論文 / 著書情報
Article / Book Information

題目(和文)	Beyond 5Gセルラ―ネットワークのためのマルチアクセスエッジコンピューティングの設計及び実装に関する研究
Title(English)	Design and Implementation of Multi-Access Edge Computing for Beyond 5G Cellular Networks
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出典(和文)	学位:博士（工学）, 学位授与機関:東京工業大学, 報告番号:甲第12186号, 授与年月日:2022年9月22日, 学位の種別:課程博士, 審査員:廣川 二郎,阪口 啓,山岡 克式,TRAN GIA KHANH,西方 敦博,青柳 貴洋,福田 英輔
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第12186号, Conferred date:2022/9/22, Degree Type:Course doctor, Examiner:,,,,,,
学位種別(和文)	博士論文
Type(English)	Doctoral Thesis

Doctoral Thesis

Design and Implementation of Multi-Access Edge Computing for Beyond 5G Cellular Networks

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Acknowledgments

I would like to acknowledge and thank my supervisor, Prof. Kei Sakaguchi, for his kind guidance and support in accomplishing this research. His advice and support throughout all stages of my research and doctoral thesis have been instrumental in helping me. In addition, I thank him for his generous support of conferences and journals. I would also like to thank Prof. Hirokawa, Prof. Yamaoka, Associate Prof. Tran, Associate Prof. Nishikata, Associate Prof. Aoyagi, and Specially Appointed Prof. Fukuda as my committee members who gave me much grateful advice to improve the quality of this thesis and research. Special thanks to Associate Prof. Maruta for valuable comments on research and feedback on problems. They were always willing and prompt to assist me; again, thank you.

Furthermore, I am grateful to emeritus Prof. Araki and special Associate Prof. Yu Tao for their valuable advice during my seminar presentations. I would also like to thank Ms. Minami and Ms. Funabashi for their kindness and assistance in Lab Life. In addition, I also would like to thank all members of Sakaguchi-Tran Lab who helped me a lot during campus life. Finally, I would like to express my deepest gratitude to Professor Emeritus Karasawa for advancing my doctoral studies. I would also like to thank my supervisors and colleagues at Fujitsu and Rakuten Mobile for their support in balancing university and work. I would also like to give special thanks to my family for their continuous support and understanding when undertaking my research and writing my project.

Abstract

The quality-of-service (QoS)/quality-of-experience (QoE) demands of mobile application services have soared and have overwhelmed the obsolescence capability of current cellular networks. Also, the satisfaction of some service requirements is still in a dilemma, especially the end-to-end (E2E) latency, which varies in different applications. Therefore, multi-access edge computing (MEC), where services, computing resources, storage, etc., would be deployed at the network's edge, is a key technology. In addition, MEC enabler for Beyond 5G, supporting next-generation communications in service guarantee (e.g., ultra-low latency, protection of network congestion, high security) from an E2E perspective. However, MEC deployment in production has several challenges due to unclear points.

This thesis proposes a new ecosystem for MEC to support as the basic platform for next-generation networks (e.g., Beyond 5G (B5G)/6G) to establish a more accurate MEC ecosystem. This thesis compares it with current ecosystems and evaluates it quantitatively through a measured traffic model. Based on that, it defines the resources required for MEC deployment and their impact on latency, computing resources, and application load in three typical variable parameters. Furthermore, an orchestrator for operational methods to support the MEC ecosystem is developed. Finally, the system is a quantitative evaluation through Proof-of-Concept fields to demonstrate its validity.

In the light of the above challenges, the new operator as a Private/Local Operator in MEC ecosystem is proposed. The proposed novelty system can support the ecosystem when MEC are deployed and guarantees the number of MEC resources that maximize the benefit of the new MEC operator. The authors further analyze the interests of other relevant operators in an ecosystem and work on the optimal number of backhaul capacity and MEC.

Finally, this dissertation designs the architecture for fully virtualized MEC 5G cellular networks with some use cases. Also, this dissertation proposes a MEC/Cloud Orchestrator implementation for intelligent deployment selection. Regarding the feasibility of this pro-

posal, B5G testbed is constructed in Ookayama Campus of Tokyo Institute of Technology. Furthermore, the author conducts proof-of-concept through an outdoor field trial where state-of-the-art hardware and software are deployed.

Chapter 1

Introduction

In the last decade, edge computing has discussed and developed rapidly. Edge computing is an integral part of the computing system and refers to deploying computing resources on the edge of networks compared to cloud computing. Other computing classifications include fog computing, which is defined in the same field as edge computing, and mobile edge computing, which is deployed in mobile networks. Further enhancement of mobile edge computing, Multi-Access Edge Computing (MEC), including wired/WiFi and mobile, will enable lower latency and reduced traffic volume. This thesis focuses on MEC, which is a part of edge computing. This Chapter overviews the MEC system, motivates the research challenge addressed in this thesis and summarizes our contributions.

1.1 Background

In modern societies, mobile communication services are ubiquitous. Over recent years, mobile traffic in cellular networks has rapidly grown [1] due to mobile devices' flourishment (e.g., Smartphones/Tables, Internet-of-Things (IoT) devices, Augmented Reality (AR)/Virtual Reality (VR)/ Mixed Reality (MR)) and these applications (e.g., multimedia streaming, social networking, and healthcare). Mobile network data traffic is expected to continuously increase at an annual average of 46 % and reach 77 exabytes per month by 2022 [2]. To accommodate such growth of mobile data traffic, the fifth generation (5G) mobile communication system adopts the millimeter-wave (mmWave) frequency band higher than 24 GHz, where rich spectrum resource is available to achieve ultra-high capacity [3,4,5,6]. In addition, beamforming technology is exploited to compensate for the coverage shortage of mmWave due to the significant path loss. Massive MIMO (Multiple-Input and Multiple-Output) and other techniques have also been introduced to 5G to enhance simultaneous connections [7] further. A heterogeneous deployment of small cell mmWave networks onto sub-6GHz macro cells has been proposed [8,9,10] to take its advantages in 5G fully. However, current leading services are mainly stemmed from the 3G/4G-driven smartphone platforms. As a result, the extraordinary features of 5G such as ultra-high throughput have not been fully leveraged [11]. Especially, there is no de-facto service or scenario demonstrated in 5G mobile communications and featuring enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), and Ultra-Reliable and Low Latency Communications (URLLC) defined by ITU-R (International Telecommunication Union) M.2083 [12] in 2015. Therefore, global mobile communication companies scramble to ship 5G services in various domains and gradually release more functions.

Meanwhile, the shift from Mobile Virtualized Network Operator (MVNO) to Mobile Network Operator (MNO) is progressing [13], , and new operators [14,15] are being established in markets dominated by the existing mobile network operators. In this trend, virtualization, which can support everything from Radio Access Networks (RAN) to applications, helps to quickly provide service at low cost. As a result, various operators [16] can more easily start and provide mobile services. Thanks to innovation in virtualization technologies, edge computing enables third-party applications to access network/computing/disk resources in resource pools without being aware of their physical locations. Hence, various businesses owner can create and provide mobile services more efficiently.

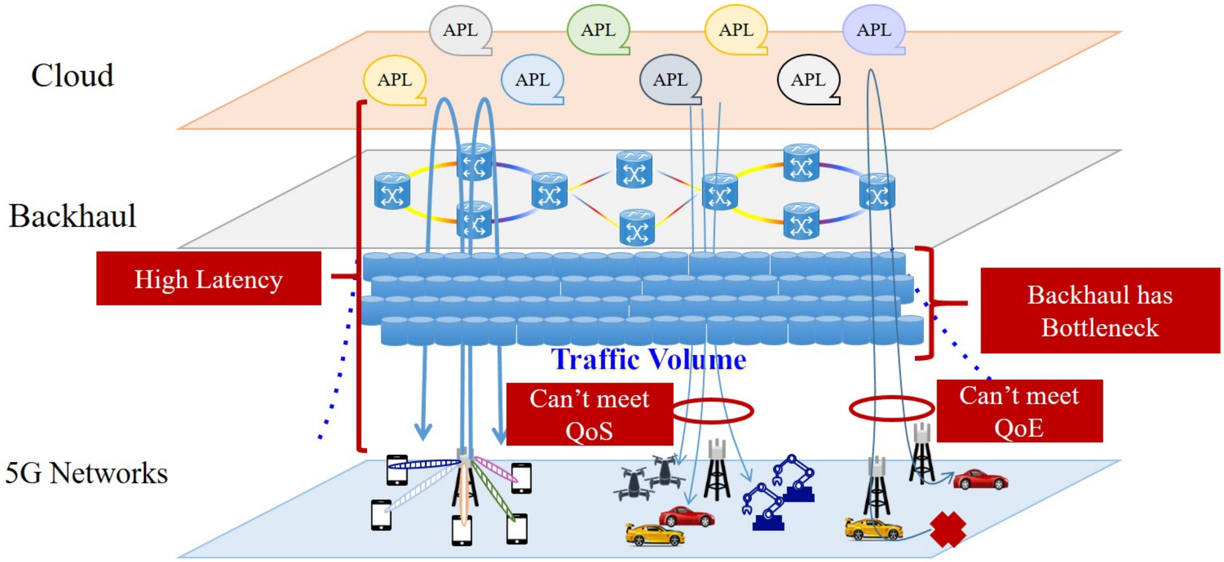
By utilizing mmWave frequency bandwidth, the 5G system can support the exponential growth of mobile data traffic demand, which is arisen from the emergence of cloud services (e.g., YouTube, Netflix, Hulu) that mainly used via WiFi or wired networks (e.g., Ethernet) [17]. The total traffic in cloud will not only exert pressure on the access side but also on the backhaul side (likewise referred to as back-net or backbone or transport network) [18,19]. Hence, the backhaul side would become a bottleneck because of the limited capacity [20,21,22,23]. Besides, since the small cells' coverage gets shorter at the higher frequencies, a large number of small cells and backhaul links (e.g., optical fiber) should be deployed, resulting in large capital expenditure (CAPEX). The penetration rates of optical fiber in most countries are still at deficient levels [24]. Even though the mmWave access is introduced in such a low-capacity backhaul network, the system throughput will be constrained due to the backhaul side's bottleneck. In Beyond 5G (B5G) era, various services are going to appear, such as automated driving, public safety utilizing the unmanned aerial vehicle (UAV), 4K video streaming, virtual/augmented reality (VR/AR), etc [25,26,27,28]. The amenity of these applications is sensitive, especially to the end-to-end (E2E) latency.

The current mobile network structure is shown in Fig. 1.1(a). Besides the backhaul bottleneck, the E2E latency increases since the application traffic are processed in the cloud. As a result, the Quality of Service (QoS)/quality-of-experience(QoE) requirements cannot be satisfied.

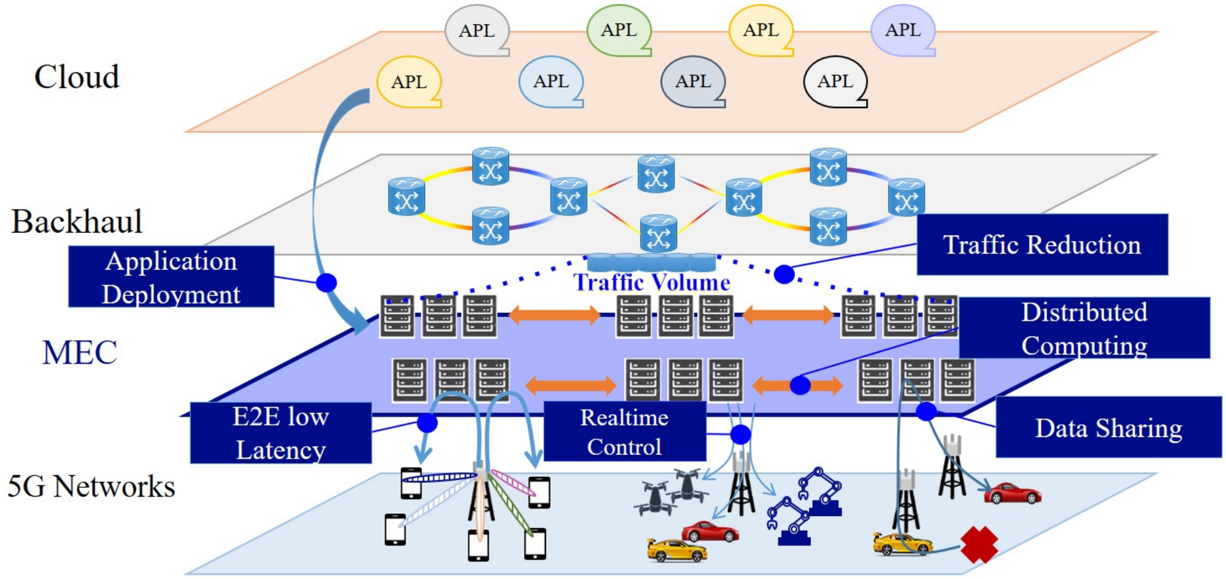
Self-driving vehicles may collide, and drones may lose control, which cause fatal accidents. To eliminate the backhaul bottleneck and reduce E2E latency, we focus on Multi-Access Edge Computing (MEC), [29,30,31,32,33,34,35,36,37] deployed at the edge of the network as shown in Fig 1.1(b). Thanks to the innovation in virtualization technologies, the application services, computing resources, and storage resources currently on the cloud side are migrated to the MEC side. It can achieve low E2E latency, reduced backhaul traffic load, and high-speed cache downloading.

Various organizations are established owing to the prospect of MEC, such as Open Edge Computing Initiative [38], Open Fog Consortium [39], Automotive Edge Computing Consortium (AECC) [40], millimeter-wave Edge cloud as an enabler for 5G ecosystem (5G-MiEdge) [41], European Edge Computing Consortium (EECC) [42], Edge Computing Consortium [43], etc., to investigate further and standardize this novel technology. Although testbeds and Proof-of-Concepts (PoCs) have been implemented worldwide [44,45,46,47,48,49,50,51,52], the feasibility and evaluation of this technology into real products and services are still unclear, especially from the operators' perspective. Most of the state-of-the-art work in 5G and beyond only show the potential benefits of MEC in terms of technical issues [53,54,55,56]. Since the 4G era, consortia and organizations of interest have been devoting efforts to promoting MEC as seen in demonstration experiments and press releases [57,58,52,50]. However, no valuable service has been delivered yet. Its discussions are still ongoing while the 5G service has started. As stated in Ref. [59,60,61,62], for its reason, new infrastructures are required to be installed to deploy MEC because current mobile networks have not been well compatible with virtualization technology. Besides, key use cases are eagerly awaited, and management and operation strategies for MEC applications should be clarified.

On the other hand, the 3rd Generation Partnership Project (3GPP) has involved MEC as local data networks in the architecture design from Release 15 [63]. It defined the N3 interface to associate MEC with the User Plane Function (UPF) of 5G Core (5GC) and designed a



(a) Problem of B5G cellular networks (w/o MEC).



(b) Benefits of Beyond 5G MEC cellular networks (w/ MEC).

Figure 1.1: Architecture of B5G MEC-assisted cellular networks.

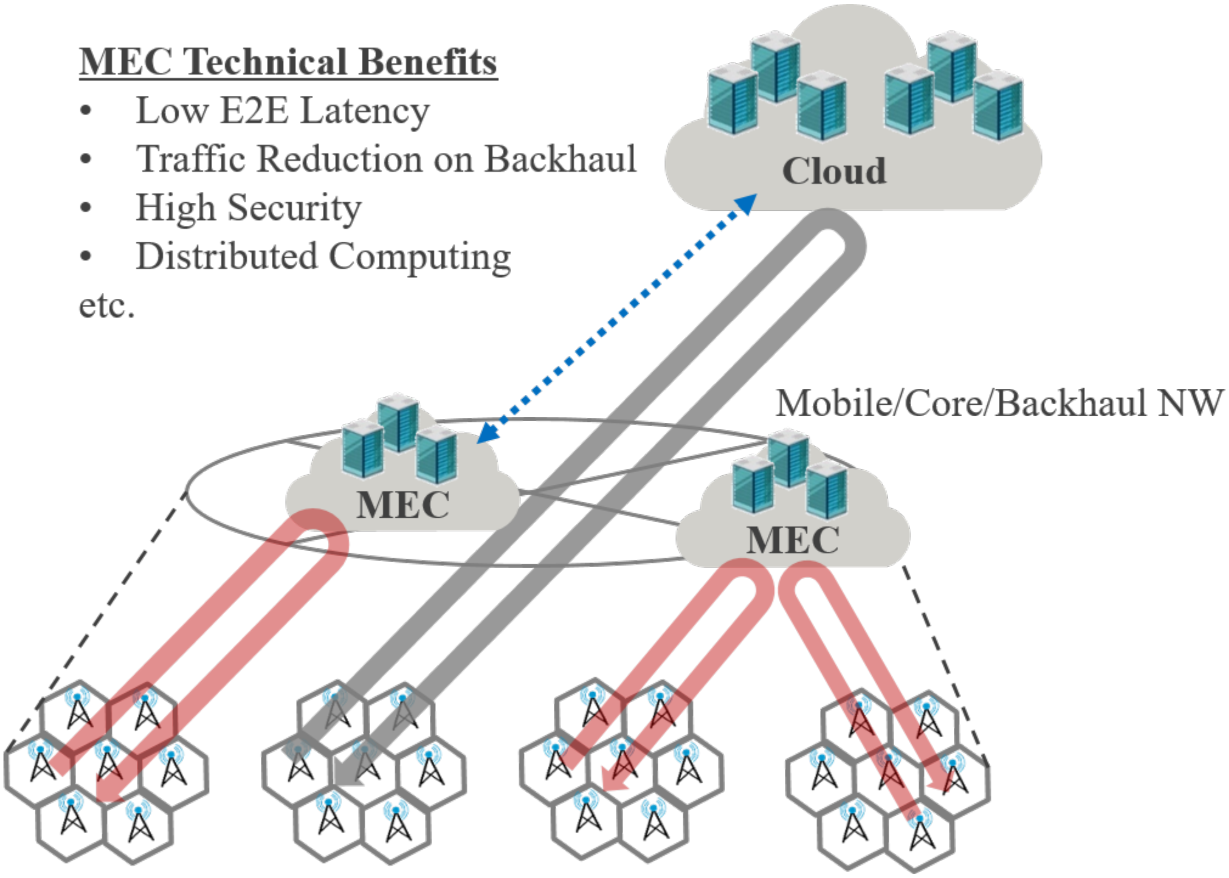


Figure 1.2: Basic benefits of MEC compared to cloud System.

local breakout for data traffic routing. Moreover, in globally published white papers on B5G, MEC employing virtualization technology has been acknowledged as one key enabler and an essential architectural network component.

In general, discussions regarding MEC are centered on technical implementation. There is a few debates concerning MEC business models like “Who will use” and “How to use”. Existing operators try to develop MEC service scenarios, but the business model for cooperation with existing cloud services designed by other players has not yet been formed. That is why MEC was under consideration since 4G has not delivered any de-facto service, and it is hard for third-parties to deploy their applications freely. In addition, previous studies rarely refer to the operators’ challenging decision of whether and how to install MEC in cellular networks due to the uncertainty of reward from their MEC investments. The realization of killer applications running on MEC could attract its attention in an absolute sense.

1.2 Related works

This section introduces the background of MEC, as shown in Fig. 1.2, from its origin and surveys existing related research on the key technologies of MEC to highlight their differences from this thesis. Table 1.1 summarizes all related works mentioned in this section, and the details are described in each Chapter.

1.2.1 The birth of MEC

Cloud computing (or cloud service) is the opposite system of the on-premise, which owns the IT infrastructure. The terminology “cloud service” is referred to by Google CEO Eric Schmidt in 2006 [64]. Since the early 1990s when internet services started blooming [65], similar systems such as Application Service Provider (ASP) have conducted considerable trial and error. Meanwhile, the history of virtualization technologies dates back to 1972, when IBM released the System/370 as a mainframe [66]. Twenty-six years later, Professor Mendel Rosenblum of Stanford University established the technology stack to virtualize x86 CPU systems [67], so the prospects of commercialization were set up. Under the fast development of OS/hardware, the hypervisor was released [68], and it has been widely used since 2008. As a key enabler of cloud computing, virtualization technologies facilitate the penetration of cloud services significantly [69].

Thanks to virtualization technologies, the orchestrator can quickly deploy applications and operates applications via API (Application Programming Interface) anywhere in a COTS server on the network anytime. In addition, fog computing is a concept advocating the deployment on the network side instead of the cloud [70]. In this background, ETSI has proposed mobile edge computing in 2014 [71]. The difference between fog computing and mobile edge computing is the proximity level to the terminal side. Mobile edge computing is closer to the terminal side and can process the GTP-U (GPRS Tunneling Protocol User plane) packet. Furthermore, the birth of MEC in 2017 targets accommodating non-cellular networks such as wired networks and WiFi to mobile edge computing [72].

1.2.2 MEC architecture studied

In this thesis, the role and location of MEC are both discussion themes. The related research and investigation results are shown below. In Ref. [73], MEC is regarded as one of the types

Table 1.1: Comparison of Related Technical Works on Several Perspectives

Aspect	**Ref**	**Main Contribution**
Trajectory of MEC	[64,65,66,67,68,69]	The history of cloud computing is summarized. (From computing to virtualization.)
	[70]	Fog computing was deployed as the first concept of deployment in the network edge side.
	[71,72]	MEC supports cellular networks and non-cellular networks.
MEC Architecture	[73]	Edge/Fog Computing Proposal Concept-Based Architecture.
	[74,75,76]	MEC deployment scenario is in front of Core function.
	[77,78,79]	Function level architecture such as DNS, Information-Centric Networking,etc.
	[80,81,82]	C-V2X specialized architecture have been discussed.
MEC/Cloud Computing Cooperation	[83,84,85,86,87,88]	Offloading cooperation such as latency and power consumption with several architecture models.
	[89,90,91]	Distributed computing discussion such as Hierarchical Edge Cloud Design, Multi Layers processing.
PoC, Test-Beds, Implementation	[92,93]	Describes the MEC orchestrator and signaling for service provision.
	[94,95]	Demonstration of edge computing: Distributed edge computing.
	[96,97,98,99]	Platform controller has been discussed about implementation comparison of Fog Computing/ cloudlet/MEC.
	[100,101,102]	Application implementation (e.g., AR) as an edge computing.
MEC Business	[103,104,105]	Several Consortiums have been discussed about business model and established several Open Labs.
	[106,107,108]	Legacy Telecom Operator scenarios in MEC have been discussed

of Edge Computing where architecture, including Edge/Fog Computing, is proposed. There is a concept-based discussion, but it does not refer to the players. In the architecture shown by ETSI in Ref. [74,75], it is possible to deploy MEC in front of the core functions. Ref. [74] mainly shows an example of use cases where the MEC holder is an existing operator, but it does not specify MEC location. Ref. [75] discusses the collaboration between multiple legacy operators but does not discuss other players such as local players or third parties. Although Ref. [76] makes architectural proposals focusing on MEC's NFV capabilities, it has not dug into the specific component level. Ref. [77,78,79] are summarized from the viewpoint of MEC functions. In Ref. [77], there is a discussion about how to operate DNS on the architecture to reduce the connection latency to MEC. There is a discussion focusing on ETSI architecture regarding MEC deployment in Ref. [78]. In addition, in Ref. [79], an architectural discussion combining Information-Centric Networking (ICN) and MEC is provided. Using case studies, the literature [80] discusses the architecture specialized for C-V2X (Cellular-Vehicle to Everything). In Ref. [81], a list of functions required for V2X data communication is summarized from the viewpoint of network connectivity. Furthermore, in Ref. [82], those necessary functions are subdivided into four functional layers/levels (Data Center/MEC/Road-Side Unit/User Equipment (e.g., Car)). However, the division of responsibilities is ambiguous because the role of the architecture has not been identified. The differences between the above-related work and this thesis cover the viewpoints of each function. Most significantly, this thesis answers who possesses the functions.

1.2.3 MEC/Cloud computing cooperation

Sharing computing resources with MEC and cloud is one of the key technologies; in other words, applications continue to be provided by MEC or cloud deployed without being aware of their physical location. So far, various discussions have been held regarding offloading using MEC and cloud [83,84,85,86,87,88]. Ref. [83,84,85] have simulated a basic computational model that divides processing tasks between MEC and cloud to minimize latency or power consumption. In addition, a more complicated definition of objective function and analysis considering the queue of computing processing is performed in [86,87,88].

On the other hand, distributed computing is also discussed by giving MEC architecture in hierarchical design [89,90,91]. Ref. [89] proposes a hierarchical edge cloud that distributes and deploys computing to reduce the amount of traffic on the backhaul side. Further, in [90], the data sent by User Equipment (UE) is once aggregated on MEC, and MEC performs the first-order analysis of the aggregated data. By transferring only the first-order analysis results to the cloud side, a hierarchical edge architecture is adopted to reduce the amount of traffic in the backhaul network and analyze unique data locally. In addition, data collected by MEC/cloud is stored in multiple different layers of information such as dynamic-map wherein essential map information and time-varying data are embedded. An architecture that links mapping information to applications that enable distribution and linkage of data from the cloud to each MEC is also being considered [91]. According to the related research mentioned above, the current deployment of applications in MEC or cloud is used to image catalog. Since micro-services that divide application functions have already attracted attention, in Beyond 5G, deploying what is needed at the required location and time will be necessary without being aware of each application function's site (MEC or cloud).

1.2.4 MEC implementation & verification

We will discuss two points in the various implementations of MEC: the orchestrators and the PoC being done worldwide. First, regarding orchestrators, in Ref. [92], the MEC Service Function (MSF) is considered an orchestrator. Furthermore, it is discussed that in MSF, applications are deployed either in the MEC or the cloud. Also, [93] describes signaling to MEC and discusses how users connect with MEC applications. However, based on the above, there is no discussion about who will hold what functions as MEC/Cloud Orchestrator, and this is an important issue to be discussed. Thus, this thesis proposes who should have what functions in the MEC/Cloud Orchestrator.

Next, in Ref. [94], the performance is evaluated by implementing the edge computing system in a chip-set. Ref. [95] implemented a framework linking edge computing and cloud computing as a use case. In addition, some other researchers have implemented prototypes for IoT devices [96]. There is also an example of implementing a controller for an edge computing platform. For example, Ref. [97] implements container-based Network Functions Virtualization Infrastructure (NFVI) control using Kubernetes. [98,99,100,101,102] discuss the comparison of Fog computing, cloudlet and MEC. Regarding application implementation in edge computing, some studies implemented and demonstrated experiments focusing on Augmented Reality (AR) and image analysis and discussed processing effectiveness at the edge. Based on the above explanation, it is not easy to understand the effect of MEC on PoC because the system has not been implemented in terms of E2E. So it could not evaluate the effect of MEC on PoC by comparing the performances offered by the E2E network without any MEC and offered by the MEC deployment. Therefore, in this thesis, the system is implemented in E2E and deployed in the outdoor field. By evaluating PoC, we validate MEC in E2E and show its effectiveness.

From the above, we will briefly explain the differences between the two points of the edge computing demonstration experiment and the implementation of the orchestrator, respectively. There is no discussion about the kinds of applications running on virtualization platforms in edge computing regarding the former. Therefore, the effect of edge computing is difficult to understand because it is not implemented based on the architecture discussion, even in the demonstration experiment. Regarding the latter, the use case of orchestrator has not been defined, but only virtualization control is implemented. Still, it is a known technology, and there is some discussion about the orchestrator, including Management and Orchestration (MANO). However, there are still many uncertainties regarding E2E system implementation and design of MEC/Cloud Orchestrator, including scenarios.

1.2.5 MEC business discussion

Trend surveys on service use cases using MEC with players are described in this related research. There are several contents in the service use case. For example, it is about efforts and business models, such as establishing a consortium and collaborating with several companies to verify new technologies with PoCs and submit/propose a requirement definition to a standardization such as 3GPP/ETSI/ITU-R. 5GPPP (5G Infrastructure Public Private Partnership), established by the European Commission, which is the policy body of the European Union, proposed the use cases of MEC and described the advantages of MEC architecture and virtualization [103]. In addition, the open EDGE computing consortium has built the Living Edge Lab as a Hands-on project, focusing on new technology verification such as application and platform tool verification for Edge and architecture verification [104]. There is a movement to establish an open lab and prepare an environment where an open lab could perform various PoC verification immediately. In the past, it was a flow of conducting desk studies and simulations, designing, and PoC. However, with the variety of tools (e.g., Open Source Software) and prototypes (e.g., Arduino) available today, the software can quickly realize ideas. Therefore, it changes to agile-type research and development that repeatedly develops the prototype of the research idea and verification [104,105].

However, it is not easy to plan a strategy for deploying MEC from the viewpoints of operators who introduce MEC. Hence, it is necessary to show the pros and cons of MEC not only from the technical aspects but also from the business aspects. Unfortunately, regarding the business model, only quite a few studies have discussed business aspects of MEC from operators' viewpoints. Several works investigated the use cases and the potential of operators' revenue regarding MEC [106,107,108]. Ref [106] proposed some use cases of MEC in 5G networks, and it mentioned the potential revenue growth for only operators with the deployment of MEC. In [107], the 5G ecosystem's business model with some use cases was proposed when new technology such as MEC is initiated in an existing market. Finally, regarding the benefit of MEC, state-of-the-art MEC deployment research was conducted in [108]. It mentions future research directions from the technical viewpoints. However, they only assumed the potential revenue growth without open data for validation. In conclusion, there is a problem that these s have many conceptual levels and are not yet mature because there are many uncertainties about the specific method of deploying the application possessed by the third parties.

1.3 Summary of contributions

This thesis develops a new paradigm scheme for MEC-assisted Beyond 5G Ecosystem by coping with the mentioned two problems: (1) "Who will use"; Unclear the benefits and business model of MEC deployment (2) "How to use"; Unclear the operation point of view regarding whether and how to install MEC in networks. First, in numerical analysis, user distributions based on uniform distribution are deployed on the heterogeneous network for hotspots and others. Then, a traffic model is generated according to the place of user deployment. Also, a wireless propagation environment model is developed, including correlations of the user's location. Then, these produce an overall network close to the real environment, considering the traffic model and user distribution. Thus, as mentioned above, it lays the foundation for designing the ecosystem to establish the E2E design. The offloading model in the case of MEC and cloud deployments is then defined to develop a new MEC ecosystem. Here, we will create an objective function that minimizes the cost model from the end user's perspective, rather than the traditional selection method with the minimum latency as offloading. Furthermore, we will consider multiple providers during the evaluation process and evaluate them by playing a strategy game to make the evaluation method more feasible and divide it into various conditions. The approach mentioned above enables the establishment of a new MEC ecosystem, shows the superiority of each business, and clarifies "Who will use."

On the other hand, we develops a design for MEC/Cloud Orchestrator. While the main focus is on the use case of MEC and the cloud coexist, some ideas are also applicable for other use cases such as MEC held by each operator. The MEC/Cloud Orchestrator is designed to be divided into two types of management methods: a centralized management method that manages MEC and the cloud together and a distributed management method that works with MEC and the cloud separately. To verify the design and development effectiveness, we designs the PoC field for Beyond 5G as an E2E design. Based on the scheme, we deploys the PoC field and the B5G Edge Cloud at the Ookayama Campus of Tokyo Institute of Technology. With this PoC field, the potential of MEC is clarified. Most importantly, the design and results are shown as "How to use."

Here it is noted that the definition of End-to-End in this study covers Layers from 0 (Physical) to 7 (Application). End-to-End means that the terminal requests the necessary traffic for each application, receives the data at the MEC/Cloud side, processes the data, and replies.

- Chapter 2: Design of B5G MEC Cellular Network Architecture
    1. Introduce basic and general MEC based on technical; The Birth of MEC, 3GPPESTI Standard Direction, and the research overview.
    2. Discuss the system model of MEC architecture and describe the E2E latency model, including wireless, fixed, and computation latency; The most important part of the research on MEC is the system model. Therefore, we will discuss the technical development of MEC and explain the system model. The formulation of the E2E delay will be described to evaluate the system model quantitatively. Finally, this section is summarized in conclusion.
    - This work is published in
        * J. Nakazato, Y. Tao, G. K. Tran and K. Sakaguchi, “Revenue Model with Multi-Access Edge Computing for Cellular Network Architecture,” IEEE ICUFN, 2019, pp. 21-26.
- Chapter 3: Market Analysis of MEC-Assisted Beyond 5G Ecosystem: ‘Who‘
    1. Discuss target use case scenarios and system details; In particular, the discussion will focus on delay and cost optimization as a model for a viable ecosystem. The section of the letter will also clarify each operator’s role in the ecosystem.

2. An objective functions and simulation evaluation for each operator in the ecosystem is performed. At first, this section will discuss only private/local operators to evaluate the trend of increasing revenue as MEC increases. Then, after the proposed objective function is valid, we will discuss the object function of backhaul owner, including the private/local operator and cloud owner. Finally, this section will be discussed those results and summarized in this section.
    - These works are published in
        * J. Nakazato, M. Nakamura, Y. Tao, G. K. Tran and K. Sakaguchi, "Benefits of MEC in 5G Cellular Networks from Telecom Operator's View Points," 2019 IEEE Global Communications Conference (GLOBECOM), 2019, pp. 1-7.
        * J. Nakazato, M. Nakamura, T. Yu, Z. Li, G. K. Tran and K. Sakaguchi, "Design of MEC 5G Cellular Networks: Viewpoints from Telecom Operators and Backhaul Owners," IEEE ICC, 2020, pp. 1-6.
        * J. Nakazato, M. Nakamura, T. Yu, Z. Li, K. Maruta, G. K. Tran, K. Sakaguchi, "Market Analysis of MEC-Assisted Beyond 5G Ecosystem," IEEE Access, Vol. 9, pp. 53996-54008, March 2021.

- Chapter 4: Proof-of-Concept for Fully Virtualized MEC Beyond 5G: 'How'

    1. The background of MEC/Cloud Orchestrator and architecture are explained. In particular, this section is described the required function and diagram and organizes the players, and roles are also included.
    2. Propose an implementation scheme and details of the MECCloud orchestrator. Several implementation schemes based on use cases are proposed. In addition, a network architecture in E2E is designed and deployed on Ookayama campus as an outdoor field. Finally, the performance of MEC in the deployed environment is evaluated.
        - These works are published in
            * J. Nakazato, Z. Li, K. Kubota, K. Maruta, K. Sakaguchi, and S. Masuko, "Fully Virtualization Edge Cloud towards B5G/6G,"EuCNC/6G Summit, 2022.

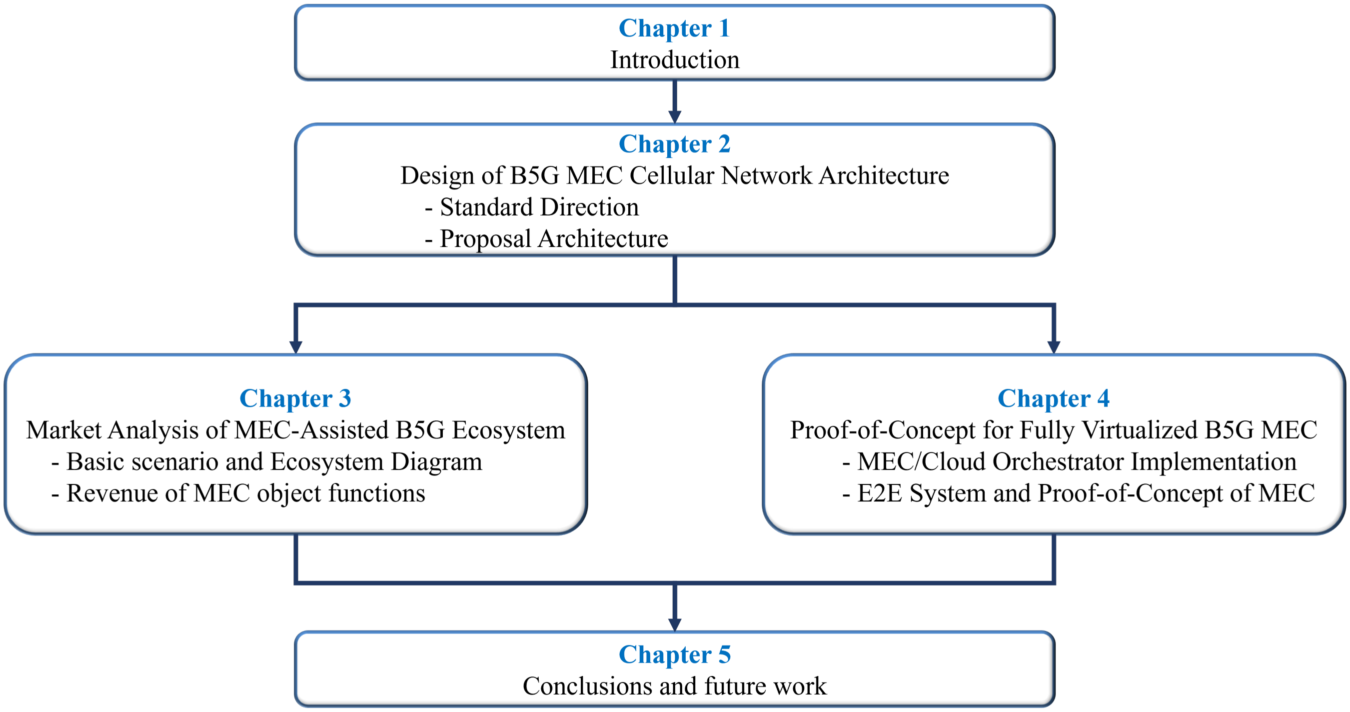


Figure 1.3: The structure and brief contribution of this thesis.

