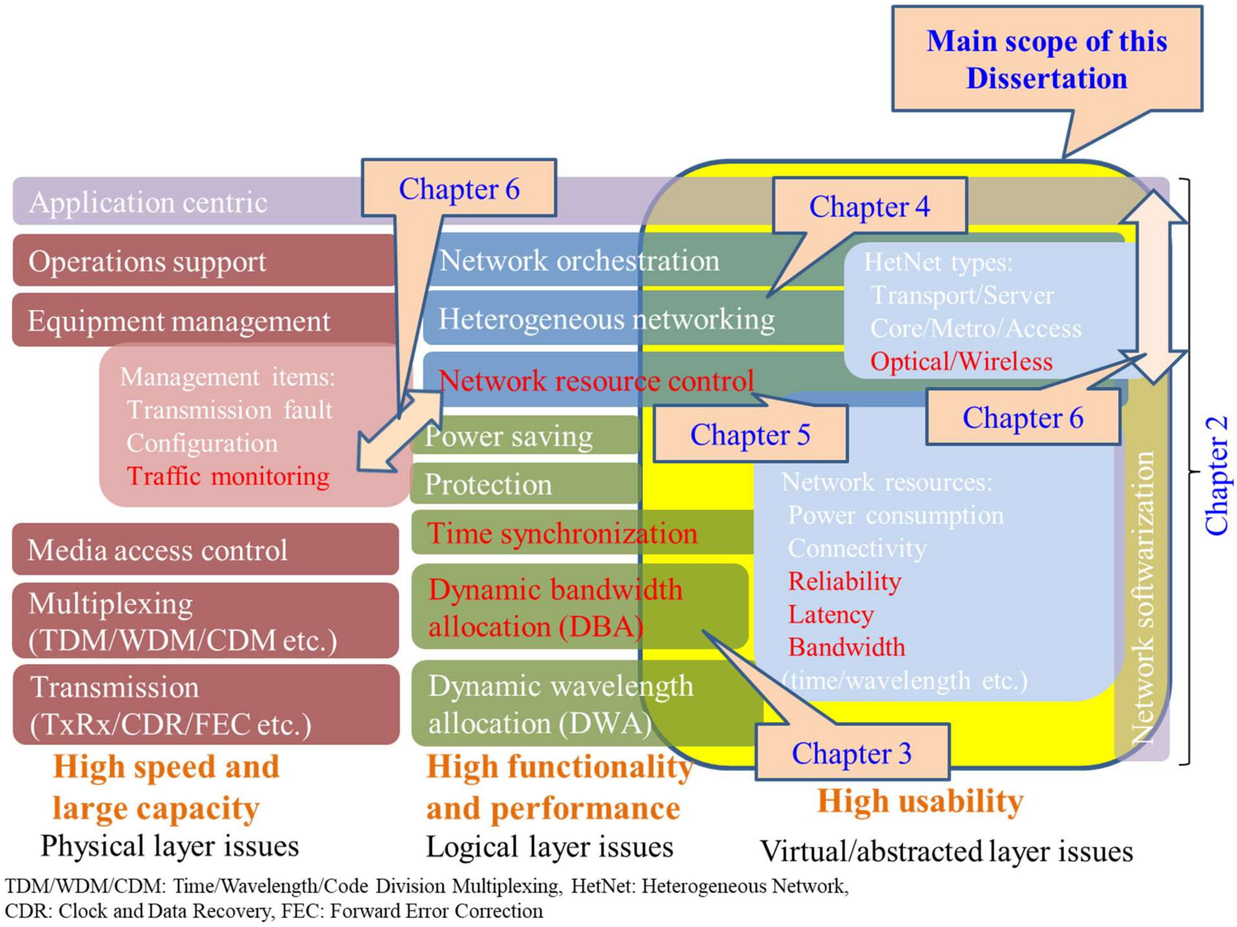

Figure 1.1 Structure overview of the dissertation

In terms of the evolution of technologies in optical access networks, dynamic bandwidth allocation is the essential technology in this dissertation. The author expands the technology with cooperation between wireless and optical networks for improving low-latency performance. The author also develops a new technology with the expansion of dynamic resource allocation by using information of application for high responsibility to change of application requirement.

1.2. Background and purpose

Optical access networks have been developed worldwide as infrastructure to support the explosive spread of Internet connection services since around the year 2000. In particular, the Passive Optical Network (PON) system, which adopted a point-to-multipoint network topology in which numerous subscribers shared central office equipment and optical fibers, was the primary method of Internet connection at the time. Compared to metal transmission methods such as Asymmetric Digital Subscriber Line (ADSL), it achieved dramatic advances in terms of speed and stability and was a method that could be implemented at low cost as an optical network system. A form of laying optical fiber directly to each home is called fiber to the home (FTTH), and PON has come to be used worldwide as a representative method to realize FTTH economically.

On the other hand, the spread of personal mobile communication terminals such as mobile phones and smartphones has progressed at a faster rate than that of optical access networks. Figure 1.2 illustrates the trends in the number of subscribers to fixed broadband services such as FTTH and mobile phones in Japan.

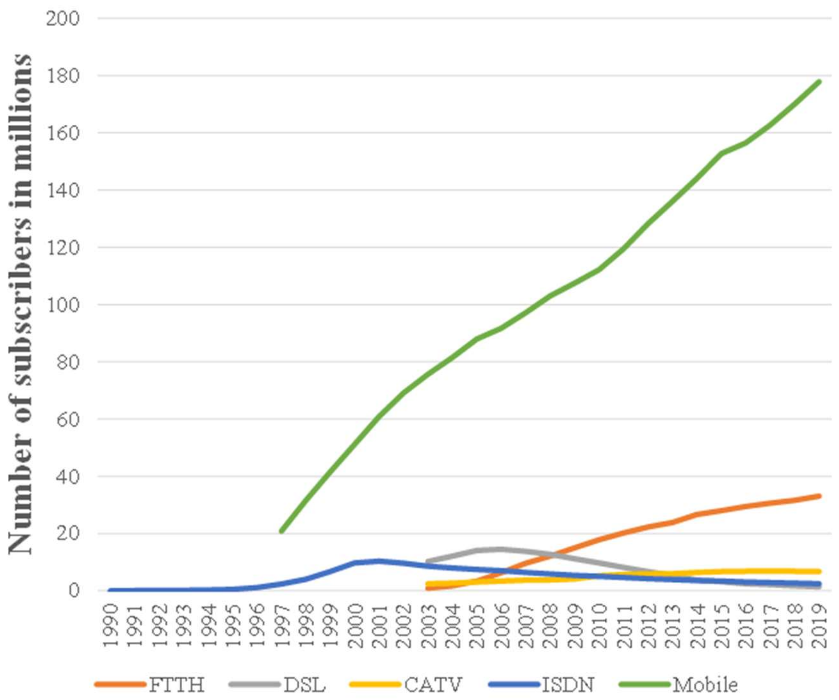

Figure 1.2 Number of fixed broadband service and mobile phone (3G/4G/5G) subscribers in Japan

Figure 1.3 presents the basic architecture and features of PON systems. The PON has been used as a representative means of providing economical optical networks since it provides high-speed services independent of distance at low cost by sharing optical passive elements and fibers that require no long-term maintenance among multiple users.

From a technical point of view, the primary issues are on the uplink direction from In-house equipment to Office equipment. The typical issues are in burst data transmission and bandwidth allocation. This dissertation mainly focuses on resource control technologies, including bandwidth allocation.

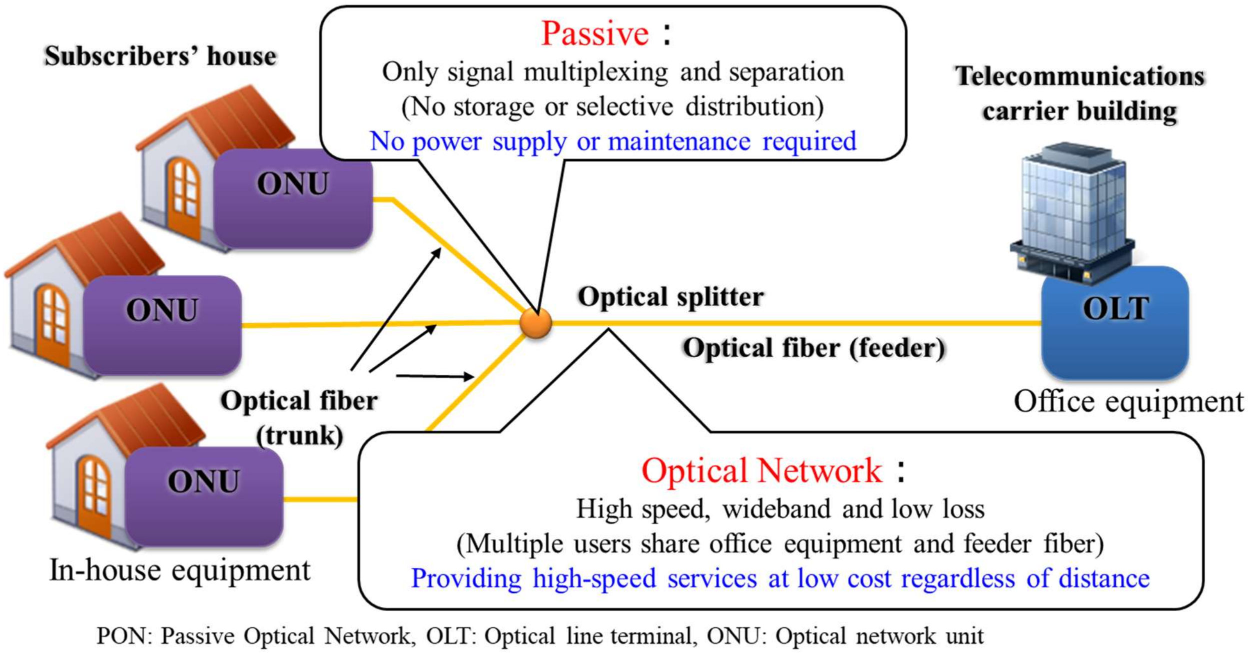

Figure 1.3 Basic architecture and main features of PON systems

Communication services using mobile phones began with voice calls and text message transfers and eventually began to handle various data such as images, and the provision of information through a wide variety of applications based on connections to the Internet has been carried out. It can be said that mobile phones and smartphones are now one of the important infrastructures of people's lives. Mobile communication networks that accommodate mobile phones and provide the above services are evolving in line with the improvement in the service level mentioned above, and 5th generation mobile communication, which has been put into practical use since around 2020, is becoming popular as modern wireless communication infrastructure. Unlike the previous 4G, 5G not only simply provides high-speed, large-capacity communication services but is also a mobile communication system standardized and designed to meet communication requirements for industrial use, such as low latency, high reliability, and simultaneous connection of massive terminals. It is expected to be used in full-scale industrial applications along with Beyond 5G, which is expected to be introduced around 2030.

Networks for connecting mobile phone base stations to backbone networks are called mobile fronthaul (MFH), mobile backhaul (MBH), etc. In mobile communication systems up to 4G, the terminal coverage area (cell) per base station is wide, and therefore, the number of cells is not large, so MFH and MBH are generally configured in a point-to-point format. However, with 5G, cells will become smaller and more numerous, so the application of PON, a point-to-multipoint network, is being considered as a means of efficiently accommodating base stations. Figure 1.4 shows mobile networks and cell architectures for 4G and 5G.

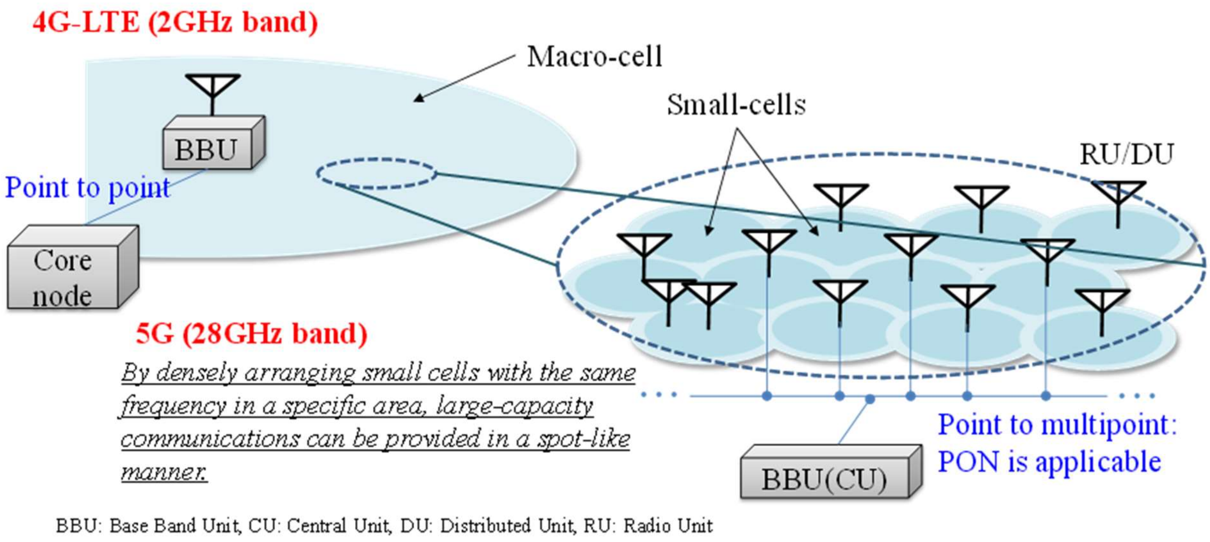

Figure 1.4　Architectures of mobile networks and cells for 4G and 5G

In optical access networks such as PON, as with mobile communication systems, the trend toward higher functionality, such as lower latency and higher reliability, has been observed since around 2010, rather than just increasing speed and capacity. In other words, optical access networks are evolving from infrastructure for FTTH to platforms for various applications. Figure 1.5 shows the technology trends of PON.

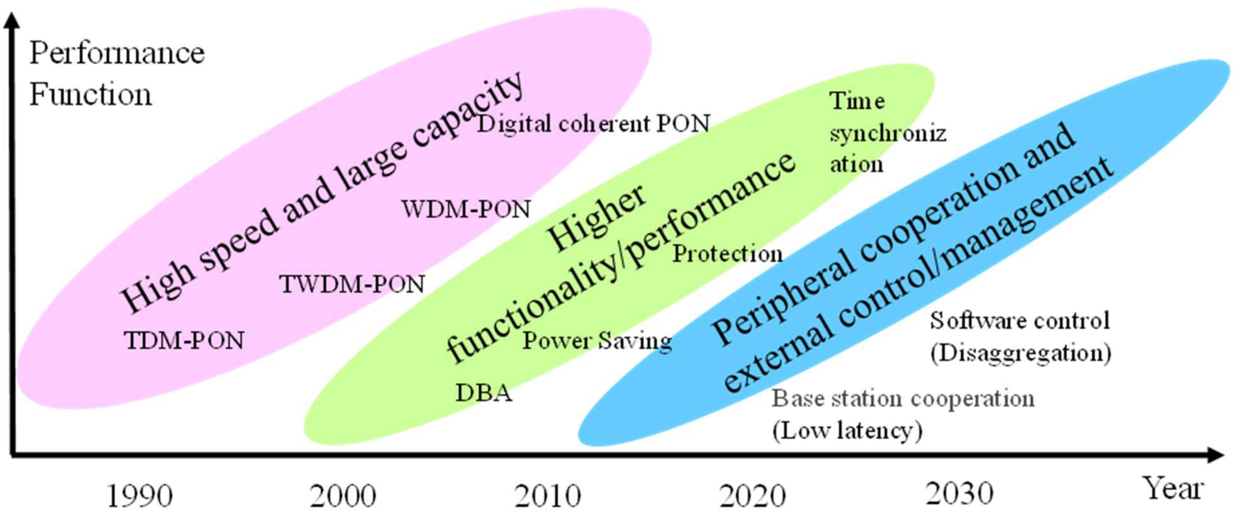

Figure 1.5　Technology trend of PON

In response to these trends, the elemental technologies that support optical access networks will also need to change. In PON systems for FTTH, the main large-capacity data, such as video distribution, flows downstream (from the station side to the subscriber side). Because there is demand for uplink data communication, including voice calls and file uploads, a function called dynamic bandwidth allocation (DBA) is implemented in OLT, which is the central office equipment and performs bandwidth allocation control for ONU installed in each subscriber house. Therefore, the important requirements in DBA for FTTH are fairness among multiple subscribers and total throughput. In addition, when PON systems for FTTH were introduced, deployed systems had a transmission capacity of 1Gbps. However, from around 2015, the next generation 10Gbps class was put into practical use, and in regions such as Japan, where the 1Gbps class was popular, accommodating a mix of 10G and 1G also became an issue.

In contrast, for networks used by various users and applications, contracts based on fixed and uniform user requirements like FTTH services are not suitable; however, dynamic contract forms that correspond to different situations for each user application should be envisioned based on temporal and geographical usage conditions and communication requirements. In some cases, there may be a form in which the usage conditions and communication requirements are automatically changed by the application. Figure 1.6 shows the difference in bandwidth demand between in system for FTTH and in system for diverse applications. In this figure, the X-axis means time, and the Y-axis means bandwidth that is necessary to reserve for application in each system. In the system for FTTH, the required bandwidth is stable from the beginning to the end of service. In the system for diverse applications, the required bandwidth can change dynamically in accordance with the combination of application states. Depending on the type of application, the required bandwidth may change even during the activated state. In the figure, the application-c is an example of the type. In such a case, the bandwidth allocation control function needs to respond to dynamic changes in application status.

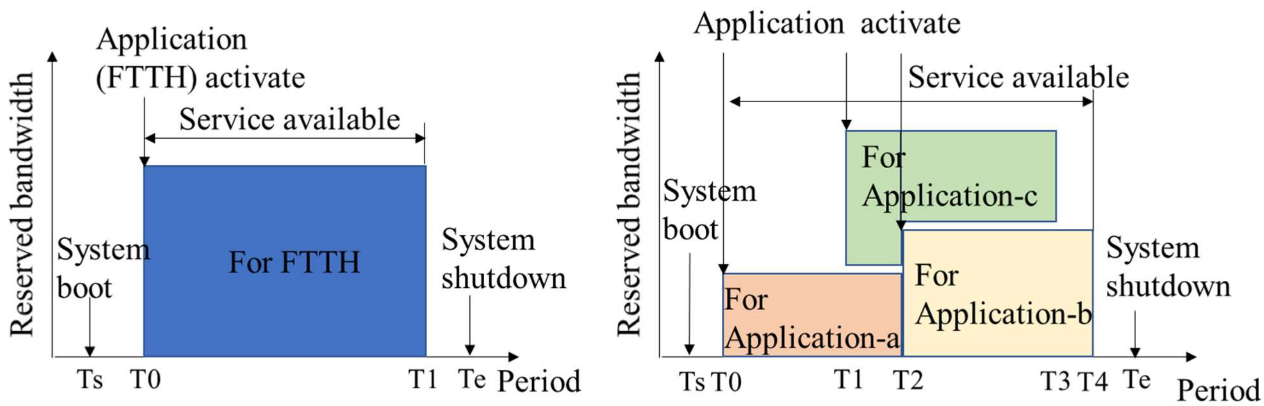

Figure 1.6 Difference in bandwidth demand between systems for FTTH and systems for diverse applications

It is also necessary to satisfy end-to-end communication requirements regardless of geographical conditions. To satisfy such usage conditions and communication requirements, the network operator needs to consider not only the communication bandwidth but also the variety of communication network resources. The resources include communication capabilities such as connectivity, certainty, and reliability. Of course, the bandwidth is one of the capabilities. Controlling allocation of the resources needs to be commonly usable for various network types.

As mentioned above, the challenge of this research is related to uplink resource allocation control in optical access networks, which are representative of PON, and the prerequisite is that various types of data traffic can be distributed via 5G radio access networks. In the environment, the issue is to establish a method and architecture that,

1) make it possible to perform a common resource control and management for heterogeneous networks,
2) make it possible to recognize changes in the status of each application,
3) make it possible to perform a resource allocation according to the changes in the application.

By realizing this, the speed and convenience of providing services using communication networks will be significantly increased compared to the past, and various industries will be able to provide applications and solutions using communication networks in a timely manner.

2. Study and standardization for expanded application of access networks

2.1. Introduction

Optical access networks have contributed significantly to the spread of high-speed broadband services as a means of realizing Fiber to the Home (FTTH) [1]. However, in the future, there is a need to increase the speed of mobile phone networks to cope with the explosive increase in mobile traffic. Accordingly, applying optical access networks is considered to efficiently accommodate small cell base stations that are expected to be deployed in large numbers at high density. Furthermore, during the introduction period of fifth-generation mobile communication systems (5G) or the period after which 5G is fully disseminated, it is assumed that the requirements for communication service quality will become more diverse, so in addition to higher speeds, larger capacity, and lower latency, networks will become more flexible and intelligent. In other words, in such a situation, network virtualization technology [2] is needed to correspond to multiple quality requirements on a single physical infrastructure simultaneously and to use virtualized network resources more efficiently. It is thought that dynamic resource control and management technology will be applied to end-to-end networks.

This study aims to clarify methods of dynamic resource control in optical access networks. In particular, this chapter provides an overview of optical access networks. It presents the latest trends based on the background of changes in the requirements for access networks due to the spread of optical access networks, their increasing popularity, and changes in network usage patterns. Subsection 2.2 explains the increasing need to apply technologies that meet requirements, such as flexibility and high efficiency. In particular, the subsection also explains the use of optical access networks that require flexible and efficient service accommodation. The author analyzes the use case and the technical issues in Subsection 2.3. Furthermore, the author proposes the architecture to solve the problem, the effect of adopting the same architecture, and describes the latest standardization status regarding the architecture in Subsection 2.4

2.2. Advancement of optical access network systems

This subsection simply summarizes major trends in optical access networks as a background for this study.

A. Progress in high-speed large-capacity development and changes in realizing technology

Figure 2.1 shows the evolution of optical access network speed increases. In optical access networks using point-to-multipoint PON systems, the optical communication band is shared among multiple subscribers using time division multiplexing, which makes the central office equipment economical and low in power consumption. The system used has been applied.

However, as bit rates exceeded 10G, it became difficult to increase speed using only time division multiplexing. Therefore, the use of other multiplexing methods in combination has been considered, and wavelength multiplexing is currently the most representative method.

For example, the NG-PON2 system [3] shown in Figure 2.2 achieves a transmission capacity of 40G by multiplexing channel signals of 10Gbit/s per wavelength into four wavelengths. (EPON is being standardized by IEEE) [4] also uses a method to obtain N times the transmission capacity by wavelength multiplexing a 25 Gbit/s signal. This trend of increasing the speed of point-to-multipoint optical access network systems follows the trend of increasing the speed of point-to-point transmission systems such as Ethernet.

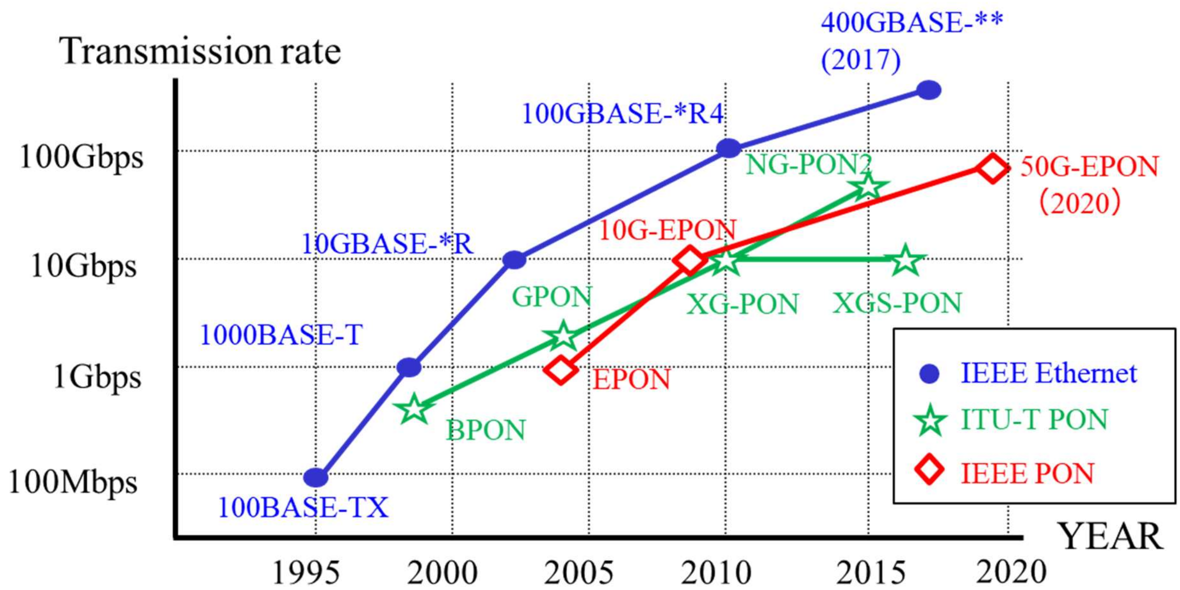

Figure 2.1 Trends in expansion of capacity of optical access networks.

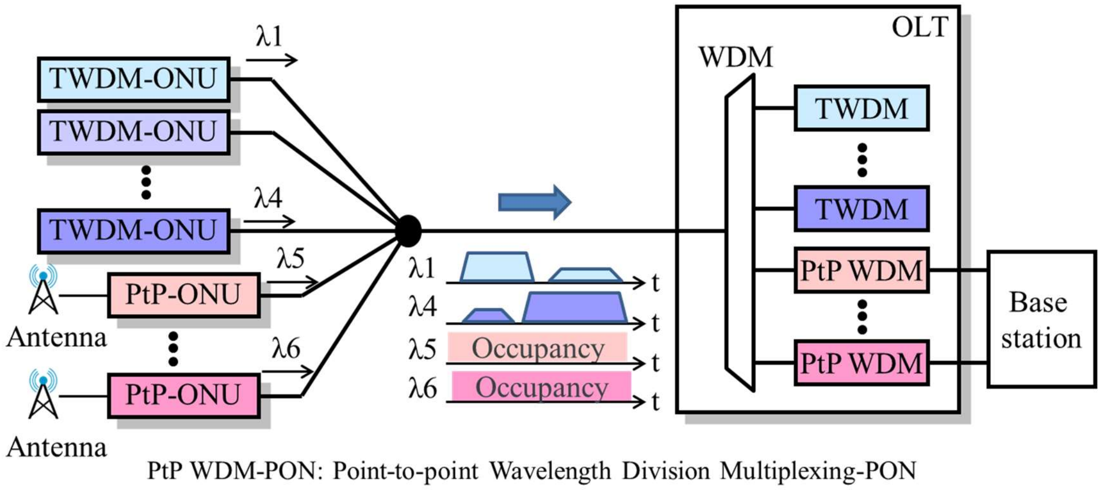

Figure 2.2 Example of MFH system configuration using NG-PON2

Furthermore, to realize high-speed, large-capacity optical access network systems, the adoption of coherent methods, which are mainstream in trunk transmission systems such as metro cores, is being considered [5]. Figure 2.3 shows a proposed configuration of an MFH system using a coherent PON system with a rate of 100 Gbit/s per wavelength. In summary, progress toward higher speeds and larger capacities in optical access network systems has been realized based on technology for point-to-point transmission systems in trunk lines, data centers, etc., and time division multiplexing, multiplexing transmission technology, etc. It can be seen that time division + wavelength multiplexing and coherent + wavelength multiplexing are used. However, a common issue is that it is not just a matter of diversion, but that it is necessary to account for the low cost and power-saving features of access network systems.

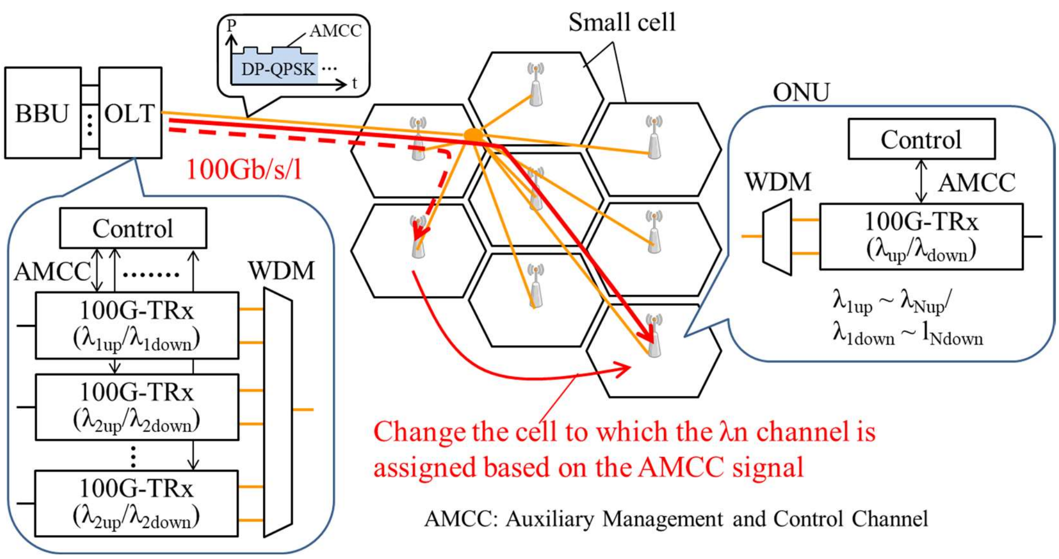

Figure 2.3 MFH system configuration proposal using 100G coherent PON

B. Changes in network usage patterns and corresponding technologies

In the previous subsection, the author introduced the progress of optical access network systems in achieving high speed and large capacity. However, the demands on modern communication networks are not limited to high speed.

One of the changes in the way of using networks is the application of industrial usage other than telecommunications. Figure 2.4 shows examples of such applications, including systems for industrial domains, e.g., FA, Railway, Building, and Electric power, as well as the integration and sophistication of equipment as a mechanism for creating new social value through collaboration between these systems. The figure also shows the structure of the social infrastructure that connects the edge and cloud with communication networks.

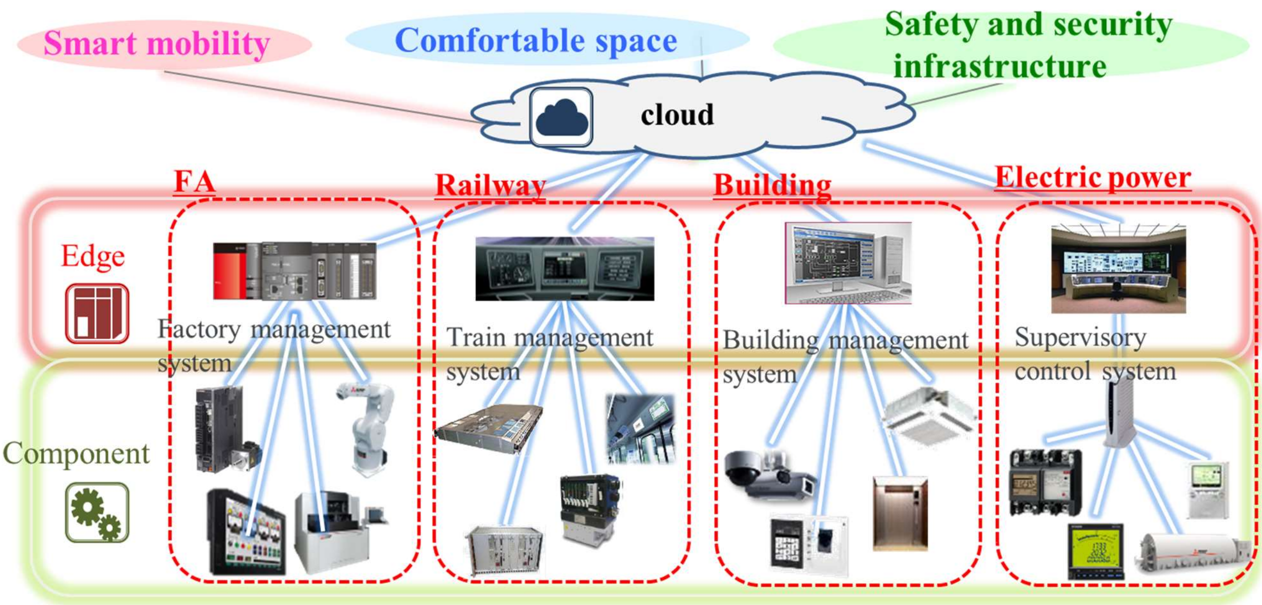

Figure 2.4 Examples of network usage (industrial applications).

In network usage described above, communication networks must meet various requirements to provide quality of service for the application. When expressing the above requirements as the characteristics of communication networks, it is required to provide multiple networks with various combinations of specifications e.g., communication speed, capacity, reliability, delay time, connectivity, and number of terminals. An important feature is network virtualization, which provides an isolated network for each application in multiple networks.

In addition to performance improvements that satisfy these requirements, 5G also offers network virtualization that virtually realizes individual networks that satisfy various combinations of these requirements on a common physical network [6]. Although these technologies have been introduced from the core parts of communication networks, assuming the above usage pattern, it is necessary to establish end-to-end requirements, so applying the technologies to access networks will be essential.

