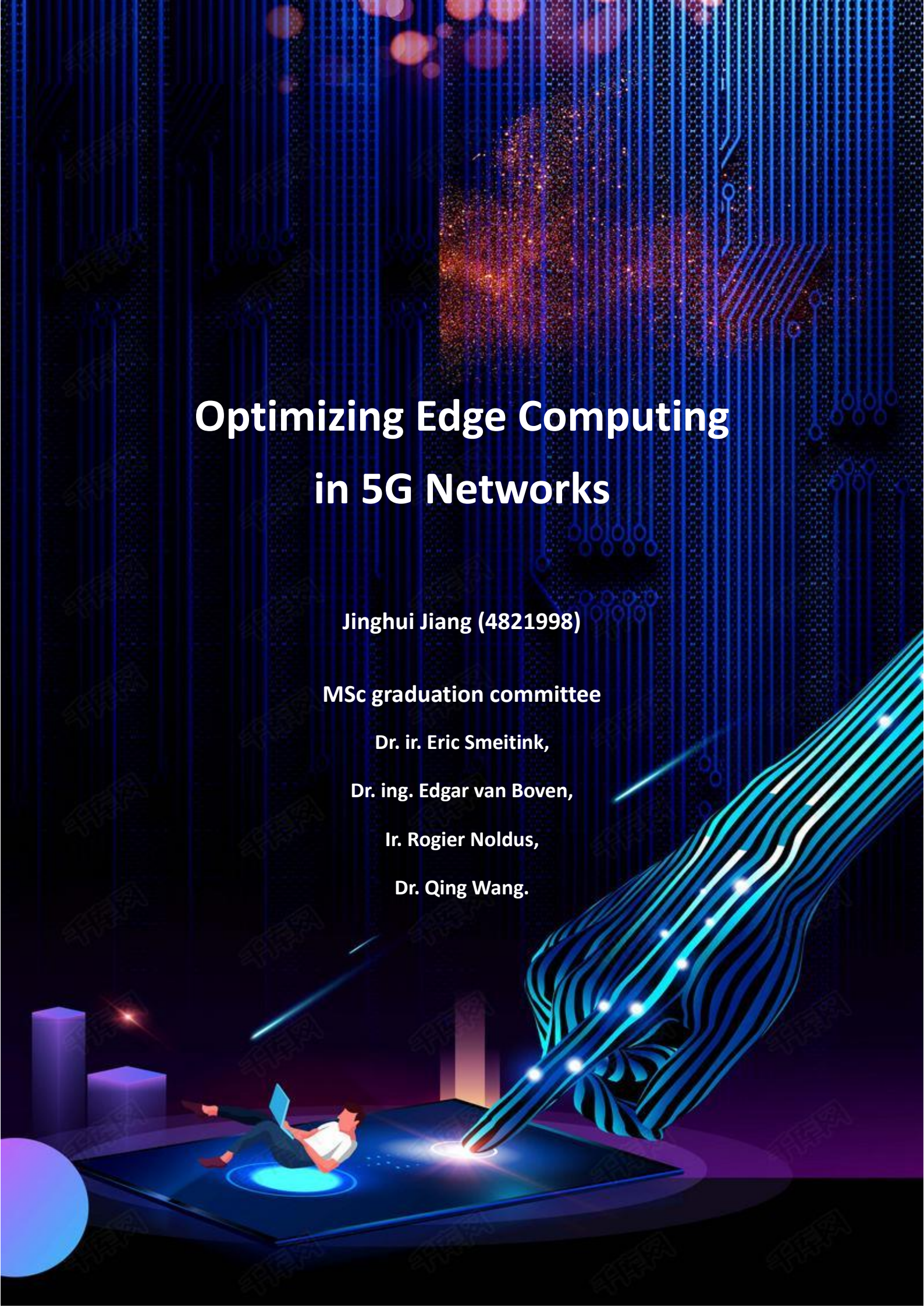

Optimizing Edge Computing in 5G Networks

Jinghui Jiang (4821998)

MSc graduation committee

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Preface

As 5G technology is developing at a high speed nowadays, edge computing starts to get noticed again. Even though the origin of edge computing can be traced back to late 1990s, there are some barriers which make the implementation of edge computing difficult and costly in practice. With network function virtualization in 5G, the deployment of edge computing needs to get close enough to the network edge to reduce latency and bandwidth usage in order to meet the requirements derived from future use cases. Network function virtualization brings flexibilities to edge computing as well as more optimization possibilities, including reducing costs and investments of companies that provide edge computing services and enhancing user experience and service qualities of edge computing. With optimizations, edge computing can provide enhanced service quality (e.g. shorter service latency, higher reliability, higher robustness, etc.) to users with a reasonably small amount of investments. These improvements provided by optimizations are desired for both customers and operators, and edge computing will get more attention, will develop faster and will be more widely used.

Acknowledgement

During the 11 months doing my master thesis, I received a lot of help in all aspects from my supervisors, my colleagues and my family and friends.

First of all, I want to give thanks to my supervisors, Ir. Rogier Noldus, Dr. ing. Edgar van Boven and Dr. ir. Eric Smeitink. Rogier is a principal architect at Ericsson Value-added Service group. He is the one who offered me this opportunity to work with him at Ericsson on my master thesis. He not only gave me this interesting topic about edge computing, but also inspired me a lot during my thesis. Whenever I ran into problems, he always offered me help and shared his brilliant ideas with me. Besides, he helped me with my thesis-related writing and presentation, gave me suggestions on the structure as well as more detailed writing and presenting skills. Edgar is an architect at KPN. He gave me a lot of instructions on writing and structuring not only my thesis, but also my research proposal, my mid-term presentation, my interview questions and my final presentation. Also, Edgar gave me nice suggestions on the direction of my master thesis and helped me redirect my thesis topic when there were some practical limitations that made part of my thesis impractical. Edgar and Rogier encouraged me to interview experts at KPN and Ericsson on edge computing since the current documentation on edge computing is not yet complete. They helped me to get in contact with these experts and organized my interview questions, attended every interview of mine and helped me do recordings and notes. Eric is a strategist at KPN and he is the chair of my master thesis committee. Eric gave me brilliant ideas when I met troubles and did not know where to find solutions, especially for problems related to mathematics, Eric inspired me a lot. Even though all my supervisors are really busy because they have work from both the university and their companies, they still managed to attend my progress meeting every two weeks and review my thesis report and other related documents several times. They are really responsible, knowledgeable and kind, and they are willing to and able to help me whenever I met problems not only in my master thesis but also in my daily working life, which makes them the best supervisors.

Also, I want to thank all my colleagues at Ericsson and TU Delft NAS group as well as the experts I interviewed. My colleagues at Ericsson are all really nice to me and I enjoyed the days working in the office in Rijen. My manager Mr. Rene van der Mast and Mrs. Inge Cavalje helped a lot when I was doing my thesis internship at Ericsson. Rene helped me extend my contract with the company because my master thesis got delayed due to the coronavirus, and he helped me to get my salary clips for requiring a Dutch health insurance. Inge helped me when my company account was blocked, she contacted the IT help desk for me many times and solved the problem. I am really grateful because they are all really busy with their daily works and meetings but they are still willing to help me. Apart from these, they all treated me well and sometimes we chatted in the office and online, which makes me feel welcomed and not nervous anymore. Before the coronavirus exploded in the Netherlands, I went to the NAS group on the ninth floor of EWI every Friday. We had lunch together with the group and we shared news and has nice talks during lunch. Also, NAS group has a nice traditional drinking at the end of each Friday, which is really relaxing. These events are valuable for me and help enhance my social ability. I would like to thank Prof. dr. ir. Piet Van Mieghem, who is the chair of NAS group and admitted me to join NAS group for my master

thesis, even though he is not my supervisor, he gave me nice advices on complex networks which is related to my research. Also, I would like to thank all the experts who I interviewed and who helped me with my research, they offered me instructions and knowledge on edge computing which is a technology that has not yet been fully developed and standardized.

Last but not least, I would like to thank my parents who supported me both mentally and economically. They encouraged me to leave home and study in the Netherlands which is more than 8000 kilometers away from home and they comforted me when I ran into problems in my daily life. I am lucky to have such supportive parents. Also, I want to thank all my friends I met in my hometown and my universities, we chatted online every day, played games together and sometimes we held parties and had big treats, so that I will not feel lonely living by myself, especially during the lockdown period.

Thanks everyone who helped me and comforted me in the past two years, any help from you matters to me.

Abstract

Multi-access Edge Computing (MEC) is a concept brought up by ETSI and it places computing, storage, processing and network resources into MEC hosts and places these MEC hosts as close as needed to the telecom network edge in order to reduce service latency and bandwidth usage. For self-driving vehicles, streaming video and real-time gaming, the devices involved (e.g. vehicles, cellphones, etc.) might not have enough capabilities to perform all the computations and might not have sufficient storage capacity; MEC can be used here for offloading data computations and content caching. To enhance service quality and user experience, MEC hosts and MEC applications should be located close(r) to the end-users, which increases the number of handovers between MEC hosts to maintain MEC service continuity for mobile end-users as well as the costs for the telecom operators. Therefore, a balance needs to be found. Consider the fact that mobile UEs need MEC service handovers to maintain service continuity and handovers may cause service interruptions which can cause severe degradation to MEC service qualities and user experience, hence the number of handovers between MEC hosts experienced by end-users should be minimized. To find a suitable deployment of MEC hosts and MEC applications in order to minimize the number of handovers, three greedy algorithms and two heuristic algorithms are introduced, implemented, tested, compared and analyzed in this thesis to see which identifies the deployment mechanism that has the smallest number of handovers. When it is time for a mobile UE to connect to a new MEC host and there are multiple potential choices of the new MEC host, the most suitable one for the UE needs to be determined dynamically according to the real-time condition of each possible MEC host. To achieve this, reinforcement learning is considered. Three different reinforcement learning algorithms based on SARSA learning and Deep Q Network are introduced, implemented, tested, compared and analyzed in this thesis. Furthermore, a decision-making mechanism is designed to cope with exceptional situations where the required service quality cannot be guaranteed.

Key words: Multi-access Edge Computing (MEC), MEC host, MEC application, MEC application instance, 5G, optimization, ETSI, 3GPP, relocation, handover, Reinforcement Learning (RL), SARSA Learning, Deep Q Network (DQN), Markov Decision Process (MDP), Python.

Contents

Chapter 1 Introduction

This chapter first introduces the architectures of 3G, 4G and 5G networks as well as basic concepts of Cloud Computing, Fog Computing, Edge Computing (EC) and Multi-access Edge Computing (MEC), followed by the problem statement, research questions, research scope, methodology and structure of this master thesis.

1.1 Context

In the context of this master thesis, only telecom networks are considered, including 3G, 4G and 5G network, and 5G network is the main concern. Details on 5G networks will be introduced later in Chapter 2. This section gives a brief introduction on the architecture of 3GPP standardized 3G, 4G and 5G networks as well as explanations to some terminology which will be mentioned frequently in the remainder of this master thesis.

A. 3G network architecture

Figure 1.1 gives an illustration on the 3GPP-defined 3G network architecture.

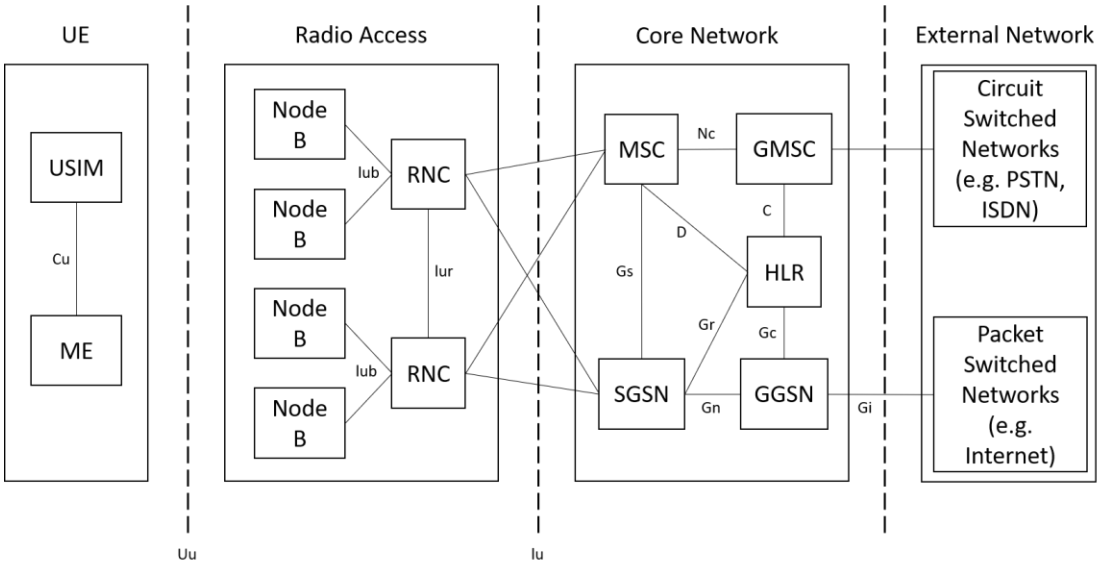

Figure 1.1: 3G network architecture [22].

A 3G network consists of three components:

1. User Equipment (UE): A UE is assigned to a single user of the telecom network and it is used by the user to access the services provided by the network. A UE contains two parts:
    i. Mobile Equipment (ME): ME is a radio terminal and it connects the user to base stations (NodeB) via radio connections.

   ii. UMTS Subscriber Identity Module (USIM): USIM is an application in the Universal Integrated Circuit Card (UICC), and USIM is used to identify and authenticate a subscriber on mobile telephony device (e.g. cellphone) and to store and provide information needed by the subscriber to access the mobile network.

2. UMTS Terrestrial Radio Access Network (UTRAN): UTRAN handles cell-level mobility. It contains two parts:
   i. Base stations (NodeB): A NodeB facilitates wireless communications between UEs and networks. A NodeB is responsible for transmissions and receptions of signals, encrypting and decrypting communications, amplifying and combing signals, etc.
   ii. Radio Network Controllers (RNC): An RNC is a single point of UTRAN to access the core network and it is the aggregation point for a group of NodeBs. An RNC controls the NodeBs that are connected to it, and it is responsible for radio resource management, mobility management functions and user data encryption.
3. Core network (CN): A Core network has gateways to external networks, and it is responsible for handovers/relocations and location management. There are several functional entities in a 3G core network and Figure 1.1 shows some of the most important ones. Home Location Register (HLR) stores subscriber data, subscriber state and location data of every subscriber of the relevant Public Land Mobile Network (PLMN). A Mobile Switching Center (MSC) holds subscriber data and state. A subscriber of the 3G network is connected to an MSC, and the MSC is responsible for setting up and releasing end to end connections between the subscriber and external networks. Besides this, the MSC handles mobility and call handovers. A Gateway MSC (GMSC) is responsible for terminating call handling and it does not hold subscriber data. A GMSC can determine which MSC a called subscriber is currently located at and route the terminating call towards that MSC. A Serving GPRS Support Node (SGSN) is responsible for the delivery of data packets from/towards the subscribers within its serving area including packet routing, transfer mobility management, authentication and charging. Gateway GPRS Supporting Node (GGSN) is the interface between the core network and external packet-switched data networks, and it provides connections to these external data networks.

B. 4G network architecture

Figure 1.2 shows the architecture of a 4G network.

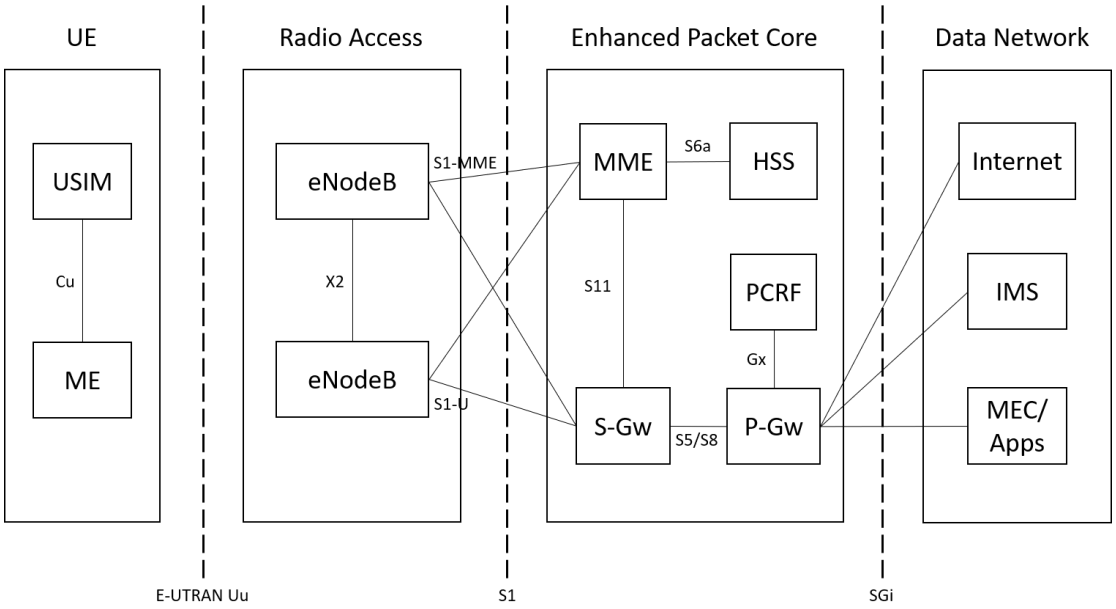

Figure 1.2: 4G network architecture [23].

A 4G network has a flat architecture in which the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) does not contain RNCs. The eNodeBs (eNB) are base stations in a 4G network, which connect to UEs via a radio interface E-UTRAN Uu and connect the E-UTRAN to the Enhanced Packet Core (EPC, the core network in 4G network) via S1 interfaces.

In the EPC the Mobility Management Entity (MME) keeps track of UEs which are registered on the LTE network. The MME is the main control element in the Enhanced Packet Core (EPC) and it is in charge of authentication, security, mobility management, etc. A Serving Gateway (S-Gw) serves a group of eNodeBs for user plane data and it is the local mobility anchor for mobile UEs. In addition, a S-Gw is also responsible for setting up and tearing down sessions for particular UEs under instructions from the MME. A Packet Data Network Gateway (P-Gw) provides access to external data networks (e.g. Internet) and collects and reports charging information. It is also the highest mobility anchor in the EPC. Policy and Charging Rules Function (PCRF) provides the P-Gw with relevant charging and traffic control/routing rules. Home Subscription Server (HSS) is the subscription data repository that storing information like subscriber data, subscriber current location information, etc. Unlike the HLR in the 3G network, the HSS is also responsible for subscriber authentication.

C. 5G network architecture

The architecture of a 5G network is conceptually illustrated in Figure 1.3. Furthermore, the NodeB in a 5G network, the next generation NodeB (gNodeB), is split into three functional entities – Antenna and Remote Radio Unit (RRU), Distributed Baseband Unit (DU) and Centralized Baseband Unit (CU). The core network architecture in a 5G network is service-based, which supports flexible procedures to efficiently expose and consume services. For simple service or information requests, a request-response model can be used, while for long-living processes, a subscribe-notify model is supported [5]. Each network function has the authorization to access each other's services without knowing the actual configuration

and processing procedures. The Access and Mobility management Function (AMF) handles mobility and the Session Management Function (SMF) handles the establishment/release/management of PDU Sessions. A PDU Session is a logical connection between the UE and data network and UE receives services through a PDU Session. User plane function (UPF) is the termination point for PDU Sessions and it interfaces with external data networks. Functionality of the UPF in 5G network is similar to the combination of the S-Gw and the P-Gw in EPC. Unified Data Management (UDM) stores subscription data, and network functions like AMF, SMF, PCF, etc. can retrieve subscriber data and context from the UDM if authorized. A Policy Control Function (PCF) is responsible for governing the network behavior, it makes policy decisions based on subscription data in the UDM and maybe instructions from other network functions, and then provides policy rules to other network functions like the SMF to enforce these rules.

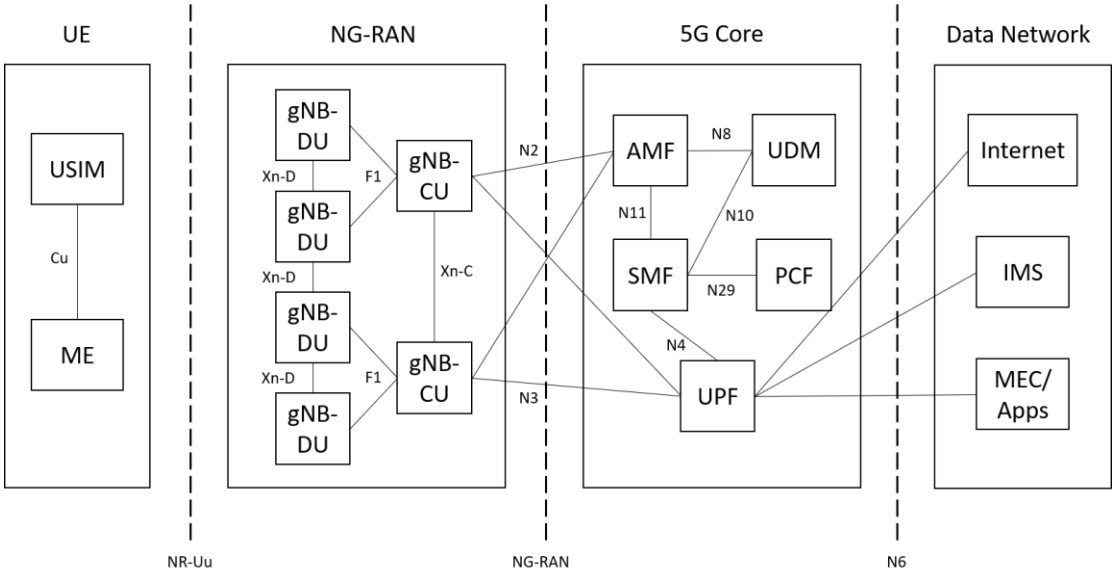

Figure 1.3: 5G network architecture

D. Functional entities in 3G, 4G and 5G networks

In different generations of telecom network, similar network functionalities may be handled by different network functional entities. Table 1.1 is a comparison table of (part of) network entities in 3G, 4G and 5G radio access networks and core networks. A complete table can be found in Appendix F.

Table 1.1: Comparison table of functional entities in 3G, 4G and 5G networks

	3G	4G	5G
Core Network	Home Location Register (HLR)	Home Subscriber Server (HSS)	Unified Data Management (UDM)
	Serving GPRS Support Node	Mobility Management Entity (MME)	Access and Mobility

<table>
<tr><td rowspan="6"></td><td>(SGSN)</td><td rowspan="2"></td><td colspan="2">Management Function (AMF)</td></tr>
<tr><td rowspan="3">Gateway GPRS Support Node (GGSN)</td><td colspan="2" rowspan="2">Session Management Function (SMF)</td></tr>
<tr><td rowspan="2">Serving Gateway (S-Gw)</td></tr>
<tr><td rowspan="2">Packet Data Network Gateway (P-Gw)</td><td colspan="2" rowspan="2">User Plane Function (UPF)</td></tr>
<tr><td colspan="2">Session Management Function (SMF)</td></tr>
<tr><td>Mobile Service Switching Center (MSC) *Related to circuit-switched networks only</td><td>N/A</td><td colspan="2">N/A</td></tr>
<tr><td>Gateway MSC (GMSC) *Related to circuit-switched networks only</td><td>N/A</td><td colspan="2">N/A</td></tr>
<tr><td>N/A</td><td>Policy and Charging Rules Function (PCRF)</td><td colspan="2">Policy Control Function (PCF)</td></tr>
<tr><td rowspan="2">Radio Access Network</td><td>NodeB (NB)</td><td rowspan="2">E-UTRAN NodeB (eNB)</td><td rowspan="2">Next Generation NodeB (gNB)</td><td>Distributed Unit (gNB-DU)</td></tr>
<tr><td>Radio Network Controller (RNC)</td><td>Centralized Unit (gNB-CU)</td></tr>
<tr><td></td><td>3G</td><td>4G</td><td colspan="2">5G</td></tr>
<tr><td rowspan="2">Core Network</td><td>Home Location Register (HLR)</td><td>Home Subscriber Server (HSS)</td><td colspan="2" rowspan="2">Unified Data Management (UDM)</td></tr>
<tr><td>Serving GPRS Support Node (SGSN)</td><td>Mobility Management Entity (MME)</td></tr>
<tr><td></td><td></td><td colspan="2">Access and Mobility Management Function (AMF)</td></tr>
</table>

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<tr><td rowspan="6"></td><td></td><td></td><td colspan="2" rowspan="2">Session Management Function (SMF)</td></tr>
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<tr><td>Radio Network Controller (RNC)</td><td>Centralized Unit (gNB-CU)</td></tr>
</table>

E. Terminology

Service latency: In the context of this project, the only latency considered is the service latency between a UE who is consuming this service and entity that is providing this service to this UE. The service latency mainly comes from the processing time of all the network functional elements between the UE and the serving entity as well as the processing time in the serving entity. Therefore, if a serving entity is closer to the base station, it can guarantee smaller service latency, since there are fewer network elements in between.

Relocation: When a mobile UE is moving, its location changes at the same time. In some

cases, a UE may move out of the serving area of its current serving entity (e.g. host, server, base station, local cloud, etc.) which means that this entity can no longer provide services to this UE anymore. To maintain the service continuity, a new entity should take over the responsibility to serve this UE, and this process of switching from the current serving entity to a new serving entity is called a relocation.

Logical location: The topology location where a host/server is placed is called the logical location of this host/server. Hosts/servers in different logical locations have different properties including service latency, since nowadays the processing time of functional entities between the UE and the host/server is one of the major sources of service latency. However, in the context of this thesis, a host/server is always located inside an external data network. Therefore, logical location of every host/server is on the network side of the UPF, and logical location is out of consideration in this master thesis.

Physical location: The actual place where a host/server is deployed in the telecom network is called the physical location of this host/server. Today, the transmission time on optical fibers is usually millisecond level or even lower, depending on the actual length of the cable. Experiments and calculations show that transferring a packet from the very southern part of the Netherlands to the very northern part of the Netherlands via optical fibers takes only 2 milliseconds (See more in Appendix D). Despite the low transmission delay on optical fiber, physical location is still crucial because one of the major sources of latency is the data transformation time. If the host/server and gNodeB are located physically close to each other, the number of transmission nodes (e.g. IP routers) in between will be reduced and the total data transformation time will decrease at the same time. The physical location of a host/server is one of the main concerns of this master thesis. For simplicity reason, it is referred to as “location” in the reminder of this master thesis.

1.2 Edge Computing, Cloud Computing, Fog Computing and Multi-access Edge Computing

In the coming 5G era, requirements on latency between the UE and the computing/storage platform are getting more and more stringent. Since ultra-low latency has become one of the main characteristics of 5G technology, various applications relying on low latency will appear in the market. Traditional cloud computing may not be able to fulfill these new latency requirements, hence, a new concept – edge computing, is now getting more and more attention.

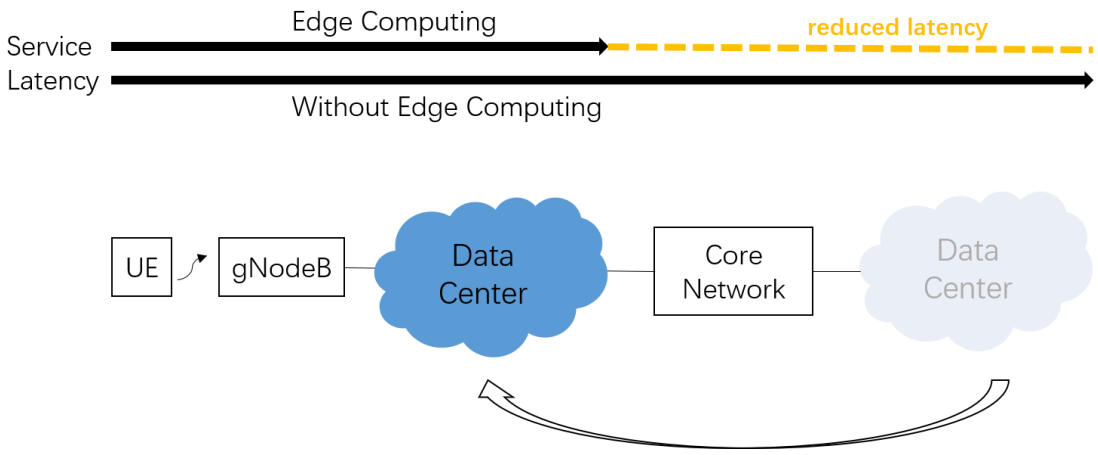


Figure 1.4: Edge computing

Edge computing is a distributed computing framework in which data processing is executed close to the edge – where data is produced [44]. Edge computing places data storage, processing and computing capabilities closer to end devices that produce the data, as illustrated in Figure 1.4, mainly for reducing the latency between the UE and the serving application as well as the required bandwidth towards the core network/cloud and offloading end devices from compute-intensive applications. Edge computing originates from Content Delivery Networks (CDN) that provide video content to users from edge servers close to them [25]. These edge servers gradually developed and in early 2000s, edge servers started to host applications [26], which finally resulting in a new distributed framework which is now known as edge computing. Another promotive factor is the conflict between the increasing amount of data to be processed in a centralized data center and the limited amount of resources in the data center. As the number of devices at the network edge keeps growing, centralized data centers are no longer sufficient to guarantee the required latencies and transfer rates. With the help of edge computing, high requirements on service quality (e.g. ultra-low service latency) which cannot be fulfilled by using cloud computing, can be satisfied.

Another concept that is similar to edge computing is fog computing. Fog computing, as defined by the Open Fog Consortium [17], is “a system-level horizontal architecture that distributes resources and services of computing, storage, control, and networking anywhere along the continuum from Cloud to Things” [12]. Fog computing describes a system-level architecture that distributes resources from the Cloud to Things, whereas edge computing typically concentrates on providing computing, processing and caching services to end-users at places that are physically close to them [13].

Multi-access Edge Computing (MEC) is a concept defined by ETSI [1]. In general, MEC is a network architecture concept that enables cloud computing capabilities and an IT service environment at the edge of a telecom network [2]. Initially, the Mobile community has been the driver behind the ideation and standardization of edge computing. Currently, edge computing is no longer exclusively related to cellular networks, as the 3GPP functional architecture connects Fixed Access Networks (FAN) and Radio Access Networks (RAN). Similar to edge computing, MEC also reduce service latency and bandwidth usage by placing the MEC hosts, where the user data is processed, close to the end-users (UEs). MEC hosts can be collocated with base stations and other cellular nodes that are closer to the network edge,

like base stations and Radio Network Controllers (RNC), while MEC applications are properly installed in these MEC hosts. MEC plays an important role in 5G, because it can help to provide a service environment that is characterized by ultra-low latency as well as real-time access to radio network information, which are both main characteristics of 5G technology.

Possible locations of MEC servers in a 3G/LTE network have been suggested by the ETSI Industrial Specification Group (ISG): A MEC server can be deployed either at

- the LTE eNodeB site,
- the 3G Radio Network Controller (RNC) site [3],
- or co-located with Serving Gateway (S-Gw)/PDN Gateway (P-Gw) [24].

In a 5G network, however, with Network Function Virtualization (NFV), MEC services are provided by virtualized functions, or MEC application instances specifically in the context of MEC, and virtualizations can bring more flexibilities to MEC implementation and deployment. More details will be introduced in Chapter 2.

There are basically two different classes of MEC. The first one is in-line processing, whereby MEC performs data processing on the path between UE and the remote end-point (e.g. an application in an external network); the other class of MEC is end-point processing, whereby the MEC application itself is the actual end-point that the UE wants to reach for a particular service.

According to the experts in the interviews (for more information on the interviews, please see Appendix D), at the initial stage, considering the high cost of software maintenance for the operator, the number of MEC hosts is limited. Under this situation, the selection of target MEC host can be trivial. However, in the future, the software maintenance expense can be reduced by new technologies, therefore, the number of MEC hosts can be significantly increased to provide much better services. In the context of this master thesis, the number of MEC hosts is not limited because MEC is a promising technology, and the number of MEC hosts needed will experience a sharp increase in the near future.

1.3 Problem statement

To save investments and to enhance service quality (e.g. service latency, service continuity), MEC hosts should be properly located. Since NFV enriches the options of MEC host location, determining which location is the optimal location for a MEC host is not a trivial problem. For example, if a MEC host is located at a higher level in the hierarchy of a telecom network, then it can serve more UEs; but in the meantime, the latency might increase due to the larger number of transmission nodes and network functional entities between this MEC host and a UE. However, if a MEC host is located at a lower-hierarchical level to reduce service latency, its serving area will shrink at the same time, implying more frequent handovers/relocations.

How to optimally locate a MEC node (e.g. MEC server, MEC host, MEC application instance) in a telecom network is an optimization-related problem that has not yet been explored, and this master thesis aims to find reasonable approaches to fill this gap. To solve this problem, the first step is to determine the aspects to be optimized, which is addressed in research question 2. After the first step is done, algorithms will be designed to find optimal locations for MEC hosts and MEC applications, which is addressed in research question 3.

For mobile end-users, their mobilities may bring up MEC service continuity problems. For

example, if one self-driving vehicle is moving on the road, receiving MEC services from its current MEC host A, and it may move out of the serving area of A after some time. To maintain the MEC services of this vehicle, another MEC host B should take over the responsibility for serving this vehicle. To achieve this, a relocation is needed to transfer user context from MEC host A to MEC host B, and MEC host B is called the target MEC host of this relocation. In a telecom network, there may exist multiple MEC hosts that can be the target MEC host of a relocation. Therefore, it is necessary to determine which MEC host is the most suitable one.

How to find the optimal target MEC host of a relocation is an optimization problem that has not yet been explored, and it is another research gap that this master thesis focuses on. Algorithms will be designed to decide on the optimal target MEC host of a relocation, which is addressed in research question 4.

1.4 Research questions

There are 4 research questions in this master thesis project:

1. What is Edge Computing and what is the relevance of different types of computing for telecom operators?
2. What aspects of Edge Computing should be considered for optimization in the context of 5G?
3. Devise an algorithm to find the optimal location of MEC hosts and the optimal location (MEC host) of a MEC application.
   To solve this, the following sub-questions are identified:
   a) Determine which aspects of MEC applications need to be considered in this master thesis.
   b) Transform the aspects chosen in sub-question a) into a set of parameters.
   c) Locate the MEC hosts as well as MEC applications properly based on these parameters.
   d) How to test the performance of the algorithm?
4. Devise an algorithm to dynamically find the optimal location of a MEC application processing instance for a UE (can be all kinds of equipment mounted in vehicles, machines, cellphones, etc.).
   To solve this, the following sub-questions are identified:
   a) What parameters of the possible target MEC hosts should be taken into consideration?
   b) How to choose the target MEC host based on these parameters?
   c) What information can be provided as feedback after a relocation to estimate the quality of this relocation and the behavior of the target MEC host? How to process/utilize the feedback information?
   d) How to test the performance of the algorithm?

1.5 Research Scope

In this master thesis, the considered MEC application users can be categorized into two categories which are described below:

1. Vehicle-to-everything (V2X) communications for self-driving vehicles. This type of UEs have high requirements on the application instance/UE context mobility service and the relocation mechanism.
   Theoretically, a large vehicle might be able to run and hold a MEC host itself and possibly has the ability to do the relevant signaling and data processing for other vehicles in its vicinity. Although using these vehicles to serve other MEC service users might significantly reduce the service latency, the high mobility of the MEC host located inside this serving vehicle may result in other problems. For instance, for a vehicle that moves at a similar speed as the serving vehicle, connecting to this serving vehicle can be a good way to reduce the number of relocations, while for the other vehicles, connecting to this moving MEC host may result in more relocations. Therefore, considering these vehicles as potential MEC hosts to serve UEs will significantly increase the complexity of this master thesis, hence, in this thesis all the MEC hosts considered are stationary MEC hosts whose locations are fixed.
2. Data caching and instant data processing for end-users on moving devices. One typical example is an end-user on a high-speed vehicle watching on-line videos or playing video games using a cellphone. For these kinds of applications/services, MEC is also important due to their requirements on instant interactions between the UEs, real-time user data processing and the fluent, high quality data stream between the UE and the server that provides the video stream. Compared to self-driving vehicles, the MEC service continuity for end-users in this category is less crucial, therefore, their mobility requirements can be less stringent.

Security and privacy aspects will not be considered in this master thesis. The 3GPP-defined 5G architecture itself contains several security-related designs already. For example, if the MEC platform/MEC orchestrator, working as an Application Function (AF), is not trusted and authorized, it will not directly interact with the Policy Control Function (PCF) but communicate with the Network Exposure Function (NEF) instead.

1.6 Methodology

Literature review and paper study are used throughout the entire master thesis. Research questions 1 and 2 especially rely on literature review since reading standardizations and white papers can help understand the meaning of relevant terminology as well as the basic ideas and usages of edge computing and MEC. Apart from that, greedy algorithms, heuristic algorithms, Markov Decision Process (MDP) and Reinforcement Learning (RL) are used to solve research questions 3 and 4, which will be further introduced in chapters 3, 4 and 5.

1.7 Structure of the thesis

Chapter 2 introduces some basic knowledge about 5G networks, MEC and MEC deployment in 5G networks. In Chapter 2 the research questions 1 and 2 are answered. Chapter 3 solves research question 3 and its sub-questions, introduces the details and technology background of all the designed algorithms, and shows, compares and analyzes the performance of these algorithms. Chapter 4 solves research question 4 and its sub-questions and introduces the details and technology background of all the designed algorithms. Chapter 5 gives the background introduction on the +31 Network in Ericsson, Rijen and shows the measurement results measured from the +31 Network. In Chapter 5, the performance of the algorithms designed in Chapter 4 are tested via simulations and the simulation tools and settings are introduced. Simulation outcomes are shown, compared and analyzed. Chapter 6 gives the overall conclusions of this master thesis and recommendations for potential future related work.

Chapter 2 Multi-access Edge Computing in the context of 5G

In this chapter, background information on 5G network is provided, including 5G network architecture, network functional entities and reference points. Apart from that, MEC system architecture, MEC entities and reference points are introduced, followed by the knowledge of MEC deployment in a 5G network, MEC-related UE mobility management and MEC lifecycle management.

2.1 5G network architecture

A 5G system, according to 3GPP standardization, consists of a 5G network and 5G User Equipment (UE) [4], and a 5G network contains a 5G Access Network (5G AN) and a 5G Core Network (5GC). A 5G AN is an access network comprising a Next Generation Radio Access Network (NG-RAN) and/or a non-3GPP Access Network (AN) connecting to a 5GC [4]. A NG-RAN consists of base stations, which are called Next Generation NodeB (gNodeB, or gNB) and Next Generation E-UTRAN NodeB (ng-eNB).

Specified by 3GPP in [4], the 5G network architecture is shown in Figure 2.1, and Figure 2.2 depicts the 3GPP [16] architecture of a 5G RAN.

At the highest system level, the 3GPP architecture contains 10 different Network Functions (NF). A network function can be realized in:

- a network element on dedicated hardware,
- an application instance running on dedicated hardware or
- a virtualized network function instantiated on an appropriate platform [4].

5G network architecture is a Service-Based Architecture (SBA), where a network function can provide services to other network functions or consume services other network functions provide. In this way, network functions communicate with each other, and the inner workings of one network function is a black box to the others. All the available services are registered in the Network Repository Function (NRF); if an authorized function needs to use a certain service, it can directly interact with the service provider, another network function, or gain the access towards the service via the Network Exposure Function (NEF).

However, untrusted entities, mainly located outside the 5G core network, cannot access the services by interacting with network functions directly. Instead, external, untrusted entities access services provided in 5GC via the NEF.

AMF, or Access and Mobility management Function, is responsible for registration management, connection management, reachability management, mobility management, access management, authorization and security-related management [4]. Besides, AMF also allows subscriptions of notifications regarding mobility events [5].

SMF is the Session Management Function. As mentioned in its name, SMF is responsible for Protocol Data Unit (PDU) Session (PDU Session) establishment, modification and release.

Unified Data Management Function (UDM) is for storing and managing subscription and

user data. Authentication Server Function (AUSF) is used for authentication.

Network Exposure Function (NEF) is a centralized service exposure point, and it is responsible for authorizing access requests from outside the network.