- J. Nakazato, M. Kuchitsu, A. Pawar, S. Masuko, K. Tokugawa, K. Kubota, K. Kazuki, K. Sakaguchi, “Proof-of-Concept of Distributed Optimization of Micro-Services on Edge Computing for Beyond 5G,” IEEE VTC Spring, 2022.
- J. Nakazato, Z. Li, K. Maruta, K. Kubota, T. Yu, G. K. Tran,K. Sakaguchi, S. Masuko, “MEC/Cloud Orchestrator to Facilitate Private/Local Beyond 5G with MEC and Proof-of-Concept Implementation,” Sensors 2022, 22, 5145.

1.4 Organization

The rest of the thesis is organized, as shown in Fig. 1.3. Chapter 2 introduces the direction of 3GPP/ETSI standard to help readers understand State-of-the-Art (SOTA) MEC trends and highlight the contributions of this thesis. In addition, our proposal’s basic architecture is described in this Chapter. Chapter 3 proposes B5G MEC ecosystem and a new operator as a private/local operator. Furthermore, we create each operator’s revenue morel and evaluate them. In evaluation, we also propose two E2E optimization models; one is latency, and the other is the cost model. In Chapter 4, MEC/cloud Orchestrator is presented and describes the implementation with network diagrams and sequences. Besides, E2E architecture and PoC environment are explained. Finally, we conclude the thesis and describe some potential future research venues in Chapter 5.

Chapter 2

Design of beyond 5G MEC cellular network architecture

2.1 Standardization

This section describes standardization trends related to MEC. First, the reference architecture [109] that has been discussed at ETSI is shown in Fig. 2.1. This figure includes functional entities (e.g., MEC host, MEC Platform) and reference interfaces (e.g., MEC Platform (Mp). The reference architecture, as shown in this figure, has two domains; service domain, management domain. The service domain has several components; MEC platform, MEC Applications, and Virtualization infrastructure, which provides virtualization resources (e.g., compute, network, storage). On the other hand, in the management domain, MEC host level and MEC system level are included. Reference points have several roles; MEC platform (Mp), management (Mn), and external entities of the MEC system (Mx). Each reference point has been mentioned in Ref. [109]. In this point, southbound interfaces include Mp2, Mn6, and Mm4. Meanwhile, Mx1 and Mx2 are northbound interfaces. The Data Plane function in virtualization platform is key to achieving low latency in MEC, converting user plane with GTP capselling to the IP layer, and handling traffic to the MEC application. The Traffic Rules control function in MEC platform can change traffic to the destination of the traffic.

Figure 2.2 shows the basic architecture of the 5GC [63]. In this figure, the 5GC architecture is divided into functional levels compared to the 4G EPC (Evolved Packet Core). Here, the functional level is similar to the concept of microservice architecture. Therefore, it is assumed that 5GC will be deployed on virtualization. The virtualization platform is shown

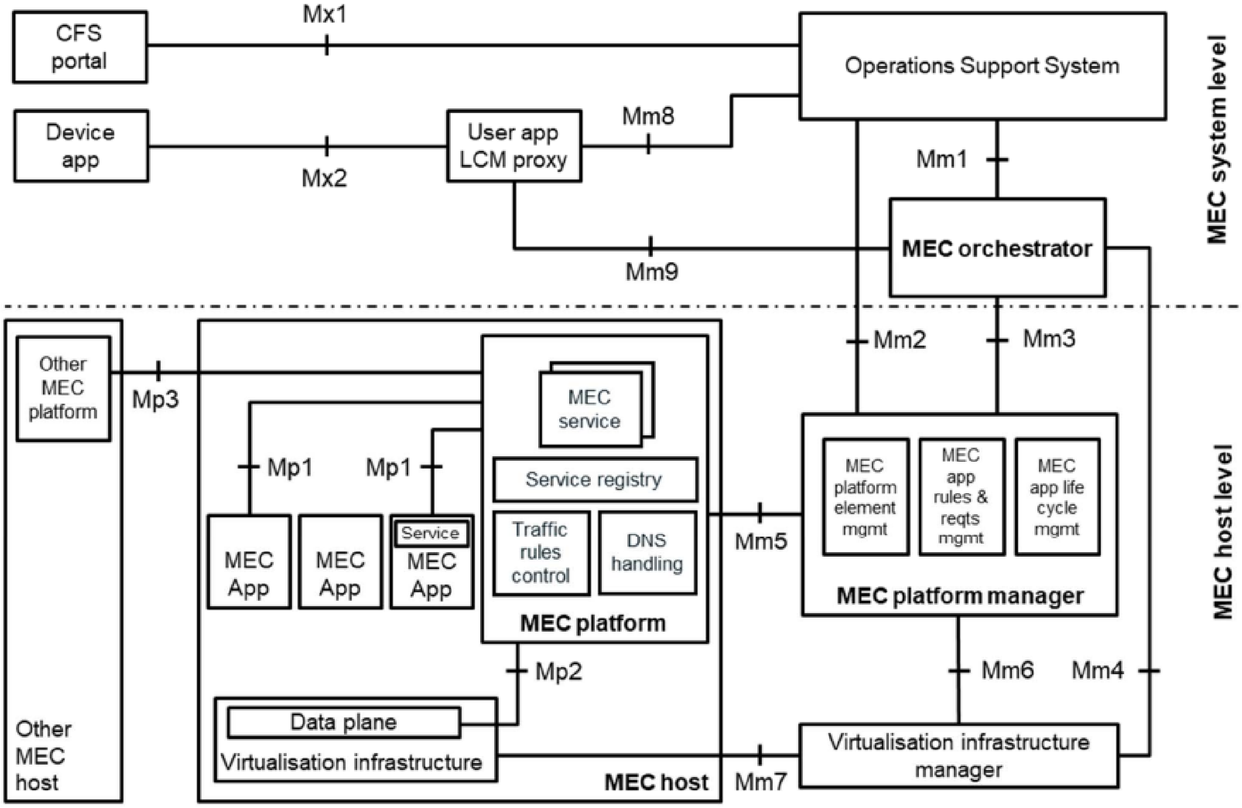


Figure 2.1: MEC Reference Architecture [109]

in Fig 2.1, and the UPF of 5GC is shown in the Data Plane. Therefore, UPF has a function to de-capsulate GTP in the user's Data Plane and is connected by MEC application with n6 interface. On the other hand, MEC Platform holds the external interface, so NEF (Network Exposure Function), AF (Application Function), etc., are similar. Hence, in 3GPP, responsibilities are classified by layer, but in the future, it will be necessary to study end-to-end, and MEC, which is discussed in ESTI, will need to be jointly studied.

2.2 System model

This section describes the system model assumed in this thesis, i.e., network architecture, E2E latency in the traffic model, and end-user's perspective.

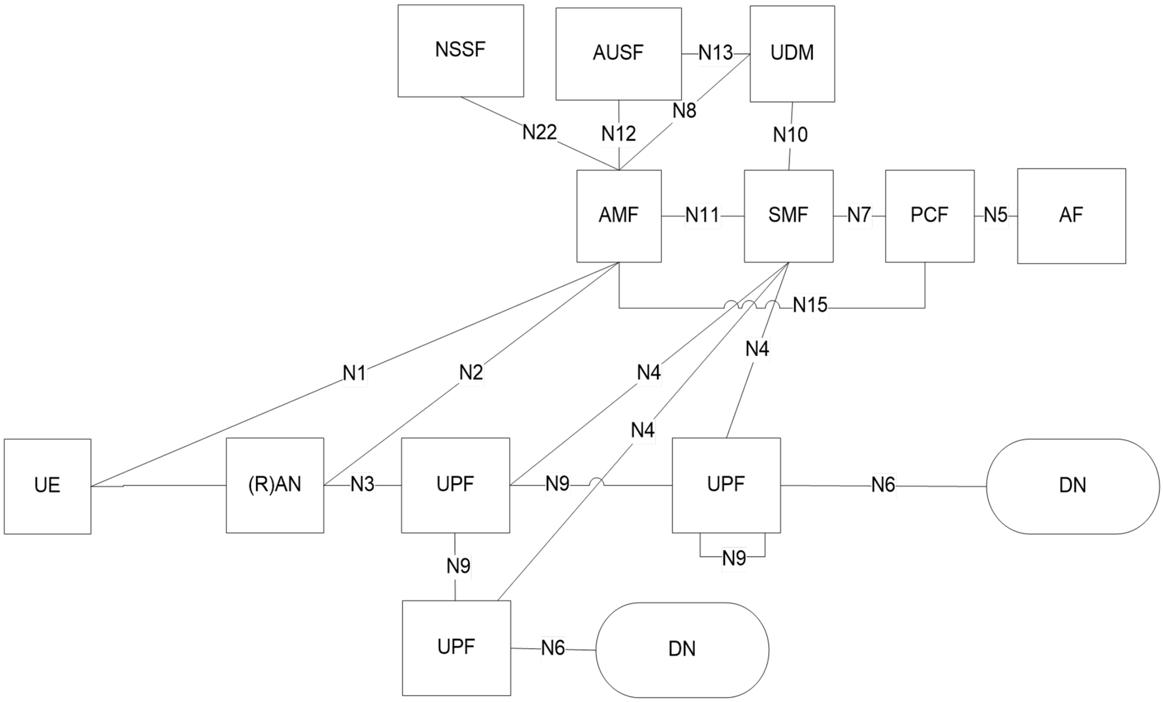


Figure 2.2: 5GC Reference Architecture [63]

2.2.1 Network architecture

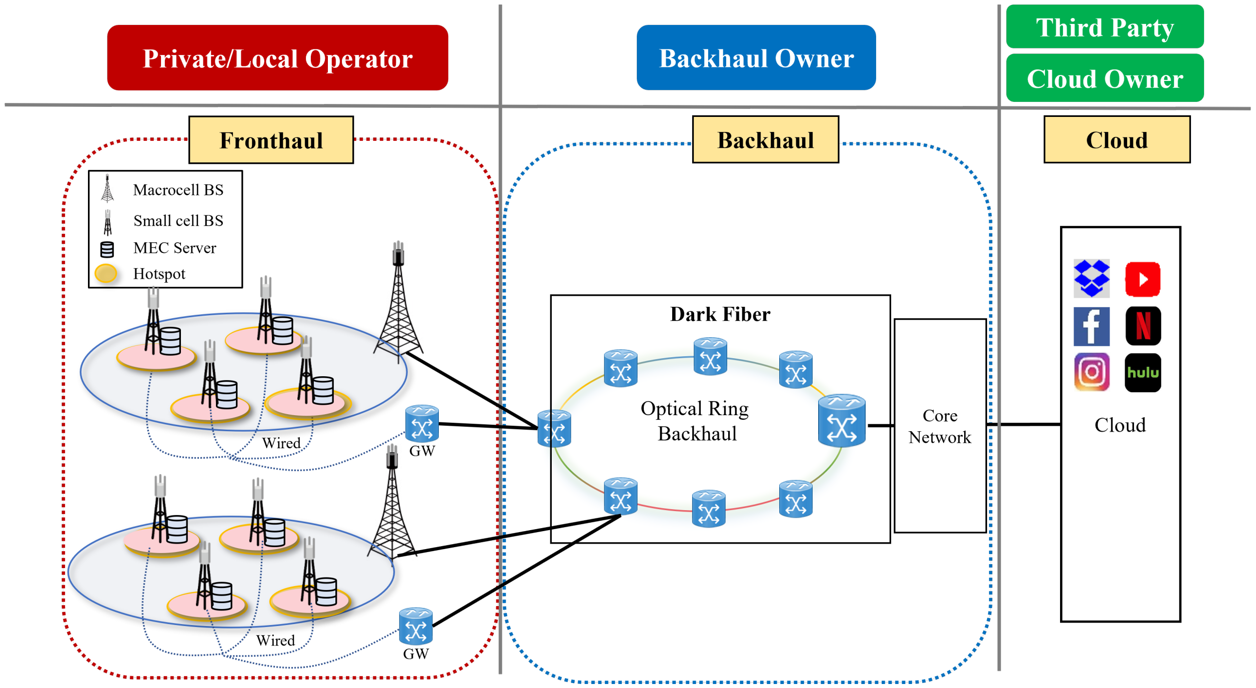
Figure 2.3(a) shows the overall network architecture of the proposed ecosystem architecture consisting of fronthaul (access), backhaul, and cloud. Creating an ecosystem model in MEC, this network architecture is divided into a telecom operator holding the fronthaul side and a backhaul owner with optical fibers that can be loaned to other operators, e.g., dark fibers. Hence, telecom operators can rent the existing backhaul from its owner without laying their private backhaul so that the current resource could be more effective. In this thesis, we propose an ecosystem model for telecom operators with only fronthaul and MEC in hotspot places containing many people, such as airports, stadiums, live events, etc., as shown in Fig. 2.3(b).

In the fronthaul side, we consider the HetNet structure, where mmWave small cells are deployed inside a conventional macrocell, again interfered with by six surrounding macrocells. we assume the network architecture model proposed in [108], where the macrocell is 3GPP (Third Generation Partnership Project) RAN (Radio Access Network), and the small cell is either 3GPP or non-3GPP. The small cell is deployed to cover the traffic concentration area, i.e., hotspot. The small cell has 6-sector mmWave access, backhaul, a wired backhaul link, and MEC. For example, the protocol and frequency band used are the same as those in [110], and the protocol of small cells is based on the IEEE 802.11ad standard [111] in order to use the unlicensed band so that telecom operators could immediately deploy the services. The frequency band of this standard has 4 sub-channels of 2.16 GHz bandwidth in the 57-66 GHz band. In this study, we use only one of the 4 sub-channels for 3-sector on the access side. In each sector, the transmit signal from a small cell is directed to the desired user by beamforming using massive antennas equipped in small cell BSs.

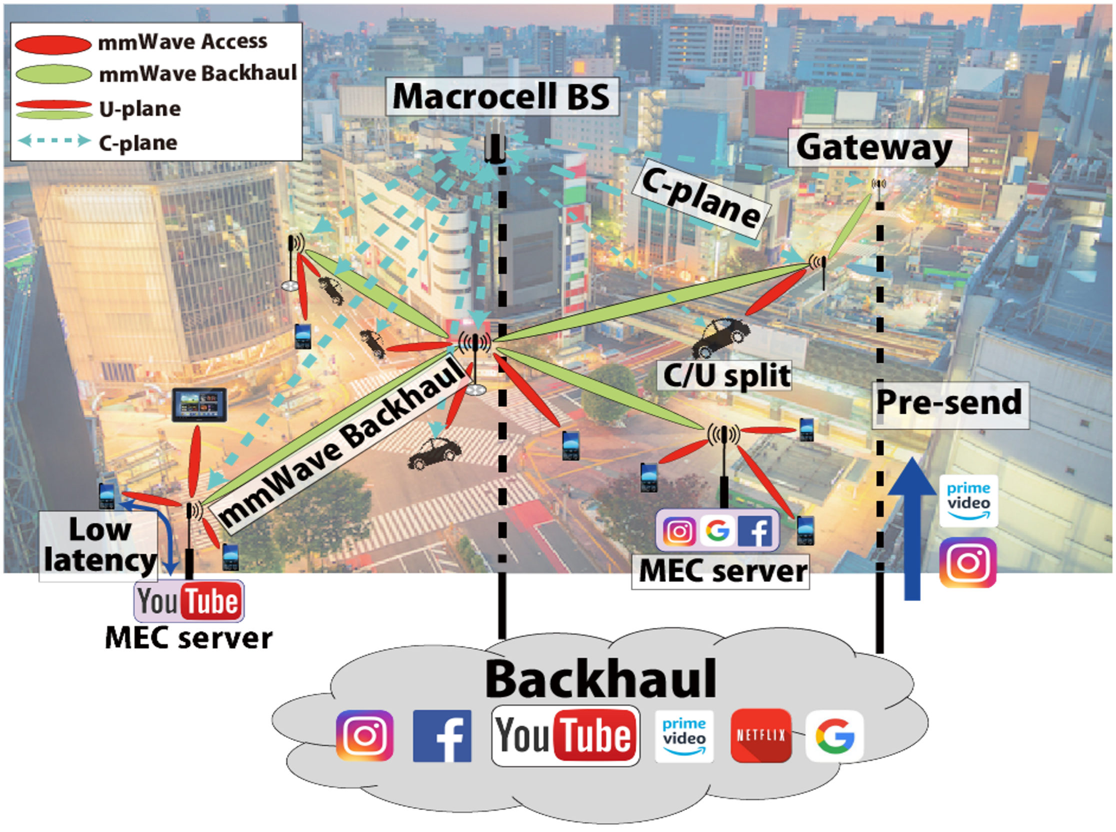
Application services such as video delivery, big data analysis (task offloading), etc., which require a large amount of MEC processing resources, are provided when users stay at each hotspot. If the user moves to another destination, this thesis assumes the application migrates to the user's next destination based on the user's context information such as location, required application, traffic information, etc. [110].

2.2.2 Mobility model among hostspots

we describe the mobility model among various types of hotspots, and this proposed model is developed in [110]. It is assumed that the user movement characteristic changes against the



(a) Overview of Network Architecture



(b) Fronthaul and MEC are deployed in the service

Figure 2.3: Network architecture of MEC ecosystem model in cellular networks

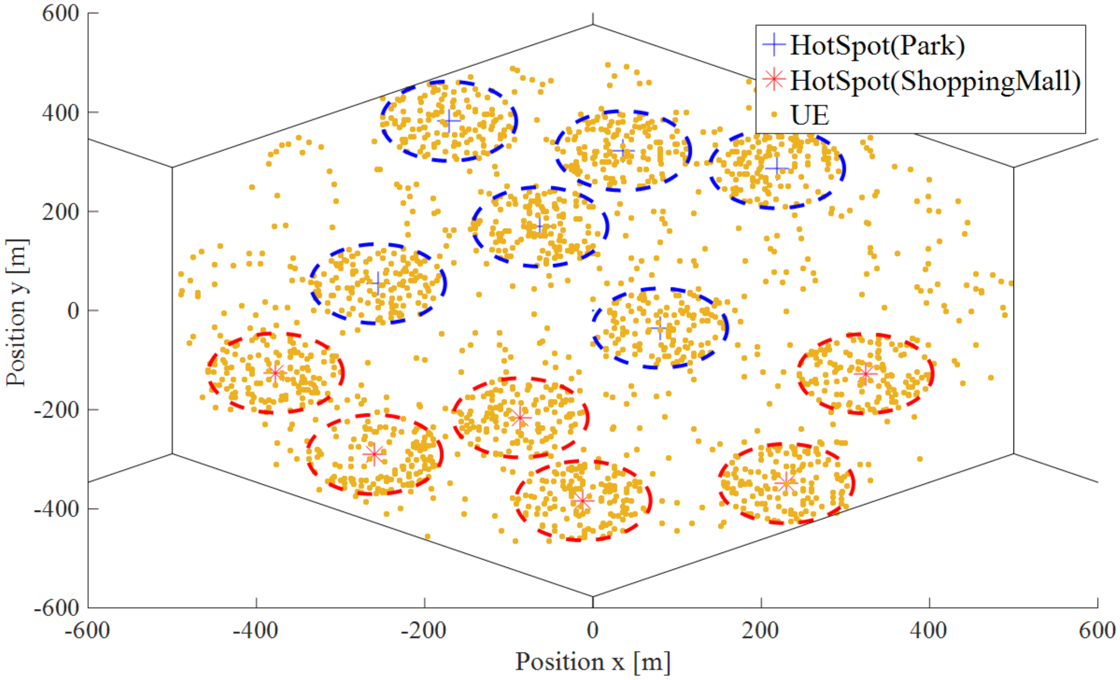


Figure 2.4: Example: User deployment in macro cell.

type of hotspots and time. There are various hotspot types, and the probability of destination transition to be selected as the destination varies depending on the hotspot types. The user's destination is determined using the Markov chain model [112].

At first, we explain the deployment of the user. Each number of hotspot user h_u is decided as below:

$$h_u = \frac{\alpha N_u}{h_n} \tag{2.1}$$

where α is the ratio of the number of users in hotspots to the total number of users, N_u is the total number of users, and h_n is the number of hotspots in one macro cell. At first, the location of the user will be determined to be inside or outside the hotspot within macrocell. Next, assume that the coordinate of the user is generated randomly based on the uniform distribution within the determined area. Figure2.4 shows the deployment of the users inside and outside the hotspot within macrocell.

Second, two types of hotspots are considered in this thesis i.e., temporary and long stay, with their corresponding probability of destination transition of the mobility model. As shown in Fig. 2.4, the red circles indicate a temporary stay place such as a station, and the blue circles indicate a long stay place such as a shopping mall. The probability of destination

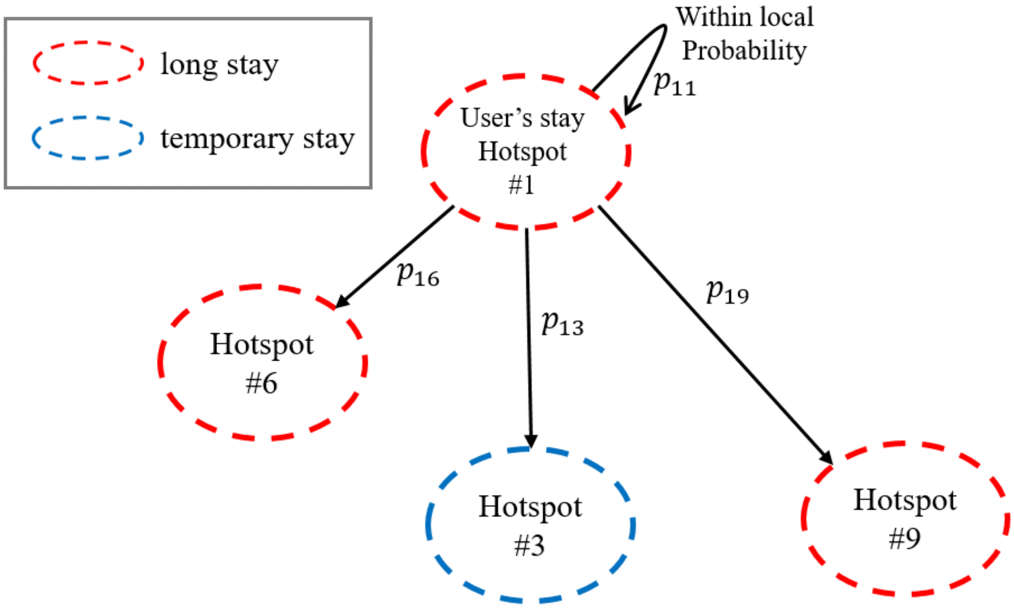


Figure 2.5: Destination probability using Markov chain model.

transition for hotspot is set to value depending on the type of hotspot and the distance to user's stay place in Fig. 2.5. Furthermore, referring to the relationship between the probability and distance among hotspots, the probability is set to four hotspots, including the user's stay place where the distance is close to the hotspot in the user stays. When the probability of destination transition should be decided in more detail, it is necessary to determine based on human behavior science. In this thesis, we assume that the probability of destination transition is set to static parameters depending on the characteristic of hotspots. Hence, we define the probability of destination transition matrix **A** as follows:

$$\mathbf{A} = \begin{pmatrix} p_{11} & \cdots & p_{1j} & \cdots & p_{1n} \\ \vdots & \ddots & & & \vdots \\ p_{i1} & & p_{ij} & & p_{in} \\ \vdots & & & \ddots & \vdots \\ p_{n1} & \cdots & p_{nj} & \cdots & p_{nn} \end{pmatrix} \tag{2.2}$$

where n is the number of the hotspot, and $p_{i,j}$ represents the probability of mobility destination from the user's location hotspot i to the destination hotspot j.

The user mobility algorithm, as shown in Fig. 2.6 is as follows:

1. The user selects destination based on the transition matrix **A** depending on deployment

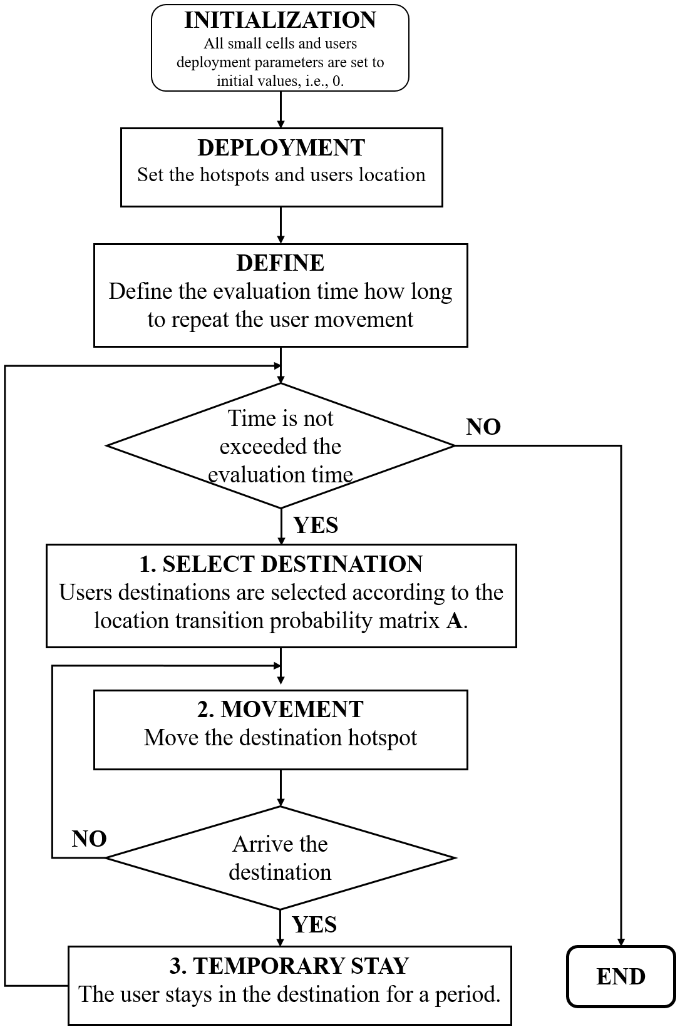


Figure 2.6: User mobility algorithm flow chart.

place such as inside or outside hotspot.

2. The user moves at a constant speed to the destination on the shortest route and stays there for a specific time.

3. After staying time, the user selects the destination based on the destination transition matrix **A** for the next destination again and again.

This 3rd step is repeated to finish the evaluation time. As an example, the movement result of one user in our simulation is shown in Fig. 2.7. The user's initial position is shown in the green circle, and the red square points to the final position. In this example, the total number of destinations is three during the evaluation. In addition, the user's movement path

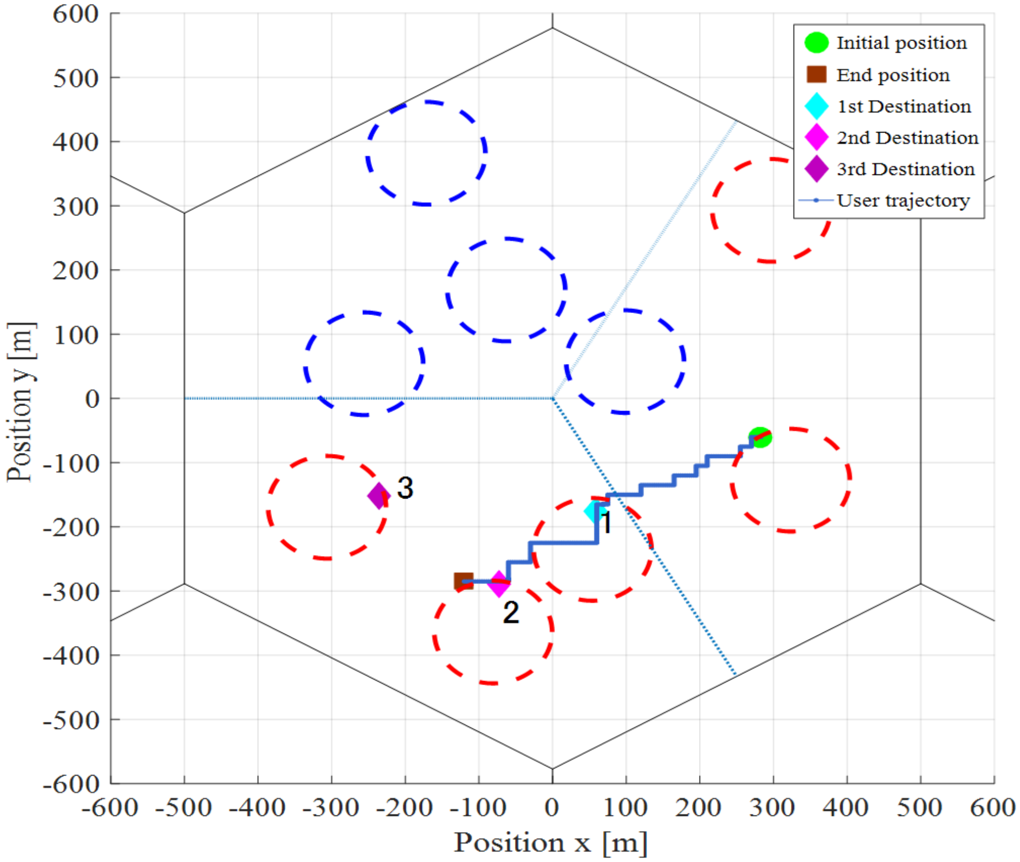


Figure 2.7: Mobility Model among Hotspots.

is shown in the blue line. Table 2.1 shows the parameters of the proposed mobility model. The staying time is set to 30 s, which is larger than the traffic interval (= 8 s) because we assume that UE moves to other hotspots after the traffic demand happens. In the future, to make the movement model closer to the real environment, such as downtown, the probability distribution of destination hotspots will be considered time-variant because the number of hotspots changes with time.

2.2.3 Traffic model

Since the user traffic distribution model has been presented in [110,113], we only briefly explain it. This model is based on user traffic data measured in Shibuya in 2012. By fitting the gamma distribution of this model, a highly accurate traffic distribution could be created

Table 2.1: Parameter of Mobility Model

Parameter	**Value**
User Speed	3 m/s
Road Interval	10 m
Staying Time	30 s

Table 2.2: Gamma distribution parameters

Parameter	**Value**
Shape parameter k	0.2892
Scale parameter θ	2.012×10^8

and defined as:

$$f(x) = x^{k-1} \frac{\exp(-x/\theta)}{\Gamma(k)\theta^k} \tag{2.3}$$

where k is a shape parameter, θ is a scale parameter, and $\Gamma(\cdot)$ is a Gamma function.

In addition, the shape parameter k will not change in the future, and the average traffic value could be controlled by the scale parameter θ. This thesis assumes that traffic has increased by 1000 times in 2020, summarized in Table 2.2 since the traffic data was measured in 2012 because it is expanding twice exponentially. As shown in Fig. 2.9, traffic data were created by this model, and QoS Class Identifier (QCI) defined in LTE (Long Term Evolution) [114] was mapped to it. And the average generation interval of the average traffic packet is 8 seconds based on exponential distribution. It is assumed that the traffic data quantity depends on the user movement status. The small traffic data is sent to the macro cell while the user is moving, and the enormous traffic data is sent to the small cell side when the user is stationary at the hotspot.

2.2.4 E2E latency model

Low-latency services such as automated driving, Vehicle-to-X (V2X), Augmented Reality (AR) conference and streaming 4K/8K media are introduced as services utilizing MEC [115, 116]. Hence, it is necessary to consider not only the latency in the wireless layer, but also the total latency, i.e., E2E latency including the service viewpoint. Meanwhile, the current mainstream services are being migrated from on-premises servers to the cloud [117] to reduce

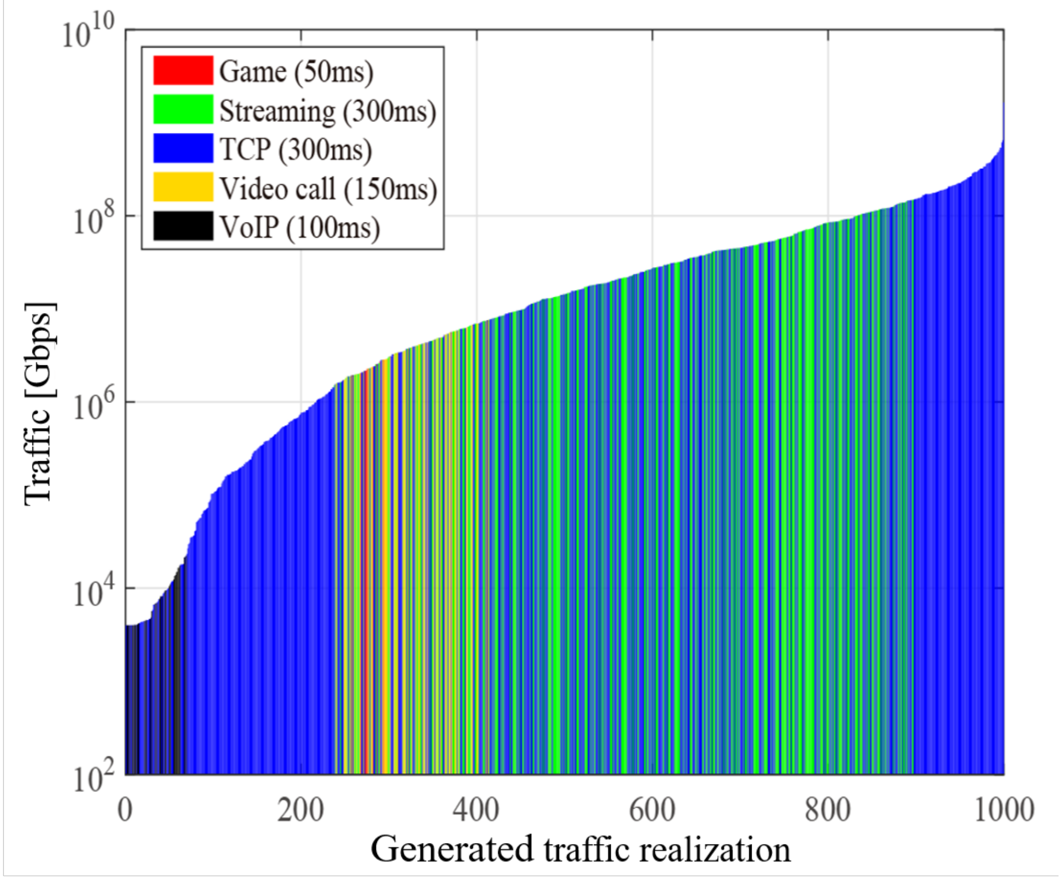


Figure 2.8: Traffic Model Example.

CAPEX and OPEX. In other words, most of the processing that should have been executed on the UE host side is performed on the cloud side. According to service requirements such as latency, the MEC conceptions further enable more flexible computation resource distribution other than cloud.