2.3. Flexible and highly efficient optical access system

In this subsection, a use case that requires flexibility and high efficiency in terms of controlling network resources in access networks is assumed, and major technical issues are summarized. The following are use cases in which technologies that improve flexibility and usage efficiency as network usage patterns change, as described in the previous subsection, are particularly important in access networks. Figure 2.5 shows an example of communication resource control for access nodes that constitute a mobile fronthaul that accommodates communication terminals (UE: User Equipment) mounted on or brought into vehicles moving between multiple mobile cells [7]. In such a case, when a mobile object such as a vehicle moves from cell a to cell b to cell c, it can be expected to improve resource efficiency through resource allocation to other services and to reduce power consumption for base stations and transmission equipment, by dynamically changing the amount of communication resources allocated to each of cells a, b, and c.

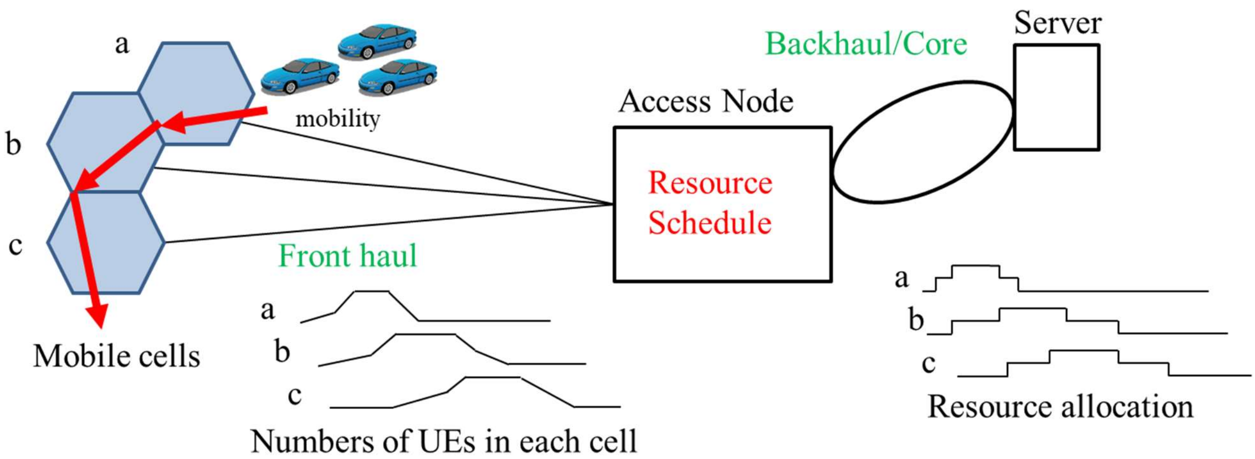

Figure 2.5 Example of use cases that require flexibility and high efficiency in access networks [7]

Considering the use cases introduced in the previous subsection, the following technical issues are primarily required for the access networks. In terms of traffic direction, resource control technologies are essential for not only down-link but also uplink considering, sensing data from vehicles.

1) Dynamic resource control
  a) Real-time and dynamic control
  b) Isolation of communication resources
  c) Management of virtual network in various units
   (e.g., each service and each user)
2) Low latency transmission (wired and wireless connection).

2.4. Dynamic resource control compatible optical access system

A. Architecture

In this subsection, the author proposes an architecture that supports dynamic resource control as the issue described above.

Figure 2.6 illustrates an example of a functional architecture for realizing dynamic communication resource control flexibly and efficiently. It consists of a data plane, including wired and wireless networks at the bottom, a server system at the top, a control system function at the top, and an orchestration function at the top. In this architecture, the Orchestrator extracts the requirements for constructing an end-to-end virtual network according to individual service requirements, divides them into domains, and inputs them to the SDN Controller. SDN Controller reserves logical network resources on OLT to secure resources according to its requirements. At this time, the SDN Controller prepares in advance a network model corresponding to resources that satisfy the requirements of the assumed service and allocates resources instantly when a request occurs.

In the case of accommodating mobility services, slices are semi-fixedly constructed for multiple service providers of the same type on the data plane on the core side of the line concentration switch (L2SW). For the access system on the terminal side from the concentrator SW, the author assumes a scenario in which slices are constructed assuming dynamic resource switching by terminal movement. In the mobile system, the core function (EPC in the figure) grasps information about the terminals within each mobile cell. Furthermore, methods are considered that allow wired and wireless access equipment to work together to notify wired communication equipment of resource allocation information to wireless terminals in real time.

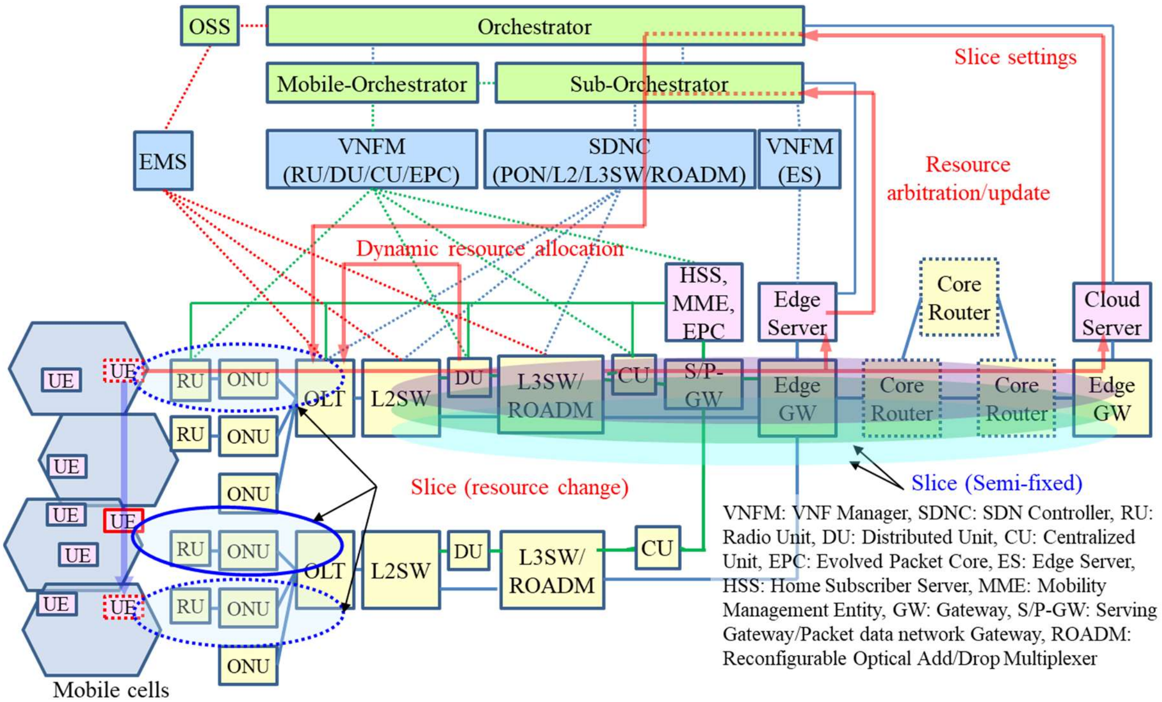

Figure 2.6 Example of an overall functional configuration for slice construction management assuming mobility service accommodation.

The points to realize real-time, dynamic, and efficient resource control using the architecture shown in Figure 2.6 are summarized as follows:

1) Orchestrator provides a network that satisfies the overall requirements of individual provided services by configuring slices through VNFM and SDNC in response to requests from Cloud Server.

2) SDNC performs resource mediation/updates based on information from the Edge Server, estimating resources based on the terminal location and communication traffic in each cell area connected with OLT/ONU or resource calculations based on terminal movement plans owned by applications related to service provision. It is executed dynamically according to instructions from the Orchestrator.

3) Resource mapping and dynamic bandwidth allocation (DBA) functions, which are performed on OLTs, execute real-time dynamic resource allocation control using wireless resource allocation information from extended base stations (DUs) to each terminal and required bandwidth calculation based on traffic monitoring between ONUs and OLTs, based on conditions (maximum allocation value, etc.) from SDNC.

B. Study on the effects of applied technology

Based on the configuration example for slice construction management that provides mobility services shown in the previous subsection, the author briefly examines the effects of the applied technology.

1) Relationship between terminal movement speed and resource control entity

When the size of a small cell is several tens of meters and a mobile object such as a car moves at high speed, it is considered effective to control the lowest layer in Figure 2.6 because it is assumed that resource switching will occur many times within one second. However, when considering handover control between OLTs and coordination with Edge Server when the service range is wide, there may be cases where resource control using the SDN Controller is efficient.

2) Relationship between mobile cell users and service providers

When a mobility service provider provides services to multiple terminal users in a specific area, it is thought that there is no need to control resources for individual terminals, and slices can be constructed and operated by monitoring and estimating the number of terminals and traffic volume for each small cell. On the other hand, when providing services at any time based on requests from individual terminal users, it is thought that functions such as resource arbitration will become effective because it is considered basic to construct slices based on each request.

C. Standardization achievement

Regarding the functional architecture described in the previous subsection, the author has been conducting standardization proposal activities at ITU-T and other organizations, and the architecture has been approved at ITU-T SG13 in March 2019 [42]. In addition, the interface requirements between the main functions of this architecture have been discussed in ITU-T SG15. Figure 2.7 shows the architecture proposed and approved in the SG13.

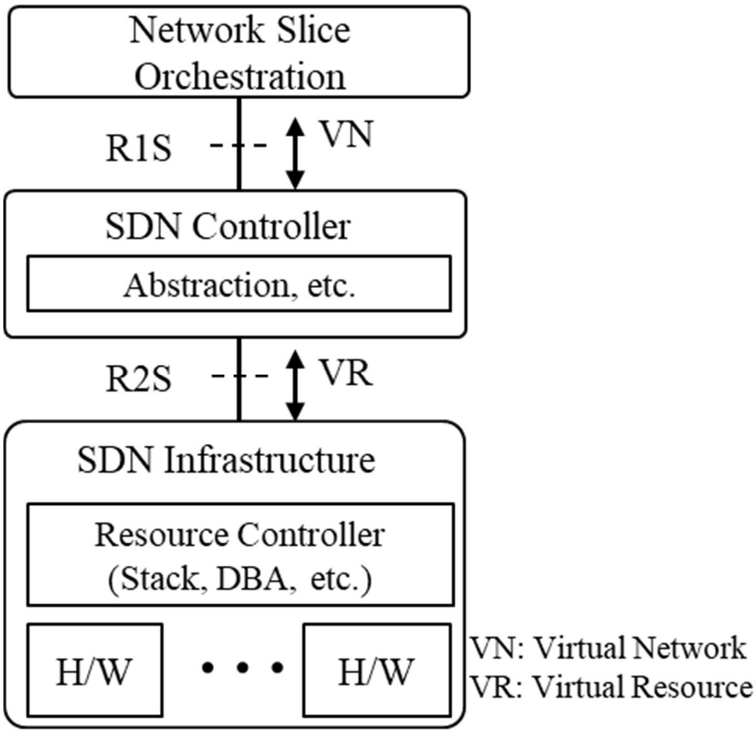

Figure 2.7 Architecture diagram proposed to ITU-T

2.5. Conclusions

The author has summarized the trends in the advancement of optical access network systems from their introduction, expansion, and expansion of application areas and has taken a bird's-eye view of the technologies applied to access network systems based on the requirements for future networks. In this chapter, the author specifically discusses the case of accommodating mobile service terminals as a specific application and identifies issues such as real-time and seamless resource allocation updates as challenges in its application. The author has discussed the architecture for solving the problem and its effects and introduced the status of discussions at ITU-T as the latest standardization trends.

2.6. References

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3. Research on dynamic bandwidth allocation control

3.1. Introduction

Gigabit Passive Optical Network (Gigabit PON) is the cost-effective solution for the Fiber-to-the-Home (FTTH) service [7, 8, 9, 10, 11, 12, 13]. EPON [14] and G-PON [15] systems have been widely deployed worldwide.

In the PON system, the downstream signals are multiplexed with TDM (Time Division Multiplexing). Conversely, uplink signals are multiplexed with TDMA (Time Division Multiple Access), as shown in Figure 3.1. Each ONU transmits its uplink data at the proper time to avoid collisions. The scheduling of the data transmission of ONUs is done in the OLT by employing a dynamic bandwidth allocation (DBA) scheme [16]. To decide the allocation bandwidth for each ONU, the OLT needs to predict the required bandwidth for ONUs. This control mechanism is one of the key technology for PON.

For the next generation access network, 10G-EPON has been standardized in IEEE in September 2009 [17], and 10Gbps capable PON has also been discussed ITU-T. The motivation for 10Gbps class PON deployment is increasing the throughput per user, the number of users per fiber keeping higher throughput than Gigabit PON. To take advantage of 10Gbps class uplink transmission capacity, DBA has some challenges as follows:

(a) Decreasing packet transmission delay to achieve high throughput in upper layer protocol such as TCP/IP.

(b) Keeping high total throughput regardless of the number of subscribers.

(c) Capability of subscribing the delay-sensitive services.

In this chapter, the author proposes a new DBA algorithm: Adaptive DBA (AD-DBA) for the 10G-EPON system. The AD-DBA achieves a low transmission delay and high bandwidth efficiency by adaptively changing the prediction method of the required bandwidth for ONUs according to the bandwidth utilization. To verify the performance of AD-DBA, The author evaluates it with the prototype system in any traffic condition.

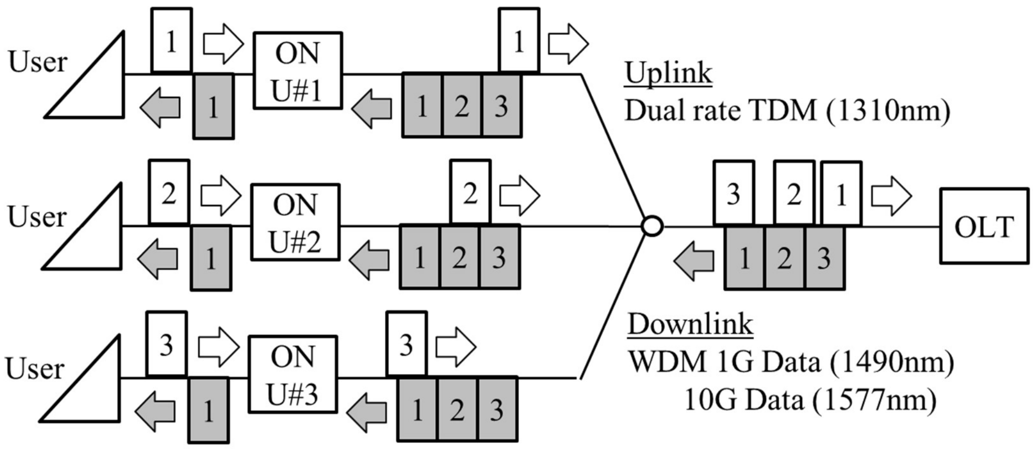


Figure 3.1 Schematic of 10G-EPON system

3.2. Bandwidth allocation mechanism

In this subsection, the author introduces the bandwidth allocation mechanism as one of the key technologies for PON. In PON systems, each ONU’s uplink bandwidth is decided by allocated time slots specified by the OLT in unit time. In the fixed bandwidth allocation (FXB), the bandwidth for each ONU is constant. On the other hand, the dynamic bandwidth allocation (DBA) changes the bandwidth for each ONU dynamically according to the uplink traffic in the ONU.

FXB is suitable for low-delay required services such as telephony. On the other hand, DBA is suitable for burst traffic, such as Internet access service, which is dominant in FTTH. By using DBA, users can be provided the wire rate of Ethernet for end users because not all users send the data simultaneously. Therefore, DBA is the key technology to provide higher bandwidth per user by efficiently utilizing the total bandwidth.

The following processes are executed in the OLT periodically, such as one-millisecond interval, to perform DBA in PON systems [18].

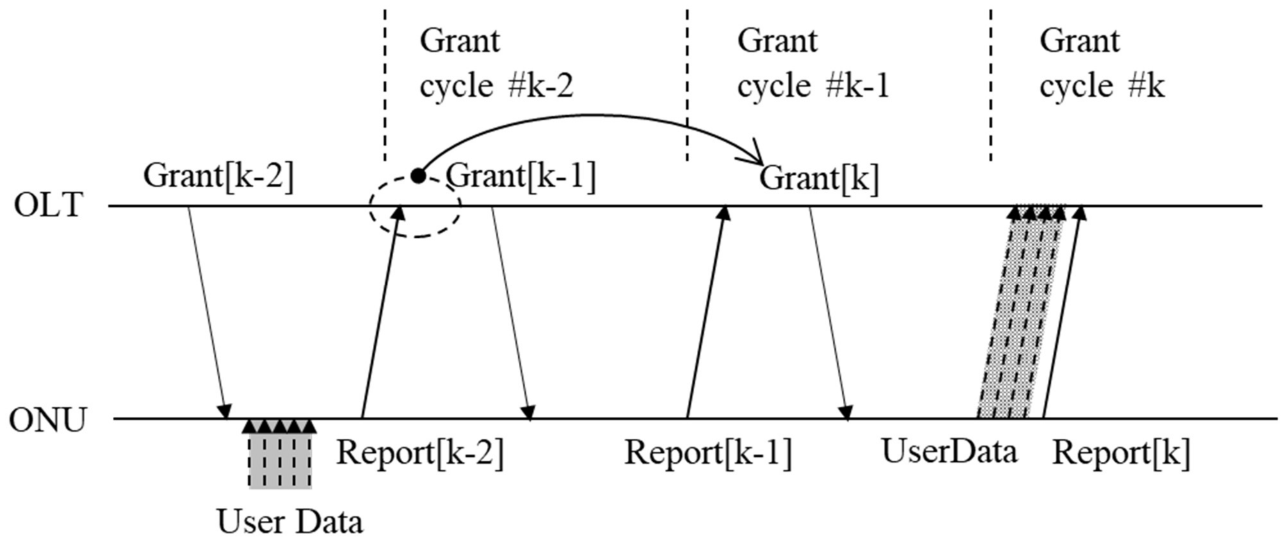
(a) Prediction of the required bandwidth for each ONU

(b) Calculation of uplink bandwidth for each ONU

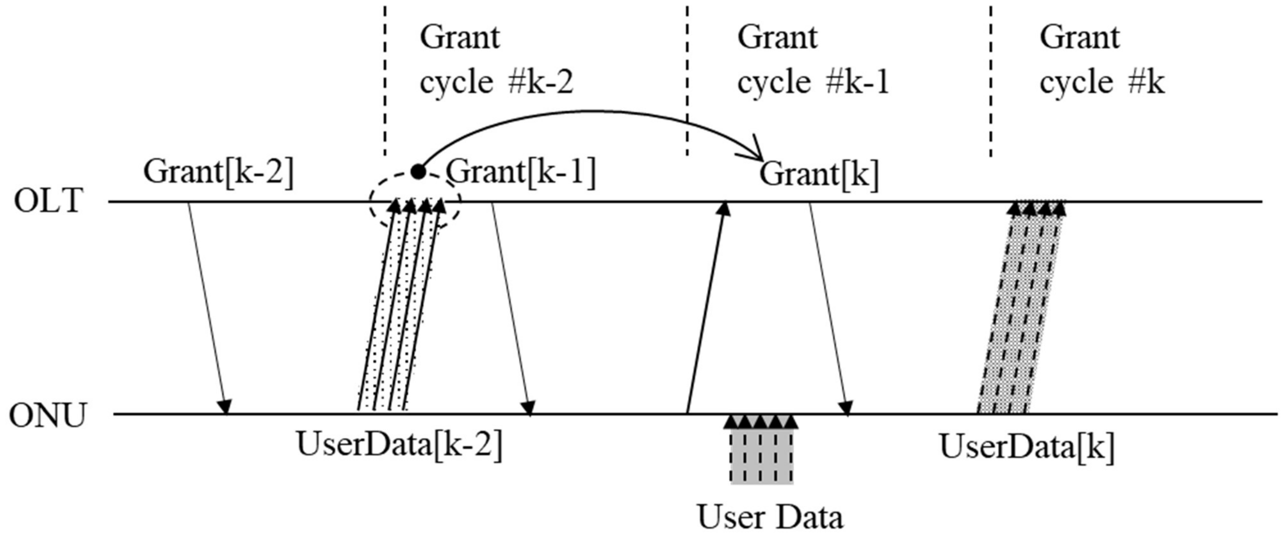
(c) Grant signal allocation to each ONU

The OLT needs to predict the required bandwidth for remote ONUs. As shown in Figure 3.2, there are two methods for bandwidth prediction [19]. One is the Status Reporting-DBA (SR-DBA). The OLT predicts the required bandwidth according to the reported queue length by the queue status reporting message from the ONUs. The other one is the Traffic Monitoring-DBA (TM-DBA). The OLT monitors the received traffic from ONUs and predicts the required bandwidth according to the grant utilization.

From the viewpoint of bandwidth utilization, SR-DBA has an advantage because the OLT can know the actual required grant according to the queue status report from the ONUs. On the other hand, from the viewpoint of the waiting time to send uplink data, TM-DBA has an advantage because it does not require the time to gather the queue status reports [13].



(a) SR-DBA



(b) TM-DBA

Figure 3.2 DBA operation between OLT and ONU

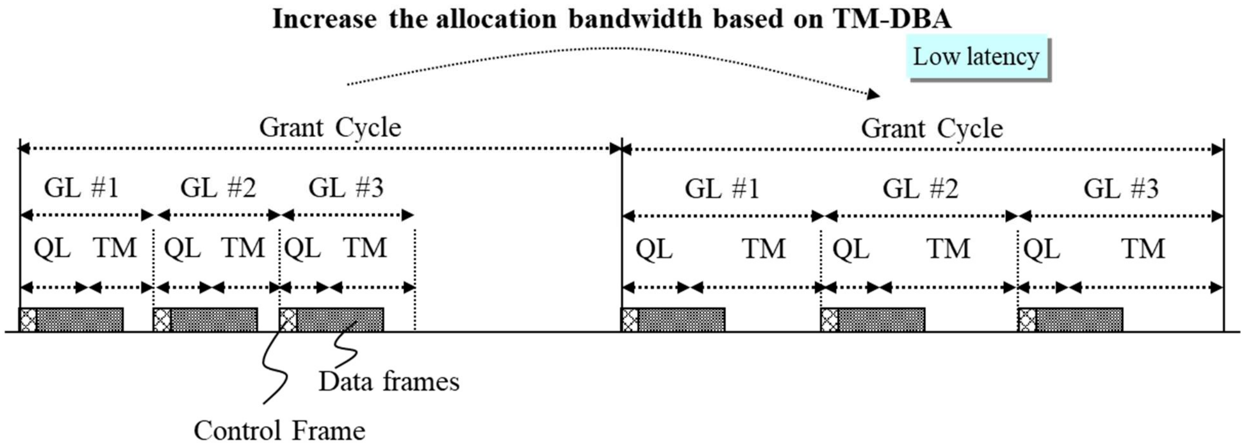
3.3. Proposed adaptive dynamic bandwidth allocation for 10G-EPON

Considering the data throughput in the upper layer protocol such as TCP/IP, low data transmission delay is desirable because data throughput depends on RTT (Round Trip Time). However, in the current EPON system, SR-DBA is dominant because RTT is not a problem below the 1Gbps rate. In the age of 10G-EPON, more high performance in application, then the lower data transmission delay will be required to realize the higher data throughput in upper layer protocol. Here, the author proposes the Adaptive Dynamic Bandwidth Allocation (AD-DBA), which is adaptively switching SR-DBA and TM-DBA according to the traffic load.

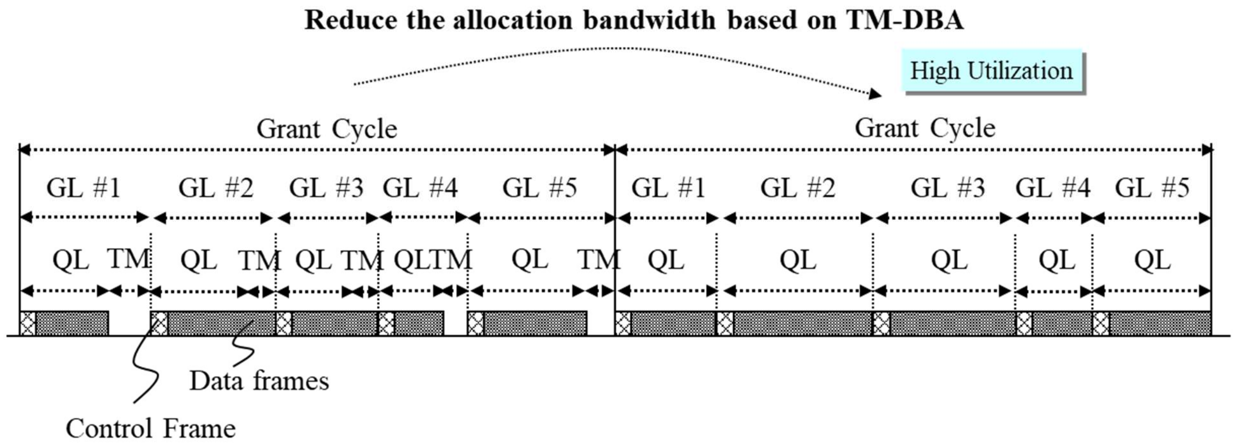
Figure 3.3 illustrates the AD-DBA scheme. The allocated bandwidth for logical link #j, polling period #k by AD-DBA is described by eq.(1). Logical Link can be assigned to each subscriber.

$$AL\_BW[j][k] = QL[j][k-2] + m * TM[j][k-2] \quad (1)$$

where AL_BW, QL, and TM are the bandwidth to be allocated, queue length reported from the ONU, and the amount of monitored traffic in the OLT, respectively.



(a) PON is not congested



(b) PON is congested

Figure 3.3 Bandwidth Allocation using AD-DBA

From eq.(1), OLT allocates the requested bandwidth from the ONU and adds the surplus bandwidth according to the monitored traffic [18]. When the allocated bandwidth is enough for the ONU; in other words, PON is not congested, QL will be a small value. In that condition, bandwidth prediction should be done by the monitored traffic. On the other side, the allocated bandwidth is not enough for the ONU; in other words, PON is congested, and QL will be a large value. In that condition, bandwidth prediction should be done by the report from the ONU for high bandwidth efficiency. In eq.(1), the variable m should be reflected for balancing the throughput and the packet transmission delay. In other words, the variable m means the weight for allocated bandwidth by TM-DBA. Here, the author sets the variable m as eq. (2) and (3).

$$m = \frac{RM_{BW}[k]}{\sum_{j=1}^{N} TM[j][k-2]} \tag{2}$$

$$RM_{BW}[k] = BW_{av} - \sum_{j=1}^{N} QL[j][k-2] \tag{3}$$

where RM_{BW}, BW_{av}, and N are the remaining bandwidth reflected by traffic load, the available bandwidth for data transmission, and the number of logical links, respectively. From eq. (2) and (3), the remaining bandwidth is efficiently allocated according to the traffic load and received traffic.

3.4. Bandwidth allocation for multiple-service

In an actual environment, multiple services, such as computer communication, VoIP, and IPTV, can be multiplexed into a single logical link. The bandwidth requirements are differ among the users and provided according to the Service Level Agreement (SLA). Therefore, the DBA algorithm needs to be designed by considering SLA configurations. In terms of fairness allocation, it is also the basic concept. In this subsection, AD-DBA for multiple services is described. Figure 3.4 shows the flow chart of the proposed bandwidth allocation scheme. SLA parameters are settled for each subscriber to guarantee the quality of services. Here, the author sets the following two SLA parameters:

(a) Delay class: low delay class or normal delay class

(b) Minimum Bandwidth

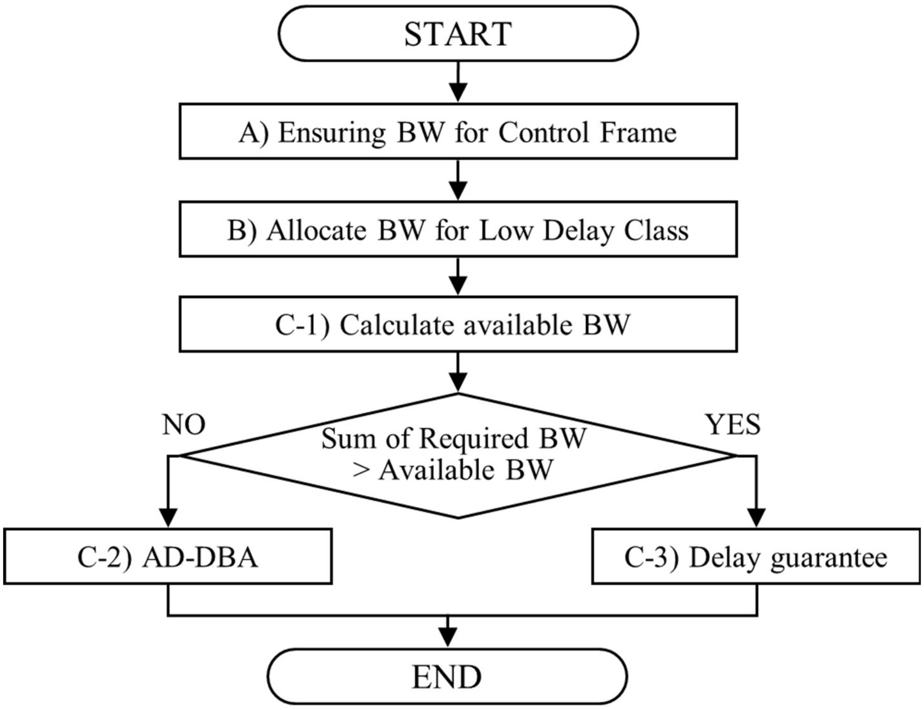


Figure 3.4 Flow of the proposed Bandwidth Allocation

The bandwidth is allocated to each logical link using these parameters. In this flow chart, there are two main flows according to uplink traffic congestion status. The detailed descriptions are as follows:

A. Ensuring bandwidth for the control frame

At first, the bandwidth for the control frame is ensured, and the bandwidth for data transmission is calculated by eq. (4).

$$BW_{data}[k] = GC - \sum_{j=1}^{N} RP[j] \qquad (4)$$

where BW_{data}, GC, and RP are bandwidth for user data transmission, data quantity in one grant cycle, and bandwidth for control frame (such as Report Frame), respectively.

B. Low delay class Bandwidth Allocation

The fixed bandwidth is allocated to the logical link of the low delay class using eq. (5) and (6).

$$BW_{LD}[j][k] = BW_{data}[k] \times \frac{MinBW[j]}{BW_{line}} \tag{5}$$

$$AL\_BW[j][k] = RP[j] + BW_{LD}[j][k] \tag{6}$$

where BW_{LD}, BW_{line}, and MinBW are the bandwidth for data transmission, line rate of 10Gbit/s, and SLA parameter of minimum bandwidth.

C. Normal Delay Class Bandwidth Allocation

1) Calculation of available bandwidth

The available bandwidth for the logical link of the normal delay class (BWav) is calculated by eq. (7).

$$BW_{av}[k] = GC - \left(\sum_{j=1}^{N} RP[j] + BW_{LD}[j][k] \right) \tag{7}$$

2) Adaptive dynamic bandwidth allocation

In the case of sumQL < BW_{av}, AD-DBA are applied for bandwidth allocation according to eq. (1)-(3).

3) Fairness guarantee based on Minimum Bandwidth

In the case of sumQL ≧ BW_{av}, PON is highly congested. SR-DBA (m=0 in eq.(1)) is adapted. To ensure the fairness of allocation bandwidth, the guaranteed bandwidth ($MinBW_{ratio}$) is calculated according to the potion of the minimum bandwidth as eq. (8).

$$MinBW_{ratio}[j][k] = BW_{av}[k] \times \frac{MinBW[j]}{\sum_{i=1(QL>0)}^{N} MinBW[i]} \tag{8}$$

In the case of QL[j][k-2] ≦ $MinBW_{ratio}$[j][k], the allocated bandwidth is decided by eq. (9) and (10).

$$AL\_BW[j][k] = RP[j] + QL[j][k-2] \tag{9}$$

$$RM\_BW[j] = MinBW_{ratio}[j][k] - QL[j][k-2] \tag{10}$$

In the case of QL[j][k-2] > $MinBW_{ratio}$[j][k], the allocated bandwidth is decided by eq. (11) and (12).

$$RM\_QL[j] = QL[j][k-2] - MinBW_{raio}[j][k] \tag{11}$$

$$AL\_BW[j][k] = RP[j] + MinBW_{ratio}[j][k] + \sum_{i}^{N} RM\_BW[i] \times \frac{RM\_QL[j]}{\sum_{i}^{N} RM\_QL[i]} \tag{12}$$

From eq. (7) to (12), the bandwidth is fairly allocated according to the SLA parameter of MinBW.

3.5. Evaluation of the proposed DBA algorithm

A. Evaluation of AD-DBA

To verify the performance of AD-DBA, the author evaluates the packet transmission delay in our 10G-EPON prototype system [20]. By using AD-DBA, the packet transmission delay should be kept low despite of traffic load to achieve high data throughput. Figure 3.5 shows the evaluation system configuration. Two 10G-ONUs are connected to the optical distribution network. Table 3.1 shows the optical parameters. Table 3.2 shows the test traffic and SLA parameters for each 10G-ONU. In this test, the author emulates the best-effort service and configures the MinBW as 0bps. The traffic load of 10G-ONU #2 is 1Gbps. The traffic load changes by increasing the traffic rate of 10G-ONU #1 from 0 bps to 8 Gbps. To verify the performance of AD-DBA, the packet transmission delay is measured and compared with SR-DBA for investigation of basic delay property.