Policy Control Function (PCF) handles policies and rules by interacting with subscription data and user context provided by the UDM as well as instructions from Network Exposure Function (NEF) and/or Application Functions (AF).

Network Slice Selection Function (NSSF) helps the UE in the network with finding proper network slice instance, and according to the slides that the UE has access to, an AMF is selected to serve the UE, which may be different from the one that is previously selected by the access network to receive the registration request from the UE. If the newly selected AMF is different from the old one, the UE will be handed off to the new AMF.

A User Plane Function (UPF) is the end-point of the PDU Session and forms the gateway to data networks. It plays an important role in MEC since it relies on UPFs to route the desired traffic towards the MEC applications. Both the MEC Orchestrator (MEO) at superior system level and the MEC platform on the host level can act as an Application Function (AF) and interfere the traffic steering rules configuration. If the AF is authorized, it will directly communicate with the PCF to manipulate traffic rules configuration; otherwise the AF will interact with the NEF, and the NEF will instruct the PCF to create rules based on the requirements from MEO. The PCF will then send the traffic rules to the relevant SMF and the SMF will instruct the UPF to do traffic steering accordingly.

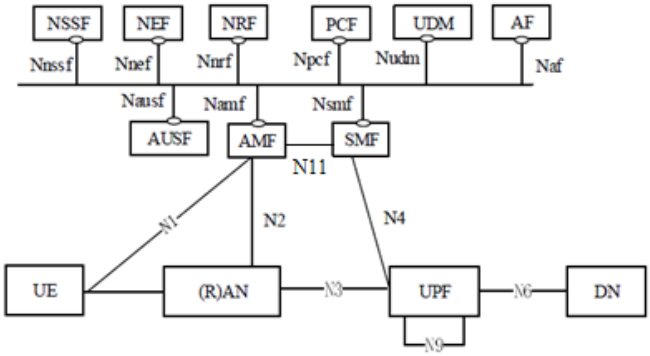


Figure 2.1: 3GPP 5G service-based architecture [4].

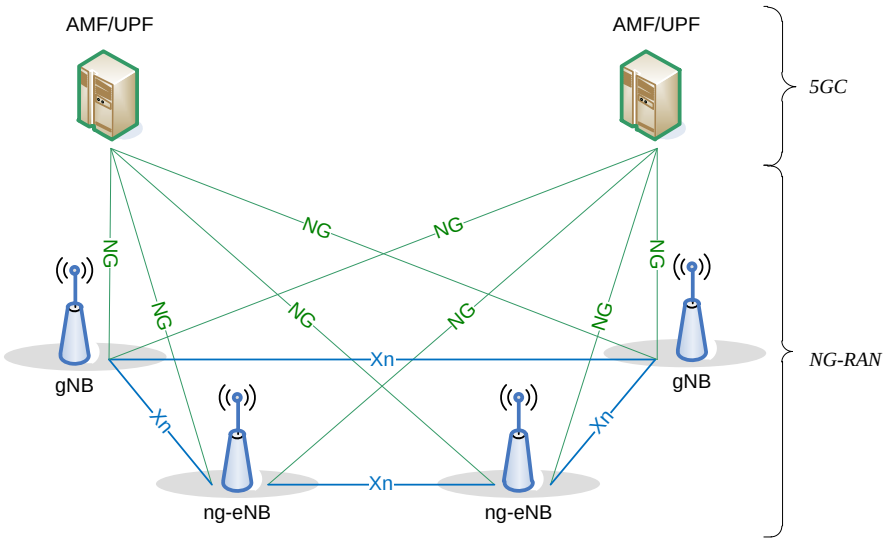


Figure 2.2: Overall NG-RAN architecture [28].

Figure 2.2 shows two types of NG-RAN nodes: Next Generation NodeB (gNB) and Next Generation E-UTRAN NodeB (ng-eNB). The gNB provides the New Radio (NR) user plane and control plane protocol terminations towards the UE, while the ng-eNB provides the Evolved UMTS Terrestrial Radio Access (E-UTRA) user plane and control plane protocol terminations towards the UE. The gNBs and ng-eNBs are responsible for radio resource management (e.g. radio bearer control, radio admission control, connection mobility control, dynamic allocation of resources to UEs in both uplink and downlink), routing User Plane (UP) data towards UPF(s) and Control Plane (CP) data towards AMF, connection setup and release, measurement and measurement reporting configuration for mobility and scheduling, QoS flow management, etc.

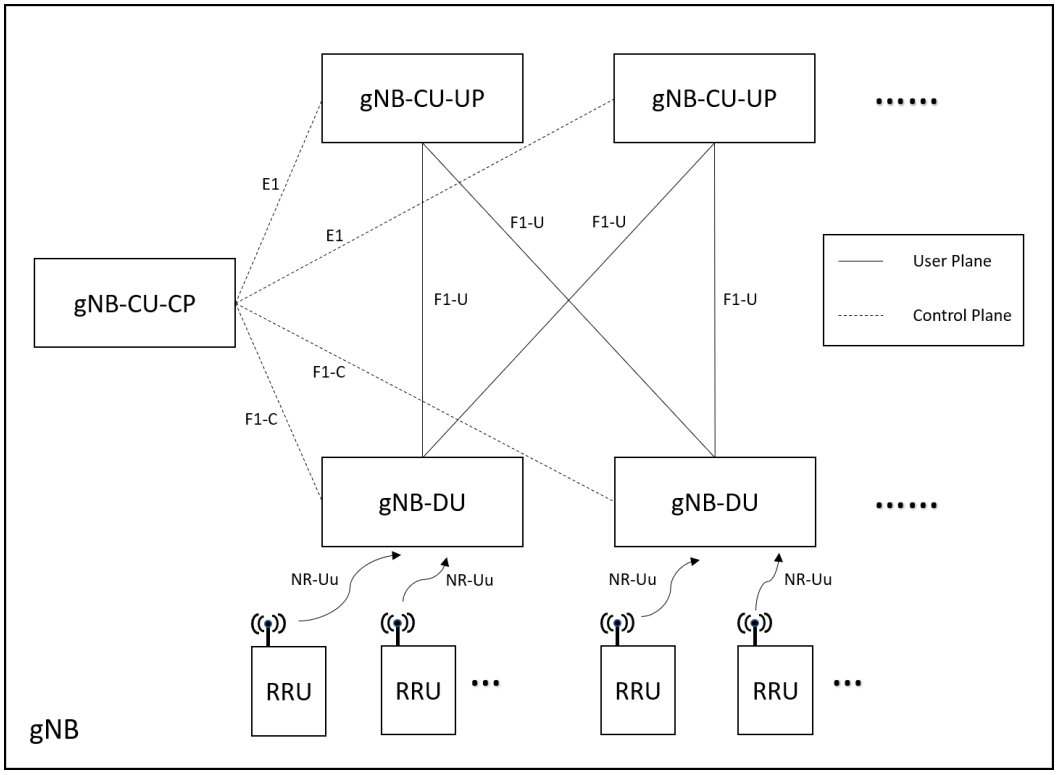


Figure 2.3: Overall architecture of a gNB.

The concept shown in Figure 2.3 is the separation of the control plane and the user plane inside a gNodeB. A Next Generation NodeB Centralized Unit Control Plane (gNB-CU-CP) can control one or more Next Generation NodeB Centralized Unit User Planes (gNB-CU-UP). A gNB-DU can be controlled by only one gNB-CU-CP but can connect to one or more gNB-CU-UPs. With network virtualization, gNB-CU-UPs can be located anywhere with required hardware resources available, for example, a gNB-CU-CP can be located physically close to a gNB-DU or an UPF.

Normally, which gNB-CU-CP controls which gNB-DUs is determined by the telecom operator. When a UE wants to establish a PDU Session, it will first send a request to the gNB-DU which it is connected to, and this gNB-DU will send another request to its corresponding gNB-CU-CP, then the gNB-CU-CP will find a suitable gNB-CU-UP to set up the bearer context.

2.2 MEC system architecture

Figure 2.4 illustrates the framework of MEC. Basically, one MEC system can be divided into three different levels [7]: MEC system level, MEC host level and MEC nework level. MEC host level consists of MEC hosts and a MEC host manager, which is mainly responsible for MEC application lifecycle management, MEC platform management, virtualization infrastructure management, etc. At superior MEC system level, the Multi-access Edge Orchestrator (MEO) has an overview of the entire MEC system.

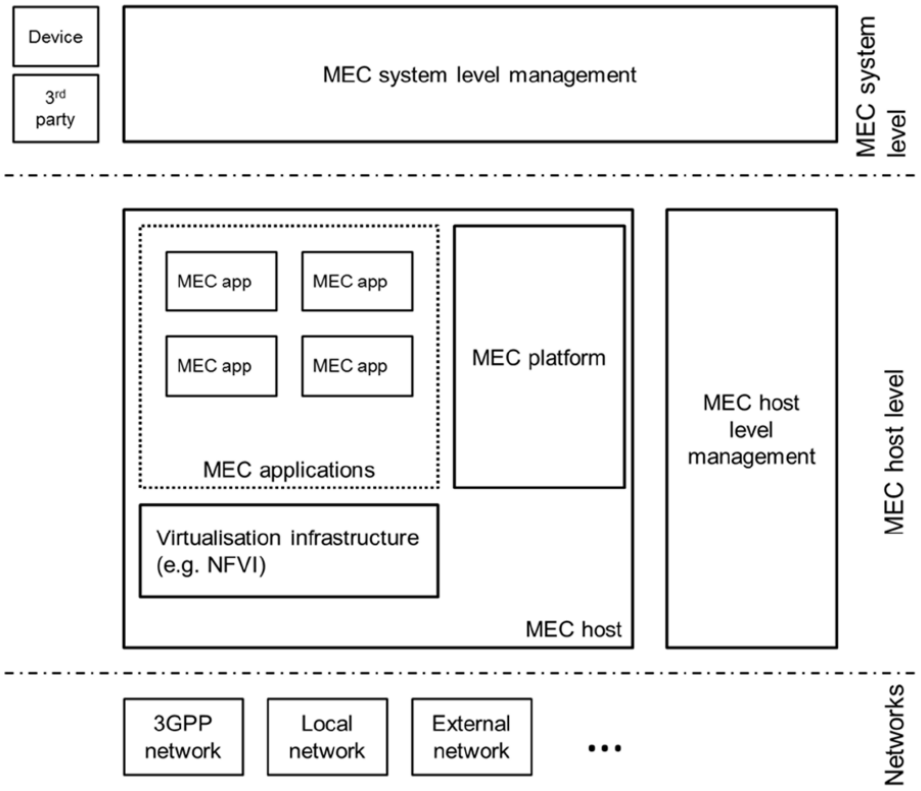


Figure 2.4: Multi-access edge computing framework [7]

Figure 2.5 shows the reference architecture of MEC. There are three types of reference points in the MEC architecture: Mp reference points represent reference points that are relevant to the MEC platform functionalities, Mx reference points are the reference points that connect the external entities to MEC and Mm reference points are management reference points.

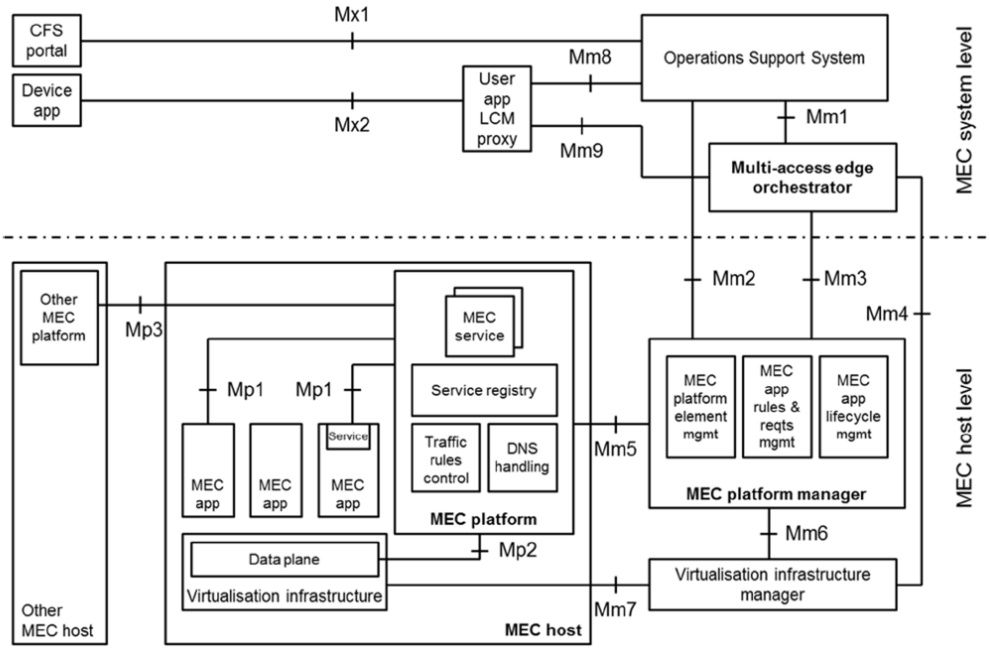


Figure 2.5: Multi-access edge computing reference architecture [7]

A. Functional elements

In this section, several important functional elements will be further introduced [7]:

1. MEC host: A MEC host consists of a MEC platform, a virtualization infrastructure and several MEC applications. The virtualization infrastructure contains a data plane, which routes traffic based on traffic rules received from the MEC platform.
2. MEC platform: A MEC platform enables MEC applications to discover, advertise, provide and consume MEC services. If supported, MEC services can be available across MEC platforms. A MEC platform receives traffic rules from the MEPM, from MEC applications and from MEC services, and it instructs the data plane to route traffic accordingly.
3. MEC Platform Manager (MEPM): The MEPM manages MEC application lifecycles, rules and requirements. In addition, the MEPM is also responsible for managing the application rules and requirements including service authorizations, traffic rules, resolving conflicts, etc.
4. Virtualization Infrastructure Manager (VIM): The VIM is responsible for allocating, managing and releasing virtualized resources (e.g. computing resources, storage resources and networking resources). The VIM also collects performance and fault information about the virtualized resources and reports to the MEPM for further processing.
5. MEC Orchestrator (MEO): The MEO maintains an overall view of the entire MEC system, including available resources, current available MEC services, deployed MEC hosts, topology information, etc. The MEO is also responsible for adding new application packages to the system and recording all the on-boarded packages. Besides, the MEO triggers MEC application instantiation and termination, and it selects suitable MEC hosts for MEC application instantiations. When relocations are

supported, the MEO will trigger relocations if needed.

6. Operations Support System (OSS): The OSS receives MEC application instantiation and termination requests from external parties and UE applications, and decides on the granting of these requests. The granted requests are forwarded to MEO for further processing.
7. Customer Facing Service portal (CFS portal): A CFS portal is used by third-party customers of operators for selecting and ordering a set of MEC applications they need and for receiving further service-level information.

B. Reference points

Reference points define conceptual points of information exchange between non-overlapping functional entities. A reference point becomes an interface when the connected functional entities are embodied in separate pieces of equipment [27]. In this section, the main reference points will be introduced in more details, information on reference points which are not mentioned below, so far as MEC is concerned, can be found in [7]:

1. Mx2: This reference point connects the MEC system and external UEs. UEs can use this reference point to request the MEC system to run a MEC application, or to move MEC applications in/out of the MEC system.
2. Mp1: This reference point connects a MEC application and the MEC platform. Mp1 is used by a MEC application to provide or consume other MEC services.
3. Mp2: This reference point connects the data plane and the MEC platform. MEC platform uses it to provide the data plane with traffic routing rules.
4. Mp3: This reference point connects two different MEC platforms, and these two MEC platforms can belong to different MEC systems if supported. Connecting two MEC platforms in two different MEC systems via Mp3 can facilitate coordination between MEC systems.
5. Mm1: This reference point connects the OSS and the MEO. Mm1 is mainly used for triggering the instantiation and termination of MEC applications.
6. Mm3: This reference point connects the MEO and the MEPM. Mm3 is used to perform MEC application lifecycle management (LCM), MEC application rules & requirements management and MEC services tracking.
7. Mm4: This reference point connects the MEO and the VIM. Mm4 is used to track available resources, manage application images and other virtualized resources related management.
8. Mm6: This reference point connects the MEPM and the VIM. Mm6 is used to manage virtualized resources in the MEC system.
9. Mm8: This reference point connects a User Application LCM Proxy (UALCMP) and the OSS. Mm8 is used to handle requests of running MEC applications in the MEC system from external UE applications (device applications).
10. Mm9: This reference point connects a UALCMP and the MEO. Unlike reference point Mm8, Mm9 is used for managing MEC applications which are requested by UE applications (device applications).

2.3 MEC system deployed in 5G network

A. Overall Introduction

Figure 2.6 shows one possible integrated deployment of MEC in 5G network. In [5], MEC is deployed in an external data network, and this data network is connected to the relevant UPFs via reference point N6. For a UE to access a MEC host, a PDU Session is established between the UE and one of the UPFs that connect to the MEC host. MEC user data is transferred via this PDU Session which ends at the UPF, and then the user data is routed to the external network where the MEC host is located.

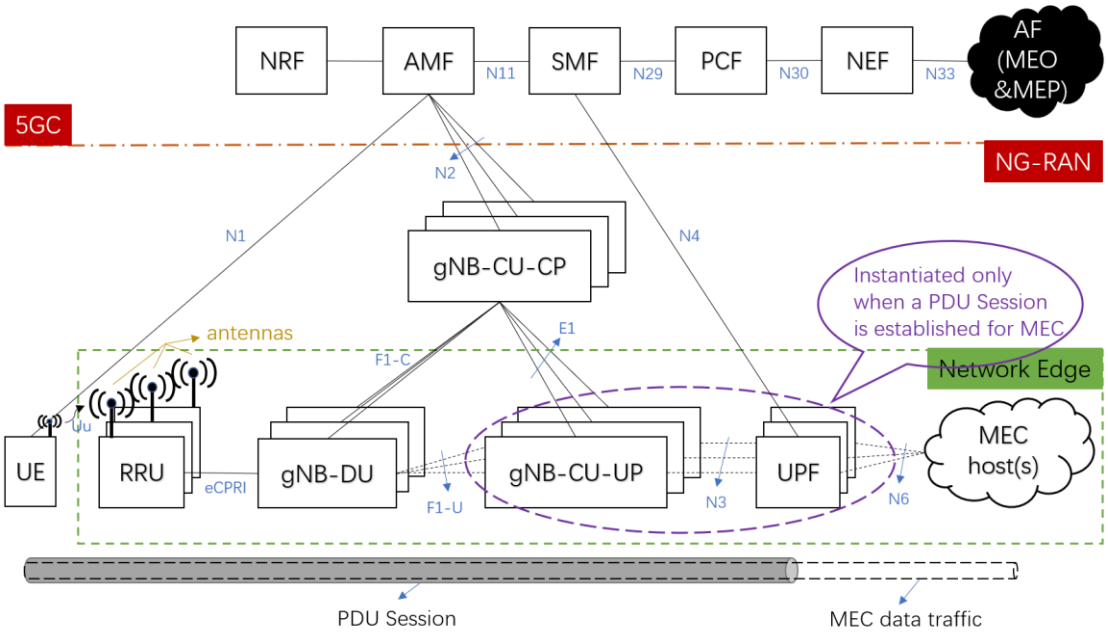


Figure 2.6: One example of integrated MEC deployment in 5G [5].

B. Access to MEC hosts

In this section, how to establish a PDU Session is introduced. Before going into details about the signaling for PDU Session establishment, a new concept – Local Area Data Network (LADN) needs to be introduced.

A LADN is a data network that is accessible by the UEs only in specific locations, that has a specific Data Network Name (DNN), and which availability is provided to the UE [29]. In this master thesis, one MEC host is always located in a LADN, and the location of a MEC host is equivalent to the location of its corresponding LADN. It is reasonable to deploy a MEC host in a LADN, because when the physical distance between a UE and its serving MEC host is too long to guarantee the required latency, even though the UE can still access this MEC host, the UE will should not be served by this MEC host anymore, which matches the property of the LADN.

If the data network is not a local area data network, the basic procedures of PDU Session

establishment are shown in Figure 2.7.

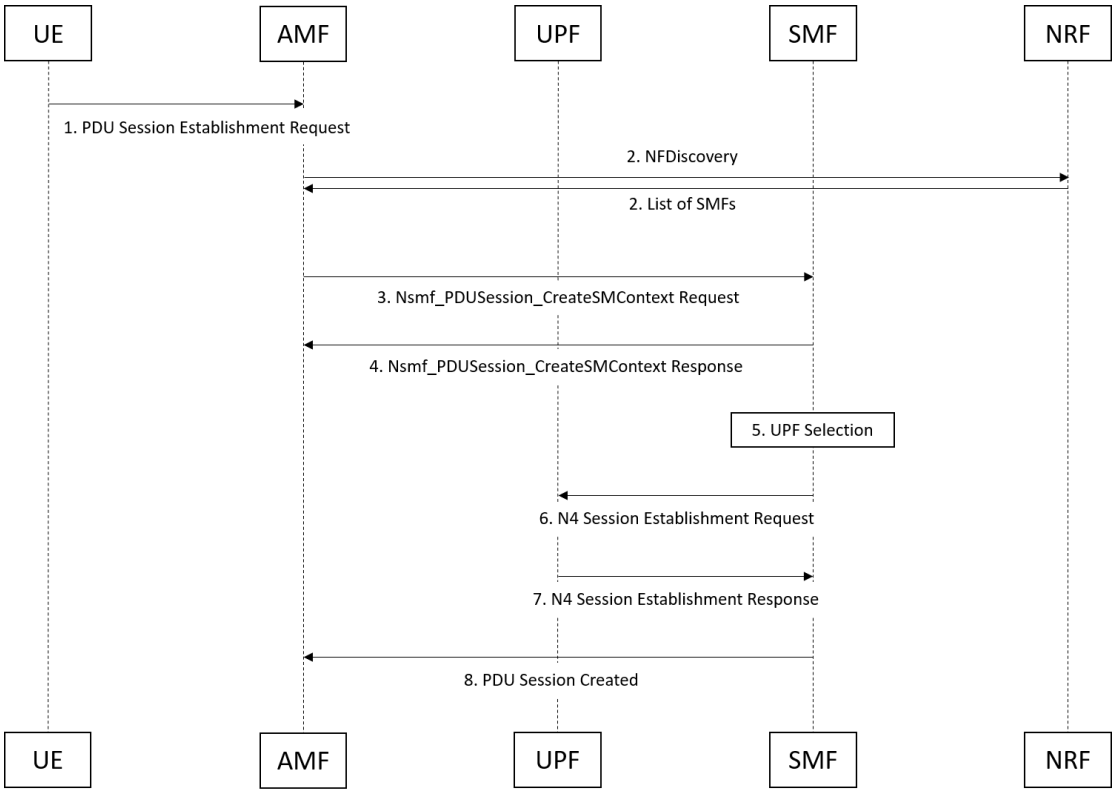


Figure 2.7: PDU Session establishment.

To establish a PDU Session for a UE, the following steps are needed [29], [30], [39]:

1. The UE first sends a Non-Access Stratum (NAS) message containing a PDU Session Establishment Request, UE requested DNN, a new PDU Session ID generated by the UE, etc. via the N1 reference point to the AMF to request a PDU Session establishment.
2. After the AMF receives the message, it handles everything related to connections or mobility management and picks a suitable SMF with the help of the NRF. The AMF provides UE location information to the NRF and then the NRF provides NF profile(s) of SMF instance(s) as well as the serving area of the SMF instance(s) to the AMF. After receiving the list of SMF instance(s), the AMF picks a suitable SMF instance.
3. The AMF sends a Nsmf_PDUSession_CreateSMContext Request, including UE requested DNN, PDU Session ID, AMF ID, PDU Session Establishment Request, user location information, etc. to the selected SMF via the N11 reference point.
4. The SMF sends the AMF a Nsmf_PDUSession_CreateSMContext Response, and in this response message, the SMF indicates whether it accepts to establish the PDU Session or not.
5. If the SMF accepts to establish the PDU Session, it will select a UPF according to parameters and information such as dynamic load,UPF capacity , statistics or predictions for UPF load, UE location information, DNN, PDU Session type and so on.
6. The SMF sends a Session Establishment Request to the selected UPF via the N4 reference point, together with packet detection, enforcement and reporting rules to

be installed on the UPF for this PDU Session.

7. The selected UPF acknowledges the request by sending a Session Establishment Response to the SMF via the N4 reference point.
8. The SMF reports to the AMF for the successful session establishment.

If the data network is a local area data network, a few more steps are needed [29].

1. The UE provides LADN Information (i.e. LADN Service Area Information and LADN DNN) to the AMF.
2. When receiving a PDU Session establishment request with the UE requested DNN, the AMF determines whether the requested DNN is configured as a LADN DNN or not. If the requested DNN points to a LADN, the AMF determines the UE's presence in the requested LADN service area and forwards the result to the SMF.
3. When receiving the session management request corresponding to a LADN, the SMF determines whether the UE is inside the LADN service area based on the indication (i.e. UE Presence in LADN service area) received. If the SMF does not receive the indication, the SMF will consider the UE to be outside the LADN service area, and the SMF shall then reject the PDU Session establishment request.

C. Possible Locations of MEC hosts

At the current stage, implementing and maintaining MEC hosts are expensive. Therefore, the total number of MEC hosts is small, in order to limit the Operations and Management (O&M) expenses from the telecom operators' side (See more in Appendix D Interview 2). In this case, optimizing MEC application and MEC host deployments as well as MEC host re-selections is trivial. However, in the near future, technological advances such as network virtualization are expected to contribute to reducing O&M cost for telecom operators. By then, locations of UPFs are not limited to the core network anymore. Instead, UPFs can be virtualized and be placed at more locations in the telecom network, for example, close to gNB-CUs or gNB-DUs. If a MEC host is located further away from the network edge, the service latency will increase, but the serving area of this MEC host will expand at the same time, implying a decrease in the number of relocations experienced by UEs. This trade-off between service latency and number of relocations makes optimizing the deployment of MEC hosts and MEC applications as well as optimizing MEC host re-selection procedure non-trivial and this topic is further discussed in this master thesis.

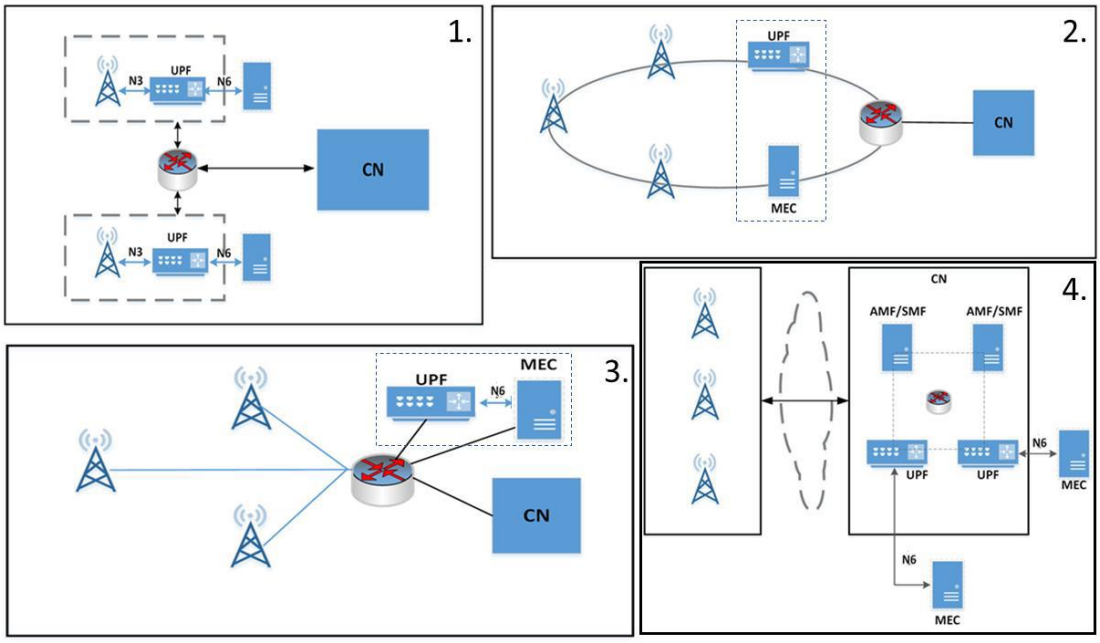


Figure 2.8: Possible physical deployments of MEC host [5].

Four possible deployment scenarios suggested by ETSI are shown in Figure 2.8:

1. MEC host and a User Plane Function (UPF) collocated with the base station.
2. MEC host collocated with a transmission node (e.g. an advanced router), possibly with a local UPF.
3. MEC host and a UPF collocated with a network aggregation point (e.g. a Metro Core).
4. MEC host collocated with the UPF inside the core network.

In scenarios 1, 3 and 4, a MEC host is always collocated with a UPF. When a MEC host is located outside the core network, a local UPF is always needed to steer traffic towards this MEC host. This UPF is dedicated to this MEC host, it is established for MEC only and as a consequence, this combination cannot be used as access to internet services in general. A UPF can connect to multiple gNB-CU-UPs controlled by different gNB-CU-CPs. When a UE requests to establish a PDU Session towards a UPF which interfaces with a data network where the required MEC host is located, the serving gNB-CU-CP of the UE will find a suitable gNB-CU-UP under its control to establish a user plane connection towards the UPF.

In scenario 2, however, ETSI purposed that a MEC host is not necessarily located with a UPF, and a MEC host is not necessarily located inside an external data network as shown in Figure 2.8. This type of deployment can further decrease service latency because the logical location of a MEC host is moved from the network side of a UPF to somewhere in the access network. However, to make this deployment come true still requires further researches and investigations, because the routine of user data should always under the control of the core network, and currently traffic rules in 5G networks are enforced by UPFs only.

In this master thesis, three different MEC host locations are considered:

i. collocated with gNB-CU-UPs that are physically close to gNB-DUs;

ii. collocated with integrated gNB-CU;

iii. collocated with a UPF inside the 5G Core Network (5GC).

D. Traffic Steering

The 5G network allows external AFs to provide traffic steering rules via the PCF or the NEF. For example, MEC Functional Elements (FE) can be considered as AFs and can manipulate traffic steering in the following ways:

1. If the MEC FE (e.g. MEP) is considered trusted by the 5G core network, this MEC FE can directly interact with the PCF for traffic steering. The MEC FE first sends a request to the PCF, identifying the traffic to be steered to the MEC system. Then the PCF transforms the request into policies and provides traffic routing rules to the SMF. Upon the arrival of the new traffic rules, the SMF will try to identify the target UPF and start traffic rules configuration.
2. If the MEC FE is not trusted by the 5G Core Network (CN), then it needs to configure desired traffic rules via the NEF.

E. Capabilities Exposure

The NEF is the functional entity in the 5GC that exposes capability information and available services to external entities (e.g. MEC FEs) for monitoring, provisioning, policy and charging. On example where the NEF is used is the Radio Network Information Service (RNIS) which is a service that provides radio network related information to MEC applications and to MEC platforms [9]. Normally, radio information needs to be routed via the core network to reach the subscribers of RNIS (e.g. MEC platforms, MEC applications). With the NEF and capacity exposure, RAN capabilities can be directly exposed to the MEC platform and reach MEC applications that subscribes to RNIS for further computing and processing. In this way, transmission latency as well as bandwidth consumption are reduced. Figure 2.9 depicts the capability exposure of the 5G network to the MEC system.

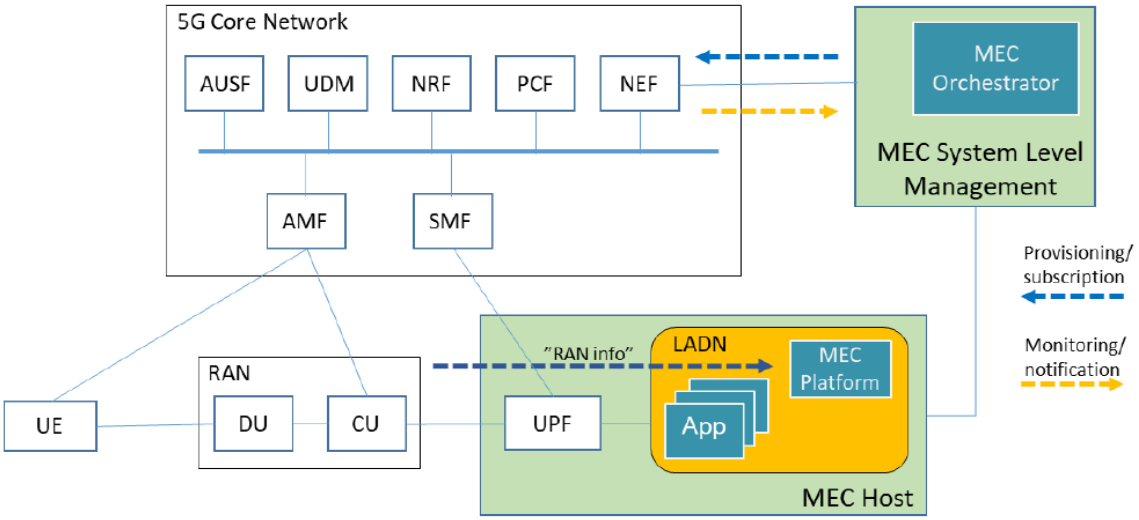


Figure 2.9: Capability exposure [5].

2.4 MEC application instance and/or UE context mobility

UEs installed in vehicles and cellphones are expected to be predominantly mobile. When a UE is moving around, its serving site (i.e. antenna & RRU) keeps changing for maintaining a continuous radio connection. When the serving site of a UE changes, its serving MEC host may remain the same, thus no relocation is needed. Only when the UE moves out of the serving area of its current serving MEC host or the change of site results in the change of UPF, will a relocation be required in order to continue the MEC services.

According to [20], two different types of MEC applications need to be considered:

1. Dedicated MEC application: A MEC application instance is dedicated to a specific UE. When a UE moves to a new MEC host which is different from its current serving MEC host, its corresponding MEC application instance should be relocated to the new MEC host from its current serving MEC host.
2. Shared MEC application: A MEC application instance serves multiple UEs. When a UE moves to a new MEC host which is different from its current serving MEC host, if the required MEC application has already been instantiated, then no new MEC application instance will be instantiated.
   Shared MEC applications can be further divided into two different types:
   i. Stateless MEC application: A stateless application is an application that does not memorize the service state or recorded data about UE for use in the next service session.
   ii. Stateful MEC application: An application that can record and store the state information which can be used to facilitate service continuity during the session transition.

Especially for stateful MEC applications and dedicated MEC applications, the synchronization between the source and target MEC application instance as well as the user context transfer are of great importance. After a relocation is triggered, the user context should be copied to the target MEC application instance, after which the target MEC host is ready to serve the UE. In order to provide seamless services, the target MEC host should be ready when the UE moves out of the serving area of its current MEC host. Otherwise, the target MEC host needs to act as a replay point and forward user data towards the source MEC host for processing. In this scenario, user data transfer between the two MEC hosts increases service latency significantly. Therefore, this scenario is not suitable for UEs with stringent service latency requirement.

The research on MEC application mobility by ETSI MEC ISG is on-going. Up to now, several possible procedures have been defined, including application mobility enablement, detection of User Equipment (UE) movement, validation of application mobility, user context transfer and/or application instance relocation, and post-processing of application relocation [5].

Figure 2.10 shows the basic idea of MEC application mobility. Traffic sent by a UE is transferred to relevant MEC application instance via a UPF. Due to the mobility of this UE, at some point of time, relocation will be necessary for the consistence of MEC service. If the relevant MEC application instance is dedicated, then it will move with the UE together to the new MEC host. If the MEC application instance is stateful, then the user context will be sent

to the new MEC host during a relocation.

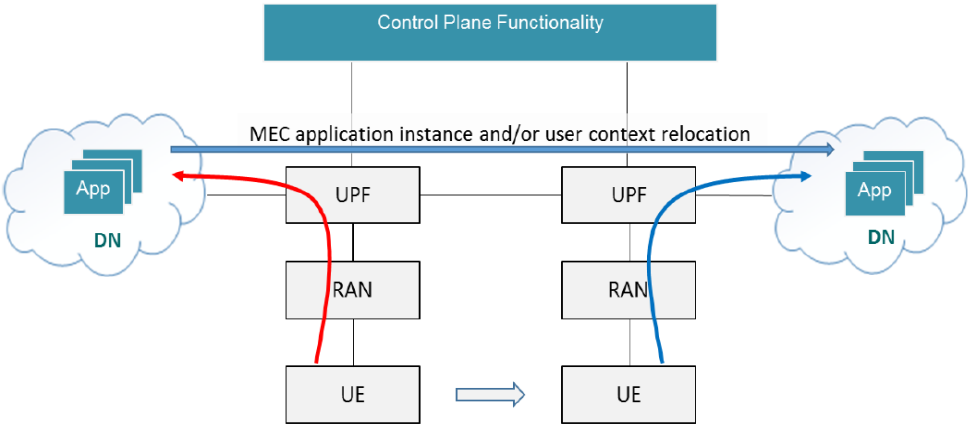


Figure 2.10: The principle of MEC application mobility [5].

Figure 2.11 precisely shows the relocation procedures: ①A UE moves to the coverage of a new site (antenna & RRU) and this new site starts to serve this UE. ②The current MEC host (source MEC host) of this UE detects this change, probably via Radio Network Information Service (RNIS) [9]. ③The source MEC host saves the current state for the UE if necessary, and sends a relocation request to the MEO. ④The MEO selects a MEC host for this UE and instructs the selected MEC host to instantiate a new MEC application instance if necessary. ⑤The source MEC host sends the user context to the target MEC host; the source gNodeB sends all access signaling, session management signaling and payload signaling to the target gNodeB; the source RRU or the target gNB-DU sends all access signaling, session management signaling and payload signaling to the target RRU. ⑥If the source RRU and the target RRU are not connected to the same gNB-DU, then there will be a change in gNB-DU. ⑦If the source gNB-DU and the target gNB-DU are not connected to the same gNB-CU, then there will be a change in gNB-CU. ⑧The MEO instructs the source MEC host to terminate the relevant MEC application instance if necessary.

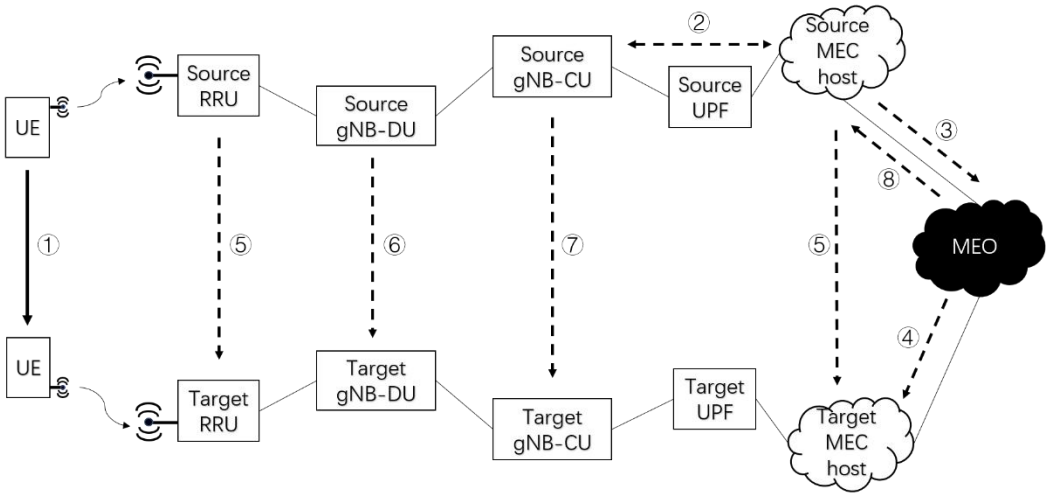


Figure 2.11: The basic procedures of MEC relocation [5].

To detect the UE mobility, two possible ways are mentioned in [5]:

1. MEC functional entities (e.g. MEC platform) can subscribe to relevant event

notifications provided by the Session Management Function (SMF) or the Network Exposure Function (NEF).

2. MEC platform can subscribe to the Radio Network Information provided by Radio Network Information Service (RNIS). By doing this, the MEC platform can notice the mobility of the UE when its serving cell changes.