Here, macrocell UE's E2E latency since hotspot UE's E2E latency is the main focus of this thesis. Previously, various approaches have been studied so far for the E2E latency [32,86,88]. The optimization problem is dealt in [32] with a that minimizes the total power consumption subject to E2E latency. In [118], the proposal of the algorithm including the latency of the queuing theory in the MEC server was implemented. Task scheduling is proposed in [118] by delay control. Hence, we assume that each user's computation related to various applications should be processed at MEC or cloud to decrease E2E latency. we assume that the UE executes only simple processing of the web brow application. MEC manages other heavy tasks of applications, thus UE energy cost can be minimized. There are two ways to consider the

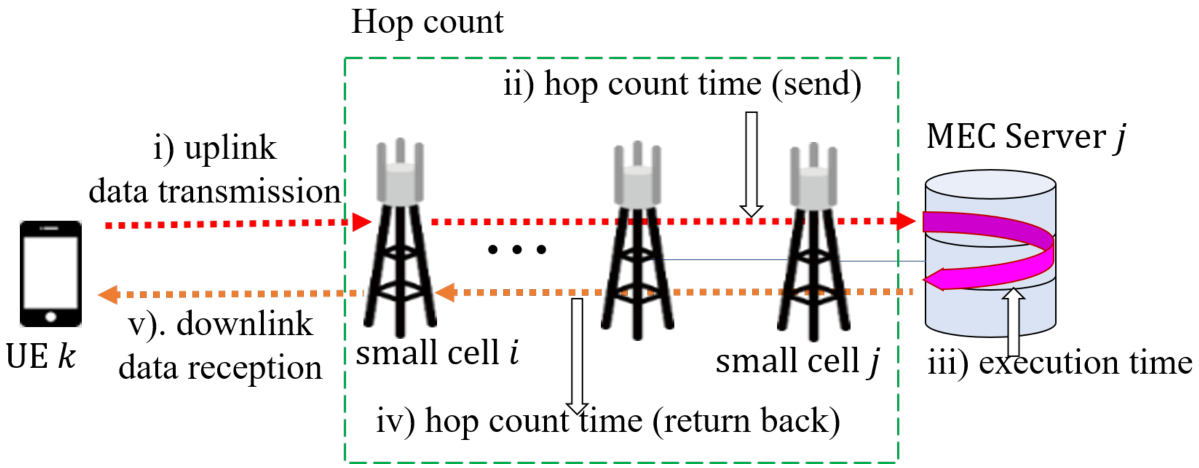


Figure 2.9: E2E latency model.

MEC original E2E latency discussion and optimization of E2E, including MEC and Cloud. In the beginning, the MEC original E2E latency will be discussed, and the latter will be discussed. While, MEC has possibility to achieve stable communication conditions by performing(or conducting) E2E communication. This will will be discussed in Chapter 4.

2.2.4.1 MEC original E2E latency

In this subsection, the E2E latency $t_(k, j)$ from UE k-th to MEC server j-th consists of four contents as shown in Fig. 2.9:

i) The time $t_{k,i}$ [sec] denotes the time duration in the wireless communication required for the k-th UE to send all information bits b_k [bits] to the i-th small cell ($i = 1, \ldots, N_h$).

ii) The time $t^p_{i,j}$ [sec] indicates the number of hop count p from the small cell i-th to the MEC server j-th.

iii) The time $t_{k,j}$ [sec] is the computation latency taken in the j-th MEC server location ($j = 1, \ldots, N_h$). Computation resource is expressed as $f_{k,j}$ [CPU cycles/sec] which is assigned to the j-th MEC server. w_k [CPU cycles] represents the task converted from information b_k [bits]. Here, computation task weight δ [CPU cycles/bit] is the ratio of computing tasks to bits. j-th MEC server is deployed on the i-th small cell.

iv) The time $t^p_{j,i}$ is same as step (ii) and return back to the small cell i-th from MEC server j-th.

v) The time $t_{i,k}$ represents the result back to the UE k-th from MEC server j-th via the small cell i-th.

These formula are defined as:

$$t_{k,j} = t_{k,i} + t^{p}_{i,j} + t_{k,j} + t^{p}_{j,i} + t_{i,k} \tag{2.4}$$

i) The time $t_{k,i}$ is given by:

$$t_{k,i} = \frac{b_k}{B_i l_{k,i}} \tag{2.5}$$

where B_i is the available bandwidth for small cell i-th, $l_{k,i}$ in bps/Hz is link capacity of UE k-th from the small cell i-th based on SINR [113].

ii) The time $t^{p}_{i,j}$ based on the emprical mode of TCP in [119] is expressed as:

$$t^{p}_{i,j} = [\log_{1.57} N_p + f(p_{\text{loss}}, \text{RTT}) N_p + 4p_{\text{loss}} \log_{1.57} N_p + 20p_{\text{loss}} + \frac{(10 + 3\text{RTT})}{4(1 - p_{\text{loss}})\, W_{max} \sqrt{W_{max}}}]\text{RTT}/2 \tag{2.6}$$

$$f(p_{\text{loss}}, \text{RTT}) = \frac{2.32(2p_{\text{loss}} + 4p_{\text{loss}^2} + 16p_{\text{loss}^3})}{(1 + \text{RTT})^3} N + \frac{1 + p_{\text{loss}}}{\text{RTT}10^3} \tag{2.7}$$

where N_p denotes the number of packets (=(b_k/8)/MSS), p_{loss} is the packet loss, W_{max} is the maximum size of the congestion window, MSS is the maximum segment size. Table 2.3 shows the parameters given in Eq.(2.7).

iii) The time $t_{j,k}$ is execution time at MEC server j. The equation of $t_{j,k}$ is given by:

$$t_{j,k} = \frac{w_{k,j}}{f_{k,j}} \tag{2.8}$$

where $f_{k,j}$ is the deployment resource of MEC server j for the user k.

iv) $t^{p}_{i,j}$ is the same as Eq.(2.7); the only differential point is the packet size N_p because the data b_k is executed by MEC server and changed analysis data.

v) $t_{i,k}$ is result of send bit data b_k from UE k-th to MEC server j via small cell i and typically only accounts for a negligible partition of the overall latency, and thus it is assumed to be a fixed value.

Table 2.3: PARAMETER OF HOP COUNT TIME

Parameter	Value
MSS	1460
$W_{\max}$	300
p_{loss}	0

Table 2.4: SIMULATION PARAMETERS

Parameters	Value
Number of UE (N_u)	2,000
Number of BS (Macro^{*1}/Small^{*1})	1/9
Number of BS sectors (Macro/Small)	3/3
Antenna Height (Macro/Small/UE)	25/10/1.5 m
Carrier frequency (Macro/Small)	2.1/60 GHz
Bandwidth (Macro/Small)	10 MHz/2.16 GHz
Tx power (Macro/Small)	46/10 dBm
Radius (Macro/Small)	500/80 m
Channel Model [120]	QuaDRiGa
Traffic model	Poisson origination
Offered load	62 Mbps /hotspot

$*1$: Macrocell, $*2$: Smallcell

we assume that Hop count time is not included in the E2E latency calculation in this thesis because the network configuration of the MEC in Fig. 2.3(b) is deployed in each small cell. However, in the future, hop-count calculation in Eq.(2.7) is needed to construct the algorithm which decides the traffic destination direction depending on the MEC calculation resource, wireless and wired traffic resource, etc. In addition, E2E latency has no impact from user mobility when mobility has happened because we assume that the user is moving to the other hotspot and the application is moved to user destination by orchestrator [110].

Regarding E2E latency in MEC, we analyze the effectiveness of the proposed Eq. (2.4) and the number of MEC is changed in different condition. The users are deployed in evaluated macrocell based on Fig 2.4. The average traffic demanded of each user is 62 Mbps in each hotspot based on Eq.(2.3). The QuaDRiGa channel model [120] which is an extension of the

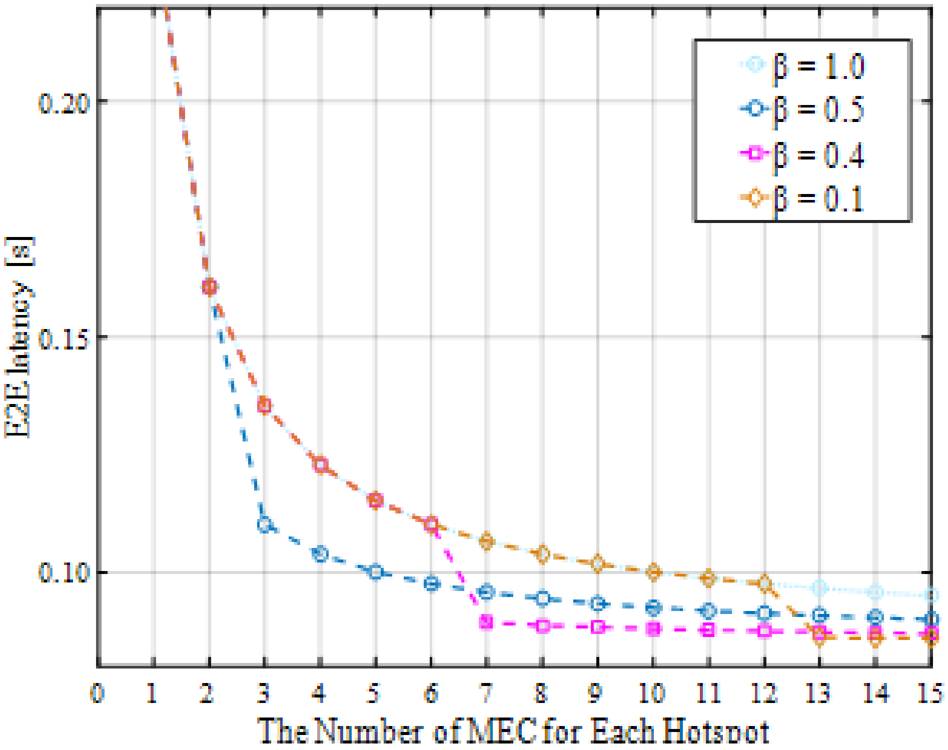


Figure 2.10: E2E latency when varying the latency in MEC (=β).

3GPP model [91] is used. The relation between deployment resource cycle $f_(k, j)$ in MEC j to the user k-th and task requests w_k converted from traffic demanded of the user k-th could be shown in $\beta(= w_k/f_{k,j})$, and this value is the condition value in this simulation. Moreover, if the only β is changed, the processing time in MEC is changed .based on Eq. (2.8) At this time, β is changed from 0.1 to 1.0. The rest of simulation parameters are listed in Table 2.4.

Figure 2.10 shows the E2E latency when β and the number of MEC vary. In this figure, as the number of MEC increases, the E2E latency is getting low compared to the number of the condition where no MEC is installed. It can be seen that the required number of MEC increases as the execution time in MEC gets slow, but the benefit on the E2E latency is getting decreased. If the number of MEC is further increased, the difference in E2E latency is approximated only to the execution time in MEC. Hence, in this thesis, the optimization of the number of MEC is needed from a business viewpoint.

2.3 Conclusion

In this chapter, we provided a discussion on the architecture of MEC, which is referenced in the following chapters. Specifically, we first discussed the reference architecture of MEC in the latest standardization trends (3GPP, ETSI), interfaces within the architecture, use cases, its position in the overall network, and its relevance to edge computing in 5GC. Next, the proposed architecture of MEC, taking into account use cases based on standardization trends, was discussed. In the discussion, the low latency of E2E in MEC was formulated, and we explained each equation and parameter. Finally, based on the proposal equations, we also evaluated them by numerical analysis. The evaluation results found that increasing the computing resources can obtain a delay reduction trend, but the benefits obtained become smaller when more resources are added.

Chapter 3

Market analysis of MEC-Assisted beyond 5G ecosystem

3.1 Motivation

The main goal of our proposal is to build the new ecosystem with MEC, and to analyze the optimization of MEC resource deployment to show the benefit from new scheme telecom operator's viewpoints. In this section, we explain motivation why the MEC ecosystem is required.

Nowadays, Cloud services (e.g., AWS) have been the mainstream, but a different business model from the formal business model will appear with the utilization of MEC. Meanwhile, Mobile Virtual Network Operators (MVNOs), which offer mobile internet access services without facilities, have been participating in the market where mobile carriers were monopolized until now. Based on these, it is assumed that a new telecom operator who owns only the fronthaul and MEC such as local 5G will appear and could rent the existing backhaul from backhaul owner without laying their private backhaul, and for the backhaul owner, it only needs to prepare sufficient backhaul capacity.

As a discussion, to accelerate the deployment of MEC, we propose an ecosystem of MEC and optimize the several resources from several different operators.

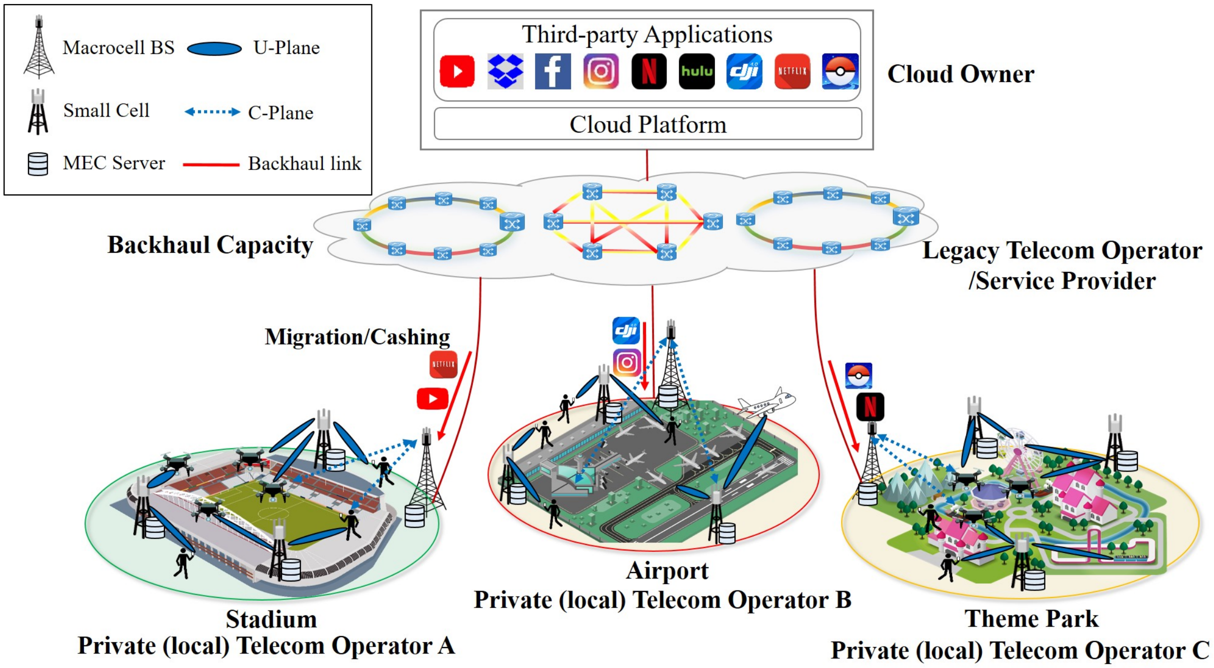


Figure 3.1: System overview classified into each player.

3.2 System Description

Fig. 3.1 depicts the system architecture of our interest where it involves three players: Private/Local operators, legacy telecom operators/service providers, and cloud owners. The figure also indicates the business field managed by each player.

Private/Local operator does not refer to a current mobile network operator (MNO) but to a future regional-specific individual business owner (e.g., local government, airport owner, theme park owner, stadium owner, etc.).

They may deploy mobile access services based on Private LTE [121,122] or local 5G service [123,124] via small and macro cells. In addition to that, computing servers can be deployed to their edge to offer application services.

Legacy telecom operators/service providers site-to-site connections such as cloud, data centers, and internet lines, and holds core networks and optical fibers leased to Private/Local operators.

The legacy telecom operators/service providers assumed here includes MNOs (e.g., AT&T, China Mobile, Vodafone). If a Private/Local operator has MEC server, the application must be deployed on MEC virtualization platform.

Currently, the cloud owner offers a wide range of application services. The cloud owner's role is also clear; to quickly support MNOs to find application service providers (i.e., third parties) in a cost and time-efficient manner. They hold cloud centers such as Amazon Web Services (AWS), Microsoft Azure, Google Cloud Platform, etc., and leases their computing resources to third party applications.

Here, the relevance of each player is described. From the ecosystem perspective, the Private/Local operator could rent the existing backhaul from legacy telecom operators/service providers without laying their private backhaul to save on Capital Expenditure (CAPEX) and Operating Expense (OPEX). The legacy telecom operators/service providers only need to prepare sufficient backhaul capacity. A typical service use case for the Private/Local operator is to support a traffic hotspot in a crowded area such as an airport, stadium, theme park, etc., as shown in Fig. 2. The mentioned application services include movie distribution (e.g., YouTube), video surveillance by drone [125,126], big data analysis, SNS, etc. These applications require a large amount of MEC processing resources. This paper assumes that end-users could receive large-volume services such as video distribution from MEC or cloud via small cells when they stay at hotspots, i.e., the traffic concentration areas. While the user moves to another destination, the application is assumed to be migrated to the user's next destination based on their context information such as location, required application, traffic information, etc. [110,127,128].

Focusing on the access services side provided by the Private/Local operator, the HetNet architecture has been proposed in [4,129] where mmWave small cells are overlaid onto a macro cell. The macro/small cells network architecture is compatible with 5G based on the Third Generation Partnership Project (3GPP) Radio Access Network (RAN) [130]. The small cell base station (BS) is constructed by three sector antennas, each of which has massive antenna elements to perform beamforming to the designated user.

5G New Radio (NR) supports 400 MHz bandwidth in the 28 GHz band [131]. Here, MEC server is located with a small cell. BSs are connected to the backhaul network leased by its owners.

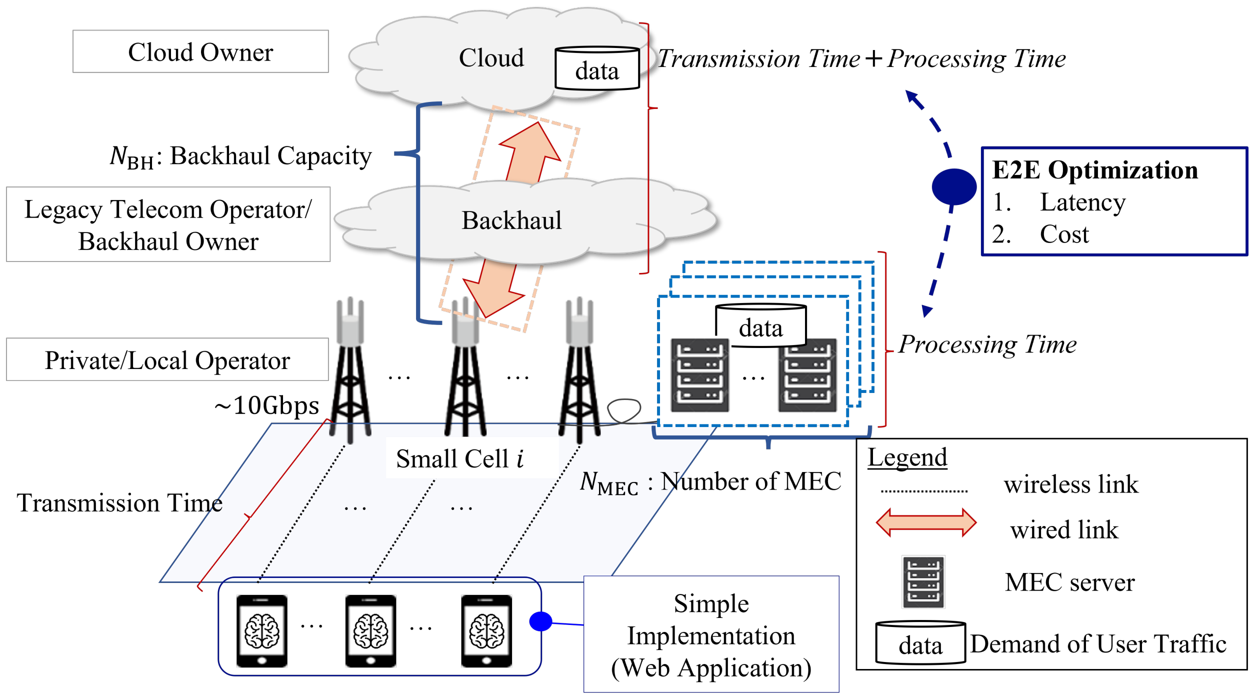


Figure 3.2: Configuration of E2E Optimization.

3.3 E2E latency optimization

The current services are moved from on-premise to Cloud [117]. In other words, the processing is performed on the Cloud side without being processed on the UE host. When MEC appears, it is necessary to move applications on Cloud to MEC side based on service requirement. Let us assume that each user's data is processed in MEC or Cloud. Here, this thesis assume that the UE only performs processing using the web browser application because the UE energy cost could be reduced by degrading the processing performance on the UE, but doing processing completely in MEC or Cloud. Therefore, in this paper, these processing methods are defined as selection model using MEC or Cloud. In E2E latency optimization, two methods are considered that judge traffic offloading algorithm as shown in Fig. 3.2. Based on this figure, one is the low E2E latency, the other is reduction of cost from end-user perspective. For the former, the latency of each of the cloud and MEC is calculated and the one with the lower latency is selected to determine where the traffic flows. For the latter, when the latency is below a certain level, the cost of each of the cloud and MEC is calculated, the end user selects the one with the lower latency, and the destination of the traffic is determined. In this section, each optimization algorithms are explained.

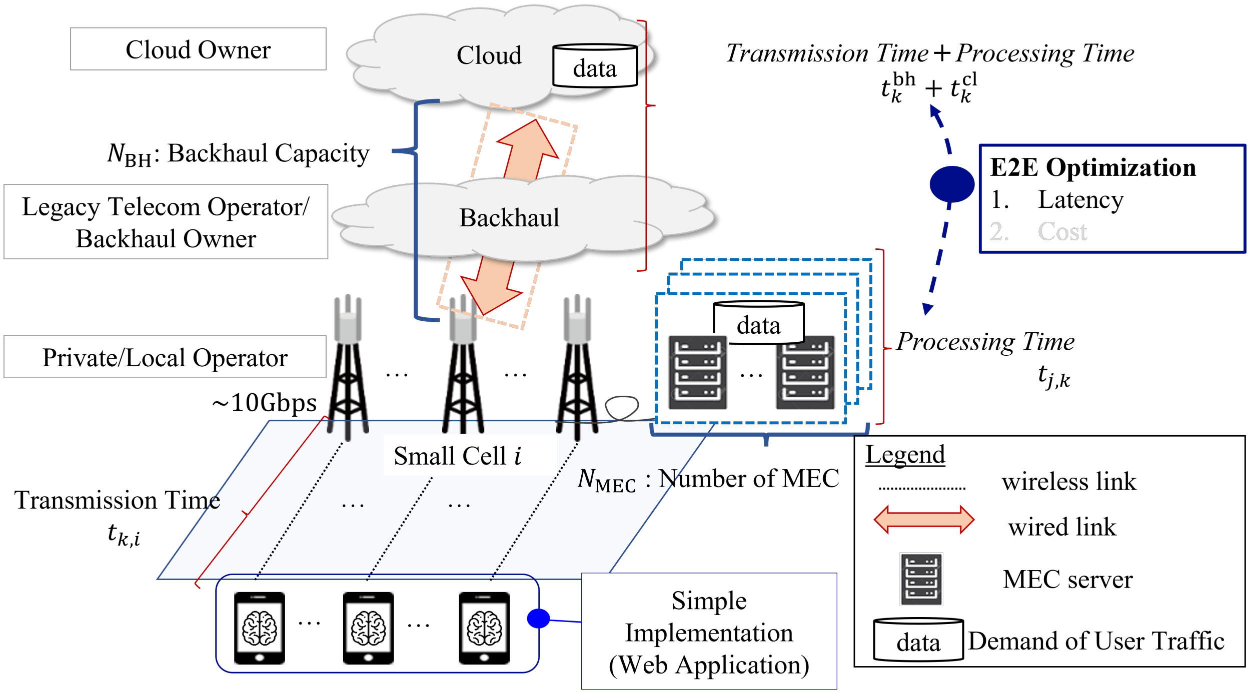


Figure 3.3: Computation resource allocation model based on E2E latency and cost constraint.

3.3.1 E2E latency optimization

The current mainstream services are being migrated from on-premises servers to the cloud [78] to reduce CAPEX and OPEX. In other words, most of the processing that should have been executed on the UE host side is performed on the cloud side. According to service requirements such as latency, the MEC conceptions further enable more flexible computation resource distribution other than cloud.

Hence, each user's computation related to various applications should be processed at MEC or cloud to decrease E2E latency.

the UE executes only simple processing of the web browser application. MEC manages other heavy tasks of applications, thus UE energy cost can be minimized.

These processing methods are defined as optimized computation allocation models with the cooperation of MEC and cloud. The data processing destination is determined to minimize the E2E latency t_k as shown in Fig. 3.3. Following four components are introduced for problem definition;

i) $t_{k,i}$ [sec] denotes the time duration in the wireless communication required for the k-th

UE to send all information bits b_k [bits] to the i-th small cell ($i = 1, \ldots, N_h$).

- ii) $t_{k,j}$ [sec] is the computation latency taken in the j-th MEC server location ($j = 1, \ldots, N_h$). Computation resource is expressed as $f_{k,j}$ [CPU cycles/sec] which is assigned to the j-th MEC server. w_k [CPU cycles] represents the task converted from information b_k [bits]. Here, computation task weight δ [CPU cycles/bit] is the ratio of computing tasks to bits. j-th MEC server is deployed on the i-th small cell.

- iii) $t_{k,\mathrm{bh}}$ denotes the backhaul transmission duration required to send the bits b_k to cloud via backhaul networks from i-th small cell.

- iv) $t_{k,\mathrm{cl}}$ stands for the computation latency in the cloud and its computation resource and task are expressed as f_{cl} and w_k, respectively.

From the above, the minimization of E2E latency can be formulated as,

$$\begin{aligned} t_k &= t_{k,i} + \Delta t_{k,x} \\ \Delta t_{k,x} &= \min_{\alpha_k}(t_{k,j}, t_{k,\mathrm{bh}} + t_{k,\mathrm{cl}}) \\ &\text{s.t.} \;\; \alpha_k = \{0, 1\} \end{aligned} \tag{3.1}$$

where $\alpha_k = 0$ indicates that cloud is selected whereas $\alpha_k = 1$ is the MEC server resources, computation task weight $\Delta t_{k,x}$ is an optimization of latency. $t_{k,i}$ is expressed as,

$$t_{k,i} = \frac{b_k}{B_i l_{k,i}} + \varepsilon_{\mathrm{tr}} \tag{3.2}$$

where B_i [Hz] is the available bandwidth for the i-th small cell, $l_{k,i}$ [bps/Hz] is the link capacity of k-th small cell UE based on SINR [70]. $\varepsilon_{\mathrm{tr}}$ is time slot allocation queue.

When $\alpha_k = 1$, the computation latency in the MEC server $t_{k,j}$ is expressed as,

$$t_{k,j} = \frac{\alpha_k w_k}{N_{\mathrm{MEC}} f_{k,j}} + \varepsilon_j \tag{3.3}$$

where N_{MEC} denotes the number of MEC servers decided by Private/Local operator's strategy and ε_j is processing queue in the MEC server.

When $\alpha_k = 0$, the bakchaul transmission time $t_{k,\mathrm{bh}}$ is expressed as,

$$t_{k,\mathrm{bh}} = \frac{(1 - \alpha_k) b_k}{N_{\mathrm{BH}} / N_{u_{\mathrm{bh}}}} \tag{3.4}$$

where N_{BH} denotes the backhaul capacity decided by legacy telecom operator/service provider's strategy and $N_{u_{\mathrm{bh}}}$ is the number of UEs using backhaul networks at the same time. In this case, the computation latency in cloud $t_{k,\mathrm{cl}}$ is expressed as,

$$t_{k,\mathrm{cl}} = \frac{(1-\alpha_k)w_k}{f_{\mathrm{cl}}} + \varepsilon_{\mathrm{cl}} \tag{3.5}$$

where $\varepsilon_{\mathrm{cl}}$ denotes the processing queue in the cloud. In order to solve (3.15), the optimum value of α_k should be determined by an exhaustive search on computation task weight $\delta t_{k,x}$. It is necessary to take into account the additional constraints as follows:

$$N_{\mathrm{MEC}} \geq 1 \tag{3.6}$$

$$N_{\mathrm{BH}} \geq 1 \tag{3.7}$$

$$B_i l_{k,i} \geq b_k, \forall k \in N_u \tag{3.8}$$

$$D_k = \min(b_k, B_i l_{k,i}), \forall k \in N_u \tag{3.9}$$

$$w_k = \delta D_k, \forall k \in N_u \tag{3.10}$$

(7) and (8) are constraints on Private/Local operator and legacy telecom operator/service provider, respectively. (9) represents the relationship between traffic volume and wireless throughput. If the generated traffic is higher than the wireless throughput, the traffic (i.e. unsent traffic) will be reassigned to the next time slot. (10) expresses the relationship between information bits and wireless throughput and (11) exhibits the relationship between executed computing task and traffic amount which is described by the computation task weight δ.

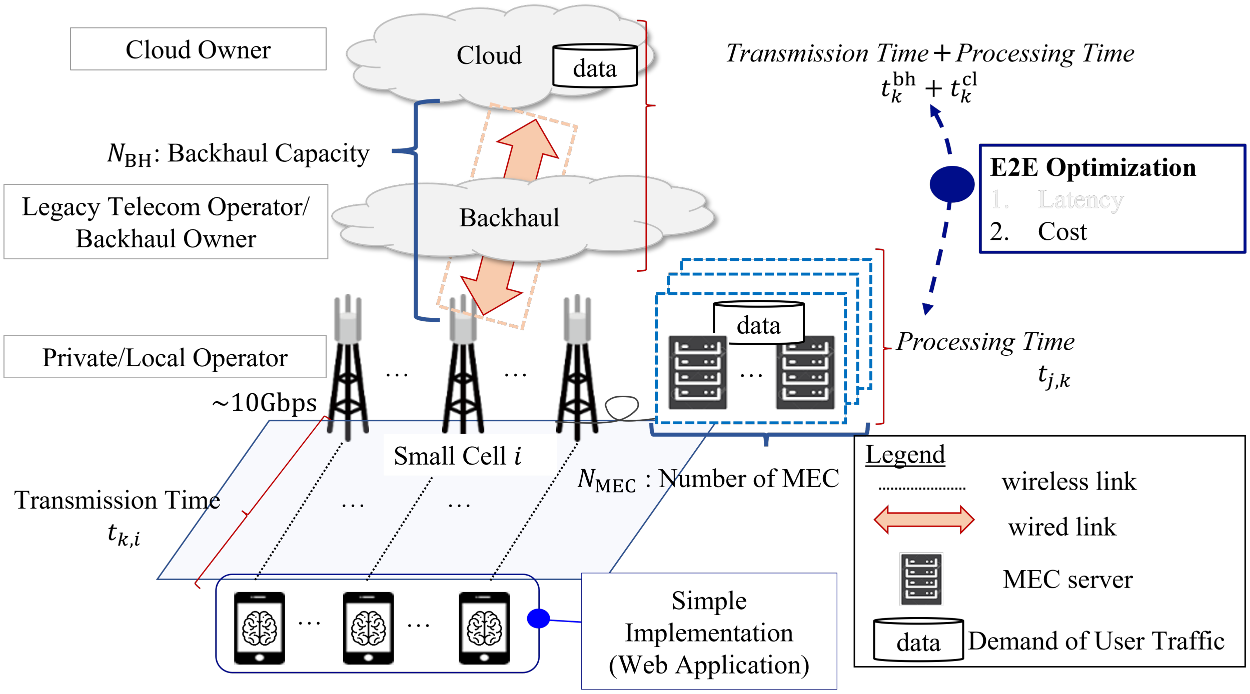


Figure 3.4: E2E Cost Optimization.

3.3.2 Cost optimization

End-users would like to choose the cheaper computation environment which also meets the latency satisfaction. This section defines the cost models on MEC and cloud and discusses the cost optimization problem under the latency constraint as shown in 3.4. First of all, end-users must pay the communication fee are assumed. Besides, the latency constraint is determined by comparing the following status;

- The initial payment status, i.e. minimum resource usage for backhaul capacity as 1 Gbps and for cloud resource as 1 CPU cycles/sec

- The additional payment status for MEC resource f_{MEC} or backhaul capacity N_{BH} and cloud resource f_{cl}.

The initial latency t_k^l and its conditions are expressed as,

$$t_k^l = \frac{b_k}{N_{\mathrm{BH}}/N_{u_{\mathrm{bh}}}} + \frac{w_k}{f_{\mathrm{cl}}} + \varepsilon_{\mathrm{cl}} \tag{3.11}$$

Here, N_{BH} is 1 Gbps and f_{cl} is 1 CPU cycle/sec. Then, the latency condition t_k^{lc} per user is defined as,

$$t_k^{\mathrm{lc}} = \psi_k t_k^l \tag{3.12}$$

where ψ_k represents user latency requirement.

Two cost model cases are considered. First case is that the end-users rent the MEC resources provided by the Private/Local operator. Its MEC cost c_{MEC} is expressed as,

$$c_{\mathrm{MEC}} = N_{\mathrm{MEC}}^{\gamma} p_{\mathrm{MEC}}^{\mathrm{lease}} w_k t_{k,j}, \alpha_k = 1 \tag{3.13}$$

where γ ($0 < \gamma < 1$) represents the weight coefficient to control the cost increasement. Here this thesis refers to the prospect theory [79] which reflects end-users' decision making behavior to determine the MEC cost. Output of the value function generally has concavity with the function input. Input and output are the number of MEC server $N_{\mathrm{MEC}}^{\gamma}$ and the MEC cost c_{MEC}, respectively. (14) reflects the market mechanism that the MEC server unit cost becomes lower according to its installation amount. This paper observes its behavior by setting the weight coefficient γ to 0.1, 0.2, and 0.3.

In the second case, the cloud cost c_{cl} where the end-users choose the cloud resources is expressed as,

$$\begin{aligned} c_{\mathrm{cl}} &= N_{\mathrm{cl}} p_{\mathrm{cl}}^{\mathrm{lease}} w_{k,\mathrm{cl}} t_{k,\mathrm{cl}} + c_{N_{\mathrm{BH}}} b_k, \alpha_k = 0 \\ c_{N_{\mathrm{BH}}} &= \begin{cases} N_{\mathrm{BH}} p_{\mathrm{BH}} & (N_{\mathrm{BH}} < N_{\mathrm{BH}}^{\mathrm{limit}}) \\ N_{\mathrm{BH}}^{\mathrm{limit}} p_{\mathrm{BH}} & (\text{otherwise}) \end{cases} \end{aligned} \tag{3.14}$$

where cloud resource cost c_{cl} is linearly increased by N_{cl} based on the current cloud service [80]. $c_{N_{\mathrm{BH}}}$ is the backhaul leasing cost for traffic transfer In/Out of application. In addition, backhaul leasing cost $c_{N_{\mathrm{BH}}}$ is nonlinear; thresholded by $N_{\mathrm{BH}}^{\mathrm{limit}}$. The N_{cl} is same as N_{BH} in this case. From (14) and (15), the minimization of cost formula subjected to latency condition per user is defined as,

$$\begin{aligned} &\min_{\alpha_k} (c_{\mathrm{MEC}}, c_{\mathrm{cl}}) \\ &\text{s.t.} \quad t_k^{\mathrm{lc}} \geq \max(t_{k,j}, t_{k,\mathrm{bh}} + t_{k,\mathrm{cl}}) \end{aligned} \tag{3.15}$$

where $\alpha_k = 0$ indicated that cloud is selected whereas $\alpha_k = 1$ is the MEC server resources.

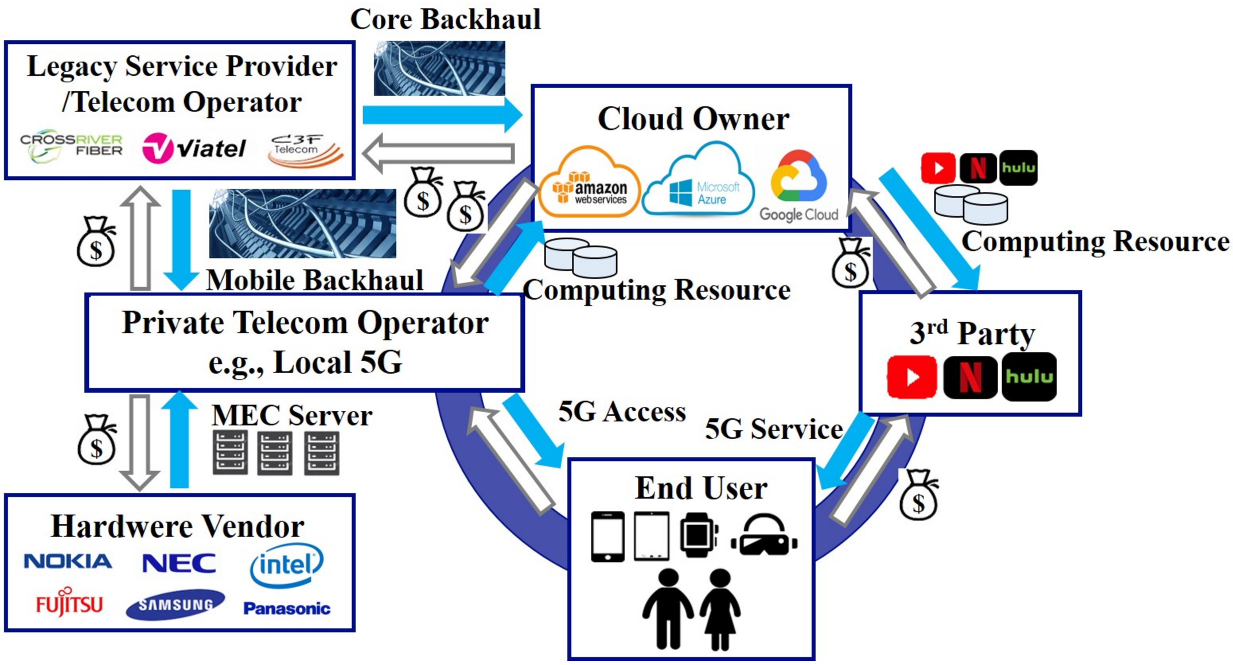


Figure 3.5: MEC-assisted ecosystem.