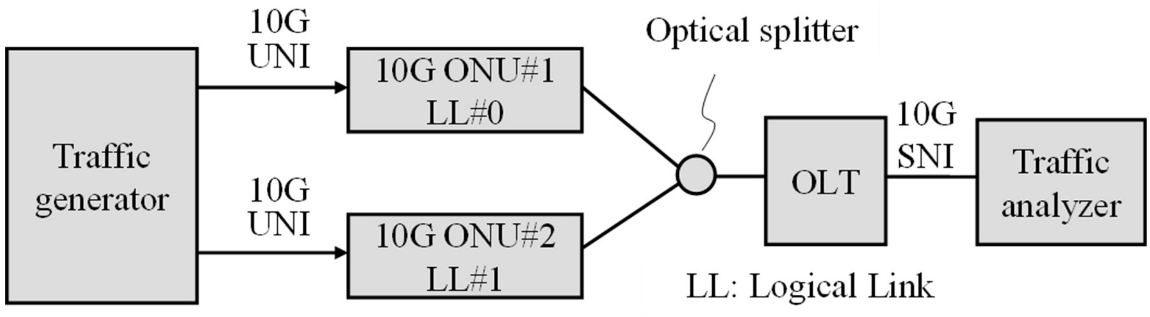


Figure 3.5 Evaluation system configuration for AD-DBA

Table 3.1 Optical parameters

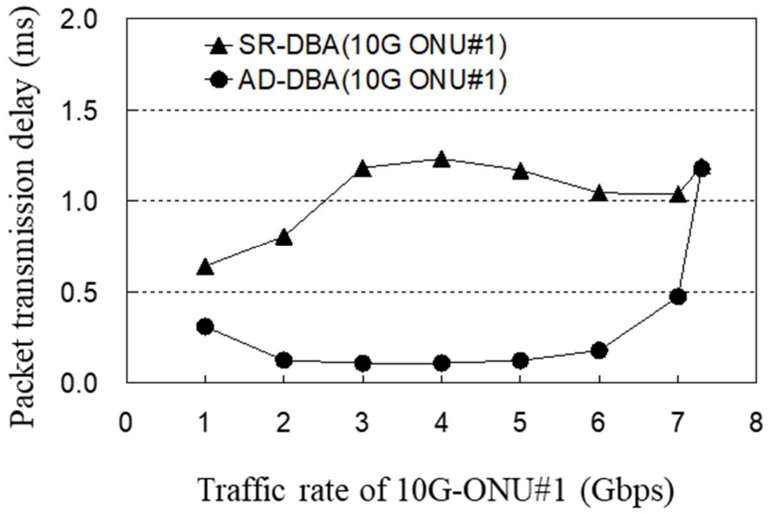
Parameters	Value
Synchronization time	1.2 us
Laser on time	512 ns
Laser off time	512 ns
Guard time	512 ns

Table 3.2 Traffic pattern and SLA parameters (number of logical links is 2)

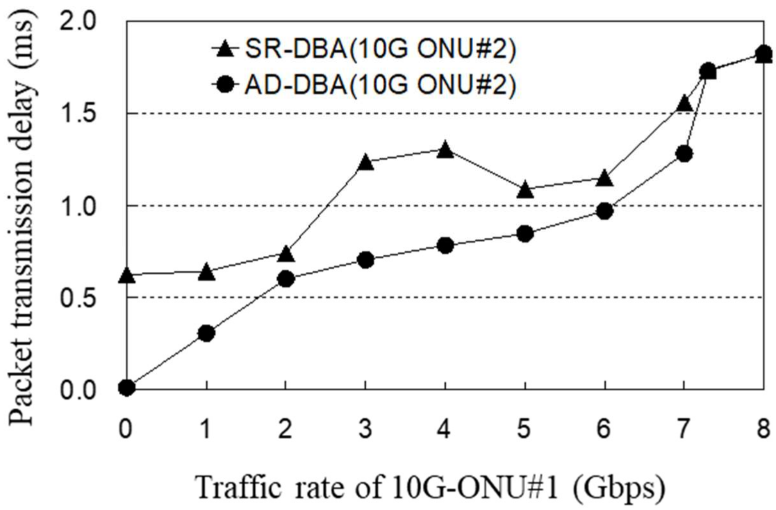
10G ONU #	LL #	Traffic		SLA parameter		
		Rate	Frame length	Application	Delay class	MinBW
1	0	0-8 Gbps	Random	Data	Normal	0 bps
2	1	1 Gbps	Random	Data	Normal	0 bps

Figure 3.6 (a) and (b) show the result of the packet transmission delay measurements of 10G-ONU #1 and #2 by changing the traffic of 10G-ONU #1. From Figure 3.6 (a) and (b), the packet transmission delay by using AD-DBA

is lower than by using SR-DBA. The packet transmission delay of 10G ONU #1 is kept low, and that of 10G-ONU #2 is increased with the traffic of 10G-ONU#1. Regarding the delay of ONU#1, the performance of AD-DBA is close to SR-DBA in the condition of high traffic rate of 10G-ONU#1 because the Sum of Required BW is nearly equal to Available BW in Figure 3.4 at the condition. In addition, the author confirms the maximum throughput of 8.63Gbps without frame loss, which is 99.7% of the theoretical limit considering the control frame, FEC (RS(255,223)) overhead, and PON overhead. From these results, the AD-DBA achieves lower packet transmission delay than SR-DBA and high bandwidth efficiency.



(a) 10G ONU #1



(b) 10G ONU #2

Figure 3.6 Packet transmission delay measurement results

B. Bandwidth allocation to 128 logical links for multiple services

To evaluate the bandwidth allocation with AD-DBA for multiple services, the author evaluates it in the environment of 128 logical links. To prepare the evaluation environment, the author develops the ONU emulator. It supports Multi-point control protocol (MPCP) of up to 64 logical links. In addition, it enables to emulate uplink buffering of data by setting the rate and frame length. According to the buffering data and grant length, the uplink data is generated and sent to OLT. Figure 3.7 shows the evaluation system configuration for 128 logical links for multiple services. Two 10G-ONUs with 64 logical links and two 10G-ONUs are connected to the optical distribution network. As for the optical parameters, guard time is zero, and other parameters have the same value, as shown in Table 3.1. Table 3.3 shows the test traffic and SLA parameters for each 10G-ONU. The SLA parameters are settled to emulate the triple play services: voice, video, and data. The traffic rate of logical link #0 in 10G-ONU #1 is 10Gbps to emulate the heavy internet user.

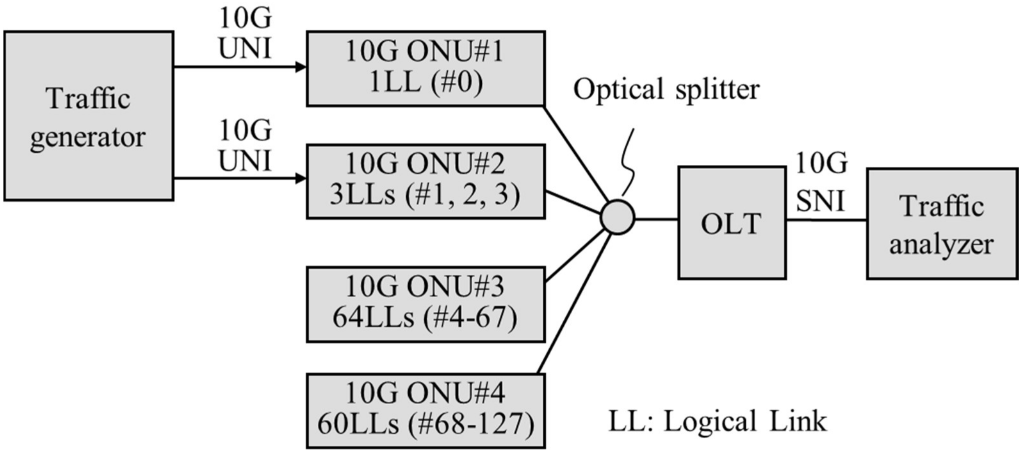


Figure 3.7 Evaluation system for multiple services and 128 logical links.

Table 3.3 Traffic pattern and SLA parameters (number of logical links is 128)

10G ONU #	LL #	Traffic pattern		SLA parameter		
		Rate	Frame length	Service	Delay class	MinBW
1	0	10 Gbps	Random	Data	Normal	0 bps
2	1	1 Mbps	218 Byte	Voice	Low	3 Mbps
	2	24 Mbps	Random	Video	Normal	50 Mbps
	3	40 Mbps	Random	Data	Normal	0 bps
3	4-67	40 Mbps	Random	Data	Normal	0 bps
4	68-127	40 Mbps	Random	Data	Normal	0 bps

The traffic rates of Logical link #1-3 in 10G-ONU #2 are 1Mbps, 24Mbps, and 40Mbps, respectively. These values are used for applications of voice, video, and data transmission. The traffic rate of logical links #4-#127 in 10G-ONU #3 and #4 is 40 Mbps as background traffic. The packet transmission delay and total throughput are measured to verify the performance of the proposed bandwidth allocation.

Figure 3.8 shows the evaluation results of the packet transmission delay and total throughput measurements by changing the number of logical links. From packet delay measurements in Figure 3.8, the average packet delays of logical links #1 and #2 are kept under 0.6 ms and 1.5 ms. In this experiment, the maximum packet delays of logical links #1 and #2 are under 0.6 ms and 1.5 ms. These values fully satisfy the delay requirements of voice and video applications [21]. On the other hand, the packet transmission delay of logical link #3 is increasing with the number of logical links. It shows that the performance of the best effort service is depending on the number of active users. From throughput measurements in Figure 3.8, The author confirms that the proposed DBA algorithm achieves the total throughput over 91 % of the theoretical limit in multiple services and 128 logical splits environment.

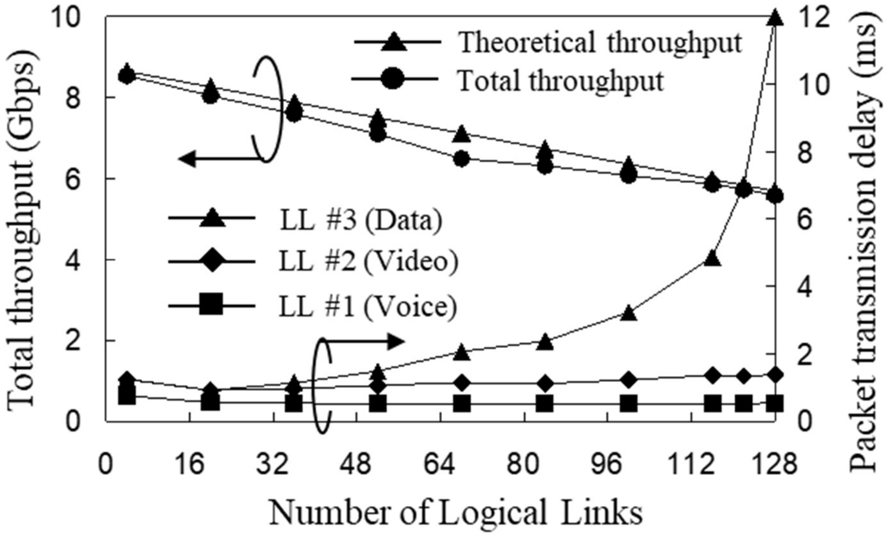


Figure 3.8 Experimental results of the packet delay and total throughput measurements of AD-DBA by changing the number of logical links (LL)

3.6. Conclusion

In this chapter, the author has proposed a new DBA algorithm: Adaptive DBA (AD-DBA) for the 10G EPON system. The AD-DBA enables network operators to take advantage of 10Gbps uplink transmission capacity by adaptively changing the prediction method of required bandwidth for ONUs according to bandwidth utilization. The author has evaluated AD-DBA by changing the traffic condition to verify the performance of AD-DBA. Evaluation results show that the AD-DBA achieves low packet transmission delay and high bandwidth efficiency. In addition, the author has also evaluated it under the multiple services and 128 logical links environment in our 10G-EPON prototype system. According to the evaluation results, the author has confirmed that the proposed DBA algorithm achieves high quality in the actual FTTH services.

3.7. References

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4. Research on low latency transmission of PON uplink

4.1. Introduction

Optical access networks are a promising means of efficiently accommodating mobile communications traffic with wireless networks such as 5G. Regarding dynamic network resource allocation, it is possible to provide by utilizing mechanisms such as PON's DBA and network virtualization technology.

However, TDM, the primary multiplex transmission method for PON, has critical issues in accommodating mobile systems.

This Subsection summarizes the issues in the case of applying TDM-PON to mobile fronthaul (MFH). It describes how to implement an optical/wireless network resource control method that supports the modularization of DBA functions. Furthermore, the author reports the evaluation results of uplink frame transmission delay time in the prototype 10G-EPON system for 5G MFH.

4.2. Problems of TDM-PON systems for mobile fronthaul

An example of the MFH is a part of the network between DU and RU, as shown in Figure 4.1. In TDM-PON systems such as 10G-EPON, each ONU transmits uplink frames at the timing that is permitted by the OLT's DBA function; then, it enables multiple ONUs to efficiently use the shared optical fiber bandwidth.

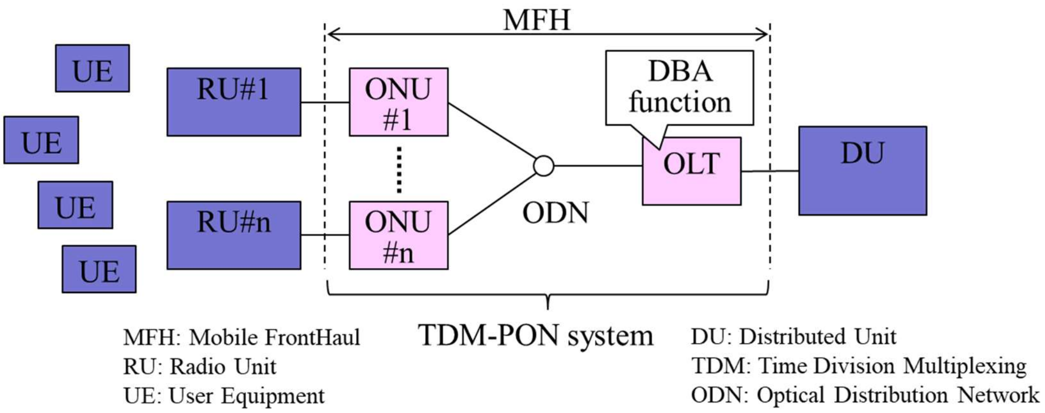


Figure 4.1 MFH applying TDM-PON system

Figure 4.2 shows the uplink frame transmission delay time using the conventional DBA (Status Report DBA) method. The conventional DBA function unit periodically performs processing to grant uplink transmission permission based on the transmission request of each ONU. Therefore, even if an ONU receives an uplink frame, it cannot transmit this frame until it sends a transmission request to the OLT and receives transmission permission. This kind of transmission waiting time at ONU is called control delay.

Figure 4.2 shows the case where the control delay is maximum. For example, if the MFH section is 20 km, the round trip time (RTT) will be approximately 200 µs, so the transmission permission period in the SR-DBA method will be more than 200 µs. Therefore, using the conventional DBA method, the maximum control delay in the MFH section of 20 km is more than 400 µs.

On the other hand, 3GPP, etc., specify the allowable transmission delay required for MFH, as shown in

Table 4.1 [22], and in Low Layer Split (Options 5 to 7), which is suitable for eMBB that requires high speed and large capacity, the frame transmission delay is 250 µs or less is required. Therefore, TDM-PON using the conventional DBA method has the problem of not satisfying the allowable transmission delay required for MFH. To apply a TDM-PON system to 5G MFH with a 20km section, it is necessary to suppress the total transmission processing delay in ONU, reception processing delay in OLT, and control delay to 150 µs or less, and a method to suppress control delay is needed.

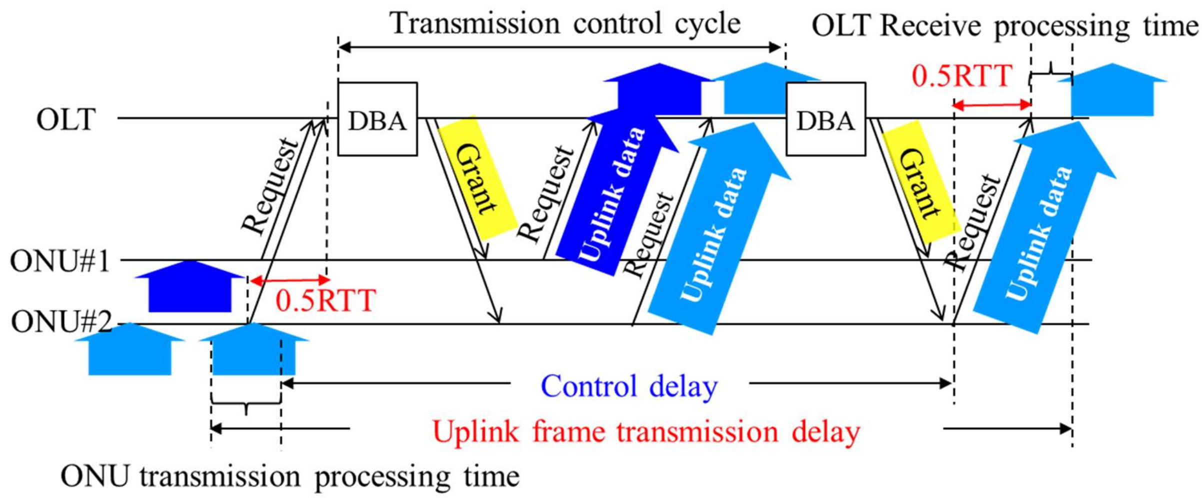


Figure 4.2 Uplink frame transmission delay in conventional DBA method

Table 4.1 Functional division point and allowable transmission delay

option	CU-DU/RU dividing point	Allowable transmission delay
Option 1	RRC-PDCP split	10 ms
Option 2	PDCP-RLC split	1.5～10 ms
Option 3	intra RLC split	1.5～10 ms
Option 4	RLC-MAC split	A few 100 µs
Option 5	intra MAC split	A few 100 µs
Option 6	MAC-PHY split	250 µs
Option 7	intra PHY split	250 µs
Ref.CPRI	PHY-RF split Non-Ethernet frame	250 µs

*: RRC: Radio Resource Control, PDCP: Packet Data Convergence Protocol, RLC: Radio Link Control, CPRI: Common Public Radio Interface

4.3. Division/reconstruction of network functions and DBA

In recent years, the trend to implement network functions using software has rapidly progressed, regardless of whether it is wireless or wired. Network functions realized by the software can be easily divided, modularized, reconfigured, and combined.

Regarding the DBA function described in the previous subsection, the author assumed various types of DBAs and developed a modular connection configuration and interface on top of the Multi-Point Mac Control (MPMC) function, which is the essential access control of TDM-PON. Studies are underway, and regarding standardization, the Broadband Forum (BBF) has defined applicable applications, requirement definitions, and standard API specifications [23]. In addition, regarding Cooperative DBA (CO-DBA), which controls PON bandwidth by sharing uplink transmission schedule information of wireless terminals between base stations and PON, ITU-T SG15 has proposed developing interface specifications with base stations in cooperation with Open Radio Access Network (O-RAN) alliances (Figure 4.3).

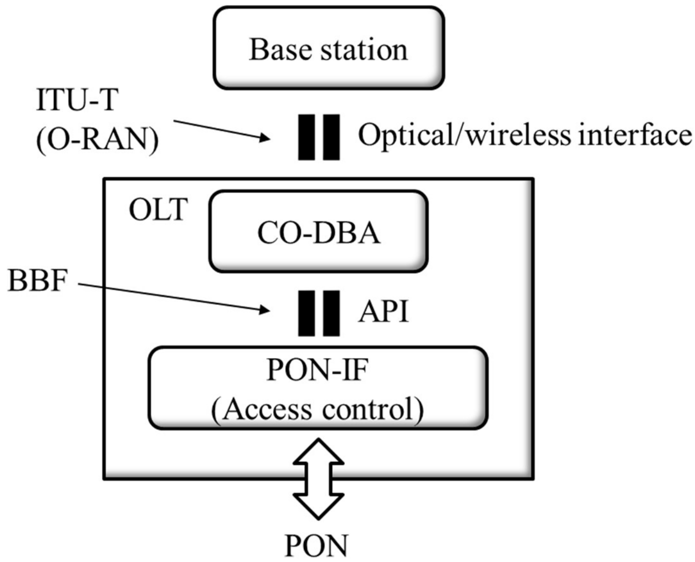


Figure 4.3 Standardization organization for the general structure of base station linked DBA and related interfaces.

4.4. Resource control method based on optical/wireless cooperation

A. Implementation method

To solve control delay problems, the author has proposed an optical/wireless cooperative resource control method.

The OLT converts uplink wireless scheduling information generated and transmitted by the MAC layer wireless uplink scheduler of the base station, i.e., the Resource Block (RB) allocation information for each mobile terminal (User Equipment: UE), into timing and rate in the PON section. Then, the OLT grants transmission permission to each ONU at the appropriate time, reducing control delays. The interface that notifies uplink wireless scheduling information from the base station to the OLT is called the optical/wireless cooperative resource control interface.

Figure 4.4 shows the internal configuration of the OLT that implements the optical/wireless resource control method. In this research, the author assumes the PON system as an EPON (Ethernet PON).

The cooperation control unit in Figure 4.4 includes an optical/wireless cooperation resource control function. The cooperative control unit consists of three functional blocks. A block that terminates the optical/wireless resource control interface extracts the transmission timing and wireless Protocol Data Unit (PDU) size for each UE and classifies them for each ONU (=each RU). A block that determines the uplink transmission request amount for each ONU in the PON link. A block that performs bandwidth allocation processing based on the uplink transmission timing and uplink transmission request amount for each ONU and gives transmission permission (grant) to each ONU via the MPMC (Multi-Point MAC Control) section of the PON card; this is Mobile DBA (M-DBA) block.

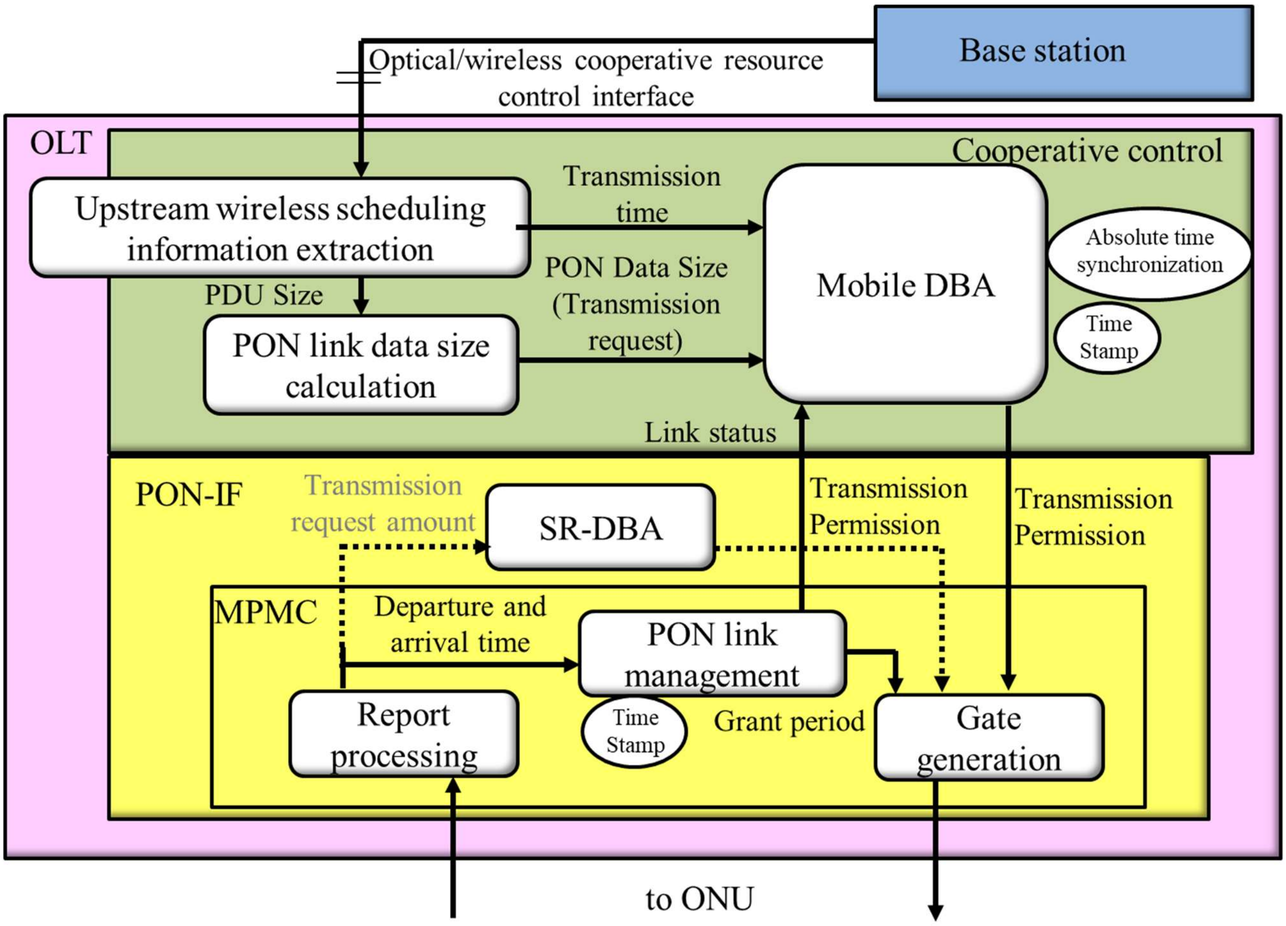


Figure 4.4 Functional configuration inside OLT that realizes optical/wireless resource control method

B. Wireless uplink data and cooperative control processing

Considering uplink wireless data transfer, the UE transmits uplink radio data at least 4 Transmit Time Interval (TTI) = 4 ms after the RU instructs the transmission timing (sends RB allocation information). Since the RU then transmits the uplink frame to the ONU, the OLT or Mobile DBA block can reduce the control delay in the TDM-

PON system by giving transmission permission to each ONU beforehand. In other words, the process of extraction, calculation, and M-DBA explained in the previous subsection can be performed within the time equivalent to 4TTI.

C. Operation sequence of the cooperation control unit and PON-IF

Figure 4.5 shows the sequence in which the PON-IF MPMC processing and the coordination control unit work together to establish a PON link and perform bandwidth allocation processing. Considering that the coordination control unit centrally manages bandwidth allocation control and the relationship between the startup timing of the Discovery window and uplink data from the UE, the architecture is adopted in which the ONU Discovery processing cycle as a part of processing sequences on PON-IF side is controlled by the coordination control unit as the master. Discovery processing itself is configured to use the PON-IF function. When the PON link is established, the PON-IF sends the RTT information of each ONU to the cooperation control unit in a Register#n message, and the cooperation control unit sends a transmission permission signal to each ONU (sends Normal Gate) based on the scheduling information from the base station and the above RTT information.

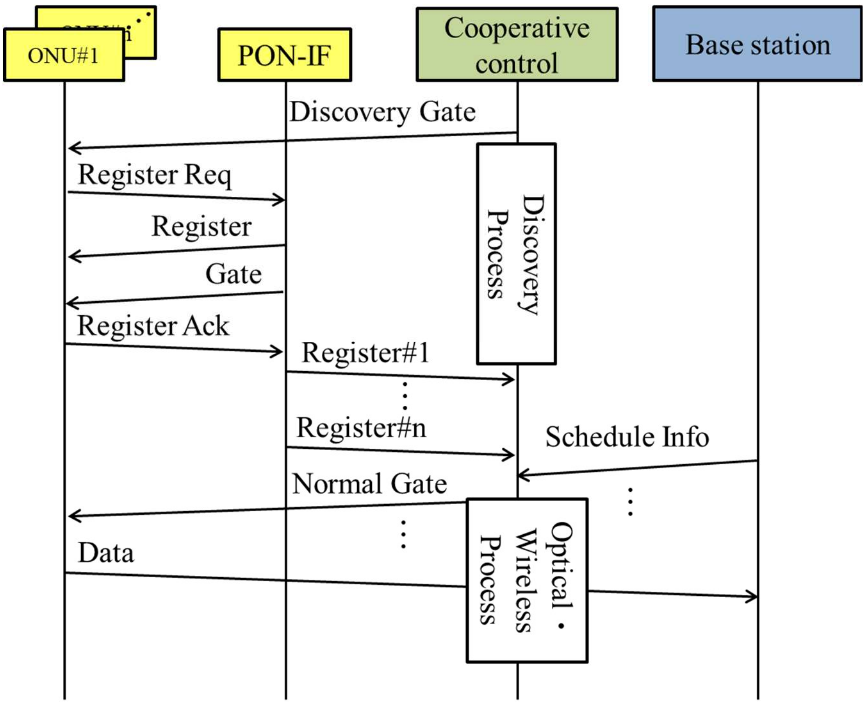
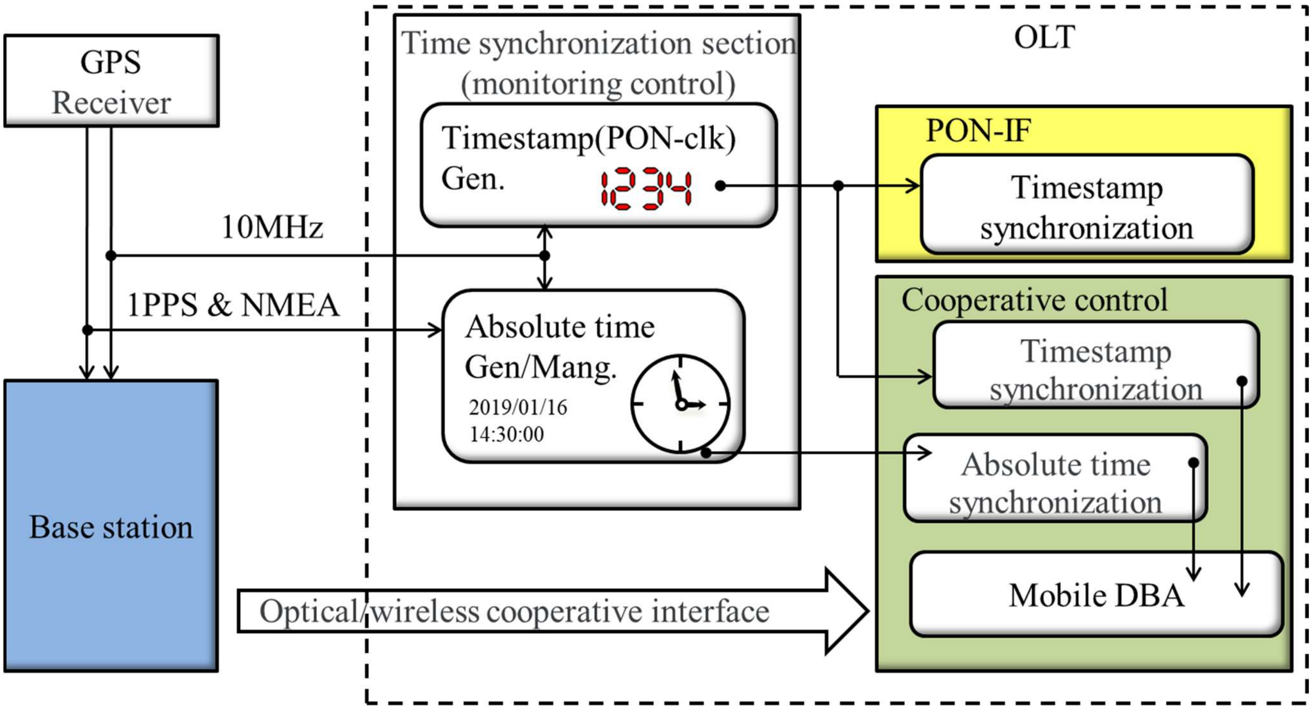


Figure 4.5 PON link/bandwidth allocation processing sequence considering optical/wireless cooperative control

D. Base station-OLT synchronization

With the above configuration and processing sequence, it is possible to use scheduling information from the base station to instruct the timing of permission for uplink data transmission to the RU/ONU in which each terminal is accommodated; there is a prerequisite that the times recognized on the PON (OLT) side match the time on the base station side. For this reason, the base station and OLT perform time synchronization using the Global Navigation Satellite System (GNSS), and the coordination control block converts the wireless transmission timing to EPON local time and allocates transmission in the PON section.

Figure 4.6 illustrates the mechanism for establishing time synchronization between the base station and OLT. A time synchronization section is implemented in the OLT's monitoring and control unit, which has functions to generate and manage PON Timestamp generation and absolute time (Year, Month, Day, Hour, Minute, and Second (in ns units)) based on time information from the GPS receiver. The PON-IF and Cooperative control unit each have a counter function for timestamp distribution and operate in synchronization with the timestamp generated by the Time synchronization section. The Cooperative control unit is also equipped with an absolute time reproduction function, which generates time information synchronized with the absolute time generated by the time synchronization unit and sends it to the Mobile DBA. Mobile DBA replaces the transmission timing information of each UE classified by ONU with absolute time using the procedure described in subsection A and further converts it into a PON Timestamp. Then, it is possible to calculate the StartTime of an uplink burst signal.