2.5 MEC Application Instance Lifecycle Management

A. MEC application instance instantiation

To instantiate a MEC application instance in the MEC system, nine steps shown in Figure 2.12 are needed:

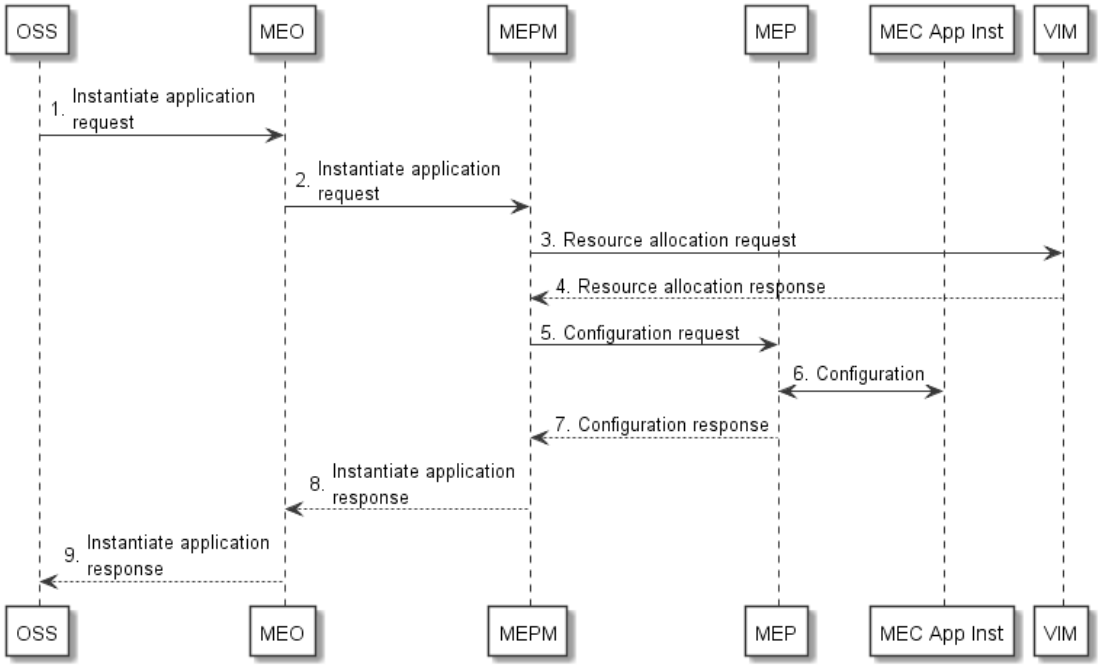


Figure 2.12: MEC application instantiation sequence diagram [34].

1. The OSS sends an instantiate MEC application request to the MEO.
2. The MEO then authorizes the request, selects the MEC host and sends an instantiate MEC application request to the corresponding MEPM.
3. The MEPM receives the request and sends a resource allocation request to the VIM, together with storage, computing and network resource requirements as well as the MEC application image information.
4. The VIM then allocates resources according to the request received from the MEPM. It instantiates the Virtual Machine (VM) in the Virtualization Infrastructure (VI),

installs the MEC application on the VM and runs the VM as well as the application instance.

5. The MEPM sends a configuration request to the MEC Platform (MEP). Then start the MEC application start-up procedure.
6. In the start-up procedure, the MEC platform can verify the authenticity of the MEC application by using an AA entity that contains the registration related information about the MEC application [38]. Then the MEC application sends a “MEC App is running” message to the MEP to indicate the success of the instantiation. By then the start-up procedure is completed, and the MEC application instance will send a service query and/or send a service registration request to the MEP to consume the MEC applications it requests and/or register the services it provides.
7. After all the configurations in step 6 are completed, the MEP sends a configuration response to the MEPM.
8. After the MEPM receives the configuration response, it sends an instantiate MEC application response to the MEO, including the information of the allocated resources for the MEC application instance.
9. The MEO sends an instantiate application response to the OSS, including the results of this instantiation operation. If the MEC application is instantiated successfully, the MEO will also return the corresponding application instance ID to the OSS.

B. MEC application instance termination

The procedure to terminate a MEC application instance is shown in Figure 2.13.

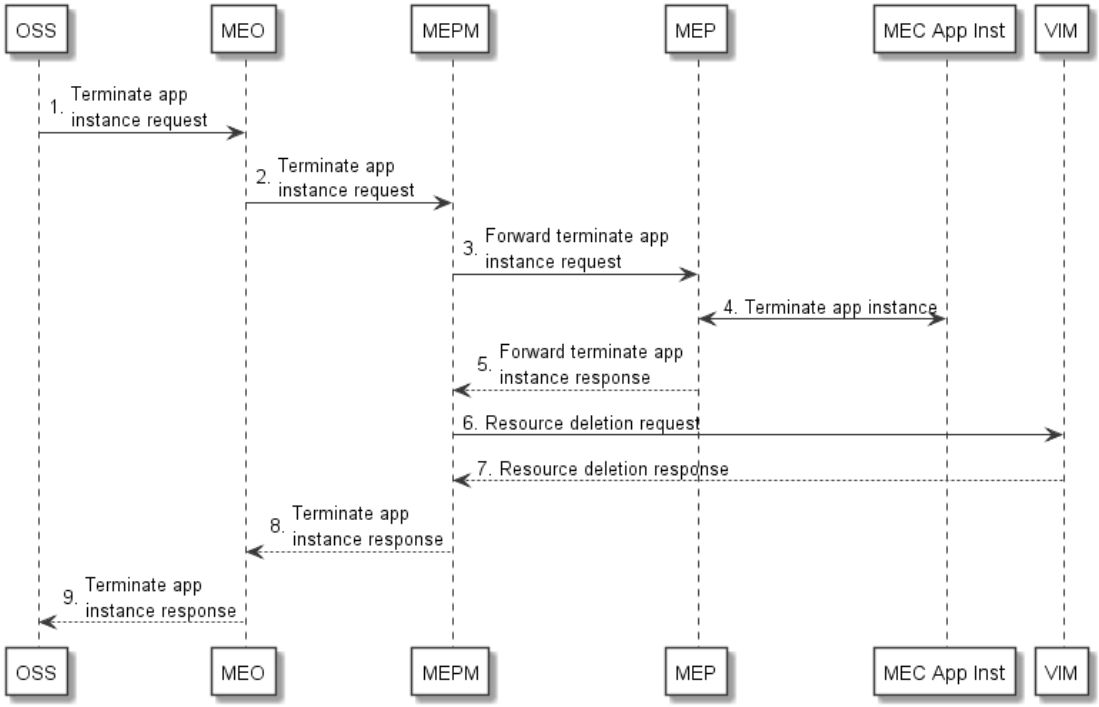


Figure 2.13: MEC application instance termination sequence diagram [34].

1. The OSS sends a terminate application instance request to the MEO, together with the MEC application instance ID of the application instance to be terminated.
2. The MEO authorizes the request and verifies the existence of the identified application instance. The MEO then sends a terminate application instance request to the MEPM.
3. The MEPM sends the terminate application instance request to the relevant MEP.
4. The MEP receives the terminate application instance request from the MEPM. If a graceful termination is requested and is supported by the MEC application to be terminated, then the MEP starts the graceful stop procedure: The MEP first sends an instance terminate notification to the MEC application instance and indicates the application instance a time interval for termination actions. Then the MEC application instance can do some application level actions (e.g. deregister the MEC services it provides) related to termination within the time interval indicated by the MEP. If the application level actions are finished or the time is up, MEP will continue to terminate the MEC application instance.
5. The MEP sends a forward terminate application instance response to the MEPM.
6. The MEPM sends a resource deletion request to the VIM for terminating the VM as well as releasing the allocated resources.
7. The VIM releases the allocated resources according to the request it receives from the MEPM. Then it sends a resource deletion response to the MEPM.

8. After the MEPM receives the response, it sends a terminate application instance response to the MEO.
9. The MEO sends a terminate application instance response to the OSS.

2.6 Radio Network Information Service

The Radio Network Information Service (RNIS) provides radio network information to MEC applications and MEC platforms (MEPs). The radio network information can be required and provided on the scale of a cell, a UE and a time period, etc. Typical radio network information includes [9]:

1. information reflecting the current radio network conditions,
2. Measurement information of the User Plane (UP),
3. Changes on information about UEs.

Some of the MEC services require real-time radio conditions for optimizing, monitoring, computing and other purposes. For example, the MEC service provided by the throughput guidance radio analytics MEC application, requires radio network information to compute the current throughput of the radio downlink interface, estimate the throughput in the next time instance accordingly and provide an indication towards the backend radio server. Another example is when a UE needs to maintain its MEC service continuity, radio network information will be required by the MEP for relocation optimization.

RNIS consumers can send messages to the RNIS for requesting various types of radio network information. The three types of information requests from RNIS consumers are listed below [9]:

1. Request for Radio Access Bearer (RAB) information. A RNIS consumer such as MEC application or MEP sends a request to the RNIS with the MEC application instance ID requiring a cell level RAB information from the cells that are associated with the requested MEC application instance, and will get a response with the identifiers of all the relevant cells, identifiers of UEs in the cells and information about their Enhanced Packet System Radio Access Bearer (E-RAB).
2. Request for PLMN information. A RNIS consumer sends a request for cell level PLMN information to the RNIS together with MEC application instance ID(s) and will receive a response with information about cells that are associated with the requested MEC application instance(s).
3. Request for S1 bearer information. A RNIS consumer sends a request to RNIS requiring S1 bearer information, which can be used for optimizing relocation process and managing traffic rules.

2.7 Relationships between Cloud Computing, Fog Computing and Edge Computing

The relationship between cloud computing, fog computing and edge computing is discussed

in this section.

Compared to cloud computing, both fog computing and edge computing move the computing power away from the central cloud. One of the main differences between fog computing and edge computing is the "destinations" of the computing power: fog computing moves the computing power as well as other intelligence to the Local Access Network (LAN), more precisely, a fog node or a gateway [15], while edge computing places the computing power in or physically close to the (local) devices that produce data [14]. Another difference between fog computing and edge computing is the architecture. Fog computing is hierarchical, fog nodes are distributed in several levels, and fog nodes in different levels have different intelligence and process different data, and edge computing simply distributes computing power to the network edge. Figure 2.14 shows the differences between cloud computing, fog computing and edge computing.

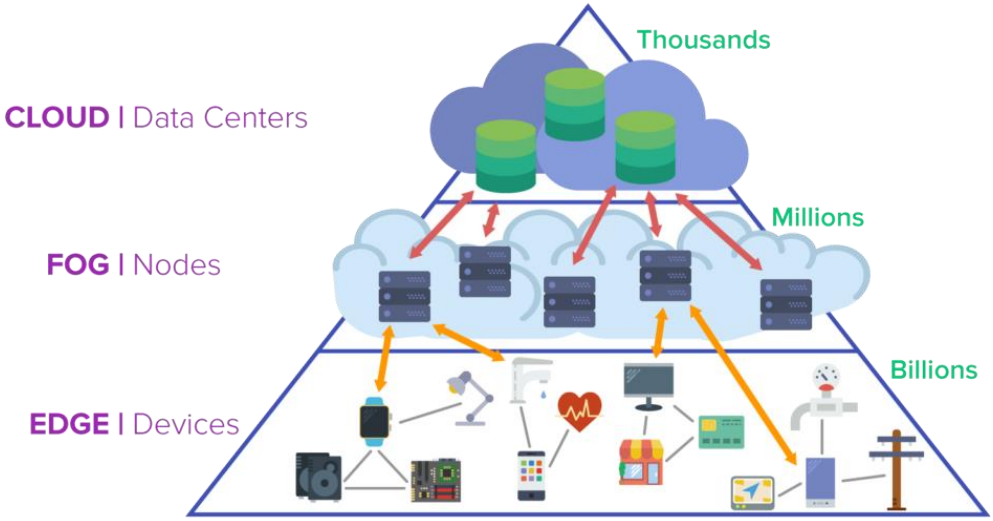


Figure 2.14: Cloud computing vs fog computing vs edge computing [15].

2.8 Aspects of Edge Computing to be optimized in the context of 5G

Optimization in the context of edge computing may, for example, aim at achieving the following results regarding:

1. Shorter service latency,
2. Fewer MEC service interruptions,
3. Fewer relocations,
4. Fewer MEC hosts needed,
5. Higher resource efficiency,

In this master thesis, the optimization goal of research question 3 is to minimize the number of relocations, to meet the requirements of each MEC application and to provide sufficient but not redundant resources to each MEC application, hence it focuses on optimization aspects 2, 3, 4 and 5. Research question 4, on the other hand, has the optimization goal of finding the MEC host that provides a UE the best service quality (e.g.

service latency, service continuity) during and after a relocation, hence it focuses on optimization aspects 1, 2 and 3.

2.9 Summary

In this chapter, context information on a 5G network and MEC are introduced. In addition, research questions 1 and 2 are answered:

1. *What is Edge Computing and what is the relevance of different types of computing for telecom operators?*

Edge Computing is a distributed computing framework which places data computing in proximity to the end devices that produce the data. The main differences between fog computing, cloud computing and edge computing are their architectures and the place where the data is processed.

Cloud computing processes data in a centralized data center, and the latency as well as bandwidth usage between end-users and the data center increases rapidly with the number of end-users and data volume.

Fog computing processes data at fog nodes closer to the network edge, and unlike cloud computing, fog computing has a hierarchical architecture and fog nodes are distributed in different levels. Fog nodes in different levels have different levels of intelligence.

Edge computing processes data at the network edge, which is physically closer to the end-users than cloud computing and fog computing. Different from cloud computing and fog computing, edge computing has a distributed architecture.

2. *What aspects of Edge Computing should be considered for optimization in the context of 5G?*

MEC host location, MEC application location, MEC service latency, number of relocations, time consumption of a relocation as well as resources-related aspects are in the scope of this master thesis. Additionally, to control the costs, the number of MEC hosts is also considered as an aspect of optimization.

The above-mentioned aspects cannot be optimized at the same time. Therefore, number of relocations, MEC service latency and time consumption of a relocation form the optimization goals in research questions 3 and 4, while the others form the constraints.

Chapter 3 Optimizing the Locations of MEC Hosts and MEC Application Instances

In this chapter, research question 3 is formulated into an optimization problem and an assignment to devise and assess algorithms that find the optimal location of MEC hosts and the optimal location of a MEC application. This optimization problem is divided into two sub-problems. By solving the two sub-problems separately, the whole optimization problem is solved. Three greedy algorithms and two heuristic algorithms are designed to solve the two sub-problems, and their performance us tested and analyzed.

3.1 System Model & Assumptions

In order to answer research question 3, in this section a geographic service area and a directed Graph (in which unit-hosts are nodes) which models the geographic service area are proposed. Additionally, 17 related assumptions are inventoried.

The geographic service area is equipped with a 5G network capable of providing MEC services to both vehicles and passengers. The size and location of this geographic service area are ignored, and one and only one straight road is in this geographic service area. The road has multiple lanes and its trajectory is known. This thesis' research takes the following two combined use cases into account:

1. Vehicles of which some are Connected Autonomous Vehicles (CAVs) may enter this geographic service area via the entrance of the road.
2. Each vehicle is assumed to transport passengers of which some can be playing mobile games or watching videos while the vehicle is driving autonomously.

Within this geographic service area, there exist N fixed sites (antenna & RRU) which can transfer messages between UEs and MEC hosts, and their radio coverages are known in advance. To model the geographic service area, a directed graph G is derived from the above information. In addition, 7 assumptions on the geographic service area are made:

1. The width of the road in this geographic service area is ignored, since the width of the road is negligible compared to the coverage radius of a site. Every UE in the geographic service area is a MEC user who only requires one MEC application.
2. The temporal aspect is ignored, and UEs that enter this geographic service area in different entrances have no difference in the context of this master thesis. For simplicity reason, it is assumed that the road has only one entrance and one exit, and all the mobile UEs enter the geographic service area from the entrance of the road and leave from the exit.
3. There are three different types of possible locations for MEC hosts considered in this master thesis [5]:
   - close to the gNB-CU-UP (e.g. collocated with gNB-CU-UPs which are physically close

to gNB-DUs),
- close to the integrated gNB-CU (combined gNB-CU-UPs and gNB-CU-CP) and
- close to the core network (e.g. located inside an external data network that is close to the core network or co-located with a UPF that is inside a 5GC).
For simplicity reason, these three types of MEC host locations will be referred to as the three MEC host locations in the remainder of this thesis.

4. Each site in the geographic service area is able to send/receive payload to/from UEs and MEC hosts in the three locations mentioned in assumption 3.
5. Each site has a corresponding "unit-host" in each of the three locations in assumption 3. A unit-host is not a MEC host but a part of a MEC host. Each unit-host contains part of the resources of a MEC host and processes data or requests from the site it corresponds to. In other words, each unit-host only provides MEC services to UEs that are within the coverage area of its corresponding site. For simplicity reason, this relationship will be called "a unit-host only serves its corresponding site" in the remainder of this thesis. A unit-host is not a real entity like MEC host, instead, it is an intermediate outcome and will be finally grouped into a MEC host (probably) with other unit-hosts. A MEC host contains several unit-hosts, and the meaning of "contain" here is that, a MEC host has all the resources of these unit-hosts and serve all the UEs that are served by these unit-hosts. The reason why this new concept has been brought up is explained in section 3.2.D.
6. All the unit-hosts have the same amount of computing/storage/processing resources, and the amount of computing, storage and processing resources in each unit-host is equal ($cr_{unit} = sr_{unit} = pr_{unit}$).
7. In the directed graph G, each node is a unit-host and two nodes are connected if their corresponding sites have overlapping coverage area.

To determine the serving area as well as the location of each MEC host and to determine the MEC hosts where each MEC application is installed, the following 10 assumptions on MEC hosts and MEC applications are made:

8. The closer the MEC host is located towards the core network, the larger the service latency is between itself and UEs. The closer the MEC host is located towards the core network, the larger number of sites that can be served by this MEC host. Here "serve a site" means providing MEC services to all the UEs that are currently within the coverage of this site.
9. A MEC host consists of several unit-hosts. These unit-hosts are connected and are in the same location. The MEC host inherits all the resources in these unit-hosts, and it is in the same location as these unit-hosts.
10. The serving coverage of a MEC host is the integrated serving coverage of all the unit-hosts it contains. As long as a UE is in the serving coverage of a MEC host and this MEC host is able to serve this UE (i.e. the MEC host has enough resources to serve the UE and has the required MEC application installed), the UE can always establish a PDU Session towards the LADN where this MEC host resides with the corresponding DNN. In this sense, although a UE is connected to only one site at a time, there could be multiple MEC hosts that are able to serve it.
11. MEC hosts in different locations have different upper limits (NU) of the number of

unit-hosts they may contain, which means that MEC hosts in different locations have different amount of available resources. MEC hosts in the same location have the same upper limit (NU).

12. Every MEC host is deployed in an external LADN with a DNN and is connected to one or more UPF(s) via the N6 reference point.
13. Only a handover that occurs between two different MEC hosts is considered as a relocation.
14. Every MEC application has a specific requirement on MEC service latency. It is assumed that the location of a MEC host is the only factor that affects the service latency. Hence, the latency requirement of each MEC application can be transformed into a set of acceptable MEC host locations.
15. Every MEC application has a certain sensitivity to MEC service relocations. Here sensitivity consists of two aspects. One aspect is the service continuity during a relocation. If a relocation of a MEC application is more likely to cause service interruptions, then this MEC application is called more sensitive to relocations, hence its sensitivity to relocations is higher. Another aspect is the impact of service interruptions, if a service interruption of a MEC application may have fatal consequences (e.g. self-driving vehicles related MEC applications), then this MEC application is more sensitive to relocations and has a higher sensitivity. The sensitivity to relocations of each MEC application will be called priority ($prior$) in the remainder of this thesis.
16. Every MEC application instance requires a certain amount of computing, storage and processing resources to serve one UE.
17. There are enough resources in the geographic service area to serve all the UEs.

Figure 3.1 gives an example of a geographic service area considered in this master thesis.

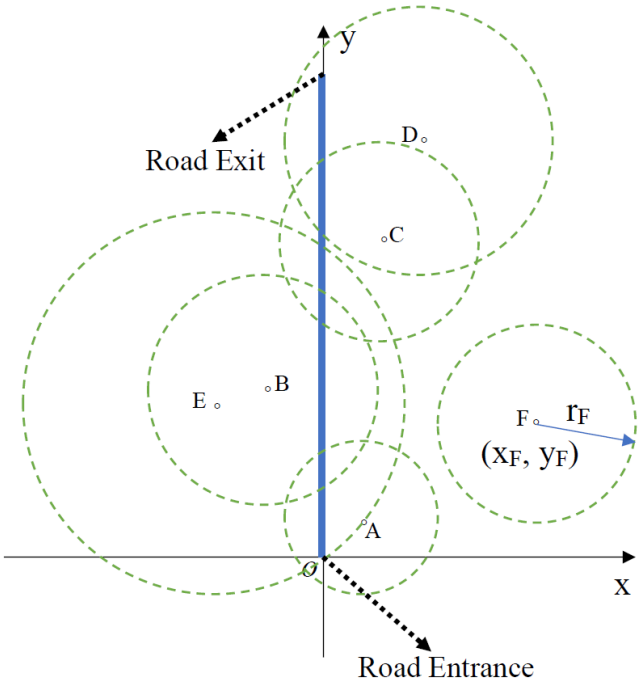


Figure 3.1: An example of a geographic service area.

For each site (e.g. site F) in the geographic service area, its location information, which is given as x, y coordinates (e.g. (x_F, y_F)), as well as coverage radius r (e.g. r_F) are known in advance. A UE that enters the geographic service area will first be served by one of the sites that cover the road entrance (e.g. site A, E). If a UE is served by one of the sites that cover the road exit (e.g. site D), it will be served by this site until it leaves the geographic serving area. Sites like site F are unable to serve UEs on the road because its coverage circle (the green circle with center point site F) does not intersect with the road (straight, blue line).

The properties of MEC hosts introduced in assumption 8 lead to a dilemma regarding the deployment of MEC hosts. If a MEC host is located far from the edge of the network and close to the core network, the service latency between UEs and the MEC host will significantly increase; if a MEC host is close to the edge of the network, the number of UEs it can serve will significantly decrease, implying an increase in the number of relocations.

With the envisaged increase of MEC usage and the development of MEC applications, there will be more MEC services required by users/applications/devices. In this situation, the main driver of MEC is not latency but the availability of (enough) resources to serve the increasing number of MEC users (see more in Appendix D). To make sure that the network has enough resources in the worst situation in which the number of MEC users in the geographic service area reaches the maximum number, enough resources and enough MEC hosts should be provided. However, having a large number of MEC hosts can result in a large number of relocations which may significantly degrade the user experience. Therefore, an optimal deployment of MEC hosts and MEC applications needs to be determined in order to minimize the number of relocations while still meeting the resource requirements.

3.2 Problem Formulation

A. Problem Description

Based on the assumptions above, research question 3 can be formulated as: *given priority, estimated UE flow, possible locations and required computing/storage/processing resources of every MEC application, computing/storage/processing capacity of each unit-host as well as the location and coverage of each site in the geographic service area, which unit-hosts should be integrated as MEC hosts in each location and in which MEC hosts should the MEC applications be installed, so as to minimize the total number of relocations and to provide sufficient but not redundant resources?*

In the above problem description, three key points can be extracted:

1. Optimization goal: Minimizing the total number of relocations
2. Guarantee continuous services for every UE
3. Reserve enough but not redundant resources for UEs of every MEC application. To achieve this, an **extreme situation** is considered. The extreme situation is that UEs are entering the geographic service area continuously, and at each time maximum number of UEs enters together. This maximum number of UEs can be estimated based on historical records (which types of UEs entered this area before and how many of

each type). Assume that all the UEs have the same, constant moving speed. Therefore, in this extreme situation, the number of UEs at any location on the road at any time is equal to the maximum number. The goal of the algorithm is to minimize the total number of relocations in this extreme situation, while still meeting the requirements on resources and service latency of each UE.

B. Problem Formulation

To minimize the total number of relocations, two steps need to be done:

Step 1: Find sites that can provide continuous MEC service for UEs. Set E_1 records all the unit-hosts that serve the sites that cover the entrance of the road, and set E_2 records all the unit-hosts that serve the sites that cover the exit of the road. Therefore, a UE will always get served by a unit-host which corresponds to one of the sites in E_1 as soon as it enters the geographic service area, and get served by one of the sites in E_2 when it leaves the area. To ensure service continuity, shortest paths between one node in E_1 and another node in E_2 in graph G need to be found. All the unit-hosts that belong to the same path are in the same location, and this location is also the location of this path.

Step 2: After step 1 is done for every MEC application, find the approach to integrate unit-hosts into MEC hosts and to minimize the number of relocations between these MEC hosts.

All the paths in G that are selected for MEC application k can be denoted by the set $\{P_{ll}^k(n)\}, \forall\, ll \in LL, \forall\, n \in \{1, \dots, PN_{ll}(k)\}$, while ll is the location of a path, LL is the set that contains all possible locations of a unit-host and $PN_{ll}(k)$ is the total number of selected paths in location ll. The total path length selected for MEC application k is

$$PL(k) = \sum_{ll \in LL} \sum_{n=1}^{PN_{ll}(k)} \mathbf{1}^{\mathrm{T}} \cdot P_{ll}^k(n) \cdot \mathbf{1} \tag{3.1}$$

where $\mathbf{1}$ represents an all-one vector, and here all-one vectors are used to calculate the summation of all the elements in a matrix. Since the number of UEs of MEC application k served by each path is different, then the total number of relocations of UEs of MEC application k experience is

$$RE(k) = \sum_{ll \in LL} \sum_{n=1}^{PN_{ll}(k)} UEP_{ll}^k(n) \cdot [\mathbf{1}^{\mathrm{T}} \cdot P_{ll}^k(n) \cdot \mathbf{1}] \tag{3.2}$$

where $UEP_{ll}^k(n)$ represents the number of UEs served by path n in location ll.

If a group of unit-hosts are integrated into one MEC host, then some relocations between different unit-hosts will become relocations within one MEC host, which means that these relocations are eliminated. Similarly, if several nodes in graph G are merged as one node, then some links will disappear. Consider the shortest paths $\{P_{ll}^k(n)\}$ mentioned above, the number of disappeared links which belong to the paths selected for MEC application k in graph G by merging nodes in the way that matrices $\{H_{ll}(m)\}(\forall\, ll \in LL)$ imply is

$$DL(k) = \sum_{ll \in LL} \sum_{n=1}^{PN_{ll}(k)} \sum_{m}^{HN_{ll}} \sum_{i=1}^{N} e_i^{\mathrm{T}} \cdot P_{ll}^{k}(n) \cdot H_{ll}(m) \cdot e_i \tag{3.3}$$

where HN_{ll} is the number of MEC hosts in location ll and matrix $H_{ll}(m)$ indicates the unit-hosts a MEC host contains and the links between these unit-hosts. Similarly, the total number of eliminated relocations can be written as

$$ER(k) = \sum_{ll \in LL} \sum_{n=1}^{PN_{ll}(k)} UEP_{ll}^{k}(n) \cdot \sum_{m}^{HN_{ll}} \sum_{i=1}^{N} e_i^{\mathrm{T}} \cdot P_{ll}^{k}(n) \cdot H_{ll}(m) \cdot e_i \tag{3.4}$$

Every MEC application has a priority which implies its importance. The MEC application with a higher priority is more important. To distinguish different MEC applications, their priorities also need to be considered. Therefore, the total weighted number of eliminated relocations can be written as

$$ERW(k) = prior_k \cdot ER(k) \tag{3.5}$$

where $prior_k$ is the priority of MEC application k. Similarly, the total weighted number of relocations before integrating unit-hosts into MEC hosts can be written as

$$REW(k) = prior_k \cdot RE(k) \tag{3.6}$$

The total weighted number of relocations of all MEC applications after integrating unit-hosts into MEC hosts can be formulated as

$$RW = \sum_{k=1}^{M} REW(k) - ERW(k) \tag{3.7}$$

where M is the total number of MEC applications that need to be deployed. Therefore, the optimization goal, minimizing the total number of relocations can be transformed into minimizing RW.

C. Constraints

To make sure that enough resources are allocated to UEs of every MEC application, Constraint 1 is defined as:

$$\sum_{ll \in LL} \sum_{n=1}^{PN_{ll}(k)} UEP_{ll}^{k}(n) \geq UE_k \ \ (\forall\, k \in [1, \dots, M]) \tag{3.8}$$

To make sure that every MEC host can meet the total resource requirements, the first thing to do is to make sure that for each unit-host, its total amount of required resources does not exceed its total amount of available resources. Sites in $\{P_{ll}^{k}(n)\}$ may have common coverage area, where each of them may only need to serve some of the UEs. However, in the context of this master thesis, each of these MEC hosts still needs to reserve enough resources for all the UEs that are in its serving area for resiliency purpose. According to this, Constraint 2 is written as:

$$\sum_{k=1}^{M} \sum_{n=1}^{PN_{ll}(k)} UEP_{ll}^{k}(n) \cdot coverage_i \cdot cr_k \leq cr_{unit} \tag{3.9}$$

$$\sum_{k=1}^{M}\sum_{n=1}^{PN_{ll}(k)} UEP_{ll}^{k}(n)\cdot coverage_i\cdot sr_k \le sr_{unit}$$

$$\sum_{k=1}^{M}\sum_{n=1}^{PN_{ll}(k)} UEP_{ll}^{k}(n)\cdot coverage_i\cdot pr_k \le pr_{unit}$$

$$(\forall\, ll \in LL, \forall\, i \in [1,\dots,N])$$

where $coverage_i$ is the length of the part of the road which is in the serving area of site i, cr_k, sr_k, pr_k are the amount of computing, storage, processing resources required to serve one UE of MEC application k.

To make sure that each $P_{ll}^{k}(n)$ represents a path that connects one node in E_1 to another node in E_2 in graph G, several additional constraints are set up:

Constraint 3: For every $P_{ll}^{k}(n)$, every link it indicates is a link in graph G. This is equivalent to:

$$e_i^{\mathrm{T}}\cdot\left[\left(P_{ll}^{k}(n)+EN_{ll}^{k}(n)\right)\cdot A^{*}\right]\cdot e_i = \mathbf{1}^{\mathrm{T}}\cdot\left(P_{ll}^{k}(n)+EN_{ll}^{k}(n)\right)\cdot e_i \quad (3.10)$$

$$(\forall\, ll \in LL, \forall\, k \in [1,..,M], \forall\, i = [1,\dots,N], \forall\, n)$$

where $EN_{ll}^{k}(n)$ is a $N\times N$ matrix that indicates the sites that cover either the entrance or the exit of the road and belong to path $n \in \{1,\dots,PN_{ll}(k)\}$ in location $ll \in LL_k$, and A^{*} is a $N\times N$ matrix that indicates the neighbors of each node in graph G.

Constraint 4: In each $P_{ll}^{k}(n)$, nodes in set E_1 or E_2 have one or no neighbor while other nodes have two or no neighbors each, this can be written as:

$$\mathbf{1}^{\mathrm{T}}\cdot\left(P_{ll}^{k}(n)+EN_{ll}^{k}(n)\right)\cdot e_i \in [0,2] \quad (3.11)$$

$$(\forall\, ll \in LL, \forall\, k \in [1,..,M], \forall\, i = [1,\dots,N], \forall\, n)$$

Constraint 5: In each $P_{ll}^{k}(n)$, for each node that has one neighbor, if this node is in set E_1, then its neighbor should be a successor of this node in graph G; otherwise, this neighbor should be a predecessor of this node in graph G. For each node that has two neighbors, one of its neighbors is its predecessor in the directed graph G and the other one is its successor:

$$\left(P_{ll}^{k}(n)+EN_{ll}^{k}(n)\right)\cdot A^{**} = \boldsymbol{O}\ (\forall\, ll \in LL, \forall\, k \in [1,..,M]) \quad (3.12)$$

where A^{**} is a $N\times N$ matrix that indicates the predecessors and successors of each node in graph G and $\boldsymbol{O}$ is an all-zero matrix.

Constraint 6: Each path should start from a node in E_1 and end at a node in E_2:

$$\sum_{i\neq j} EN_{ll}^{k}(n)_{ij} = 0\ (\forall\, ll \in LL, \forall\, k \in [1,..,M]) \quad (3.13)$$

$$\sum_{i=1}^{N} EN_{ll}^{k}(n)_{ii} = 2\ (\forall\, ll \in LL, \forall\, k \in [1,..,M]) \quad (3.14)$$

$$ev_1\cdot EN_{ll}^{k}(n)\cdot \mathbf{1} = 1\ (\forall\, ll \in LL, \forall\, k \in [1,..,M]) \quad (3.15)$$

$$ev_2\cdot EN_{ll}^{k}(n)\cdot \mathbf{1} = 1\ (\forall\, ll \in LL, \forall\, k \in [1,..,M]) \quad (3.16)$$

where ev_1 is a $1\times N$ vector that indicates the sites that cover the entrance of the road, and ev_2 is a $1\times N$ vector that indicates the sites that cover the exit of the road.

Finally, it is important to make sure that unit-hosts are integrated properly, and Constraint

7 is defined accordingly.

Constraint 7-1: There shall be no unit-host that is included in two MEC hosts:

$$\sum_{m=1}^{HN_l} e_i^{\mathrm{T}} \cdot H_{ll}(m) \cdot e_i \leq 1 \ (\forall\ ll \in LL, \forall\ i \in [1, \dots, N]) \tag{3.17}$$

Constraint 7-2: Every MEC host can meet the total resources requirements. It is guaranteed by Equation 3.9 that the total amount of required resources of each unit-host does not exceed its total amount of available resources. Therefore, in this step, it only needs to be ensured that the number of unit-hosts that are integrated into one MEC host is smaller than or equal to the upper limit NU. This can be represented by inequation 3.18:

$$\sum_{i=1}^{N} e_i^{\mathrm{T}} \cdot H_{ll}(m) \cdot e_i \ \leq NU_{ll} \ (\forall\ ll \in LL, \forall\ m \in [1, \dots, HN_{ll}]) \tag{3.18}$$

D. Problem Decomposition

In the remainder of this chapter, approximation algorithms to minimize RW under the seven constraints discussed in the previous section are designed, tested and compared. To start with, the optimization problem needs to be decomposed.

In the original problem both MEC hosts and MEC applications need to be located. Locations of MEC hosts need to be determined, and MEC applications need to be installed in MEC hosts, which makes it impossible to determine the locations of MEC applications first since they run on MEC hosts. However, information on MEC applications can help determine the appropriate deployment of MEC hosts; without considering the MEC applications that need to be deployed, it is difficult to determine how good a deployment of MEC hosts is. To overcome this dilemma, the concept of “unit-host” has been brought up in this project. A unit-host can be seen as a fraction of a MEC host with resources, MEC applications and MEC application instances. These fractions can be combined into several complete MEC hosts. A MEC host inherits all the resources, MEC applications and MEC application instances from the unit-hosts it contains. Unit-hosts are not implemented and running in the telecom network like MEC hosts, they are intermediate outcomes and will be eventually transformed into MEC hosts.

Having defined the concept of “unit-host”, the original problem can be further decomposed into two sub-problems, also called two phases in this thesis.

Phase 1: Locate enough but not redundant resources for each MEC application in unit-hosts in its acceptable locations, in a way that the total number of relocations between unit-hosts is minimized. Two algorithms - Greedy algorithm and Simulation based algorithm are implemented and investigated in Phase 1.

Phase 2: Combine unit-hosts into MEC hosts properly. This sub-problem can be transferred into a graph partitioning problem - minimum k-Cut problem, which can be either NP-Hard or NP-Complete. If the number k is not given, the problem is an NP-Hard problem. The sub-problem to be solved in Phase 2 does not give the total number of MEC hosts in advance, instead it is a factor that needs to be determined under certain constraints, hence, this problem is NP-Hard. To solve such a problem, a purely greedy algorithm, two heuristic

algorithms (Variable Neighborhood Search and Multi-Kernighan Lin) have been implemented and investigated in Phase 2.

3.3 Algorithms in Phase 1

In this section, two algorithms are proposed – greedy algorithm and simulation-based algorithm. Both algorithms are used to solve the location problem of MEC applications in Phase 1. The final goal of each algorithm is locating each MEC application in proper unit-hosts, which can minimize the total number of relocations between unit-hosts in the geographic service area under the extreme situation and guarantee enough resources as well as satisfied service latency for each UE.

Based on the equations in section 3.2, four principles for deploying MEC applications in unit-hosts are made:

1. Pick the shortest available path (with enough serving resources) between one node in set E_1 and one node in set E_2 in graph G. In Equation 3.2, when there are fewer 1's in matrix $P_{ll}^{k}(n)$, which means that its corresponding path in graph G is shorter, $RE(k), \exists k \in \{1,2,\dots,M\}$ (the number of relocations between unit-hosts) tends to be smaller. Therefore, MEC applications should be located in the unit-hosts which are on the shortest available paths, which is also referred to as MEC applications should be located in shortest paths in the remainder of the thesis.
2. Put more UEs on shorter paths. For each MEC application, enough resources should be provided by the MEC hosts, which brings out Constraint 1 (defined by Equation 3.8). As discussed previously, a shortest available path, or an available path with shortest length, means that a UE will experience the fewest relocations between unit-hosts if it chooses this path. Therefore, to minimize REW, as many UEs as possible should follow the shortest available path. Since the total number of estimated UEs for each MEC application is fixed, if more UEs choose the shortest available path, the total number of relocations will be reduced.
3. MEC applications with a higher priority should always be allocated resources to earlier than the ones with a lower priority. MEC applications with a higher priority are more sensitive to relocations. If a MEC application 1 is located in unit-hosts before another MEC application 2 with a higher priority is located, MEC application 1 may fully occupy the resources in the unit-hosts that are on the shortest paths in graph G, as a consequence, MEC application 2 may be located in some other longer paths. Since MEC application 2 is more sensitive to relocations, it does not make sense to locate it in longer paths, therefore, allocating resources for MEC applications with higher priority earlier than the ones with lower priority is the basic rule in Phase 1.
4. Required service latency of each UE should be satisfied. The requirement on service latency of each MEC application is transformed into a set of acceptable MEC host/unit-host locations (assumption 14). To meet the required latency, each MEC application is located only in the unit-hosts that are in its acceptable locations.

Considering the above four principles of MEC applications, greedy algorithm is a simple

but good enough approach and it will be introduced precisely in the following sections.

A. Greedy Algorithm

As described above, each MEC application has a set of acceptable locations, and LL_k is used to denote the set of acceptable locations of MEC application k. Locations in LL_k are sorted from the closest towards the network edge to the farthest from the network edge. Three steps are considered in order to find optimal unit-hosts for MEC application k:

Step 1: Select the shortest path in the first location in LL_k between one node in E_1 and one node in E_2 and then determine the amount of resources each unit-host in this path can provide.

Step 2: If each unit-host on the selected path can provide enough resources to serve all the UEs of MEC application k within its serving area, then reserve the resources required and end the procedure.

Step 3: If the current available resources in some unit-hosts on the selected path are not enough, determine the maximum number of UEs this path can serve, and reserve required resources for these UEs. Then determine the shortest path between one node in E_1 and one node in E_2 in the next location (the next element in LL_k), and repeat Step 2 for MEC application k.

Based on the above three steps, two algorithms are proposed. Table 3.1 and Table 3.2 show them separately.

Table 3.1: Algorithm 1

Algorithm 1. Allocate resources for MEC application k on MEC hosts in one location $ll \in LL_k$	
Input:	
G:	The graph that represents all the unit-hosts in the geographic service area. If the two corresponding sites of two nodes have an overlapping coverage area, these two nodes in graph G are connected by a directed link that starts from the node which corresponding site is closer to the entrance of the road and that ends at the node which corresponding site is closer to the exit of the road. Hence, graph G is a directed graph.
LW_{ll}:	A set of link weights of all links which both end nodes are in location ll.
E_1:	A set of unit-hosts which corresponding sites cover the entrance of the road in the geographic service area.
E_2:	A set of unit-hosts which corresponding sites cover the exit of the road in the geographic service area.
R_{ll}:	A set of currently available resources in all unit-hosts in location $ll \in LL$.
$prior_k$:	Priority of MEC application k.
$coverage = \{coverage_i\}$ $(\forall\, i \in N)$:	
	$coverage_i$ is the coverage of site i $(i = 1, \dots, N)$.
$resources_k$:	Required amount of resources per UE of MEC application k.
UE_k:	Estimated maximum number of UEs of MEC application k that enters the

geographic service area at the same time.