3.4 MEC ecosystem

This thesis aims to design the MEC ecosystem between private/local operator, legacy telecom operator/service provider, and cloud owner. Their relationships are drawn in Fig. 3.5. To analyze the proposed MEC ecosystem, this thesis build the maximization issue for the social revenue model among the above players. Its optimization problem is resolved in terms of MEC resource or backhaul capacity investment. Before explaining the ecosystem model with MEC, this thesis will define each operator's strategy against MEC.

3.4.1 Ecosystem model definition

Each player's role and relationship is discussed in this sub-section. Figure 3.6 shows relationship chart of possible 5 players. These details are described from 3.4.1.1 to 3.4.1.4.

3.4.1.1 Private/Local operator

Currently, Mobile Virtual Network Operators (MVNOs), which offer mobile internet access services without facilities, have been participating in the market where mobile carriers were monopolized until now. Furthermore, various countries focus on the local telecom services

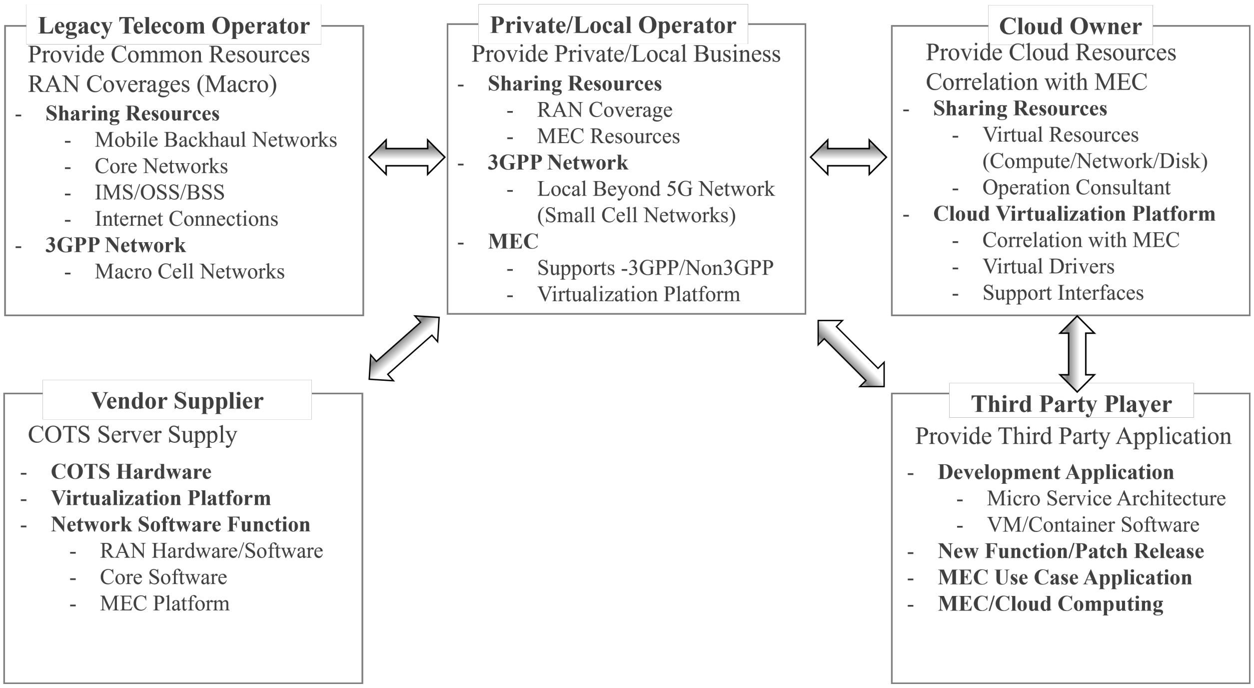


Figure 3.6: Relationship chart for each player.

such as private LTE. For example, in USA, Citizens Broadband Radio Service (CBRS) [132] and MulteFire [133] are being introduced as private LTE systems to extend not only conventional public use cases but also general commercial use cases. Referring to these initiatives, in the 5G and beyond era, we can expect that a Private/Local operator who owns the fronthaul networks inclusive of MEC will appeare worldwide, especially in the regionally local 5G. Many discussions have already begun in various countries [134,135,136] to support this assumption. Private/Local Telecom Operator mainly provides two services: an end-user application service and a business-to-business service. Regarding the former service, there are generally multiple application service types from a third-party perspective; the service provider purchases the application itself from third party and advertising is done in the application, as well as billing [137,138]. Most application providers use Freemium and subscription models [139,140]. If these models are applied to MEC-oriented platform, the Private/Local Operator has two types of service options. First, it collects the cost of using the application itself from the end user based on the resources running at the MEC. Second, it sell the application's license.

Besides, private telecom operators can rent existing backhaul networks (e.g., dark fiber) from legacy telecom operators/service providers without laying their private backhaul.

3.4.1.2 Legacy Telecom Operator/Service Provider

The legacy telecom operator is defined as the existing telecom operators (e.g., AT&T, Vodafone, Orange) in addition to the current service provider (e.g., Metro, Cross River Fiber, Viatel). The existing Legacy Telecom Operator has been providing mobile communication services to end-users using its infrastructure equipment and spectrum resources assigned by the government. Besides, they decide the investment strategy of backhaul networks (mobile/core networks) to satisfy customers' demands. However, in the B5G era, they will not always be able to survive due to the exhausting spectrum resources part of which are released for regional operators, e.g., private 4G/5G and MVNOs. Therefore, it is necessary to provide new operators with development assets and infrastructure such as equipment and RAN/Core software to expand their service areas. Legacy carriers needed mobile infrastructure such as RAN and Core using dedicated servers, but the development/innovation of RAN using virtualization technology through NFV and open interfaces empowered by O-RAN alliance is supporting the above framework. As described above, various technologies and existing infrastructure (mobile backhaul, macro coverage, etc.) etc. can be provided to private/local carriers. Therefore, by anticipating the technological background and future growth, it is also possible to support from the viewpoint of operation.

3.4.1.3 Vendor Supplier

The vendor suppliers mainly provide hardware such as RU and COTS server, which is a general-purpose server. In addition, it is possible to provide a their virtualization platform software and network functions (RAN/Core software, MEC platform) based on standardization (e.g., ITU-R/3GPP/ETSI/O-RAN). Since standardization organizations play a central role in implementing multi-vendor support to avoid market monopoly by one vendor's specifications, each software shall be in line with the standardization specifications, and Private/Local Telecom Operator shall be multi-vendor. On the other hand, for Private/Local Telecom Operator to develop the above products, it is necessary to acquire human technical resources because many specific skill holders are required. If it is difficult to describe the above option, there is a model provided by Legacy Telecom Operator for all resources. That's why it is possible to obtain know-how not only for equipment provision but also for operation.

3.4.1.4 Cloud Owners

Recently, cloud services (e.g., AWS, Microsoft Azure, Google Cloud Platform) have been the mainstream globally to replace on-premises services. With the introduced MEC, each cloud owner has already released a strategy to migrate smoothly to MEC platform in the edge cloud from their cloud platform [141,142,143]. For example, in AWS strategy [141], AWS IoT Greengrass enhances seamless cooperation with edge devices and cloud. In Microsoft Azure [142], Azure IoT Edge enables easy orchestration between code and services to support seamlessly and securely between the cloud and edge. Moreover, in Google's strategy announcement [143], Global Mobile Edge cloud will deliver a portfolio and marketplace of 5G solutions built jointly with telecommunication companies to accelerate 5G services. Cloud owners could become an orchestrator for migrating between MEC and cloud by fully exploiting their knowledge cultivated in cloud operation and relationship with third-party application players. Cloud Owners can provide cloud resources (e.g., computing, network, storage). Each resource can manage the application-like cycle management with the officially released interface (e.g., Restful API, CLI, etc.). In addition, when using the Orchestrator held by Cloud Owner, it is possible to run the application using unofficial information (physical server/network location, etc.). On the other hand, from an application perspective, applications need compatibility support (e.g., w/o hard cording, container/virtual machine, support north-bound/south-bound interface) to deploy on both platforms of MEC/Cloud. The virtualization platform is required that necessary conditions such as the driver of the virtual interface and the number of virtual interfaces will occur for each OS and application to ensure compatibility between MEC and cloud. Furthermore, it is required to provide a virtualization platform that can support virtual machine-based and container-based at the same time. Finally, it is necessary to create rules for each holder, such as cluster-based and server-based.

3.4.1.5 Third Party Application Players

As the evolution of communication systems and equipment, there have been a plethora of applications appeared in our life. Moreover, in the 5G and beyond era, advanced technical applications are coming such as fully autonomous operation, machine learning application, etc. Adapting to future situations, a network system that meets various requirements such as network slicing is mandatory. Third party is required to design, and create a microservice architecture model in consideration of deployment cases for the application itself and each function level in MEC/cloud. Developed software functions can also be deployed to virtual machine or container basis; their functional splitting should be optimized. In addition, the development of new content and the provision of patches also play a role in expanding applications support. Use case examination is needed in collaboration with Private/Local Telecom Operator or Cloud Owner to satisfy the requirements for application functions. Meanwhile, third party independently registers for a subscription; it requires examination/inspection by application platform owner, e.g., Apple Store/Google Play. Therefore, application development process needs to take into account existing business models such as application-only purchase model, function purchase model, advertising revenue model, free model, subscription model, and donation model [137,138,139,140].

This paper evaluates each player's revenue from two viewpoints of E2E latency requirement and cost minimization to meet user satisfaction.

3.5 Numerical results

3.5.1 Private/Local Operator v.s. Backhaul Owner

3.5.1.1 Problem formula

In this subsection, focusing on Private/Local operator and backhaul owner, we propose a new ecosystem model with MEC and backhaul capacity as shown in Fig. 3.5. In the proposed model, players are divided into end users, telecom operator, backhaul owner, Cloud owner, and third parties. End users can use unlimitedly by paying flat-rate communication fees to the telecom operator. Furthermore, the end user pays for the application service to the third parties and receives the services depending on the cost. The telecom operator buys MEC server from the vendor and leases MEC resources to Cloud owner. Cloud owner is an orchestrator and operates the third party's application in MEC because Cloud owner has both the knowledge and technology in Cloud services. Third parties pay the cost of resources to Cloud owner to deploy their services depending on the end user's demanded services. Here, we define the revenue problem formulae for backhaul owners and telecom operators when increasing backhaul capacity and the amount of MEC resources. we assume that backhaul owner has sufficient backhaul capacity (e.g., dark fiber). From the viewpoint of the backhaul owner, according to the amount of user traffic that is offloaded to Cloud via the backhaul network as well as the number of MEC resources and backhaul capacity in Eq. (3.16), the telecom operator should pay the corresponding backhaul cost to the backhaul owner. Hence, the revenue problem f_1 for the backhaul owner can be formulated as:

$$\begin{aligned} &\arg\max_{N_{\mathrm{BH}}} f_1(N_{\mathrm{BH}}, N_{\mathrm{MEC}}) = \\ &p_{\mathrm{bh}} \sum_{k \in N_u} (1-\alpha_k) D_k - p_{\mathrm{bh}}^{\mathrm{run}} N_{\mathrm{BH}} \\ &\text{s.t.} \qquad \text{E.q.(3.9)} \\ &\qquad\qquad 1 \le N_{\mathrm{BH}} \end{aligned} \tag{3.16}$$

where the optimization problem formula attempts to maximize the revenue between the demanded traffic and the Fig.5 backhaul capacity which is denoted by N_BH. p_{bh} denotes the backhaul cost, N_{MEC} is the number of MEC server, $p_{\mathrm{bh}}^{\mathrm{run}}$ is the backhaul running cost. Meanwhile, the revenue problem f_2 for the private/local operator can be formulated as:

$$\begin{aligned} &\arg\max_{N_{\mathrm{MEC}}} f_2(N_{\mathrm{BH}}, N_{\mathrm{MEC}}) = \\ &p_{\mathrm{a}} N_u + p_{\mathrm{MEC}}^{\mathrm{lease}} \sum_{j \in N_h} \sum_{k \in N_{u_h}} \alpha_k w_{k,j} t_{k,j} - (p_{\mathrm{MEC}} + \\ &p_{\mathrm{MEC}}^{\mathrm{run}}) N_{\mathrm{MEC}} - p_{\mathrm{bh}} \sum_{k \in N_u} (1-\alpha_k) D_k \\ &\text{s.t.} \qquad \sum_{j \in N_h} \sum_{k \in N_{u_h}} f_{k,j} \le f_s N_{\mathrm{MEC}} \\ &\qquad\qquad 0 \le \sum_{k \in N_u} (1-\alpha_k) D_k \\ &\qquad\qquad 0 \le N_{\mathrm{MEC}} \\ &\qquad\qquad \delta = \frac{w_{k,j}}{D_{k,j}} \end{aligned} \tag{3.17}$$

where p_a denotes the flat-rate communication fee, $p_{\mathrm{MEC}}^{\mathrm{lease}}$ is the leasing cost of MEC resource for the cloud owner. p_{MEC} and $p_{\mathrm{MEC}}^{\mathrm{run}}$ denote the cost of MEC server per unit (including software licensing fee, etc.) and the MEC running cost, respectively. N_{u_h} and $D_{k,j}$ denote the number of UEs using MEC server computation and the demanded traffic sent from the k-th UE to the j-th MEC server, respectively.

Therefore, the operators' revenue formulae f_1 and f_2 could be maximized with the same number of MEC resource N_{MEC} and backhaul capacity N_{BH}, which are formulated as:

$$\begin{aligned} &f_1(N_{\mathrm{BH}}^*, N_{\mathrm{MEC}}^*) = \max_{N_{\mathrm{BH}}} f_1(N_{\mathrm{BH}}, N_{\mathrm{MEC}}^*) \\ &f_2(N_{\mathrm{BH}}^*, N_{\mathrm{MEC}}^*) = \max_{N_{\mathrm{MEC}}} f_2(N_{\mathrm{BH}}^*, N_{\mathrm{MEC}}) \\ &\text{s.t.} \qquad 0 \le N_{\mathrm{MEC}} \\ &\qquad\qquad 1 \le N_{\mathrm{BH}} \end{aligned} \tag{3.18}$$

Table 3.1: SIMULATION PARAMETERS

Parameters	**Value**
Number of UE (N_u)	2,000
Number of BS (Macro^{*1}/Small^{*1})	1/9
Number of BS sectors (Macro/Small)	3/3
Antenna Height (Macro/Small/UE)	25/10/1.5 m
Carrier frequency (Macro/Small)	2.1/60 GHz
Bandwidth (Macro/Small)	10 MHz/2.16 GHz
Tx power (Macro/Small)	46/10 dBm
Radius (Macro/Small)	500/80 m
Channel Model [120]	QuaDRiGa
Traffic model	Poisson origination
Offered load	62 Mbps /hotspot
Flat-Rate Communication fee [144]	40 $
Backhaul Cost	30 [145] $
MEC server cost per unit	600 [146] $
MEC resource cost	0.02-0.20 [$/kb]

$*1$: Macrocell, $*2$: Smallcell

where the optimization problem formula attempts to maximize the revenue for both the telecom operator and the backhaul owner.

3.5.1.2 Numerical results

At first, we analyze the effectiveness of the two revenue models for MEC i.e. whether additional funds would be paid for the deployment of MEC, or additional revenues would be got in Fig. 3.7. To verify the revenue for the private/local operator, we vary the number of MEC N_{MEC} to confirm the revenue maximization formula in Eq. (3.17). Table 3.1 summarizes the simulation parameters. we set one macro cell and 9 small cells as well as 9 hotspots. For the fronthaul side, the parameters of macro cells and small cells are based on 3GPP and IEEE802.11ad. The flat-rate communication fee is set as p_a=40 $ [144]. For the backhaul side, the backhaul cost p_{bh} is 30 $ [145]. The MEC server per unit is assumed to hold 1 GHz cycle, and its price is 600 $ [146]. The MEC resource cost is in the range of 0.01 $/0.5 kB to

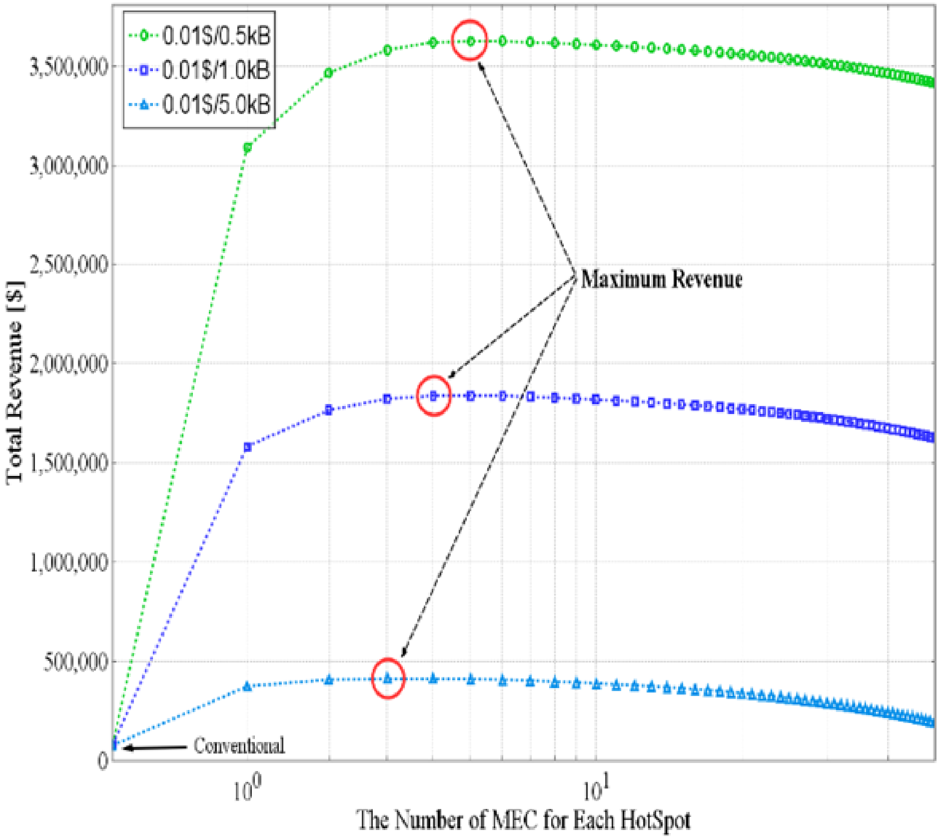


Figure 3.7: Revenue optimization when varying MEC resource cost.

0.01 $/5.0 kB. Each Hotspot in the evaluation macro cell are deployed according to a uniform distribution. Figure 3.9 shows the analysis result of the revenue for mobile operator where the horizontal axis shows the number of MEC deployed in each hotspot and the vertical axis shows the achieved revenue. As shown in Fig. 3.9, it can be seen that the total revenue is increased by increasing the MEC resource cost, up to a certain point. Firstly, revenue is tending to increase against the number of MEC deployed owing to the edge signal processing and the reduction of traffic burden over the backhaul side. However, the revenue starts to saturate and then decrease since sufficient MEC resources are capable of processing all traffic on the access side. The revenue is then decreased due to excessive capital investment of MEC servers. Moreover, we also see the tendency of the revenue maxima shift to the right as the cost for MEC resource increases. The analysis result of the revenue formula in Eq.(3.17) is shown in Fig. 3.8 under the condition of $\beta \times \gamma$ is 50 when the MEC resource cost is changed. The total revenue is increased by setting the MEC resource cost higher, but the optimal number of

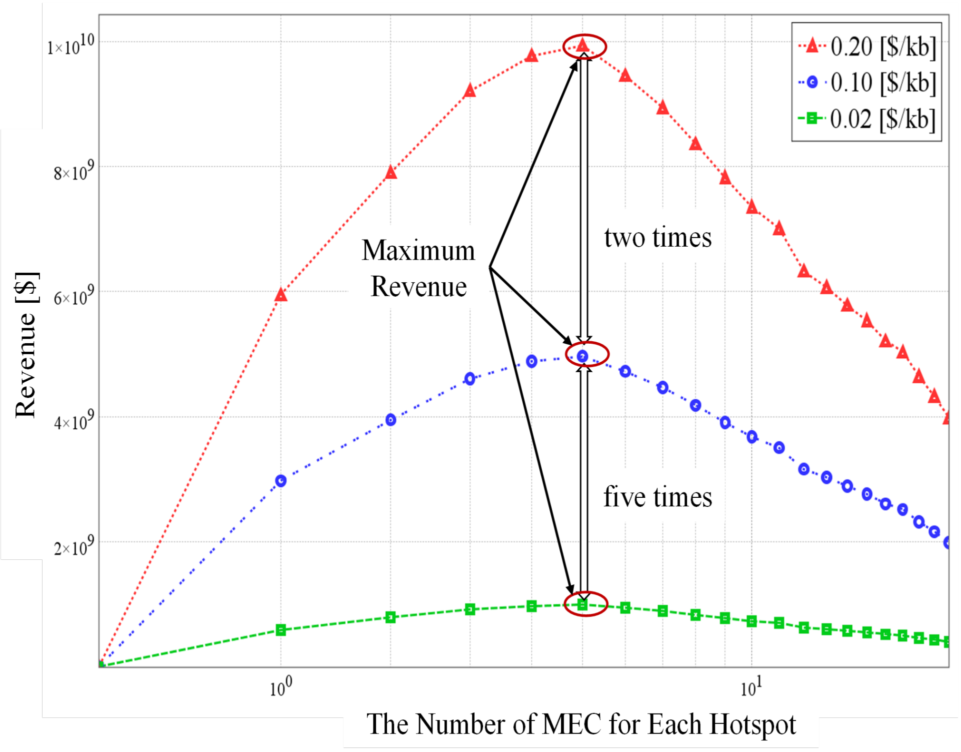


Figure 3.8: Revenue when varying MEC resource cost in 50 (=$\beta \times \gamma$).

MEC is the same point at 5 under different MEC resource costs. However, as the number of MEC increases, the revenue decrease since sufficient MEC resources are capable of processing all traffic on the access side and invests the excessive capital of MEC servers. In addition, the difference in the decreasing rate of revenue appears between the green line and the red line in the Fig. 3.8 because a profit of revenue is not gotten depending on MEC resource costs. Figure 3.9 shows the revenue cost when the MEC resource cost is 0.10 $/kb. In order to compare the different application requirement such as latency in MEC, MEC resource, etc., we set the parameter values with $\beta \times \gamma$ of 30-100. In the figure, the optimal number of MEC is shifted to the right as the condition of $\beta \times \gamma$ increases. As can be seen from the figure, the revenue cost exponential increases compared $\beta \times \gamma$ of 100 to 50. Moreover, the optimal number of MEC linear increases compared to the same condition. The reason the difference in the decreasing rate under $\beta \times \gamma$ vary is the relationship with the revenue.

Next, we analyze the effectiveness of an ecosystem model with the investment strategy for the number of MEC as well as the backhaul capacity. To find the optimal numbers of social revenue cost problem formulae in Eqs. (3.16)-(3.18), the number of MEC N_{MEC} and

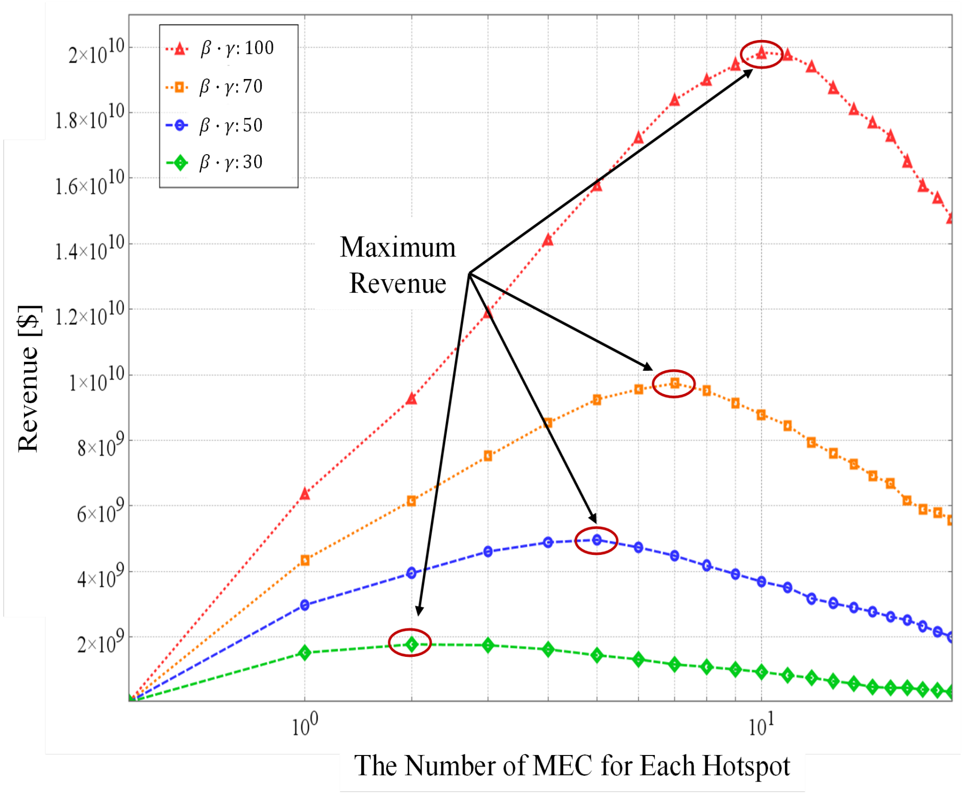


Figure 3.9: Revenue when varying $\beta \times \gamma$

Table 3.2: SIMULATION PARAMETERS

Parameters	**Value**
Number of UE (N_u)	2,000
Number of BS (Macro^{*1}/Small^{*1})	1/12
Carrier frequency (Macro/Small)	2.1/28 GHz
Bandwidth (Macro/Small)	10/400 MHz
Tx power (Macro/Small)	46/31 dBm
Radius (Macro/Small)	500/50 m
Traffic model	Poisson origination
Offered load	62 Mbps /hotspot
Flat-Rate Communication fee [144]	40 \$
Backhaul Cost [145]	30 \$/1Gbit
Backhal running cost	$N_{\mathrm{BH}}\times$ 30 \$ $\times$ 10 % $\times$ month^{*3}
MEC server cost per unit [146]	6,000 \$
MEC server running cost	$N_{\mathrm{MEC}}\times$ 6,000 \$ $\times$ 10 % $\times$ month^{*3}
MEC resource cost	10 [\$/kb]

$*1$: Macrocell, $*2$: Smallcell, $*3$: 60sec × 60mins × 24hours × 30days

backhaul capacity N_{BH} are varied. δ is changed from 10 to 1000, and this value is the control parameter in our numerical analyses. The addition simulation parameters are listed in Table 3.2 compared to Table 3.1.

The mean selection ratio to MEC is shown in Fig. 3.10 when the number of MEC resource and backhaul capacity are varied. As shown in this figure, as the number of MEC resource increases, the mean selection ratio is getting higher compared to the situation where no MEC is deployed. If the number of MEC resource is further increased, the mean selection ratio becomes almost constant. Therefore, in this paper, the optimization of the number of MEC resource and backhaul capacity is needed from a business viewpoint. The analysis result of the revenue formula in Eq. (6) for Private/Local operator with δ=100 is shown in Fig. 3.11 when the number of MEC resource and backhaul capacity are varied. In this figure, as the number of MEC resource increases with the backhaul capacity fixed, the revenue can be seen also increasing. However, as the number of MEC resource exceeds a certain value, the revenue decreases since the profit from MEC resource fee is saturated, while the operating

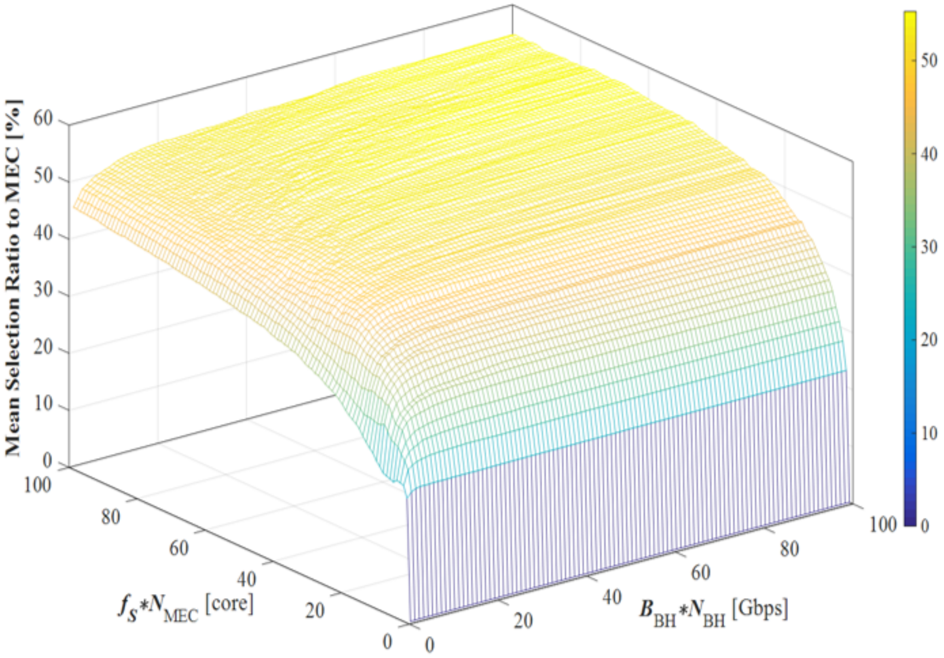


Figure 3.10: Mean Selection Ratio to MEC (%).

and investment costs have become more dominant. Meanwhile, the revenue for backhaul owner in Eq. (5) is shown in Fig. 3.12 under the same condition as in Fig. 5(B). The revenue of the backhaul owner is the highest when there is no MEC (N_{MEC}=0). However, it can be seen that the revenue formula for the backhaul owner has a convex shape when MEC is deployed. Hence, in this paper, since it turns out that the results of revenue formulae for telecom operator and backhaul owner are both convex functions, the optimal N_{MEC} and N_{BH} are required so as to satisfy the maximization of telecom operator and backhaul owner's revenue concurrently. Figure 3.13 shows the number of MEC resource N_{MEC} and backhaul capacity N_{BH} optimizations from the perspective of telecom owner and backhaul owner when δ is varied. In this figure, the dotted line shows the result of the optimal number of MEC resource N_{MEC} from the telecom operator's viewpoint with a fixed backhaul capacity, and the dashed line shows the result of optimal the backhaul capacity N_{BH} from the telecom operator's viewpoint with a fixed number of MEC resource. When the two player's results are met (=red circle in Fig. 3.13, the optimal number is the same based on Eq. (9). As a result, as the value of δ increases, the processing amount on MEC side decreases. Hence, it turns out that the advantage of MEC can be exploited by using both Cloud and edge resource rather than processing all on MEC side.

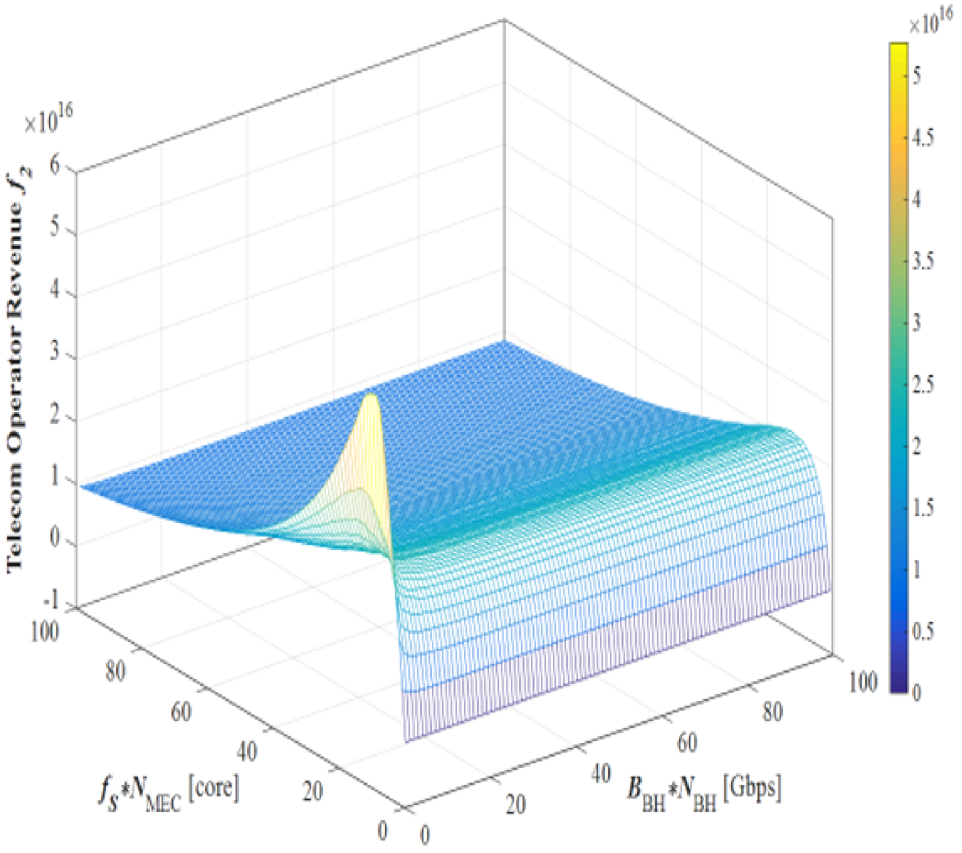


Figure 3.11: Private/Local Operator.