1PPS: 1 Pulse Per Second
NMEA: National Marine Electronics Association

Figure 4.6 Mechanism for establishing time synchronization between base station and OLT

The author investigates the control delay reduction effect when applying the proposed optical/wireless cooperative resource control method to a 10G-EPON system and the theoretical maximum transfer rate per DU in the PON section.

In the conventional method based on SR-DBA, the uplink frame transmission delay is 285 μs when the optical fiber length between OLT and ONU is 7 km, which does not meet the requirements of 5G MFH. However, the proposed method does not depend on the optical fiber length. The control delay is 39.3 μs, the uplink frame transmission delay time is 139.3 μs, and the maximum transfer rate is 1,832 Mbps over an optical fiber length of 20 km.

4.5. Implementation and evaluation of optical/wireless resource control method

This subsection summarizes the prototyping and evaluation results of the optical/wireless cooperative resource control method.

A. Implementation details

The author has prototyped a cooperative control card that implements the optical/wireless cooperative resource control method discussed in the previous subsection. The cooperative control card is equipped with an FPGA-SoC with a built-in processor, and the three functions of extraction, calculation, and Mobile DBA are realized using the FPGA circuit and software. The optical/wireless cooperative resource control interface and the PON-IF card interface are realized using separate FPGAs, and the FPGAs are connected using a serial interface with a transfer capacity of 10 Gbps. Figure 4.7 illustrates an overview of the cooperative control card and 10G-EPON OLT prototype device.

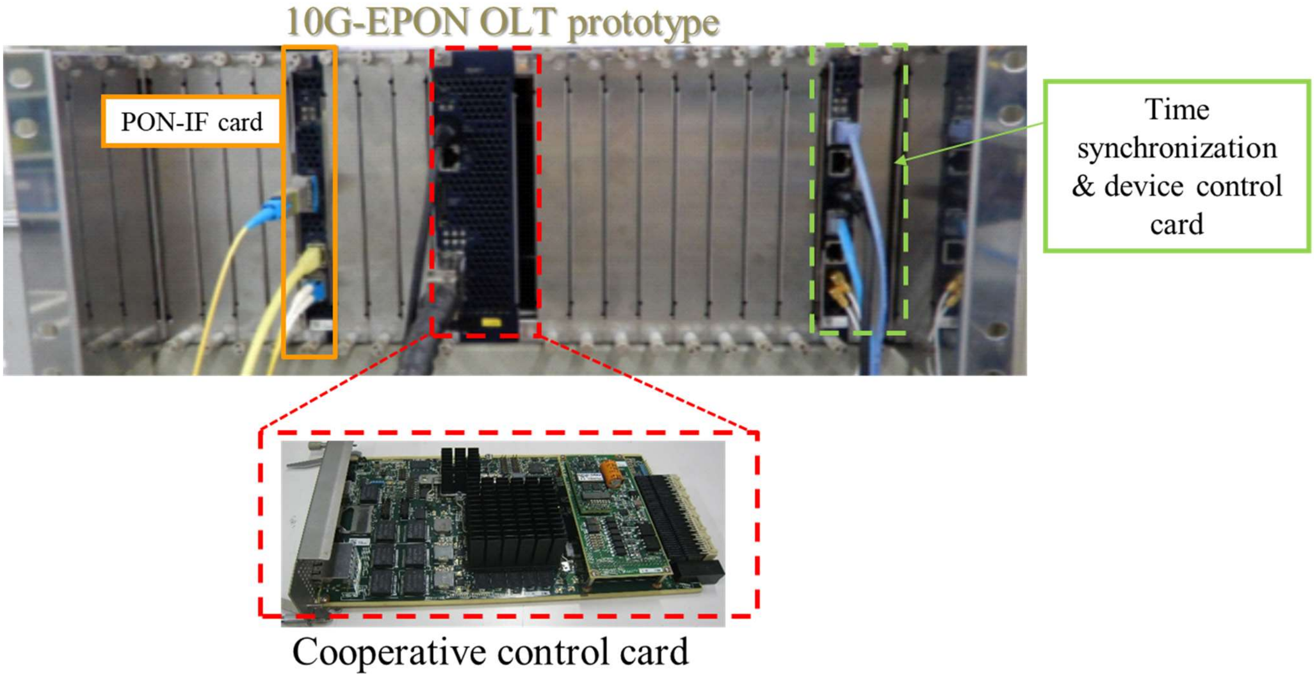


Figure 4.7 Cooperative control card and 10G-EPON OLT prototype device

B. Uplink frame transmission delay time evaluation

The author evaluates the uplink frame transmission delay time using the above prototype device. The evaluation system is illustrated in Figure 4.8.

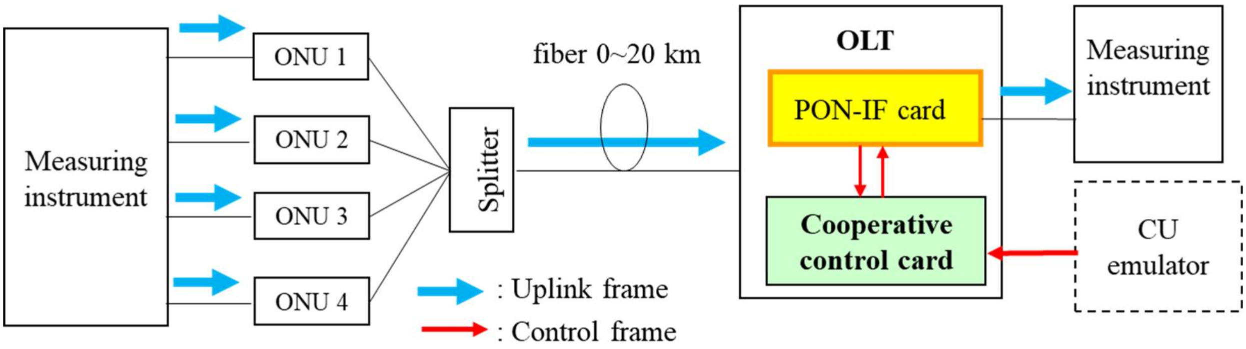


Figure 4.8 Uplink frame transmission delay time evaluation system

Figure 4.9 compares transmission delay times (maximum and minimum) with the conventional method. The conventional method does not meet the required delay time of 250 µs or less for 5G MFH, even if the optical fiber length is 0 km. In contrast, the proposed method satisfies the requirement regardless of the optical fiber length. The difference between the dashed line connecting the minimum value in the figure (the sum of optical fiber propagation delay, ONU processing delay, and OLT processing delay) and the dashed line connecting the maximum value indicates the control delay. The control delay is 40.1 µs±2% regardless of the optical fiber length.

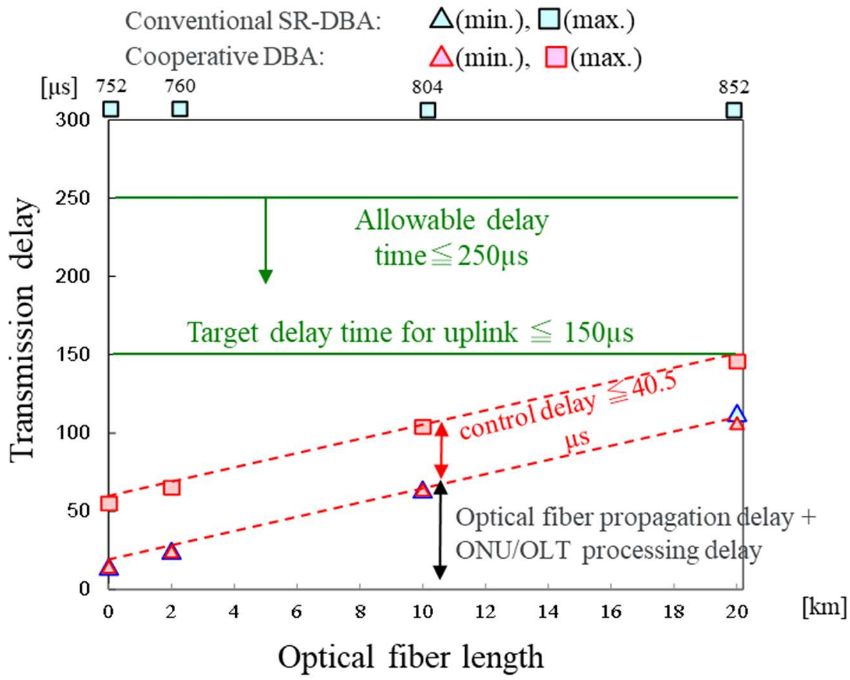


Figure 4.9 Uplink frame transmission delay time (Maximum minimum)

4.6. Conclusions

To realize 5G networks that require ultra-high speed and large capacity, high-density deployment of small cell base stations is considered, and the application of TDM-PON systems to MFH for such 5G wireless access is considered. The author has shown that the issue when applying TDM-PON to 5G MFH is uplink frame transmission latency and that the main factor is control delay. To address this issue, the author proposes an optical/wireless cooperative resource control method that can utilize the access control function of TDM-PON, which is widely used for FTTx, etc., and demonstrates its effectiveness in reducing control delays.

The author has produced a cooperative control card that implements the proposed optical/wireless cooperative resource control method, fabricated a prototype 10G-EPON system that implements this card, and measured the uplink frame transmission delay time. When the transmission permission period is set to 50 μs, the author has confirmed that the control delay could be reduced to 40.1 μs ± 2% over an optical fiber length of 0 to 20 km, meeting the required delay time of 250 μs or less for 5G MFH.

For further works, the remaining issues include verifying the cost impact of the time synchronization function; thus, the author will consider its practical application.

4.7. References

[22] 3GPP, 3GPP TR 38.801 V14.0.0, Mar. 2017.

[23] BBF, BBF TR403, Issue 1.0, Dec. 2018.

5. Research on abstracted resource control in wireless/wired integrated network

An Efficient Resource Allocation Using Resource Abstraction for Optical Access Networks for 5G-RAN

5.1. Introduction

Optical access networks based on PON (Passive Optical Network) have become widespread as platforms that can provide low-cost broadband access services, mainly for consumers. Thus, speed and capacity have driven the major technology trends in the evolution of optical access network systems.

However, in recent times, such communication systems have come to play a role as the infrastructure that connects not only consumers but also the systems used by various enterprises. Since the requirements placed on communication networks by enterprises are very diverse, the network connection durations and locations are expected to vary dynamically. In the vision for 5G [24], the systems of the various enterprises will use the required network as and when needed, and accommodating this with allocations based on fixed contracts is very inefficient. It is expected that new mechanisms will be applied to supervise the underlying network resources and provide end-to-end network resources using network slicing technology [2] on an application or user-centric basis.

With the above background, and assuming a suitable set of conditions, the establishment of a control method that enables efficient use of the communication resources, especially on the premise of application to mobile backhaul and fronthaul, is the motivation of this study. To achieve this purpose, it is necessary to study the control method, develop the control functions, and verify the improvement in utilization efficiency when applying the functions to optical access networks. However, these issues have not been resolved in earlier investigations.

In response to these circumstances, resource abstraction technology is here used as a control method that can be applied across various network resources. In addition, an abstracted-resource model with attributes selected for mobile fronthaul and a resource abstraction method introducing resource classification based on specific parameters are proposed. Furthermore, it is shown that the proposed model and method can shorten the resource allocation processing time, which greatly improves the network utilization efficiency when performing dynamic resource control.

This dissertation is organized as follows. In Subsection 5.2, the author investigates and reviews the achievements of earlier related work and clarifies the outstanding issues. Subsection 5.3 summarizes the technical requirements in access networks when providing diverse and flexible services, assuming their use by a range of enterprises. Subsection 5.4 clarifies the prerequisites for this research, which are the network architecture of the mobile fronthaul and backhaul using PON and control architecture for the network resources. Subsection 5.5 describes the abstracted-resource model and the resource abstraction method, which comprise the proposed method being investigated. Subsection 5.6 presents the study of the application of the proposed method. In Subsection 5.7, the resource allocation processing time is evaluated by simulation using the functions developed for the implementation study in Subsection 5.6. Finally, the author shows that the proposed approaches have the effect of shortening the allocation processing time.

5.2. Related work

The application of virtualization technologies such as SDN (Software Defined Networking) and NFV (Network Functions Virtualization) to the network infrastructure has been studied to accommodate a number of users with diverse network requirements on heterogeneous networks, each of which has different physical characteristics and functions. In a virtualized network, a logical network is deployed for each user by allocating the network's resources to correspond to the users' requirements.

For example, [25] & [26] proposed a resource allocation algorithm that accounts for the delay constraints, which many business verticals would require, and evaluates its processing time and cost analysis for network deployment plans for optical metro networks between Data Centers (DCs). The algorithm of [27], with the strategy of adding backup connectivity resources between wireless access points and DCs, shows a low blocking probability for requests based on availability as well as delay. The work in [28] evaluated multiple resource allocation algorithms in terms of the maximum bandwidth provided and the processing time for intra-data-center and inter-data-center networks. In [29], a resource allocation scheme is proposed to improve the transmission rate performance under a delay constraint as an optimization problem in sub-channel allocation and power control, adopting both linear approximation and stochastic approximation to reduce its high computational complexity.

Generally speaking, the computational complexity of such algorithms increases with the size of the target network, although they do improve the resource efficiency of the deployed network infrastructure. One key technique for dynamic resource allocation is abstraction. In [30], an orchestration architecture is proposed for heterogeneous optical transport networks that employ topology abstraction of each network domain and distributed path computation based on the IETF's ABNO (Application-Based Network Operations) architecture [31], while [32] & [33] demonstrate the dynamic provisioning of a logical network in sub-second time on each relevant testbed for mobile virtual backhaul network deployment over multilayer aggregation networks, and end-to-end resource allocation over multi-domain networks across core and long-reach PON access systems. Furthermore, the control architecture shown in [34], which is in line with the IETF's ACTN (Abstraction and Control of Traffic Engineered Networks) framework [35] and in which a common OpenROADM (Reconfigurable Optical Add/Drop Multiplexer) model [36], is used for both the physical devices and the abstracted network domains, is validated for abstracted multi-domain transport networks.

On the other hand, from abstraction, there arises a trade-off between the volume of information, processing, interaction, etc., and the control system's performance. For example, topology abstraction simplifies path searching but may lead to a suboptimal selection. In [37] & [38], the trade-off between efficiency (connection request blocking probability) and complexity (abstraction information update rate) is examined for multiple abstraction models with different degrees of abstraction. Table 5.1 shows a summary of the related work mentioned above.

Table 5.1 Summary of work related to this research.

	Control architecture for abstracting resources	Access network targeted	Abstraction model	Resource allocation time & efficiency evaluation
[25], [26]				□
[27]- [29]				□
[30]	□			
[32]	□			□
[33]		□		□
[34]	□		□	□
[37], [38]	□		□	□

Despite having been several significant investigations, no one has defined an abstracted-resource model for optical access networks and verified the resource efficiency when the abstracted resources are allocated. Therefore, the author has studied abstracted-resource modeling and an allocation method for improving the efficiency of optical access networks for application to 5G-RAN (Radio Access Network) [39], [40] and has confirmed their effectiveness by a simple evaluation of the allocation processing time [41].

In this article, based on our previous work, the parameters relevant to the resource allocation processing time are examined in detail, and the processing time is verified by simulation.

5.3. Challenges of an Access Network for Providing Varied and Flexible Services

In this subsection, the author addresses the issues with access networks that provide a wide variety of services and defines the requirements in terms of a network system. The types of data transferred to the network, the usage pattern of the network, the locations of use, etc., are the main variables.

A. Accommodation of varied application data and traffic

It is assumed that the access network will be used not only by Internet service consumers who place importance on high-speed, high-capacity transmission but also by users in various enterprises who use a range of devices and applications. In this study, enhanced Mobile Broadband (eMBB), massive Machine Type Communication (mMTC), and Ultra-Reliable and Low Latency Communications (URLLC) are assumed as typical types of traffic in 5G [24]. The author assumes a usage pattern in which these types are mixed, and users share a set of physical network resources.

B. Diversity of usage patterns

Assuming that users in a range of enterprises will use the access network, a user-centric or application-centric form of contract, in which they use it only at the required time and place, can be applied instead of the fixed type of contract used for conventional services such as Internet access. In such a usage pattern, it is very important to allocate network resources dynamically according to the status of the user or application in terms of efficient utilization of the overall network resources. Its importance will increase in the future since such usage is expected to increase.

C. Diversity of usage locations and connection locations

When the users of the network are diverse, it should be assumed that not only the types and usage patterns of the data traffic but also the number of points (terminals) connected to the network and variations in the parameters of the connected locations themselves will increase. Infrastructure sharing and expansion of the utilization of heterogeneous networks can be considered to deal with such a situation. As a measure to satisfy the user's requirements in any one place, it is necessary to have the commonality of the network resource management system for the various physical network resources.

The measure to solve the issues of an access network, that can provide a wide variety of services, consists of the three main elements, (1) network resource modeling, (2) dynamic resource allocation, and (3) sharing the resources abstracted from various physical resources. Figure 5.1 illustrates the relationship between the assumed requirements and the measures that should be taken to meet those requirements. In this figure, three requirements and the conditions (network characteristics/functions, usage patterns, physical network types) that arise from them, and the functional measures (1) network resource modeling, (2) dynamic resource allocation, and (3) sharing of the abstracted resources corresponding to those conditions, are described.

For Issue (1), the accommodation of varied application data and traffic, a resource allocation suitable for the use cases can be provided by broadly categorizing the combination of network characteristics and functions corresponding to the various requirements and preparing a resource model according to these categories. For Issue (2), the diversity of usage patterns and dynamic resource control is important so that resource allocation can be performed at high speed and in a limited area because of the increase in the variations in usage times and locations. For Issue (3), the diversity of usage locations and connection locations, since various usage locations and connection locations are assumed, the physical network resources are not uniform, which can be resolved by abstracting the resources and managing them in the form of a common communication resource.

An example showing the implementation of each measure is presented in Subsection 5.6 (see Figure 5.8). In this study, the author focuses on mobile fronthaul (MFH) and mobile backhaul (MBH) as access networks that make up 5G-RAN, examines the substance of the above problem-solving elements, and verifies their effects.

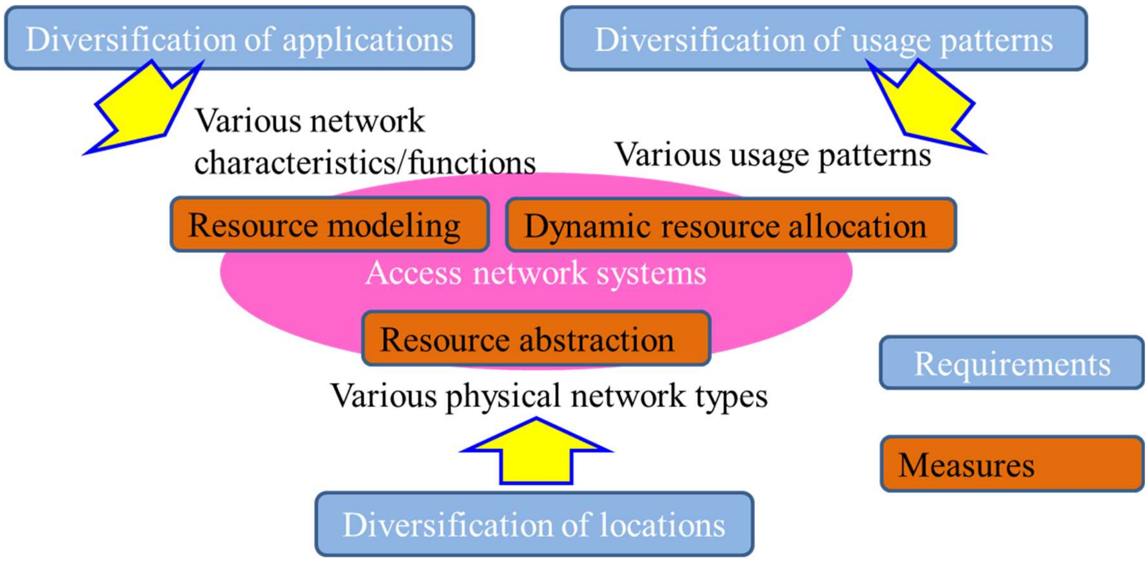


Figure 5.1 Network requirements, major conditions and measures to provide a wide variety of services

5.4. Flexible, Dynamic Control Architecture for MFH &MBH

Network slicing is known as a network management and control technology that flexibly supports the various network requirements and usage patterns described in the previous subsection and provides efficient operation using a single physical network resource. It is studied as a method for building end-to-end logical networks. A logical network constructed by this technology is called a slice, each slice being allocated resources to meet its own network requirements, and the network resources are so managed that isolation between the slices is established.

In the transport network for 5G, a configuration that adopts the Centralized-Radio Access Network (C-RAN) method to split out the base station functions and connect them hierarchically is considered an architecture for efficiently accommodating small cells arranged at high density. Figure 5.2 shows an example of a 5G transport network configuration. A C-RAN can be realized efficiently using a point-to-multipoint PON topology for the MFH, which is the network connecting the Central Unit (CU) to the Distributed Unit (DU). DU accommodates the User Equipment (UE) through the antenna.

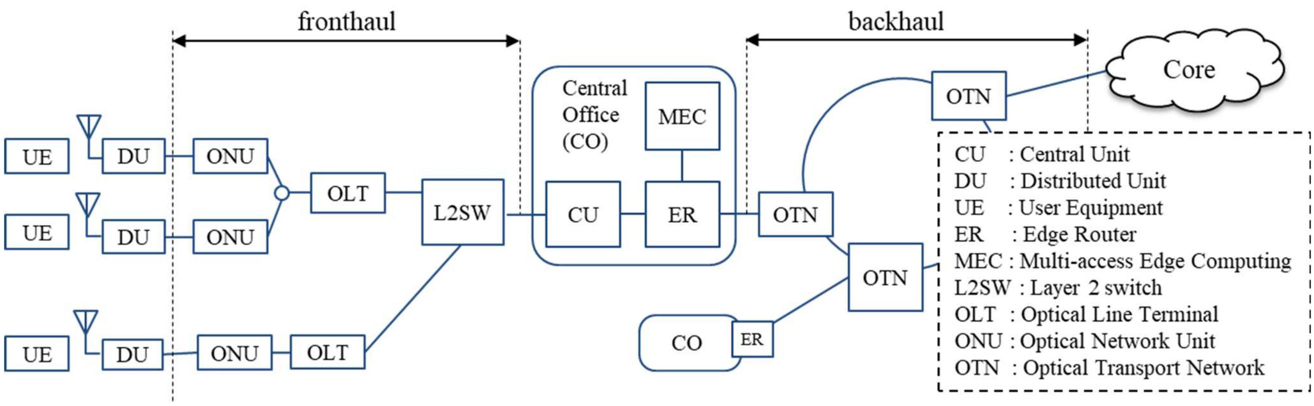


Figure 5.2 An example of a 5G transport network configuration

A control and management architecture suited to such a transport network configuration and slice construction is being studied by the ITU-T and others. Figure 5.3 illustrates the architecture adopted by ITU-T SG13 [42]. The Network Slice Support function part in the overall configuration shown on the right-hand side of the figure is divided into the SDN part, the NFV part, and the Other Infrastructure part, and the configuration of the SDN part is shown on the left-hand side of the figure. The optical access system focused on in this study belongs to the SDN part.

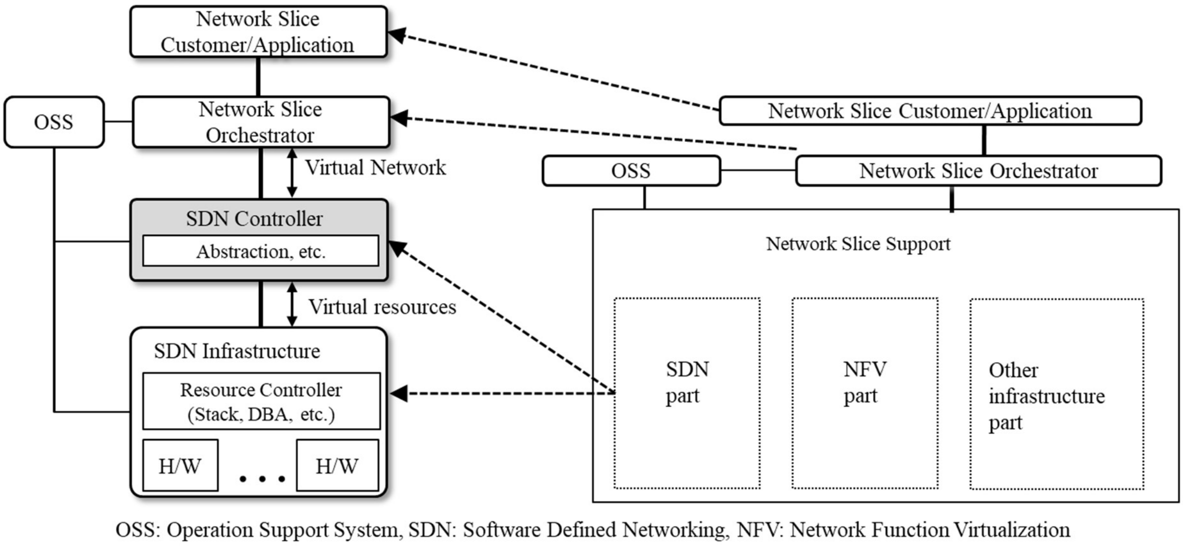


Figure 5.3 Slice control and management architecture (ITU-T Y.3151 [42])

An overview of an architecture that supports slice control and management is shown in Figure 5.4. As mentioned above, the PON is part of the SDN infrastructure, just as the L2 switch, edge router, and OTN are. They are all connected to and managed by the SDN controller. It is assumed that the ONUs are controlled and managed via the OLTs, and DUs are controlled and managed via the CU.

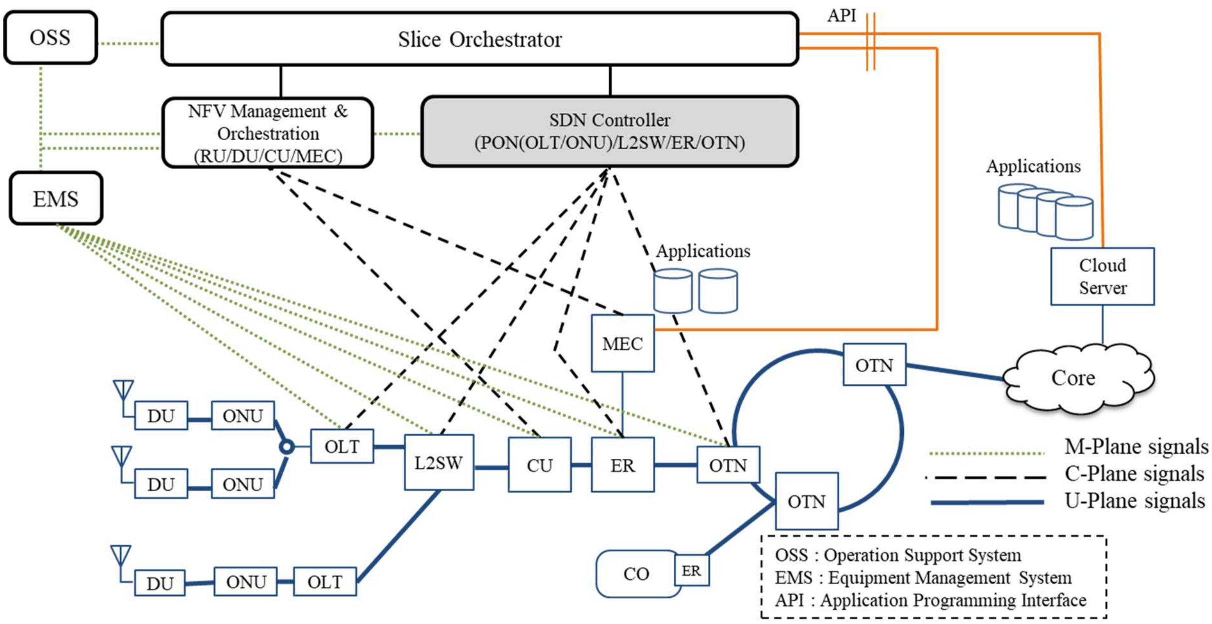


Figure 5.4 Network architecture supporting slice control and management

5.5. Proposal for abstracted-resource model and resource abstraction method

In this subsection, based on the slice control management architecture presented in Subsection 5.4, the proposed abstracted-resource model and abstraction method are described. There are two main types of abstracted-resource models: (i) a physical path model that hides the nodes and links of the target network and summarizes their resources for every physical path [43], and (ii) a virtual link model that abstracts the whole network topology and manages the resources for each virtual link, each of which links virtually to the exterior I/Os of the boundary nodes between the target and external network, [37], [38], & [44]. The author focuses on the latency values of the slice requirements, typically taking discrete rather than continuous values depending on the use case. Then, based on the virtual link abstractions, I propose a resource model that can manage the resource information at the physical path level by classifying the physical path resources in terms of their latency values.

A. Abstracted-resource model for 5G-RAN

1) Analysis of network performance requirements for 5G services

Typical use cases for 5G are eMBB, URLLC, and mMTC, as mentioned in Subsection 5.3, and target values of the transmission capacity, transfer delay time, and number of terminals as primary capabilities of 5G are listed in the IMT Vision document [24]. In terms of the capabilities described in that document, I extract the performance requirements for MFH and MBH applications. As a result of that extraction, the main performance requirements for the wired networks are seen to be latency, data rate, and availability. In the case of actual application to various 5G services, it is necessary to define these performance requirements as abstracted resources and select and allocate them according to the combination of performance requirements required by the particular application.

2) Proposed abstracted-resource modeling method and system configuration

The network domains targeted by this study are MFH and MBH. For fronthaul, I assume a PON-type transport network as it has cost advantages for accommodating DUs in the high-density cell environment expected in the 5G era. Therefore, MFH in this study refers to the network between the CU and DUs. On the other hand, MBH in this study refers to the network between the core network and the CU. This subsection describes a proposal for an abstracted-resource model assuming the CU and DUs are connected by a PON system.

Figure 5.5 shows the abstracted-resource model for MFH with a PON configuration based on the overall architecture shown in Figure 5.2. The nodes connected to the target network hosts are extracted. The hosts on the core network side high-level hosts (HH) and the hosts on the user equipment side low-level hosts (LH) are also extracted. For MFH, the HH is the CU, and the LHs are the DUs. An HH and LH pair is called a “host pair.” For the next step, the physical resource information, such as the node, link, and topology information of the host pairs is concealed, and the resulting connection information between the host pairs is defined in the form of abstract paths. Each host pair has one abstract path. In the RAN in Figure 5.5, the two host pairs CU1/DU1 and CU1/DU2 are represented by abstract paths without reference to any physical nodes or links. In this way, it is not necessary to be aware of the node types, such as OLT and ONU. In addition, each abstract path has an abstract path resource. The author has defined the following three parameters for the abstract path resources: (a) "latency class," (b) maximum data rate, and (c) maximum availability. Then, the author address the maximum data rate (b) and the maximum availability (c) for each of several "latency classes." Here, the "latency class" is a classification based on a predefined latency threshold. With the introduction of latency classes, it is possible to represent abstract path resources for the maximum data rate and availability for each latency class. The classification of physical paths (p-paths) by latency class enables rapid searching of p-paths satisfying the slice request. In addition, representing the maximum data rate and the maximum availability for each latency class enables rapid determination that a resource satisfying the slice request cannot be allocated in a case where the required data rate and availability are better than the maximum data rate and availability for that latency class. Such rapid determination makes it possible to get started quickly on the next action (e.g., processing the next slice request). Using the above definition, the proposed abstracted resource can be expressed as a group of abstract paths with multiple resource attributes.