$Paths_{ll}(k)$: A set that saves all paths in location $ll \in LL_k$ that are selected to reserve resources for MEC application k as well as the estimated number of UEs each path serves.

Output:

Updated UE_k

Updated $Paths_{ll}(k)$

Updated R_{ll}

Updated LW_{ll}

While $True$ **do**

  $sp = \boldsymbol{shortestpath}(G, E_1, E_2)$;

  //Initialize set ue_{max}, which saves the maximum number of UEs each unit-host in path sp can serve per unit length

  $ue_{max} = \{\}$;

  for all $node \in sp$ **do**

    $ue_{max} = ue_{max} \cup \{R_{ll}(node)/(resources_k * coverage_{node})\}$;

  end for

  $ue_{min} = \boldsymbol{Min}(ue_{max} \cup \{UE_k\})$;

  $Paths_{ll}(k) = \boldsymbol{Update1}(Paths_{ll}(k), ue_{min}, sp)$;

  for all $index \in \{1, 2, \dots, \boldsymbol{length}(sp)\}$ **do**

    $node = sp(index)$;

    //Update the current available resources of unit-hosts (R_{ll})

    $R_{ll}(node) = R_{ll}(node) - ue_{min} * resources_k * coverage_{node}$;

    if $index \in \{1, 2, \dots, \boldsymbol{length}(sp) - 1\}$ **do**

      $node_{next} = sp(index + 1)$;

      $LW_{ll} = \boldsymbol{Update2}(LW_{ll}, ue_{min}, node, node_{next}, prior_k)$;

    end if

  end for

  $UE_k = UE_k - ue_{min}$;

  if $UE_k == 0$ **do**

    $\boldsymbol{Break}$;

  end if

end While

When it starts running, Algorithm 1 will first find one shortest path in graph G that connects one node in E_1 to one node in E_2, which is achieved by function $\boldsymbol{shortestpath}$. After the shortest path has been found, every unit-host in path sp will be checked. For each unit-host, calculate the maximum number of UEs per unit length it can currently serve and save the value in set ue_{max}. The smallest number ue_{min} in set $ue_{max} \cup \{UE_k\}$ is the number of UEs per unit length that path sp will reserve resources for. Function $\boldsymbol{Min}$ is used to find the smallest value in a set.

After the value of ue_{min} has been determined, four updates will take place:

1. Update the value of UE_k: The number of UEs need to be served per unit length will be reduced by ue_{min}.

2. Update $Paths_{ll}(k)$: This is done by function $\boldsymbol{Update1}$. To be more precise, if path sp has already been chosen by the same MEC application k, it should already exist in $Paths_{ll}(k)$, then $\boldsymbol{Update1}$ will update its recorded number of serving UEs per unit length by adding ue_{min} to the original value; if path sp does not exist in $Paths_{ll}(k)$, then add a new record.
3. Update R_{ll}: Every unit-host on path sp will reserve new resources for MEC application k, and their amount of available resources will decrease in the meantime. For each unit-host, its corresponding record in R_{ll} needs to be updated. Function $\boldsymbol{length}$ returns the number of elements in a set.
4. Update LW_{ll}: This is done by function $\boldsymbol{Update2}$. Links in path sp represent relocations. The link weight of a link is the weighted (by the priority of the MEC application a UE uses) number of UEs per unit length on this link. Since new UEs are added to each link, LW_{ll} needs to be updated. For each link, update link weight by adding $prior * ue_{min}$ to its current value.

Table 3.2: Algorithm 2

Algorithm 2: Allocate resources for MEC application k in all its possible locations
Input:
LL_k: A set of possible locations for MEC application k.
$R = \{R_{ll}\}, \forall\ ll \in LL$: R_{ll} is the set of currently available resources in all unit-hosts in location $ll \in LL$.
G: The directed graph that represents all the sites.
E_1: A set of unit-hosts which corresponding sites cover the entrance of the road in the geographic service area.
E_2: A set of unit-hosts which corresponding sites cover the exit of the road in the geographic service area.
$LW = \{LW_{ll}\}, \forall\ ll \in LL$: LW_{ll} is the set of link weights of all links which both end nodes are in location ll.
$Paths(k) = \{Paths_{ll}(k)\}, \forall\ ll \in LL_k$: $Paths_{ll}(k)$ is the set that saves all paths in location $ll \in LL_k$ that are selected to reserve resources for MEC application k as well as the estimated number of UEs each path serves.
$prior_k$: Priority of MEC application k.
$coverage = \{coverage_i\}$ $(\forall\ i \in N)$: $coverage_i$ is the coverage of site i $(i = 1, \dots, N)$.
$resources_k$: Required amount of resources per UE of MEC application k. UE_k: Estimated number of UEs of MEC application k that enters the geographic service area at the same time.
Output:
Updated $Paths(k)$
Updated R
Updated LW

While **True do**
  for all $ll \in LL_k$ **do**
    $UE_k, LW_{ll}, Paths_{ll}(k), R_{ll} =$
    $\boldsymbol{A1}(UE_k, G, LW_{ll}, E_1, E_2, Paths_{ll}(k), R_{ll}, prior_k, coverage, resources_k)$;
    if $UE_k == 0$ **do** //Enough resources have been allocated
      $\boldsymbol{Break}$;
    end if
  end for
end While

Algorithm 2 is designed to allocate resources for MEC application k in all its acceptable locations if necessary. Function $\boldsymbol{A1}$ represents Algorithm 1 in Table 3.1.

B. Simulation-Based Algorithm

This algorithm is an improved greedy algorithm, and the improvement comes from the fact that there are three different types of resources and the required amount of different types of resources may be different. If well organized, one unit-host may be able to serve more UEs without increasing the total amount of resources it holds. Figure 3.2 demonstrates the difference between well-organized deployment and not well-organized deployment clearly.

Define ratio of a unit-host as the ratio of the available amount of three different types of resources (computing, storage and processing) in the unit-host. The ratio before any resources has been allocated/reserved is called the original ratio, and according to assumption 6, original ratio = $1:1:1$. For a group of MEC applications that have the same priority $APP = \{app_1, app_2, \dots, app_k\}$, and each with a required amount of resources which is saved in vector $RR = \{r_{11}, r_{12}, r_{13}, \dots, r_{k1}, r_{k2}, r_{k3}\}$, where r_{i1}, r_{i2}, r_{i3} represent the required amount of computing, storage, processing resources of MEC application i separately. If there exists a vector $V = \{v_1, v_2, \dots, v_k\}$, with $0 \le v_i \le UE_i, v_i \in N, \forall i \in \{1,2,\dots,k\}$, and this vector V has at least two non-zero elements, which satisfies the following inequations:

$$\begin{aligned} \max_{j\in\{1,2,3\}} \frac{\sum_{i=i}^{k} r_{ij} v_i}{\sum_{i=1}^{k} v_i} &\le \min_{\substack{i\in\{1,2,\dots,k\} \\ v_i>0}} \max_{j\in\{1,2,3\}} r_{ij} \\ r_{11}v_1 + r_{21}v_2 + \cdots + r_{k1}v_k &< cr_{unit} \\ r_{12}v_1 + r_{22}v_2 + \cdots + r_{k2}v_k &< sr_{unit} \\ r_{13}v_1 + r_{23}v_2 + \cdots + r_{k3}v_k &< pr_{unit} \end{aligned} \tag{3.19}$$

then MEC applications $\{app_i | i \in \{1,2,\dots,k\}, v_i > 0\}$ are called a group of complementary MEC applications.

Since it is assumed that the amount of computing, storage and processing resources in a unit-host is equal (cr_{unit} = sr_{unit} = pr_{unit}), then the type of resources which running a MEC application instance to serve a UE needs the most determines the maximum number of UEs one unit-host can serve. This type of resources is similar to the short slab of a bucket. Complementary MEC applications have the same priority and can be deployed together to even the usage of different types of resources and to make the short slab not short anymore.

However, even by deploying MEC applications together, a short slab may still exist, and it can be written as $\max_{j\in\{1,2,3\}} \frac{\sum_{i=i}^{k} r_{ij} v_i}{\sum_{i=1}^{k} v_i}$. Therefore, for a group of MEC applications, only when the new short slab is longer than the old short slab of each MEC application, which can be written as $\max_{j\in\{1,2,3\}} r_{ij}$ for MEC application i, can these MEC applications be a group of complementary MEC applications. For instance, in Figure 3.2, MEC application 1 has a complementary MEC application 2. If using the greedy algorithm designed in the previous section, one unit-host can serve 3 or 4 UEs. For the two MEC applications in Figure 3.2, a vector $V = \{1, 1\}$ can be found to make Inequation 3.19 hold. This means that, one UE of MEC application 1 and one UE of MEC application 2 are put into the same unit-host each time until the available resources in the unit-host are not sufficient to serve a UE.

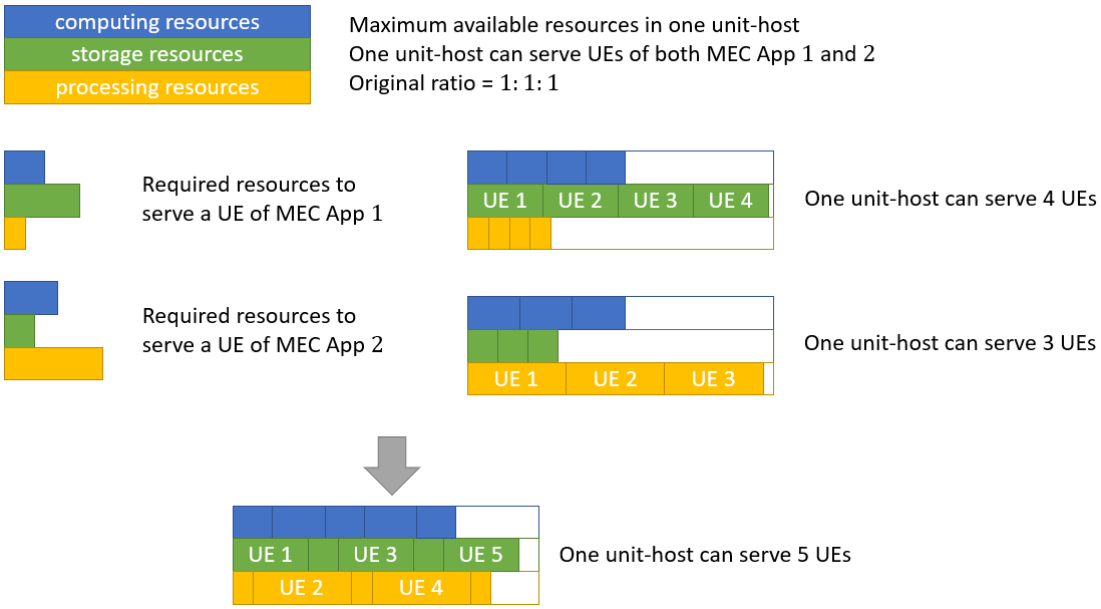


Figure 3.2: One unit-host can serve more UEs if well organized

To enhance resource efficiency, there is a simpler approach than finding the vector V but can achieve the same improvement, and that is called the simulation-based algorithm. Table 3.3 shows the pseudocode of this simulation-based algorithm.

Table 3.3: Algorithm 3

Algorithm 3. Simulation-based Algorithm
Input:
M: Total number of MEC applications needs to be located.
$priors$: A set of priorities, ranked in a descending order.
$app\_priors = \{p_1, p_2, \dots, p_M\}$: p_k is the priority of MEC application k ($k \in \{1,2, \dots, M\}$).
$app\_ll = \{LL_1, LL_2, \dots, LL_M\}$: LL_k is the set of possible locations for MEC application k.
$R = \{R_{ll}\}, \forall\, ll \in LL$: R_{ll} is the set of currently available resources in all unit-hosts in location $ll \in$

LL.

G: The directed graph that represents all the sites.

E_1: A set of unit-hosts which corresponding sites cover the entrance of the road in the geographic service area.

E_2: A set of unit-hosts which corresponding sites cover the exit of the road in the geographic service area.

$LW = \{LW_{ll}\}, \forall\ ll \in LL$:

LW_{ll} is the set of link weights of all links which both end nodes are in location ll.

$Paths = \{Paths(k)\}, \forall\ k \in \{1,2, \dots, M\}$:

$Paths(k)$ records all the paths selected for MEC application k and the number of UEs each path serves.

$coverage$: The set of coverage of all the site.

$resources = \{resources_1, resources_2, \dots, resources_M\}$:

$resources_k$ is the required amount of resources per UE of MEC application k.

$UE = \{UE_1, UE_2, \dots, UE_M\}$:

UE_k is the estimated number of UEs of MEC application k that enters the geographic service area at the same time.

Output:

Updated $Paths$

Updated R

Updated LW

for all $p \in priors$ **do**

$R_{temp} = \{\}$;

$Paths_{temp} = \{\}$;

$LW_{temp} = \{\}$;

$Diff = inf$;

$app_{temp} = None$;

While $\exists\ app \in M, app\_priors(app) == p$ and $UE(app) \neq 0$ **do**

for all $app \in M$ **do**

if $app\_priors(app) != p$ or $UE(app) == 0$ **do**

$\boldsymbol{Continue}$;

end if

$Paths_t, R_t, LW_t =$

$\boldsymbol{A2}(app\_ll(app), R, G, E_1, E_2, LW, Paths(app), p, coverage, resources(app), 1)$;

$diff = \boldsymbol{Difference\_between\_ratios}(R_t)$;

if $diff < Diff$ **do**

$R_{temp} = R_t$;

$Paths_{temp} = Paths_t$;

$LW_{temp} = LW_t$;

$Diff = diff$;

$app_{temp} = app$;

end if

```
        end for
        Paths = Paths_temp;
        R = R_temp;
        LW = LW_temp;
        UE(app_temp) = UE(app_temp) − 1;
    end While
end for
```

Define a simulation of MEC application app as a process in which one UE using MEC application app is assumed to enter the geographic service area, a suitable path will be selected for this UE, and resources will be reserved in the unit-hosts on the selected path. Any operation in a simulation of MEC application app will not affect the real network conditions (e.g. the amount of available resources in a unit-host, the MEC applications installed in a unit-host).

For every MEC application with the same priority, the algorithm will first do a simulation of this MEC application, and calculate for each unit-host on the chosen path, if it reserves resources for this UE, the difference between its ratio after resource reservation and the original ratio, and then add these differences up. Function $\boldsymbol{Difference\_between\_ratios}$ is responsible for the calculations, and the final result is saved in variable $diff$. After every MEC application has one simulation, pick the MEC application with the smallest $diff$, and then allocate resources for one UE of this MEC application in the unit-hosts on the path selected in the simulation. This time the variables that reflect the actual network conditions (e.g. $R, LW, Paths$) need to be updated.

3.4 Algorithms in Phase 2

The goal of Phase 2 is to optimally integrate unit-hosts into MEC hosts in the three MEC host locations mentioned in assumption 3. Consider the similarity of the three locations, once the optimal locating mechanism of MEC hosts in one location is solved, then the integrations of unit-hosts in the other two locations can use the same locating mechanism. Therefore, the sub-problem needs to be solved in Phase 2 is to optimally location MEC hosts in one location, and here locating a MEC host is to determine which unit-hosts it contains.

The above sub-problem can be transformed into a classical mathematical problem – minimum k-cut problem: Given a graph $G(V, E)$, with node set V, link set E, and different link weights on the links in link set E. The goal of the problem is to partition V into several disjoint subsets of limited sizes, in a way that minimizes the sum of the weights of the subset of links that cross from one subset to another subset, which is denoted by T. In the context of this specific sub-problem, graph $G(V, E)$ is the graph G generated in **Phase 1**, node set V is the collection of unit-hosts, a link weight is the weighted number of UEs per unit length on the link. Each subset of nodes is a MEC host, which is considered as a collection of limited number of unit-hosts. The limitation on number of unit-hosts NU_{ll} depends on the location ll of one MEC host, and NU_{ll} is larger if the location ll of the MEC host is closer to the core network.

For minimum k-cut problem, if the total number of subsets k is given, then this

problem has been proved to be a NP-Complete problem [41]. However, the above-described problem does not treat k as an input but as an uncertain value and needs to be determined, hence, this problem is NP-Hard. Three approximation algorithms are designed to solve the sub-problem in Phase 2, and they will be introduced separately in the following sections.

A. Purely Greedy Algorithm

This greedy algorithm basically consists of 3 steps and it solves the minimum k-cut problem in the location ll:

Step 1: First rank all the links in graph G by the corresponding link weights from the highest to the lowest.

Step 2: According to the sorted sequence in step 1, take out links one by one. If $NU_{ll} = 1$, then these unit-hosts can be directly transformed into MEC hosts without integration. Otherwise, for each link, try to merge its two end nodes (unit-hosts) into one MEC host.

Step 3: If both unit-hosts have been merged with other unit-hosts, then directly skip to the next link. If one of the unit-hosts has been merged into a MEC host and this MEC host can still accept an extra unit-host, then merge the other unit-host into this MEC host; if the MEC host cannot accept another unit-host, then skip to the next link. If both unit-hosts have not been merged yet, then merge the two unit-hosts into a new MEC host.

Algorithm 4 shown in Table 3.4 gives more precise introduction on this greedy algorithm.

Table 3.4: Algorithm 4

Algorithm 4: Integrate unit-hosts as MEC hosts in all locations and minimize the number of relocations
Input:
LL: A set of all possible locations. Three possible locations are considered in this master thesis: collated with gNB-DU, collated with gNB-CU and located close to the core network
$LW = \{LW_{ll}\}, \forall\ ll \in LL$: LW_{ll} is the set of link weights of all links which both end nodes are in location ll.
H_{ll}: $H_{ll} = \{h_1, h_2, \dots, h_m\}$, where h_i is a set of all unit-hosts that belong to an already existed MEC host i in location $ll \in LL$, m is the current number of MEC hosts in location ll and it keeps changing.
$H = \{H_{ll}\}, \forall\ ll \in LL$
$NU = \{NU_{ll}\}, \forall\ ll \in LL$: NU_{ll} is the maximum number of unit-hosts one MEC host in location ll can contain.
Output:
Updated H
While **True do**

```
    for all ll ∈ LL do
        for e ∈ sort(LW_ll) do
            node_in = e(1);
            node_out = e(2);
            if node_in ∉ H_ll and node_out ∉ H_ll do
                if NU_ll ≥ 2 do
                    H_ll = H_ll ∪ {{node_in, node_out}};
                else do
                    H_ll = H_ll ∪ {{node_in}};
                    H_ll = H_ll ∪ {{node_out}};
                end if
            end if
            if node_in ∉ H_ll and node_out ∈ H_ll do
                host = find_host(H_ll, node_out);
                if length(host) ≤ NU_ll do
                    host = host ∪ {node_in};
                else do
                    H_ll = H_ll ∪ {{node_in}};
                end if
            end if
            if node_out ∉ H_ll and node_in ∈ H_ll do
                host = find_host(H_ll, node_in);
                if length(host) ≤ NU_ll do
                    host = host ∪ {node_out};
                else do
                    H_ll = H_ll ∪ {{node_out}};
                end if
            end if
        end for
    end for
    Break;
end While
```

In Table 3.4, function ***sort*** is responsible for sorting all links in graph G by their link weights in descending order. If a unit-host has already been merged into a MEC host, function ***find_host*** is used to find which MEC host it belong to and the other unit-hosts this MEC host contains.

B. Heuristic Algorithm – Variable Neighbor Search (VNS)

Since a greedy algorithm may not be able to give satisfactory results, to find better solutions, a heuristic algorithm called Variable Neighbor Search (VNS) is used in Phase 2.

The concept of a neighborhood of a point represents a set of points containing the original point where one can move some amount in any direction away from that point without

leaving the set. In neighbor search algorithms, an operation can be taken to transfer a point into one of its neighbors, and by repeatedly doing so, one neighborhood of this point can be generated. Obviously, there are usually multiple choices of possible operations, which results in multiple neighborhoods for one point.

In Phase 2, a point is a solution, or a possible combination of unit-hosts, whose neighbor is another similar solution derived from itself by taking an operation. Neighbors generated by the same operation make a neighborhood.

Variable Neighbor Search (VNS) is a heuristic algorithm which is used to approximate a solution for NP-Hard optimization problems. VNS algorithm is based on the local search algorithm, which outcome tends to fall into a local optimum and never gets out. VNS is an improved local search algorithm because it has mechanism that can force it to step out of the local optimum.

VNS consists of two main steps: Variable Neighborhood Descent and Shaking Procedure.

Variable Neighborhood Descent (VND)

The pseudocode of VND is shown in Table 3.5.

Table 3.5: Variable Neighbor Descent

Procedure VND
Input:
x: The original solution.
ne: The number of neighborhoods provided.
$NE = \{NE_i\}, i = \{1,2, \dots, ne\}$: NE_i is the i-th neighborhood.
Output:
Updated x
$i = 1;$
While $True$ **do**
$x' = \boldsymbol{local\_search}(NE(i), x);$
if $x' \neq x$ **do**
$i = 1;$
$x = x';$
else
$i = i + 1;$
end if
if $i > ne$ **do**
$\boldsymbol{Break};$
end if
end While

First of all, there should be an original solution x as an input to VND. This solution can be a random solution, or a sub-optimal solution derived from simpler algorithms, for example, greedy algorithm. Besides, ne neighborhoods should be pre-determined. The algorithm has four steps listed below:

1. Select the first neighborhood N_1 and continue with step 2.

2. Do local search in the selected neighborhood. Local search is the procedure to search all the neighbors of solution x in the neighborhood and find the optimal one among them. Function $\boldsymbol{local\_search}$ is used to do the local search procedure, and the local optimal solution is saved in variable x'. If $x' \neq x$, which means that a solution better than the current solution x has been found, assign this optimal solution x' to variable x and move back to step 1, otherwise continue with step 3.
3. Select the next neighborhood N_{i+1} and return to step 2 if $i < ne$.
4. End when no better solution has been found in all neighborhoods ($i = ne + 1$).

Figure 3.3 depicts the VND procedure more vividly. Basically speaking, when an improved solution/neighbor is discovered, the algorithm will restart from the first neighborhood N_1, otherwise the algorithm will keep searching for better solutions in the following neighborhoods until no better solution is found in any neighborhood.

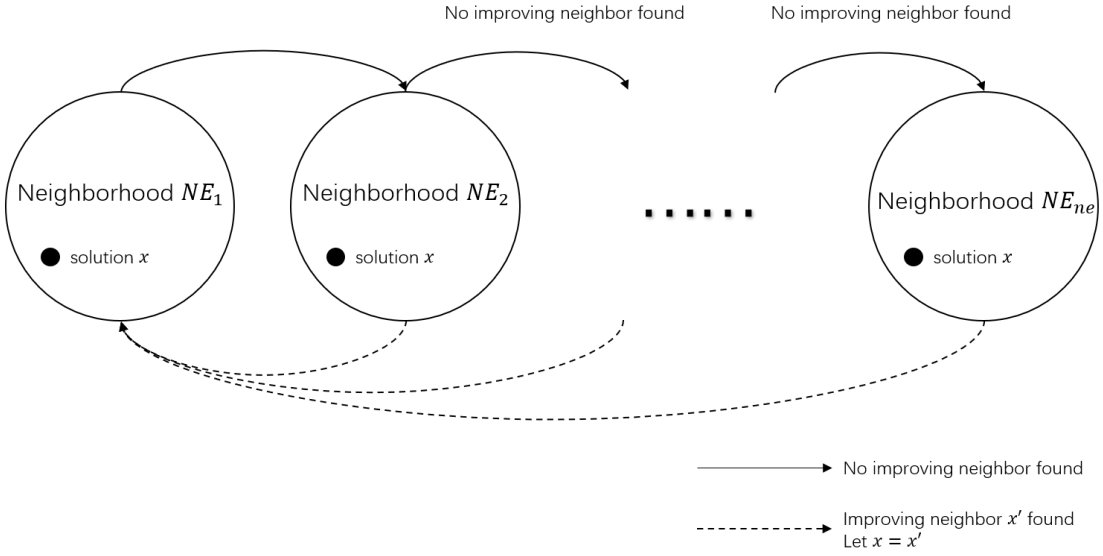


Figure 3.3: VND procedures

Shaking procedure

A shaking procedure is used to further extend the searching area by generating more neighborhoods. When the VND algorithm gets an optimal solution, the shaking procedure will force it to step out of the current neighborhoods and start to search for better solutions in new neighborhoods. A typical approach to do shaking is to generate a new neighbor of the current optimal solution by an operation and use the new neighbor as the input for next VDN procedure.

All these two steps have the same core idea, that is to change the current solution into its neighbor solution in order to expand the searching area and get closer to the global optimum. This simple but powerful mechanism makes it possible for VNS to avoid falling into local minimum.

The complete procedure of VNS is shown in Table 3.6. Function $\boldsymbol{VND}$ is described in Table 3.5 and function $\boldsymbol{shaking}$ is used to do the shaking procedure.

Table 3.6: VNS Algorithm

Algorithm VNS

Input:
x: The original solution.
ne: The number of neighborhoods provided.
$NE = \{NE_i\}, i = \{1,2, \dots, ne\}$:
NE_i is the i-th neighborhood.
Output:
Updated x

While $True$ **do**
  $x' = \boldsymbol{VND}(x, ne, NE)$;
  $x'' = \boldsymbol{shaking}(x')$;
  $x = x''$;
  if ending criterion is met **do**
    ***Break*;**
  end if
end While

C. Classical Algorithm – Multi-Kernighan Lin Algorithm

Multi-Kernighan Lin algorithm is a classical algorithm to solve minimum k-cut problem. Multi-Kernighan Lin algorithm is based on Kernighan Lin algorithm.

Kernighan Lin

Kernighan Lin (KL) algorithm is a heuristic algorithm that partitions nodes of a graph into two subsets A and B with equal or nearly equal size and minimizes the sum of link weights of the links that connect the two subsets A and B. The sum of links weights of links between different subsets is denoted by T.

To describe the algorithm more clearly and precisely, two concepts – internal cost and external cost – will be introduced. Internal cost of a node is the sum of link weights between this node and other nodes in the same subset, while external cost of a node is the sum of link weights between this node and other nodes in the other subsets. For each $a \in A \; or \; B$, let I_a denote the internal cost of a, E_a denote the external cost of a and $D_a = E_a - I_a$ denote the difference between the external cost and internal cost of a. If two nodes, a and b are interchanged, then the new sum T_{new} can be written as $T_{new} = T_{old} - D_a - D_b + 2c_{a,b}$ where $c_{a,b}$ is the sum of weights of the links between nodes a and b. The Kernighan Lin algorithm will first divide all the nodes into two subsets A and B randomly and find an optimal set of interchange operations between nodes in subsets A and B which minimizes T, then the optimal operations will be executed and give the optimal partitions of the input graph.

In this master thesis, a built-in function called “kernighan_lin” in Python “networkx” package is used, and this built-in function is based on Kernighan Lin algorithm introduced above.

The basic steps of multi-Kernighan Lin (multi-KL) algorithm are as follows:

1. Partition the node set of the input graph into two disjoint subsets using Kernighan Lin algorithm; the two subsets shall have the same or almost the same number of nodes.
2. Check each newly generated subset to see whether its size violates the limitation or not. If not, proceed with the next step; otherwise, further partition each of the subsets with sizes exceed limitation into two subsets and repeat this step.
3. Check all the subsets, find and mark all the subsets with sizes smaller than the size limitation. Then choose one of the marked subsets with the largest size and find a node, which can minimize T after being moved to the chosen subset, in another marked subset. Repeat this step until there is at most 1 subset with a size smaller than the limitation.

By doing step 1 and step 2, local minimums have been achieved each time, however, a combination of local minimums cannot guarantee a global minimum, and sometimes, it is not even close to the global minimum. To further improve the solution derived from multi-Kernighan Lin algorithm, a greedy algorithm is added, and its main idea is described as follows:

1. Randomly pick two nodes from two different subsets, check whether the T value is decreased after exchanging the positions of the two nodes. If yes, exchange these two nodes.
2. Repeat step 1 until some criteria have been met. For example, no improvement on T in a certain number of continuous repetitions of step 1.

Table 3.7 shows the basic steps of multi-Kernighan Lin algorithm.

Table 3.7: Algorithm 5

Algorithm 5. Multi - Kernighan Lin	
Input:	
G:	The directed graph that represents all the sites.
$size_{max}$:	The maximum number of unit-hosts one MEC host can contain.
Output:	
tot:	Total number of subsets.
$S = \{s_1, s_2, \dots, s_{tot}\}$:	Subsets of nodes.
$repeat_{max}$:	End loop threshold in the greedy algorithm.

$S_{large} = \{\boldsymbol{nodes}(G)\}$;
$S_{small} = \{\}$;
$S = \{\}$;
// Part 1
While $True$ **do**
  for all $s \in S$ **do**
    $s_a, s_b = \boldsymbol{KL}(s)$;
    if $\boldsymbol{size}(s_a) > size_{max}$ **do**
      $S_{large}.\boldsymbol{append}(s_a)$;
    else if $\boldsymbol{size}(s_a) == size_{max}$ **do**
      $S.\boldsymbol{append}(s_a)$;

```
            else
                S_small.append(s_a);
            end if
            if size(s_b) > size_max do
                S_large.append(s_b);
            else if size(s_b) == size_max do
                S.append(s_b);
            else
                S_small.append(s_b)
            end if
            S.remove(s);
            if S == {} do
                Break;
            end if
        end for
    end While
    // Part 2
    While True do
        s_m = find_largest(S_small);
        s_max = None;
        node_max = None;
        d_max = 0;
        for all s ∈ S_small/{s_m} do
            for all node ∈ s do
                d = E_node,s_m − I_node;
                if d > d_max do
                    s_max = s;
                    node_max = node;
                    d_max = d;
                end if
            end for
        if d_max > 0 do
            s_m.append(node);
            s_max.remove(node);
        end if
        if size(s_m) == size_max or d_max == 0 do
            S.append(s_m);
            S_small.remove(s_m);
        end if
        if S_small == {} do
            Break;
        end if
    end While
    // Part 3
```

$repeat = 0$;
While $repeat < repeat_{max}$ **do**
  $s_1 = \boldsymbol{random2}(S)$;
  $s_2 = \boldsymbol{random2}(S \backslash \{s_1\})$;
  $a = \boldsymbol{random2}(s_1)$;
  $b = \boldsymbol{random2}(s_2)$;
  $d = D_a + D_b - 2c_{a,b}$;
  if $d > 0$ **do**
    $s_1.\boldsymbol{append}(b)$;
    $s_2.\boldsymbol{append}(a)$;
    $s_1.\boldsymbol{remove}(a)$;
    $s_2.\boldsymbol{remove}(b)$;
    $repeat = 0$;
  else
    $repeat = repeat + 1$;
end While

This multi-Kernighan Lin algorithm consists of three sequential sections. In pseudocode, each part is a "while loop".

Part 1 partitions the nodes of the input graph into several subsets whose sizes are no larger than the size limitation $size_{max}$. This is done by repeatedly partitioning the subsets with more than $size_{max}$ nodes into two subsets using Kernighan Lin algorithm until no subsets violates this limitation. In this part, several functions are involved: function $\boldsymbol{nodes}(G)$ returns a set of all the nodes in graph G; function $\boldsymbol{KL}$ is the kernighan_lin function in networkx package in Python; function $\boldsymbol{size}(A)$ returns the number of elements in set A; function $A.\boldsymbol{remove}(a)$ removes element a from set A and function $A.\boldsymbol{append}(a)$ can add element a to set A.

To further optimize the original solution provided by part 1, parts 2 and 3 are added.

Part 2 attempts to combine the subsets with less than $size_{max}$ number of nodes, and these subsets are saved in set S_{small}. Each time, one of the subsets $s_m \in S_{small}$ with the largest number of nodes will be chosen by function $\boldsymbol{find\_largest}$ and a node $node$ from another subset in S_{small} which maximizes $d = E_{node,s_m} - I_{node}$, where E_{node,s_m} is the sum of weights of the links between node $node$ and nodes in subset s_m, will be moved to the chosen subset s_m from its current subset. If the size of s_m equals $size_{max}$ or no such $node$ has been found, subset s_m will be removed from set S_{small}. Part 2 ends when S_{small} is empty.

Part 3 is a greedy algorithm that helps to further improve the solution. Two nodes a, b belonging to two different subsets s_1, s_2 separately are chosen randomly by function $\boldsymbol{random2}$. If the value of T can be reduced, then interchange the two nodes a, b. Repeat this procedure until no improving interchanging has been found in the most recent $repeat_{max}$ repetitions.

D. One Remark

It is not mandatory for a UE to strictly follow the paths chosen by the algorithms designed in the previous sections, which can be seen in Chapter 4. However, when the network is busy, it is the best way to follow the chosen paths to decrease the total number of relocations experienced by all the UEs in the geographic service area. This can be further explained by Figure 3.4.

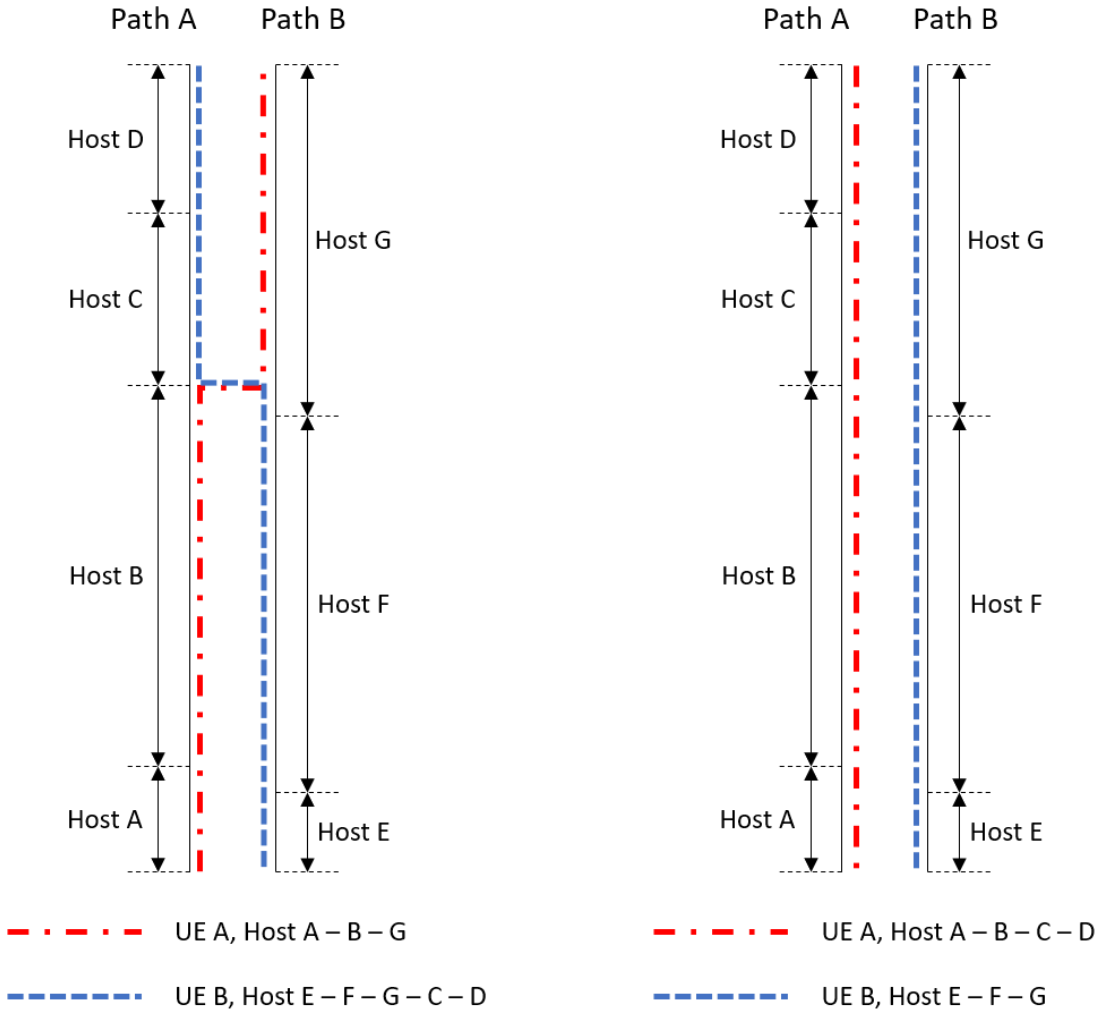


Figure 3.4: Switching between two different paths (same MEC application).

UE A and UE B in Figure 3.4 are using the same MEC application. If UE A and UE B stick to their own original paths, depicted in the right part of Figure 3.4, the total number of relocations is $3 + 2 = 5$. However, if UE A leaves Host B and switches to Host G instead of Host C, then UE B, which is currently served by Host G, needs to switch to Host C because the network is busy and Host G is fully loaded. This is shown in the left part of Figure 3.4, and the total number of relocations is $2 + 4 = 6 > 5$. To avoid resource shortage under the extreme situation, if one UE switches to another path, then other UEs may be forced to change their current paths as well, which may result in increasing the number of relocations, therefore, when the network is busy, each UE needs to stick to its original path

and avoid switching paths.

However, if the network is not busy and UE B can still be served by Host G, then the total number of relocations is $2 + 2 = 4 < 5$. The scenario where the network is not busy is further discussed in chapters 4 and 5.

3.5 Tests

Using the algorithms introduced in section 3.3 and 3.4, six locating mechanisms to locate MEC hosts and MEC applications properly have been generated: greedy + greedy, greedy+ VNS, greedy + multi-KL, simulation-based + greedy, simulation-based + VNS, simulation-based + multi-KL. In this section, these six locating mechanisms are tested and analyzed.

A. Testing environment

Simulated environments

- Number of sites: 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100. The first 50 sites have the same coverage radius (e.g. r_F in Figure 3.1) as well as the same distance towards the road (e.g. $|x_F|$ in Figure 3.1), and these sites are uniformly located along the road. Other sites with different locations and coverage radius are gradually added to the geographic service area, 5 sites at a time.
- Road length: 126 unit lengths.
- Three types of locations: close to or co-located with gNB-DU, close to or co-located with gNB-CU, collocated with a UPF which is inside the core network.
- MEC hosts information is shown in Table 3.8. A location No. is used to represent a location in simulations in this chapter and Chapter 5 for simplicity reason.

Table 3.8: MEC hosts information

Location of MEC hosts	Close to gNB-DU	Close to gNB-CU	Close to 5GC
Location No.	1	2	3
Maximum number of sites one MEC host can process data from	1	3	5
Maximum amount of available resources in one MEC host (computing/storage/processing)	100/100/100	300/300/300	500/500/500

Test the performance of all six locating mechanisms in the simulated geographic service area described above. Their performance includes the following aspects:

- The total number of relocations (weighted) = number of relocations experienced by each UE × priority of the MEC application this UE uses.
- The total number of MEC hosts/unit-hosts involved.
- The total amount of resources reserved.

MEC applications

To fully investigate and compare the performance of the six locating mechanisms, three

groups of MEC applications with different settings are used to test the mechanisms. Tables 3.9 - 3.11 show the three different groups separately.

Table 3.9: MEC applications group 1

MEC APP	Required Resources per UE (computing/storage/processing)	Priority	Acceptable Locations	Maximum number of UEs enter the geographic service area together
1	2/2/6	2	1, 2	3
2	3/3/3	1	1, 2, 3	2
3	2/6/2	2	1, 2, 3	5
4	10/4/3	3	1, 2	2
5	2/8/5	3	1	3

Table 3.10: MEC applications group 2

MEC APP	Required Resources per UE (computing/storage/processing)	Priority	Acceptable Locations	Maximum number of UEs enter the geographic service area together
1	2/2/3	2	1, 2	3
2	3/3/3	1	1, 2, 3	2
3	2/2/3	2	1, 2, 3	5
4	10/4/3	3	1, 2	2
5	2/8/5	3	1	3

Table 3.11: MEC applications group 3

MEC APP	Required Resources per UE (computing/storage/processing)	Priority	Acceptable Locations	Maximum number of UEs enter the geographic service area together
1	2/2/3	2	1, 2	3
2	3/3/3	1	1, 2, 3	2
3	2/2/3	3	1, 2, 3	5
4	10/4/3	4	1, 2	2
5	2/8/5	5	1	3

B. Test Results and analysis

Test 1: Test results of MEC application group 1 are shown in Figures 3.5 - 3.8. In the legends

in these figures, “sim” represents simulation-based algorithm and “kl” represents Kernighan Lin algorithm.