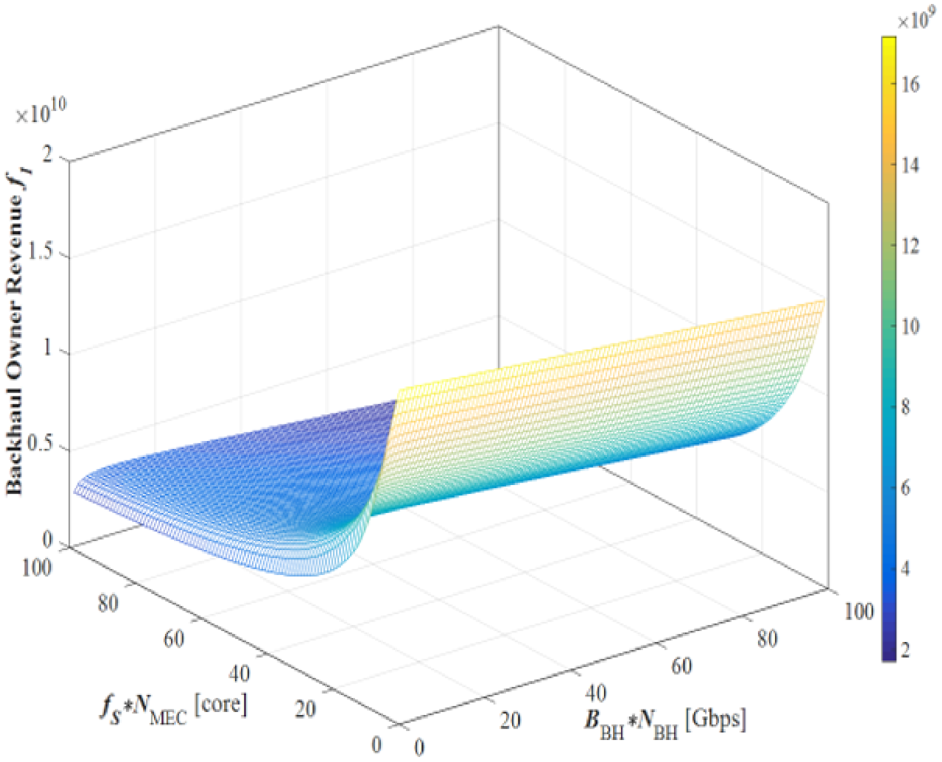


Figure 3.12: Backhaul Owner

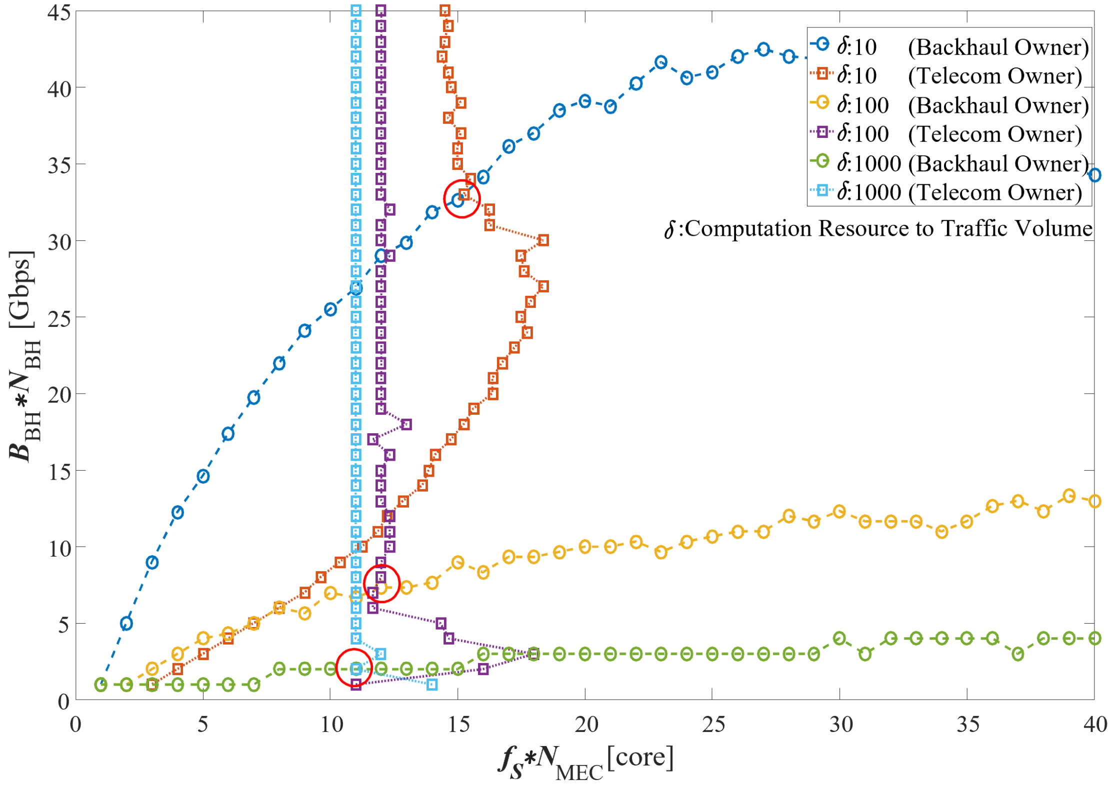


Figure 3.13: Revenue when varying $\beta \times \gamma$

3.5.2 Private/Local Operator v.s. Cloud Owner

3.5.2.1 Problem formula

Here we formulate the revenue model for Private/Local operators to decide the investment strategy for the number of MEC servers N_{MEC} and backhaul capacity N_{BH}. Cloud owner's revenue should also be taken into account for Private/Local operator's revenues. These revenues are including legacy telecom operators/service providers' fees. The overall revenue is evaluated based on satisfaction of end-users, that is, latency requirement.

End-users can enjoy unlimited communication by paying flat-rate fees to the Private/Local operator. Furthermore, the end-users pay for the application service to the third parties and receives the services depending on the cost. The Private/Local operator purchases the MEC server from the vendor and leases MEC resources to the cloud owner.

First, the optimization problem regarding the Private/Local operator's revenue f_1 can be formulated as,

$$
\begin{aligned}
&\arg\max_{N_{\mathrm{MEC}}} f_1(N_{\mathrm{BH}}, N_{\mathrm{MEC}}) = \\
&p_{\mathrm{a}} N_u + p_{\mathrm{MEC}}^{\mathrm{lease}} \sum_{j \in N_h} \sum_{k \in N_{u_h}} \alpha_k w_{k,j} t_{k,j} - (p_{\mathrm{MEC}} + \\
&p_{\mathrm{MEC}}^{\mathrm{run}}) N_{\mathrm{MEC}} - p_{\mathrm{bh}} \sum_{k \in N_u} (1-\alpha_k) D_k \\
&\text{s.t.} \qquad \sum_{j \in N_h} \sum_{k \in N_{u_h}} f_{k,j} \leq f_s N_{\mathrm{MEC}} \\
&\qquad\qquad 0 \leq \sum_{k \in N_u} (1-\alpha_k) D_k \\
&\qquad\qquad 0 \leq N_{\mathrm{MEC}} \\
&\qquad\qquad \delta = \frac{w_{k,j}}{D_{k,j}}
\end{aligned}
\tag{3.19}
$$

where p_a denotes the flat-rate communication fee, $p_{\mathrm{MEC}}^{\mathrm{lease}}$ is the leasing cost of MEC resource for the cloud owner. p_{MEC} and $p_{\mathrm{MEC}}^{\mathrm{run}}$ denote the cost of MEC server per unit (including software licensing fee, etc.) and the MEC running cost, respectively. N_{u_h} and $D_{k,j}$ denote the number of UEs using MEC server computation and the demanded traffic sent from the k-th UE to the j-th MEC server, respectively. The optimization problem about the cloud owner's revenue f_2

can be formulated as,

$$
\begin{aligned}
&\arg\max_{N_{\mathrm{MEC}}} f_2(N_{\mathrm{BH}}, N_{\mathrm{MEC}}) = \\
&(p_{\mathrm{cl}} - p_{\mathrm{cl}}^{\mathrm{run}}) \sum_{k\in N_u} (1-\alpha_k) w_k t_k - p_{\mathrm{MEC}}^{\mathrm{lease}} \sum_{j\in N_h} \sum_{k\in N_{u_h}} \alpha_k w_{k,j} t_{k,j} \\
&-(p_{\mathrm{bh}} - c_{N_{\mathrm{BH}}}) \sum_{k\in N_u} (1-\alpha_k) D_k
\end{aligned} \tag{3.20}
$$

$$
\begin{aligned}
\text{s.t.} \qquad & t_{i,j} \leq \frac{\delta D_{i,j}}{N_{\mathrm{MEC}} f_{\mathrm{MEC}}} \\
& 0 \leq \sum_{k\in N_u} (1-\alpha_k) D_k
\end{aligned}
$$

Here, cost minimization in Eq. (3.15) should be jointly considered. The above optimization problem attempts to maximize the cloud owner's revenue in terms of the demanded traffic, the backhaul capacity N_{BH}, and the number of MEC server N_{MEC} which are included in (16). p_{cl} denotes the cloud resource cost. $p_{\mathrm{cl}}^{\mathrm{run}}$ is cloud running cost.

The above formulae E.q. (3.19)–(3.20) represents the interests of *Private/Local operator versus cloud owner*. Application deployment costs should be minimized to discount their payment under the latency requirement constraint from the end-users' perspective.

In this case, the application provider leases the computation resources from Private/Local operator or cloud owner to maximize their revenue. Eq. (3.15) is jointly considered to solve E.q. (3.19).

Each investment strategy could be decided in terms of the number of MEC servers N_{MEC} and the backhaul capacity N_{BH}. It should be noted that each player cannot know others' strategy which is highly confidential information. To solve the above multi-objective optimization problems, Nash equilibrium solutions are employed [147].

Players' revenue f_1 and f_2 could be maximized with the range of the number of MEC resource N_{MEC} and backhaul capacity/cloud resource N_{BH};

$$
\begin{aligned}
& f_1(N_{\mathrm{BH}}^*, N_{\mathrm{MEC}}^*) = \max_{N_{\mathrm{BH}}} f_1(N_{\mathrm{BH}}, N_{\mathrm{MEC}}^*) \\
& f_2(N_{\mathrm{BH}}^*, N_{\mathrm{MEC}}^*) = \max_{N_{\mathrm{MEC}}} f_2(N_{\mathrm{BH}}^*, N_{\mathrm{MEC}}) \\
\text{s.t.} \qquad & 0 \leq N_{\mathrm{MEC}} \\
& 1 \leq N_{\mathrm{BH}}
\end{aligned} \tag{3.21}
$$

where N_{BH}^* and N_{MEC}^* indicate Nash equibilium points, respectively.

3.5.2.2 Numerical results

The possible range of the number of MEC N_{MEC} and backhaul capacity N_{BH} are observed through an extensive system level simulation.

In this simulation, 12 hotspots N_h and one macro cell are deployed. UE deployment follows Sect. III. The hotspot traffic demand originated from each UE is 62 Mbps on average same as [113]. Computation task weight δ is changed from 10 to 1000, and this value is the control parameter in our numerical analyses. Detailed simulation parameters are listed in Table 3.3. The QuaDRiGa channel model which is an extension of the 3GPP model [91] is used. To evaluate the investment strategy, the numerical calculation is performed by "the private (local) telecom operator versus the cloud owner". The evaluation metric is the computation allocation ratio which is defined as,

$$R = \frac{N_{\alpha_k=1}}{N_{\alpha_k=0}} \tag{3.22}$$

where $N_{\alpha_k=1}$ and $N_{\alpha_k=0}$ represent the numbers for which MEC or cloud is selected by resolving the optimization problem, respectively.

3.5.2.2.1 Basic Revenue Characteristic Fig. 3.14 shows the average computation allocation ratio R as the output of the overall optimization problem. Parameters are set to computation task weight $\delta = 100$, $\psi = 0.05$ sec, the weight coefficient $\gamma = 0.2$.

The range of the number of MEC servers N_{MEC} is from 0 to 50 and that of backhaul capacity N_{BH} is from 1 to 50 Gbps. Value of f_{cl} is assumed to be same as N_{BH}. In the region where the backhaul capacity N_{BH} is around 15 or less, the optimized computation allocation ratio is increased with N_{MEC} up to 20. Advantage of MEC deployment is emphasized when the backhaul capacity is insufficient.

Meanwhile, in other blue region, latency requirement is satisfied even with the cloud which can offer lower cost. Superiority of MEC comes back at around $N_{\mathrm{BH}} \geq 10$. Moreover, at $N_{\mathrm{BH}} > 20$, the traffic destination is reverted back to MEC, but CAPEX is larger than revenue of the private telecom operator. From this observation, optimizing the number of MEC N_{MEC} and the backhaul capacity N_{BH} are needed from both the private telecom operator and the cloud owner's viewpoints.

Fig. 3.15 shows resultant revenue of the private telecom operator and the cloud owner, respectively. Parameters are the same as the previous evaluation. From Fig. 3.15(a), increasing MEC resource is profitable for the private telecom operator up to $N_{\mathrm{MEC}} = 20$ whereas

Table 3.3: SIMULATION PARAMETERS

Parameters	**Value**
Number of UE (N_u)	2,000
Number of BS (Macro/Small(N_h))	1/12
Number of BS sectors (Macro/Small)	3/3
Antenna Height (Macro/Small/UE)	25/10/1.5 m
Carrier frequency (Macro/Small)	2.1/28 GHz
Bandwidth (Macro/Small)	10/400 MHz
Tx power (Macro/Small)	46/31 dBm
Noise Factor (Macro/Small)	4/10 dBm
Noise Power Density	-174 dBm/Hz
Radius (Macro/Small)	500/50 m
Channel Model [120]	QuaDRiGa
Flat-Rate Communication Fee (p_a) [144]	40 \$/month
Backhaul fee (p_{bh}) [145]	30 \$/Gbps
Backhaul Running Cost($p_{\mathrm{bh}}^{\mathrm{run}}$)	$N_{\mathrm{BH}}\ p_{\mathrm{bh}} 10\%$
MEC server cost/unit (p_{MEC}) [146]	6,000 \$
MEC Running Cost ($p_{\mathrm{MEC}}^{\mathrm{run}}$)	$N_{\mathrm{MEC}}\ p_{\mathrm{MEC}} 10\%$
Cloud resource cost(p_{cl})	1.1×10^{-5} \$/cycle
MEC resource cost($p_{\mathrm{MEC}}^{\mathrm{lease}}$)	1.1×10^{-4} \$/cycle
Traffic model	Poisson origination
Offered load	62 Mbps /hotspot

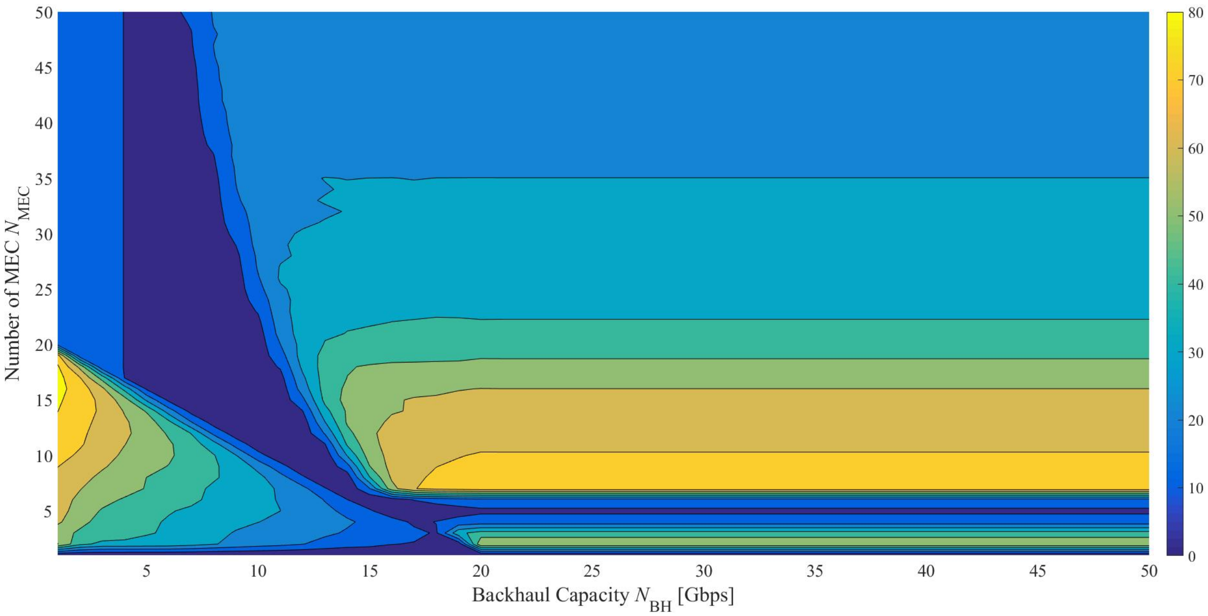


Figure 3.14: Computation Allocation Ratio ($\delta = 100$, $\psi = 0.05$, $\gamma = 0.2$).

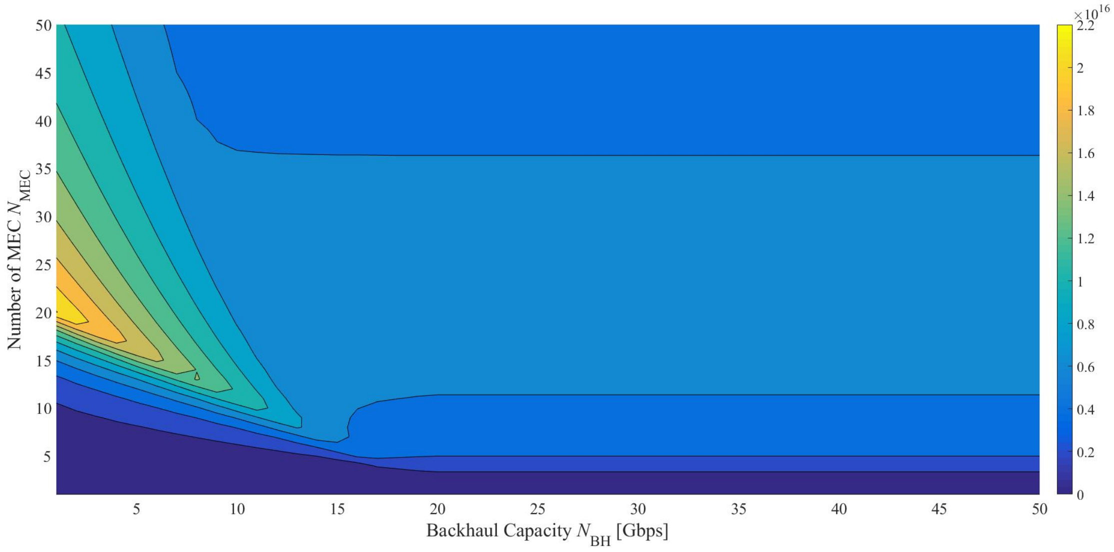
exceeding this point conversely reduces the revenue. It is because that the revenue from MEC resource fee is saturated and the operation and investment costs have become more dominant than that. we can observe that, if sufficient backhaul capacity of more than 15 Gbps is available, it is necessary to cooperate with the cloud instead of utilizing all MEC.

It also implies that lowering backhaul running cost is an important issue for the spread of MEC. Fig. 3.15(b) shows that the cloud owner's revenue increases as the backhaul capacity is released up to $N_{\text{BH}} = 20$ Gbps. Exceeding this point, the revenue becomes constant.

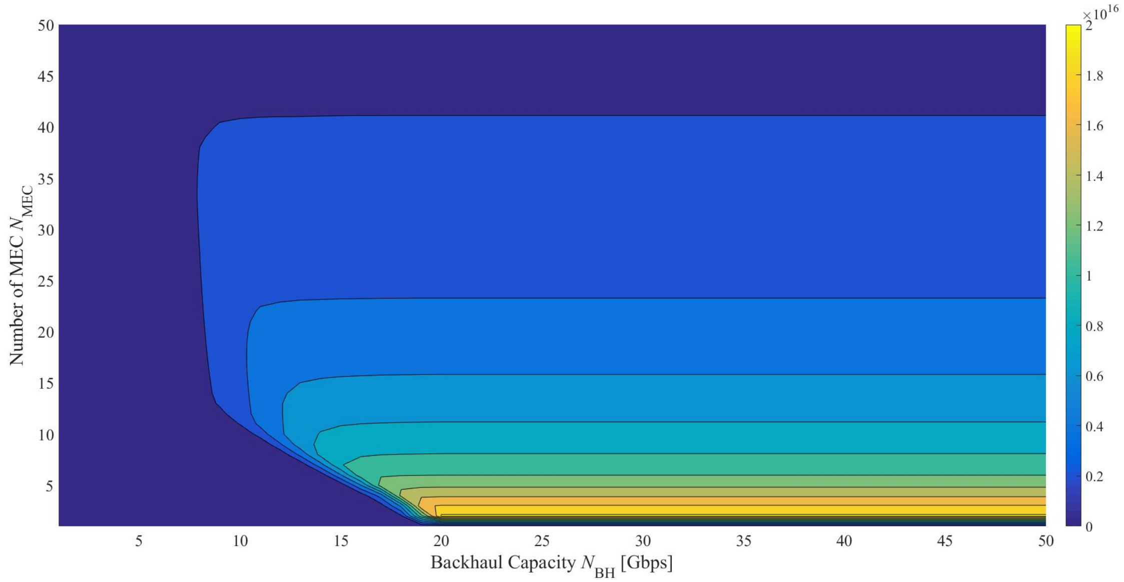
Comparing Fig. 3.14 and Fig. 3.15(b), when the backhaul capacity N_{BH} is more than 20 Gbps and the number of MEC N_{MEC} is around 5, the offload amount decreases as appeared in Fig. 3.14, which means that the cloud resource is being utilized. However, in Fig. 3.15(b), the cloud revenue doesn't increase because the revenue from cloud is relatively lower than the payment for the MEC resource utilization. Sufficient backhaul capacity is required to maximize his profit.

In this region, the revenue decreases as the number of MEC server N_{MEC}. Although we can see the impact that the computation resource is migrated to MEC as shown in Fig. 3.15, the optimality of backhaul capital investment should be considered.

Therefore, there should exist optimal values for the MEC servers and the backhaul capacity. Following evaluation attempts to solve these multi-objective optimization problems by



(a) Private/Local telecom operator revenue.



(b) Cloud owner revenue.

Figure 3.15: **Revenue characteristics ($\delta = 100$, $\psi = 0.05$, $\gamma = 0.2.$).**

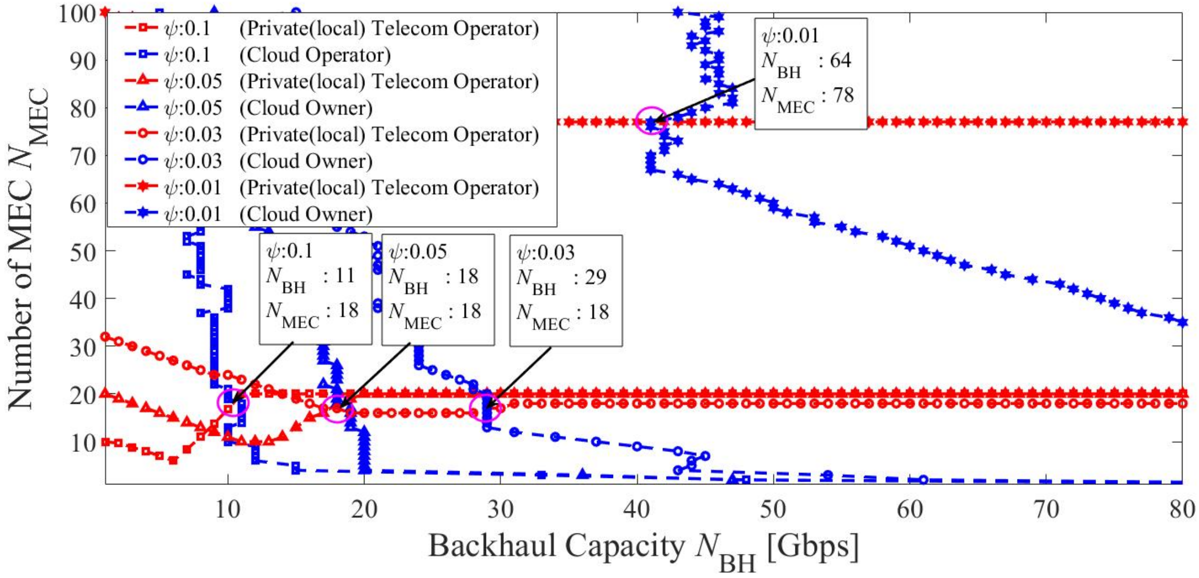


Figure 3.16: Optimized resources with latency requirements ψ (the weight coefficient $\gamma = 0.2$, computation task weight $\delta = 100$).

the game theory in (19) under the constraint that each player does not know other players' strategies.

3.5.2.2.2 Optimal resources Here we analyze Nash equilibrium points with various parameters such as latency requirement, MEC cost and traffic demand.

1. Latency requirement ψ

   First, Nash equilibrium points are analyzed with the latency requirement ψ varied from 0.01 to 0.1 sec. Fig. 3.16 shows the optimized relationship between the number of MEC N_{MEC} and backhaul capacity N_{BH}. Here, weight coefficient for MEC cost is $\gamma = 0.2$ and computation task weight is $\delta = 100$, respectively. The Nash equilibrium point with each ψ can be found as the intersection of optimized curves for private (local) telecom operator and cloud owner, denoted as magenta-colored circles. For example, the optimal combination can be seen as $(N_{\text{MEC}}, N_{\text{BH}}) = (11, 18)$ at the latency requirement of 0.1 sec. This requirement is loose and means that it can be accommodated in the cloud and MEC. When the latency requirement is less than 0.03 sec, the more number of MEC servers and backhaul capacity tend to be required. It indicates that MEC is quite advantageous to satisfy such stringent

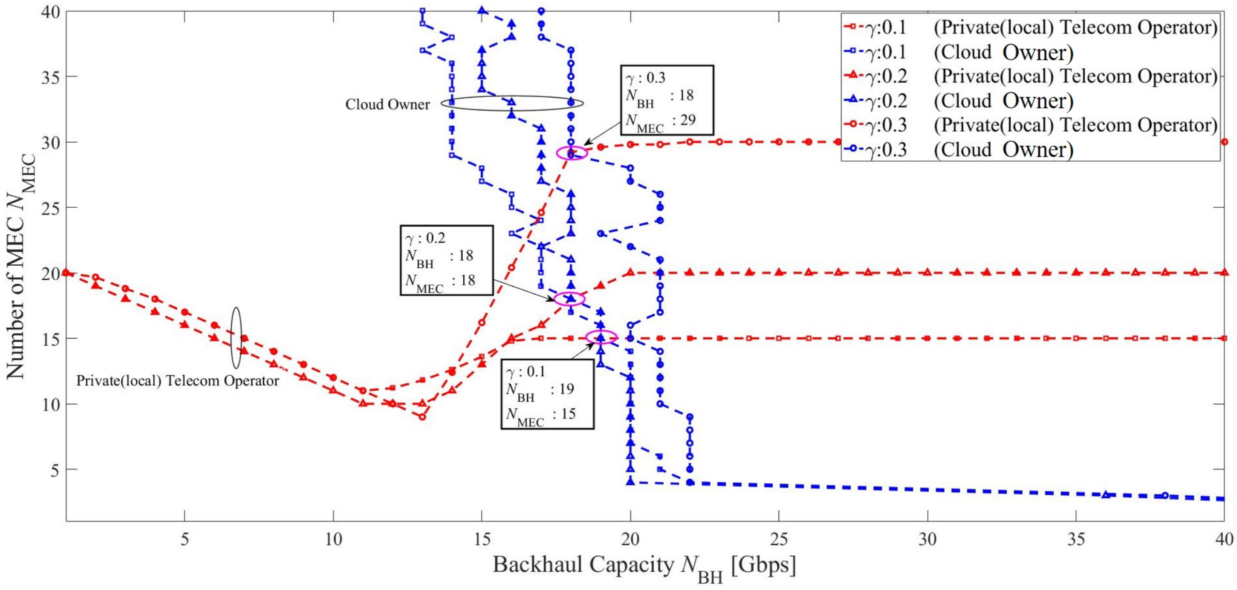


Figure 3.17: Optimized resources with weight coefficient of MEC cost the weight coefficient γ ($\psi = 0.05$, $\delta = 100$.

latency requirements represented by mission critical services. Also, to perform critical service, it is necessary to use both computation resources.

2. Weight for MEC cost of the weight coefficient γ

   As formulated in (14), MEC cost depends on the weight coefficient γ. Fig. 3.17 plots its dependency on optimized resources. Here latency requirement is set to $\psi = 0.05$ sec. At the weight coefficient $\gamma = 0.1$, the MEC cost can be kept low even when a number of computation servers are installed at the edge side. It indicates that the benefits of installing a MEC can be preserved for high backhaul capacity; the optimal resources can be seen at around $N_{\mathrm{BH}} = 20$. When the weight coefficient γ increases to 0.2 or more, MEC costs, that is, the unit price for the MEC resource, rise and its advantage will be lost. To satisfy the latency requirement more cost-effectively, more MEC should be installed. Therefore the optimum number of MEC servers N_{MEC} is increased. On the other hand, the optimum backhaul capacity N_{BH} remains almost the same value. The cloud owner's profitability is substantially independent of MEC cost; hence its optimized characteristics are consistent for each weight coefficient γ.

3. Computation task weight δ

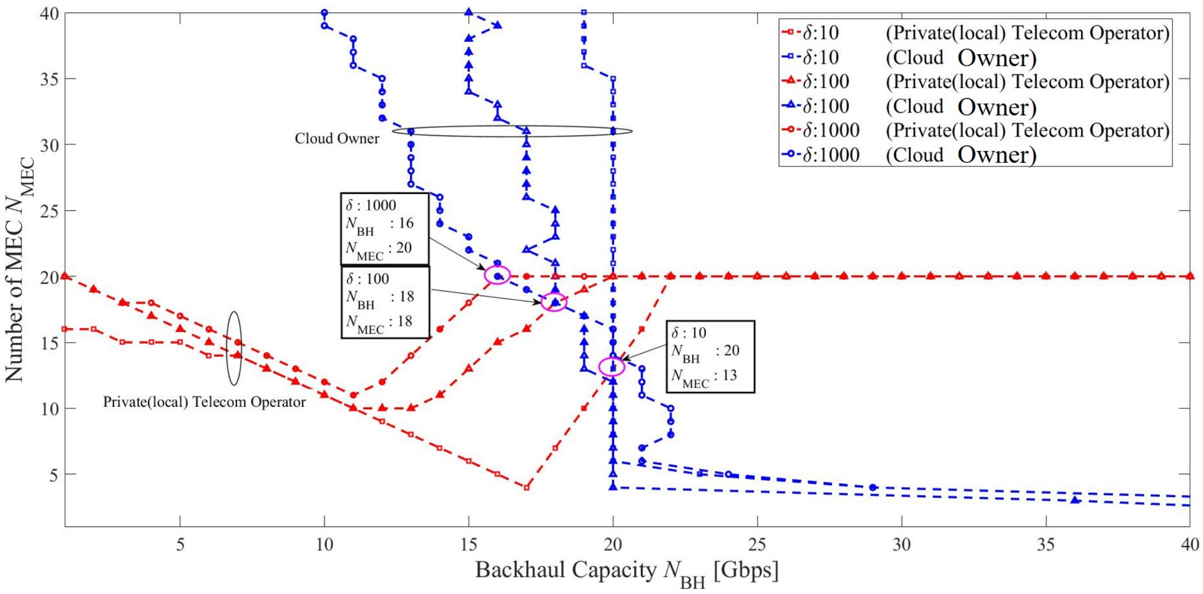


Figure 3.18: Optimized resources with computation task weight δ (the weight coefficient $\gamma = 0.5$, $\psi = 0.1$.

Fig. 3.18 presents optimized relationship of (N_{MEC}, N_{BH}) in terms of the computation task weight δ which represents traffic demand to be processed at the network. δ is set to 10, 100, and 1000.

As the computation task weight δ increases, it can be seen that the optimal backhaul capacity for the cloud owner decreases. Instead, the optimal MEC resource for the private (local) telecom operator gradually rises. This tendency is quite reasonable. In the case where the traffic demand is slight as $\delta = 10$, each player's revenue and expenditure are dominated by fixed cost; Nash equilibrium point is (N_{MEC}, N_{BH}) = (13, 20). The benefit of edge computing becomes to stand out as δ is increased. When heavy traffic should be processed as in the case of computation task weight $\delta = 1000$, most of the computing resources should be migrated to MEC, i.e., (N_{MEC}, N_{BH}) = (20, 16), which can better satisfy the latency requirement.

The above result validated our proposed social revenue model that designed MEC-assisted mobile communication systems to satisfy user experience in terms of end-to-end transmission latency.

3.6 Conclusion

Based on the structure and configuration of practical cellular networks, this paper designs a mobile ecosystem to support MEC to accelerate its deployment in 5G and beyond cellular networks. we proposed a revenue model involving three players: private/local operators, backhaul owners, and cloud owners. Our initial evaluation of the private/local operator in the proposed model showed that the profit/loss tends to increase with the addition of MECs and that the number of MECs that can generate the maximum revenue depends on the MEC resource costs and application requirements. Thus, private/local operator revenues vary depending on the duration of MEC resource use and the number of MEC resources deployed.

Next, a social maximization revenue model with an investment strategy, in which the telecom operator determines the number of MECs and the backhaul owner leases backhaul capacity, has been evaluated. The proposed delayable selection model increases the selection rate when the number of MEC resources exceeds a certain threshold and the average selection rate by MECs is saturated. From the revenue formulas for carriers and backhaul operators, the results are interpreted in terms of a convex function. That is, N_{rmMEC} and N_{rmBH} should be optimized so that the revenues of the telecom operator and the backhaul owner are maximized simultaneously. As a result, based on game theory, we analyzed the optimal number of cases where the maximized revenue outcome of the two players is satisfied. The results show that MEC can be advantageous by using cloud and edge resources in parallel instead of processing all traffic on the MEC side.

Finally, a social maximization revenue model with an investment strategy, in which the telecom operator determines the number of MECs and the cloud operator leases backhaul capacity, has been evaluated. This thesis also formulated a computational resource allocation problem that maximizes their revenue under the constraint of satisfactory end-to-end delay as QoS/QoE on the user side; MEC resources and backhaul capacity are the key resource parameters optimized. A game-theoretic approach was adopted, and large-scale simulations obtained the solution based on a heterogeneous network of millimeter-wave small cells on macrocells. In addition, we observed the optimized characteristics using various parameters such as delay requirements, the cost of deploying MEC, and the number of computational tasks. The results reveal the benefits of MEC and show that both edge and cloud computing resources are essential to maximize revenue for all players and satisfy user QoS/QoE. In particular, MEC is essential for mission-critical application services. The proposed approach can provide valuable insights into enabling MEC-enabled system design for the Beyond 5G.

Chapter 4

Proof-of-concept for fully virtualized MEC beyond 5G

4.1 Motivation

Since 2019, the fifth-generation mobile communication systems (5G) have been commercialized worldwide [7,148]. However, current leading services are primarily driven by the 3G/4G-enabled smartphone platforms. The extraordinary features of 5G, such as ultra-high throughput, have not been fully leveraged [11]. No de-facto service or scenario has been demonstrated in 5G mobile communications, including enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), and Ultra-Reliable and Low Latency Communications (URLLC) as defined by International Telecommunication Union (ITU-R) M.2083 [12] in 2015. Therefore, mobile communication companies around the world are scrambling to ship 5G services in various areas and release more functions gradually. Meanwhile, the shift from Mobile Virtualized Network Operator (MVNO) to Mobile Network Operator (MNO) is progressing [13], and new operators [14,15] are being established in markets dominated by the existing mobile network operators. In this trend, virtualization, which can support everything from RAN to applications, helps quickly provide service at a low cost. As a result, various operators [16] can more easily start and provide mobile services. Thanks to the innovation in virtualization technologies, edge computing enables third-party applications to access network/computing/disk resources in resource pools without being aware of their physical locations. As its name implies, edge computing utilizes resources in proximity to users. European Telecommunications Standards Institute (ETSI) defined Multi-access Edge Computing (MEC) that can support mobile networks as well as fixed/WiFi networks [29,72,33]. With the assistance of near-site computing resources, MEC can handle large amounts of mobile user data and alleviate traffic load on the backhaul [149,150,151]. Since the 4G era, consortia and organizations of interest have been devoting efforts to promote MEC as seen in many demonstration experiments and press releases [57,58,52,152,50]. However, no practical service has been delivered yet. Their discussions are still ongoing while the 5G service has started. As stated in Refs. [59,60,61,62], to take off the MEC, new infrastructures are required to be installed because current mobile networks have not been well compatible with virtualization technology. Besides, key use cases are eagerly awaited, and management and operation strategies for MEC applications should be clarified.

On the other hand, the 3rd Generation Partnership Project (3GPP) has involved MEC as local data networks in the architecture design from Release 15 [63]. It defined the N6 interface to associate MEC with User Plane Function (UPF) of the 5G Core (5GC) and designed a local breakout for data traffic routing. Moreover, in globally published white papers on Beyond 5G (B5G), MEC employing virtualization technology has been acknowledged as one key enabler and an essential architectural network component.

In previous studies in Chapter 2 and 3, we have focused on "Who will use MEC (whether and how).“ Specifically, we discussed about MEC principle and how to assuarance the low latency in MEC in Chapter 2. In addition, we first proposed a new Private/Local Operator to deploy MEC and analyzed the number of MEC that could maximize revenue as mentioned in chapter 3. However, to consider the impact of MEC on other operators, Private/Local Operator and Cloud Owner were discussed and analyzed by game theory. The above results allowed us to establish a MEC ecosystem. However, what remains is the uncertainty of MEC management, which will shake operators' operations about how to manage the life cycle of third-party applications in MEC. In this light, this chapter builds on previous work in chapter 3, proposes a detailed MEC/Cloud Orchestrator to make it work, and provides a PoC implementation of the E2E system. Specifically, the contributions of this chapter are unique and distinctive in two aspects: (i) First, we clearly explain the definition of players related to MEC and each player's role therein. Then, we discuss orchestrators' issues, which have not been discussed among the players, and propose a new MEC/Cloud Orchestrator architecture. This chapter also proposes a deployment method to enhance the feasibility of MEC applications within this architecture. This deployment method is discussed and detailed in two cases. The first case is that the Cloud Owner has the MEC/Cloud Orchestrator, and the second case is that the Cloud Owner and Private/Local Operator have the MEC/Cloud Orchestrator divided into function levels. The implementation method is designed for each case, and the advantages and disadvantages are discussed. From the end-user's perspective, these implementation methods, including SDN/NFV, improve Quality of Service (QoS) and Quality of Experience (QoE) because SDN/NFV contributes to flexible application deployment based on user locations as well as enhanced scalability of E2E network connections [52]. (ii) Next, we design the entire system to verify the superior performance of the proposed architecture. The implemented system is deployed as an edge cloud at Ookayama Campus of Tokyo Institute of Technology. A Proof-of-Concept (PoC) testbed for Beyond 5G is constructed by installing and deploying radio units outdoors. The testbed is built with State-of-the-Art (SOTA) production hardware (e.g., 5G, Sub-6/mmWave, fully virtualized). The proposed system with MEC is validated in this PoC field. The verification results suggest achieving lower latency services and further prove that stable communication is enabled. This demonstration provides our readers with the uniqueness of the proposed architecture.