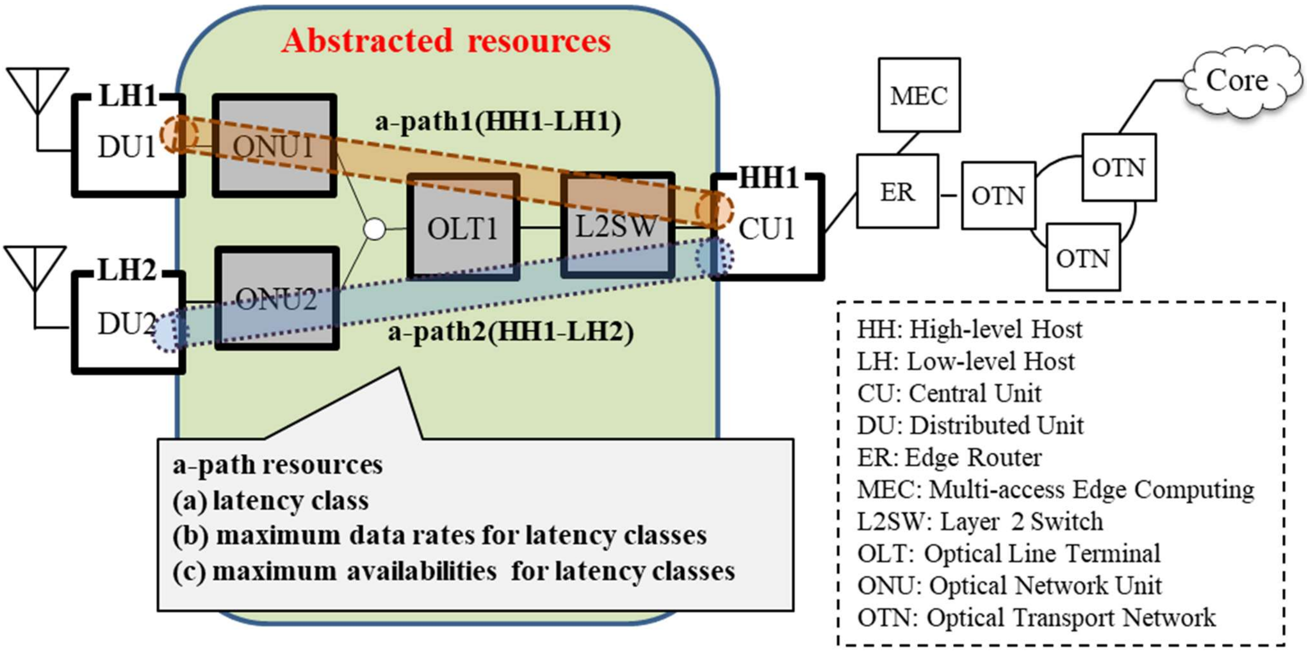


Figure 5.5 Abstracted-resource model for MFH with PON configuration

In this study, the types of parameters and the classification of the values that represent the abstract path resources are defined in consideration of the requirements for MFH and MBH; however, by changing the resources to be abstracted and the parameter definitions, it is easy to generate a model suitable for other networks' requirements.

The above abstracted-resource representation makes it easier for the slice orchestrator and network operators to manage and control the physical resources to meet their performance requirements because they do not need to know the details of the physical resources. Furthermore, by preparing models for MFH, MBH, etc., according to the state of the physical resources, it is possible to find resources that meet the requirements in a short time. Therefore, it is possible to construct slices quickly and flexibly.

B. Resource abstraction method for a variety of physical networks

In this subsection, the proposed abstracted resource generation method is illustrated using an example of an MFH network. Figure 5.6 shows an example of a physical resource configuration for MFH. The network topology of the MFH is based on the architecture shown in Figure 5.2.

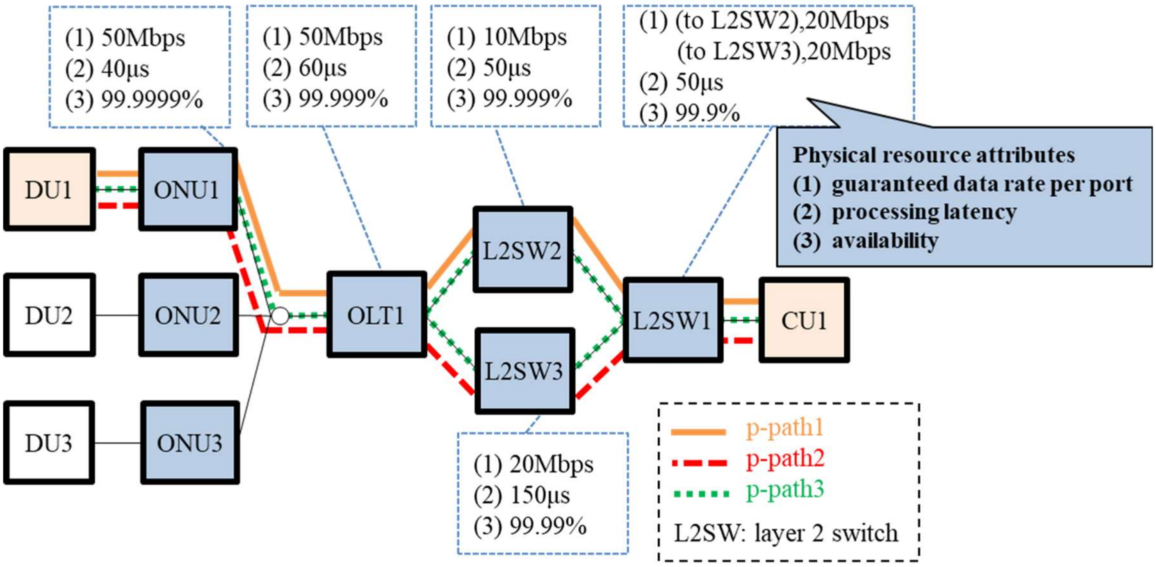


Figure 5.6 Example of physical resources for MFH

Each L2SW, OLT, or ONU node has the following parameters as physical resource attributes: (1) guaranteed data rate per port, (2) processing latency, and (3) availability (note that only the downlink parameters are shown in Figure 5.6). The abstracted resources are created via the four steps in Figure 5.7, which shows the flowchart for abstracted resource generation.

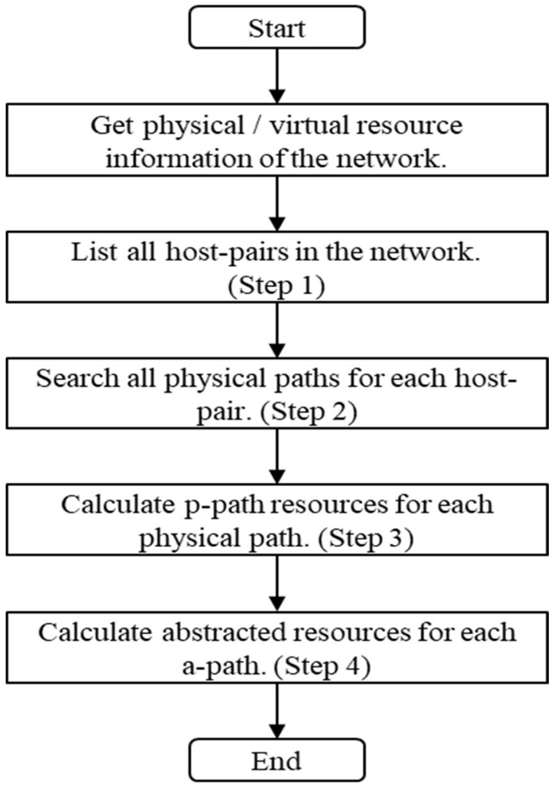


Figure 5.7 Flowchart for generating abstracted resources

The idea behind the abstraction in Step 4 is that the latency class is set in consideration of the application to MFH (in this case) and that the maximum values of the main parameters (data rate and availability) are selected to accelerate the abstracted-resource allocation process.

Step 1: Create a list of all the host pairs

Create a list of all the host pairs that are combinations of HH and LH in the target network. In the example shown, CU1 is assigned as HH, and DU1, DU2, and DU3 are assigned as LH. There are thus three host pairs: CU1 and DU1 (host pair 1), CU1 and DU2 (host pair 2), and CU1 and DU3 (host pair 3).

Step 2: Find all the physical paths

Find all the physical paths (p-paths) between the HH and LH for each host pair. Identify each path individually as a single path if the host pair can take multiple paths. A serial path is called a single path, and a parallel path is called a redundant path. Redundant paths allow the system to maximize the data rate and availability. For example, host pair 1, shown in Figure 5.6, has three p-paths. P-path3 contains the following nodes: CU1-L2SW1- (L2SW2 and L2SW3)-OLT1-ONU1-DU1.

Step 3: Calculate the p-path resources

Calculate the three parameters of each p-path as their p-path resources. A p-path resource is a collection of the physical resource attributes of the nodes that make up each p-path.

(i) Data rate: Minimum guaranteed rate between all nodes on the p-path

(ii) Latency: The total latency obtained by summing all the latencies of the nodes and links on the p-path.

(iii) Availability: Values calculated using Equation (1) for serial cases and Equation (2) for parallel cases, respectively. When the p-path is composed of a combination of nodes connected in serial and nodes connected in parallel, the availability of the p-path is calculated by dividing it into serial parts and parallel parts.

$$\text{availability} = \Pi_{\text{node i} \in \text{p-path}} \text{availability\_node i} \quad (1)$$

$$\text{availability} = 1 - \Pi_{\text{node i} \in \text{p-path}} (1 - \text{availability\_node i}) \quad (2)$$

Table 5.2 lists the results of calculating the resources of each p-path belonging to host pair 1 using the guaranteed data rate, latency, and availability values of each node shown in Figure 5.6.

Table 5.2 The p-path resources for host pair1

	Data rate [Mbps]	Latency [μs]	Availability [%]
p-path1	10	200	99.8979
p-path2	20	300	99.8889
p-path3	30	300	99.8989

Step 4: Calculate the a-path resources

Calculate the abstract path (a-path) resources as follows.

Latency class: Each p-path is classified based on each of the latency thresholds for the latency class in the host pair.

Maximum data rate per latency class: The maximum data rate among all the p-paths classified in each latency class in the host pair.

Maximum availability by latency class: The highest availability of all p-paths classified in each latency class in the host pair.

Each latency class in the host pair contains all the p-paths with sub-threshold latency. In this example, 250 μs is used as the threshold value. This is because it is one of the most essential delay values for the MFH functional split option specified in 3GPP [45]. Assuming that the two resulting latency classes are the 250 μs class and the unconstrained class, the resource calculation results for host pair 1 are listed in Table 5.3.

Table 5.3 The a-path resources for host pair1

Latency lass	Maximum data rate [Mbps]	Maximum availability [%]
250μs class	10	99.8979
unconstrained class	30	99.8989

By expressing the a-path resources using the characteristics of the p-path resources, it is possible to hide the complexity of the network by the above method of abstracting the various physical resources.

5.6. Study of the implementation of the resource allocation management method for slice construction

In this subsection, based on the slice control management architecture explained in Subsection 5.4, the proposed abstracted-resource model and abstraction method are described.

A. Functional configuration of SDN controller

Figure 5.8 shows the proposed functional configuration of an SDN controller based on the high-level architecture of Figure 5.3. The Domain Orchestrator (D-ORCH) receives a slice request from the Slice Orchestrator and converts it into a request for each domain. The Slice Element Controller (SEC) manages the abstracted resources for each host pair in the domain. When the SEC receives a slice request from the D-ORCH, the SEC evaluates whether there are enough abstracted resources for the request and, if there are, allocates the abstracted resources. The Physical Resource Controller (PRC) collects information from the SDN Infrastructure, monitors the physical resources, converts them into abstracted resources, and supplies them to the SEC as abstracted-resource information. In addition, after the SEC allocates an abstracted resource, it processes the allocation of the physical resources corresponding to the abstracted resource and notifies the SEC of the results as either success or failure. The PRC can handle not only physically separated resources but also logically separated resources as a virtual resource in the same manner as a physical resource. The SEC and PRC have the essential functions of (1) network resource modeling, (2) dynamic resource allocation, and (3) resource abstraction, described in Subsection 5.3.

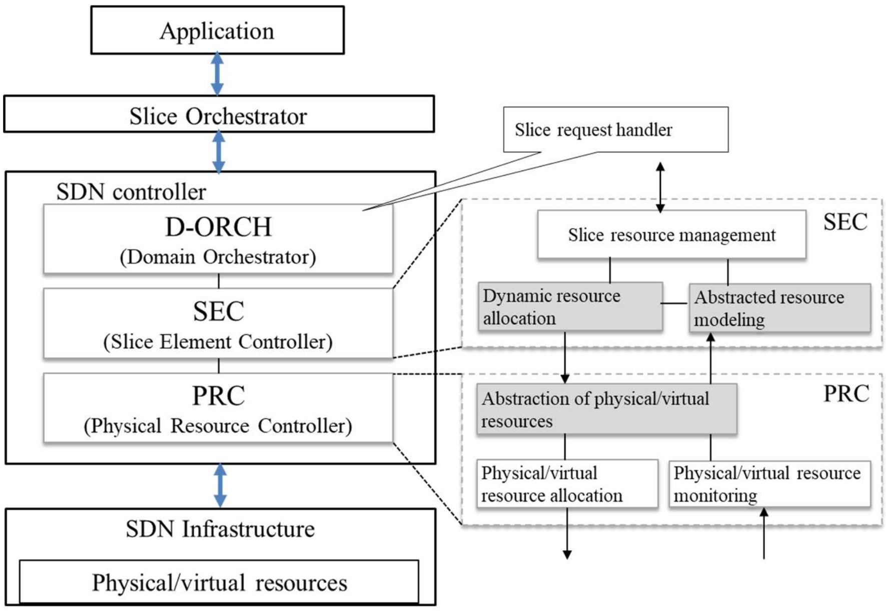


Figure 5.8 Functional configuration of the proposed SDN controller

B. Processing sequence

The author has proposed a slice generation method that uses abstracted resources to allocate resources based on a slice request from the slice orchestrator and network operator. A specific example is given in earlier work [39]. For ease of explanation of the proposed resource allocation method, Figure 5.9 shows the resource allocation processing flowchart in the case of a slice request consisting of only one host pair. As shown in Figure 5.9, the judgement using the a-path resources (S1) is executed before the judgement using the p-path resources (S4). When there are many candidate p-paths, it can take a long time to complete judging in S4 whether a p-path satisfying the slice request exists. This is because the p-paths are examined one by one in S4. In particular, a result that a p-path satisfying the slice request does not exist (the resource allocation has failed) cannot be given until all the p-paths have been examined. The a-path resources represent the maximum performance values of the p-path resources. Therefore, it is possible to report that the resource allocation will fail by examining the a-path resources in S1.

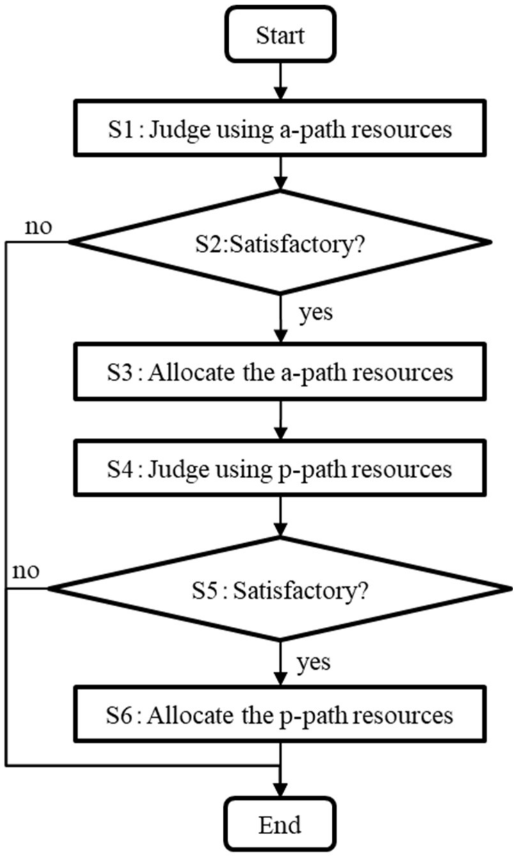


Figure 5.9 Resource allocation flowchart

5.7. Evaluation of processing time in the resource allocation function

The resource utilization efficiency associated with network resource sharing and slicing is improved by dynamic allocation control [46]. It is clear that the shorter the allocation processing time, the better the performance in terms of utilization efficiency.

In this subsection, it is shown that by introducing the abstracted-resource model described in Section 5.5, the processing time for resource management and allocation can be reduced compared to the processing time for management and allocation using physical resources.

In the author’s earlier work [39], [40], [41], the quantities of physical paths and physical path resources are set virtually without assuming a specific network topology (nodes, links, and their connectivity) and its attributes of latency, bandwidth, and the availability of each node and link. In the current investigation, the verification is performed with a concrete network model assumed.

Figure 5.10 illustrates the network topology used for the evaluation. It is assumed that PON is used as the MFH to accommodate a high density of DUs and that a multi-ring network with network nodes is used for aggregating the PONs and connecting to the CUs. Several DUs can be accommodated by branching the PON. A series of lines connecting each node in each host pair represents a physical path. In the PON area, four physical paths can be used per ONU, assuming the use of multiple logical links. Under this assumption, for each host pair, the maximum number of physical paths between the CU as HH and the DU as LH is 112, excluding any redundant paths.

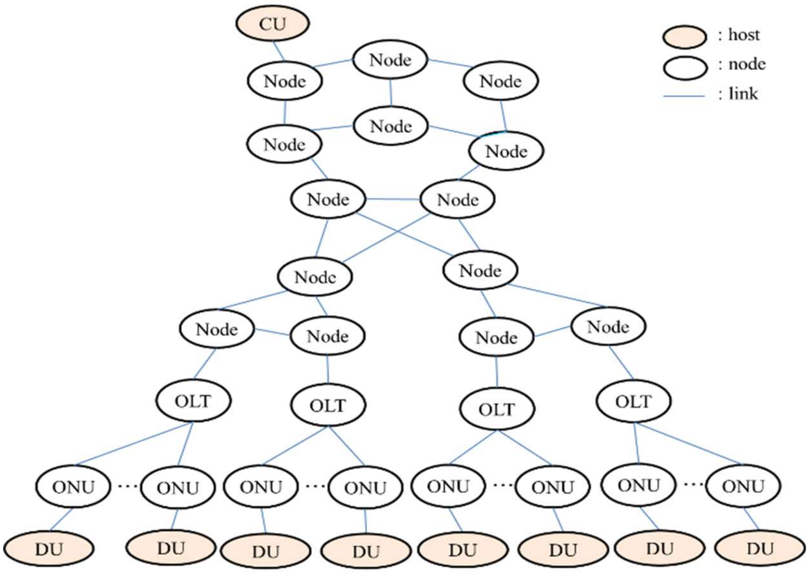


Figure 5.10　Network topology used for the evaluation

For the evaluation, the author develops the SEC and PRC functions based on the controller configuration described in Subsection 5.6 and evaluates by simulation, including these functions. The parameters for the evaluation are the number of physical paths and the latency, bandwidth, and availability of the physical paths. As a specific parameter range, the values given below are used, assuming the scale of the MFH network to be accommodated for typical 5G base stations. Since this verification targets the MFH section, it does not consider radio-specific characteristics such as fading and shadowing.

・Number of physical paths (per host pair): 28, 56, 84, 112

・Physical path resource: Derived from node and link attributes

(node attributes: data rate, latency, availability)

(link attribute: latency)

(i) Data rate: 500 Mbps/link for PON area, 100 Mbps/link for Nodes

(ii) Latency: 250, 500, 750, 1000 us for PON uplink,

250 us for PON downstream, 10 us for a Node

(iii) Availability: 99.9% for PON and all Nodes

Figure 5.11 shows the configuration of the evaluation system by simulation. As a form of evaluation by simulation, a series of processes for extracting and abstracting the physical paths based on the network topology are executed on a server, and the processing times for allocating resources by the SEC and the PRC are recorded by logging.

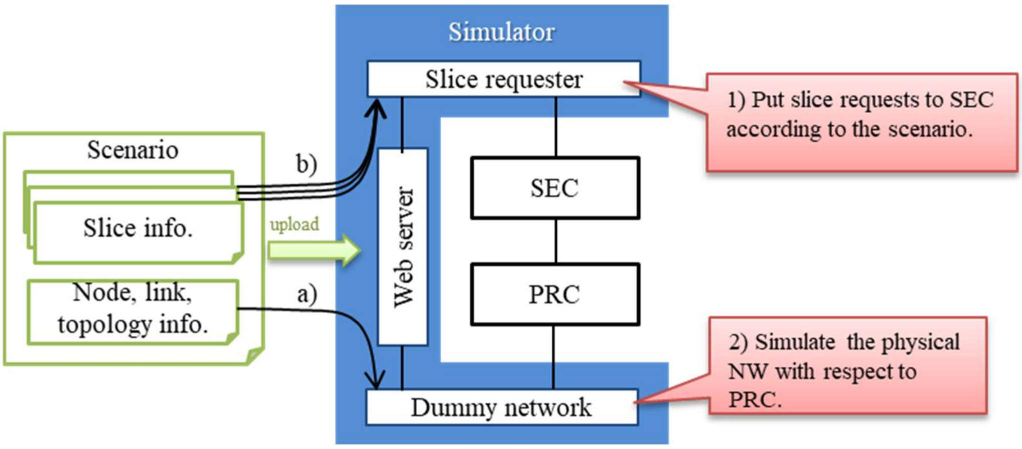


Figure 5.11 Evaluation system configuration diagram

Table 5.4 lists the salient specifications of the server used for the simulation, developing and running the SEC and PRC functions, and implementing and running the SDN controller function.

Table 5.4 Specifications of Simulation Server

Item	Specification
CPU	Intel® Core™ i5-8500CPU
Clock frequency	3.00 GHz
Cache	9 MB
Bus speed	8 GT/s
Memory size	32 GB

To verify the effectiveness of the proposed method, the author compares the resource allocation processing time in the proposed method with a comparison method. In this evaluation, the resource allocation process in Figure 5.9 is executed every time a slice request is received. The number of host pairs per slice request is one. The difference between the proposed method and the comparison method is whether or not to judge using a-path resources. For this evaluation, the resource allocation process of the proposed method is defined as the steps from S1 to S6 in Figure 5.9, and the time taken for this process is measured. The number of latency classes is set to four, and the latency threshold values are set to 900μs, 1200μs and 1500μs. For these values, it is assumed that the bandwidth allocation cycle of the PON should be 250μs as specified in 3GPP as the minimum latency in an MFH and that there are four latency cycle types (1-fold, 2-fold, 3-fold and 4-fold based on 250μs), in addition to taking into account the latency in the Nodes and Links. The resource allocation process of the comparison method is defined as the steps from S4 to S6 in Figure 5.9. However, if the resource allocation process has already been completed up to S4, the subsequent steps of the slice request process are not executed. For this reason, measurement of the time taken by the comparison method cannot be made in that case. Therefore, if the resource allocation process has been completed up to S4, the resource allocation processing time of the comparison method is estimated as the pre-measured time taken to evaluate all the p-paths.

For the simulation conditions, the relationships between the network resources and the required resources held in the slice requirement are variable parameters. For the required resources in a host pair, there are 4 levels within each key parameter of latency, data rate, and availability, as shown in Table 5.5, Table 5.6, Table 5.7, and Table 5.8. For the simulation, there are 4 cases with variable probabilities of the levels, as shown in Table 5.8.

Table 5.5 Simulation parameters of required levels (Latency)

Item	Level 1	Level 2	Level 3	Level 4
Latency[□s]	600	900	1200	1500

Table 5.6 Simulation parameters of required levels (Data rate)

Item	Level 1	Level 2	Level 3	Level 4
Data rate [Mbps]	40	30	20	10

Table 5.7 Simulation parameters of required levels (Availability)

Item	Level 1	Level 2	Level 3	Level 4
Availability [%]	99.5	99.3	99.1	98.9

Table 5.8 Simulation cases by required level combination

Case (condition)	A	B	C	D
Probability of level 1 for each parameter [%]	70	50	25	0
Probability of level 2 for each parameter [%]	10	15	25	0
Probability of level 3 for each parameter [%]	10	15	25	0
Probability of level 4 for each parameter [%]	10	20	25	100

Figure 5.12, Figure 5.13, Figure 5.14, and Figure 5.15 show the relationship between the allocation processing time and the number of physical paths in cases A, B, C, and D. Each value of processing time is averaged over 30 slice requests. The vertical bar for each plot represents the standard deviation of the allocation processing time in 30 slice request trials.

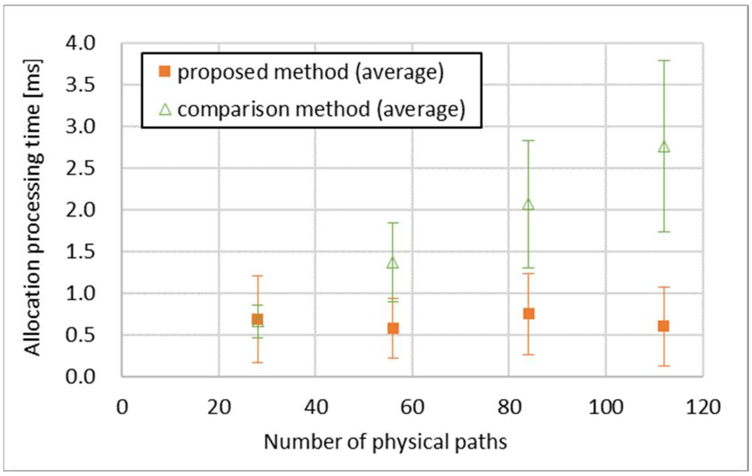


Figure 5.12 Resource Allocation Processing Time (Case A)

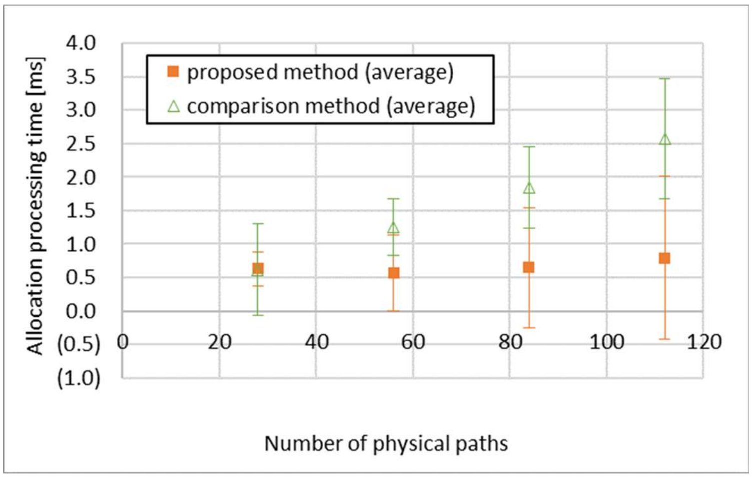


Figure 5.13 Resource Allocation Processing Time (Case B)

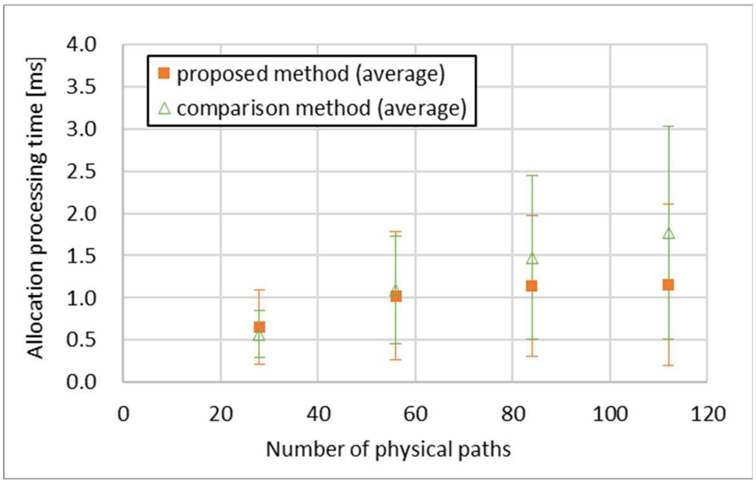


Figure 5.14 Resource Allocation Processing Time (Case C)

From the results for cases A, B, and C, it is confirmed that the allocation processing time with the comparison method is longer, especially as the number of physical paths increases. On the other hand, the processing time with the abstracted-resource model is almost constant regardless of the number of physical paths. In particular, when many slice requests are judged as failures, such as in Case A, it is confirmed that the proposed method effectively reduces the allocation processing time compared to the comparison method.

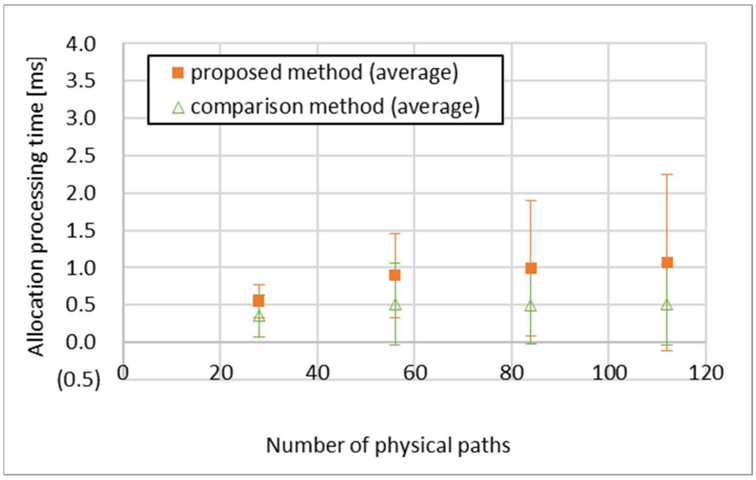


Figure 5.15 Resource Allocation Processing Time (Case D)

However, there are some cases in which the processing time of the proposed method is longer, such as Case D. In such cases, the required resources are nevertheless found rapidly by both the proposed method and the comparison method. Figure 5.16 shows the concrete processing time characteristics of the abstract path allocation. This figure indicates that the time taken for a-path allocation processing is always about 0.5 ms. An important factor affecting the processing time of the proposed method is the latency class configuration. The more latency classes are added, the more the volume of information increases, so the processing time increases. It is important to set appropriate latency thresholds and number of latency classes considering the required latency for the services concerned. In addition, this value is obtained with a server with the specification shown in Table 5.4, so it may vary depending on the server specification. It may also vary depending on the implementation of the proposed method. The concrete design needs to be optimized for the network scale and the specification of the server.

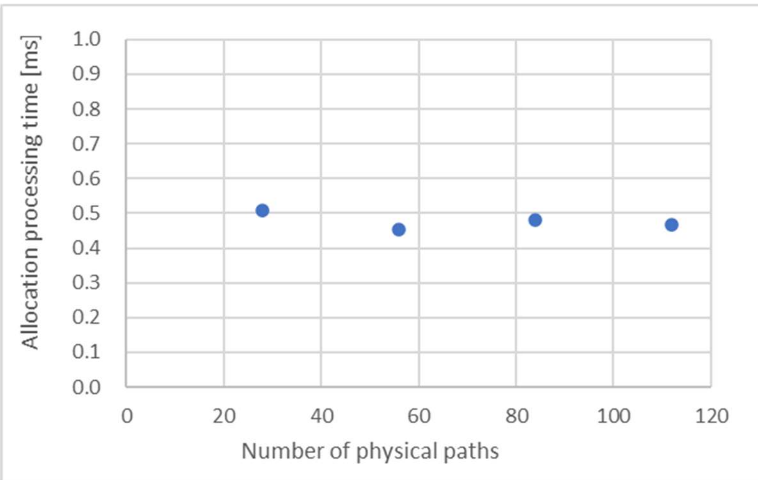


Figure 5.16 A-path Allocation Processing Time

The IEEE stipulates a latency of 10 ms for the control plane [47]. Although the processing time of the proposed method does vary, falls within the latency stipulated by the IEEE. It can be assumed that resource control at the abstraction layer eases the design of the control functionalities because its processing time appears stable. Therefore, the effectiveness of the abstracted-resource models and the abstraction methods of the proposed method is proven.

5.8. Conclusions

For applying optical access networks to communication systems that dynamically provide a wide variety of services, the author has proposed novel methods to improve the utilization efficiency of the network resources and shorten the resource allocation processing time. The author has studied the implementation of the proposed method and developed software prototypes of functions, including resource abstraction and allocation, based on the results of the study. The author has evaluated the method’s performance by a simulation incorporating those functions. This evaluation compares the abstraction layer and physical layer methods of resource allocation in terms of the processing time.

For the evaluation by simulation, a topology consisting of concrete nodes and links simulating an access network whose scale mirrored that of a typical MFH has been established. The series of processes for extracting and abstracting physical paths, based on this network topology, has been evaluated on a computer in the form of a server with a specification appropriate for implementing and running the SDN controller function.

This simulation has revealed that the allocation processing time of the physical layer model increases with the number of physical paths, while the processing time at the abstraction layer is stable regardless of the number of physical paths. These results show that the proposed method is suitable for network systems that support dynamic resource control. The author has also obtained some criteria for designing the controller performance under the condition of the set-up time and the number of services to be supported.

5.9. References

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6. Research on resource control responding to dynamic changes in application requirements

6.1. A user-level traffic control function for interworking between optical access and 5G mobile networks

A. Introduction

The deployment of the fifth generation (5G) mobile networks has attracted considerable research attention worldwide. Features of 5G networks have been specified in the International Mobile Telecommunications-2020 (ITU IMT-2020 standard), e.g., [48] and [49]. As characterized in [50], 5G involves new requirements for massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC) for the operation of IoT services, in addition to traditional mobile broadband (MBB). Hence, it seems reasonable that optical access networks based on passive optical network (PON) technologies should perform aggregation among cells of 5G mobile networks [51] in addition to legacy usages, e.g., fiber-to-the-home and fiber-to-the-building (FTTH/FTTB). Therefore, control of uplink traffic appears to be an imperative issue because services in 5G mobile networks described in [50] expect symmetric or uplink priority transmission capacity.

5G mobile networks and optical access networks have been deployed independently. In this study, the author proposes a bandwidth allocation scheme for traffic flows over these networks, focusing on uplink traffic. The proposed scheme is implemented based on a linear regression model using a real-time traffic monitor.

B. Proposed method

Two major multiplexing technologies are used for optical access networks, including time-division multiplexing (TDM) [1] and wavelength division multiplexing (WDM) [52]. TDM technology uses a fixed wavelength for the uplink, as the appropriate uplink bandwidth is allocated to each optical network unit (ONU) via dynamic bandwidth allocation (DBA) [1]. Recently, WDM technologies have been applied to optical access networks based on passive optical networking (PON) technologies [1]. In this case, because ONUs can be connected to an optical line terminal (OLT) transparency, bottleneck points are not recognized.