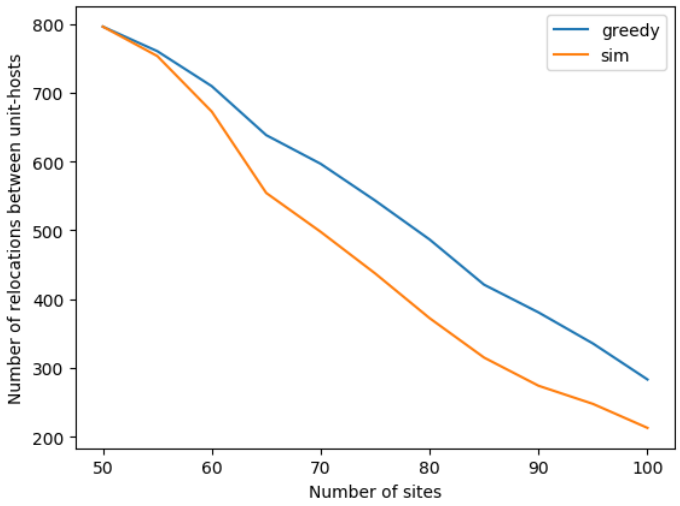


Figure 3.5: Number of relocations (weighted) between unit-hosts vs Number of sites in the geographic service area – test 1

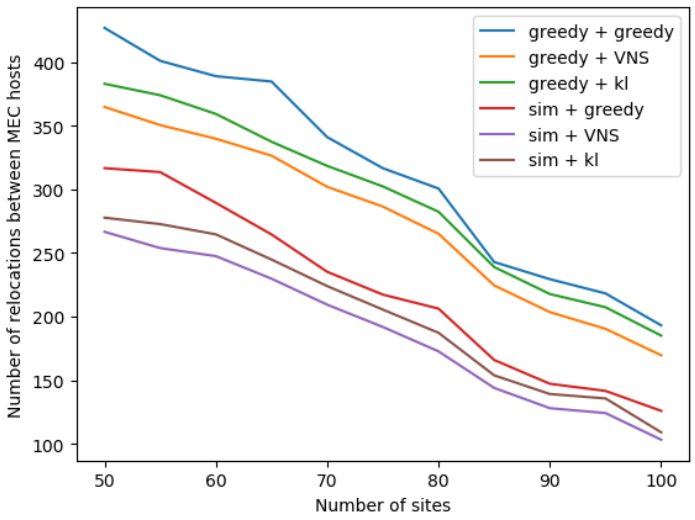


Figure 3.6: Number of relocations (weighted) between MEC hosts vs Number of sites in the geographic service area – test 1

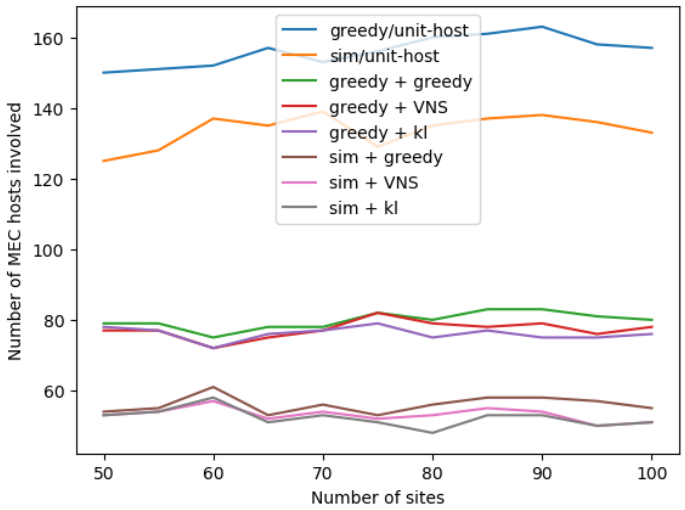


Figure 3.7: Number of involved MEC hosts vs Number of sites in the geographic service area – test 1

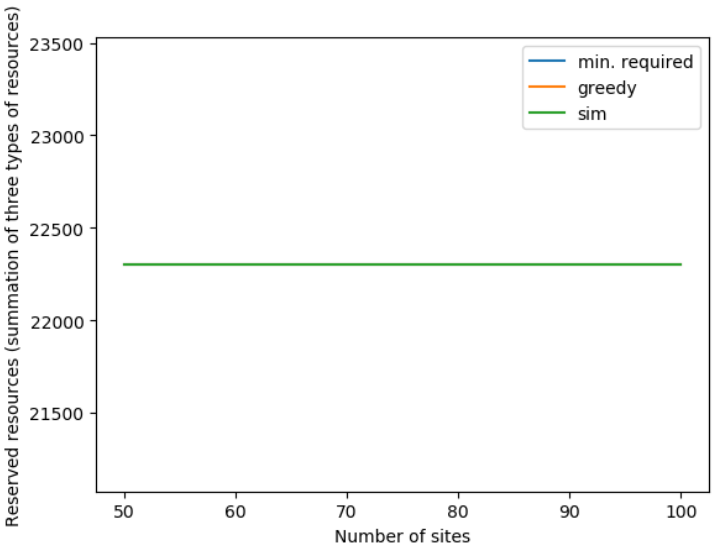


Figure 3.8: The amount of reserved resources by greedy algorithm and simulation-based algorithm and the required amount of resources – test 1

Figure 3.5 and Figure 3.6 both show a trend that as the number of sites in the geographic service area increases, the total number of relocations under extreme situation decreases at the same time. This trend also applies to the following two tests – Test 2 and Test 3. Generally, when there are more resources available, user experience will at least not degrade. In this specific case, if some of the added sites can decrease the number of relocations, their corresponding unit-hosts will be selected in Phase 1, otherwise algorithms will stick to the previous deployments of MEC hosts and MEC applications. Therefore, the total number of relocations will not be larger than before when some more sites are added to the geographic service area.

Apart from that, in Figure 3.5, when there are only 50 sites in the geographic service area, the total number of relocations between unit-hosts of greedy algorithm and simulation-

based algorithm is equal. This is because these 50 sites are uniformly distributed and no matter which path a UE takes from the entrance towards the exit, the number of sites (unit-hosts) along that path is always the same. Therefore, although simulation-based algorithm involves fewer unit-hosts, as shown in Figure 3.7, its total number of relocations is still as large as that of the greedy algorithm. Similarly, the overlapping starting points in Figure 3.9 and Figure 3.13 can be explained.

In Table 3.9, based on the definitions, MEC app 1 and 3, 4 and 5 are two groups of complementary MEC applications. To be more precise, for MEC app 1 and 3, there exists a vector $V = \{1,1\}$ which makes $\max_{j\in\{1,2,3\}} \frac{\sum_{i=i}^{k} r_{ij} v_i}{\sum_{i=1}^{k} v_i} = 4 < \min_{v_i>0} \max_{j\in\{1,2,3\}} r_{ij} = 6$ come into existence. Similarly, for MEC app 4 and 5, there also exists a vector $V = \{1,1\}$ for which $\max_{j\in\{1,2,3\}} \frac{\sum_{i=i}^{k} r_{ij} v_i}{\sum_{i=1}^{k} v_i} = 6 < \min_{v_i>0} \max_{j\in\{1,2,3\}} r_{ij} = 8$ holds. Since there are two groups of complementary MEC applications, it is expected that simulation-based algorithm will outperform the purely greedy algorithm. Figure 3.5 shows that the number of relocations between unit-hosts given by simulation-based algorithm is much smaller than that of the purely greedy algorithm. Figure 3.7 shows that simulation-based algorithm uses fewer unit-hosts than greedy algorithm because the former can deal with uneven usage of different types of resources in unit-hosts and make it possible for one unit-host to serve more UEs. Since the maximum number of unit-hosts one MEC host in a certain location can contain is fixed, when the number of involved unit-hosts is smaller, the number of MEC hosts is usually smaller too. This can be discovered from Figure 3.7, all the mechanisms using simulation-based algorithm have smaller number of MEC hosts than those using greedy algorithm instead. Besides, greedy algorithm in Phase 2 performs worse than the other two algorithms both in the number of relocations and in the number of MEC hosts involved, which further proves that the total number of relocations is positively related to the number of MEC hosts.

It can be discovered from Figure 3.6 that the VNS algorithm performs the best – it gives an outcome that has the smallest number of relocations, and multi-Kernighan Lin algorithm is the second best. In fact, both algorithms include exploring procedure, and if the end criteria are stricter, both algorithms can get closer to the actual global optimal solution. Unfortunately, considering the processing and computing capabilities of the device are limited, it is impossible to use stringent criteria in the tests. It can also be noticed that, using similar end criteria, VNS algorithm outperforms multi-Kernighan Lin algorithm because the searching area of VNS algorithm is larger than the exploring area of multi-Kernighan Lin algorithm. In the part 3 of multi-Kernighan Lin algorithm, only two nodes are explored each iteration to see whether these two nodes can be interchanged. In comparison, in one iteration in VNS algorithm, the VND procedure can search in multiple neighborhoods of the current optimal solution, and the shaking procedure further expands the searching area. Therefore, after the same number of iterations, the VNS algorithm can give a solution that is closer to the global optimum than the solution given by multi-Kernighan Lin algorithm. It is not a surprise that the greedy algorithm performs the worst of the three algorithms in Phase 2, because it simply tries to merge unit-hosts one by one in a greedy way which can easily reach a local optimum but then no operations are done to force itself to jump out of this local optimum, so it cannot perform as well as the other two algorithms which both are capable

to step out of the current local optimum and explore other possible combinations of unit-hosts.

For MEC application group 1, the simulation-based algorithm significantly outperforms the greedy algorithm, and the worst minimum k-cut solution given by the former is better than the best minimum k-cut solution given by the latter. Therefore, the six locating mechanisms ranked by their performances in a descending order are: simulation-based + VNS, simulation-based + multi-KL, simulation-based + greedy, greedy + VNS, greedy + multi-KL, greedy + greedy.

Figure 3.8 shows the amount of reserved resources by the greedy algorithm and the simulation-based algorithm in Phase 1 as well as the required amount of resources by MEC application group 1. Although the number of sites in the geographic service area is increasing, the road length, required amount of resources to serve one UE and estimated maximum number of the UEs that enter the geographic service area at the same time are not changing with it, hence the increase in the number of sites cannot affect the total amount of required resources. Both algorithms in Phase 1 reserve exactly the required amount of resources, which is desired because no redundant resources are reserved, and more resources are available for further usage.

Test 2: Testing results of MEC application group 2 are shown in Figures 3.9 - 3.12.

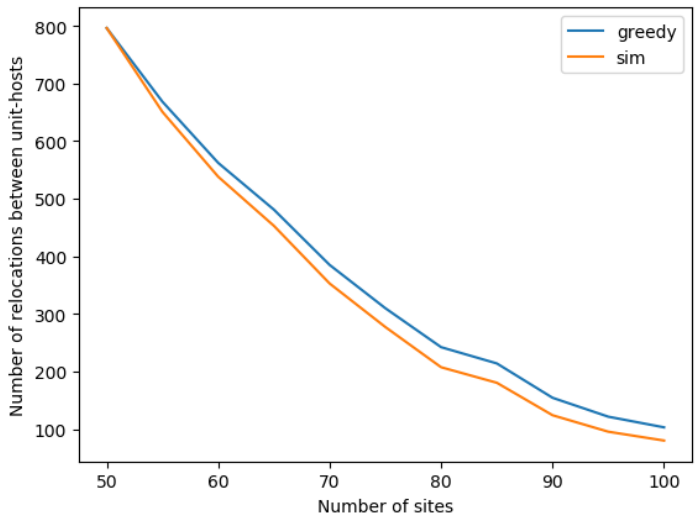


Figure 3.9: Number of relocations (weighted) between unit-hosts vs Number of sites in the geographic service area – test 2

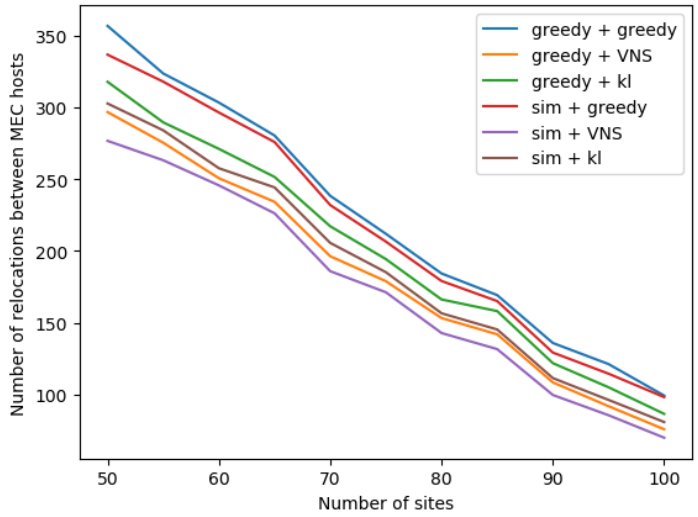


Figure 3.10: Number of relocations (weighted) between MEC hosts vs Number of sites in the geographic service area – test 2

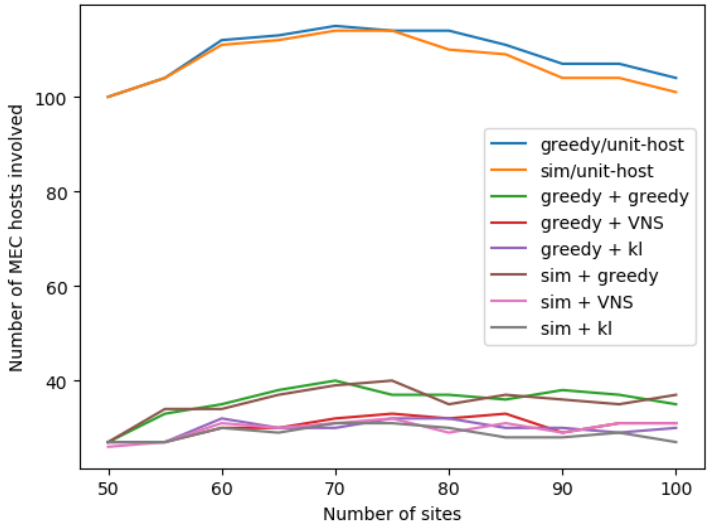


Figure 3.11: Number of involved MEC hosts vs Number of sites in the geographic service area – test 2

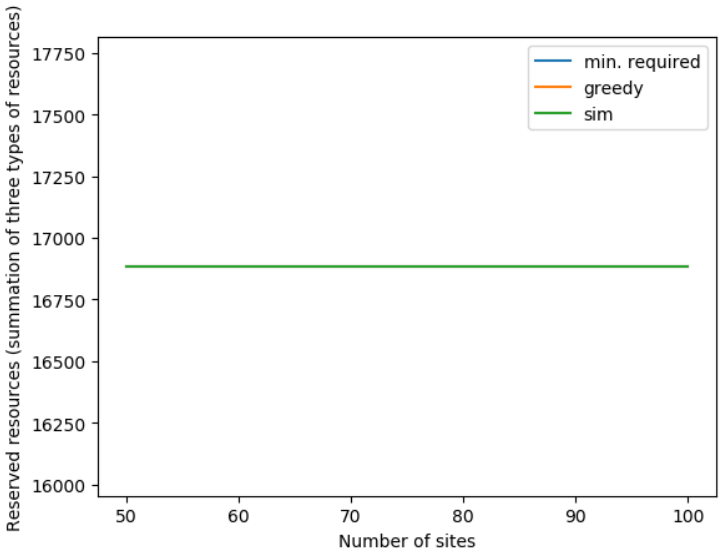


Figure 3.12: The amount of reserved resources by greedy algorithm and simulation-based algorithm and the required amount of resources – test 2

In Figure 3.9, simulation-based algorithm outperforms greedy algorithm, however, if compared to Figure 3.5, the difference between the outcome of the two algorithms is much smaller in Figure 3.9 The reason behind is that, in the settings of MEC application group 2, although MEC applications 1 and 3 are still complementary MEC applications based on the definition, MEC applications 4 and 5 can no longer complement each other's resource usages. This is because both MEC applications 4 and 5 in Table 3.6 have larger required amount of computing resources than the two other types of resources, hence there does not exist a vector $V = \{v_4, v_5\}$ $(v_4 > 0, v_5 > 0)$, for which the Inequation 3.19 holds. Differences between the two curves that represent the number of involved unit-hosts in Figure 3.11 are much smaller than the differences in Figure 3.7 due to the same reason – there is only one group of complementary MEC applications in Table 3.10, and the advantage of simulation-based algorithm on high resource efficiency decreases accordingly. Since the number of MEC hosts is related to the number of selected unit-hosts in Phase 1, differences between curves that represent the number of MEC hosts in Figure 3.11 are also smaller than the differences in Figure 3.7. Unsurprisingly, greedy algorithm in Phase 2 gives the highest number of relocations as well as MEC hosts, and the reason is explained in the analysis of Test 1.

The changes in MEC application settings in Table 3.10 also affect the performances of the six locating mechanisms. Although the rank of performances of the three graph partitioning algorithms in Phase 2 remains the same, the difference between the performances of the two algorithms in Phase 1 is smaller, hence the rank of the six locating mechanisms becomes: simulation-based + VNS, greedy + VNS, simulation-based + multi-KL, greedy + multi-KL, simulation-based + greedy, greedy + greedy.

Although the MEC application settings have been changed, both algorithms in Phase 1 can still avoid allocating more resources than needed. The only difference between Figure 3.12 and Figure 3.8 is in the y-axis, since MEC applications group 2 has different requirements on resources.

Test 3: Testing results of MEC application group 3 are shown in Figures 3.13 – 3.16.

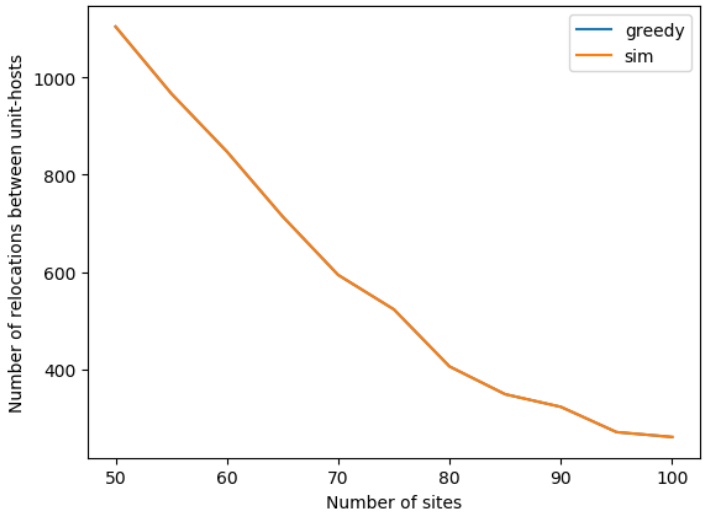


Figure 3.13: Number of relocations (weighted) between unit-hosts vs Number of sites in the geographic service area – test 3

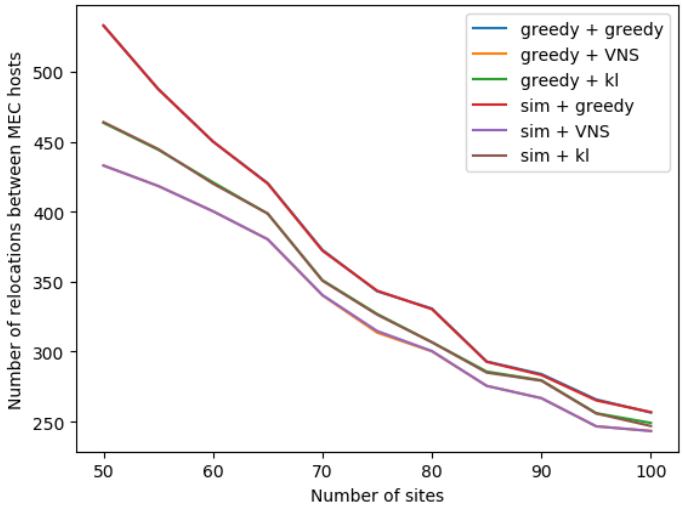


Figure 3.14: Number of relocations (weighted) between MEC hosts vs Number of sites in the geographic service area – test 3

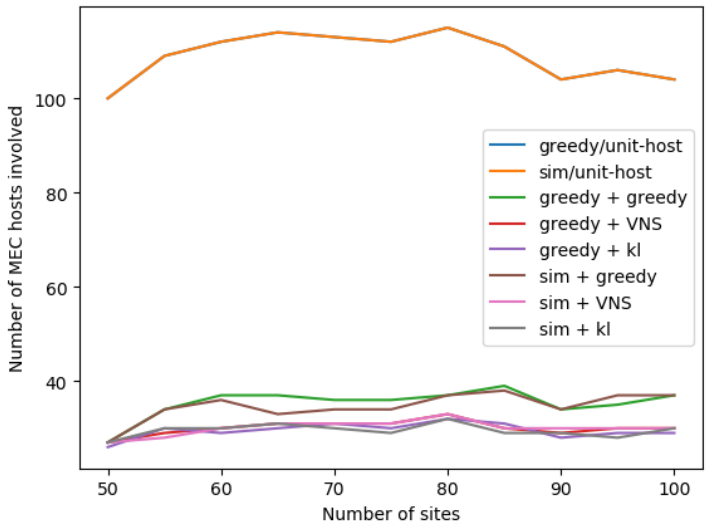


Figure 3.15: Number of involved MEC hosts vs Number of sites in the geographic service area – test 3

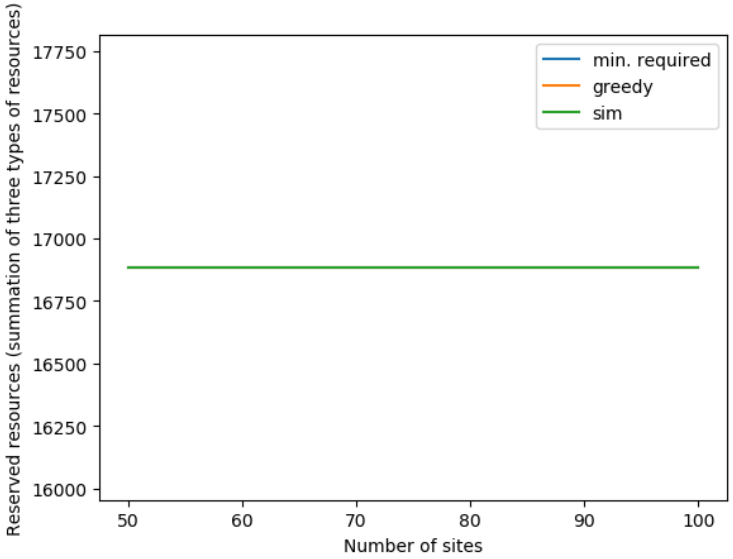


Figure 3.16: The amount of reserved resources by greedy algorithm and simulation-based algorithm and the required amount of resources – test 3

Every MEC application in Table 3.11 has a unique priority, which means that no complementary MEC applications can be found. Therefore, the performances of the two algorithms in Phase 1 should be the same. In Figure 3.13, the two curves that represent number of relocations between unit-hosts using greedy algorithm and simulation-based algorithm overlap with each other. In Figure 3.15, the numbers of unit-hosts used by the two algorithms in Phase 1 – greedy and simulation-based algorithms – are equal, and that is the reason why the four other curves, which represent the numbers of MEC hosts required by the four different locating mechanisms – greedy + VNS, greedy + Multi-KL, simulation-based + VNS and simulation-based + Multi-KL – separately, are closer to each other. Like what has been discovered in Tests 1 and 2, in Test 3, greedy algorithm in Phase 2 again gives the highest

number of MEC hosts as well as relocations, the reason behind this outcome is explained in the analysis of Test 1.

The performances of the three algorithms in Phase 2 are still different and the ranking based on their performances remains unchanged: VNS algorithm $\geqslant$ Multi-KL algorithm > Purely greedy algorithm. The six locating mechanisms ranked by their performances in a descending order are: simulation-based + VNS and greedy + VNS, simulation-based + multi-KL and greedy + multi-KL, simulation-based + greedy and greedy + greedy.

The only difference between Table 3.10 and Table 3.11 is the priorities of MEC applications, which has nothing to do with the two factors – estimated number of UEs that enter the geographic service area at the same time and the required amount of resources to serve a UE – that can affect the total amount of required resources. Hence, Figure 3.16 is exactly the same as Figure 3.12.

C. Conclusions

1. The performance of the algorithms in Phase 1: simulation-based algorithm $\geqslant$ purely greedy algorithm.
2. The performance of the algorithms in Phase 2: VNS algorithm $\geqslant$ Multi-KL algorithm > purely greedy algorithm.
3. When new sites are added to the geographic service area, the number of relocations will never decrease.
4. The larger the difference $\min\limits_{v_i>0} \max\limits_{j\in\{1,2,3\}} r_{ij} - \max\limits_{j\in\{1,2,3\}} \frac{\sum_{i=i}^{k} r_{ij} v_i}{\sum_{i=1}^{k} v_i}$ is, the better the performance of the simulation-based algorithm is.
5. If every MEC application has a unique priority, the two algorithms in Phase 1 give the same outcome.
6. Even though minimizing the number of relocations and the number of MEC hosts together can be impossible sometimes, at least when the number of relocations has been minimized, the number of MEC hosts is also small. This means that when the service continuity is optimized, the O&M costs of MEC hosts also reach a low level.
7. Minimizing the latency and minimizing the total number of relocations cannot be achieved simultaneously due to the dilemma introduced in section 3.1. In this project, considering the fact that relocations might cause service interruptions which can significantly degrade user experience, minimizing the total number of relocations is chosen as the optimization goal, and the latency requirements of MEC applications become a constraint.
8. The performances of the six locating mechanisms changes with MEC application settings. However, no matter how the settings change, mechanism “simulation-based + VNS” always gives the best outcomes while mechanism “greedy + greedy” always gives the worst.
9. In Phase 2, greedy algorithm the worst performances but it is the fastest algorithm among the three and requires the fewest running resources. Due to the fact that this algorithm is used to determine the deployment of MEC hosts and MEC applications before the MEC system comes into use, the running time of the algorithm is not an

essential factor. Therefore, heuristic algorithm is a better choice to solve the question in Phase 2.

3.6. Summary

Chapter 3 mainly answers the four sub-questions of research question 3: Devise an algorithm to find the optimal location of MEC hosts and the optimal location (MEC host) of a MEC application.

1. *Determine which aspects of MEC applications need to be considered in this master thesis.*

Required service latency, required amount of resources and sensitivity to service relocations are considered. Service latency is the latency between a UE and its serving MEC host. A certain amount of resources is required to serve a UE using this MEC application. Sensitivity to service relocations consists of two aspects. One aspect is the service continuity during a relocation. If a relocation of a MEC application is more likely to cause service interruptions, then this MEC application has a higher sensitivity to service relocations. Another aspect is, when service interruption occurs during a relocation, how severe can the consequence be. The more dangerous the consequence is, the higher the sensitivity of this MEC application to service interruptions is.

2. *How to transform the aspects chosen in sub-question a) into a set of parameters?*

The above three aspects are transformed into three parameters. Required service latency and amount of resources are directly used as two parameters. Sensitivity to service relocations is transformed into the priority of this MEC application. The higher the sensitivity is, the higher the priority is.

3. *How to locate the MEC hosts as well as MEC applications properly based on these parameters?*

To locate the MEC hosts and MEC applications properly, optimization is needed. The total number of relocations is selected as the optimization object because service interruptions during relocations can have bad impacts and, sometimes, threats to lives. Besides, the number of relocations is positively related to the total number of MEC hosts in the geographic service area. Therefore, minimizing the total number of relocations can not only limit the occurrence of unwanted consequences, but also decrease the investments on running and maintaining MEC hosts. Meanwhile, UEs' requirements on service latency and resources are satisfied.

The extreme situation where the number of UEs that in the geographic service area reaches its maximum value is considered to make sure that the network can handle the worst situation and always meet UEs' requirements on resources and service latency. The total number of relocations is minimized under this extreme situation, using greedy algorithms and heuristic algorithms.

4. *How to test the performance of the algorithms?*

The test of algorithms is done by simulations in Python. The five algorithms used in sub-question c) can form six different locating mechanisms to deploy MEC hosts and MEC

applications. Three tests are designed to test the performance of the six locating mechanisms under different settings of MEC applications. The outcomes show that, mechanism “simulation-based + VAS” always gives the smallest number of relocations, as well as a small number of MEC hosts to be deployed, while mechanism “greedy + greedy” always have the worst performance among the six locating mechanisms.

Chapter 4 Optimizing the Relocation Process using Reinforcement Learning

Chapter 3 focuses on the extreme situation where the network is fully loaded. When the network is not busy, a UE can have many options of a target MEC host. These alternatives come from two aspects:

1. One MEC host is located in a LADN. As mentioned in section 3.1 and section 3.4, any UE within the serving area of a MEC host can access this MEC host, and it is not necessary for a UE to follow the paths chosen by the algorithms in Chapter 3, especially when the network is not busy. Therefore, when a MEC application is assigned with multiple paths, a UE which uses this MEC application and requires a relocation can be handed over to a MEC host that has the required MEC application installed but does not belong to the current path of this UE, hence there might be more than one options of potential target MEC hosts for this UE.
2. The site that one UE is connected to can access MEC hosts in different locations, some of which may be able to reduce the number of relocations this UE needs to experience. However, the MEC hosts that reduce the number of relocations may not have the required MEC application installed. If the UE chooses one of these MEC hosts, the number of relocations will decrease but one relocation may take longer time because of the extra MEC application installing procedure.

To find the optimal target MEC host among all the alternatives, research question 4 is formed into an optimization problem. Traditional reinforcement learning algorithm, SARSA learning, Deep Q Network (DQN), as well as a newly designed algorithm – quick-start SARSA learning algorithm are used to solve research question 4.

4.1 Markov Decision Process

A Markov Decision Process (MDP) is a discrete time stochastic control process. It is an extension of a Markov Chain with multiple actions allowing for choice and rewards used to indicate the quality of decisions. MDPs are very important in optimizing decision problems, methodologies like dynamic programming and reinforcement learning need MDPs to solve optimization problems.

The main components of an MDP are listed below [35]:

1. A set of decision epochs.
   Decision epochs are the points in time where decisions are made. In this specific project, one decision epoch is when a UE needs a relocation. Since the number of relocations that a UE experiences is limited, the number of decision epochs for a UE is also limited.
2. A set of system states.
   At each decision epoch, the system occupies a state. In this state, a decision needs to be made to decide which action to be taken. In a Markov Decision Process, there exist one or more end states. If the system reaches one of these end states, the current episode ends.

3. A set of available actions.
   In an MDP model, all actions that can be taken to move from the current state in the model to a new state are saved in an action set. At each decision epoch, an action that belongs to this action set should be chosen. After taking the selected action, the system will reach a new state. If the new state is an end state, then no further actions will be chosen.
4. A set of state and action dependent immediate rewards.
   After the chosen action has been taken, the system will receive an immediate reward. The reward should reflect the quality of the selected action, hence, in most of the cases, the reward is related to the action itself. In the context of this master thesis, the reward is also related to the MEC application type.
5. A set of state and action dependent transition probabilities.
   After taking an action, the system will leave its current state and transit to a new state. Usually, there are multiple potential new states after taking one action, and the system will reach one of these states following a certain transition probability distribution. However, in the context of this project, there is only one possible next state after taking an action, hence the transition probability always equals 1. This will be further explained in section 4.4.

4.2 Reinforcement Learning

A. Overall Introduction

Reinforcement Learning (RL) is an area of machine learning which is commonly used for optimizations, and it is one of three basic machine learning paradigms, alongside supervised learning and unsupervised learning. In reinforcement learning, the software agents should be able to decide on the actions to take and then attempt to maximize the rewards based on the feedback from the environment [36].

Compared to supervised learning, reinforcement learning does not need labelled input-output pairs for training [36]. Instead, the software agents will learn from the environment, which is usually formulated as an MDP model, by exploring and optimizing itself during the process. The focus of reinforcement learning is to find a balance between exploration (of uncharted territory) and exploitation (of current knowledge) [36].

In addition, there are three important terms that need explanations [35]:

1. Decision rules: A decision rule prescribes a procedure for action selection in each state at a specified decision epoch. There are basically four types of decision rules: History dependent and Randomized (HR), History dependent and Deterministic (HD), Markovian and Randomized (MR) and Markovian and Deterministic (MD). The selection of a target MEC host for a UE is related to its current serving MEC host but not the MEC hosts previously served this UE. This proves that the system is Markovian (memoryless). In addition, because reinforcement learning has both exploration and exploitation aspects, at each decision epoch, either a random action (randomized) or the current optimal action (deterministic) is selected. Therefore, the most suitable decision rules for this master thesis are MR and MD.

2. Policy (π): A policy consists of decision rules of all the decision epochs. It provides a prescription for action selection under any state at any decision epoch. In short, a policy is a sequence of decision rules.
3. Episode: A sequence of states, actions and rewards, which ends with the end state. More precisely, in this master thesis, one episode is the entire procedure starts from a UE enters the geographic service area and ends when this UE leaves.

B. Epsilon-greedy

Epsilon-greedy is one of the strategies for solving a multi-armed bandits problem [37]. Here, epsilon is a value within interval $[0,1]$ and it reflects the probability of choosing the current optimal action. The current optimal action is taken (exploitation) with probability ε, and a random action is taken (exploration) with probability $1-\varepsilon$.

Although epsilon-greedy is one of the simplest and earliest strategies to solve multi-armed bandit problems, it is powerful and is used in classical RLs, for example the two RL algorithms introduced in the following sections, Q learning and SARSA learning, to generate action choosing strategies. To be more precise, in each decision epoch, the algorithm will generate a random number within interval $[0, 1]$, and then compare it with ε. If the random number is smaller, the algorithm will choose the action that is currently estimated as the best option; otherwise, the algorithm will randomly pick one action from the actions set.

C. Advantages of using Reinforcement Learning

In the real world, the conditions of the entire network keep changing all the time. This indicates the requirement on immediate awareness of the changes as well as the ability to quickly react and make adjustment accordingly. Reinforcement learning is good at noticing the dynamic changes by exploring and learning the real-world situation all the time, so reinforcement learning is suitable for solving research question 4. In addition, it is suggested in [43] that: "…the estimated QoS performance of the available cells (e.g. based on the RNI service defined in [9] and the enhancements to RNIS) can help with optimal base station and MEC host selection so that the UE vehicle can always receive the maximum QoE along the trajectory." However, a RNIS can only estimate the current conditions of the target MEC host but not the MEC hosts that may serve this UE afterwards. Reinforcement learning can give a reliable estimation of both the performance of the target MEC host, and the overall performance of all the MEC hosts that might be chosen in later steps. Therefore, reinforcement learning is used in this chapter for determining the most suitable target MEC host in each relocation.

D. Q Learning

Q learning can learn directly from raw experience without a model of the environment

dynamics [33], which brings it more flexibility and makes it more suitable for use cases in the real world, since it is sometimes impossible or difficult to get the environment dynamics in reality.

Q learning uses a q table to save a q value for each state-action pair (s, a), which means taking action a in state s. The q value of state-action pair (s, a) represents the current estimated summation of the reward of state-action pair (s, a) and the rewards of its subsequent state-action pairs. When Q learning receives new feedback from the environment, it will update relevant q values immediately. Equation 4.1 shows the basic idea of Q learning to update estimated q values:

$$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha \left[R_{t+1} + \gamma \max_a Q(S_{t+1}, a) - Q(S_t, A_t) \right] \quad (4.1)$$

where $Q(S_t, A_t)$ is the estimated q value of state-action pair (S_t, A_t), R_{t+1} is the actual reward of taking action A_t in state S_t, $\max_a Q(S_{t+1}, a)$ is the maximum q value among all the q values of state-action pairs with state being S_{t+1}, γ is the future reward decay and α is the learning rate. Figure 4.1 specifies the procedures of Q learning. The action a^* which maximizes $Q(S_{t+1}, a)$ is not necessarily the actual action A_{t+1} chosen in state S_{t+1}.

Q learning

For each decision epoch t
- Current state S_t
- Choose action A_t using ε-greedy algorithm
- Take action A_t, observe reward R_{t+1}, move to state S_{t+1}
- $Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha \left[R_{t+1} + \gamma \max_a Q(S_{t+1}, a) - Q(S_t, A_t) \right]$
- $S_t \leftarrow S_{t+1}$

Stop when an end state is reached

Figure 4.1: Basic procedures of Q learning [33].

E. SARSA Learning

The basic procedure of SARSA learning is very similar to that of Q learning, both approaches use epsilon-greedy for action selecting and q tables to record the currently learnt information from the environment. Figure 4.2 gives the detailed steps.

SARSA learning

At decision epoch 1
    Choose action A_1 usingε-greedy algorithm
For each decision epoch $t, t > 1$
    Current state S_t, next action A_t
    Choose action A_{t+1} using ε-greedy algorithm
    Take action A_t, observe reward R_{t+1}, move to state S_{t+1}
    $Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha[R_{t+1} + \gamma Q(S_{t+1}, A_{t+1}) - Q(S_t, A_t)]$
    $S_t \leftarrow S_{t+1}$
    $A_t \leftarrow A_{t+1}$
Stop when an end state is reached

Figure 4.2: Basic procedures of SARSA learning [33].

The major difference between Q learning and SARSA learning is their method to update q values. The mechanism that SARSA learning uses for updating the q table is shown in Equation 4.2.

$$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha[R_{t+1} + \gamma Q(S_{t+1}, A_{t+1}) - Q(S_t, A_t)] \quad (4.2)$$

where $Q(S_t, A_t)$ is the estimated q value of state-action pair (S_t, A_t), γ is the future reward decay and α is the learning rate. To accomplish an update in Equation 4.2, $S_t, A_t, R_{t+1}, S_{t+1}, A_{t+1}$ are needed, and that is why this algorithm is called "SARSA" learning algorithm.

A SARSA learning algorithm first selects the action A_{t+1}, which will be taken in state S_{t+1} and then updates $Q(S_t, A_t)$ using the q value of state-action pair (S_{t+1}, A_{t+1}). In comparison, a Q learning algorithm updates $Q(S_t, A_t)$ with the action a^*, and this action is not necessarily the actual action A_{t+1} which will be taken in state S_{t+1}. A reinforcement algorithm like SARSA learning is called an on-policy reinforcement learning algorithm, and a reinforcement learning algorithm like Q learning is called an off-policy reinforcement learning algorithm. Off-policy algorithms can efficiently figure out the optimal policies but it does not update and evaluate other policies. Therefore off-policy algorithms are more suitable for agents that do not explore much and stick to the optimal action most of the time. On-policy algorithms, on the other hand, estimate and update all the policies that are followed by the agents, including the policies with MR decision rules followed by the agents that explore. Therefore, compared to off-policy algorithms, on-policy algorithms have a more comprehensive estimation on the policies and are more suitable for agents that explore. In this master thesis, agents are UEs, and since the network conditions keep changing, the UEs need to explore the environment to update the current knowledge of the network at a reasonable frequency, which makes SARSA learning a better option than Q learning.

4.3 Target MEC host selecting mechanisms

At present, installing MEC applications and instantiating MEC application instances in MEC hosts is a time-consuming procedure and costs resources in MEC hosts. Therefore, the deployment of MEC applications needs to be done beforehand following the locating

mechanisms in Chapter 3, in order to save time and resources. The selection of the target MEC host for a UE is limited to the MEC hosts with the required MEC application installed in advance and with enough available resources. This target MEC host selecting mechanism is called a “fixed target MEC host-selecting mechanism”.

However, as relevant technologies are developing, it is possible that in the future, installing MEC applications in MEC hosts can be much faster and consume fewer resources. Therefore, the selection of the target MEC host for a UE is not necessarily limited to MEC hosts where the required MEC application has been installed. Instead, any available MEC host can be selected as the target MEC host, as long as the service continuity can be maintained. This means that the selection has more flexibilities, and especially when the network is not busy, MEC applications with lower priorities can get served by the MEC hosts that are assigned to MEC applications with higher priorities, which can further decrease the total number of relocations. However, when the network gets busy, UEs of MEC applications with higher priorities may experience a large number of relocations by sharing MEC hosts with other MEC applications with lower priorities, and the increased number of relocations may cause more service interruptions and other negative consequences.