4.2 System description

This section elaborates the entire architecture and use case concept proposal, including an introduction of each player and a clear description of their roles.

Figure 4.1 describes the proposed concept with use cases. In this figure, our target scenario includes use cases such as stadiums, campuses, workplaces, and real estate agents/post offices with local bases in various places and own space. The users in MEC purchase subscriptions via the control plane in lower frequency bands that have comprehensive coverage, such as LTE, and acquire the computing resources that they can use to obtain the several kinds of applications (e.g., mandatory, frequently use). It can be used in a form that suits each scenario, such as cache content and offloading processing. Furthermore, the allocated computing resources can be used locally via the user plane in a closed state to receive the service at a higher data rate and lower latency. Therefore, it is possible to obtain a lower-cost service because it does not use network facilities such as backhaul networks and Internet connection. In addition, applications and data are automatically taken over as one move to share more seamless information or virtual space with others. On the other hand, it is also possible to receive local-specific services (e.g., VR attractions, AR autonomous driving support). A MEC/Cloud Orchestrator can control MEC or cloud by receiving and responding to requests

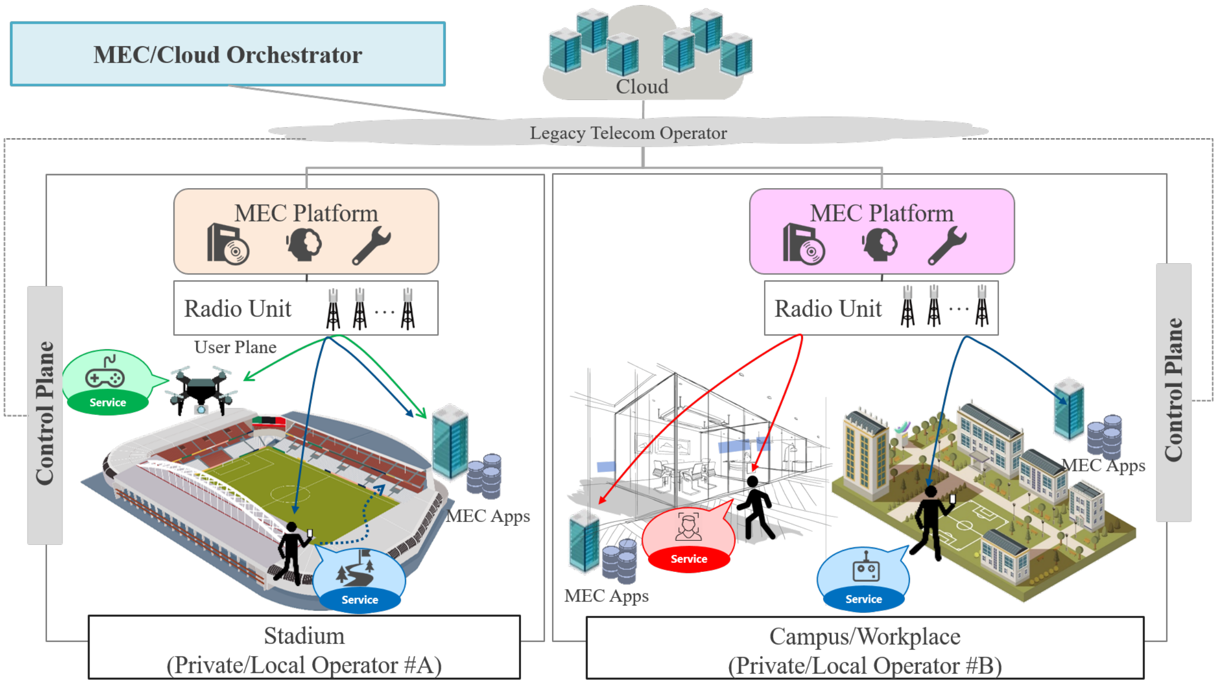


Figure 4.1: Overview of the Concept proposal for Private/Local Telecom Operator.

from users and determining required resources to realize the above services.

Private/Local Telecom Operator has important role for driving local service and providing critical applications service. Figure 4.2 shows the entire system architecture that makes the above concept feasible. In this figure, there are Private/Local Telecom Operator, Legacy Telecom Operator, Cloud Owner, and MEC/Cloud Orchestrator. Based on the application requirement (e.g., minimization of latency, minimization of CAPEX/OPEX) and the traffic requirements of the end-user, MEC/Cloud Orchestrator can automatically deploy the application for both MEC provided by the private/local operator and cloud resource/platform given by the Cloud Owner. With the above logic, it is possible to control the traffic generated by the end-user and obtain benefits such as traffic reduction, suppression of network congestion, and high security [153,154]. In addition, from the end-user's perspective, the application throughput in MEC is faster than during regular use (on the cloud), which improves QoS/QoE. The network shared with end-users must be recognized as a personal space network (individual slicing of shared resources). Here, the difference between the proposed architecture and MEC provided by the conventional telecommunications operators (Legacy Telecom Operator) is that it is a local business that holds physical resources (locations) where edge computing such as MEC can operate closer to the user as well as free utilization space for Commercial Off-

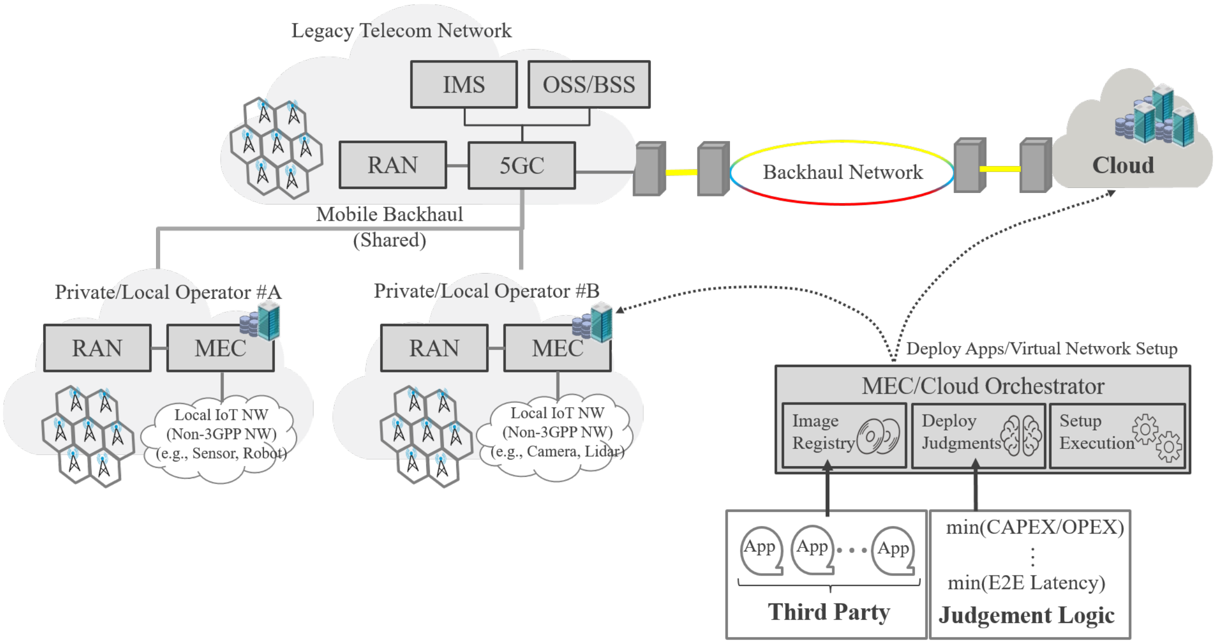


Figure 4.2: Illustration of the System Architecture with a MEC/Cloud Orchestrator for Private/Local Telecom Operator and Cloud Cooperation.

The-Shelf (COTS) server. Furthermore, the Private/Local Telecom Operator also provides end-user data and supports control data via the Legacy Telecom Operator. In other words, the Legacy Telecom Operator provides a stable RAN service from the perspective of coverage, and the Private/Local Telecom Operator provides the Application service for hotspots and local points. Therefore, the difference is that the network is closed to end-users in local secure data and assurance of latency.

Figure 4.3 shows a network configuration diagram in the Private/Local Telecom Operator network in the above architecture. This figure focuses only on the Private/Local Telecom Operator network. First, installation of a Radio Unit (RU) can support higher frequency bands (e.g., Sub6/mmWave) with a local RAN network to accommodate as much traffic as a user plane data in a hotspot. XR/AR/VR/UAV, C-V2X, Robotics, IoT, etc., are given as examples of terminal devices that connect to the control/user plane. The RU is connected to the virtualized Distributed Unit (DU) pool via the fronthaul. The vDU is connected to the virtualized Centralized Unit (CU) pool via the F1 interface in the midhaul. Here, vCUs are classified into vCU-CP with a control plane and vCU-UP with a user plane, and they are deployed in the same/different place. Packets GTP encapsulated by CU-UP are GTP decapsulated in MECs that hold the UPF function. MEC analyzes the destination

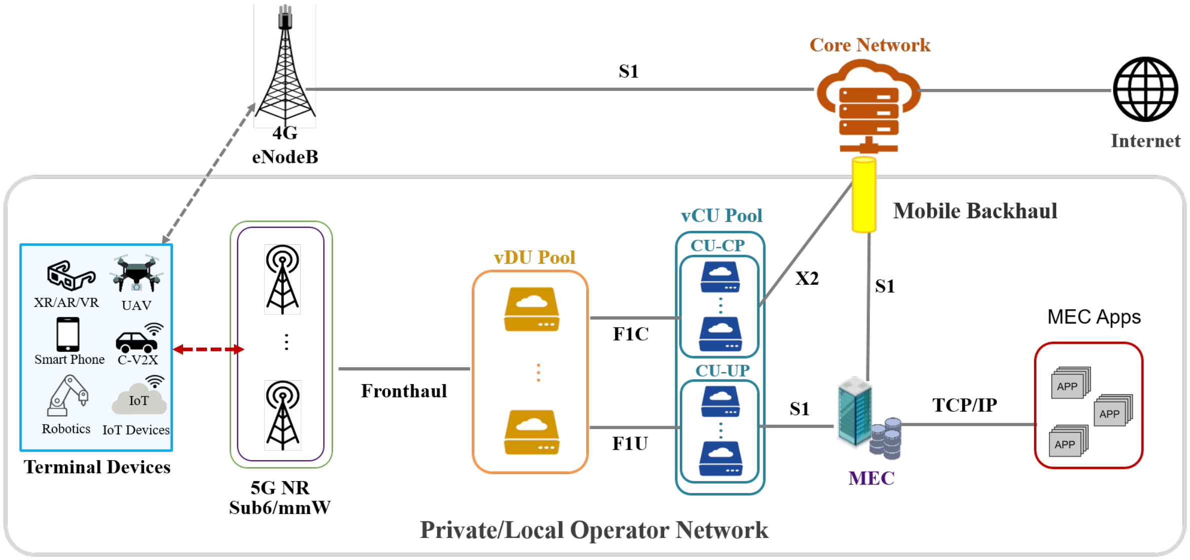


Figure 4.3: Network Architecture in Private/Local Telecom Operator.

information in the packet and refers to the registry information whether it is operating as MEC Apps. If there is a target MEC Apps, the traffic is passed to MEC Apps at the TCP/IP layer, but if not, it is encapsulated again by GTP, and the traffic is passed to the mobile network again. Meanwhile, vCU-CP requests the X2 interface in 4G BBU to receive RU support for a wide area. Here, as an example, we request a 4G BBU to anchor via the X2 interface. As a result, terminal devices can use C-Plane and U-Plane, setup Protocol Data Unit (PDU) sessions, and receive services.

4.3 Implementation of MEC/Cloud orchestrator

This section describes the implementation of MEC/Cloud Orchestrator for deploying applications on MEC or the cloud. This Orchestrator plays an essential role in acquiring the end-user request and deploying the application based on the collected information and algorithm. The architecture and implementation sequence are also included separately for the centralized and distributed types explained in the previous section.

MEC/Cloud Orchestrator needs to consider two optional model use cases: centralized and decentralized. In the centralized type, the Orchestrator supports multiple Private/Local Telecom Operators and is held by the Cloud Owner. On the other hand, some functions exist on the Internet in the distributed type, and other parts are retained in each Private/Local

Telecom Operator. For the centralized type, it is possible to deploy the application to MEC that considers the end-user usage information (e.g., usage access log) on the cloud. For the distributed type, it is possible to deploy the application to MEC that guarantees high security. The functions provided as Orchestrator manage the catalog image of the application and support the northbound and southbound interfaces (MEC Platform, cloud Platform, DNS Entry, User request management). The main functions are application's life cycle management.

On the other hand, various studies have been conducted from the user's point of view regarding MEC and locality. Since there are still many unstudied factors regarding how to control MEC, this chapter provides a detailed explanation of the MEC/Cloud Orchestrator. Also, we will explain the implementation of MEC/Cloud Orchestrator in the next sub-section.

4.3.1 Relationship in MEC ecosystem

Each player's role and relationship between MEC/Cloud Orchestrator is discussed in this sub-section. Figure 4.4 shows relationship chart of possible 6 players. Other players exluding MEC/Cloud Orchestrator are described in chaper 3.4.1. MEC/Cloud Orchestrator needs to consider two optional model use cases: centralized and decentralized. In the centralized type, the Orchestrator supports multiple Private/Local Telecom Operators and is held by the Cloud Owner. On the other hand, some functions exist on the Internet in the distributed type, and other parts are retained in each Private/Local Telecom Operator. For the centralized type, it is possible to deploy the application to MEC that considers the end-user usage information (e.g., usage access log) on the cloud. For the distributed type, it is possible to deploy the application to MEC that guarantees high security. The functions provided as Orchestrator manage the catalog image of the application and support the northbound and southbound interfaces (MEC Platform, cloud Platform, DNS Entry, User request management). The main functions are application's life cycle management.

On the other hand, various studies have been conducted from the user's point of view regarding MEC and locality. Since there are still many unstudied factors regarding how to control MEC, this chapter provides a detailed explanation of the MEC/Cloud Orchestrator. Also, we will explain the implementation of MEC/Cloud Orchestrator in the next section.

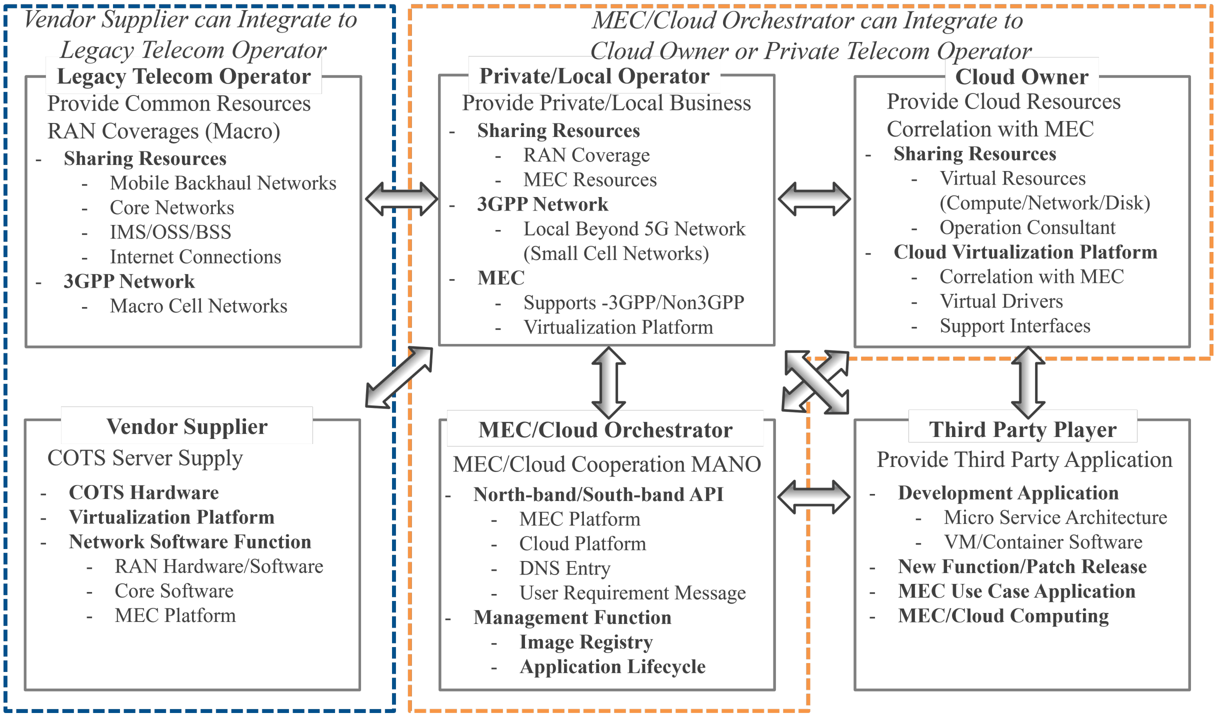


Figure 4.4: Relationship chart, including MEC/Cloud Orchestrator.

4.3.2 Implementation of proposed architecture

This section describes the implementation of MEC/Cloud Orchestrator for deploying applications on MEC or the cloud. This Orchestrator plays an essential role in acquiring the end-user request and deploying the application based on the collected information and algorithm. The architecture and implementation sequence are also included separately for the centralized and distributed types explained in the previous section.

Each of the functions of the GUI and the Orchestrator is explained below in detail. The GUI function consists of the GUI View function and the Subscription Management function. The Orchestrator function consists of six parts: Service Query function, Service Registry function, Database Update function, Image Registry function, Deploy Judgments function, and Setup Execution function. The GUI View function allows end-users to connect to wide-area wireless network provided by Legacy Telecom Operator via the control plane using an HTTP/HTTPS.

After accessing the GUI, the end-user starts using it by registering a subscription (billing) with secure connection. Here, the user management access information and subscription management used by the end-user at the time of access by the GUI function are performed by the Subscription Management function. In addition, the application subscription information is managed by the Subscription Management function. On the other hand, the GUI View function functions as a request received on the Web and a transaction role for each part. Request information for application requirement request received on GUI View function is sent to Orchestrator function via Southbound Interface (e.g., Restful API, Curl, SSH, CLI). Then, end-user can request the deployment application according to subscription payment. Meanwhile, the Orchestrator function regularly monitors the resources usage/allocation of cloud and MEC for computing/network/storage. And, the Database Update function updates/manages on Database based on monitoring info. The Service Registry function starts the registration of the application deployment requested by the Service Query function. The application selected here starts the deployment process using either the one registered in the Image Registry function provided by the third party in advance or the cached content generated by the learning function by AI/ML. When starting the deployment process, the Deploy Judgments function is determined by the logic based on the scenario in which either cloud or MEC (e.g., physical location) possessed by Private/Local Telecom Operator is registered. Examples of registered strategies include minimum latency, cost, and processing performance. Finally, the Setup Execution function executes the Config set in the virtual machine or container remotely when the deployment is completed. As a result, the end-user can be received the service from the deployed application via user plane.

4.3.3 Centralized MEC/Cloud orchestrator

4.3.3.1 Logical implementation

Firstly we propose a centralized MEC/Cloud Orchestrator on the Cloud Owner that collectively manages multiple Private/Local Telecom Operators' MEC and integrates with cloud services. Figure 4.5 shows a proposal overview. MEC/Cloud Orchestrator consists of GUI and Orchestrator functions and has northbound/southbound interfaces. For the northbound interface, GUI functions are provided to the end-user. For the southbound interface, the Orchestration function is used for application deployment, setup, information collection/monitoring to each cloud, and multiple MECs. Here, managing multiple MECs collectively has mainly three advantages;

1) The usage log information of the application that the end-user has used in the cloud can be used as input information to AI/ML. Then, by AI/ML, the cached content can be

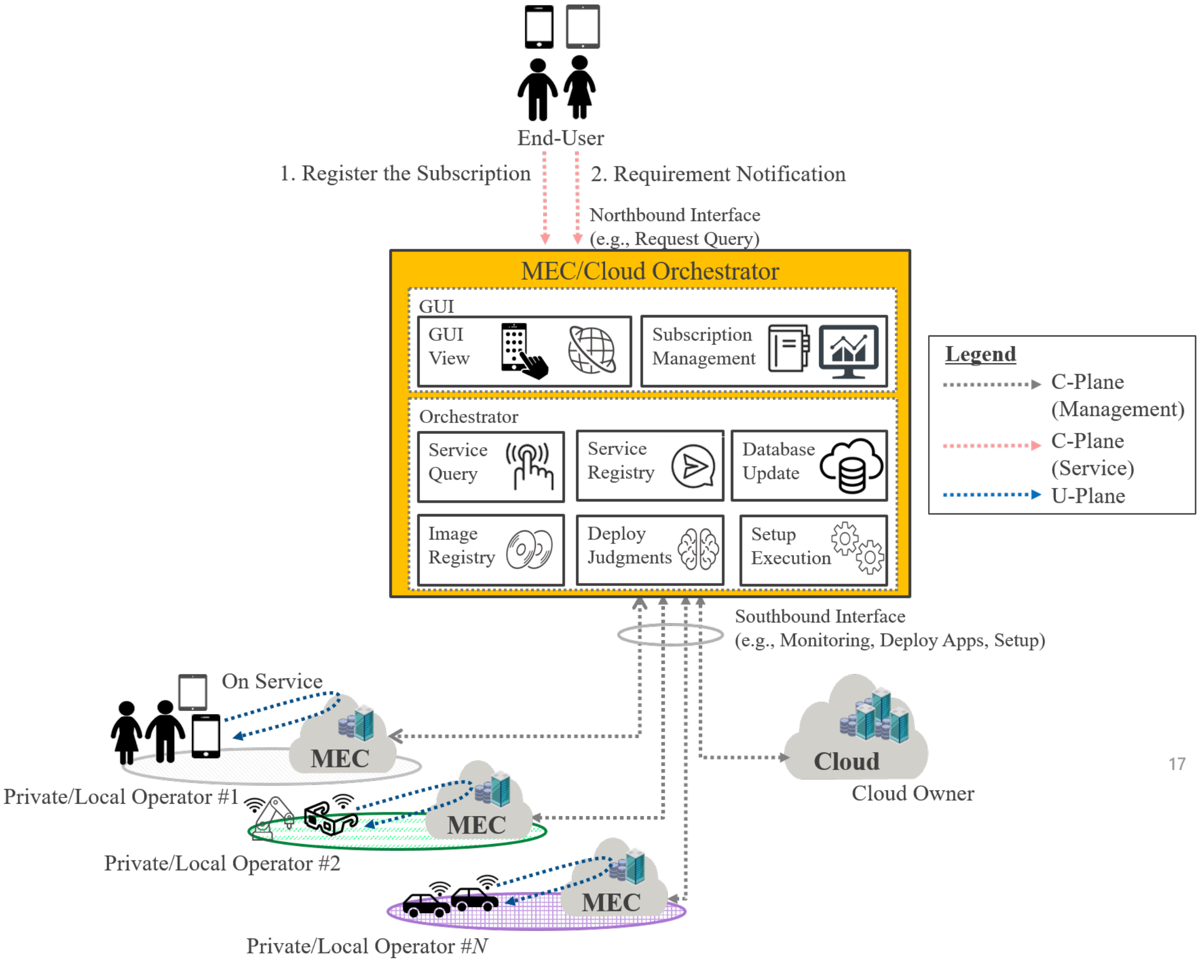


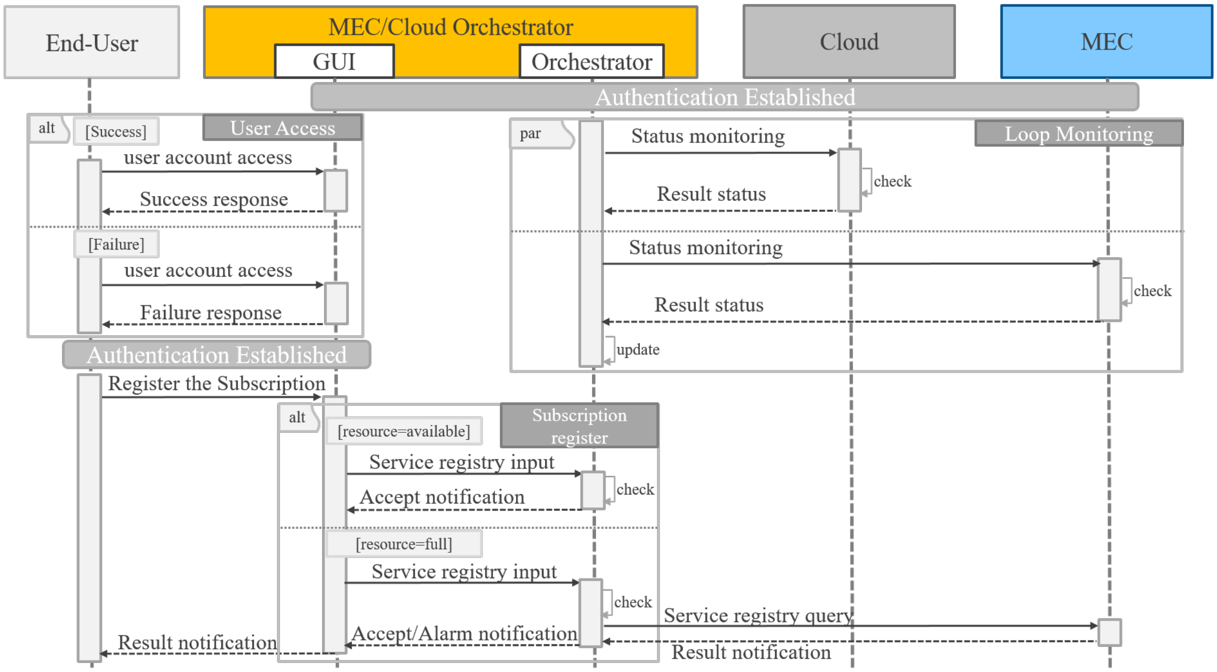
Figure 4.5: Illustration of the Centralized Type of a MEC/Cloud Orchestrator.

deployed on MEC as usage prediction or made known to end-users as recommendation information and selected.

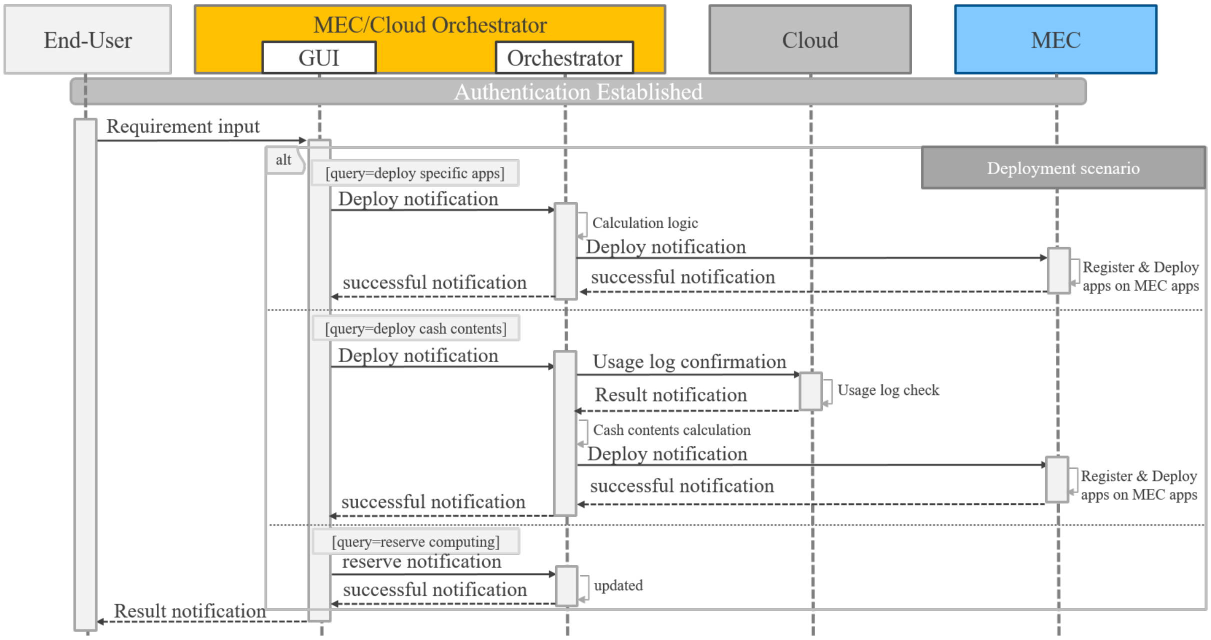
2) When the end-user has contracts with multiple Private/Local Telecom Operators, it is possible to track the movement of the application used by MEC when the end-user moves entirely because multiple MECs are managed collectively.

3) Since MEC/Cloud Orchestrator monitors each resource, the awareness of the physical location and the visualization management of the entire network can be performed so that the network route change in the event of a disaster, etc., is taken into consideration.

Thanks to the above-mentioned advantages, the proposed centralized scheme can collectively manage and operate multiple MECs.



(a) Subscription Registration Process.



(b) Deployment Process

Figure 4.6: **Sequence of MEC/Cloud Orchestrator for Implementation.**

4.3.3.2 Sequence implementation

There are two main steps for the end-user to gain the Private/Local Telecom Operator's services. The first is subscription registration, and the other is application deployment. The implementation detail of the proposed Centralized sequences is shown in Fig. 4.6. First, the end-user needs to access the GUI view using a registered account. Here, if the user access with a registered account, the one can receive a success message in GUI view. However, if the user access with an unregistered account, the one will receive a failure message response. The above sequence is a basic rule for blocking unauthorized access using a registered account in Fig. 4.6(a). On the other hand, a sequence in Fig. 4.6(a) acquires information on the cloud and multiple MECs regularly, which is a sequence different from user access. An authentication session has been established because the key authentication format has been distributed in advance. As monitored by the polling method, the status of the physical/logical information of the resource area (Computing, Network, Storage) secured in advance on the cloud system is confirmed. Similarly, the status of the physical/logical information of the resource area that can be used as MEC held by each Private/Local Telecom Operator is checked. The database inside the Orchestrator function is updated based on the information learned here. Although Fig. 4.6(a) also exemplifies the polling method, of course, a notification format in Syslog/Trap format is conceivable. Regarding the deployment resource space, since it is assumed that the Cloud Owner holds MEC/Cloud Orchestrator, the application deployment computing resource in the cloud can be changed by MEC/Cloud Orchestrator according to the usage status of the application. The resource area in MEC can be determined/changed according to the contract with the Private/Local Telecom Operator.

Next, the end-user describes the sequence of registering a subscription based on the access information. The end-user makes a subscription registration request. Here, the end-user needs to input the Private/Local Telecom Operator service data and select the range of use and the type of service. Orchestrator GUI then receives a registration request with the GUI function and make a service registration request to the Orchestrator function. The Orchestrator function confirms whether the resource area on the MEC side is open for the received request. If there is no problem, it gives a successful notification. Otherwise, if the resource area is insufficient, a request is made to the Private/Local Telecom Operator to update the contract to get the additional resources. MEC side is notified of the possibility that the resource area is insufficient. The service requirements (latency, cost, etc.) are not positively required. Orchestrator notifies to the end-user that the processing performance is

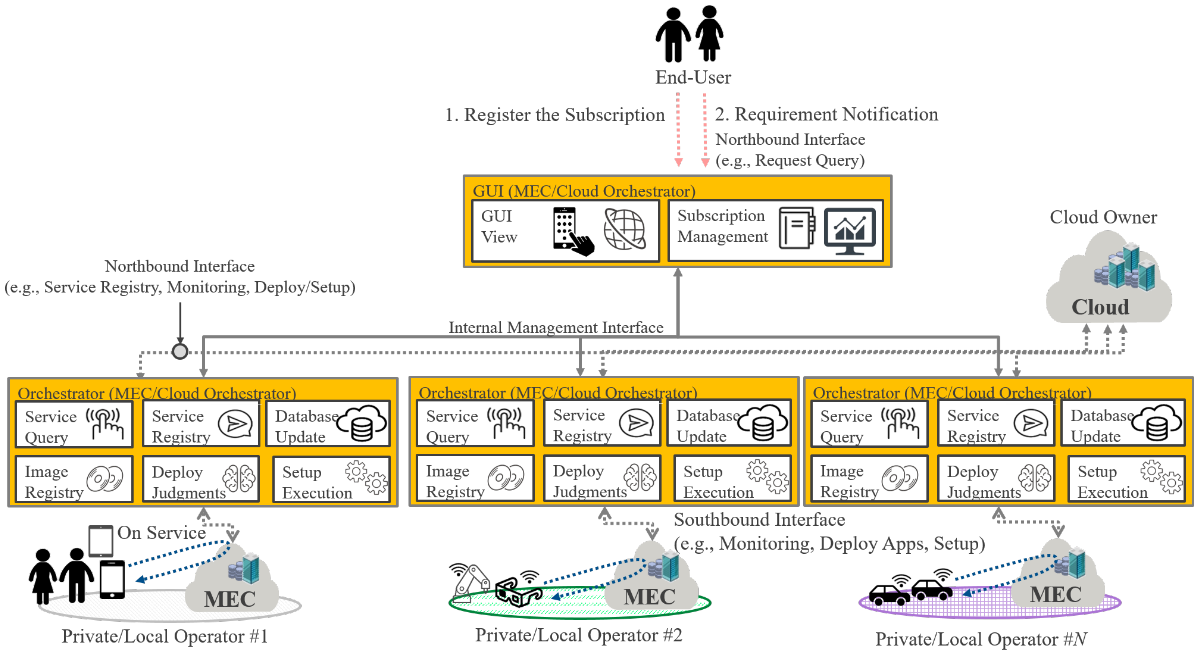


Figure 4.7: Illustration of the Distributed Type of a MEC/Cloud Orchestrator.

not guaranteed in this case. When further subscribing, it is necessary to consider the priority compared to other end-users.

Secondly, the application deployment sequence is shown in Fig. 4.6(b). The end-user starts the application deployment based on the subscription. There are three designs as an application deployment method as follows; (1) Specific application deployment method. (2) Cloud cached content of application specified in the cloud. (3) Computing resource reservation method.

Deployment method in (1) is deploying a basic application on a virtualization platform via VIM (Virtualized Infrastructure Management). Method of (2) is an intelligent method that generates cache content based on the access usage log information of cloud applications that end-users have used so far and deploys it on MEC. This method is possible because the Cloud Owner holds MEC/Cloud Orchestrator. Regarding (3), unlike (1) and (2), it is a method of reserving computing resources in advance. The resource reserved here could be used as a calculation resource or would be used as (1) and (2). Subscriptions only occur after you start using computing. With the above, it is possible to deploy the application on the cloud or MEC.

4.3.4 Distributed MEC/Cloud orchestrator

4.3.4.1 Logical overview

In a distributed manner, the orchestrator function and GUI function are separately deployed to each Private/Local Telecom Operator and the Internet, respectively. An overview of this architecture is illustrated in Fig. 4.7. The GUI functionality of MEC/Cloud Orchestrator is deployed at a higher level, e.g., on the Internet, so that end-users can access to it.

Meanwhile, a part of orchestration function, that is, the deployment function, is assigned to each Private/Local Telecom Operator.

The GUI function determines which Private/Local Telecom Operator service range is provided based on the end-user's registration information and requests it via the internal management interface. Based on the request information, the Orchestrator function in Private/Local Telecom Operator receives the information at the API interface published by Cloud Owner via the northbound interface. It is compared with MEC information acquired via the southbound interface and then the deployment destination is registered. Finally, the application is deployed based on the scenario judgment logic. A plurality of merits when MEC/Cloud Orchestrator is used The distributed manner has some advantages when MEC/Cloud Orchestrator is employed and managed for each Private/Local Telecom Operator listed as below;

1) It supports concealing confidential information such as network information, physical context information, server information, for each Private/Local Telecom Operator.