Network configurations of 5G mobile networks and optical access networks include several options, such as front- and backhaul options in [51] and [53], respectively. When TDM-PON [1] is applied to optical access networks, optimization of the uplink is performed by DBA. In contrast, when WDM-PON [52] is applied, traffic from each ONU is generated asynchronously and multiplexed inside the OLT, which depends on the buffer performance in the OLT.

In the next subsection, the author applies WDM-PON to optical access networks and proposes a new bandwidth allocation scheme to accommodate 5G traffic. An example is shown in Figure 6.1. In this figure, several small cells are deployed and aggregated by WDM-PON.

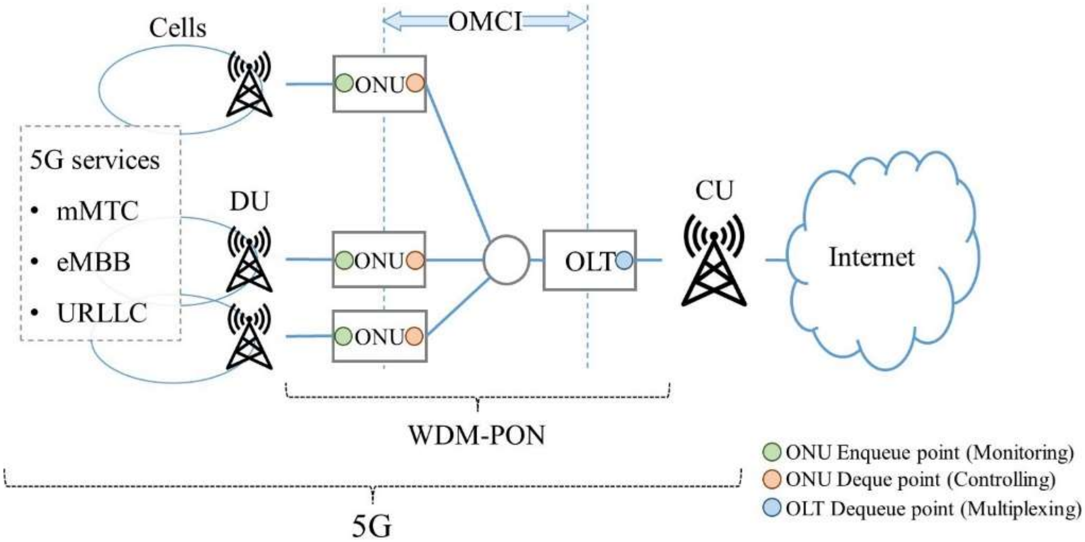


Figure 6.1 Overview of the network configuration

Incoming traffic is monitored at ingress points in the optical access network, as shown in Figure 6.1. Then, information on incoming traffic is transferred to egress points in the optical access network through a management channel, e.g., an extension of the ONU management control interface (OMCI) standardized in the International Telecommunications Union Telecommunication Standardization Sector (ITU-T) [54]. Traffic control focusing on bandwidth allocation is invoked at the egress point of each ONU.

C. Implementation of the traffic control function

The traffic control function is implemented as shown in Figure 6.2(a). This function consists of traffic monitoring and bandwidth allocation parts.

In the traffic monitoring part, an ONU includes Yet Another Flowmeter (YAF) as a tool for traffic monitoring adhering to the IP Flow Information Export (IPFIX) protocol [55]. YAF monitors the incoming traffic at ONUs and forwards the traffic data to a tool that aligns traffic information, called Silk, which acts as an IPFIX collector at the OLT. Silk periodically records traffic information in a traffic data file.

The bandwidth allocation part consists of a server and a client developed by the author. The server periodically reads the traffic data file generated by Silk and predicts the required bandwidth at the next point in time. The predicted required bandwidth is sent to the client, which limits the inflow of traffic based on the received required bandwidth.

The server in the bandwidth allocation part periodically reads monitoring information from the traffic data file. These information sets are modeled by a linear regression model, as shown in Eq. (1). In this equation, X_i denotes monitoring traffic at time i.

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \quad (i = 1,2,\dots,n). \tag{1}$$

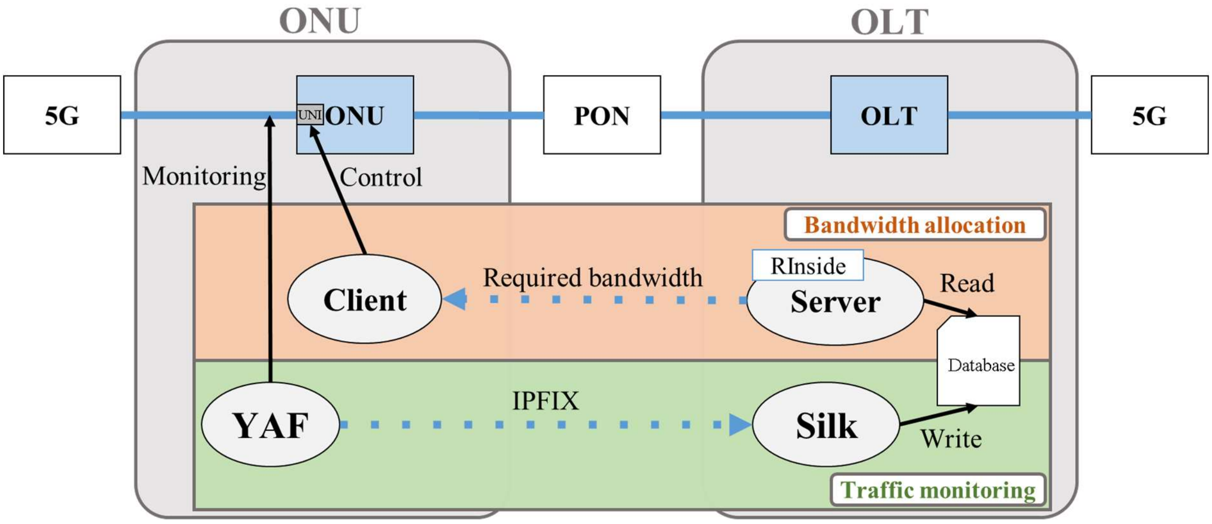
Then, β_0 and β_1 are estimated in Eq. (2) and Eq. (3) as time series information, where the error factor ε_i is minimized.

$$\widehat{\beta_1} = \frac{\sum_i (X_i - \overline{X})(Y_i - \overline{Y})}{\sum_i (X_i - \overline{X})^2}. \tag{2}$$

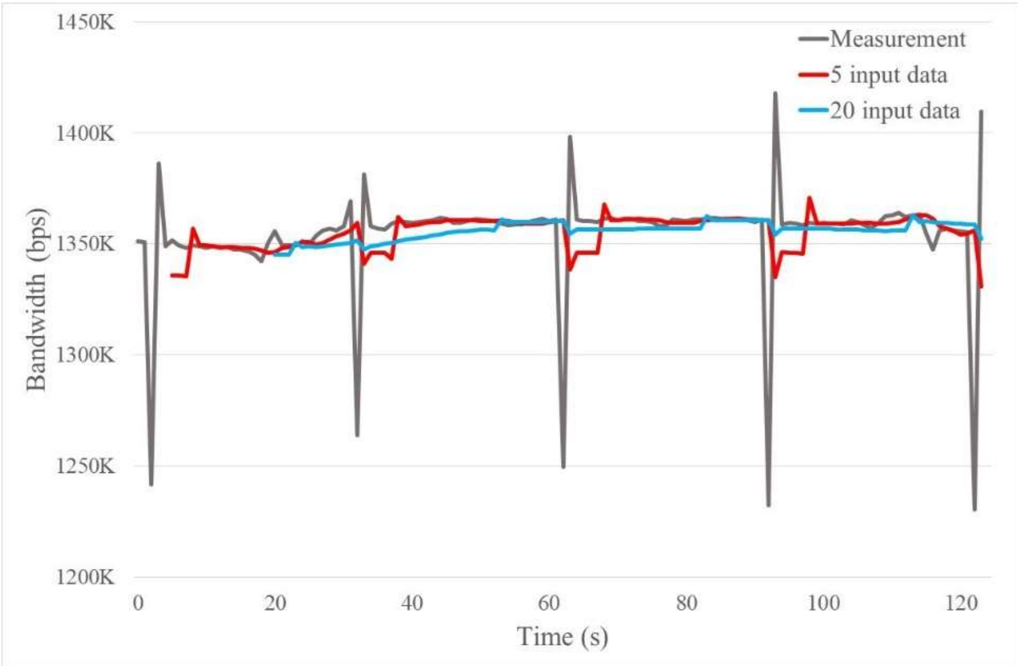
$$\widehat{\beta_0} = \overline{Y} - \widehat{\beta_1}\overline{X}. \tag{3}$$

After these equations are calculated, the required bandwidth of the next time slot is predicted by the extrapolation techniques. In the server, these computations are executed by embedded code written in the R programming language. Then, the required bandwidth is transferred to the client in another subpart through socket-level communication. In this case, the RInside module is applied as the compiler of the embedded R language for socket-level communication. Finally, the client provisions the required bandwidth to the egress point of an OLT.

An example of the client bandwidth allocation is shown in Figure 6.2(b). In this example, incoming traffic is video data specified by a resolution of 800 x 600 pixels and a framerate of 30 fps. As shown in Figure 6.2(b), incoming traffic volume is monitored at an interval of one second. Therefore, the assigned bandwidth is updated by this cycle. In this linear regression analysis, monitoring traffic in five previous points is applied to predict the next assigned bandwidth. In Figure 6.2(b), the red and blue lines show the prediction results when the number of data samples used in the linear regression analysis are 5 and 20, respectively, for the real traffic shown as the black line.



(a) Functional blocks in the traffic control function



(b) Example of operations for bandwidth allocation

Figure 6.2 Bandwidth allocation mechanism

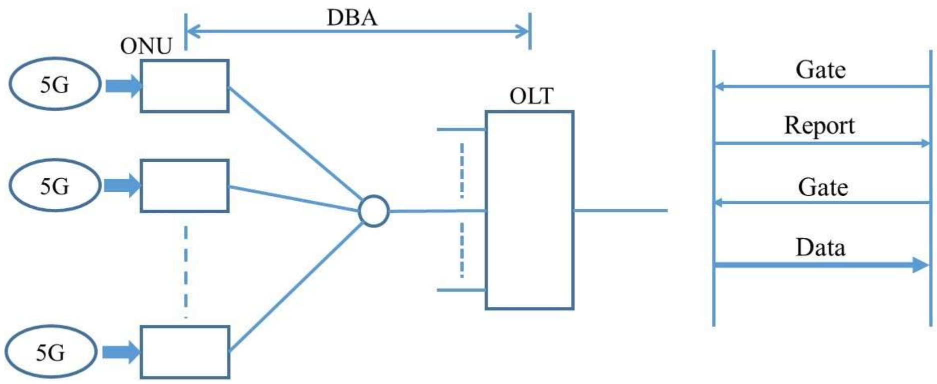
In this subsection, the author presents an example of integrating traffic control functions into ONUs and OLTs. This implementation provides flexible traffic control because the placement of the traffic measurement and bandwidth allocation sections can be easily changed.

D. Example of applying the proposed method to TDM-PON

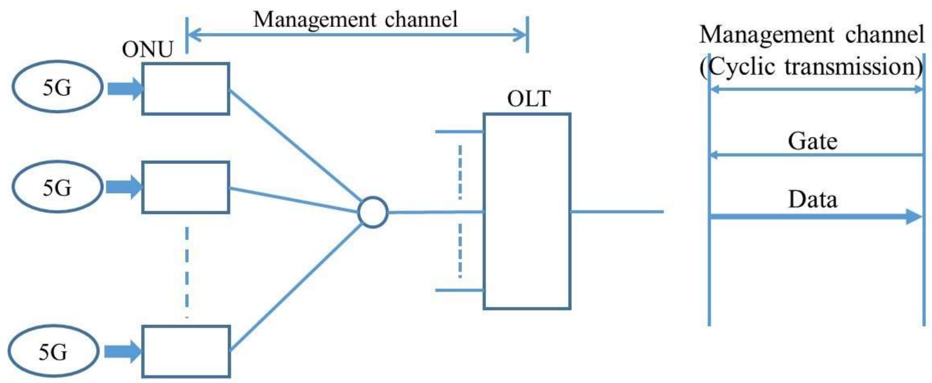
The bandwidth allocation scheme described in the previous subsection can be similarly applied to TDM-PON by placing the client of the bandwidth allocation section in the OLT; Figure 6.3(a) shows the conventional DBA scheme, and Figure 6.3(b) shows the proposed bandwidth allocation scheme.

In the conventional DBA-based access control, e.g., multi-point control protocol (MPCP) [56] specified for Ethernet base PON, a Gate frame must be sent once to check the buffer storage capacity of the ONU. When accommodating 5G traffic, this overhead may affect communication quality because communication between 5G and PON must be seamless.

In contrast, the proposed bandwidth allocation scheme performs the IPFIX transfer between the ONU and OLT periodically using the Management channel; this eliminates the need to visit the ONU buffer size, thus reducing the bandwidth due to MPCP control. Furthermore, because traffic data is exchanged over IPFIX, flexible control of traffic is possible through QoS control. Although the response performance of this method is worse than that of the conventional DBA method, the proposed approach is suitable for accommodating 5G traffic because the responsiveness of low-latency services and IoT traffic are important in 5G and are expected to be non-bursty, constantly sending small amounts of data.



(a) Conventional DBA scheme



(b) Proposed bandwidth allocation scheme

Figure 6.3 Example of DBA process using proposed bandwidth allocation algorithm

The proposed bandwidth allocation scheme can be applied to both fronthaul and backhaul traffic. When applied to fronthaul, traffic fluctuations can be suppressed by narrowing the MPCP control bandwidth and QoS control. Buffer overflow of ONUs can be prevented by applying the proposed approach to backhaul traffic.

E. Conclusion

In this study, the author has proposed a bandwidth allocation mechanism for interworking between 5G mobile networks and optical access networks. This method measures traffic using linear regression analysis and lightweight processing and enables 5G traffic to be accommodated by seamlessly connecting 5G and PON in the fronthaul section and preventing ONU buffer overflows in the backhaul section. The proposed approach is expected to establish a foundation for cooperative traffic control among different types of networks.

In future work, the author intends to evaluate the application of various prediction algorithms to the proposed bandwidth allocation scheme. In addition, the author plans to study the architecture and implementation of an OLT incorporating a cooperative traffic control mechanism.

6.2. A proposal on the management interface in BCOM for bandwidth allocation in cooperation between 5G and PON systems

A. Introduction

5G systems have begun to be deployed. Particularly, it is expected that small cells will be deployed to achieve higher speeds. In this case, Passive Optical Network (PON) technology [1] has been a promising candidate for multiplexing traffic from each small cell. The author has researched lightweight bandwidth allocation algorithms over interconnections between cells of 5G systems and PON, e.g., [57] and [58]. One of these algorithms is referred to as Bandwidth Control based on Online Monitoring (BCOM).

In this study, the author proposes the management interface to operate BCOM. It specifies the extension of conventional PON management interfaces standardized by ITU-T [59].

B. Overview of BCOM

The key functions of BCOM are shown in Figure 6.4. In BCOM, incoming traffic on a demarcation point between a DU and an ONU is monitored. Then, the bandwidth allocation at a multiplexing point is calculated and updated in an OLT. The lightweight calculation is provided by the embedded R language. Its detailed implementation is described in [58].

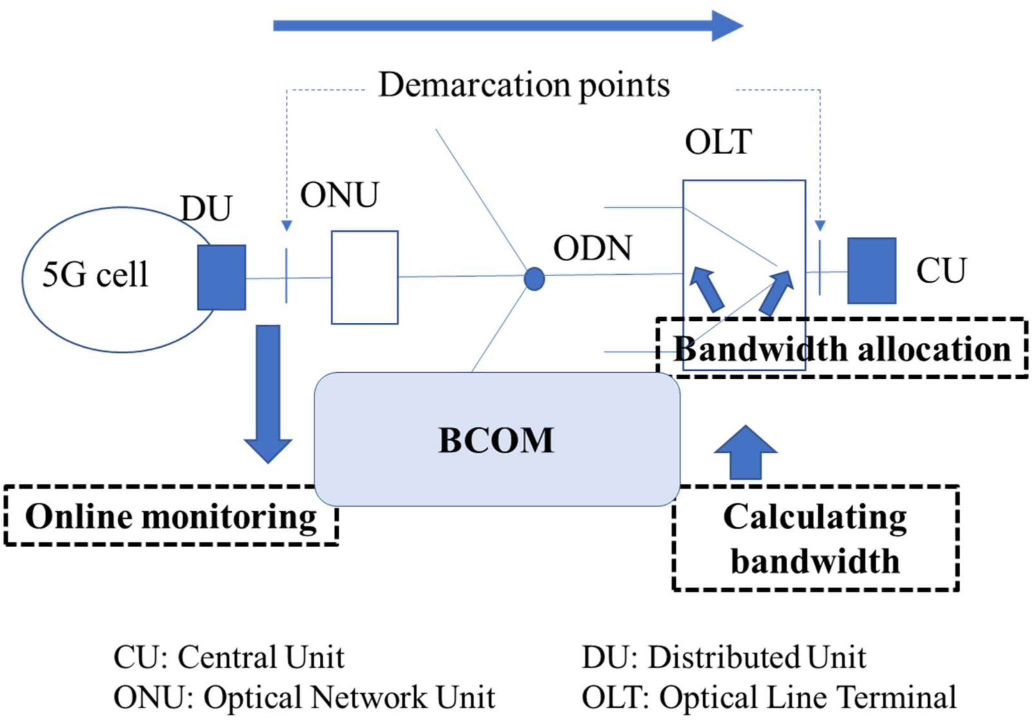


Figure 6.4 Key functions in BCOM

C. Proposal on transfer management information

One of the required specifications in BCOM is the transfer scheme of management information over PON. This subsection proposes some extensions of ONU Management and Control Interface (OMCI) as a generic management specification independent of PON types for this scheme.

The proposed scheme is shown in Figure 6.5. In this scheme, IPFIX [55] is applied as one of the generic methods for monitoring the demarcation point between the DU and the ONU because generic schemes should be applied. In this figure, #1-#3 are added to the protocol-independent MIB of OMCI.

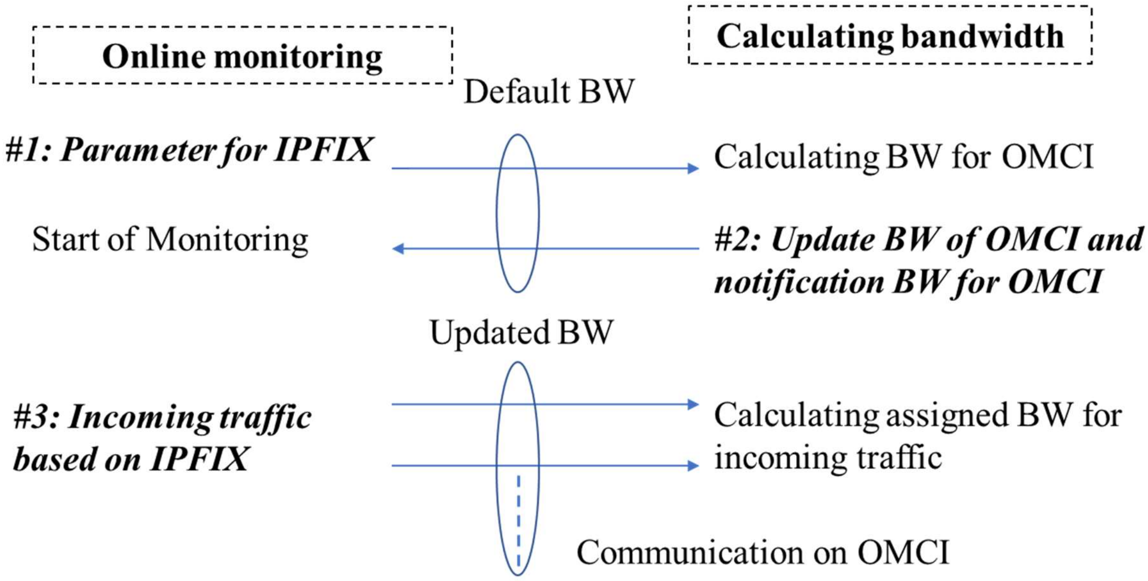


Figure 6.5 Transfer sequence using OMCI over PON

D. Conclusion

This section has described interoperations among functions in BCOM. It has been proposed that OMCI, with some extension, is applied to management information for BCOM. Evaluation of effectiveness is for further issue.

6.3. Resource control of access networks by traffic monitoring for efficient accommodation of mobile terminals

A. Introduction

In high-speed mobile communications (5G / Beyond5G) [24], small cells are expected to be introduced to realize high-speed, high-capacity service provision. To efficiently accommodate a large number of small cells, Passive Optical Network (PON) technology [1] can be applied and is being considered in international standardization activities [51].

5G is characterized by key communication performance features such as low latency, high reliability, and simultaneous multiple terminal connections, in addition to high speed and high capacity. It is capable of accommodating multiple applications with different requirements in the same network. Network slicing is a typical technology used to achieve this. However, to achieve the accommodation with slicing technology, QoS control must be performed in each of the domains that constitute the end-to-end communication path. In addition, when considering the use of networks for various purposes, it is necessary to consider a wide range of usage conditions, such as the time and location of network use and the situation where users with different usage requirements connect to and disconnect from the network concurrently. In such a case, there are two essential issues. One is a resource control method that can span different networks to provide a seamless QoS. The other one is a bandwidth allocation method responding to dynamic changes in application requirements.

The first issue of common control over different networks involves the application of network virtualization technology, which has been studied in the past mainly for mission-critical networks. In contrast, the author has conducted research on resource abstraction and the management of abstracted resources in optical access networks. In the research, the author has presented a method to realize end-to-end resource control, including access systems. However, a method to rapidly control physical resources is not established. For the second issue of this study, the author has proposed and verified a method to perform resource control with high-speed processing in situations where the requirements change dynamically. The author calls the method Bandwidth Control based on Online Monitoring (BCOM). It is a lightweight bandwidth allocation method that uses linear regression analysis and extrapolation based on input traffic measurements.

For the background of proposing BCOM, there are three types of basic technologies regarding resource control. The first one is the M-plane method, where the network operator decides related parameters in advance. The second one is the C-plane method, where the office-side equipment determines the quota by a declaration from terminal-side equipment. The third one is the D-plane method, where the office-side equipment has some prediction of the required resource quota using a monitor of user data traffic. In this study, the author selects the D-plane method because of an assumption that the range of application requirement change is dynamic and significant.

In this study, the author presents the concept of BCOM and describes its implementation and operation.

B. Related work

In this subsection, the author conducts a detailed survey of prior work on common resource control in heterogeneous networks and dynamic resource control for 5G traffic in access networks. In this study, a heterogeneous network is defined as a network that combines communication methods of different types, standards, and ranges. The content stated in the previous section will be explained in this section using specific prior works. The works in subsection A have superordinate concepts, and the subsection surveys existing research on resource control in the heterogeneous network. Subsection B surveys on the cooperative control of 5G and PON.

1) Heterogeneous Network Integrated Resource Control

With regard to methods for performing common resource control across different networks, network virtualization technology has been applied and studied in advance, mainly for mission-critical networks. For example, [26] proposed a network resource control method for constructing metro networks between data centers by considering latency constraints required for many industrial applications and evaluating the processing time and cost. In [27], an algorithm for adding redundant connection resources between data centers and wireless access points is proposed. The work reported in [28] evaluated multiple resource allocation algorithms, focusing on the maximum bandwidth and processing time for intra-datacenter and inter-datacenter networks, and [29] proposed a resource allocation method to improve transmission rate performance under delay constraints as an optimization problem for sub-channel allocation and power control. In addition, one of the key technologies for dynamic resource allocation is an abstraction and related research has been conducted in [30], where topology abstraction and distributed path computation for each network domain are used based on the Application-Based Network Operations (ABNO) architecture of the IETF. An orchestration architecture for heterogeneous optical transport networks using topology abstraction and distributed path computation for each network domain is proposed. In [31], [32], and [33], mobile virtual backhaul deployment over multi-layer aggregated networks, end-to-end resource allocation, and dynamic provisioning of logical networks in less than 1 second are shown in each related testbed.

In contrast, the author has studied the application of network virtualization techniques to access networks for resource abstraction and managing abstracted resources. In [39], the author proposed a method to accelerate the allocation process for abstracted resources in access networks carrying 5G traffic. In [40], the author proposed a network resource abstraction model that supported the characteristics of mobile fronthaul for 5G-RAN and studied a method to improve the efficiency of allocated resource utilization. In [41], a proposal and a simple evaluation of the allocation processing time are made. These are related to the method to manage the abstracted resources proposed and evaluated in [39] and [40]. Then, in [60], based on the research results in [39], [40], [41], a control architecture for transport networks to support 5G-RAN is proposed, and a system for efficient resource control using resource abstraction and abstraction models is developed and logically verified. Through these studies, the author showed a method to realize end-to-end control, including access systems. Furthermore, the author proposed an architecture that enables end-to-end static and dynamic resource control over mobile and transport systems and examined and verified it in conjunction with applications on the cloud and edge servers in the overall network configuration shown in Figure 6.6.

These studies have identified a basic architecture for resource control in the system integrating 5G and optical access networks and other wireless and wired networks and a common resource management scheme. However, it is necessary to provide a method to control the resources when the application requirements change dynamically rapidly.

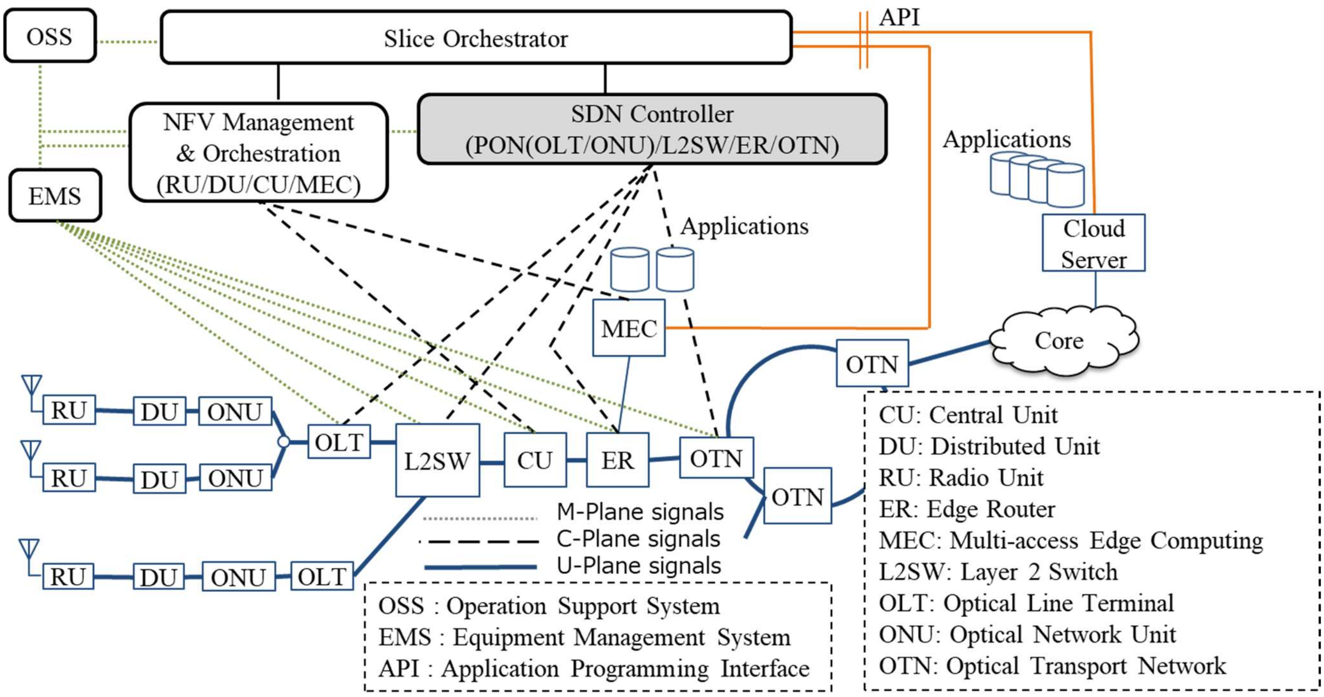


Figure 6.6 Example of integrated wired and wireless slice control architecture

2) 5G Traffic Accommodation and Dynamic Resource Allocation

In the course of prior research for allocating network resources such as bandwidth assuming 5G traffic, a method to calculate resource allocation, including edge computing based on the parameters of delay and packet loss rate assuming different 5G applications, is proposed [61]. The proposed method allocates resources in multiple domains based on common requirements parameters [61]. Research that worked on a scheme for bandwidth allocation control using AI [62] is also an example.

As a basic technology related to the above issues, many studies have been conducted on dynamic bandwidth allocation of network resources, and recently, some studies on allocation control combined with the latest information processing technologies have been published. For example, these include a study proposing a learning-based dynamic bandwidth allocation scheme [63], a study on a dynamic slice resource allocation scheme based on traffic prediction [64], and a study on a self-adaptive resource allocation scheme combining traffic prediction and user satisfaction [65]. A study [29] used a linear value function approximation for dynamic virtual resource allocation in a RAN, and a study [66] described a case in which a learning-based algorithm is effective. A study [67] proposed improving the ITU-T compliant Dynamic Bandwidth Allocation (DBA) algorithm for bandwidth allocation in optical access networks.

These studies have identified methods to realize dynamic resource allocation control of access networks to accommodate traffic for different 5G applications. However, consideration of allocation response characteristics in response to changes in application status and requirements and realization of allocation control schemes common to multiple physical resources such as wavelengths and time slots are issues to be addressed.

C. Overview of dynamic resource control in PON system

Since mobile systems, such as 5G, employ cellular-based communication techniques, their cell size decreases as the transmission rate increases and the total number of cells increases. Therefore, as a network that can efficiently realize traffic multiplexing from such mobile systems, a PON with high-speed transmission performance and efficient use of station-side equipment and optical fiber resources is suitable [1].

This subsection describes the basic mechanisms related to PON, problems and countermeasures for DBA, and the latest trends.

1) Basic Mechanism of PON

PON is an economic access network in which multiple subscriber-side devices share a single optical fiber resource and station-side device. It has been standardized by the ITU-T [68] and the IEEE [69].

Typical transmission schemes for PON are shown in Table 6.1. The main conventional multiplexing scheme is Time Division Multiplexing (TDM), and most of the systems currently standardized and commercially deployed are based on this scheme [24]. On the other hand, non-TDM schemes such as Wavelength Division Multiplexing (WDM) are also considered due to the trend toward high-speed, high-capacity systems [52].

The basic mechanism of bandwidth allocation on PON uplink is shown in Figure 6.7. In the PON for FTTH, downlink bandwidth is essential. However, in the case of usage for various services and applications, uplink bandwidth is also a major issue since many kinds of devices are connected. Regarding bandwidth allocation control, the TDM method is based on bandwidth sharing within an Optical Distribution Network (ODN), while the non-TDM method is based on bandwidth sharing. As shown in the figure, the OLT is generally configured to combine multiple ODN interfaces (PON interfaces) and to connect them to the upper-level equipment. It is assumed that bandwidth control over multiple ODN interfaces may be required in some cases.

Table 6.1 Classification of major PON transmission schemes

	TDM	Non-TDM
Type	B-PON, G-PON, XG-PON, GE-PON, 10G-EPON	WDM-PON, OFDM-PON, FDM-PON, SDM-PON
Bandwidth sharing	Shard bandwidth intra-ODN	Dedicated bandwidth intra-ODN

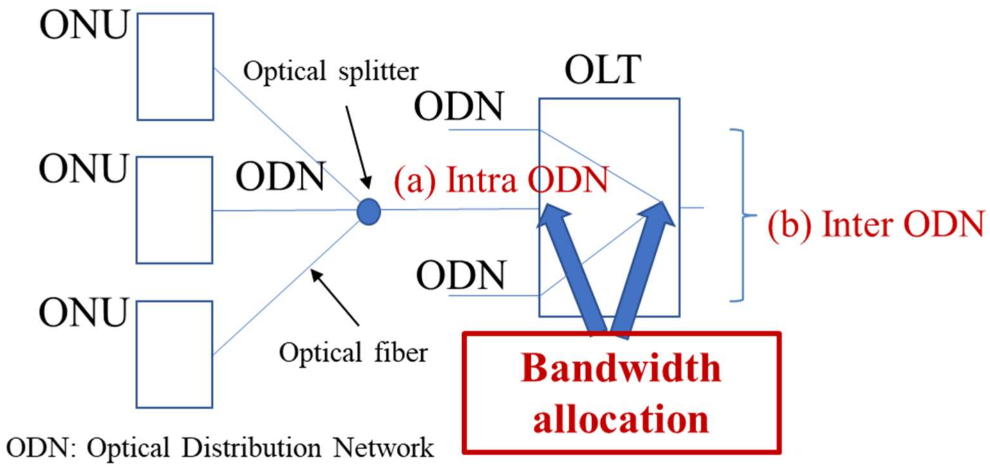


Figure 6.7 PON Bandwidth Allocation Mechanism

2) DBA Problems

DBA in PONs is an excellent method for efficiently controlling bandwidth allocation according to user usage in a TDM scheme [24, 56]. However, as mentioned in the previous section, DBA cannot be applied in a non-TDM scheme because each ONU occupies multiplexed channel bandwidth, such as wavelengths within the ODN interface. Furthermore, in a configuration where the OLT combines multiple ODN interfaces, it is necessary to apply a method other than DBA for bandwidth control across multiple ODN interfaces.