To avoid the above situation, two new target MEC host-selecting mechanisms are proposed in this section. The differences between the three different target MEC host selecting mechanisms mainly reside in the number of possible MEC hosts. Here two assumptions are applied:

1. MEC applications are installed properly in the MEC hosts to minimize the total number of relocations and avoid resource shortage under extreme situation. The MEC hosts with a MEC application installed are addressed as the MEC hosts that are assigned to this MEC application.
2. The reinforcement learning has fully and correctly learnt the network conditions which always stay stable, so that q values in the q table can correctly reflect the rewards of all state-action pairs, and target MEC hosts are selected based on corresponding q values.

In the first selecting mechanism, each MEC application which is sensitive to relocations can have a maximum number of relocations it can accept, and this maximum number is derived from its own requirements. If the relocation number exceeds this threshold, UEs of other MEC applications are not allowed to use the resources reserved for this application. This target MEC host-selecting mechanism is called a “share-and-block” target MEC host-selecting mechanism, then the network is not busy, MEC applications share resources that have been allocated to them in advance, and when the average relocation number cannot satisfy a MEC application’s requirement, this MEC application will stop sharing resources and will block others from using the resources that have been assigned to it. Figure 4.3 and Figure 4.4 give the results of this “share-and-block” selecting mechanism.

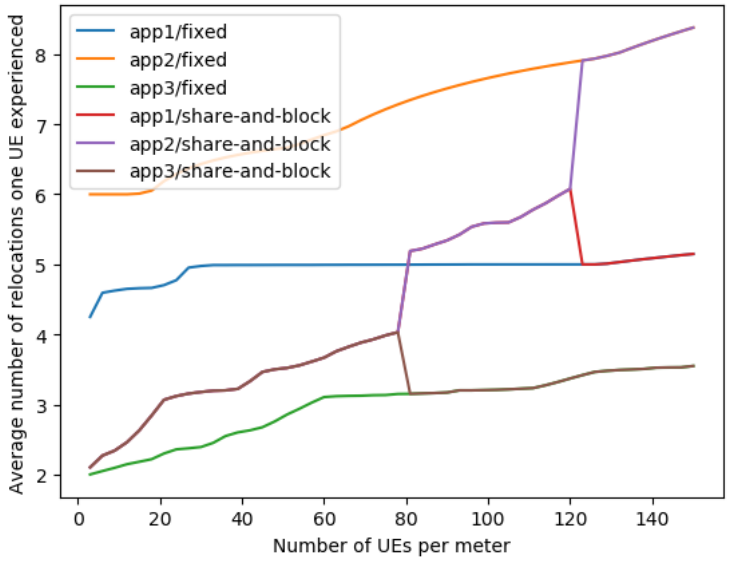


Figure 4.3: Average number of relocations versus number of UEs per unit length per MEC application (fixed selecting mechansim & “share-and-block” selecting mechanism)

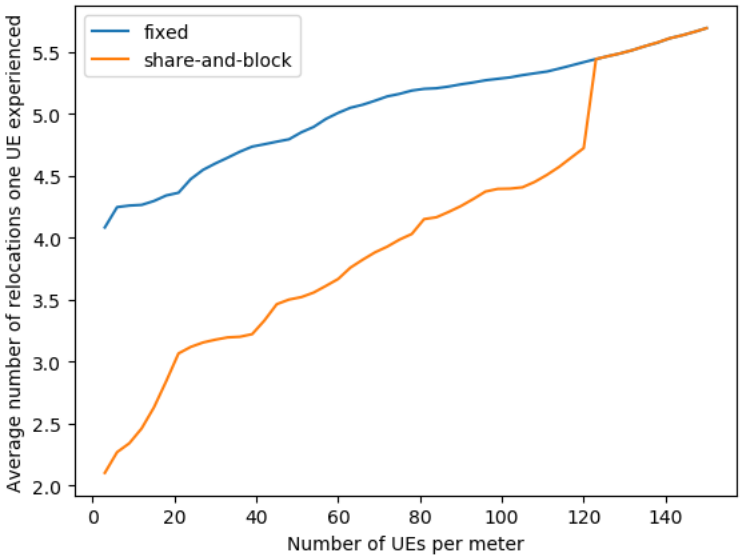


Figure 4.4: Average number of relocations versus number of all UEs per unit length (fixed selecting mechansim & “share-and-block” selecting mechanism)

In Figure 4.3, MEC application 3 and 1 have higher priorities than MEC application 2 because they are more senstitive to relocations. For MEC application 1, its threshold is 6, which means that when the average number of relocations one UE of MEC application 1 experienced exceed 6, the selection of target MEC hosts for UEs of MEC application 1 will only be limited to the MEC hosts assigned to application 1, and other MEC applications couldn’t occupy resources reserved for it. For MEC application 3, this threshold is 4, because it is more sensitive to relocations and thus has a higher priority.

From Figure 4.3, it can be seen that at the very beginning, the average relocation number of the three MEC application is the same, because they are all using MEC hosts that can minimize the number of relocations. However, as the number of UEs at the same location of the road increases, the average number of relocations increase too because the MEC hosts which have larger coverage are gradually loaded, therefore some of the UEs need to get served by MEC hosts with smaller coverage and experience more relocations. The average number of relocations of MEC application 3 is larger than when using the fixed selecting mechanism, because currently MEC application 3 is sharing its good resources with the other two MEC applications, whose average numbers of relocations have been lowered. After the average number of relocation reaches 4, UEs of MEC application 3 will only get served by the MEC hosts designated to them under extreme situation in Chapter 3. Therefore, the average number of relocations experienced by UEs of MEC application 3 given by the "share-and-block" mechanism is first higher than that given by the fixed selecting mechanism, and after the former reaches 4, these two values become equal. At the same time, the average number of relocations of MEC applications 1 and 2 increases because some of the resources in MEC hosts with larger coverage and can provide longer service are reserved for MEC application 3 and cannot be used by others. This time the average number of relocations of MEC application 1 gets larger than using fixed selecting mechanism because it cannot share better MEC hosts with MEC application 3 anymore and in the meantime, it has to share its own assigned MEC hosts with MEC application 2. When the average number of relocations reaches 6, the same happens to MEC application 1 thus its average number of relocations decreases and the average number of relocations of MEC application 2 increases rapidly again and reaches the value given by the fixed selecting mechanism.

The goal of the "share-and-block" mechanism is to mimimize the number of relocations of all UEs when the network is not busy, under the assumption that installation and instantiation of a new MEC application (instance) are easy and fast enough. From Figure 4.4 it can be seen that when there are fewer than 120 UEs per unit length, the new mechanism can reduce the average number of relocations of all the UEs in the geographic service area.

The other new selecting mechanism of target MEC host is called a preemptive target MEC host-selecting mechanism. When there are multiple UEs requiring a relocation, this selecting mechanism always starts from selecting MEC hosts for the UEs with the highest priority to selecting MEC hosts for the UEs with the lowest priority. Therefore, UEs of MEC applications which are more sensitive to relocations can always get served by the better target MEC hosts. Figure 4.5 and Figure 4.6 shows the results of preemptive target MEC host-selecting mechanism.

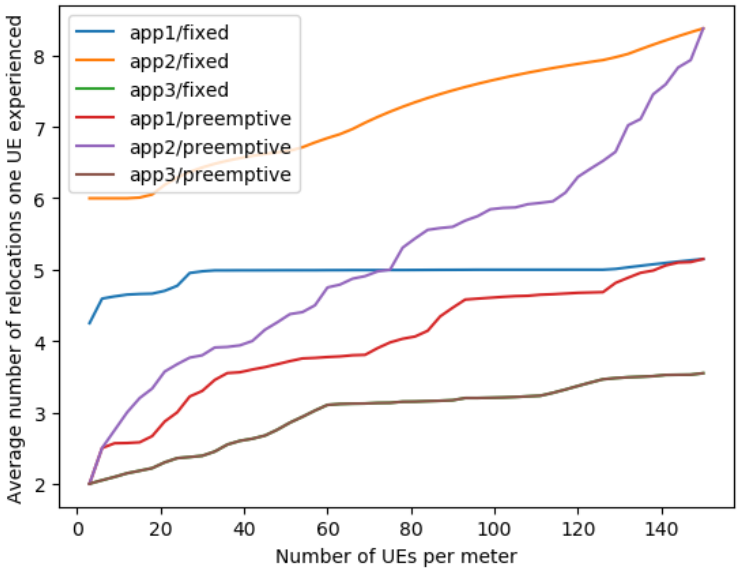


Figure 4.5: Average number of relocations versus number of UEs per unit length per MEC application (fixed selecting mechansim & preemptive selecting mechanism)

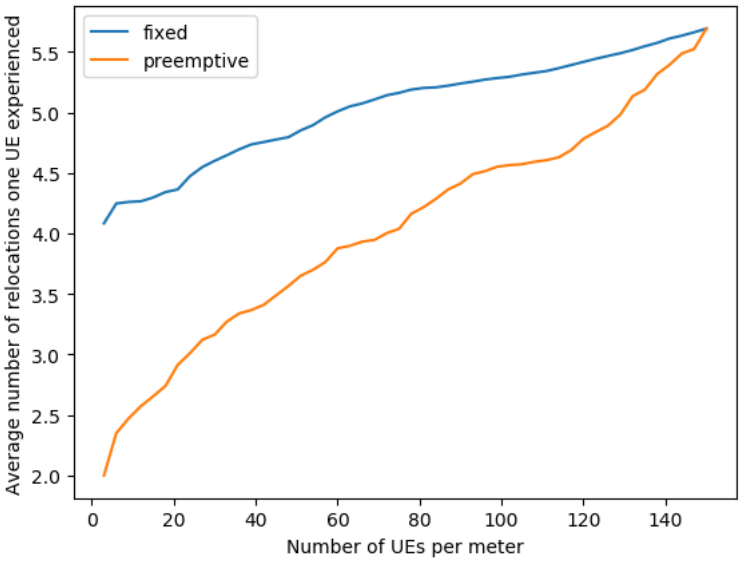


Figure 4.6: Average number of relocations versus number of all UEs per unit length (fixed selecting mechansim & preemptive selecting mechanism)

In Figure 4.5, the average number of relocations of UEs of MEC application 3 given by fixed selecting mechanism and preemptive selecting mechanism are the same, because MEC application 3 has the highest priority among the three applications, its corresponding UEs can always be served by the best target MEC hosts, and other UEs can only select their own target MEC hosts later. That is why fixed selecting mechanism and preemptive selecting mechanism give the same average number of relocations of UEs of MEC application 3, and the average number of relocations of UEs of a MEC application with higher priority never

exceeds that of a MEC application with lower priority. The main difference between these two mechanisms resides in the average relocation numbers of UEs of MEC application 1 and 2. UEs of these two MEC applications can get served by better MEC hosts as long as these MEC hosts are still available after the selections performed by the central controller for the UEs of MEC application 3, and this is not possible in fixed selecting mechanism. Therefore, in Figure 4.6, the average number of relocations of all UEs using preemptive selecting mechanism is lower than the average relocation number using fixed selecting mechanism, only except for the extreme situation - 150 UEs per unit length, where the average number of relocations of the preemptive selecting mechanism and the fixed selecting mechanism are the same.

In this section as well as in Chapter 3, only the number of relocations is minimized. In fact, user experience can be affected by many other factors, such as service latency, service interruptions and so on. To guarantee an overall satisfied user experience, while selecting target MEC hosts using the above three mechanisms, these factors can also be taken into account, like what is done in section 4.4.

4.4 System MDP Model & Assumptions

Relocations (defined in sections 1.1 and 3.1) help with the continuity of MEC services, however, relocations may also cause problems. For example, if the target MEC host is not capable to handle the required MEC application instance due to some reasons like no enough resources, required MEC application not installed, etc., then after relocating the MEC application to this target MEC host, it is possible that the UE cannot receive required services. Other possible problems include the latency between the UE and the target MEC host is too large, the number of relocations afterwards is too large, the relocation takes too much time, the service failed during the relocation, etc. To achieve the best of each relocation, it is significant to find a suitable target MEC host, which is addressed in research question 4.

Considering all the aspects mentioned above, four relocation performance indicators are selected to evaluate the performance of each relocation:

1. The duration time of the relocation
2. Whether there is a service interruption during the relocation
3. The service latency at the target MEC host of the relocation
4. The current available resources in the target MEC host of the relocation

The duration time of relocation is related to the type of MEC application (e.g. dedicated, stateful, stateless), the transmission delay between the target MEC host and the current MEC host, the time to install a MEC application, the time to instantiate a MEC application instance, and the time to set up a PDU Session; service interruption probability is related to the type of the MEC application and the duration time of a relocation; the service latency between a UE and the target MEC host is related to the location of this MEC host and the relevant MEC application type; the current available resources in a MEC host must be enough to serve the UE, otherwise this MEC host cannot be a potential target MEC host for this UE. After each relocation, information related to these four performance indicators will be collected, calculated and sent to the MEC system as the feedback of this relocation.

The entire relocation process can be modelled as a Markov Decision Process (MDP). In this MDP model, S is the set of states, each state $s \in S$ represents a MEC host. The end states in this MDP model are the MEC hosts whose serving areas cover the exit of the road in the geographic service area. A_s^{app} is the set of all possible actions that can be taken for a UE, which is now receiving services provided by MEC application app in MEC host s and needs a relocation. Each action $a \in A_s^{app}$ is selecting a target MEC host for the UE and handing the UE over to the selected MEC host. After an action is executed, the UE will move to a new state/MEC host, with probability $p = 1$. The reward of each action $reward_a$ is derived from the first three performance indicators mentioned above. The reward of each action is calculated from Equation 4.3:

$$reward_a = -5 \times \text{duration time of relocation} - 1 \text{ (if there is a service interruption) or } 0 \text{ (if there is no service interruption)} \times \text{priority of the MEC application} - 10 \times \text{the service latency at the target MEC host selected in action } a \quad (4.3)$$

Assumptions in section 3.1 are still applied in this chapter. Besides, some extra assumptions are made:

1. All relocation processes are controlled by the central controller, which can be the MEO or some other system-level functional element in MEC.
2. Installation of MEC applications are costly, both time-wise and resource-wise. Therefore, it saves time and resources to choose a MEC host which has enough resources and has required MEC application installed. This target MEC host-selecting mechanism, which is introduced as “fixed target MEC host-selecting mechanism” in section 4.3, is the focus in the following sections.
3. In section 1.5, it has been discussed whether to include mobile MEC hosts in this master thesis or not, and considering the potential increase in the complexity of the project, mobile MEC hosts are left out and only stationary/fixed MEC hosts are considered. Relocations can only take place between stationary/fixed MEC hosts.

As explained in section 4.2, SARSA learning algorithm is more suitable for optimizing the relocation process.

However, considering the fact that the size of the geographic service area has no limitation, it is possible that the number of MEC hosts in this area is very large, which will result in a large state space in the system MDP model. Under this circumstance, classical SARSA learning needs a tremendous big table to save all the q values, and it may take too much time for searching a required q value in this big q table. Furthermore, when the state space becomes larger, it takes longer time for the q table to converge. To solve this problem, a combination of deep learning and SARSA learning, which is called “Deep SARSA” in this article, is used. The basic idea of “Deep SARSA” comes from Deep Q Network (DQN) developed by Google DeepMind team [42]. The only difference between these two algorithms is the same as the difference between SARSA learning and Q learning. The most outstanding contribution of DQN is that, it uses a neural network to predict the q values, instead of using a table to save them. By doing this, the size of the state space is not a critical factor anymore, no matter how big the state space is, the only parameters that need to be saved and updated are simply the parameters in the deep neural network and the convergence time will not grow rapidly with the size of the state space.

Although introducing a deep neural network into a traditional reinforcement learning algorithm can help solving the state space explosion problem, it also brings up other problems. For example, the structure as well as the parameters (e.g. learning rate) of the deep neural network are crucial to the neural network training and the accuracy of its prediction. Compared to the straightforward way to save q values in a q table separately, using a neural network to predict the q values has the impact that different state-action pair may affect each other, since they share the same deep neural network to do the prediction. Therefore, the key to increase the accuracy of predictions given by the deep neural network is that it can find the internal relations between the rewards and the corresponding state-action pairs and modify the parameters accordingly, which is not easy to achieve since determining suitable structure of the neural network, activation functions and optimization function requires experience and lots of experiments. For different environments, their suitable deep neural networks for prediction can be different.

Since the two algorithms have their own upsides and downsides, in this master thesis, both are implemented, tested, compared and analyzed. Furthermore, a quick-start SARSA learning algorithm is designed to combine the advantages of both algorithms. The performance indicators used to evaluate the algorithms in this chapter include the speed of convergence and the convergence value. The faster the algorithm converges, the better the algorithm performs; the higher the convergence value is, the better the algorithm performs. The choice of algorithm should be based on not only the performance of the algorithm, but also other factors including the actual scale of the problem, financial requirements, etc.

4.5 Algorithms using Deep SARSA learning

In this section, algorithms for choosing target MEC hosts, updating parameters in deep neural network, performing reinforcement learning and handling exceptional case are introduced, each of them is a sub-algorithm of the entire algorithm.

A. Choose target host

To select a suitable target host for each UE, algorithm 6 is designed, and the details are included in Table 4.1.

Table 4.1: Algorithm 6

Algorithm 6. Choose target host for a UE of application app in state s	
Input:	
MDP:	System MDP model
s:	The current state this UE is in, that is, the current serving MEC host of this UE
app:	The application whose instance needs to be moved
$DNN_{predict}$:	The deep neural network used to update q values for MEC hosts.
ε:	The parameter used in ε-greedy algorithm.
$Paths$:	$Paths(k)$ records all the paths selected for MEC application k and the number of UEs each path serves.
$resources_{app}$:	The required amount of resources per UE of MEC application app.

Output:

a_s^{app}: The action taken in state s for MEC application app.

s': Next state/target MEC host

$q^{app}(s, a_s^{app})$: The estimated q value of state-action pair (s, a_s^{app}).

Updated $Paths$

$e = \boldsymbol{random1}(0,1)$;
$qvalues = \{\}$;
$A_s^{app} = \boldsymbol{get\_actions}(MDP, s, app, Paths)$;
if $e \leq \varepsilon$ **do**
  for all $a \in A_s^{app}$ **do**
    $q = DNN_{predict}(s, a, app)$;
    $qvalues = qvalues \cup \{q\}$;
  end for
  $q^{app}(s, a_s^{app}), index = \boldsymbol{Max}(qvalues)$;
  $a_s^{app} = A_s^{app}(index)$
else
  $a_s^{app} = \boldsymbol{random2}(A_s^{app})$;
  $q^{app}(s, a_s^{app}) = DNN_{predict}(s, a, app)$;
end if
$s' = MDP(s, a_s^{app})$;
$Paths = \boldsymbol{reserve\_resources}(Paths, resources_{app}, s', app)$;

To select an action, the first step is to generate a random number between 0 and 1, function $\boldsymbol{random1}(0,1)$ is used for this purpose. Then, find all possible target MEC hosts that can be selected, these MEC hosts should have the required MEC application installed, should have enough resources to serve the UE and should have overlapping serving area with the current serving MEC host of the UE. Function $\boldsymbol{get\_actions}$ is designed to find all the actions/target MEC hosts that satisfy all the above requirements and return a set A_s^{app} including all the possible options. Its inputs MDP, s and app are used to find all the MEC hosts which have overlapping serving area with the current MEC host and have required application installed, input $Paths$ is used to check the amount of available resources in each target MEC host. After getting the possible actions set, compare the generated number *e* with epsilon value (ε). Based on the result of comparison, different actions will be taken:

- If the generated number *e* is larger than ε, then algorithm will exploit the current learned q values this time and pick the action $a_s^{app} \in A_s^{app}$ with the highest q value. Function $\boldsymbol{Max}$ is used to find the largest value in a set.
- If the generated number *e* is smaller than ε, then algorithm will explore the real world by randomly selecting a possible action. Function $\boldsymbol{random2}$ will randomly pick one element from the input set.

In Deep SARSA learning, q values can be derived from a deep neural network ($DNN_{predict}$). The current state s, the selected action a and application type app and $DNN_{predict}(s, a, app)$ are used to get the predicted q value for state-action pair (s, a).

After both action a_s^{app} and its corresponding q value $q^{app}(s, a_s^{app})$ are determined,

Algorithm 6 determines the next state/MEC host s' in the system MDP model MDP according to the selected action a_s^{app} and reserves resources for this UE in the selected target MEC host s' with function $\boldsymbol{reserve\_resources}$.

B. Update parameters of deep neural network

Table 4.2 introduces the approach to update deep neural networks in Deep SARSA Network.

Table 4.2: Algorithm 7

Algorithm 7. Update deep neural networks $DNN_{predict}$ and DNN_{update}	
Input:	
s:	The current state this UE is in, that is, the current serving MEC host of this UE.
$reward_{a_s^{app}}$:	The reward of taking action a_s^{app}.
app:	The application whose one instance needs to be moved with the UE.
$DNN_{predict}$:	The deep neural network used to update q values for MEC hosts.
DNN_{target}:	The deep neural network used to provide q values when selecting MEC hosts.
s':	The next state, or, the selected target MEC host of this UE.
a_s^{app}:	The action which is selected to be taken at current state.
$a_{s'}^{app}$:	The action which is selected to be taken at next state.
γ:	Future reward decay.
$memory$:	A table that saves historical records.
$memory\_size$:	The maximal number of historical records can be saved in table $memory$ for future training.
$batch\_size$:	The number of samples utilized in one iteration of training.
$period$:	Update period of DNN_{update}.
$counter$:	The number of training iterations of $DNN_{predict}$ after the latest update of DNN_{target}, its initial value is 0.
Output:	
Updated $DNN_{predict}$	
Updated DNN_{target}	

$new\_record = \{s, a_s^{app}, reward_{a_s^{app}}, s', a_{s'}^{app}\}$;

$memory = \boldsymbol{add\_record}(memory, new\_record, memory\_size)$;
$batch = \boldsymbol{random3}(memory, batch\_size)$;
for all $record \in batch$ **do**
    $state = record(1)$;
    $a = record(2)$;
    $reward = record(3)$;
    $state' = record(4)$;
    $a' = record(5)$;

$q_{predict} = DNN_{predict}(state, a, app)$;
$q_{target} = reward + \gamma \cdot DNN_{target}(state', a', app)$;
$DNN_{predict} = \boldsymbol{Update3}(DNN_{predict}, q_{predict}, q_{target})$;
$counter = counter + 1$;
if $counter == period$ **do**
$counter = 0$
$DNN_{target} = DNN_{predict}$
end if
end for

To reduce the correlation between two sequential states and their q values, deep SARSA learning applies two deep neural networks with the same structure but different parameters. One neural network, or evaluate network ($DNN_{predict}$), is used for learning and providing q values during action selection, while the other neural network, or target network (DNN_{target}), is used only for estimating the real-world q values. Evaluate network updates its parameters according to the q values (q_{target}) given by the target network, and target network also updates its parameters to the parameters of evaluate network periodically.

Every time a new record (new_record) is generated, it will be added to a table ($memory$), if the table is full (the number of records in table $memory$ reaches its maximum size $memory\_size$), then the oldest record in the table will be removed. Then, $batch\_size$ number of historical records are randomly picked from $memory$ by function $\boldsymbol{random3}$. These records are used to update $DNN_{predict}$, and function $\boldsymbol{Update3}$ is responsible for the updates. RMSProp algorithm [40] is the core method to update parameters in $DNN_{predict}$ based on the squared difference between q_{target} and $q_{predict}$.

C. Dealing with exception – No MEC hosts currently available

When no MEC host with required MEC application installed has enough resources to serve a UE, a MEC host that has enough resources should be selected to serve the UE temporarily. For load-balancing purpose, the MEC host with the largest amount of available resources will be selected as the temporary MEC host.

Even though this situation is considered, it is not a desired situation of the entire system. However, due to the uncertainties in the reality, exceptions may occur at any time. To guarantee service continuity for every UE, Algorithm 8 is introduced, which basic procedure is shown in Table 4.3.

Table 4.3: Algorithm 8

Algorithm 8. Choose a temporary target MEC host for a UE of MEC application app	
Input:	
MDP:	System MDP model.
LL:	A set of all possible locations.
s:	The current state this UE is in, that is, the current serving MEC host of this UE.

app:	The application whose one instance needs to be moved with the UE.
$R = \{R_{ll}\}, \forall\ ll \in LL$:	
	R_{ll} is the set of currently available resources in all unit-hosts in location $ll \in LL$.
G:	The directed graph that represents all the sites.
$resources_{app}$:	The required amount of resources per UE of MEC application app.
Output:	
Updated R	
s':	The next state of this UE.

$successors = \boldsymbol{successors}(G, s)$;
$max\_resources = resources_{app}$;
$max\_host = None$;
for all $successor \in successors$ **do**
  for all $ll \in LL$ **do**
    if $R_{ll}(successor) \geq max\_resources$ **do**
      $max\_host = successor$;
      $max\_location = ll$
    end if
  end for
end for
$s' = MDP(max_{host}, max_{location})$;
$R_{max\_location}(max\_host) = R_{max\_location}(max\_host) - resources_{app}$;

The basic idea of Algorithm 8 is straightforward: Find all the MEC hosts that have overlapping serving area with the current serving MEC host of the UE, and this is done by function $\boldsymbol{successors}$. Then check current available resources in each MEC host found and pick the one with the largest amount of available resources as the temporary target MEC host, install the required MEC application app on the MEC host and reserve enough resources in this MEC host. Finally, determine the corresponding state s' of this temporary MEC host in system MDP model MDP, and state s' is UE's next state in MDP.

Since this MEC host is temporarily providing MEC application app, after the UE has left this MEC host, uninstall the MEC application and release all the related resources. Besides, the rewards/feedback of this MEC host will not be recorded for further training, in case it affects the performance of $DNN_{predict}$.

If this exceptional case does not occur frequently, it can be ignored. However, if within a certain period of time, the number of UEs of MEC application app that run into this problem exceeds a certain threshold, which means that the actual number of UEs using app in the geographic service area is larger than the estimated number, then scaling up MEC application app becomes urgent and necessary. In this project, more precisely, if the number of UEs that need to be served by a temporary MEC host exceeds 10% of the estimated maximum number of UEs, allocate 30% extra resources for app in the network.

E. Deep SARSA Learning

Algorithm 9 showed in Table 4.4 gives an overall structure of the Deep SARSA learning.

Table 4.4: Algorithm 9

Algorithm 9. Reinforcement learning algorithm related to one UE of MEC application app	
Input:	
MDP:	System MDP model.
s_{start}:	The starting state of this UE, that is, the first MEC host that serves the UE in the geographic service area.
app:	The application whose one instance needs to be moved with the UE.
ε:	The parameter used in ε-greedy algorithm.
$Paths$:	$Paths(k)$ records all the paths selected for MEC application k and the number of UEs each path serves.
$resources_{app}$:	The required amount of resources per UE of MEC application app.
$DNN_{predict}$:	The deep neural network used to update q values for MEC hosts.
DNN_{target}:	The deep neural network used to provide q values when selecting MEC hosts.
s':	The next state of this UE.
α:	Learning rate.
γ:	Future reward decay.
$memory$:	A table that saves historical records.
$memory\_size$:	The maximal number of historical records can be saved in table $memory$ for future training.
$batch\_size$:	The number of samples utilized in one iteration of training.
$period$:	Update period of DNN_{update}.
$counter$:	The number of training iterations of $DNN_{predict}$ after the latest update of DNN_{target}, its initial value is 0.
Output	
Updated $DNN_{predict}$	
Updated DNN_{target}	

$s = s_{start}$;

$a, s', q, Paths = \boldsymbol{A6}(MDP, s, app, DNN_{predict}, \varepsilon, Paths, resources_{app})$;

While $True$ **do**

$Oberserve\ the\ reward\ of\ taking\ action\ a\ in\ state\ s: \boldsymbol{reward_a}$;

$a', s'', q', Paths = \boldsymbol{A6}(MDP, s', app, DNN_{predict}, \varepsilon, Paths, resources)$;

$DNN_{predict}, DNN_{target} = \boldsymbol{A7}(s, reward_a, app, DNN_{predict}, DNN_{target}, s', a, a', \gamma, memory, memory\_size, batch\_size, period, counter)$

;

$If\ the\ UE\ moves\ out\ of\ the\ area, end\ While\ loop$

$s = s'$;

$a = a'$;

$s' = s''$;
end While

From the procedures of Algorithm 9 it can be seen that, after a UE enters the geographic service area, the central controller will continuously help the UE to find new MEC hosts for maintaining the UE's MEC service continuity. When the UE finally reaches one MEC host that can cover the exit of the road, it will be served by this MEC host till it moves out of the geographic service area, and no relocation is needed.

4.6 Algorithm using Traditional SARSA learning

The classical SARSA learning algorithm is similar to the deep SARSA learning algorithm introduced in section 4.5, therefore, only the different parts are introduced in this section.

A. Update q values in the q table

Traditional SARSA learning uses a q table to save all the q values. To update q values that are saved in a q table, algorithm 10 is designed, and detailed information is in Table 4.5.

Table 4.5: Algorithm 10

Algorithm 10. Update q table for MEC hosts	
Input:	
s:	The current state this UE is in, that is, the current serving MEC host of this UE.
$reward_{a_s^{app}}$:	The actual reward of taking action a_s^{app}.
app:	The application whose one instance needs to be moved with the UE.
$QTable$:	The table used to save all estimated q values in traditional SARSA learning algorithm.
$q^{app}(s', a_{s'}^{app})$:	Estimated q value of state-action pair $(s', a_{s'}^{app})$ of MEC application app.
α:	Learning rate.
γ:	Future reward decay.
Output:	
Updated $QTable$	
$q_{predict} = QTable(s, a_s^{app}, app);$	
$q_{target} = reward_{a_s^{app}} + \gamma \cdot q^{app}(s', a_{s'}^{app});$	
$q_{new} = q_{predict} + \alpha(q_{target} - q_{predict});$	
$QTable(s, a, app) = q_{new};$	

Since the q values of MEC hosts are saved directly in $QTable$, they can be reached and updated directly. The updating mechanism is the same as what is shown in Equation 4.2.

B. Traditional SARSA Learning

Table 4.6 shows the overall structure of the traditional SARSA learning algorithm. Function $\boldsymbol{A6}$ is Algorithm 6, and function $\boldsymbol{A10}$ is Algorithm 10.

Table 4.6: SARSA learning algorithm

Algorithm 11. SARSA learning algorithm related to one UE of MEC application app	
Input:	
MDP:	System MDP model.
s_{start}:	The starting state of this UE, that is, the first MEC host that serves the UE in the geographic service area.
app:	The application whose one instance needs to be moved with the UE.
$QTable$:	The table used to save all estimated q values in traditional SARSA learning algorithm.
ε:	The parameter in ε-greedy algorithm.
$Paths$:	$Paths(k)$ records all the paths selected for MEC application k and the number of UEs each path serves.
$resources_{app}$:	The required amount of resources per UE of MEC application app.
s':	The next state of this UE.
α:	Learning rate.
γ:	Future reward decay.
Output	
Updated $QTable$	

$s = s_{start}$;
$a, s', q, Paths = \boldsymbol{A6}(MDP, s, app, QTable, \varepsilon, Paths, resources)$;
While $True$ **do**
  $Oberserve\ the\ reward\ of\ taking\ action\ a\ in\ state\ s: \boldsymbol{reward_a}$;
  $a', s'', q', Paths = \boldsymbol{A6}(MDP, s', app,\ QTable, \varepsilon, Paths, resources_{app})$;
  $QTable = \boldsymbol{A10}(s, reward_a, app, QTable, q', \alpha, \gamma)$;
  $If\ the\ UE\ moves\ out\ of\ the\ area, end\ While\ loop$
   $s = s'$;
   $a = a'$;
   $s' = s''$;
end While

4.7 Quick-start SARSA learning algorithm

It has been discussed in section 4.4 that both the deep SARSA algorithm and the traditional SARSA algorithm have advantages and disadvantages. This can be discovered from Figure 4.7. The deep neural networks used in the deep SARSA learning algorithm are two identical deep neural networks with three densely-connected layers each.

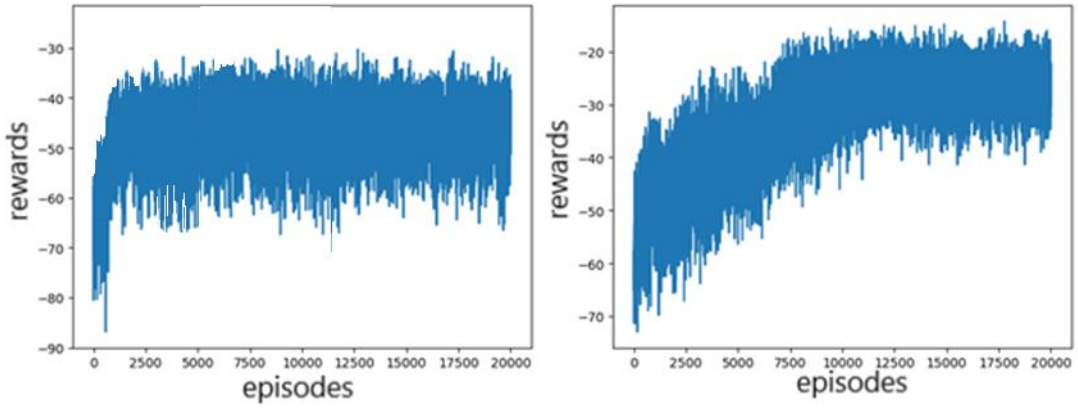


Figure 4.7: Rewards given by the deep SARSA learning (left) and the traditional SARSA learning (right) versus episodes

Figure 4.7 is derived from a simulation where the geographic service area contains 1000 sites. One episode starts when a UE enters the geographic service area and ends when it leaves the area. The reward at each episode is $\sum_{a\in A} reward_a$, where A is a collection of all the actions taken in this episode, and $reward_a$ is calculated from Equation 4.3. The better the user experience in this episode is, the higher the corresponding reward is.

It can be observed from Figure 4.7 that deep SARSA learning algorithm converges after about 2500 episodes, and that is much faster than the traditional SARSA learning algorithm, which converges after 12500 episodes. However, deep SARSA learning algorithm converges at a lower value than traditional SARSA learning algorithm. The reason behind is explained in section 4.4.

What is desired is to combine all the advantages of both algorithms and get rid of their disadvantages. More precisely, the desired algorithm can converge fast and converge at a high reward. In this section, a quick-start SARSA learning algorithm which is capable to do both is introduced, and the pseudocode is shown in Table 4.7. Function $\boldsymbol{A7}$ is Algorithm 7.

Table 4.7: The quick-start SARSA learning algorithm

Algorithm 12. The quick-start SARSA learning algorithm	
Input:	
MDP:	System MDP model.
s_{start}:	The starting state of this UE, that is, the first MEC host that serves the UE in the geographic service area.
app:	The application whose one instance needs to be moved with the UE.
$QTable$:	The table used to save all estimated q values in traditional SARSA learning algorithm.
ε:	The parameter in ε-greedy algorithm.
$Paths$:	$Paths(k)$ records all the paths selected for MEC application k and the number of UEs each path serves.
$resources_{app}$:	The required amount of resources per UE of MEC application app.
s':	The next state of this UE.
α:	Learning rate.

γ:	Future reward decay.
$DNN_{predict}$:	The deep neural network used to update q values for MEC hosts.
DNN_{target}:	The deep neural network used to provide q values when selecting MEC hosts.
$memory$:	A table that saves historical records.
$memory\_size$:	The maximal number of historical records can be saved in table $memory$ for future training.
$batch\_size$:	The number of samples utilized in one iteration of training.
$period$:	Update period of DNN_{update}.
$counter$:	The number of training iterations of $DNN_{predict}$ after the latest update of DNN_{target}, its initial value is 0.

Output

Updated $QTable$

Updated $DNN_{predict}$

Updated DNN_{target}

$s = s_{start}$;

$a, s', q, Paths = \boldsymbol{A6}(MDP, s, app, QTable, \varepsilon, Paths, resources_{app})$;

While $True$ **do**

$Oberserve\ the\ reward\ of\ taking\ action\ a\ in\ state\ s: \boldsymbol{reward_a}$;

$e = \boldsymbol{random1}(0,1)$;

$qvalues = \{\}$;

$A_s^{app} = \boldsymbol{get\_actions}(MDP, s, app, Paths)$;

if $e \leq \varepsilon$ **do**

for all $a \in A_s^{app}$ **do**

$q = QTable(s, a, app)$;

if $q == 0$ **do**

$q = DNN_{predict}(s, a, app)$;

end if

$qvalues = qvalues \cup \{q\}$;

end for

$q^{app}\left(s, a_s^{app}\right), index = \boldsymbol{Max}(qvalues)$;

$a_s^{app} = A_s^{app}(index)$

else

$a_s^{app} = \boldsymbol{random2}(A_s^{app})$;

$q^{app}(s, a_s^{app}) = DNN_{predict}(s, a, app)$;

end if

$s' = MDP(s, a_s^{app}, app)$;

$Paths = \boldsymbol{reserve\_resources}(Paths, resources_{app}, s', app)$;

$QTable = \boldsymbol{A10}(s, reward_a, app, QTable, q', \alpha, \gamma)$;

$DNN_{predict}, DNN_{target} = \boldsymbol{A7}(s, reward_a, app, DNN_{predict}, DNN_{target}, s', a, a',$
$\gamma, memory, memory\_size, batch\_size, period, counter)$;

$If\ the\ UE\ moves\ out\ of\ the\ geographic\ service\ area, end\ While\ loop$

$s = s'$;

$a = a'$;

$s' = s''$;
end While

The main difference between the quick-start SARSA learning algorithm and the deep/traditional SARSA learning algorithms lies in the action selection part. if the state-action pair has not been visited, hence, its corresponding q value in the q table $QTable$ still has the initial value 0, then deep neural network $DNN_{predict}$ will be used to predict the q value of this state-action pair. If the state-action pair has been visited before, its corresponding q value will be provided by the q table $QTable$. To make this work, both deep neural networks $DNN_{predict}, DNN_{target}$ and the q table $QTable$ need to be updated.

Figure 4.8 shows the results given by the quick-start SARSA learning algorithm. The geographic service area considered here is the same as the geographic service area used in Figure 4.7.

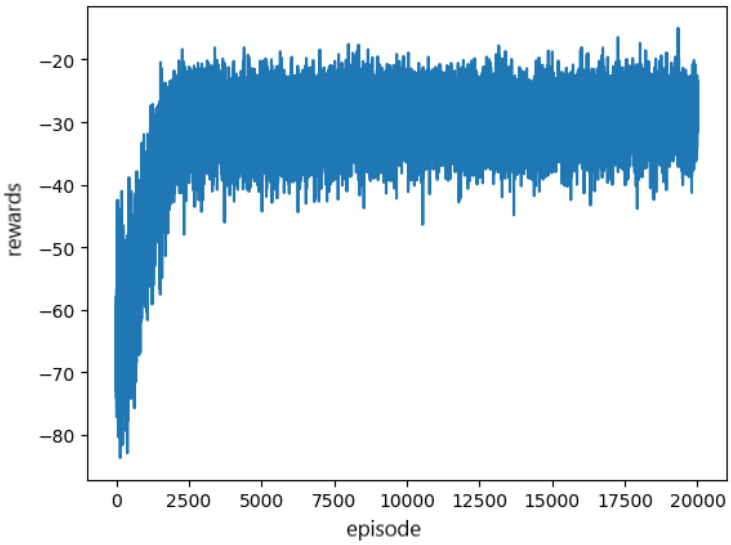


Figure 4.8: Rewards given by the quick-start SARSA learning algorithm versus episodes

The quick-start SARSA learning algorithm converges after about 2500 episodes, which is as quick as the deep SARSA learning, and converges at a reward value around -30 which is as high as the traditional SARSA learning. The reason why this quick-start SARSA learning algorithm can give a satisfying performance is that it combines prediction in deep SARSA learning and the q table in traditional SARSA learning. By predicting the reward (q value) of an unvisited state-action pair using the deep neural network, the convergence of the quick-start SARSA learning algorithm is faster than the traditional SARSA learning algorithm; and by saving the updated q value of each visited state-action pair in the q table separately, the convergence value of the quick-start SARSA learning algorithm is higher than the deep SARSA learning algorithm.