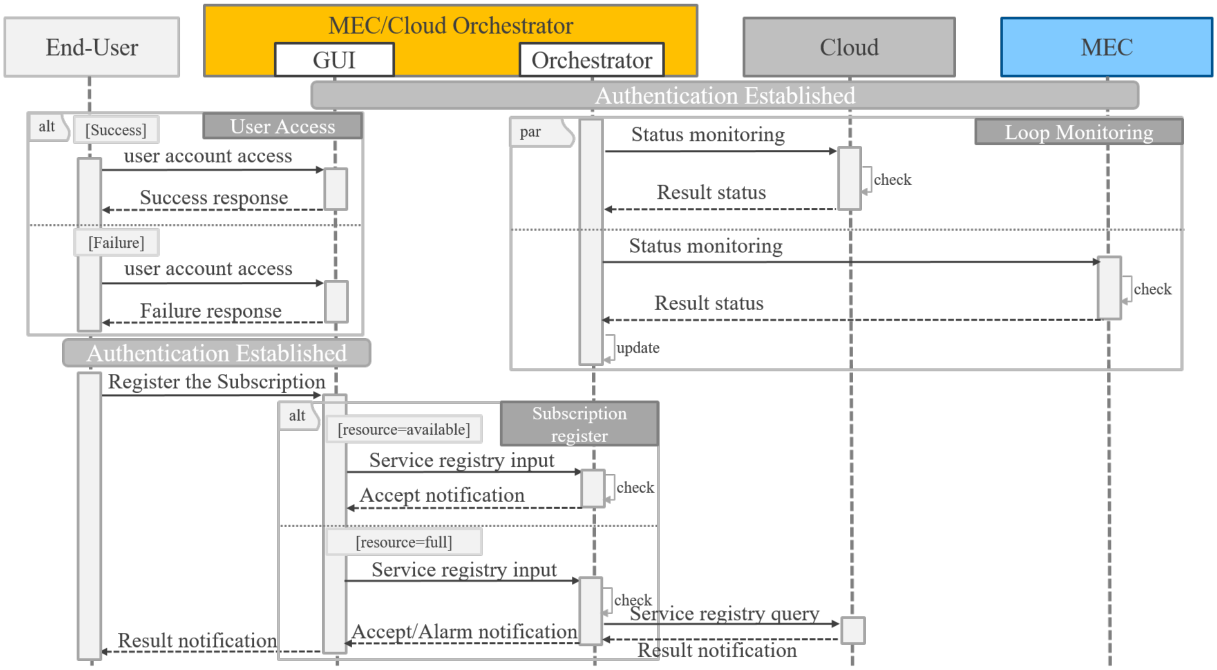
2) It recommends to end-users enjoying the Private/Local service according to the predicted regional information by algorithmizing the application in MEC which they hold as input information to AI/ML.

3) When a Private/Local Telecom Operator covers multiple areas, the log/tracking data and update of the application used by the end-users can be shared among regions.

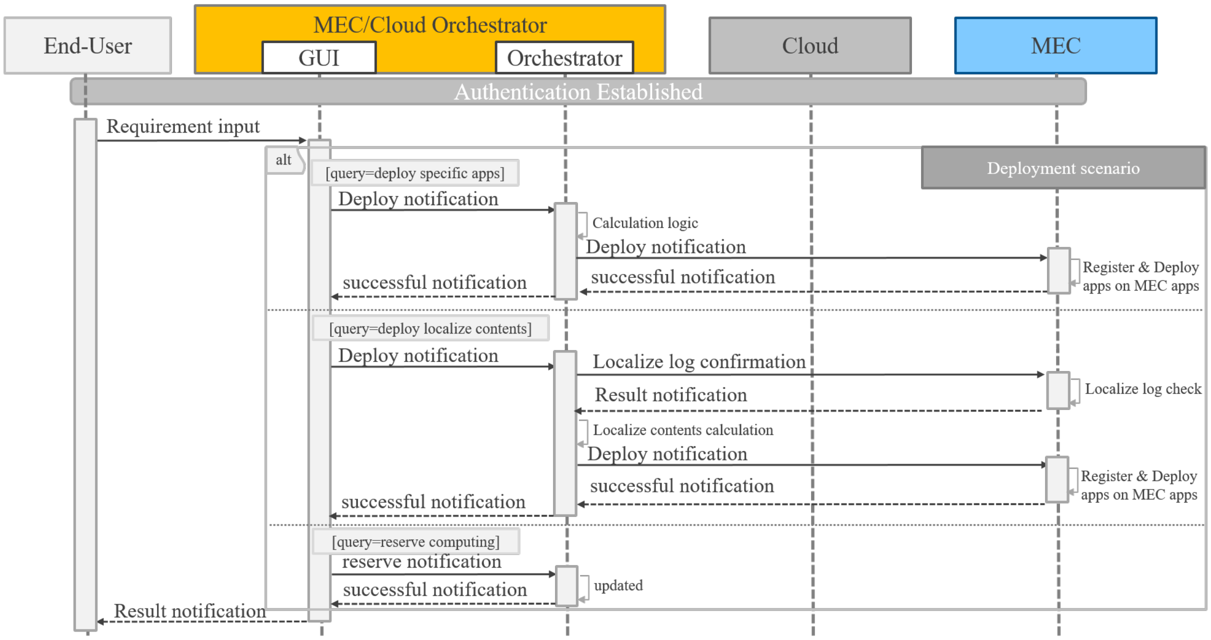
Because of the advantages described above, the distributed architecture can be one solution to manage and utilize MEC for each Private/Local Telecom Operator.

4.3.4.2 Sequence implementation

The basic sequence flow triggered by the end-user is the same as section 4.2.2. Here, the supplementary information in the distributed type sequence is mainly explained with support



(a) Subscription Registration Process.



(b) Deployment Process

Figure 4.8: **Sequence of MEC/Cloud Orchestrator in Distributed Type.**

of Fig. 4.8. In Fig. 4.8(a), regarding the sequence of regularly collecting data on the cloud and MEC, the cloud side needs to get the physical/logical data via the interface officially published by Cloud Owner. On the other hand, since the resource area on MEC side is inside the network, resource controller considers information such as RAN. MEC then becomes available because main function of MEC/Cloud Orchestrator is under the Private/Local Telecom Operator. Thanks to the above information, a roadmap for future hardware procurement, etc., could be planned. The Private/Local Telecom Operator can easily decide the purchase order supported by MEC/Cloud Orchestrator. Regarding subscription registration, when resource usage is about to exceed the capacity pre-reserved on the cloud, MEC/Cloud Orchestrator will request the cloud owner or end user to acquire additional resources.

Next, the application deployment sequence in Fig. 4.8(b) is described below. The application deployment sequence is almost the same as the centralized type. The difference is the deployment method by the localized cached contents method. In the localized cached contents, the subscription registered user is based on the analysis result of the usage logs of the ranking information in which many applications are used and the stored end-user information based on the history information of the application used in Private/Local Telecom Operator. In the localized cache contents, the cached application is deployed based on the analysis result of application ranking and trend given by end-user. This kind of application deployment method can be classified as localized information-based digital twins.

4.4 Performance evaluation of MEC beyond 5G cellular network

In this chapter, outdoor PoC work is conducted with realistic 5G. Detailed scenario of field trial is presented and the benefit of the Private/Local Telecom Operator has shown in the results.

4.4.1 Proof-of-concept description

The experiment field structure is drawn in Fig. 4.9. The outdoor PoC field was constructed in Tokyo Institute of Technology, Ookayama campus. As the 5G environment, multiple RUs were deployed for n77/n257 frequency bands and one LTE sector was deployed for various kind of applications. Table 4.1 shows hardware equipment and radio information such as

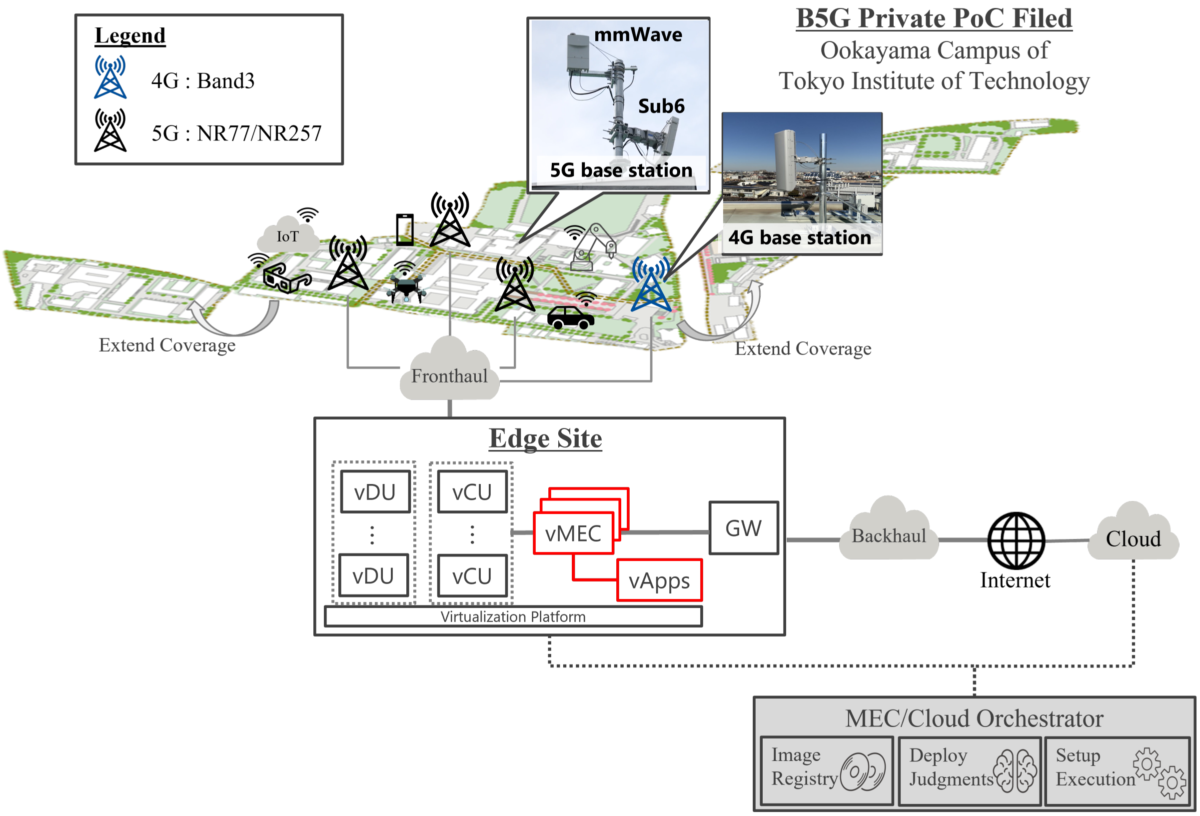


Figure 4.9: Outdoor PoC Field Design.

Table 4.1: Hardware Equipment Condition

Hardware Name	**Specifications**
LTE RU	Frequency Band: Band 3 System bandwidth: 5MHz
Sub6 RU	Frequency Band: n77 System bandwidth: 100MHz
mmWave RU	Frequency Band: n257 System bandwidth: 400MHz
UE Device [155]	CPU: Qualcomm® Snapdragon™ 765G 5G mobile platform OS: Android Support Band: Band3/n77/n257 Band3 Tx Rate: UL $\leq$ 18Mbps, DL $\leq$ 100Mbps n77 Tx Rate: UL $\leq$ 217Mbps, DL $\leq$ 2.13Gbps n257 Tx Rate: UL $\leq$ 273Mbps, DL $\leq$ 2.80Gbps
PC/Laptop	Model: dynabook G83/DN OS: Microsoft Windows 10 Pro CPU(Phy)/MEM: 4Core/8GB USB ports:2

the frequency of each RU. 4G uses 5MHz channel bandwidth (UL: 1825-1830MHz, DL: 1730-1735MHz) in the Band 3 (FDD), and 5G bands are prepared in both Sub6 n77 (TDD, 3.8-3.9GHz) and mmWave n257 (TDD, 27.0-27.4GHz). In case of the mmWave band, 400MHz Bandwidth, i.e., 4CC (4 x 100MHz Component Carrier), is assigned to the downlink while that for the uplink is 100MHz Bandwidth, i.e., 1CC (1x 100MHz CC). As a network connection, Edge Cloud is defined from after Fronthaul to before Internet Security Getaway. 4G/5G of RAN (vDU/vCU) was deployed in Edge cloud, and MEC and Apps that can be capsulized by GTP of User Plane were prepared. In addition, cloud vApps server is prepared in cloud side. In the vApps, an iperf3 software is installed to compare the communication performance of MEC and cloud. As a user equipment terminal, 5G compliant Rakuten Big s [155] is used. Its local App can specify IP for Iperf3 of vApp in MEC, and register itself in DNS for IPerf3 of Apps in cloud. Each of those settings can be confirmed by connecting with the specified Name. In addition, 4G is used for C-Plane signalling, and measurement is performed based on conditions in a state where PDU session establishment is completed. In other words, this PoC measurement starts from UE connection establishment and does not take into account the latency imposed by the attach procedure and any handover scenario. That is why only stational terminal is involved in the PoC, and the measurement is performed in a static condition because the main purpose of this PoC is to verify how essential and efficient the use of 5G MEC is for Private/Local Operators scenarios from the user plane performance standpoint. This PoC field coverage can be expanded by additionally deploying more RUs to fully support 5G area. Regarding to the connectives of the terminal, a PC is connected to the terminal via USB3.0 and the log information of the terminal is collected via XCAL [156]. With this measurement tool, it is also possible to acquire information such as RSRP, each protocol sequence, physical/MAC layer information, and wireless throughput. Captured data can be combined and analyzed by using XCAP [157]. Performance tendency per different network configuration for fronthaul/backhaul will be investigated separately. In the measurement, the application deployment location (either MEC or Cloud) is determined by the objective function to minimize the cost that satisfies the latency conditions.

End-users would like to select the more inexpensive computation environment. Here, the cost model based on chapter 3.3.2 is calculated by numerical analysis conducted with the actual field measurement results. The actual results in the testbed field are obtained by measuring the performance on the RAN side by XCAL.

Meanwhile, the logic of judgment needs to be added in MEC/Cloud Orchestrator, as shown in Fig. 4.2. In this chapter, we explain how to determine the minimum latency. The latency on the MEC side can be determined by the computing process because it is assumed that the MEC will be deployed on the RAN side. Regarding to the latency imposed on the cloud side, it is necessary to consider two kinds; backhaul network bandwidth and computing processing. The cloud side needs to evaluate both the latency effect and cost increase, whether the network bandwidth or computing resource is added. The MEC latency $t_{k,j}$ based on chapter 3.3.2 is expressed as,

$$t_{k,j} = \frac{\alpha_k w_k}{N_{\mathrm{MEC}} f_{k,j}} + \varepsilon_j, w_k = \delta b_k \tag{4.1}$$

where N_{MEC} denotes the number of MEC resources decided by private (local) telecom operator's strategy, w_k [CPU cycles] represents the task converted from information b_k with task weight δ, computation resource is expressed as $f_{k,j}$, and ε_j is processing queue in the MEC side as seen in Eq. (4.1). In the cloud side, the latency $t_{k,\mathrm{cl}}$ and cost c_{cl} is expressed as,

$$t_{k,\mathrm{cl}} = \frac{(1-\alpha_k)b_k}{N_{\mathrm{BH}}} + \frac{(1-\alpha_k)w_k}{N_{\mathrm{cl}} f_{\mathrm{cl}}} + \varepsilon_{\mathrm{cl}} \tag{4.2}$$

where N_{BH} denotes backhaul capacity, N_{cl} is the number of cloud resources, f_{cl} is computing resources, and $\varepsilon_{\mathrm{cl}}$ denotes the processing queue in the cloud as seen in Eq. (4.2). Since the measurement is performed using one sector, the sector j is set to 1, and user k is also one UE because RU is possible to allocate the maximum resource block (RB). It is possible to input highly reliable information as an input in the numerical calculation based on the measured delay performance.

4.4.2 Edge platform virtualization implementation

The edge computing platform held by the Private/Local Telecom Operator requires that various applications (RAN/Core/Apps) run on shared hardware. Figure 4.10 shows the architecture that the applications can run on the platform of virtualization. In this figure, COTS HW requires an MGMT (Management) GUI function that remotely controls the OS and power supply. As the OS, a general-purpose OS such as Ubuntu/CentOS/RedHat/Windows is used. As a Virtualization Platform, HW has vFPGA/ vMEM/ vCPU/ vGPU/ vSSD/ vHDD/ vNetwork/ vNIC/ vDriver that can be provided as virtualization as NFVI that can be managed by VIM, and specify it at the time of deployment according to the application

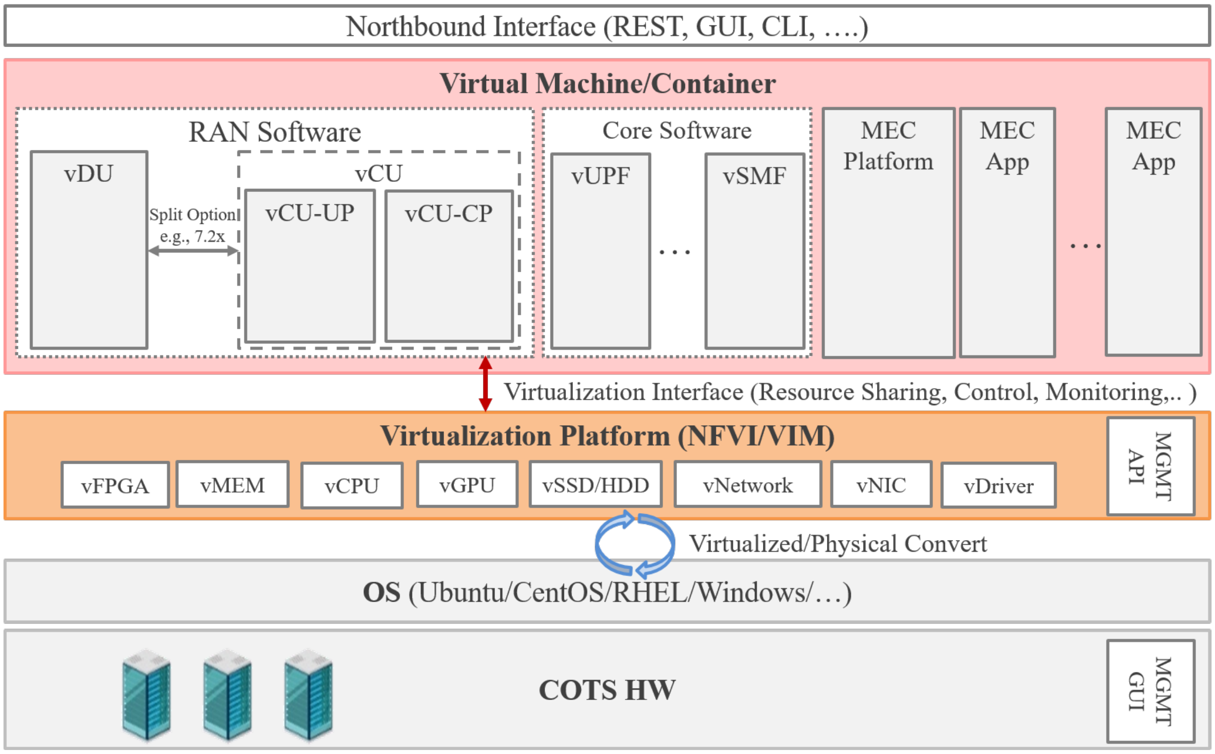


Figure 4.10: Edge Platform.

requirements for virtualization. API (Restful/CLI/SSH/YANG) can control VIM for NFVI via MGMT NW. RAN Software/Core Software/MEC Platform/MEC Apps can be operated as an application. RAN Software is divided into vDU/vCU. Furthermore, vCU is separated by CUPS and is divided into vCU-CP/vCU-UP. The interface between vDU and vCU is cut by Split Function (e.g., Split Option 6). Core Software is a 5GC-based function that can be deployed as needed, such as UPF, AMF, and SMF. MEC Platform and MEC App, etc., mainly indicate applications used by end-users when a local breakout is required. Since it runs on the same COTS HW as the above application, it can be operated by sharing resources and managing and monitoring it on the virtualization platform. In addition, the virtualization platform is adopted a single factor without multiplication to accommodate virtual applications for processing high performance.

4.4.3 Result of field trial

The basic throughput performance of the Sub6 and mmWave was measured through the NSA configuration. The measurement results in E2E were approx. 0.9 Gbps for Sub6 and 1.6

Table 4.2: Throughput Performance in PoC Field employing MEC

	w/ MEC		w/o MEC
	Sub6 n77	**mmW n257**	**Internet**
Throughput [Gbps]	0.9	1.6	0.9

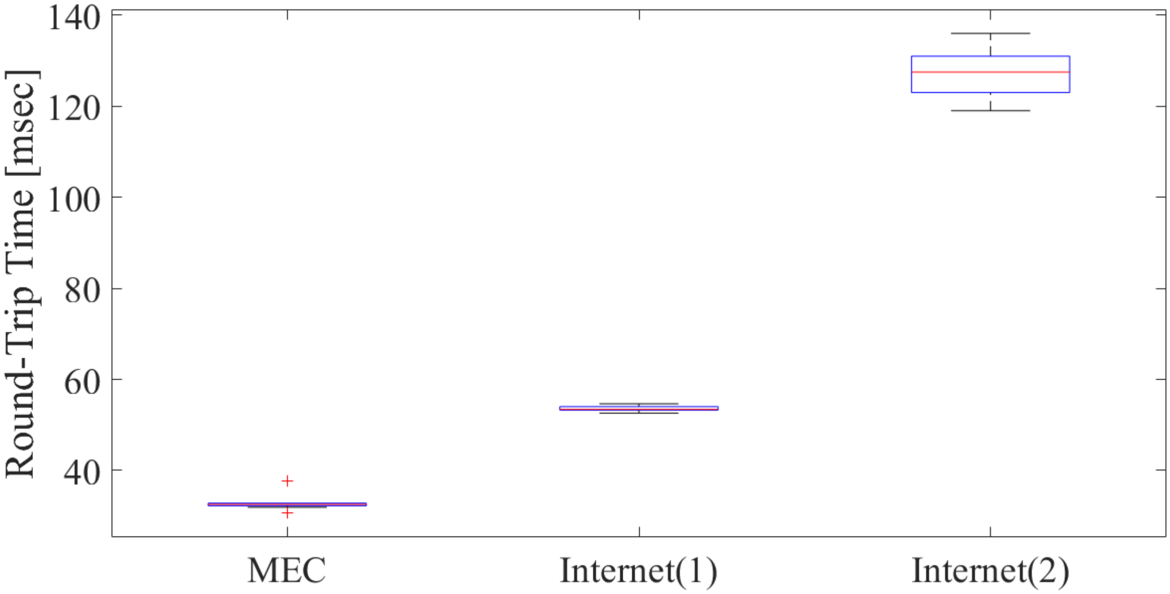


Figure 4.11: Latency Comparison of MEC and Internet.

Gbps for mmWave under the same 4G coverage in Table 4.2. This result includes throughput on the 4G side and is based on RF level, which depends on the development status of RAN software. It should be noted that the throughput in this measurement could not be the maximum performance. Meanwhile, to highlight the benefit of MEC, which support stable communication compared to the internet, we executed the throughput performance from Ookla sppedtest [158] which works in San Francisco, United State, via mmW from UE. As shown in Table 3, the performance in MEC via mmW is higher than on the internet. Hence, the performance of MEC is not only stabler but also higher than the internet. As for the latency performance, one packet of 56-bit data was transmitted via 5G and thus it does not occupy the RB and compares to throughput; a quantitative evaluation can be performed. Fig. 4.11 shows the latency result between MEC and Internet. For the Internet servers, the comparison of MEC was conducted using officially prepared ping servers in Hokkaido, Japan [159] and

San Francisco, United State. In internet, former was executed by ping from UE with IPv4 address in Hokkaido ping server, and latter was executed by Ookala sppedtest [158] in UE. In this figure, Internet (1) refers to the Hokkaido Ping server (ping-hokkaido.sinet.ad.jp) and Internet (2) to the San Francisco, United State. These results show averaged performance with 10 measurement trials in 100 sec period at UE. From the figure, it can be seen that the average latency of MEC via Sub6/mmW is approximately 33 msec, which is an improvement of about 20 msec compared to the Internet (1). It also shows that the improvement of latency depends on the server location in the Internet based on physical distance. Based on the above results, we can estimate that the latency between the RU and the CU was about 5 msec when installed on the near side of the base station, so the latency can be reduced to about 5 msec to 15 msec. These results were implemented assuming a Private/Local Operator as a MEC that partially verifies the designed MEC/Cloud Orchestrator. As a result, the application was correctly deployed and implemented in E2E, and the communication stability and delay were more stable and lower than in the case of the Internet cloud. In other words, the throughput in MEC is more stable than w/o MEC because the distance of E2E network has not only been shortened, but also the network's condition has become more stable as there are fewer in-between network devices.

4.5 Conclusion

This chapter addresses the challenge of managing and deploying applications in MEC. In particular, we proposed a detailed implementation for the MEC/Cloud Orchestrator. In addition, we designed a case where the MEC/Cloud Orchestrator would be owned by either an existing Cloud Owner or a Private/Local Operator that would split the functionality of the MEC/Cloud Orchestrator. During the design process, it was found that deploying the RAN and MEC on a virtualized platform and renting other equipment from Legacy Telecom Operators facilitates the participation of Private/Local Operator in a MEC ecosystem. For the system implementation of this proposal, we designed an E2E system and constructed a PoC field at Ookayama Campus of Tokyo Institute of Technology. In this field, an edge cloud was implemented on campus, and SOTA hardware and software were deployed. In this field, we conducted a PoC through an outdoor field trial to verify the essential effectiveness of the proposed concept from an E2E perspective. In addition, the obtained verification results showed lower latency and more stable communication than current cloud services. In the future, to generalize the implementation system this time, this work will consider and implement open-source-based system implementation and microservices. In addition, in the PoC outdoor field constructed in this chapter, we will utilize it in various researches toward Beyond 5G.

Chapter 5

Conclusion

5.1 Summary

This chapter concludes this thesis and presents future prospects. Chapter 2 is discussed about the architecture of MEC, which is referenced in the following chapters. Specifically, we first discussed the current status of reference architecture of MEC in the latest standardization trends (3GPP, ETSI). Next, the proposed architecture of MEC, taking into account use cases based on standardization trends, was discussed. In the discussion, the low latency of E2E in MEC was formulated, and we explained each equation and parameter. Finally, based on the proposal equations, we also evaluated them by numerical analysis. The evaluation results found that increasing the computing resources can obtain a delay reduction trend, but the benefits obtained become smaller when more resources are added.

Chapter 3 designs a mobile ecosystem to support MEC to accelerate its deployment in 5G and beyond cellular networks. In this Capter, a revenue model involving three players has been proposed: private/local operators, backhaul owners, and cloud owners. Our initial evaluation of the private/local operator in the proposed model showed that the profit/loss tends to increase with the addition of MECs and that the number of MECs that can generate the maximum revenue depends on the MEC resource costs and application requirements. Thus, private/local operator revenues vary depending on the duration of MEC resource use and the number of MEC resources deployed. Next, we evaluated a social maximization revenue model with an investment strategy in which the telecom operator determines the number of MECs and the backhaul owner leases backhaul capacity. The proposed delayable selection model increases the selection rate when the number of MEC resources exceeds a certain threshold and the average selection rate by MECs is saturated. From the revenue formulae for carriers and backhaul operators, the results are interpreted in terms of a convex function. That is, N_{MEC} and N_{BH} should be optimized so that the revenues of the telecom operator and the backhaul owner are maximized simultaneously. As a result, based on game theory, we analyzed the optimal number of cases where the maximized revenue outcome of the two players is satisfied. The results show that MEC can be advantageous by using cloud and edge resources in parallel instead of processing all traffic on the MEC side. Finally, we evaluated a social maximization revenue model with an investment strategy in which the telecom operator determines the number of MECs and the cloud operator leases backhaul capacity. we also formulated a computational resource allocation problem that maximizes their revenue under the constraint of satisfactory end-to-end delay as QoS/QoE on the user side; MEC resources and backhaul capacity are the key resource parameters optimized. A game-theoretic approach was adopted, and large-scale simulations obtained the solution based on a heterogeneous network of millimeter-wave small cells on macrocells. In addition, we observed the optimized characteristics using various parameters such as delay requirements, the cost of deploying MEC, and the number of computational tasks. The results reveal the benefits of MEC and show that both edge and cloud computing resources are essential to maximize revenue for all players and satisfy user QoS/QoE. In particular, MEC is essential for mission-critical application services. The proposed approach can provide valuable insights into enabling MEC-enabled system design for the Beyond 5G.

Chapter 4 addresses the challenge of managing and deploying applications in MEC. In particular, we proposed a detailed implementation for the MEC/Cloud Orchestrator. In addition, we designed a case where the MEC/Cloud Orchestrator would be owned by either an existing Cloud Owner or a Private/Local Operator that would split the functionality of the MEC/Cloud Orchestrator. During the design process, it was found that deploying the RAN and MEC on a virtualized platform and renting other equipment from Legacy Telecom Operators facilitates the participation of Private/Local Operator in a MEC ecosystem. For the system implementation of this proposal, we designed an E2E system and constructed a PoC field at Ookayama Campus of Tokyo Institute of Technology. In this field, an edge cloud was implemented on campus, and SOTA hardware and software were deployed. In this field, we conducted a PoC through an outdoor field trial to verify the essential effectiveness of the proposed concept from an E2E perspective. In addition, the obtained verification results showed lower latency and more stable communication than current cloud services. In the future, to generalize the implementation system this time, this work will consider and implement open-source-based system implementation and microservices. In addition, in the PoC outdoor field constructed in this chapter, we will utilize it in various researches toward Beyond 5G.

5.2 Suggestion for future works

This section explains the future several research directions related to the work presented in this thesis.

5.2.1 Verification of Ecosystem in Beyond 5G PoC Fields

Chapter 3 evaluated the MEC ecosystem through discussion and numerical analysis. This evaluation is based on desk discussions and shows its effectiveness. However, when considering universality, the usefulness of the proposed formulae need to be partly verified through empirical experiments. Therefore, it is necessary to demonstrate the validity of the formulae using the cost required for the constructed experimental field. Also, CAPEX and OPEX need to be measured over a long period. Furthermore, there is a need to calculate the MEC's resource rental for multiple use cases, although some hypotheses are necessary.

5.2.2 Experimental verification of several use cases in beyond 5G PoC fields

Chapter 4 proposed a B5G/6G platform where Edge Cloud connects the physical space to cyberspace. In the future, there has two research directions of edge cloud, such as "how to control applications deployed automatically and migrate user data between edge cloud" and "how to achieve the intelligence of edge cloud." This discussion raised such issues in realizing services close to end-users. In addition, this section is described the state-of-the-art of Private B5G PoC field in Ookayama Campus of Tokyo Institute of Technology, Japan, and introduced the future research direction. Furthermore, PoC is necessary to discover the specificity of one important cutting-edge research as B5G/6G. In addition, worldwide, there are several projects in various countries where PoC-capable field development is being carried out using university campus fields (5GTN (Finland) [160], 5G/6G CAMPUS TESTBED (UK)) [161]. Therefore, it will also play an essential role as a research and development base in this PoC

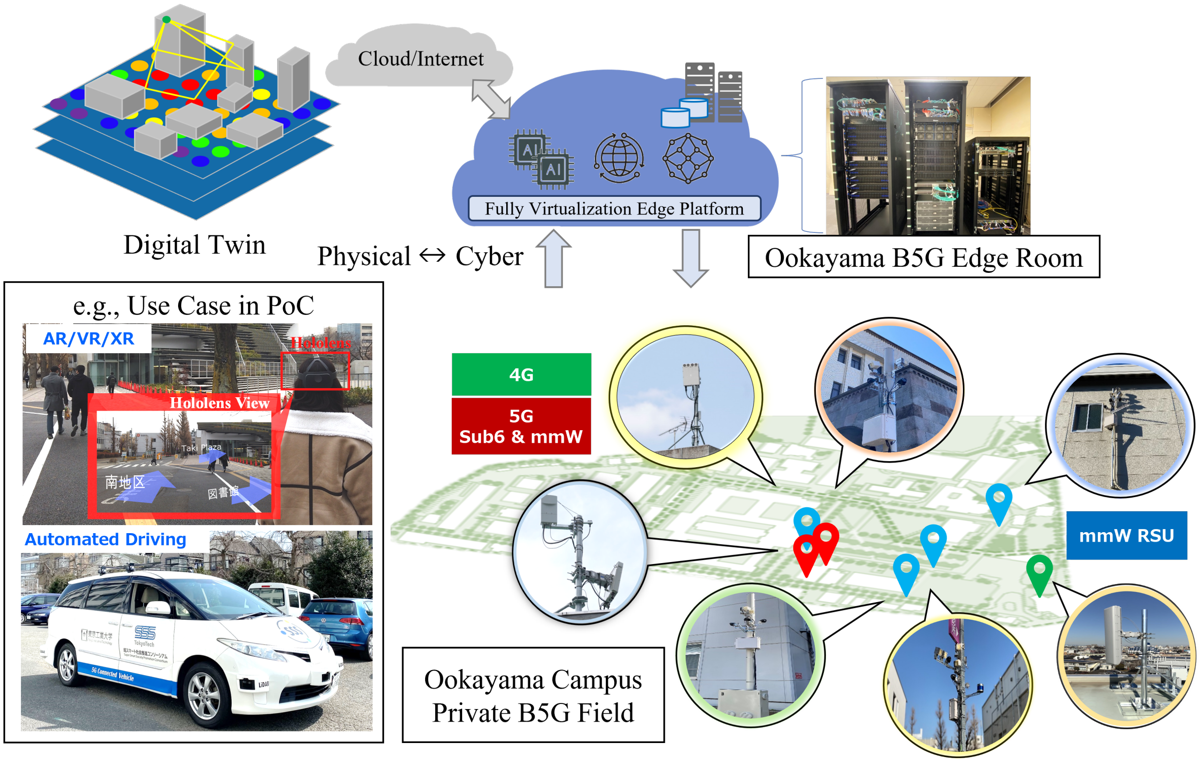


Figure 5.1: B5G Outdoor Field Extension.

field. Furthermore, this PoC Field will become more active in discussions to contribute to standardization in the future. Specifically, the research will be carried out in the future using this PoC field such as Edge Enabler AI, Cellular V2X, Digital Twin as shown in Fig. 5.1.

Appendix I

List of Publications

I.1 Journal papers

- **J. Nakazato**, M. Nakamura, T. Yu, Z. Li, K. Maruta, G. K. Tran, K. Sakaguchi, “Market Analysis of MEC-Assisted Beyond 5G Ecosystem,” IEEE Access, Vol. 9, pp. 53996-54008, March 2021.
- **J. Nakazato**, Z. Li, K. Maruta, K. Kubota, T. Yu, G. K. Tran,K. Sakaguchi, S. Masuko, “MEC/Cloud Orchestrator to Facilitate Private/Local Beyond 5G with MEC and Proof-of-Concept Implementation,” Sensors 2022, 22, 5145.

I.2 Journal papers not related to this thesis

- **J. Nakazato**, D. Okuyama, Y. Morimoto, and Y. karasawa, "Frequency-Domain Differential Coding Schemes under Frequency-Selective Fading Environment in Adaptive Baseband Radio," IEICE Trans., Commun.vol. E99-B, no. 2, pp. 488-498, 2016.
- **J. Nakazato** and Y. Karasawa, "Multi-user Extension of Low-Power-Density Baseband Radio Based on FrequencyDomain Differential Coding for Spectrum Spreading," IEICE Trans., Commun.vol.J101-B, no.2, pp. 100-110, Feb. 2018.
- M. Nakamura, H. Nishiuchi, **J. Nakazato**, K. Koslowski, J. Daube, R. Santos, G. K. Tran, and K. Sakaguchi. “Experimental Verification of SDN/NFV in Integrated mmWave Access and Mesh Backhaul Networks.” IEICE Transactions on Commun. 104, no. 3 (2021): 217-228.

I.3 International conferences

- **J. Nakazato**, Y. Tao, G. K. Tran and K. Sakaguchi, “Revenue Model with Multi-Access Edge Computing for Cellular Network Architecture,” IEEE ICUFN, 2019, pp. 21-26.[**Best Paper Award**]

- **J. Nakazato**, M. Nakamura, Y. Tao, G. K. Tran and K. Sakaguchi, "Benefits of MEC in 5G Cellular Networks from Telecom Operator’s View Points," 2019 IEEE Global Communications Conference (GLOBECOM), 2019, pp. 1-7.

- **J. Nakazato**, M. Nakamura, T. Yu, Z. Li, G. K. Tran and K. Sakaguchi, "Design of MEC 5G Cellular Networks: Viewpoints from Telecom Operators and Backhaul Owners," IEEE ICC, 2020, pp. 1-6.

- **J. Nakazato**, Z. Li, K. Kubota, K. Maruta, K. Sakaguchi, and S. Masuko, "Fully Virtualization Edge Cloud towards B5G/6G,”EuCNC/6G Summit, 2022.