The above problems are expected to become apparent when accommodating a variety of applications with different communication requirements, as envisioned for 5G, and when dealing with users who expect to be connected over a wide geographic area. These are precisely the problems related to the objective of this study.

Regarding the level of dynamism that should be addressed here, a change within the defined service requirements, as in the so-called DBA of the PON system, is not an issue. What should be assumed is a situation where the usage requirements themselves change across multiple systems. Therefore, the solution for the issues is not exclusive to the DBA of the PON, but the issues are solved by working together. For example, the control cycle order of DBA is several hundred us ~ several ms. In contrast, the dynamic changes in requirements, which are the subject of this study, occur in seconds, minutes, and hours. Therefore, while DBAs are necessary, functions outside of DBAs will be considered.

3) Recent Trends in PON

As for trends in technology and standardization related to PON systems, various issues have been raised in response to the needs mentioned above for diversification of usage patterns and requirements, not just the old high-speed, large-capacity technology. These include the trend toward diversified application conditions such as low latency transmission [70, 71], low power consumption [72, 73], and high reliability [74], and the trend toward increased sophistication to accommodate a wide variety of applications by connecting to various networks, such as

5G.

In this subsection, the author specifically discusses the latter trend, including the advancement of OLT functions and softwarizations.

Older telecommunication facilities have hardware configurations according to the service applications, and the PON system is no exception. However, designing a system for each of the various applications listed above would be highly inefficient in terms of both development and operation. For this reason, studies have been actively conducted to apply Software Defined Networking (SDN) / Network Function Virtualization (NFV) -related technologies to realize the functions of station-side telecommunication equipment on general-purpose hardware. A typical project is the "Data Center Networking Project" (DNP), a project to develop a network for data centers. A representative project is Central Office Rearchitected as a Datacenter (CORD), which uses data center technology to realize the station-side functions. The Open Networking Foundation (ONF), an OSS development community, is promoting the development of SDN Enabled Broadband Access (SEBA), a platform for the virtualization of various optical access systems [75]. This project sees the virtualization and software of PON OLT functions as its primary target and also envisions the utilization of computing resources such as edge servers. In addition, the Broadband Forum (BBF), which standardizes PON use cases and test specifications, establishes the componentization and modularization of DBAs and other essential PON functions [76, 77]. Furthermore, standardization discussions on PON slicing are underway [78], and a mechanism for slice control of end-to-end integrated wired and wireless access networks, including 5G, is being established.

Based on the above trend in OLT upgrading, this study proposes a scheme to realize a dynamic bandwidth control function that can respond to various service forms and hardware configurations.

D. Proposal of bandwidth allocation method using traffic monitoring and information on mobility

To solve the DBA and other problems described above, the author has been working on Bandwidth Control based on Online Monitoring (BCOM) [58, 79], a lightweight bandwidth allocation method using linear regression analysis and extrapolation based on traffic measurements. The study [58] describes the basic principle of predicting the required bandwidth from traffic measurement results using linear regression. Moreover, the study [79] describes the information transmission method for supervisory control between OLT and ONUs. A systematized method based on the combination of the results is BCOM. Furthermore, BCOM+ is a method that clarifies the operational issues of BCOM and expands functionality. This research summarizes them and evaluates their implementation.

1) Overview of BCOM

Figure 6.8 illustrates the functional configuration of a 5G-RAN and PON access network with BCOM. Traffic with characteristics such as massive Machine Type Communications (mMTC), enhanced Mobile BroadBand (eMBB), and Ultra-Reliable and Low Latency Communications (URLLC) from 5G cells is input to each ONU via a DU. First, the traffic on the demarcation point between the DU and ONU is monitored <Step 1>. Next, bandwidth calculation is performed at the multiplexing point based on the results of each monitoring process <Step2>. Finally, the OLT performs bandwidth allocation control and bandwidth update processing <Step3>.

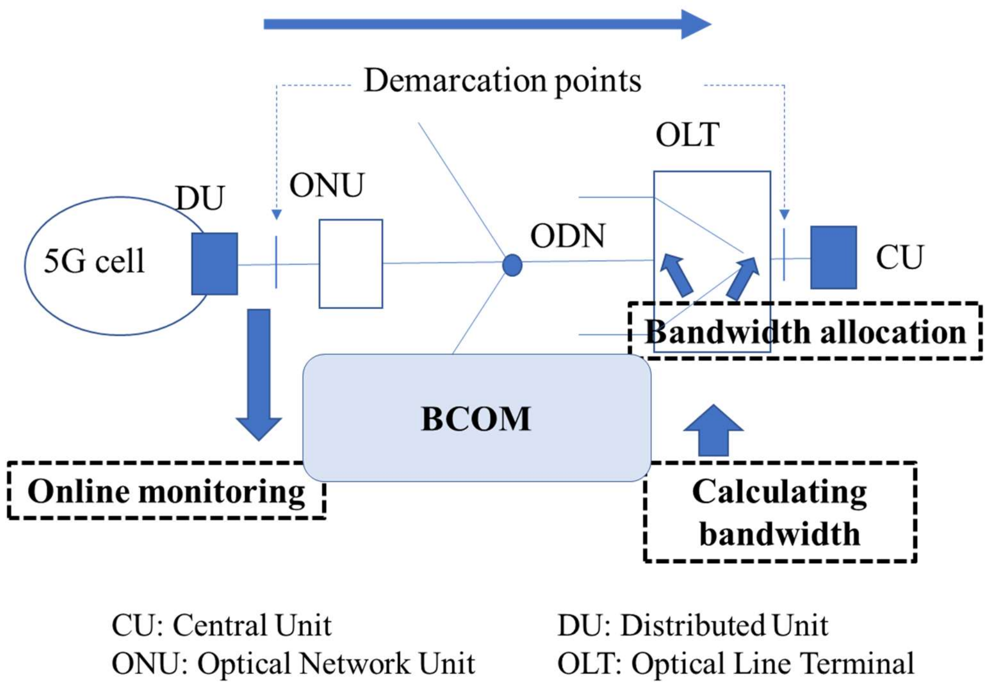


Figure 6.8 Schematic functional diagram of BCOM

The amount of bandwidth to be allocated is calculated by a prediction process that extrapolates the bandwidth one second later from the regression line obtained in the linear regression analysis.

The calculation process is performed as in Equation (1). Here, Xi is traffic monitored at time i. Yi is the calculated bandwidth at time i.

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \quad (i = 1,2, \ldots, n) \qquad (1)$$

$\boldsymbol{\beta_0}$ and $\boldsymbol{\beta_1}$ are estimated as in Equation (2) and (3) as time series information, where the error factor $\boldsymbol{\varepsilon_i}$ is minimized.

$$\widehat{\beta_1} = \frac{\sum_i (X_i - \overline{X})(Y_i - \overline{Y})}{\sum_i (X_i - \overline{X})^2} \qquad (2)$$

$$\widehat{\beta_0} = \overline{Y} - \widehat{\beta_1}\overline{X} \qquad (3)$$

BCOM has as a parameter of reference time (the number of samples used in the regression analysis). If the reference time is short (few data points used in the regression analysis), the forecasts follow traffic fluctuations rapidly; if the reference time is long (many data points used in the regression analysis), the forecasts can be produced at moderate speed.

2) BCOM Issues and Measures

Figure 6.9 shows an example of the traffic from a mobile entity to the BCOM via the ONU. In this case, the traffic changes extremely rapidly because the mobile entity passes through a cell connected to the ONU between the time of the 150s and the 200s. The actual traffic is shown by the black line, the prediction results are shown in orange when the reference time is 3 seconds, and the results are shown in blue when the reference time is 20 seconds. In general, longer reference time makes stable performance of bandwidth allocation and achieves high utilization efficiency. However, in case input traffic changes rapidly, as shown in the figure, the longer the reference time, the slower the rise of the prediction when burst traffic occurs. The slower the rise of the forecast, the higher the frame loss rate sent out by the mobile. Therefore, the forecast tracking needs to be improved.

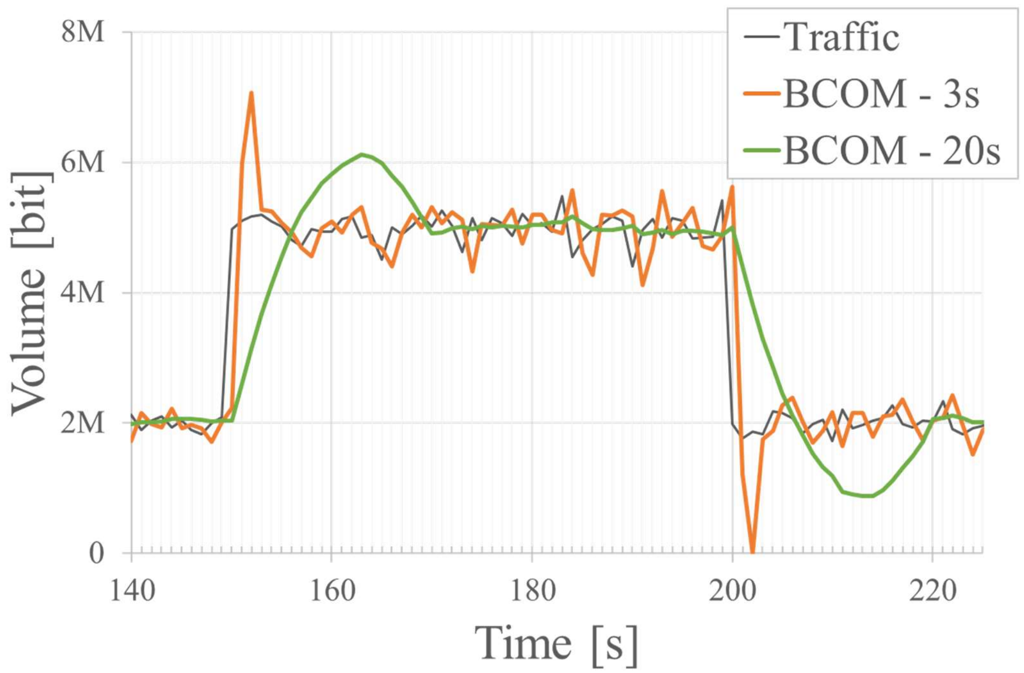


Figure 6.9 An example of bandwidth allocation

3) Enhanced approach

To solve the above issues, the author developed BCOM+, which increases the bandwidth when a mobile entity passes through the cell and reduces the bandwidth at other times, utilizing information that the time when a mobile is in the cell where each DU/ONU is located, is known in advance.

In BCOM+, the bandwidth calculated on a BCOM basis is increased when a mobile entity passes through the cell of an RU/DU connected to ONU. At other times, the bandwidth is decreased. The decreased bandwidth is allocated to other ONUs that the mobile entity passes through.

The increased bandwidth α is calculated by multiplying the BCOM bandwidth by a coefficient of increase ratio. The decreased bandwidth β is calculated as in Equation (4).

$$\beta = \frac{\alpha}{\min(2, \text{the number of onus})} \qquad (4)$$

Figure 6.10 shows an example of BCOM+ operation when a mobile entity passes through a cell connected to ONU3 of 8 ONUs. The system with BCOM+ aims to provide sufficient bandwidth to respond to the increase in mobile traffic due to the passage of the mobile and to reduce the frame loss rate of the mobile traffic. The increased bandwidth when the mobile entity passes through an ONU is divided among and subtracted at other ONUs that it does not pass, thereby distributing the impact.

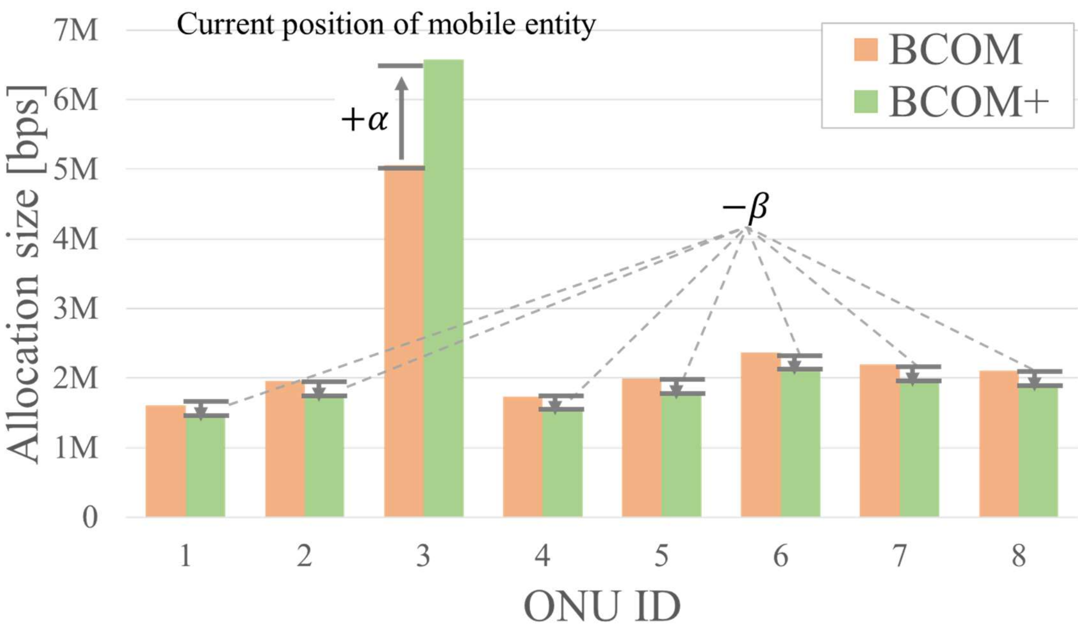


Figure 6.10 An example of BCOM+ operation

E. Evaluation of efficiency in the dynamic bandwidth allocation function

This subsection compares the bandwidth allocation control schemes (BCOM and BCOM+) and their respective assumptions for situations where traffic sources move beyond communication coverage boundaries, such as 5G cells due to terminal movement, and defines verification models and traffic models. Then, it presents the simulation environment and the main simulation results. Finally, the cases in which the proposed method is effective are discussed.

As a specific example of an application with dynamically changing requirements, the author assumes a case in which a group of terminals that are part of a service target move as a group as the mobile entity moves in an area where a local information service is provided. In particular, the author considers a situation in which the mobile entity has a predetermined route and operation plan, such as a train or bus, and the movement of the moving group of terminals can generally be predicted.

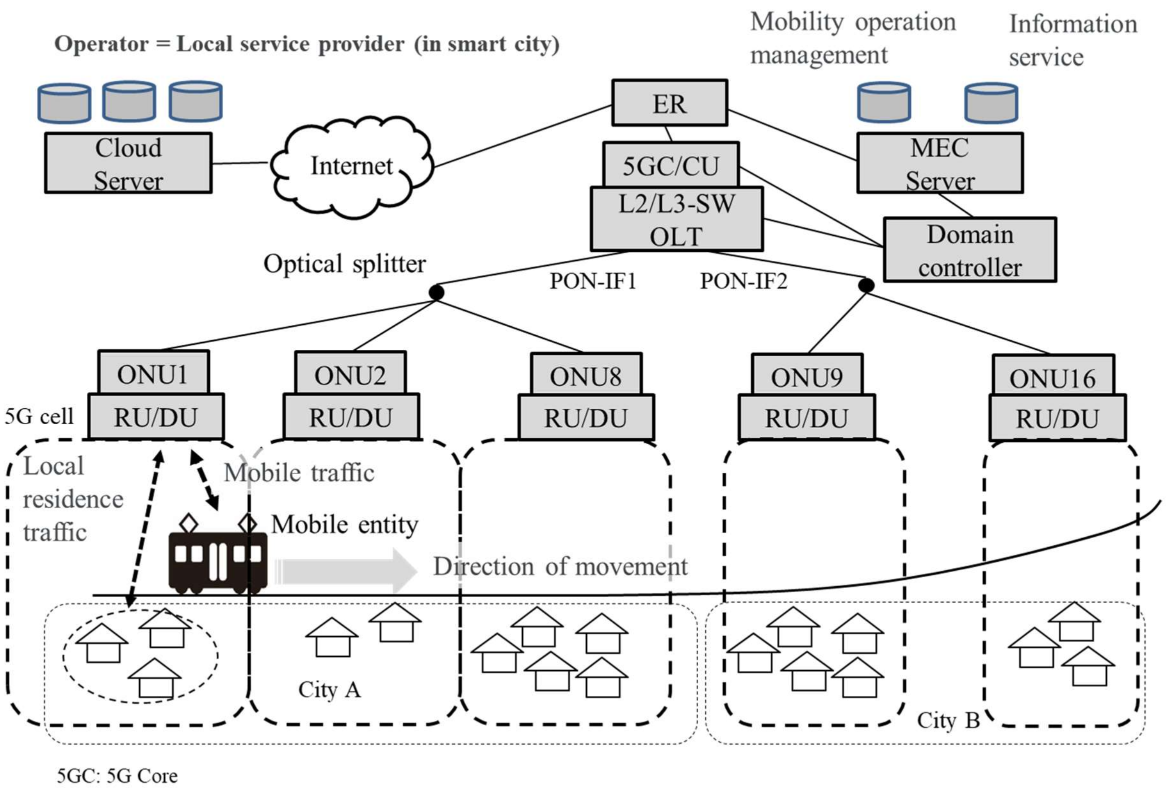


Figure 6.11 Example of an application where dynamic requirement changes occur

1) Methods of Evaluation Target

In the application shown in Figure 6.11, where mobile traffic sources move one after another through multiple 5G cells in a PON system, a comparative evaluation of different bandwidth allocation control schemes in the PON system is performed. It is assumed that the time when the mobile entity passes through each cell is known by the OLT via the Mobility operation management.

BCOM: traffic monitor-based dynamic bandwidth allocation

As described in the BCOM overview, it performs near-term traffic forecasting based on the results of traffic monitoring at the input stage of each ONU, calculates the required bandwidth, and performs the allocation process.

BCOM+: Coordination of traffic monitoring and planning allocation

Based on the bandwidth calculated by BCOM, increasing allocation processing is performed when the mobile entity passes through, and decreasing allocation processing is also performed at other times.

2) Models for Evaluation

a) Verification model

The system configuration of the target verification model is shown in Figure 6.12. The number of ONUs in each PON-IF of the OLT is 8, and 16 ONUs are connected to the upper L2SW via two PON-IFs. Mobile traffic generated from terminals on the mobile entity is preferentially accommodated and forwarded to the upper network, distinguishing it from traffic generated from the homes of residents in the vicinity. The traffic is monitored at each ONU and used for bandwidth calculation. In addition, mobility schedule information from Mobility Operation Management is used for the calculation.

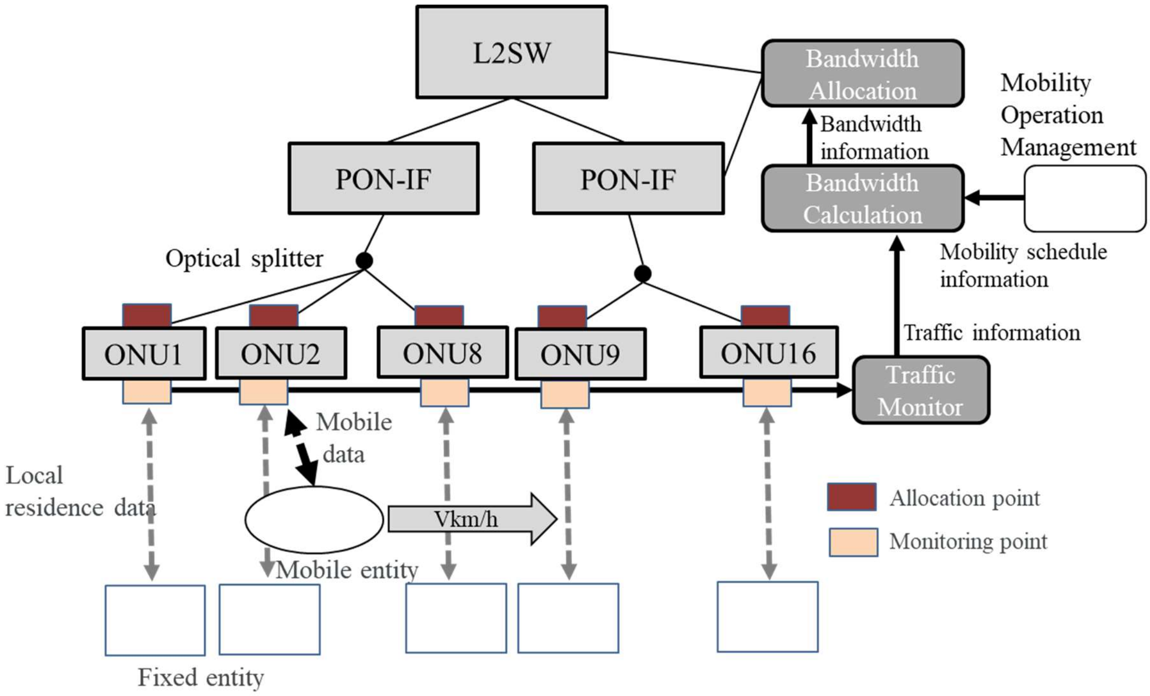


Figure 6.12 Verification system configuration

b) Specification of a typical traffic model for a 5G system

The traffic model for BCOM is so specified as to consider the traffic characteristics of URLLC/mMTC/eMBB in 5G systems.

First, because URLLC/mMTC is an ultra-low latency and multi-connected communication system, it is assumed to be less bursty than eMBB. Therefore, traffic multiplexed with these types can be modeled by an exponential distribution. It can be regarded as pessimistically random traffic since the coefficient of variation is less than 1 when traffic with different periods is multiplexed. Therefore, it can be approximated by an exponential distribution with no memory. Therefore, RLLC/mMTC is expressed by the probability density function of the exponential distribution in equation (5). This model is referred to as the random model.

$$(x) = \lambda e^{-\lambda} , x > 0 \qquad (5)$$

In equation (5), λ represents the rate of traffic generation in a given occurrence interval. An example of traffic generation for the random model is shown in Figure 6.13.

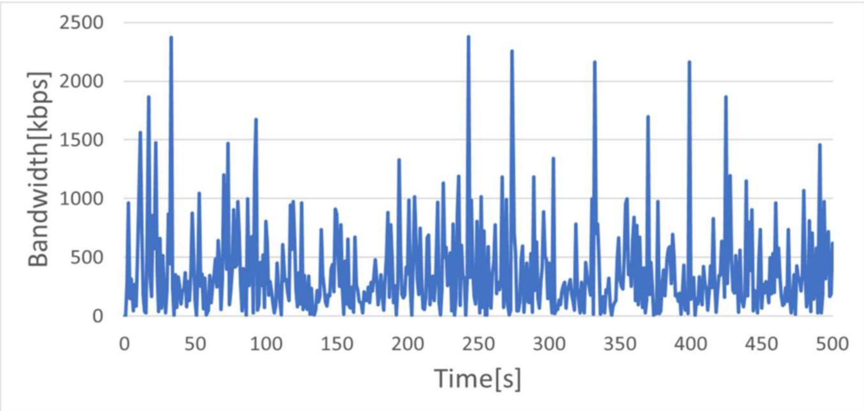


Figure 6.13 Example of traffic generation in a random model

Next, the traffic model for eMBB is specified. eMBB is very bursty traffic due to its ultra-high speed and high capacity, i.e., the coefficient of variation between occurrences exceeds 1. It can be represented by multiplexing the ON-OFF model. It can be approximated by a second-order super-exponential distribution that can be represented by a single distribution. The specific process is as follows. At first, the author assumes that high- and low-frequency occurrence intervals of traffic on a single line follow the exponential distributions α^{-1} and β^{-1}, respectively. It is also assumed that traffic occurs at a constant interval T in each traffic generation interval. The average occurrence rate λ, the coefficient of square variation (variance/mean2)2a, and the skew (cubic central product rate/variance3/2) can be expressed as follows:

$$\lambda = \beta / T(\alpha + \beta) \qquad (6)$$

$$_{\alpha}C = 1 - (1 - \alpha T)^2 / T^2 (\alpha + \beta)^2 \qquad (7)$$

$$_{k}S = 2\alpha T(\alpha^2 T^2 - 3\alpha T + 3)/[\alpha T(2 - \alpha T)]^{3/2} \qquad (8)$$

The ON-OFF model is then multiplexed, and using equations (6), (7), and (8), a Markov Modulated Poisson Process (MMPP) can be approximated as in equation (9) [80]. Equation (9) is the probability density function of a second-order hyper-exponential distribution.

$$f(x) = k_H \lambda_{H1} e^{-\lambda H1 x} + (1 - k_H) \lambda_{H2} e^{-\lambda H2 x} \qquad (9)$$

λ_{H1} represents the incidence of high-frequency occurrence intervals of traffic, and λ_{H2} represents the incidence of low-frequency occurrence intervals. In addition, k_H shows the ratio of each occurrence interval. An example of the occurrence of traffic with a super-exponential distribution is shown in Figure 6.14.

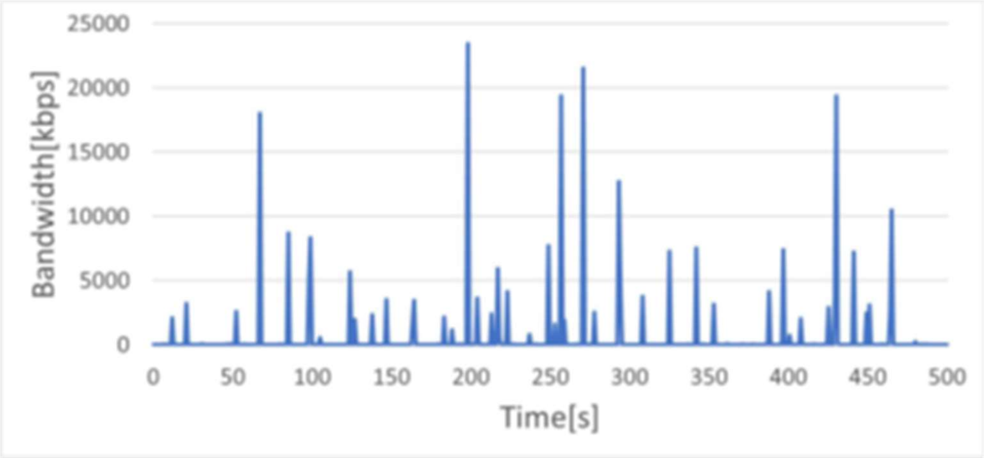


Figure 6.14 Example of traffic generation by super exponential distribution

c) Verification conditions

The conditions for the simulation evaluation are shown in Table 6.2. A significant value derived from the above parameters is that the time for a mobile to be in the cell connected to each ONU is 50s at a speed of 36 km/h and 25s at 72 km/h.

Table 6.2 Simulation conditions

Items	Specifications
Communication coverage range per ONU	500m
Mobile traffic rate (average)	300Mbps
Local residence traffic rate (average)	50 Mbps/ONU
Moving object speed	36 km/h or 72 km/h
Reference time	variable
BCOM+ bandwidth increase rate	10, 30, 50, 80, 100 %
Time resolution	1s

d) Simulation environment

The simulation environment conditions are shown in Table 6.3.

Table 6.3 Simulation environment conditions

Items	Specifications
Size of CPU	48 cores
Clock frequency	3.8 GHz (Max)
Cache	L1d:768KiB, L1i:768KiB, L2:12MiB, L3:128MiB
Memory size	62GB

*:L1d/L1i: L1 data/instruction cache

3) Verification

a) Overall operation check

Figure 6.15 and Figure 6.16 illustrate the overall operation, showing the time evolution of the bandwidth allocated by BCOM and BCOM+ for the generated traffic based on the traffic model described in Subsection E.2. Figure 6.15 shows the measured traffic and allocated bandwidth for ONU1, and Figure 6.16 for ONU8. Figure 6.15 shows a situation that a mobile entity is passing through a cell connected to ONU1 at times between the 70s and the 120s. The movement speed is 36 km/h, and the allocation ratio in BCOM+ is 30%.

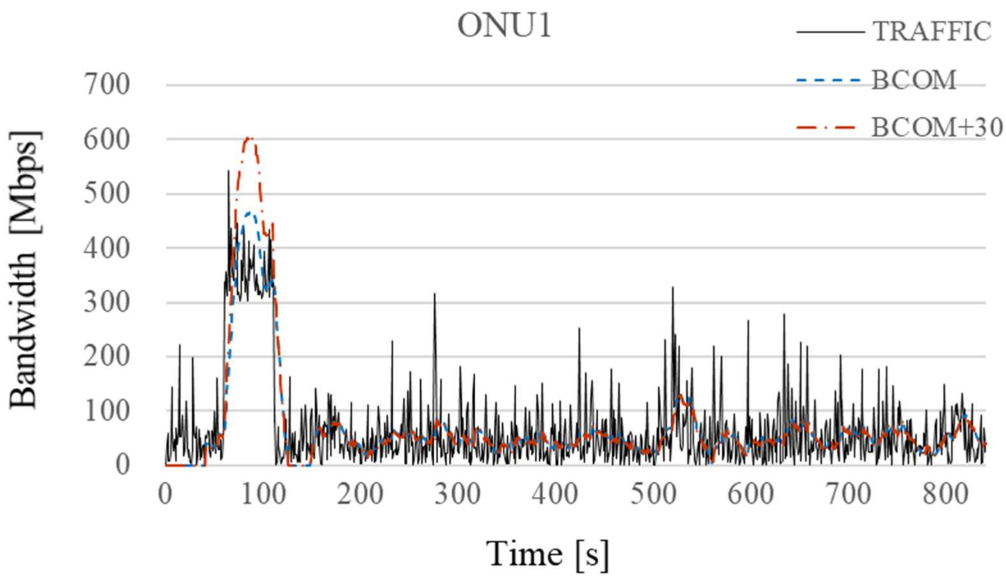


Figure 6.15 Overall operation diagram (ONU1)

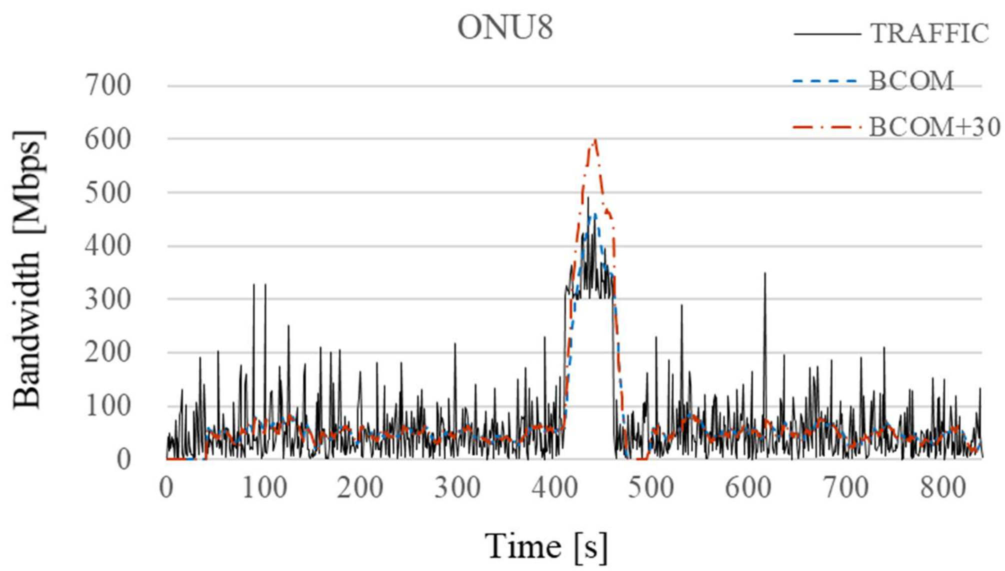


Figure 6.16 Overall operation diagram (ONU8)

b) Reference Time

Figure 6.17 through Figure 6.18 show the bandwidth control response characteristics with BCOM and BCOM+ (rate increase of 30%) of an ONU when a mobile passes by, depending on the reference time. The speed of the mobile entity is 36 km/h. The cases of 10%, 50%, 80%, and 100% increase in the rate of BCOM+ are also verified, and it is found that the overshoot to the rise of real traffic is suppressed when the reference time is 40 s or longer in all cases. In addition, the author quantitatively measures the degree of safety (bandwidth surplus: potential margin against traffic fluctuations) and the degree of risk (bandwidth shortage: potential risk of shortage against traffic fluctuations) of allocated bandwidth concerning actual traffic (Figure 6.19 ~ Figure 6.20) and found that the characteristics are better when the reference time is 40 s. The results are shown in Figure 6.19 ~ Figure 6.20. Therefore, a reference time of 40 s is recommended for a mobile speed of 36 km/h. The unit of the vertical axis of the safety and risk graphs is the difference between the allocated bandwidth and the actual traffic, integrated into the time direction, divided by the total time value of the actual traffic. Similarly, the case of 72 km/h mobile speed is also verified, and a reference time of 20 s is found to be the optimal value.