Although the quick-start SARSA learning algorithm performs well, it is not always necessary to choose it to solve research problem 4. As mentioned in section 4.4, the choice of algorithms depends on the actual situation:

1. If the geographic service area is small enough, or, the convergence time of the

traditional SARSA learning algorithm is acceptable, then it is redundant to maintain a deep neural network at the same time, simply using traditional SARSA learning is the most economical way.

2. If the geographic service area contains (too) many sites and thus requires a huge q table which is infeasible/costly, or, the convergence value of the deep SARSA learning algorithm is acceptable, then the deep SARSA learning becomes the best choice since it can save storage resources and it converges fast.
3. If the geographic service area has a lot of unit-hosts, and the required convergence speed and convergence value are high, then the quick-start SARSA learning algorithm is definitely the one to choose.

4.8 Decision-making mechanism

To decide on the group of possible target MEC hosts when an exception takes place, a decision-making mechanism is proposed in this section. Figure 4.9 illustrates the basic procedure to determine the possible target MEC hosts following the proposed decision-making mechanism.

For a MEC application, if the current available MEC hosts with this MEC application installed are unable to support all the UEs that use this MEC application, but there are still resources available in other MEC hosts (Exception 1), Algorithm 8 will determine temporary MEC hosts to serve UEs among these MEC hosts. The required MEC application will be temporarily installed in the MEC hosts selected by Algorithm 8. If the number of resource shortage problems of the same MEC application exceeds a certain threshold defined in section 4.5 (Exception 2), then the “simulation-based + VNS” locating mechanism in Chapter 3 is invoked to allocate more resources for this MEC application.

When the current available MEC hosts in the geographic service area are unable to support all the UEs (Exception 3), the “simulation-based + VNS” locating mechanism is used again to properly add more MEC hosts to the network.

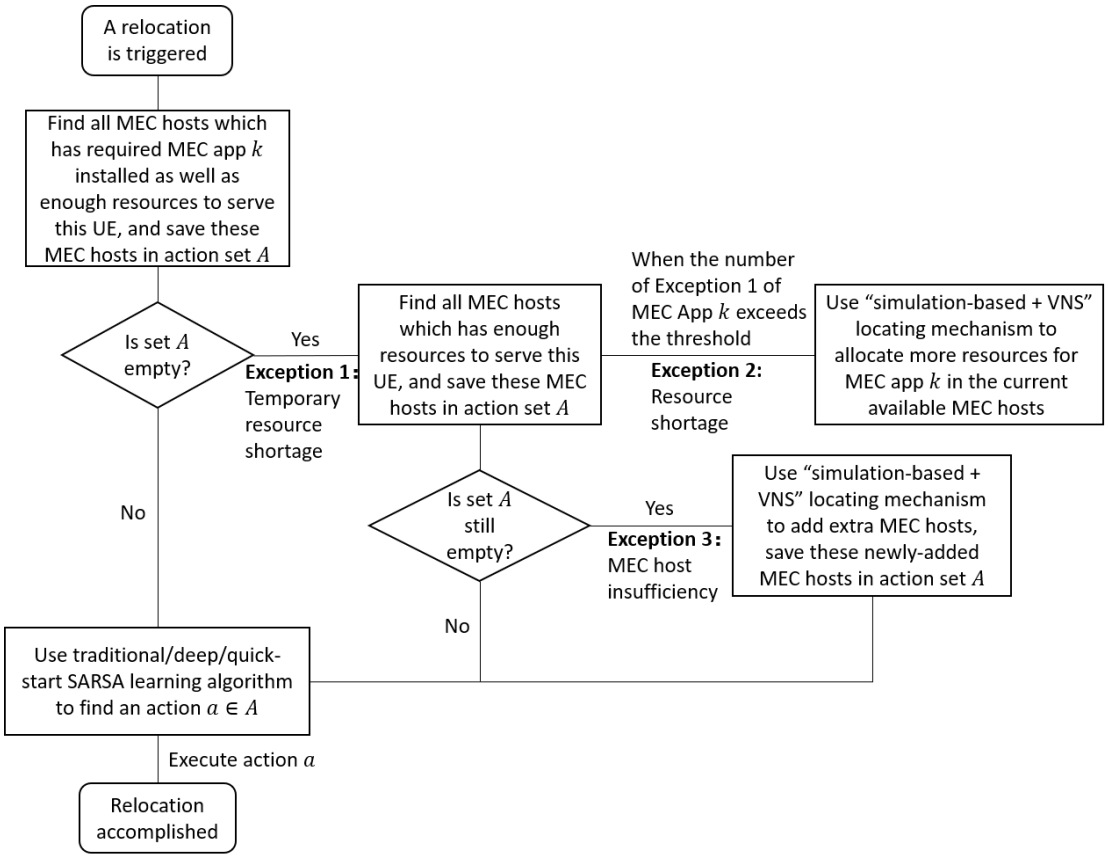


Figure 4.9: A decision-making mechanism.

4.9 Summary

Chapter 4 mainly answers the first three sub-questions of research question 4: Devise an algorithm to dynamically find the optimal location of a MEC application processing instance for a UE (can be all kinds of equipment mounted in vehicles, machines, cellphones, etc.).

a) What parameters of the possible target MEC hosts should be taken into consideration?

Four aspects are considered to estimate the behavior of a possible target MEC host in a relocation: 1. The duration time of the relocation; 2. Whether there is a service interruption during the relocation; 3. The latency between the UE and the MEC host; 4. The current amount of available resources in the MEC host.

The duration time of the relocation and the service latency between the UE and the MEC host can be directly transformed into two parameters. There is another parameter that indicates the occurrence of a service interruption during a relocation. If there is no service interruption, the value of this parameter will be 0; otherwise, the value will be $prior_k$, where k is the MEC application required by the UE. The current amount of available resources inside the MEC host is not transformed into a parameter. Instead, it is used to filter the MEC hosts that do not have enough resources to serve the UE.

b) How to choose the target MEC host based on these parameters?

The three parameters determined in sub-question a) are weighted and added to each other

to evaluate the overall performance of a possible target MEC host in a relocation (as shown in Equation 4.3). For a UE, not only the performance of its next serving MEC host, but also the performances of MEC hosts that may serve it afterwards are important. Therefore, an MDP and reinforcement learning are considered in this sub-question. An MDP is used to model the network topology and the MEC hosts inside the network. Reinforcement learning can estimate the overall performances of each possible target MEC host and its subsequential MEC hosts. Based on the estimations, reinforcement learning algorithms will choose the most suitable target MEC host for a UE.

c) *What information can be provided as feedback after a relocation to estimate the quality of this relocation and the behavior of the target MEC host? How to process/utilize the feedback information?*

In sub-question b), the most suitable MEC host for a UE is chosen based on the overall performance of each MEC host estimated by a reinforcement learning algorithm. To estimate the overall performance, feedback is needed. When a relocation is finished and the UE is handed over to the target MEC host, the duration of this relocation, the service latency between the UE and its new MEC host as well as the number of service interruptions in this relocation will be recorded, calculated and reported to the central controller in which the reinforcement learning algorithm is implemented. Questions like which entities are responsible to collect, calculate and transfer the feedback and how the feedback is collected and calculated are out of the scope of this master thesis.

Every time after receiving the feedback, the reinforcement learning algorithm will first use the feedback to update its estimations on the overall performance of the relevant MEC hosts, and then it will decide on the most suitable MEC host for UEs based on the new estimations.

Chapter 5 Simulations and Tests

In this chapter, descriptions and measurements on the +31 Network at Ericsson Rijen are included, as well as various simulations that are set up to test the performance of the algorithms designed in Chapter 4. The simulation outcomes are shown, compared and analyzed in this chapter.

5.1 Measurements of MEC in real 5G environment

A. 5G Network Setup at Ericsson Rijen

One of Ericsson's 5G network is in Rijen, the Netherlands, and it is also known as the +31 Network. +31 Network uses a None Stand-Alone (NSA) architecture. In the NSA architecture, the core network is an EPC instead of an independent 5G core, and there exist eNodeBs and gNodeBs, both of which a UE can connect to via different interfaces. If a UE is connected to an eNB, user signaling and data will be transferred via E-UTRAN interface; if it is connected to a gNB, all the signals and data will be transferred via NR-Uu interce. MME is the main controller in the EPC, to be able to support 5G NR, MME together with other core network entities such as PCRF, S-Gw, P-Gw and HSS need to be updated accordingly. Control and User Plane Separation (CUPS) is applied in the core of the +31 Network, so the S-Gw and P-Gw are split up into S-Gw-C/P-Gw-C and S-Gw-U/P-Gw-U. In the +31 Network, there is one S-Gw and one P-Gw and they are combined into one common gateway.

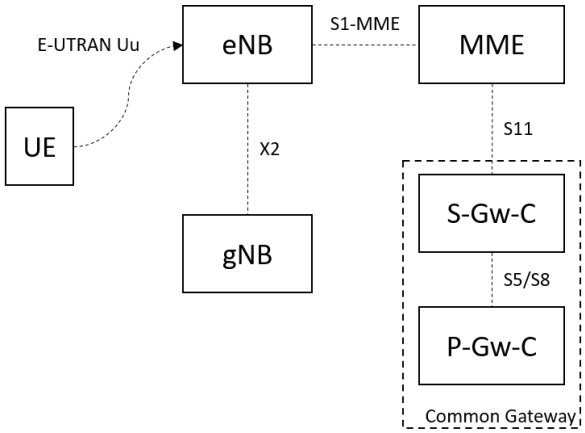


Figure 5.1: Control plane architecture of the +31 Network.

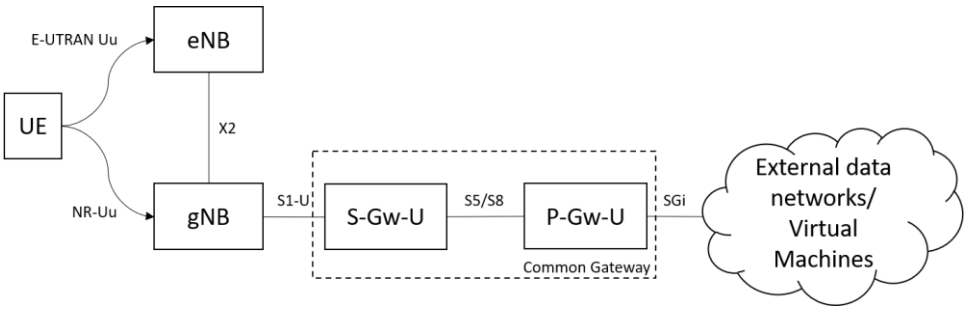


Figure 5.2: User plane architecture of the +31 Network.

A PDN connection is established between the UE and the common gateway to transfer user data, and user data can reach external networks and services via the common gateway under the control of core network entities (e.g. MME. PCRF, etc). When a UE wants to access to an external network, cloud or virtual machines, signaling will be transferred in control plane towards the EPC via eNB as shown in Figure 5.1, while the payloads will be transferred in user plane towards the EPC via gNB and finally reach the external data network (e.g. IMS, virtualized machines) via the common gateway, as shown in Figure 5.2. External data networks might be located far away from the common gateway in Rijen, for example, IMS network connected to the +31 Network is in Sweden. Even though transmission via optical fibers can reach a speed of approximately 200,000,000 m/s, the large number of transmission nodes in between can cause big delays. With edge computing, this problem will be solved, because the data computing, storage and processing capacities are located physically close to the common gateways.

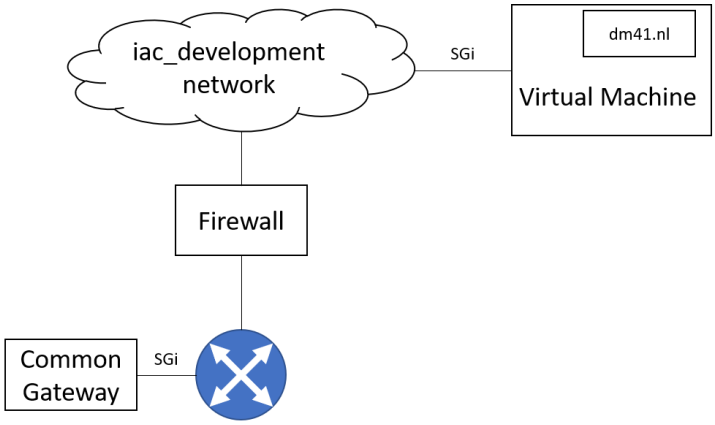


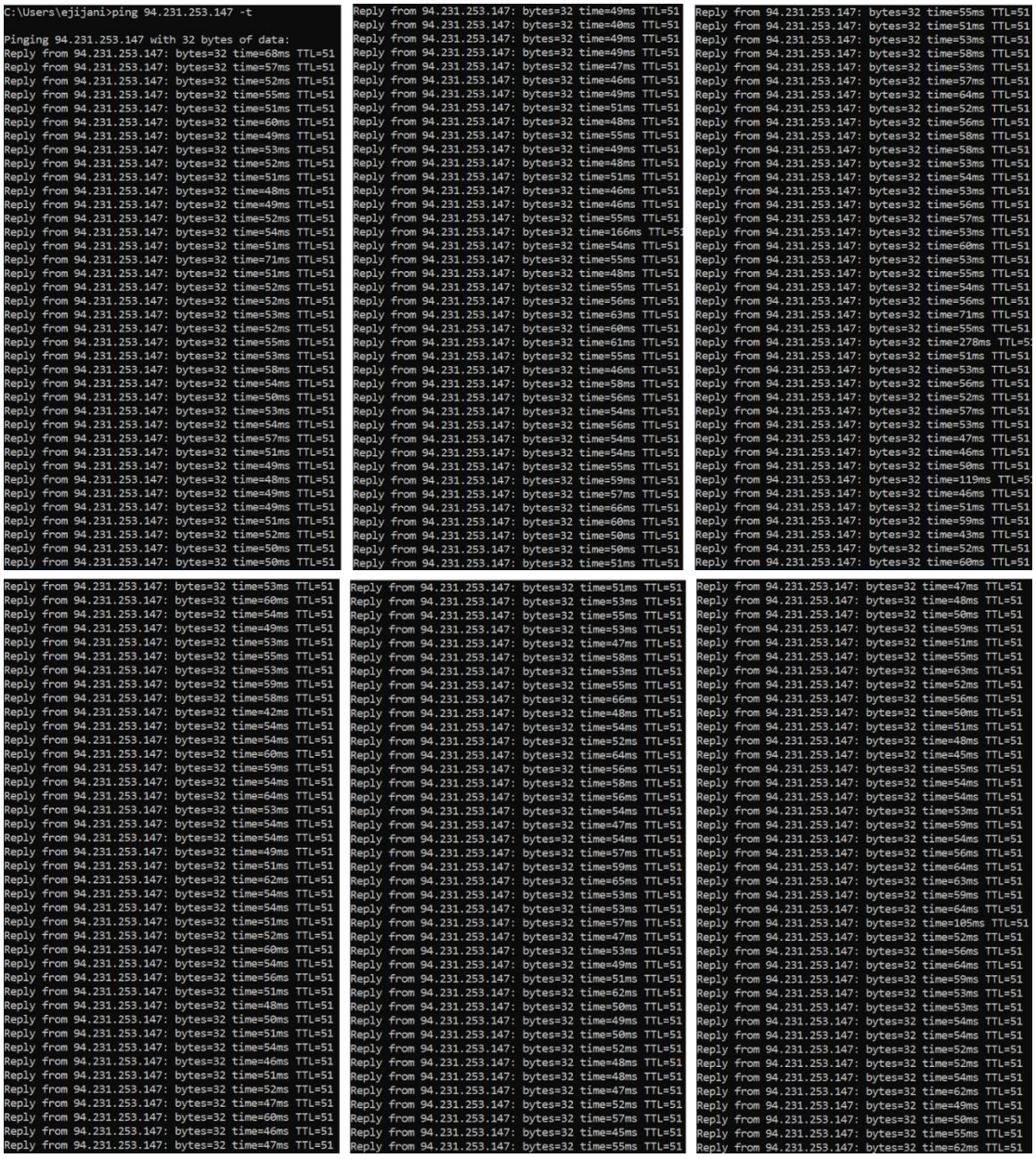
Figure 5.3: Access to the VM.

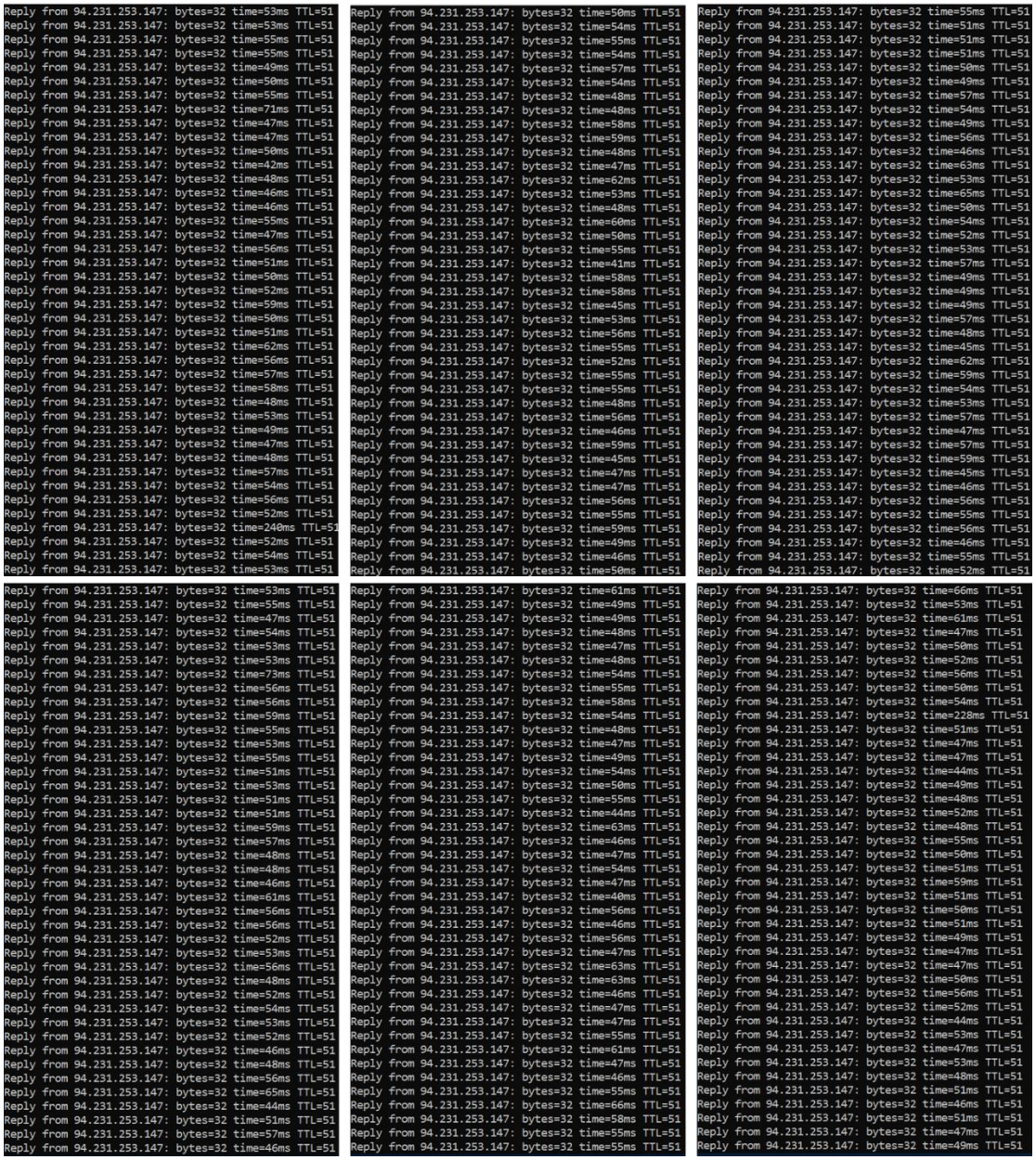
In the +31 Network, one VM is used for measurements, and its connection towards the common gateway in EPC is shown in Figure 5.3. Data sent from the laptop first goes through the access network and enters the EPC, then the data leaves the EPC via common gateway and reaches a router, which forwards the data towards a firewall. Though the firewall, the data reaches iac_development network and is then forwarded towards the VM. The VM (IP: 192.168.254.70/28) is running on VMware on a HP server, and it is connected to the iac_development network (IP: 192.168.254.64/27). Upon the VM, there is a host called dm41.nl (IP: 94.231.253.147). The Round-Trip Time (RTT) is measured between the laptop

and dm41.nl, and RTT can represent the service latency. Measurement results are used in simulations in section 5.3 to generate a mechanism for simulating a test environment that is close to reality.

B. Measurements

The measured RTT between the laptop and host dm41.nl is shown in Figure 5.4. Figure 5.4 contains multiple pings, and the “time” in each record is a RRT, the maximum RRT in Figure 5.4 is 253ms. This dm41.nl host is located close to the core network, and the service latency can be reduced if the MEC host is located closer to the network edge.

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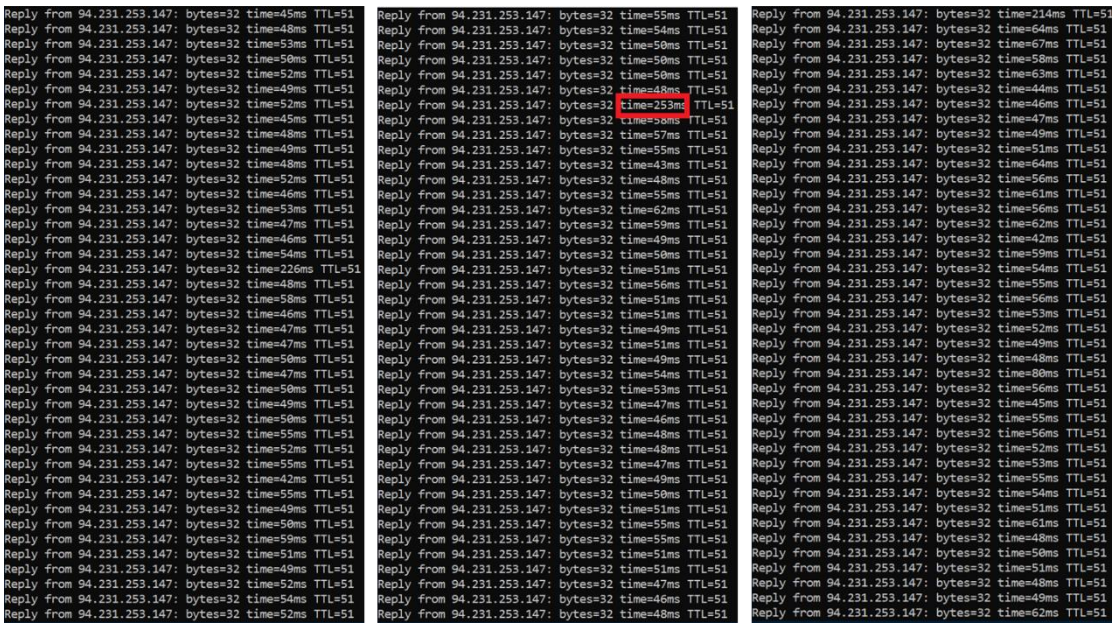

Figure 5.4: The measured RTTs between the laptop and host dm41.nl

5.2 Simulations

A. Assumptions

Before describing the settings of the various simulations in this chapter, the following set of assumptions is proposed which is applicable to all the simulations in this chapter.

1. All the MEC applications that are provided to the UEs in the geographic service area are installed in the MEC hosts properly to meet the latency and resource requirement of every UE under the extreme situation, as what is done in Chapter 3. This means that, for each MEC application, all the MEC hosts that have it installed can meet this MEC application's latency requirement. Therefore, the latency requirement can be guaranteed by only selecting MEC hosts that have the required MEC application installed.
2. The only trigger for relocations analyzed in this master thesis is MEC service discontinuity. When a UE moves out of the coverage of its current serving MEC host, a new MEC host must be able to serve the UE immediately.

B. Use case

In [20], several end-to-end mobility use cases of MEC have been introduced. Among these use cases, the use case "prediction of relocation timing" is the most relevant to this thesis project and will be discussed in this section.

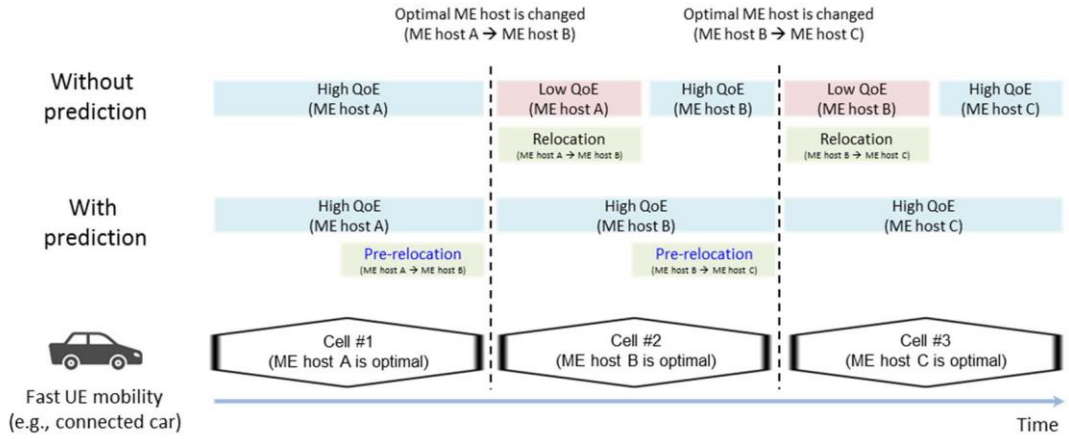

Figure 5.5: Pre-relocation of application state information

There are basically two types of relocations in MEC. The first type is application state relocation, serving for stateful applications. The application instance in the target MEC host will be instantiated and subsequently the two MEC hosts (current and target) will start to interact with each other to enable the transfer of the application states and user context from the current MEC host to the target MEC host. The second relocation type is application instance relocation, where the application instance will be copied from the current MEC host to the target MEC host. This second type of relocation is commonly used in relocations of application instance dedicated to a UE. Transferring user context/application states takes time and adds delay to the relocation, and the extra delay might increase the probably of having a service interruption and degrade user experience.

Pre-relocation is the transfer of the user data/application state from the current serving MEC host to the target MEC host and preparing the target MEC host to serve the UE earlier than needed. If a relocation is triggered in advance (that is, relocation triggered when the current serving host can still provide the UE with required service level), then this relocation is a pre-relocation. Figure 5.5 shows more details about pre-relocations. If a pre-relocation is done, the UE can directly be served by the target host when the QoE of the current host decreases. However, the timing of triggering a pre-relocation is important, since triggering a relocation too early or too late can cause relocation failure or waste of resources. To make sure the pre-relocation takes place appropriately, predictions are needed to determine a proper timing for pre-relocation.

On the road in the geographic service area defined in section 3.1, the direction of a moving UE is unchangeable since it is forbidden for a running vehicle on the road to drastically change its direction (for safety reasons). Therefore, the moving UE will keep moving in the same direction which makes it possible to precisely predict its future locations. Apart from the direction, the speed of a mobile UE is also an important factor to predict its locations and the speed of a UE can be provided by the UE itself, for instance, via an in-car navigation system. Having both the speed and the direction of a UE, the central controller is then able to estimate the transit time of this UE in the serving area of its current MEC host [43].

C. Prediction

The approach used in this master thesis to predict the timing for pre-relocation is described as follows:

1. Relocations of different MEC applications have different durations. Considering the volume of data transferred during relocation, the duration can (usually) be ranked as stateless < stateful < dedicated. When a UE starts to get served by a new host, its estimated relocation duration will be determined firstly.
2. The UE will keep reporting its current speed to the central controller and the central controller will keep tracking its location information by the Location Service (LS) defined in [32] (for more details, please see Appendix E). More precisely, the central controller can request the current location of a UE periodically by sending a UE location Lookup request to the LS or by subscribing to the UE Tracking Subscribe service.
3. The central controller has the overview of the entire geographic service area, so it should know the serving area of each MEC host. Otherwise, if supported, the Radio Node Location Lookup service can be used to retrieve the set of radio nodes that are currently associated with a MEC host (see more in Appendix E).
4. Every time the central controller receives the location and the speed information of a UE, it starts to calculate how much time this UE remains in the serving area of its current MEC host. If the remaining time is short enough, the pre-relocation is triggered. If supported, another alternative is to make use of the UE Distance Lookup service in LS by sending a request that includes the UE identity and the coordinates of the farthest boundary of the serving area of the UE's current MEC host to get the distance between UE and the serving area boundary of its current MEC host.
5. After the pre-relocation is done, the central controller will instruct the UE to connect to the new MEC host which is timely prepared for its arrival.

To make sure the above approach works properly, the speed of vehicles shouldn't change significantly in a very short time, and the reporting and location tracking period should be short enough. Otherwise, the accuracy of predictions cannot be guaranteed, and may finally result in fatal consequences.

In [6], another relocation mechanism is introduced. The relocation is triggered by the serving MEC platform (S-MEP) which is subscribed to RNIS. When a UE crosses a cell boundary in the underlying network, the RNIS of the serving MEC host (S-RNIS) will notify the cell change to the S-MEP, and the S-MEP further checks whether the UE has moved out of the serving area of its serving MEC host. If yes, a relocation will be triggered. When the UE moves out of the serving area of its source MEC host and the target MEC host is not ready, its user data will be sent to its source MEC host for processing via the target MEC host. The data transfer between two MEC hosts takes extra time, and user experience will be degraded accordingly. This mechanism is not further researched in this master thesis.

5.3 Scenarios & Settings

In this section, three scenarios are designed to test the algorithms in Chapter 4. In addition, settings of simulations are also introduced.

A. Scenarios

Different scenarios may occur in real world. In this master thesis, three scenarios are considered:

1. Stable network conditions. The conditions of the network stay stable and the actual number of UEs is no larger than the estimated number (i.e. no resource shortage problem). In this scenario, deep SARSA learning algorithm, traditional SARSA learning algorithm and the quick-start SARSA learning algorithm gradually learn from the feedback that reflects the network conditions and update their estimations on the current network conditions.
2. MEC hosts go down. In this scenario, 5% or 25% of the MEC hosts in which MEC applications are installed go down suddenly. More precisely, this scenario can be further divided into two sub-scenarios:
    a. The sudden defects of MEC hosts are noticed immediately by the network and the MEC applications installed in these defected MEC hosts are relocated in other MEC hosts which are still available, possibly instructed by the MEO.
    b. The sudden defects of MEC hosts fail to get noticed by the network, so no other MEC hosts take the work of the defected MEC hosts, and some of the UEs might not be able to find suitable MEC hosts. To maintain the service continuity for every UE, Algorithm 8 should be able to find temporary MEC hosts when needed, and the central controller will instruct the chosen temporary MEC hosts to install the required MEC applications and to instantiate MEC application processing instances. If the defected MEC hosts are not repaired after some time, locating mechanism “simulation-based + VNS” should be automatically invoked to allocate more resources for the MEC applications that face resource shortage problem in the current available MEC hosts, and to deploy new MEC hosts in the geographic service area if necessary (as illustrated in Figure 4.9).
3. Too many UEs. If the geographic service area gets busier than expected, some UEs may run into problems that no MEC hosts with the required MEC application installed can serve them anymore. Although there are MEC hosts available to serve UEs, these MEC hosts have not installed the required MEC application(s) (yet). According to the decision-making mechanism, a temporary MEC host should be selected carefully by Algorithm 8 for each UE that couldn’t find an available MEC host with the required MEC application installed.

B. Settings

Simulated environments

- Number of sites: 800 sites with their axes and coverage radius known in advance,
- Road length: 500 unit lengths
- Locations: co-located with gNB-DU, co-located with gNB-CU, located close to/inside the core network,
- MEC hosts information is shown in Table 5.1.

Table 5.1: MEC hosts information

Location of MEC hosts	Close to gNB-DU	Close to gNB-CU	Close to 5GC
Location No.	1	2	3
Total number of MEC hosts	168	150	131
Maximum amount of available resources in one MEC host (computing/storage/processing)	100/100/100	300/300/300	500/500/500

- The approach to simulate the four KPIs to estimate the condition and behavior of a MEC host is shown below. Because the conditions of network as well as MEC hosts are dynamic, an indicator may have a range instead of an exact value, and its exact value will be uniformly and randomly generated from this range.
  - The duration time of the relocation = time to transfer user context and state between two MEC hosts (between 0.05-2s) + time to install an MEC application (between 0-2s) + time to instantiate a MEC application instance (0.005-0.01s) + time to set up a new PDU Session towards the new MEC host (between 0.01-0.1s, according to the measurements)
    - Time to transfer user context and state: The average time to transfer user context and state of UE of a particular MEC application between a certain pair of current and target MEC hosts is fixed and the range of the exact time is 10% of the average.
    - Time to install an MEC application: This value will be 0 unless a UE has to choose a MEC host without the required MEC application installed (e.g. when experiencing resource shortage). In this case, for installing the same MEC application in different MEC hosts, average installation time is fixed, and it depends on the MEC application, and the range of the installation time is 10% of the average; for installing the same MEC application in the same MEC host, time will not change.
    - Time to instantiate a MEC application instance: This value is fixed for each MEC application.
    - Time to set up a new PDU Session towards the new MEC host: For each MEC host, the average setup time is fixed and the range of the exact setup time is 10% of the average.
  - Whether there is a service interruption during the relocation: During a relocation of a UE in a simulation, the probably p of having one and only one

service interruption during a relocation is positively related to the duration time of this relocation. In each relocation, to determine whether there is a service interruption or not, a random number between 0 and 1 will be generated. If this random number is smaller than the corresponding p, then there is a service interruption in this relocation; otherwise, there is no service interruption.

- The latency at the target MEC host of the relocation: This can be generated according to measurement results, in simulations in the following sections, the actual service latency of a MEC host is between 0.01-0.3s, and the exact value depends on the MEC application and the MEC host itself. That is to say, for the same MEC application in the same MEC host, the average service latency is fixed and the range of service latency is 10% of the average service latency.
- The current available resources in the target MEC host of the relocation: This can be derived directly from the maximum available amount of resources in the MEC host and the amount of resources that are currently occupied to serve UEs.

MEC applications

Three MEC applications are used in the following tests. Table 5.2 gives more detailed information.

Table 5.2: MEC applications information

MEC APP	Required Resources per UE (computing/storage/processing)	Priority	Acceptable Locations	Maximum number of UEs per unit length	MEC application type
1	1/0.5/1	2	1, 2	7	stateful
2	3/3/3	1	1, 2, 3	10	stateless
3	1/5/5	3	1, 2	3	dedicated

Deep Neural Network

Structure of the deep neural network used in Deep SARSA learning is described in Table 5.3. This deep neural network consists of three different densely-connected layer. The input dimensionality of a layer is the number of elements in one input of the layer, and similarly, the output dimensionality of a layer is the number of elements in one output of the layer.

Table 5.3: Deep neural network structure

Layer	Type	Input Dimensionality	Output Dimensionality
1	Densely-connected layer	1	20
2	Densely-connected layer	20	10
3	Densely-connected layer	10	1

5.4 Outcomes & Analysis

A. Stable network conditions

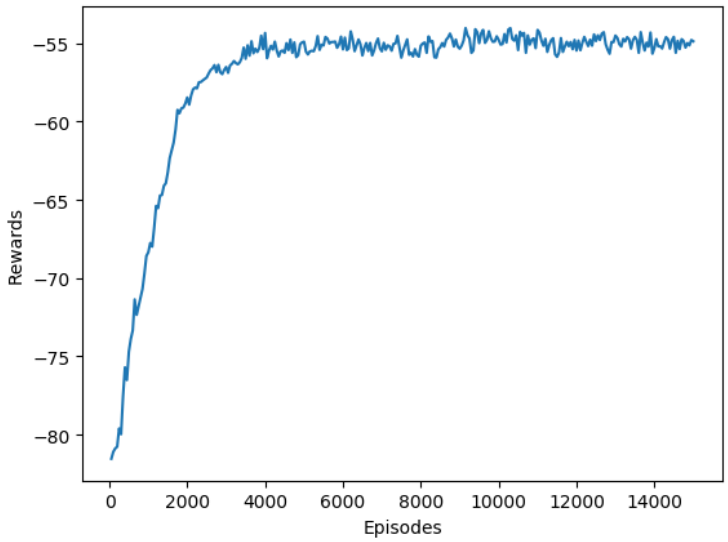

Figure 5.6: Rewards given by the Deep SARSA algorithm versus episodes (stable scenario)

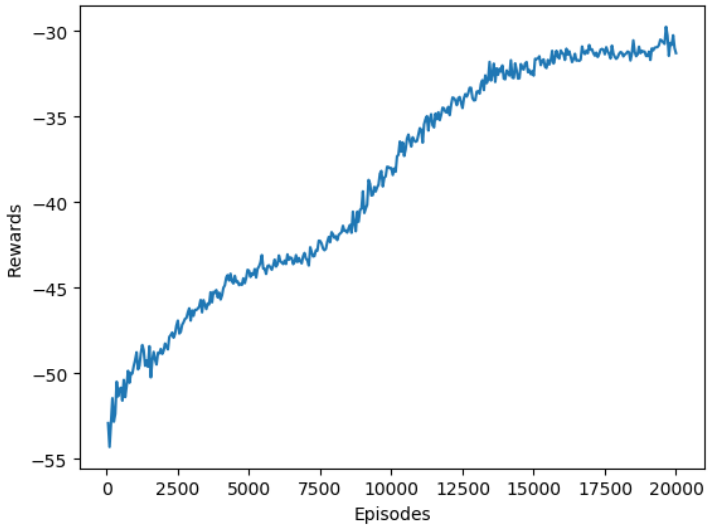

Figure 5.7: Rewards given by the traditional SARSA algorithm versus episodes (stable scenario)

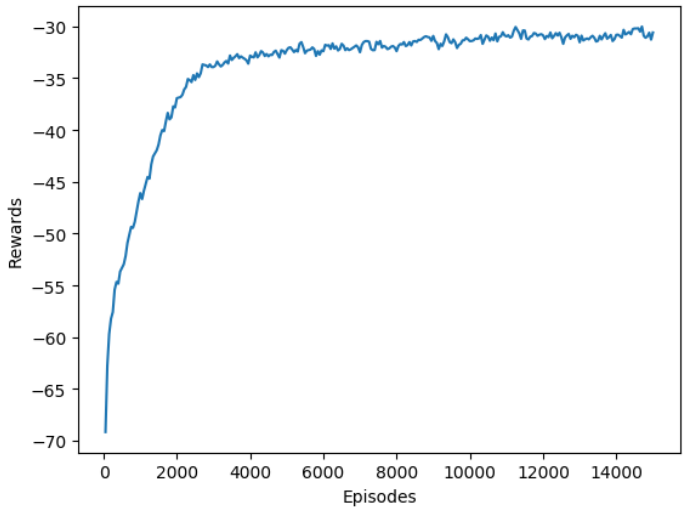

Figure 5.8: Rewards given by the quick-start SARSA learning algorithm versus episodes (stable scenario)

When the network conditions are stable, traditional SARSA learning algorithm, deep SARSA learning algorithm and the quick-start SARSA learning algorithm will gradually learn from the feedback received from the environment, and this feedback reflects part of the current network conditions. Figures 5.6 – 5.8 show the learning procedure of Deep SARSA learning, of traditional SARSA learning and of the quick-start SARSA learning separately. Compared to Figures 4.7 and 4.8, Figures 5.6 – 5.8 show more smooth curves because these curves show the average results of more than 100 iterations, in order to make the learning procedure of these reinforcement learning algorithms clearer. In reality, the curves will be more similar to what is shown in Figures 4.7 and 4.8 because the reinforcement algorithms do not always take the current optimal option but explore other possible options with a certain probability.

Deep SARSA learning converges before episode 4000, which is much faster than traditional SARSA learning which converges after 15000 episodes. However, traditional SARSA learning converges at a higher result value (around -32) than deep SARSA learning (around -55), implying that traditional SARSA can give more accurate estimations on network conditions. The performance of deep SARSA learning algorithm shown in Figure 5.6 is not satisfying and the reason behind is that the three-layer densely-connected neural network is not the most suitable structure to predict the conditions of this network. In comparison, while using the same updating mechanism (shown in Equation 4.2 in section 4.2), the traditional SARSA learning algorithm converges at a higher reward because the up to date q values are saved separately in a q table and will not affect each other. However, the traditional SARSA learning algorithm converges much slower than deep SARSA learning algorithm. To compensate this shortcoming while maintaining the advantage of traditional SARSA learning, the quick-start SARSA learning algorithm is proposed, and Figure 5.8 indicates that the rewards given by the quick-start SARSA learning algorithm increase rapidly in the first 2000 episodes and then reach a reward of -35 around episode 2000. After that the rewards gradually increase and finally converge at -32 around episode 10000.