- **J. Nakazato**, M. Kuchitsu, A. Pawar, S. Masuko, K. Tokugawa, K. Kubota, K. Kazuki, K. Sakaguchi, “Proof-of-Concept of Distributed Optimization of Micro-Services on Edge Computing for Beyond 5G,” IEEE VTC Spring, 2022.

I.4 International conferences not related to this thesis

- M. Ozasa, **J. Nakazato**, K. Hirata, G.K. Tran and K. Sakaguchi, "Design of Millimeter-wave UAV Base Station for Access Link", 2020 IEEE 92nd Vehicular Technology Conference, Dec. 2020.[**IEEE VTS Japan chapter VTC young researcher’s encouragement award in VTC20-spring**]

- G. Cho, Y. Shinyama, **J. Nakazato**, K. Maruta, K. Sakaguchi, “Object Recognition Network using Continuous Roadside Cameras,” Proc. The 2022 IEEE 95th Vehicular Technology Conference (VTC2022-Spring), Helsinki, Finland, June 2022.[**IEEE VTS Japan chapter VTC young researcher’s encouragement award in VTC22-spring**]

- K. Tokugawa, K. Maruta, K. Sakaguchi, **J. Nakazato**,M. Kuchitsu, S. Masuko, “Design of mmW Digital Twin Platform Toward B5G/6G -High-Precision Measurement System and Relay Station Deployment-,” Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC2022), Virtual, September 2022.

I.5 Domestic conferences

- **J. Nakazato**, M. Nakamura, T. Yu, Z. Li, G. K. Tran, K. Sakaguchi, “Design of MEC Cellular Networks:Viewpoints from Telecom Operator and Backhaul Owner,” IEICE RCS Technical Report, Dec. 2019.
- **J. Nakazato**, Z. Li, K. Maruta, K. Sakaguchi, “Viewpoint from Local Telecom Operators and Cloud Owners” IEICE Technical Report, RCS, Mar. 2021.
- **J. Nakazato**, M. Kuchitsu, M. Nanri, J. Kusumi, S. Masuko, K. Maruta, K. Sakaguchi, "Design of Edge/Cloud Virtualization Platform towards Beyond 5G", IEICE Society Conference, IEICE, Sep. 2021.
- **J. Nakazato**, M. Kuchitsu, A. Pawar, M. Nanri, J.Kusumi, S. Masuko, K. Maruta, K. Sakaguchi, "Edge Cloud RD towards Beyond 5G", Optoelectronics Industry and Technology Conference, Nov. 2021.
- J**J. Nakazato**, M. Kuchitsu, M. Nanri, J. Kusumi, S. Masuko, K. Maruta, K. Sakaguchi, "Edge Cloud Virtualization Platform towards Beyond 5G", CCSE2021 Conference, Dec. 2021.
- **J. Nakazato**, M. Kuchitsu, A. Pawar, S. Masuko, K. Tokugawa, K. Kubota, K. Maruta, K. Sakaguchi, "Proof-of-Concept of Micro-Service Distributed Optimization on Edge Computing over Beyond 5G", IEICE Technical Report, vol. 121, no. 391, RCS2021-263, pp. 62-67, March, 2022.
- **J. Nakazato**, M. Kuchitsu, M. Nanri, J. Kusumi, S. Masuko, K. Kubota, K. Maruta, K. Sakaguchi, " Design of Edge/Cloud Cooperation in Virtualization Platform towards Beyond 5G ", IEICE Society Conference, IEICE, March, 2022.
- **J. Nakazato**, M. Kuchitsu, S. Masuko, K. Tokugawa, K. Kubota, K. Sakaguchi, "Deployment of PoC Field towards Beyond 5G/6G“, IEICE Technical Report, vol. 122, no. 49, RCS2022-17, pp. 20-25, May, 2022.

References

[1] E. Bastug, M. Bennis, and M. Debbah. Living on the edge: The role of proactive caching in 5g wireless networks. *IEEE Communication Magazine*, Vol. 52, No. 8, pp. 82–89, August 2014.

[2] Cisco. Cisco annual internet report (2018–2023) white paper, March 2020.

[3] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez. Millimeter wave mobile communications for 5g cellular: It will work! *IEEE Access*, Vol. 1, pp. 335–349, 2013.

[4] K. Sakaguchi, T. Haustein, S. Barbarossa, E. Strinati, A. Clemente, G. Destino, A. Pärssinen, I. Kim, H. Chung, J. Kim, W. Keusgen, R. J. Weiler, K. Takinami, E. Ceci, A. Sadri, L. Xian, A. Maltsev, G. K. Tran, H. Ogawa, K. Mahler, and R. W. Health. Where, when, and how mmwave is used in 5g and beyond. *IEICE Transactions on Electronics*, Vol. E100.C, No. 10, pp. 790–808, 2017.

[5] M. Agiwal, A. Roy, and N. Saxena. Next generation 5g wireless networks: A comprehensive survey. *IEEE Communications Surveys Tutorials*, Vol. 18, No. 3, pp. 1617–1655, 2016.

[6] W. Roh, J. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar. Millimeter-wave beamforming as an enabling technology for 5g cellular communications: theoretical feasibility and prototype results. *IEEE Communications Magazine*, Vol. 52, No. 2, pp. 106–113, 2014.

[7] A. Ghosh, A. Maeder, M. Baker, and D. Chandramouli. 5g evolution: A view on 5g cellular technology beyond 3gpp release 15. *IEEE Access*, Vol. 7, pp. 127639–127651, 2019.

[8] H. Ishii, Y. Kishiyama, and H. Takahashi. A novel architecture for lte-b :c-plane/u-plane split and phantom cell concept. In *2012 IEEE Globecom Workshops*, pp. 624–630, 2012.

[9] K. Sakaguchi, G. K. Tran, H. Shimodaira, S. Namba, T. Sakurai, I. Siaud, K. Takinami, E. C. Strinati, A. Capone, I. Karls, R. Arefi, and T. Haustein. *IEICE Transactions on Communications*, Vol. E98.B, No. 3, pp. 388–402, 2015.

[10] S. Zhang, Q. Wu, S. Xu, and G. Y. Li. Fundamental green tradeoffs: Progresses, challenges, and impacts on 5g networks. *IEEE Communications Surveys Tutorials*, Vol. 19, No. 1, pp. 33–56, 2017.

[11] S. Li, L. D. Xu, and S. Zhao. 5g internet of things: A survey. *Journal of Industrial Information Integration*, Vol. 10, pp. 1–9, 2018.

[12] Recommendation ITU-R M.2083-0:. Imt vision - framework and overall objectives of the future development of imt for 2020 and beyond. September 2015.

[13] W. Lehr, F. Queder, and J. Haucap. 5g: A new future for mobile network operators, or not? *Telecommunications Policy*, Vol. 45, No. 3, p. 102086, apr 2021.

[14] Rewheel research:. 1&1 drilisch's 4th mno entry in germany - will it work? September 2021.

[15] DISH and AWS Form Strategic Collaboration to Reinvent 5G Connectivity and Innovation.

[16] M. Salem, P. Imai, P. Vajrabhaya, and T. Amin. A perspective on autonomous networks from the world's first fully virtualized mobile network. *IEEE Wireless Communications*, Vol. 28, No. 2, pp. 6–8, 2021.

[17] A. Reaz, V. Ramamurthi, and M. Tornatore. Cloud-over-woban (cow): An offloading-enabled access network design. In *2011 IEEE International Conference on Communications (ICC)*, pp. 1–5, 2011.

[18] Cisco VNI Forecast. Cisco visual networking index: Forecast and trends,2017–2022, February 2019.

[19] Market Research Future Company. Cisco visual networking index: Forecast and trends,2017–2022. `https://www.marketresearchfuture.com/reports/public-cloud-market-2291`, July 2018.

[20] A. Abouaomar, A. Filali, and A. Kobbane. Caching, device-to-device and fog computing in 5^{th} cellular networks generation : Survey. In *2017 International Conference on Wireless Networks and Mobile Communications (WINCOM)*, pp. 1–6, 2017.

[21] M. Kamel, W. Hamouda, and A. Youssef. Ultra-dense networks: A survey. *IEEE Communications Surveys Tutorials*, Vol. 18, No. 4, pp. 2522–2545, 2016.

[22] M. Jaber, M. A. Imran, R. Tafazolli, and A. Tukmanov. 5g backhaul challenges and emerging research directions: A survey. *IEEE Access*, Vol. 4, pp. 1743–1766, 2016.

[23] J. Zhao, T. Q. S. Quek, and Z. Lei. Coordinated multipoint transmission with limited backhaul data transfer. *IEEE Transactions on Wireless Communications*, Vol. 12, No. 6, pp. 2762–2775, 2013.

[24] OECD Broadband statics. Percentage of fiber connections in total broadband. `http://www.oecd.org/sti/broadband/broadband-statistics/`, June 2020.

[25] A. Ghosh, A. Maeder, M. Baker, and D. Chandramouli. 5g evolution: A view on 5g cellular technology beyond 3gpp release 15. *IEEE Access*, Vol. 7, pp. 127639–127651, 2019.

[26] A. Osseiran, F. Boccardi, V. Braun, K. Kusume, P. Marsch, M. Maternia, O. Queseth, M. Schellmann, H. Schotten, H. Taoka, H. Tullberg, A. M. Uusitalo, B. Timus, and M. Fallgren. Scenarios for 5g mobile and wireless communications: the vision of the metis project. *IEEE Communications Magazine*, Vol. 52, No. 5, pp. 26–35, 2014.

[27] K. Serizawa, M. Mikami, K. Moto, and H. Yoshino. Field trial activities on 5g nr v2v direct communication towards application to truck platooning. In *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, pp. 1–5, 2019.

[28] J. Pilz, B. Holfeld, A. Schmidt, and K. Septinus. Professional live audio production: A highly synchronized use case for 5g urllc systems. *IEEE Network*, Vol. 32, No. 2, pp. 85–91, 2018.

[29] Y. C. Hu, M. Patel, D. Sabella, N. Sprecher, and V. Young. Mobile edge computing: A key technology towards 5g, September 2015.

[30] I. Morris. Etsi drops 'mobile' from mec, September 2016.

[31] T. Taleb, K. Samdanis, B. Mada, H. Flinck, S. Dutta, and D. Sabella. On multi-access edge computing: A survey of the emerging 5g network edge cloud architecture and orchestration. *IEEE Communications Surveys Tutorials*, Vol. 19, No. 3, pp. 1657–1681, 2017.

[32] S. Barbarossa, S. Sardellitti, E. Ceci, and M. Merluzzi. Chapter 16 - the edge cloud: A holistic view of communication, computation, and caching. In Petar M. Djurić and Cédric Richard, editors, *Cooperative and Graph Signal Processing*, pp. 419–444. Academic Press, 2018.

[33] ETSI White Paper No. 30:. Mec in an enterprise setting: A solution outline, September 2018.

[34] Y. Mao, C. You, J. Zhang, K. Huang, and K. B. Letaief. A survey on mobile edge computing: The communication perspective. *IEEE Communications Surveys Tutorials*, Vol. 19, No. 4, pp. 2322–2358, 2017.

[35] J. Moura and D. Hutchison. Game theory for multi-access edge computing: Survey, use cases, and future trends. *IEEE Communications Surveys Tutorials*, Vol. 21, No. 1, pp. 260–288, 2019.

[36] R. Khan, P. Kumar, D. N. K. Jayakody, and M. Liyanage. A survey on security and privacy of 5g technologies: Potential solutions, recent advancements, and future directions. *IEEE Communications Surveys Tutorials*, Vol. 22, No. 1, pp. 196–248, 2020.

[37] T. X. Tran, A. Hajisami, P. Pandey, and D. Pompili. Collaborative mobile edge computing in 5g networks: New paradigms, scenarios, and challenges. *IEEE Communications Magazine*, Vol. 55, No. 4, pp. 54–61, 2017.

[38] Open Edge Computing Initiative. `https://www.openedgecomputing.org/`.

[39] Open Fog Consortium. `https://www.iiconsortium.org/index.htm`.

[40] Automated Edge Computing Consortium. `https://aecc.org/`.

[41] 5G-MiEdge. `https://5g-miedge.eu/2016/10/13/5g-miedge-eu-japan-project-started/`.

[42] Europe Edge Computing Consortium. `http://ecconsortium.eu/`.

[43] Edge Computing Consortium. `http://en.ecconsortium.org/Content/index/cid/2.html`.

[44] C. Parada, F. Fontes, C. Marques, V. Cunha, and C. Leitão. Multi-access edge computing: A 5g technology. In *2018 European Conference on Networks and Communications (EuCNC)*, pp. 277–9, 2018.

[45] O. Mämmelä, T. Ojanperä, J. Mäkelä, O. Martikainen, and J. Väisänen. Evaluation of lidar data processing at the mobile network edge for connected vehicles. In *2019 European Conference on Networks and Communications (EuCNC)*, pp. 83–88, 2019.

[46] A. Karamoozian, A. Hafid, and E. M. Aboulhamid. On the fog-cloud cooperation: How fog computing can address latency concerns of iot applications. In *2019 Fourth International Conference on Fog and Mobile Edge Computing (FMEC)*, pp. 166–172, 2019.

[47] D. Sabella, N. Nikaein, A. Huang, J. Xhembulla, G. Malnati, and S. Scarpina. A hierarchical mec architecture: Experimenting the raven use-case. In *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, pp. 1–5, 2018.

[48] M. Emara, M. C. Filippou, and D. Sabella. Mec-assisted end-to-end latency evaluations for c-v2x communications. In *2018 European Conference on Networks and Communications (EuCNC)*, pp. 1–9, 2018.

[49] C. Huang S.Yang, Y. Tseng and W. Lin. Multi-access edge computing enhanced video streaming: Proof-of-concept implementation and prediction/qoe models. *IEEE Transactions on Vehicular Technology*, Vol. 68, No. 2, pp. 1888–1902, 2019.

[50] Successful PoC demonstration of data flows control function by edge computing. `https://www.kddi-research.jp/english/newsrelease/2018/022301.html`.

[51] C. Li, Y. Lin, Y. Lai, H. Chien, Y. Huang, P. Huang, and H. Liu. Transparent aaa security design for low-latency mec-integrated cellular networks. *IEEE Transactions on Vehicular Technology*, Vol. 69, No. 3, pp. 3231–3243, 2020.

[52] M. Nakamura, H. Nishiuchi, K. Koslowski, J. Daube, R. Santos, G. K. Tran, and K. Sakaguchi. Performance evaluation of prefetching algorithm for real-time edge content delivery in 5g system. In *2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall)*, pp. 1–5, 2019.

[53] N. Abbas, Y. Zhang, A. Taherkordi, and T. Skeie. Mobile edge computing: A survey. *IEEE Internet of Things Journal*, Vol. 5, No. 1, pp. 450–465, 2018.

[54] W. Zhuang, Q. Ye, F. Lyu, N. Cheng, and J. Ren. Sdn/nfv-empowered future iov with enhanced communication, computing, and caching. *Proceedings of the IEEE*, Vol. 108, No. 2, pp. 274–291, 2020.

[55] Z. Chen, Q. He, L. Liu, D. Lan, H. Chung, and Z. Mao. An artificial intelligence perspective on mobile edge computing. In *2019 IEEE International Conference on Smart Internet of Things (SmartIoT)*, pp. 100–106, 2019.

[56] S. Olariu. A survey of vehicular cloud research: Trends, applications and challenges. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 21, No. 6, pp. 2648–2663, 2020.

[57] M. Tsukada, T. Oi, A. Ito, M. Hirata, and H. Esaki. Autoc2x: Open-source software to realize v2x cooperative perception among autonomous vehicles. In *2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall)*, pp. 1–6, 2020.

[58] H. Jamali-Rad, V. van Beveren, X. Campman, J. van den Brand, and D. Hohl. Continuous subsurface tomography over cellular internet of things (iot). *IEEE Sensors Journal*, Vol. 20, No. 17, pp. 10079–10091, 2020.

[59] B. Cao, L. Zhang, Y. Li, D. Feng, and W. Cao. Intelligent offloading in multi-access edge computing: A state-of-the-art review and framework. *IEEE Communications Magazine*, Vol. 57, No. 3, pp. 56–62, 2019.

[60] S. Lee, S. Lee, and M. Shin. Low cost mec server placement and association in 5g networks. In *2019 International Conference on Information and Communication Technology Convergence (ICTC)*, pp. 879–882, 2019.

[61] Z. Liu, J. Zhang, Y. Li, and Y. Ji. Hierarchical mec servers deployment and user-mec server association in c-rans over wdm ring networks. *Sensors*, Vol. 20, No. 5, 2020.

[62] M. Cui, Y. Fei, and Y. Liu. A survey on secure deployment of mobile services in edge computing. *Security and Communication Networks*, Vol. 2021, pp. 1–8, 2021.

[63] 3GPP TS 23.501 V16.3.0. System architecture for the 5g system. `https://www.3gpp.org/ftp/Specs/archive/23_series/23.501/23501-g30.zip`.

[64] MIT Technology Review. Who coined 'cloud computing'? `https://www.technologyreview.com/2011/10/31/257406/who-coined-cloud-computing/`.

[65] ENCYCLOPEDIA. Internet Service Provider (ISP). `https://www.encyclopedia.com/science-and-technology/computers-and-electrical-engineering/computers-and-computing/internet-1`.

[66] IBM. System/370 announcement. `https://www.ibm.com/ibm/history/exhibits/mainframe/mainframe_PR370.html`.

[67] VMware co-founder Mendel Rosenblum resigns . `https://www.computerworld.com/article/2533106/vmware-co-founder-mendel-rosenblum-resigns.html`.

[68] Microsoft releases Hyper-V for download. `https://www.computerworld.com/article/2534421/microsoft-releases-hyper-v-for-download.html`.

[69] I. M. Llorente B. Sotomayor, R. S. Montero and I. Foster. Virtual infrastructure management in private and hybrid clouds. *IEEE Internet Computing*, Vol. 13, pp. 14–22, 2009.

[70] Mandeep Kaur Saroa and Rajni Aron. Fog computing and its role in development of smart applications. In *2018 IEEE Intl Conf on Parallel & Distributed Processing with Applications, Ubiquitous Computing & Communications, Big Data & Cloud Computing, Social Computing & Networking, Sustainable Computing & Communications (ISPA/IUCC/BDCloud/SocialCom/SustainCom)*, pp. 1120–1127, 2018.

[71] White Paper: ETSI's Mobile Edge Computingexplained. `https://portal.etsi.org/Portals/0/TBpages/MEC/Docs/Mobile-edge_Computing_-_Introductory_Technical_White_Paper_V1%2018-09-14.pdf`.

[72] ETSI Multi access Edge Computing starts second phase and renews leadership team. Addressing current and future heterogeneous networks. `https://www.etsi.org/newsroom/news/1180-2017-03-news-etsi-multi-access-edge-computing-starts-second-phase-and-renews-leadership-team`.

[73] C. Lu M. Berg S. Duquennoy Y. Y. Chen Y. H. Hsu A. Zabala R. Ferrari S. Gonzalez C. Y. Li P. H. Kuo, A. Mourad and H.T. Chien. An integrated edge and fog system for future communication networks. In *2018 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, pp. 338–343, 2018.

[74] ETSI GR MEC 022 V2.1.1. Multi-access edge computing (mec); study on inter-mec systems and mec-cloud systems coordination. `https://www.etsi.org/deliver/etsi_gr/MEC/001_099/022/02.01.01_60/gr_MEC022v020101p.pdf`.

[75] ETSI GR MEC 035 V3.1.1. Multi-access edge computing (mec); study on mec support for v2x use cases. `https://www.etsi.org/deliver/etsi_gr/MEC/001_099/035/03.01.01_60/gr_mec035v030101p.pdf`.

[76] K. Samdanis V. Sciancalepore, F. Giust and Z. Yousaf. A double-tier mec-nfv architecture: Design and optimisation. In *2016 IEEE Conference on Standards for Communications and Networking (CSCN)*, pp. 1–6, 2016.

[77] J. R. Kim M. Mellia M. M. Munafo R. Torres, A. Finamore and S. Rao. Dissecting video server selection strategies in the youtube cdn. In *2011 31st International Conference on Distributed Computing Systems*, pp. 248–257, 2011.

[78] ETSI White Paper No. 24. Mec deployments in 4g and evolution towards 5g. `https://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp24_MEC_deployment_in_4G_5G_FINAL.pdf`.

[79] T. Taleb Q. Nguyen T. Toshitaka I. Benkacem, M. Bagaa and T. Sato. Integrated icn and cdn slice as a service. In *2018 IEEE Global Communications Conference (GLOBECOM)*, pp. 1–7, 2018.

[80] M. C. Filippou M. Emara and D. Sabella. Mec-assisted end-to-end latency evaluations for c-v2x communications. In *2018 European Conference on Networks and Communications (EuCNC)*, pp. 1–9, 2018.

[81] Matti Kutila, Kimmo Kauvo, Petri Aalto, Victor Garrido Martinez, Markku Niemi, and Yinxiang Zheng. 5g network performance experiments for automated car functions. In *2020 IEEE 3rd 5G World Forum (5GWF)*, pp. 366–371, 2020.

[82] P. Aalto V. G. Martinez M. Niemi M. Kutila, K. Kauvo and Y. Zheng. 5g network performance experiments for automated car functions. In *2020 IEEE 3rd 5G World Forum (5GWF)*, pp. 366–371, 2020.

[83] S. Leng Q. Zhao L. Li X. Peng L. Pan S. Maharjan Y. Zhang K. Zhang, Y. Mao. Energy-efficient offloading for mobile edge computing in 5g heterogeneous networks. *IEEE Access*, Vol. 4, pp. 5896–5907, 2016.

[84] S. Leng Y. He K. Zhang, Y. Mao and Y. Zhang. Mobile-edge computing for vehicular networks: A promising network paradigm with predictive off-loading. *IEEE Vehicular Technology Magazine*, Vol. 12, No. 2, pp. 36–44, 2017.

[85] S. H. Song Y. Mao, J. Zhang and K. B. Letaief. Stochastic joint radio and computational resource management for multi-user mobile-edge computing systems. *IEEE Transactions on Wireless Communications*, Vol. 16, No. 9, pp. 5994–6009, 2017.

[86] J. Zhang J. Liu, Y. Mao and K. B. Letaief. Delay-optimal computation task scheduling for mobile-edge computing systems. In *2016 IEEE International Symposium on Information Theory (ISIT)*, pp. 1451–1455, 2016.

[87] C. Wu S. Mao Y. Ji X. Chen, H. Zhang and M. Bennis. Optimized computation offloading performance in virtual edge computing systems via deep reinforcement learning. *IEEE Internet of Things Journal*, Vol. 6, No. 3, pp. 4005–4018, 2019.

[88] M. Bennis C. Liu and H. V. Poor. Latency and reliability-aware task offloading and resource allocation for mobile edge computing. In *2017 IEEE Globecom Workshops (GC Wkshps)*, pp. 1–7, 2017.

[89] K. Yunoki and H. Shinbo. Backhaul bandwidth consideration for workload placement in hierarchical edge cloud architecture. In *2019 IEEE Wireless Communications and Networking Conference Workshop (WCNCW)*, pp. 1–6, 2019.

[90] X. Kong Z. Ning, P. Dong and F. Xia. A cooperative partial computation offloading scheme for mobile edge computing enabled internet of things. *IEEE Internet of Things Journal*, Vol. 6, No. 3, pp. 4804–4814, 2019.

[91] J. Zhang H. N. Dai X. Long L. Chen, J. Wu and M. Yao. Dependency-aware computation offloading for mobile edge computing with edge-cloud cooperation. *IEEE Transactions on Cloud Computing*, pp. 1–1, 2020.

[92] MiEdge D1.3. System architecture and requirements.

[93] MiEdge D3.1. Architecture of mmwave edge cloud and requirement for control signaling.

[94] Y. C. Lee H. Han H. Lee, S. Lee and S. Kang. iedge: An iot-assisted edge computing framework. In *2021 IEEE International Conference on Pervasive Computing and Communications (PerCom)*, pp. 1–8, 2021.

[95] M. A. U. Rehman R. Ullah and B. S. Kim. Design and implementation of an open source framework and prototype for named data networking-based edge cloud computing system. *IEEE Access*, Vol. 7, pp. 57741–57759, 2019.

[96] J. Lobo R. Barreto and P. Menezes. Edge computing: A neural network implementation on an iot device. In *2019 5th Experiment International Conference (exp.at'19)*, pp. 244–246, 2019.

[97] T. Kondo H. Watanabe and T. Ohigashi. Implementation of platform controller and process modules of the edge computing for iot platform. In *2019 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, pp. 407–410, 2019.

[98] K. Dolui and S. K. Datta. Comparison of edge computing implementations: Fog computing, cloudlet and mobile edge computing. In *2017 Global Internet of Things Summit (GIoTS)*, pp. 1–6, 2017.

[99] Y. Tsai S. Singh, Y. Chiu and J. S. Yang. Mobile edge fog computing in 5g era: Architecture and implementation. In *2016 International Computer Symposium (ICS)*, pp. 731–735, 2016.

[100] L. Xing Y. Xiong, Y. Sun and Y. Huang. Extend cloud to edge with kubeedge. In *2018 IEEE/ACM Symposium on Edge Computing (SEC)*, pp. 373–377, 2018.

[101] J. Chen P. Ren, X. Qiao and S. Dustdar. Mobile edge computing – a booster for the practical provisioning approach of web-based augmented reality. In *2018 IEEE/ACM Symposium on Edge Computing (SEC)*, pp. 349–350, 2018.

[102] L. Bai C. Guo Y. Hu J. Zhang, Y. Niu and J. Guo. Design and implementation of a face recognition system based on edge computing. In *2019 IEEE International Conference on Power, Intelligent Computing and Systems (ICPICS)*, pp. 363–366, 2019.

[103] 5GCroco. `https://5gcroco.eu/images/templates/rsvario/images/5GCroCo_D3_2.pdf`.

[104] Living Edge Lab. `https://www.openedgecomputing.org/living-edge-lab/`.

[105] H3C and China Mobile Edge Computing Open Lab Jointly Release OTII Server at MWC 2019. `https://www.h3c.com/en/d_201903/1160804_294554_0.htm`.

[106] Z. Wang and Y. Cai. Management optimization of mobile edge computing (mec) in 5g networks. In *2019 IEEE International Conference on Communications Workshops (ICC Workshops)*, pp. 1–6, 2019.

[107] business models MiEdge D1.4. Final report on joint EU/JP vision and eco-system impact. Millimeter-wave edge cloud as an enabler for 5g ecosystem. `https://www.h3c.com/en/d_201903/1160804_294554_0.htm`, June 2019.

[108] A. S. Spiliopoulou A. Dardamanis I. Neokosmidis T. Rokkas I. P. Chochliouros, A. Kostopoulos and L. Goratti. Business and market perspectives in 5g networks. In *2017 Internet of Things Business Models, Users, and Networks*, pp. 1–6, 2017.

[109] ESTI GS MEC 003. Multi-access edge computing (mec);framework and reference architecture. `https://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/03.01.01_60/gs_MEC003v030101p.pdf`, March 2022.

[110] K. Sakaguchi H. Nishiuchi, G. K. Tran. Performance evaluation of 5g mmwave edge cloud with prefetching algorithm - invited paper. In *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, pp. 1–5, 2018.

[111] IEEE 802.11 ad. Part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications, December 2016.

[112] H.-w. Shu C.-h. Hsu W.-j. Hsu, K. Merchant and A. Helmy. Weighted waypoint mobility model and its impact on ad hoc networks. *SIGMOBILE Mob. Comput. Commun. Rev.*, Vol. 9, No. 1, p. 59–63, jan 2005.

[113] H. Shimodaira G. K. Tran and K. Sakaguchi. User satisfaction constraint adaptive sleeping in 5g mmwave heterogeneous cellular network. *IEICE Transactions on Communications*, Vol. E101.B, , 2018.

[114] 3GPP TS 23.203 V13.6.0. Policy and charging control architecture (release 13), 2012.

[115] AECC. General principle vision white paper. `https://aecc.org/wp-content/uploads/2019/04/AECC_White_Paper_v2.1_003.pdf`, 2019.

[116] ETSI. Mec in an enterprise setting: A solution outline. `https://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp30_MEC_Enterprise_FINAL.pdf`.

[117] D. Katsaros S. Bibi and P. Bozanis. Business application acquisition: On-premise or saas-based solutions? *IEEE Software*, Vol. 29, No. 3, pp. 86–93, 2012.

[118] S. Kalyanaraman B. Sikdar and K. S. Vastola. An integrated model for the latency and steady-state throughput of tcp connections. *Performance Evaluation*, Vol. 46, No. 2, pp. 139–154, 2001.

[119] T. Taleb and A. Ksentini. An analytical model for follow me cloud. In *2013 IEEE Global Communications Conference (GLOBECOM)*, pp. 1291–1296, 2013.

[120] mmMAGIC 2.1. Measurement campaigns and initial channel models for preferred suitable frequency ranges, May 2019.

[121] R. Ferrus and O. Sallent. Extending the ltelte-a business case: Mission- and business-critical mobile broadband communications. *IEEE Vehicular Technology Magazine*, Vol. 9, No. 3, pp. 47–55, 2014.

[122] S. Zygiaris. Smart city reference model: Assisting planners to conceptualize the building of smart city innovation ecosystems. 10 2013.

[123] V. Seppänen P. Ahokangas-H. Hämmäinen M. Matinmikko-Blue, S. Yrjölä and M. Latva-Aho. Analysis of spectrum valuation elements for local 5g networks: Case

study of 3.5-ghz band. *IEEE Transactions on Cognitive Communications and Networking*, Vol. 5, No. 3, pp. 741–753, 2019.

[124] M. Matinmikko-Blue-Marja K. B. M. Shashika, K. Hiltunen and M. Latva-Aho. Performance comparison of alternative indoor 5g micro-operator deployments in 3.6-ghz and 26-ghz bands. *IEEE Transactions on Cognitive Communications and Networking*, Vol. 5, No. 4, pp. 886–899, 2019.

[125] T. Yu Y. Takaku, Y. Kaieda and K. Sakaguchi. Proof-of-concept of uncompressed 4k video transmission from drone through mmwave. In *2020 IEEE 17th Annual Consumer Communications Networking Conference (CCNC)*, pp. 1–6, 2020.

[126] Y. Kaieda T. Yu, Y. Takaku and K. Sakaguchi. Design and poc implementation of mmwave-based offloading-enabled uav surveillance system. *IEEE Open Journal of Vehicular Technology*, Vol. 2, pp. 436–447, 2021.

[127] K. K. Leung B. J. Ko A. Machen, S. Wang and T. Salonidis. Live service migration in mobile edge clouds. *IEEE Wireless Communications*, Vol. 25, No. 1, pp. 140–147, 2018.

[128] N. Zhang S. Wang, J. Xu and Y. Liu. A survey on service migration in mobile edge computing. *IEEE Access*, Vol. 6, pp. 23511–23528, 2018.

[129] K. Sakaguchi, G.K. Tran, H. Shimodaira, S. Nanba, T. Sakurai, K. Takinami, I. Siaud, E.C. Strinati, A. Capone, I. Karls, R. Arefi, and T. Haustein. Millimeter-wave evolution for 5G cellular networks. *IEICE Transactions on Communications*, Vol. E98-B, No. 3, pp. 338–402, March 2015.

[130] T. E. Bogale and L. B. Le. Massive mimo and mmwave for 5g wireless hetnet: Potential benefits and challenges. *IEEE Vehicular Technology Magazine*, Vol. 11, No. 1, pp. 64–75, 2016.

[131] S. Parkvall E. Dahlman and J. Sköld. *5G NR: The next generation wireless access technology.* Academic Press, 2020.

[132] Private LTE based on CBRS. `https://www.digi.com/private-lte-based-on-cbrs`.

[133] MulteFire Private network outlook: LTE and 5G NR-U. `https://www.rcrwireless.com/20190605/5g/private-network-outlook`.

[134] Germany opens process for private 5G licenses. `https://www.rcrwireless.com/20191121/5g/germany-opens-process-for-private-5g-licenses`.

[135] Private 5G Mobile Networks for Industrial IoT. `https://www.qualcomm.com/media/documents/files/private-5g-networks-for-industrial-iot.pdf`.

[136] Next Generation Mobile Technologies: A 5G Strategy for the UK. `https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/597421/07.03.17_5G_strategy_-_for_publication.pdf`.

[137] H. S. Chang C. Y. Chuang and Y. J. Hung. An inter-store transaction mechanism to distribute mobile applications. In *2012 IEEE Globecom Workshops*, pp. 1016–10206, 2012.

[138] O. Hernandez M. C. Mighell J. Sacks C. Tucker Q. Gu M. Carter, J.Fiala and W. Scherer. Advertising.com pre-install app campaign. In *2016 IEEE Systems and Information Engineering Design Symposium (SIEDS)*, pp. 84–88, 2016.

[139] A. Benlian T. M. Wagner and T. Hess. the advertising effect of free – do free basic versions promote premium versions within the freemium business model of music services? In *2013 46th Hawaii International Conference on System Sciences*, pp. 2928–2937, 2013.

[140] F. Kollmann. A flexible subscription model for broadcasted digital contents. In *2013 46th Hawaii International Conference on System Sciences*, pp. 589–593, 2007.

[141] AWS IoT Greengrass. `https://aws.amazon.com/greengrass/?nc1=h_ls`.

[142] Azure IoT Edge. `https://azure.microsoft.com/ja-jp/resources/videos/microsoft-ignite-2017-enable-edge-computing-with-azure-iot-edge/`.

[143] Google strategy announcement. `https://cloud.google.com/press-releases/2020/0305/google-cloud-telco-strategy`.

[144] NTT DOCOMO. Xi pake-hodai light. `https://www.nttdocomo.co.jp/english/charge/packet/xi_pake_hodai_l/index.html`.

[145] The condition of the rule of connection rule related to subscription of optical fiber (In Japanese). `http://www.soumu.go.jp/main_content/000340534.pdf`.

[146] Y. Li L. Tong and W. Gao. A hierarchical edge cloud architecture for mobile computing. In *IEEE INFOCOM 2016 - The 35th Annual IEEE International Conference on Computer Communications*, pp. 1–9, 2016.

[147] X. Yu and L. Tang. Competition and cooperation between edge and remote clouds: A stackelberg game approach. In *2018 IEEE 4th International Conference on Computer and Communications (ICCC)*, pp. 1919–1923, 2018.

[148] The Mobile Economy 2020. `https://www.gsma.com/mobileeconomy/wp-content/uploads/2020/03/GSMA_MobileEconomy2020_Global.pdf`, 2020.

[149] P. Kuure U. Rauschenbach D. Sabella, A. Vaillant and F. Giust. Mobile-edge computing architecture: The role of mec in the internet of things. *IEEE Consumer Electronics Magazine*, Vol. 5, No. 4, pp. 84–91, 2016.

[150] S. Sebbah S. Ayoubi H. A. Alameddine, S. Sharafeddine and C. Assi. Dynamic task offloading and scheduling for low-latency iot services in multi-access edge computing. *IEEE Journal on Selected Areas in Communications*, Vol. 37, No. 3, pp. 668–682, 2019.

[151] AECC (Automotive Edge Computing Consortium). Distributed computing in an aecc system, August 2021.

[152] J. Nakazato K. Koslowski J. Daube R. Santos G. K. Tran M. Nakamura, H. Nishiuchi and K. Sakaguchi. Experimental verification of sdn/nfv in integrated mmwave access and mesh backhaul networks. *IEICE Trans. Commun.*, Vol. 104-B, pp. 217–228, 2021.

[153] M. Wu J. Li S. Liu Y. Zhu, Y. Liu and J. Zhao. Research on secure communication on in-vehicle ethernet based on post-quantum algorithm ntruencrypt. *Electronics*, Vol. 11, No. 6, 2022.

[154] How a quantum computer could break 2048-bit RSA encryption in 8 hours. `https://www.technologyreview.com/2019/05/30/65724/how-a-quantum-computer-could-break-2048-bit-rsa-encryption-in-8-hours`.

[155] Rakuten Mobile Releases New Original 5G Smartphone. Rakuten big s. `https://corp.mobile.rakuten.co.jp/english/news/press/2021/0419_02/`.

[156] XCAL. `https://accuver.com/sub/products/view.php?idx=6`.

[157] XCAP. `https://accuver.com/sub/products/view.php?idx=14`.

[158] Ookla Speedtest by Ookla. The global broadband speed test. `https://www.speedtest.net/`.

[159] SINET Ping Connection [Japanese]. `https://www.sinet.ad.jp/connect_service/service/ping`.

[160] Arctic 5G Test Network. `http://arctic5g.eu/about-the-project-43167310`.

[161] 5G TESTBED & TRIALS PROGRAMME. `https://uk5g.org/discover/5G-projects/5G-testbed-trials-programme/`.