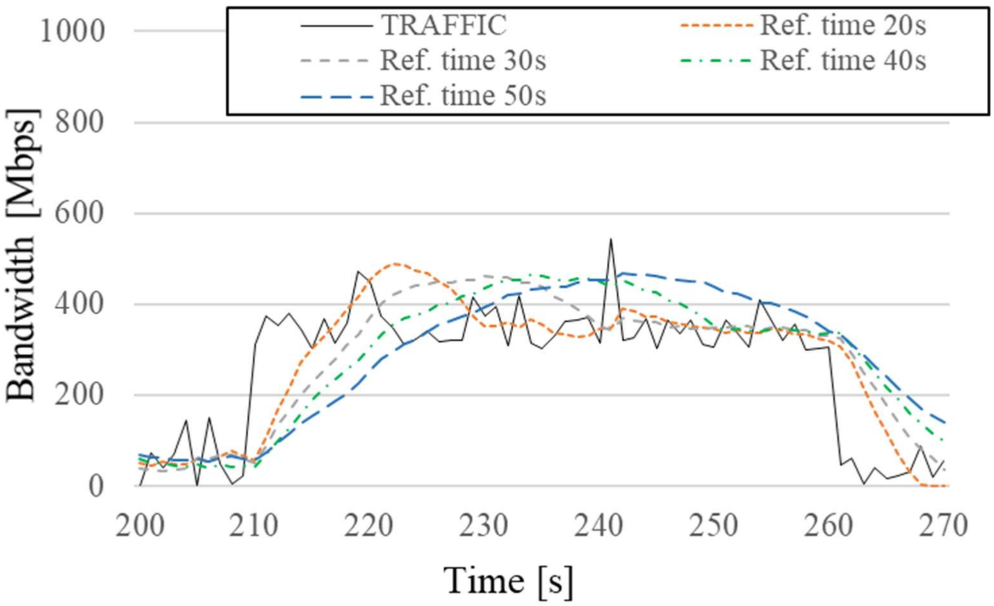


Figure 6.17 Allocation characteristics by reference time (BCOM)

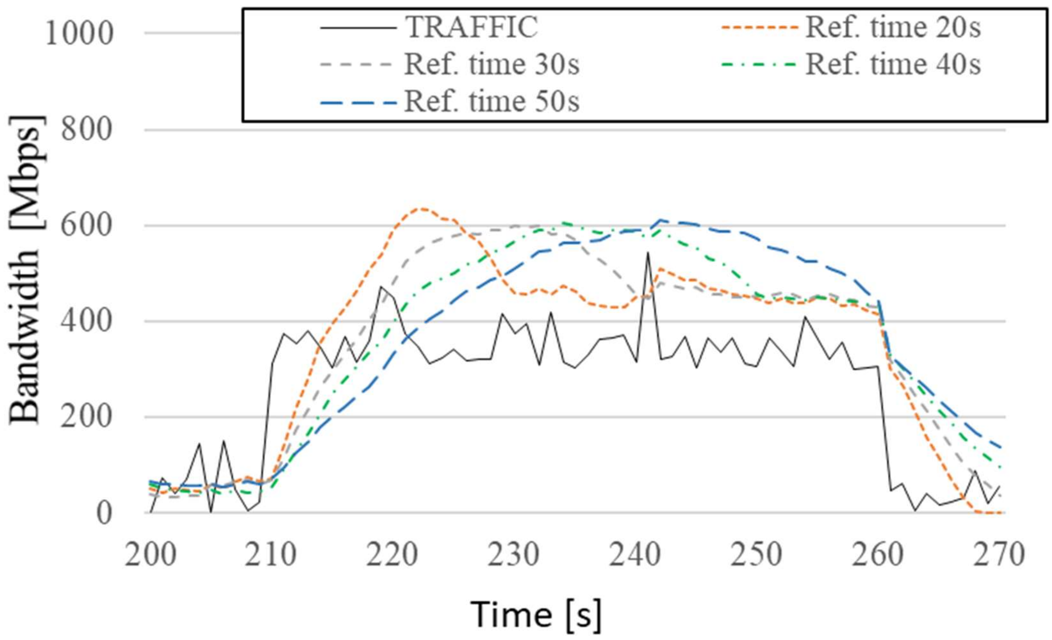


Figure 6.18 Allocation characteristics by reference time (BCOM+(increase rate 30%))

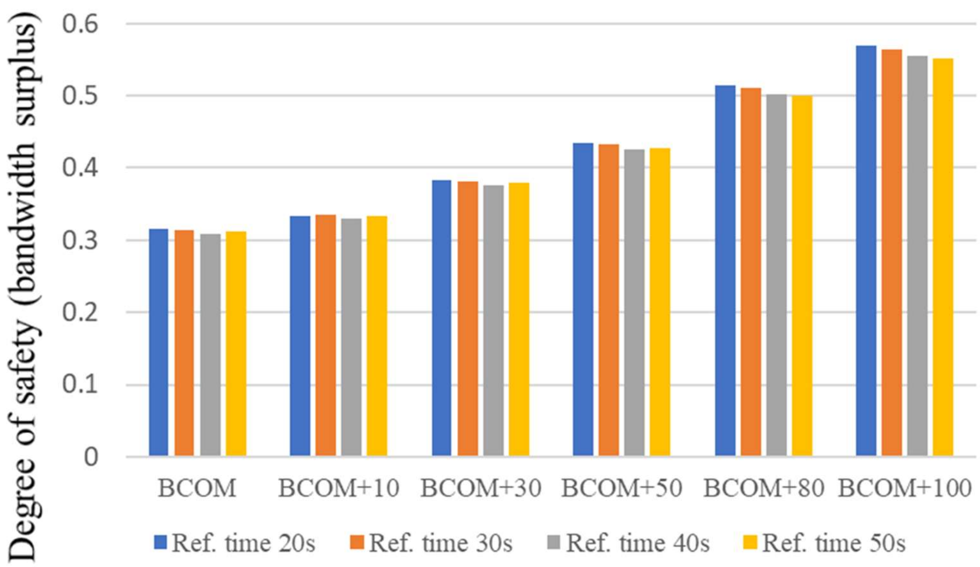


Figure 6.19 Potential margin of allocated bandwidth

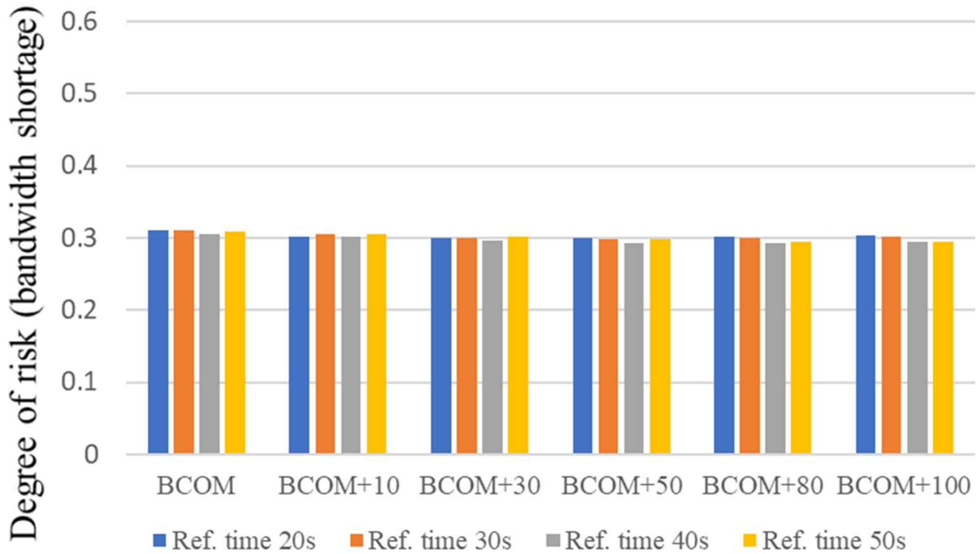


Figure 6.20 Potential risk of allocated bandwidth

c) Mobile traffic-oriented allocation characteristics

Figure 6.21~Figure 6.22 shows the degree of safety and risk of bandwidth allocation for each method for actual traffic passing through a mobile. The results indicate that BCOM+ has a clear advantage when the rate of increase is 30% or more. However, since these safety and risk factors conflict regarding the accuracy of bandwidth allocation, an inadvertent increase is undesirable from the standpoint of overall network resource efficiency.

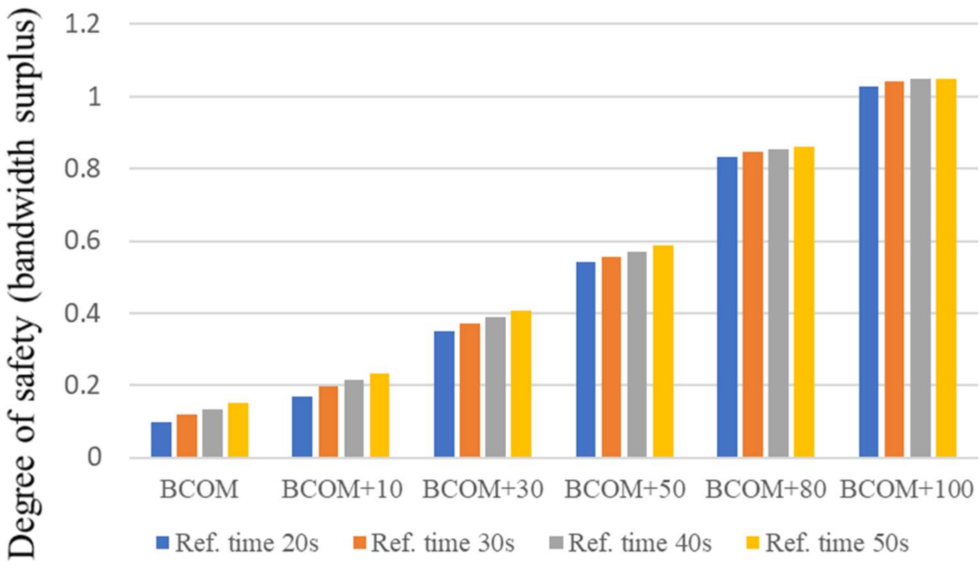


Figure 6.21 Potential margin of allocated bandwidth (when passing through a mobile)

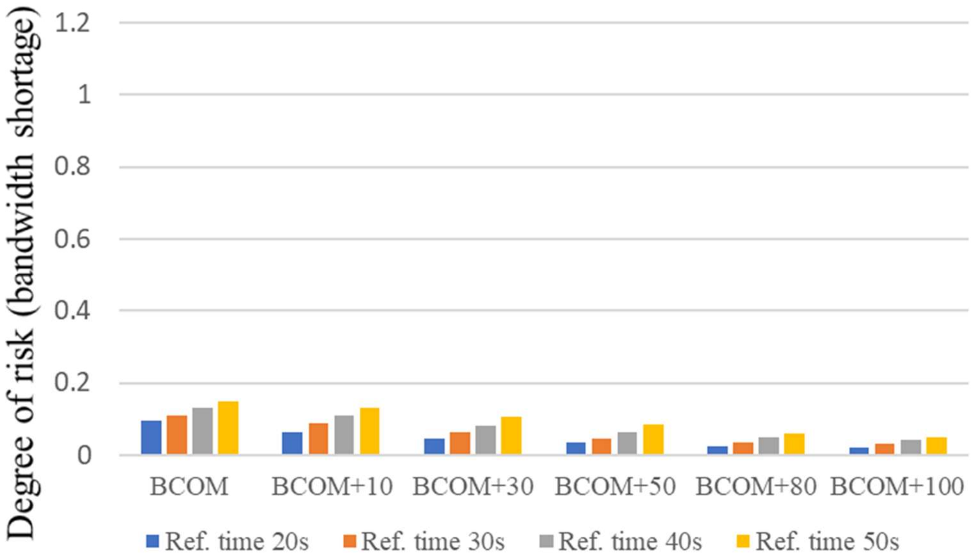


Figure 6.22 Potential risk of allocated bandwidth (when passing through a mobile)

d) Method for comparison (BCOM and BCOM+)

Based on the above preliminary verification, it is concluded that a reference time of 40 s (20 s for 72 km/h) at a mobile entity speed of 36 km/h and a BCOM+ increase rate of bandwidth of approximately 30% are suitable as key parameters.

In the following, the author will proceed with verifying the characteristics when the movement of the mobile entity deviates from the plan, which is assumed to be a benefit of BCOM+ under the above major parameter settings.

Figure 6.23 shows the actual traffic and bandwidth allocation characteristics when the time when a mobile entity passes through each cell is delayed from the scheduled time. For example, in the case of traffic in Japan, minute-by-minute changes are always known, so it is assumed that deviations of less than 60 seconds would occur outside the control range as delay orders. Here, the characteristics are shown for a delay of 20 seconds.

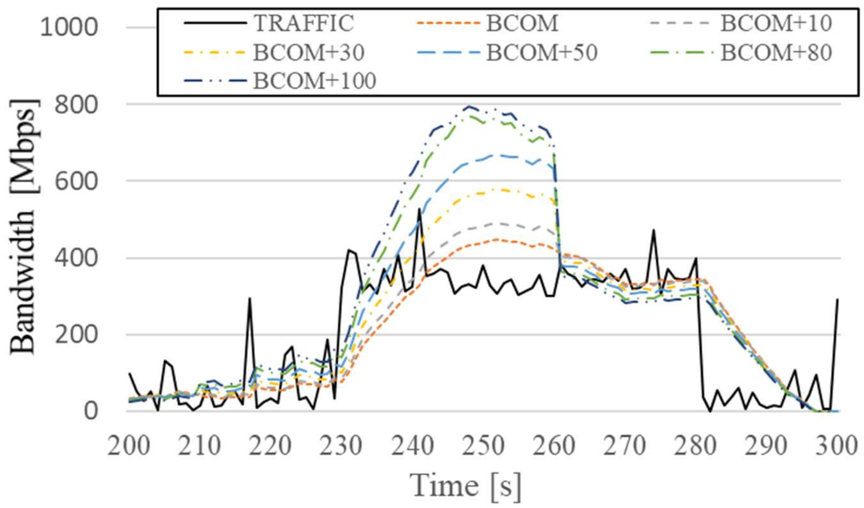


Figure 6.23 Allocation characteristics when mobile delay (the 20s) occurs

Under the above conditions, a comparison of bandwidth allocation margins and shortages during mobile transit is performed in the same way as described in c) above. The results are shown in Figure 6.24 ~ Figure 6.25. BCOM+ (here assuming a rate of increase of 30% based on the results of c) above) is superior to BCOM when the delay time of the mobile is 20s and 30s but is comparable for 40s and inferior for 50s. A possible reason for this result is that increasing allocation control, which is a feature of BCOM+, cannot be performed during the transit time of a mobile entity, and the time ratio of decreasing allocation control is large.

Regarding the above results, two significant points must be sorted out for future BCOM+ performance improvement. The first essential factor is the relationship between the mobile's cell coverage time and delay time. In this verification, based on the mobile entity's speed and assumed cell range, the existing time in the cell is calculated as 50s, which is smaller than the assumed maximum delay time of 60s for the mobile. If the cell range is twice the current assumption, the coverage time would be 100s, and even if the maximum delay time is 60s, the extra BCOM+ control will work for 40% of the time, and the performance regarding safety and risk should be equal to or better than BCOM for all delay time cases.

The second point is to study expanding the time axis direction of the incremental control range, taking into account the delay of the mobile entity. In this case, in addition to the increase in the time period for the incremental control, the time for the incremental control overlaps among the ONUs, and the issue is how to adjust for this overlap.

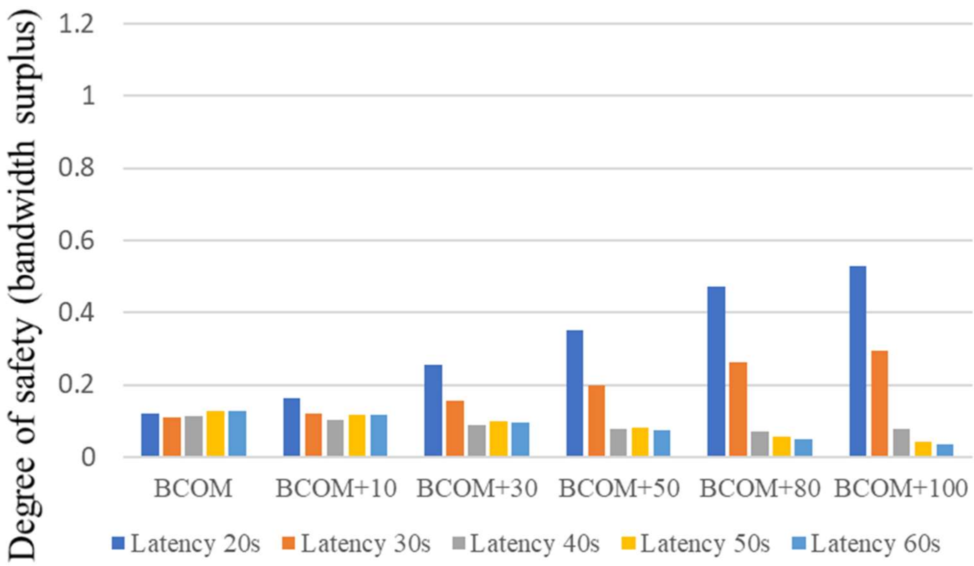


Figure 6.24 Potential margin of allocated bandwidth (when mobile delay occurs)

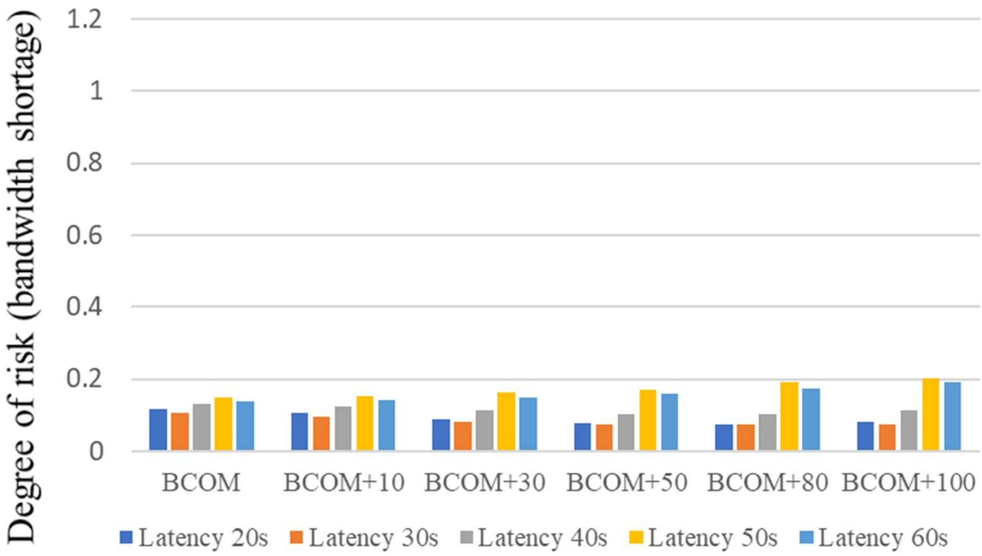


Figure 6.25 Potential risk of allocated bandwidth (when mobile delay occurs)

F. Conclusion

The author has studied bandwidth control schemes for optical access networks that can dynamically implement end-to-end resource control by connecting to wireless communication systems that provide various applications such as 5G and support diverse usage patterns. In particular, as a case where the user requirements change dynamically, the author has studied, proposed, and verified a quick and stable bandwidth allocation scheme for a system that provides a variety of information to both mobile passengers, e.g., on trains and buses, and local residents. The simulation results showed that the proposed method is superior to the conventional method in terms of both safety and risk of bandwidth allocation, regardless of the delay times of the trains and other entities from the scheduled time, as long as the delay time of the entity is approximately half of the time the entity remains in each cell. In the future, the author plans to expand further on the conditions under which significance can be demonstrated and to conduct an evaluation that considers the efficiency of network resource utilization.

Furthermore, it is considered necessary to evaluate bandwidth allocation assuming two-dimensional movements, such as buses and the flow of people. Additionally, the author should also discuss at what is the point of statistical multiplexing effects. Through the discussion, it becomes possible to organize the architecture of the network systems.

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7. Conclusions

This dissertation summarizes results of research and development on resource control for optical access networks that support FTTH, mobile accommodation, and even diverse application for industrial use cases. It also includes outcomes of standardization proposals for high-speed, large-capacity and virtualization for PON systems.

In Chapter 2, trends in sophistication toward the spread of optical access networks and expansion of application areas are presented. There are trends from FTTH to industrial applications linked to wireless networks such as 5G. International standardization of architecture for applying virtualization technology to optical access networks is also presented as one of results regarding this dissertation. The standardized architecture has been developed to serve as the basis for realizing the above industrial applications. The primary achievement is the standardization of ITU-T Recommendation Y.3151.

In Chapter 3, Optical access network for FTTH is described. Prototype of bandwidth allocation method that supports mixed migration from 1G class PON to 10G class PON is demonstrated. One of the main results is that author confirmed the effect of reducing data transfer time (up to about 1/10) compared to the conventional SR-DBA method. The second one is achievement of maximum throughput of 8.63Gbps (99.7% of theoretical maximum bandwidth).

In Chapter 4, optical access network suitable for accommodating mobile communication base stations is introduced. Prototype of bandwidth allocation method compatible with low-latency transfer required for mobile fronthaul is demonstrated. The main result is achievement of low latency transmission (at 20km) of 139us upstream, which fully satisfies the mobile fronthaul requirement of 250us.

In Chapter 5, optical access network supporting resource control of wired and wireless integrated networks is introduced. Verification of a resource control method using network virtualization technology for commonality between heterogeneous networks is performed. The main result is achievement of dynamic allocation with a processing time of 0.5ms (at 30 slices) using a judgement method using abstract resources.

In Chapter 6, optical access network with resource control functions that respond to dynamic requirements changes is introduced. Enhanced responsiveness of allocation control by linking applications to the method predicting requested resources using traffic monitors is proposed. The main result is high response characteristics by utilizing location information (application) of moving objects (trains, buses, etc.).

From a technical point of view, researched technologies in each chapter are shown in Figure 7.1.

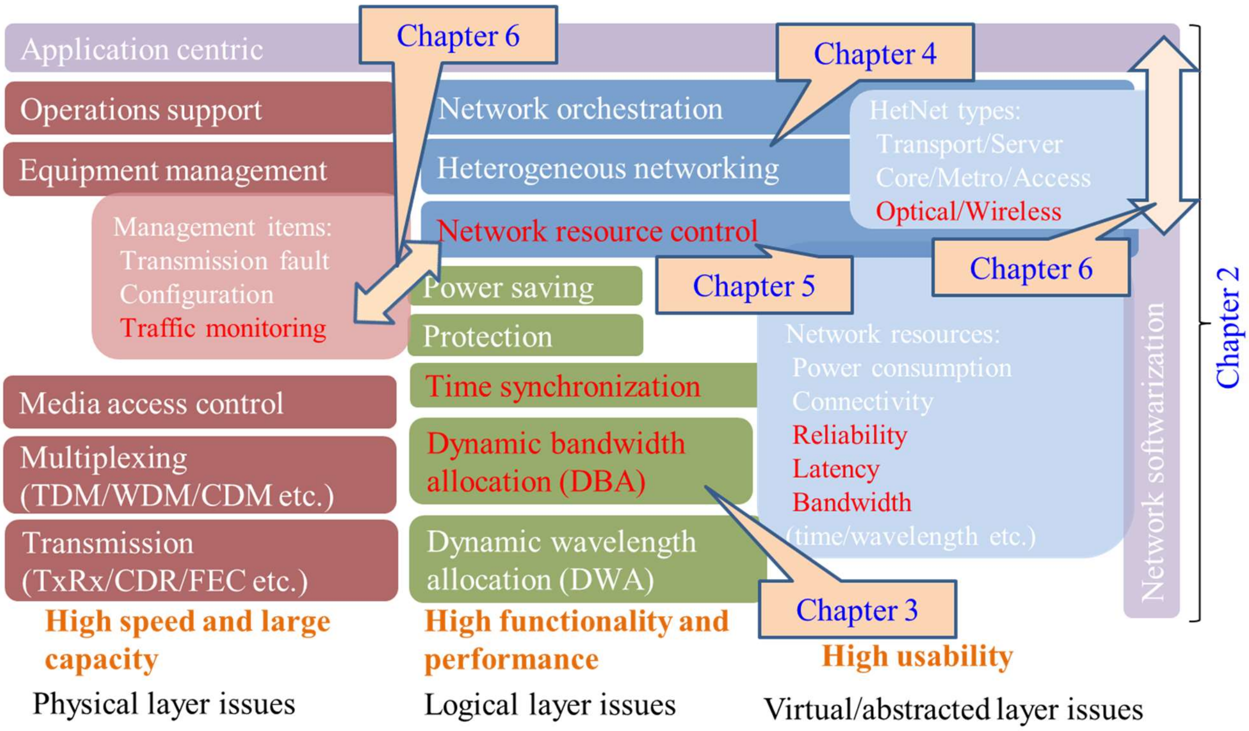


Figure 7.1 Technical overview of the dissertation.

In Chapter 2, although it does not mention specific technical items, it states that many technologies are necessary to expand the application of optical access networks. In order to expand its application, in addition to application-level requirements such as mobility, scalability, flexibility, and connectivity, network requirements such as high speed, large capacity, low latency, reliability, and availability are also involved.

Chapter 3 mainly describes DBA technology that leads to improved data transfer capacity in optical access networks for FTTH. The main technical issues are for higher speed and larger capacity.

Chapter 4 describes research results related to bandwidth control on heterogeneous networks using wired and wireless integration. And it technically produces results that lead to improved performance regarding low latency, mobility and connectivity.

Chapter 5 describes resource control technology for optical access networks that is intended for application to mobile fronthaul that accommodates mobile base stations, and targets delay time, bandwidth, and availability as the main resources to be controlled. The requirements to be solved by the research results in this chapter include various multi-services, scalability, and flexibility.

Chapter 6 discusses resource control methods that respond to changes in application requirements, taking traffic fluctuations on mobile devices as a specific example. Other technical features of this research are common control method applying to various network types and utilization of information on applications.

Based on the main results and the challenges solved by the key technologies in each chapter, the author summarize technical contributions of this dissertation in the form of relationships with the main requirements of communication networks (Table 7.1).

Table 7.1 Relationship between technical contributions and requirements of communication networks

Requirements	Key technology	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6
		All	DBA	HetNet	Resource control	TM&AP based RC
Specification	High speed / large capability	Related	Applicable		Related	
	Low latency	Related		Applicable	Related	
	Availability / Reliability	Related			Related	
Application	Mobility	Related		Applicable		Applicable
	Scalability / Flexibility	Related			Applicable	Applicable
	Connectivity	Related		Applicable	Related	
	Multiple services	Applicable			Applicable	Applicable

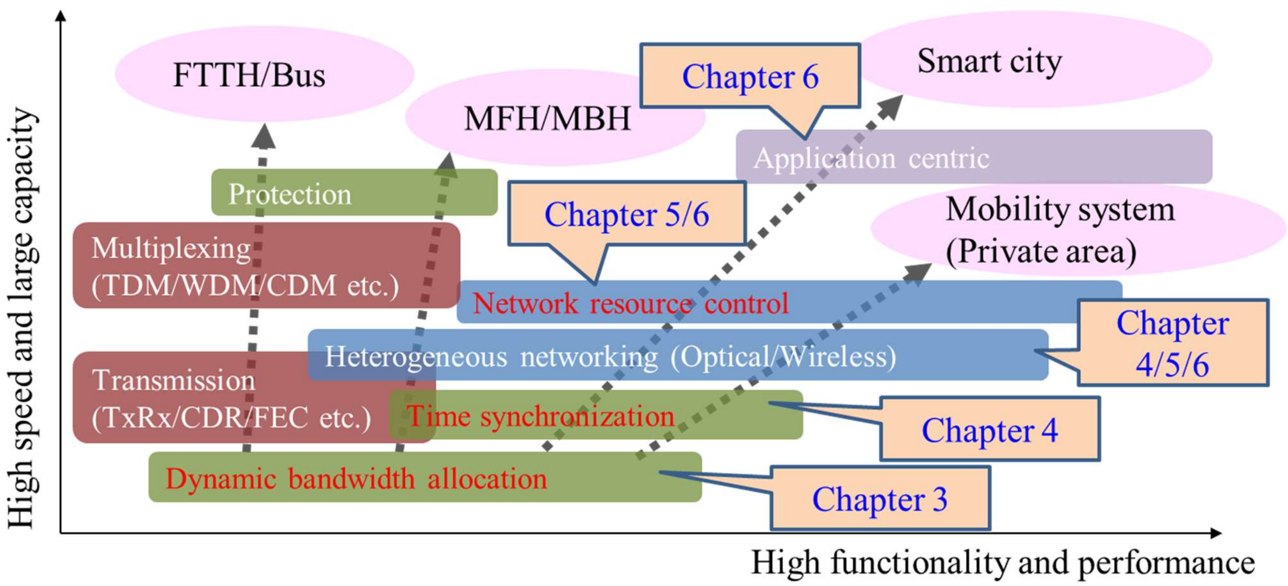
*: HetNet: Heterogeneous Network, TM: Traffic Monitoring, AP: Application, RC: Resource Control

Finally, author concludes this dissertation with future vision of utilizing research results to expand the application of optical access networks. Figure 7.2 shows business areas as application of optical access network. There are 2 types of technologies, one is for high speed and large capacity, the other one is for high functionality and performance. Primary targets of each type of technologies are as follows;

1) High-speed, large-capacity technology: Upgrade for FTTH, expansion for offices
2) High functionality and performance
(time synchronization for wireless base station accommodation, optical wireless cooperative control):
Application to mobility service infrastructure in private and/or limited areas.
3) Integration of both types (adding technologies such as abstracted resource control and application linkage):
a) Application to accommodating mobile communication base stations supporting multi-services such as 5G/6G.
b) Expansion into a smart city that implements various applications such as regional information, seamless movement, and regional disaster prevention.

The high-speed, large-capacity technologies that have produced results in Chapter 3 are expected to be upgraded for FTTH and expanded to offices. The high functionality and performance technologies such as low latency and mobility described in Chapter 4, and multi-services and scalability/flexibility described in Chapter 5 are expected to be applied to infrastructure for mobility services in private areas and restricted areas. Furthermore, by combining these technologies and adding technologies such as abstracted resource control and application coordination, it is expected to provide network systems that can accommodate 5G/6G base stations supporting multi-services, and the systems for smart cities that implement various applications.

The author closes the dissertation by describing future research topics. When considering application to enterprise usages such as office environments, there is room for consideration in the future in combination with technology that improves reliability such as PON protection. Additionally, it is also necessary to consider the sophistication of optical access networks in case that 6G technologies are applied to the network. In particular, it is expected that the range of application will further expand by improving network autonomy through the use of AI, etc., by realizing dynamic control of network load and PON placement using virtualization technology, and by dynamically linking with applications. From the perspective of standardization, it will also be important to consider architecture and interfaces for collaborative control of wireless and wired systems in real time, as well as collaboration at the controller level between SDN systems and NFV systems.



FTTBus: Fiber to the Business, MFH/MBH: Mobile Front/Back Haul

Figure 7.2 Expected business areas as application of optical access network.

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Achievements

A. List of paper for the dissertation:

[A1] Seiji Kozaki, Akiko Nagasawa, Takeshi Suehiro, Kenichi Nakura and Hiroshi Mineno, "An Efficient Resource Allocation Using Resource Abstraction for Optical Access Networks for 5G-RAN," IEICE transactions-B Vol.E105-B, No.4, pp.411-420, Apr. 2022

B. List of papers and conferences related to the dissertation:

[B1] Yuki Hatanaka, Kohei Sasagawa, Tetsuya Yokotani, Seiji Kozaki, Hiroshi Mineno, Takeshi Suehiro, Kenichi Nakura and Satoshi Shirai, "A user-level traffic control function for interworking between optical access and 5G mobile networks," IEICE Communications Express (ComEx), Volume 11, Issue 12, 852-857, Dec. 2022

[B2] Seiji Kozaki, Hiroshi Mineno, Takeshi Suehiro, Kenichi Nakura, Satoshi Shirai, Yuki Hatanaka and Tetsuya Yokotani, "A proposal on the management interface in BCOM for bandwidth assignment in cooperation between 5G and PON systems," Proceedings of ICETC 2022, S13-8, Dec. 2022

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[B4] Seiji Kozaki, Hiroshi Mineno, Tetsuya Yokotani, Takeshi Suehiro, Kenichi Nakura and Satoshi Shirai, "Evolution of optical access networks and implementing low-latency transfer systems," Proceedings of JAC-ECC 2023, pp.102-107, Dec. 2023

[B5] Seiji Kozaki, Hiroshi Mineno, Yuta Tachikawa, Ryo Murakami, Yuki Hatanaka, Tetsuya Yokotani, Takeshi Suehiro, Kenichi Nakura and Satoshi Shirai, "Resource control of access networks responding a dynamic change of application requirements," Proceedings of ICOIN 2024, pp.132-137, Jan. 2024.

Awards

1. The Ichimura Prize in Industry for Excellent Achievement, Ichimura Foundation for New Technology, April 2018.
2. IEICE Milestone, The Institute of Electronics, Information and Communication Engineers, September 2017.
3. National Commendation for Invention, Japan Institute of Invention and Innovation, June 2012.
4. Certificate of appreciation for development of IEEE standard, IEEE SA, April 2010.