B. MEC hosts go down

Simulations in this section as well as the next section are designed to test the robustness the decision-making mechanism illustrated in Figure 4.9. The robustness of the decision-making mechanism is not related to the reinforcement learning algorithm, and in the following simulations, traditional SARSA learning algorithm is selected to decide on the most suitable target MEC host in a relocation. In each of the following simulations, the first learning procedure of the traditional algorithm is not shown because it is not relevant to the goal of the simulation.

Figure 5.9 and Figure 5.10 show the performances of the decision-making mechanism in sub-scenarios a and b which are introduced in section 5.3.

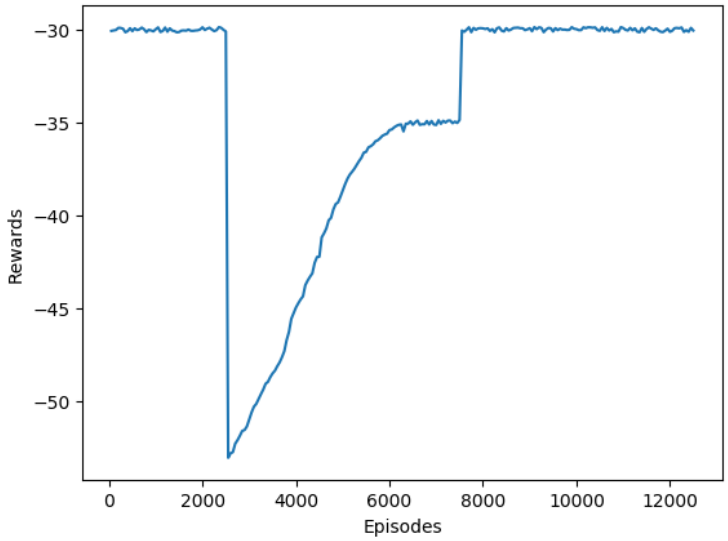

Figure 5.9: Rewards given by decision-making mechanism versus episodes (sub scenario a, 25% of the MEC hosts go down)

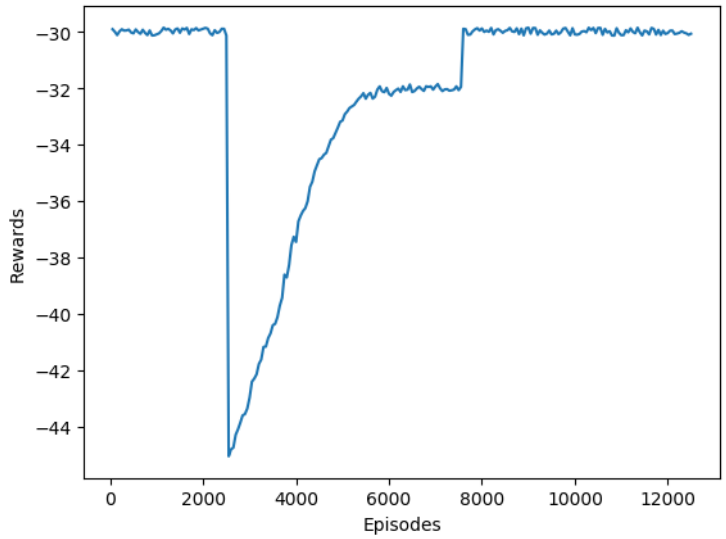

Figure 5.10: Rewards given by decision-making mechanism versus episodes (sub-scenario a, 5% of

the MEC hosts go down)

In the simulation for sub-scenario a, 25% of the MEC hosts go down at episode 2500, thus a sudden decrease in rewards occurs in Figure 5.9. The central controller immediately notices the defections and uses the locating mechanism “simulation-based + VNS” to relocate MEC applications installed in the failing MEC hosts in other available MEC hosts. If resources in the current available MEC hosts are not sufficient, new MEC hosts will be added to the network. After all the MEC applications are re-located successfully, the rewards start to increase because SARSA learning keeps learning from the new environment, and the rewards converge around episode 6500. The new convergence value is lower than before, because the previous deployment is optimized, and the new deployment without defected MEC hosts is no better than the previous one. At episode 7500, all the defected MEC hosts have been repaired and the MEC applications which have been relocated are moved back to their original places, so the rewards increase sharply. Here it is assumed that those repaired MEC hosts have the same conditions as before, hence the rewards directly jump to the original reward level.

Figure 5.10 shows the performance of the decision-making algorithm when 5% of the MEC hosts go down at episode 2500. Compared with Figure 5.9, the rewards between episode 2500 and episode 7500 in Figure 5.10 is higher, because fewer MEC hosts have gone down so the impact to user experience (rewards) is smaller too.

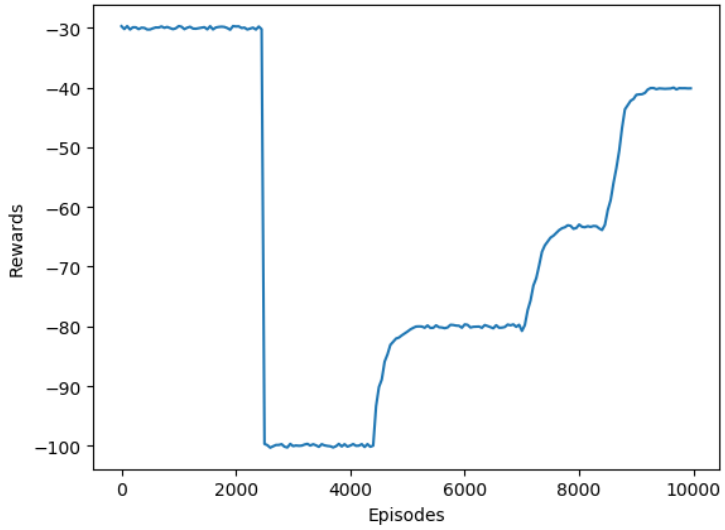

Figure 5.11: Rewards given by decision-making mechanism versus episodes (sub-scenario b, 5% MEC hosts go down)

In the simulation for sub-scenario b, the defects of 5% of the MEC hosts which takes place at episode 2500 are not discovered, which has the consequence that the reserved resources in the geographic service area might be insufficient. The performance of the traditional SARSA learning algorithm in this scenario is shown in Figure 5.11.

When the reserved resources are not enough to serve a UE, Algorithm 8 is used to find a currently available MEC host which can maintain the service continuity for the UE, and this MEC host is called a temporary MEC host. The selection of a temporary MEC host is

introduced in Table 4.3. According to the decision-making mechanism, more resources will be allocated for a MEC application when the number of resource-insufficient cases of this MEC application reaches a certain threshold (detailed information can be found in section 4.5). This is the reason why the rewards increase three times after the degradation – different MEC applications have different thresholds, once extra resources have been allocated for a MEC application, the rewards will increase because these new resources are carefully allocated to enhance the rewards. After about 8500 episodes, enough resources have been allocated to all the three MEC applications, but the rewards are lower than the original level because of the defected MEC hosts.

C. Too many UEs

In the simulation for this scenario, the network stays stable and every MEC host works properly. However, the number of UEs in the geographic service area is more than expected so resources allocated by the locating mechanism designed in Chapter 3 are not enough anymore. Under this situation, the decision-making mechanism should be able to assign UEs to temporary MEC hosts, and allocate more resources if needed. Figure 5.12 shows the performances of the decision-making mechanism in case too many UEs are present in the geographic service area.

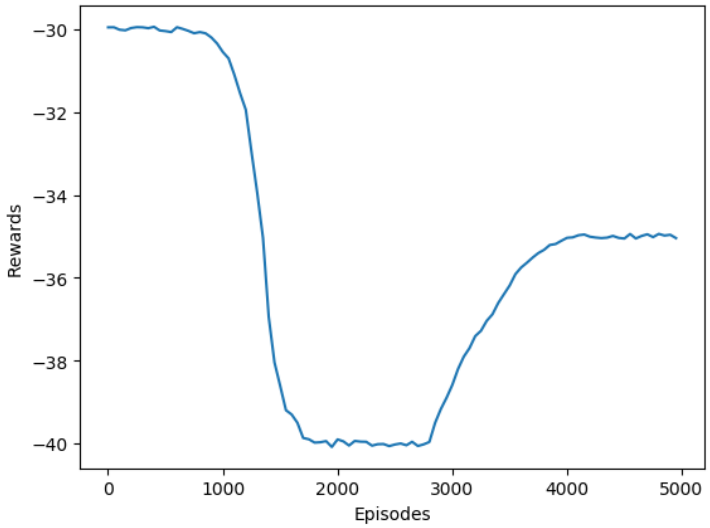

Figure 5.12: Rewards given by decision-making mechanism versus episodes (Too many UEs)

The total number of UEs within in the geographic service area gradually increases after episode 900 and then stays stable after another 800 episodes, hence in Figure 5.12, the rewards gradually decrease between episode 900 and episode 1700. When all of the reserved resources have been used, temporary MEC hosts are selected, which further decrease the rewards. Fortunately, around episode 2800, the number of resource-insufficient cases reaches the threshold to trigger the locating mechanism “simulation-based + VNS” algorithm to start to allocate extra resources, after which the rewards increase again. After extra resources are allocated, the rewards converge at a lower level than before because there are

more UEs in the geographic service area so the overall user experience degrades.

D. Average number of relocations versus the number of UEs in the geographic service area

Generally, if there are more UEs in the geographic service area, the average user experience will degrade, or at least remain unchanged. This is further proved in this section. Figure 5.13 shows the average number of relocations one UE experiences when there are different numbers of UEs per unit length in the geographic service area. Figure 5.13 shows a clear trend: when the number of UEs per unit length increases, the average number of relocations that one UE experiences increases at the same time. The reason behind this trend is that, when the network is busy, MEC hosts with larger serving area can be fully loaded. Therefore, some of the UEs are served by MEC hosts with smaller serving area instead, which increases the number of relocations.

It is also shown in Figure 5.13 that no matter how many UEs are in the geographic service area, as long as the reserved resources are enough, the average number of relocations of one UE of a MEC application with a higher priority (e.g. MEC application 3) can hardly exceed that of a MEC application with a lower priority (e.g. MEC application 2). This is partially because of the basic rule in section 3.3, and another reason is that, relocations related to MEC applications with higher priorities have more effects on the weighted number of relocations (RW), therefore, to minimize RW, eliminating the relocations (between unit-hosts) experienced by the UEs that are using MEC applications with higher priorities is more effective.

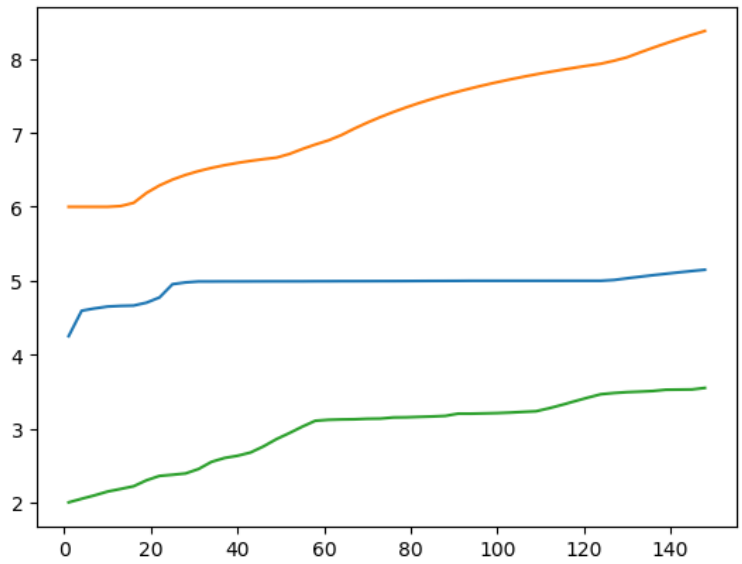

Figure 5.13: Average number of relocations experienced by a UE versus the number of UEs per unit length within the geographic service area

5.5 Summary

In this chapter, the Non-Stand Alone (NSA) architecture of the Ericsson +31 Network is introduced, and the RRT between a UE and a VM which is attached to the common gateway of the +31 Network is measured and shown. The measured RRTs are used as service latencies between a UE and MEC hosts in the simulations that are used for testing the three reinforcement algorithms designed in Chapter 4. In the simulations, a relocation is triggered by the MEO before it is actually needed. This type of relocation is called pre-relocation and relies on UE location prediction to determine an appropriate starting time. Simulation outcomes are displayed, compared and analyzed in this chapter. According to the outcomes, compared to the two other algorithms, the quick-start SARSA learning algorithm gives the satisfied result in the shortest time. However, the selection of the most suitable algorithm is based on multiple factors, so different telecom networks and different telecom operators' requirements may result in selecting different reinforcement learning algorithms.

To enhance the robustness of MEC, a decision-making mechanism is designed in section 4.8 to make sure that each UE can still receive required MEC services when there is an exception. To test the resiliency of this decision-making mechanism, two scenarios where several MEC hosts suddenly break down and too many UEs suddenly enter the geographic service area, are added. Simulation outcomes show that, in these two scenarios, the decision-making mechanism can quickly react and effectively deal with the exceptions.

Chapter 6 Conclusions and Future work

This chapter presents this thesis' conclusions and recommendations for future research. Section 6.1 summarizes the answers to the research questions and sub-questions given in the chapters 2, 3 and 4, as well as the performance of all the algorithms and mechanisms designed in chapters 3 and 4. Section 6.2 proposes recommendations for future research as many aspects deserve a more in-depth analysis at the current initial stage of 5G implementation.

This thesis' central theme is optimizing Multi-access Edge Computing in a 5G network context and is analyzed from the user experience and service quality aspects, mainly including service latency, service continuity, resource efficiency, resource sufficiency and exception handling.

6.1 Conclusions

This section gives an overview of this thesis' research output and summarizes the conclusions.

Regarding Research Question 1: What is Edge Computing and what is the relevance of different types of computing for telecom operators, the following is inferred.

Cloud computing processes data in a centralized data center, and the latency as well as bandwidth usage between end-users and the data center increases rapidly with the number of end-users and data volume. Fog computing processes data at fog nodes closer to the network edge, and unlike cloud computing, fog computing has a hierarchical architecture and fog nodes with different intelligence levels are distributed in different levels. Edge computing processes data at the network edge, which is physically closer to the end-users than cloud computing and fog computing. Different from cloud computing and fog computing, edge computing has a distributed architecture. Compared to cloud computing, edge computing can decrease the service latency and the required bandwidth by moving computing, storage and network resources to the very edge of the telecom network. Multi-access Edge Computing (MEC) is defined by ETSI. When realized, this concept will provide edge computing services to UEs via 3GPP defined access and non-3GPP defined access (e.g. Wi-Fi). A MEC host can be located in an external data network with connections towards one or several User Plane Functions (UPF), while the main controller of the MEC system – the MEC Orchestrator (MEO) – interferes traffic routing by interacting with the Policy Control Function (PCF) or the Network Exposure Function (NEF) in the 5G Core Network (5GC) as an Application Function (AF).

Regarding Research Question 2: What aspects of Edge Computing should be considered for optimization in the context of 5G, the following is inferred.

The optimization goal of research question 3 is to minimize the number of relocations, to meet the requirements of each MEC application and to provide sufficient but not redundant resources to each MEC application, hence it is related to the number of MEC service interruptions, the number of relocations, the number of MEC hosts involved and resource efficiency. Research question 4, on the other hand, has the optimization goal of finding the MEC host that provides a UE the best service quality (e.g. service latency, service continuity)

during and after a relocation, hence it is related to service latency, the number of MEC service interruptions and the number of relocations.

Regarding Research Question 3: Devise an algorithm to find the optimal location of MEC hosts and the optimal location (MEC host) of a MEC application, the following is inferred.

With technology like Network Function Virtualization (NFV), locating a MEC host will become more flexible and less costly. According to the current architecture of 5G networks, the logical location of a MEC host in a telecom network is always on the network side of the UPF(s), but possible physical locations for a MEC host can include locations physically close to the core network, locations physically close to gNB, locations physically close to aggregation nodes, etc. Different physical locations imply different levels of service latency, but it does not mean that the closer a MEC host is to the UE, the better the user experience is. When a MEC host is located closer to the UE, its serving area tends to be smaller, thus resulting in a larger number of relocations experienced by a UE. In other words, there is a trade-off between service latency and the number of relocations and these two aspects cannot be optimized at the same time.

When the network is extremely busy, MEC hosts should be optimally located to provide enhanced service quality. Since the number of relocations and service latency conflict with each other, only one of these two can be minimized. In this master thesis, minimizing the total number of relocations is chosen as the optimization goal. On one hand, a smaller number of relocations can decrease the probability of the occurrence of service interruptions, which can be fatal to (users of) UEs like self-driving vehicles; on the other hand, a smaller number of relocations implies a smaller number of MEC hosts to be deployed, as well as lower O&M cost. Meanwhile, the required service latency and required computing/storage/processing resources of every UE become the constraints of this optimization problem. To sum up, the optimization goal of research question 3 is to minimize the number of relocations, to meet the requirements of each MEC application and to provide sufficient but not redundant resources to each MEC application.

To achieve the optimization goal as well as not violating the constraints, the optimization problem is divided into Phase 1 and Phase 2. Algorithms designed in Phase 1 determine where to install MEC applications, and algorithms designed in Phase 2 determine the location and serving area of each MEC host. By combining the algorithms in Phases 1 and 2, six different locating mechanisms are configured. According to the simulation outcomes, the mechanism “simulation-based + VNS”, which applies simulation-based algorithm in Phase 1 and heuristic algorithm VNS in Phase 2, is considered to be the best locating mechanism, while the “greedy + greedy” mechanism, which uses two different greedy algorithms in Phase 1 and Phase 2 separately, is the worst locating mechanism.

Regarding Research Question 4: Devise an algorithm to dynamically find the optimal location of a MEC application processing instance for a UE, the following is inferred.

When the network is less busy, there may be multiple MEC hosts that are capable to serve a UE. In this case, when a relocation is required, the most suitable MEC host that can provide the requested user experience needs to be determined for each UE. To achieve this, the first step is to determine which MEC hosts can be the possible target MEC hosts of this relocation. If installation of MEC applications can largely increase the duration of the relocation, then only the MEC host that has the required MEC application installed, has a serving area which

overlaps with the current MEC host of the UE and has enough resources to serve this UE can be a possible target MEC host. If the installation of MEC application is quick enough, then every MEC host that has enough resources to serve the UE and has a serving area which overlaps with the current MEC host of the UE can be a possible target MEC host. At present, installing a MEC application is time-consuming, therefore, in this master thesis, only the MEC host with the required MEC application installed has the possibility to be a possible target MEC host.

After the possible target MEC hosts are determined, the target MEC host needs to be selected. Considering that the conditions of a telecom network are dynamic, reinforcement learning is suitable to decide on the target MEC host. The reinforcement learning algorithm is implemented in the central controller (e.g. the MEO) of the MEC system. This algorithm estimates the overall performance of each MEC host based on the service latency between the UE and this MEC host as well as the MEC hosts that might serve the UE afterwards, number of relocations one UE may experience afterwards and the current load of this MEC host. Based on the estimations it makes, the reinforcement learning algorithm decides on the target MEC host. Three different reinforcement learning algorithms are designed in this master thesis: traditional SARSA learning algorithm, deep SARSA learning algorithm as well as the quick-start SARSA learning algorithm that combines the advantages of both the previous two algorithms. Traditional SARSA learning algorithm can make better decisions than deep SARSA learning algorithm, and deep SARSA learning algorithm learns faster from the environment than traditional SARSA learning algorithm. The quick-start SARSA learning algorithm learns (almost) as fast as the deep SARSA learning algorithm and makes satisfying decisions. The selection of the most suitable algorithm among the three reinforcement learning algorithms depends on the scale of the problem and telecom operator's requirements. If the number of MEC hosts involved is small enough, using traditional SARSA learning is the best option; if the number of MEC hosts is (too) large and the requirement on user experience is not stringent, deep SARSA learning is the most suitable algorithm; if there are a large number of MEC hosts and the requirement on user experience is stringent, then the quick-start SARSA learning algorithm should be chosen to make decisions.

For resiliency purpose, a decision-making mechanism is designed to find a temporary MEC host for a UE when there is no MEC host with the required MEC application installed available. This decision-making mechanism can allocate more resources for one MEC application when the resources currently reserved for this MEC application are not enough to serve all its UEs. Additionally, when the current MEC hosts are not sufficient to provide satisfying services to all the UEs, this mechanism can properly deploy new MEC hosts to serve UEs.

Regarding the interviews, the following is inferred.

Transmission speed on optical fiber is around 200,000,000 m/s, which significantly suppresses the transmission time of data packets to the millisecond level. However, the transformation time and processing time in the routers can still affect the transmission delay. Therefore, MEC hosts, which process data physically close the network edge, can decrease the service latency. At present, network operators prefer to place MEC hosts near the core network or metro cores, to reduce Operations and Management (O&M) costs. In the future, when MEC is widely used and has more consumers (e.g. self-driving vehicles), more MEC

hosts are needed to satisfy the requirements of these MEC service consumers. The growing number of MEC hosts brings up the problem of locating these MEC hosts properly as well as selecting a suitable MEC host for every consumer, which is discussed in this master thesis.

6.2 Future Work

In future research the following aspects can be investigated:

More realistic geographic service area. In this master thesis, the geographic service area is simplified into a straight road with one entrance and one exit. However, in reality, it is likely that a road has several entrances and exits as well as crossroads and bends. Furthermore, there might be buildings or trees along the roadside which may block radio signals between UEs and sites and force the UEs to change their serving MEC hosts.

More use cases of MEC. In this master thesis, only the use cases that are sensitive to service continuity are considered. However, MEC has more use cases, and for some use cases, service continuity is not a crucial factor and thus other factors that really matter need to be figured out and optimized for different use cases.

Better approximation algorithms. To solve the minimum k-cut problem addressed in Chapter 3, greedy algorithms and heuristic algorithms are used and analyzed. However, there may exist other approximation algorithms which can further decrease the number of relocations.

More aspects of user experience. In this master thesis, only a few aspects of user experience are considered: service latency, service continuity and serving resources. User experience may contain many more aspects, such as data transmission rate, number of transmissions and retransmissions, that can be investigated and optimized. Besides, security and privacy aspects are left out in this master thesis, which are worth researching in the near future as well.

Combination of MEC and regular cellular network services (e.g. telephony, IMS). In this master thesis, only the performance of MEC is considered and optimized. In real situation, since MEC is deployed in a telecom network, it is entangled with other services provided by the cellular network. Therefore, it is always better to optimize MEC together with other network services, find trade-offs and conflicts between each other and try to figure out a best way to optimize the overall performance of the cellular network.

Appendix A. Definitions and Abbreviations

Definitions

Application function: The AF is a logical element of the 3GPP Policy and Charging Control (PCC) framework which provides session related information to the Policy and Charging Rules Function (PCRF) in support of PCC rule generation [21]. In the 5G architecture, the AF will interact with the Network Exposure Function (NEF) or other network functions (e.g. Policy Control Function).

Application instance relocation: The procedure of moving an application instance running on a MEC host to another MEC host, to support service continuity over underlying network [20].

Application instance state transfer: The procedure of transferring the operational state of application instance from the source MEC host to the instance of the same application in the target MEC host [20].

Application mobility: Part of mobility procedure for MEC system, it may contain application instance relocation and/or application instance state transfer [20].

Application processing: A procedure to provide certain services to consumer(s)/users based on the logic of the application.

Application processing instance: A realized software program executed in MEC host, which can provide service to serve consumer(s) [20].

MEC application: MEC applications run on VMs on top of the virtualization infrastructure provided by the MEC host, and can they interact with the MEC platform to consume and provide MEC services. In certain cases, MEC applications can also interact with the MEC platform to perform certain support procedures related to the lifecycle of the application, such as indicating availability, preparing relocation of user state, etc. MEC applications can have a certain number of rules and requirements associated to them, such as required resources, maximum latency, required or useful services, etc. These requirements are validated by MEC system level management, and can be assigned to default if missing [19].

MEC host: An entity that contains the MEC platform and a virtualization which provides compute, storage and network resources for the MEC applications [19].

MEC host level management: It consists of a MEC platform manager and a virtualization infrastructure manager [19].

MEC orchestrator: The core functionality in MEC system level management. It is responsible for maintaining an overall view of the MEC system based on deployed MEC hosts, available resources, available MEC services and topology; onboarding of application packages, including checking the integrity and authenticity of the packages, validating application rules and requirements and if necessary adjusting them to comply with operator policies, keeping a record of on-boarded packages, and preparing the virtualization infrastructure manager(s) to handle the applications; selecting appropriate MEC host(s) for application instantiation based on constraints, such as latency, available resources and available services; triggering application instantiation and termination; triggering application relocation as needed when supported [19].

MEC platform: It is responsible for offering an environment where the MEC applications can discover, advertise, consume and offer MEC services, including, when supported, MEC services available via other platforms; receiving traffic rules from the MEC platform manager, applications or services, and instructing the data plane accordingly; hosting MEC services; providing access to persistent storage and time of day information [19].

MEC platform manager: It is responsible for managing the life cycle of applications including informing the MEC orchestrator of relevant application related events; providing element management functions to the MEC platform; managing the application rules and requirements including service authorizations, traffic rules, DNS configuration and resolving conflicts. It also receives virtualized resources fault reports and performance measurements from the virtualization infrastructure manager for further processing [19].

MEC system level management: Consists of a MEC orchestrator, an operations support system (OSS) and user application lifecycle management proxy [19].

Operation support system (OSS): It receives requests via the CFS portal and from UE applications for instantiation or termination of applications, and decides on the granting of these requests. Granted requests are forwarded to the MEC orchestrator for further processing. When supported, the OSS also receives request from UE applications for relocating applications between external clouds and the MEC system [19].

PDU Session: "In telecommunications, a Protocol Data Unit (PDU) is a single unit of information transmitted among peer entities of a computer network. A PDU consists of protocol specific control information and user data" [18]. In 5G networks, a PDU session is similar to a PDN connection in 4G networks, it is a logical connection set up between UE and UPF for data transfer.

Relocation: When a UE is moving around, sometimes, a relevant MEC application processing instance and/or MEC application instance state and/or MEC application instance need to be relocated in order to maintain its MEC services.

Relocation mechanism: Mainly includes finding the optimal target MEC host, determining how/what to transfer during a relocation, etc.

User application: A MEC application that is instantiated in the MEC system in response to a request of a user via an application running in the UE [19].

User application lifecycle management proxy: It allows UE applications to request on-boarding, instantiation, termination of user applications and when supported, relocation of user applications in and out of the MEC system. It also allows informing the UE applications about the state of the user applications. It authorizes requests from UE applications in the UE and interacts with the OSS and MEC orchestrator for further processing of these requests. It is only accessible from within the mobile network, and it is only available when supported by MEC system [19].

Virtualization infrastructure manager: It is responsible for allocating, managing and releasing virtualized resources of the virtualization infrastructure; preparing the virtualization infrastructure to run a software image. The preparation includes configuring the infrastructure and can include receiving and storing the software image; collecting and reporting performance and fault information about the virtualized resources; when supported, performing application relocation. For application relocation from/to external cloud environments, the virtualization infrastructure manager interacts with external cloud

manager to perform the application relocation, possibly though a proxy [19].

Abbreviations

AF	Application Function
AMF	Access and Mobility management Function
AN	Access Network
AuC	Authentication Center
AUSF	Authentication Server Function
CAV	Connected Autonomous Vehicle
CFS	Customer Facing Service
CN	Core Network
CP	Control Plane
D2D	Destination to Destination
DN	Data Network
DNN	Data Network Name (Chapter 2)
DNN	Deep Neural Network (Chapter 4, 5)
DQN	Dee Q Network
EC	Edge Computing
eCPRI	enhanced Common Public Radio Interface
eNB	E-UTRAN NodeB, or, eNodeB
EPC	Enhanced Packet Core
E-RAB	Enhanced Packet System Radio Access Bearer
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UMTS Terrestrial Radio Access
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FE	Functional Elements
GGSN	Gateway GPRS Support Node
GMSC	Gateway Mobile service Switching Center
gNB	Next Generation NodeB, or, gNodeB
gNB-DU	gNodeB Distributed Unit
gNB-CU	gNodeB Central Unit
gNB-CU-CP	gNodeB Central Unit Control Plane
gNB-CU-UP	gNodeB Central Unit User Plane
GPRS	General Packet Radio Service
HLR	Home Location Register
HSS	Home Subscriber Server
ISG	Industrial Specification Group
ISDN	Integrated Services Digital Network
LADN	Local Area Data Network
LAN	Local Area Network
LCM	Lifecycle Management
LS	Location Service
LTE	Long Term Evolution

MD	Markovian and Deterministic decision rule
MDP	Markov Decision Process
ME	Mobile Equipment
MEC	Multi-access Edge Computing
MEO	MEC orchestrator
MEP	MEC Platform
MEPM	MEC platform manager
MME	Mobility Management Entity
MR	Markovian and Randomized decision rule
MSC	Mobile service Switching Center
NAS	Non-Access Stratum
NB	NodeB
NEF	Network Exposure Function
NF	Network Function
NFV	Network Function Virtualization
NG	New Generation
ng-eNB	Next Generation E-UTRAN NodeB
NG-RAN	Next Generation Radio Access Network
NN	Neural Network
NR	New Radio
NSA	Non-Stand Alone
NRF	Network Repository Function
NSSF	Network Slicing Selection Function
NWDAF	NetWork Data Analytics Function
PCC	Policy and Charging Control
PCF	Policy Control Function
PCRF	Policy and Charging Rules Function
PDU	Protocol Data Unit
P-Gw	Packet data network Gateway
PLMN	Public Land Mobile Network
PSTN	Public Switched Telephone Network
O&M	Operations and Maintenance
OSS	Operations Support System
QoS	Quality of Service
RAB	Radio Access Bearer
RAN	Radio Access Network
RL	Reinforcement Learning
RNC	Radio Network Controller
RNI	Radio Network Information
RNIS	Radio Network Information Service
RRU	Remote Radio Unit
RTT	Round-Trip Time
SA	Stand Alone
SBA	Service-Based Architecture

SGSN	Serving GPRS Support Node
S-Gw	Serving Gateways
S-MEP	Serving MEC Platform
SMF	Session Management Function
TCP	Transmission Control Protocol
T-MEH	Target MEC Host
T-MEP	Target MEC Platform
UALCMP	User Application LCM Proxy
UDM	Unified Data Management function
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UP	User Plane
UPF	User Plane Function
USIM	UMTS Subscriber Identity Module
UTRAN	UMTS Terrestrial Radio Access Network
VI	Virtualization Infrastructure
VIM	Virtualization Infrastructure Manager
VM	Virtual Machine
V2X	Vehicle-to-everything
5GC	5G Core network

Appendix B. References

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Appendix C. Mathematical Symbols

M	Number of MEC applications
N	Number of sites in the geographic service area
G	The graph that represents all the unit-hosts in the geographic service area. If the two corresponding sites of two nodes have overlapping coverage area, these two nodes in graph G is connected by a directed link starts from the node whose corresponding site is closer to the entrance of the road and ends at the other node. Hence, graph G is a directed graph
ev_1	$1 \times N$ vector that indicates the sites that cover the entrance of the road, $ev_{1i} = \begin{cases} 1 & if\ site\ i\ covers\ the\ entrance\ of\ the\ road \\ 0 & otherwise \end{cases}$
ev_2	$1 \times N$ vector that indicates the sites that cover the exist of the road, $ev_{2i} = \begin{cases} 1 & if\ site\ i\ covers\ the\ exit\ of\ the\ road \\ 0 & otherwise \end{cases}$
A^*	$N \times N$ matrix that indicates the neighbors of each node in graph G, $A^*_{ij} = \begin{cases} 1 & if\ site\ j\ is\ i's\ sucessor\ or\ i = j\ and\ i\ in\ E_2 \\ 1 & if\ site\ i\ is\ j's\ sucessor\ or\ i = j\ and\ i\ in\ E_1 \\ 0 & otherwise \end{cases}$
A^{**}	$N \times N$ matrix that indicates the predecessors and successors of each node in graph G, ${A^{**}}_{ij} = \begin{cases} 1 & if\ site\ j\ is\ i's\ sucessor\ or\ i = j\ and\ i\ in\ E_2 \\ -1 & if\ site\ i\ is\ j's\ sucessor\ or\ i = j\ and\ i\ in\ E_1 \\ 0 & otherwise \end{cases}$
UE_k	Estimated maximum number of UEs of MEC application $k \in \{1, \dots, M\}$ that enters the geographic service area per unit length
$prior_k$	Priority of MEC application $k \in \{1, \dots, M\}$
cr_k	Required computing resources per UE of MEC application $k \in \{1, \dots, M\}$
sr_k	Required storage resources per UE of MEC application $k \in \{1, \dots, M\}$
pr_k	Required processing resources per UE of MEC application $k \in \{1, \dots, M\}$
cr_{unit}	The maximum computing resources one unit-host can provide
sr_{unit}	The maximum storage resources one unit-host can provide
pr_{unit}	The maximum processing resources one unit-host can provide
LL	A set of all possible MEC host locations. Three types of MEC host locations are considered in this master thesis: collated with gNB-DU, collated with gNB-CU and located close to the core network
LL_k	A set of possible locations for MEC application $k \in \{1, \dots, M\}$
NU_{ll}	Maximum number of unit-hosts one MEC host in location $ll \in LL$ can contain
$coverage_i$	The coverage of site $i \in \{1, \dots, N\}$
$PN_{ll}(k)$	Number of paths selected for application $k \in \{1, \dots, M\}$ in location $ll \in LL_k$
$P^k_{ll}(n)$	$N \times N$ matrix that indicates links belong to a path selected for MEC application $k \in \{1, \dots, M\}$ in location $ll \in LL_k$,

$$P_{ll}^{k}(n)_{ij} = \begin{cases} 1 & if\ site\ i\ and\ j\ are\ connected\ in\ path\ n \\ 0 & otherwise \end{cases}$$
$$(n = 1, \dots, PN_{ll}(k))$$

$EN_{ll}^{k}(n)$ $N \times N$ matrix that indicates the sites that cover either the entrance or the exit of the road and belong to path $n \in \{1, \dots, PN_{ll}(k)\}$ in location $ll \in LL_k$,

$$P_{ll}^{k}(n)_{ij} = \begin{cases} 1 & if\ i = j\ and\ site\ i\ in\ path\ n\ and\ i\ in\ E_1\ or\ E_2 \\ 0 & otherwise \end{cases}$$

$UEP_{ll}^{k}(n)$ Estimated number of UEs per unit length of MEC application $k \in \{1, \dots, M\}$ of path $n \in \{1, \dots, PN_{ll}(k)\}$ in location $ll \in LL_k$

HN_{ll} Number of MEC hosts in location $ll \in LL$

$H_{ll}(m)$ $N \times N$ matrix that indicates the links inside MEC host m,

$$H_l(m)_{ij} = \begin{cases} 1\ if\ site\ i\ and\ j\ are\ connected\ and\ both\ in\ host\ m \\ 1 \quad if\ i = j\ and\ site\ i\ in\ host\ m \\ 0 \quad otherwise \end{cases}$$
$$(m = 1, \dots, HN_{ll}, ll \in LL)$$

$PL(k)$ The total length of paths selected for MEC application $k \in \{1, \dots, M\}$

$RE(k)$ The total number of relocations UEs of MEC application $k \in \{1, \dots, M\}$ experience

$DL(k)$ The number of disappeared links which belong to the paths selected for MEC application $k \in \{1, \dots, M\}$ in graph G by merging nodes in the way that matrices $\{H_{ll}(m)\}(\forall\ ll \in LL)$ imply

$ER(k)$ The total number of eliminated relocations of MEC application $k \in \{1, \dots, M\}$ by merging nodes in graph G in the way that matrices $\{H_{ll}(m)\}(\forall\ ll \in LL)$ imply

$ERW(k)$ The total weighted number of eliminated relocations of MEC application $k \in \{1, \dots, M\}$ by merging nodes in graph G in the way that matrices $\{H_{ll}(m)\}(\forall\ ll \in LL)$ imply

$REW(k)$ The total weighted number of relocations UEs of MEC application $k \in \{1, \dots, M\}$ experience before integrating unit-hosts into MEC hosts

RW The total weighted number of relocations of all MEC applications after integrating unit-hosts into MEC hosts

LW_{ll} A set of link weights of all links which both end nodes are in location $ll \in LL$

E_1 A set of unit-hosts which corresponding sites cover the entrance of the road in the geographic service area

E_2 A set of unit-hosts which corresponding sites cover the exit of the road in the geographic service area

R_{ll} A set of currently available resources in all unit-hosts in location $ll \in LL$

$resources_k$ Required amount of resources per UE of MEC application $k \in \{1, \dots, M\}$

$Paths_{ll}(k)$ A set that saves all paths in location $ll \in LL_k$ that are selected to reserve resources for MEC application $k \in \{1, \dots, M\}$ as well as the number of UEs each path serves

H_{ll} $H_{ll} = \{h_1, h_2, \dots, h_m\}$, where h_i is a set of all unit-hosts that belong to an already existed MEC host i in location $ll \in LL$, m is the current number of

	MEC hosts in location ll
ne	The number of neighborhoods
NE_i	The i-th neighborhood used in the Variable Neighbor Descent (VND) procedure, $i \in \{1, \dots, ne\}$
T	The sum of links weights of links between different subsets
I_a	The internal cost of node a
E_a	The external cost of node a
D_a	The difference between the external cost and internal cost of node a
$c_{a,b}$	The sum of link weights of the links between nodes a and b
MDP	A Markov Decision Process model that models the geographic service area. The states in this model are MEC hosts
S	State space in the system MDP model MDP
$s \in S$	A state in the MDP model MDP, each state is corresponded to one unit-host in one location
A_s^{app}	A set of possible actions for UEs which are using application app and are in state $s \in S$
$a_s^{app} \in A_s^{app}$	The selected action for a UE which is using application app and is in state $s \in S$
$reward_{a_s^{app}}$	The reward of taking action a for UEs which are using application app and are in state $s \in S$
$p_{s,s'}(a)$	Transition probability from state $s \in S$ to state $s' \in S$ by taking action a, here $p_{s,s'}(a) = 1, \ \forall\, s, s' \in S, \forall\, a$
$DNN_{predict}$	The deep neural network used to update q values for MEC hosts
DNN_{target}	The deep neural network used to provide q values when selecting MEC hosts
$QTable$	The table used to save all estimated q values in traditional SARSA learning algorithm
$q^{app}(s, a)$	The estimated q value for the state-action pair (s, a) related to MEC application app
ε	The … parameter used in the ε-greedy algorithm
α	Learning rate
γ	Future reward decay
$batch\_size$	The number of samples utilized in one iteration of training
$memory$	A table that saves historical records
$memory\_size$	The maximum number of historical records can be saved in table $memory$ for future training
$period$	Update period of DNN_{update}
$counter$	The number of training iterations of $DNN_{predict}$ after the latest update of DNN_{target}, its initial value is 0. When $counter = period$, parameters in DNN_{target} are updated to the parameters in $DNN_{predict}$

Appendix D. Expert Interviews

Interview Questions and Answers

1. *How many MEC hosts do you estimate (order of magnitude) in the Netherlands in the initial stage of Multi-access Edge Computing deployment and 5 years later?*
   At the very early stage, the number of MEC hosts will be limited. But when the O&M cost can be reduced significantly and the number of end-users of MEC services are substantial enough, the number of MEC hosts will increase. However, the number of MEC hosts in 5 years' time is currently hard to predict. (Question answered in interviews 1, 2 and 3)
2. *At which levels in the telecom hierarchy of the network of a Dutch Telco and at which locations of a telecom network would you position MEC hosts initially and after 5 years of deployment?*
   KPN will position MEC hosts at its Metro Cores and superior Cores, as well as locations near to the end-users of MEC services. Because for KPN, optimizing fiber routes can bring more benefits than locating the MEC hosts closer to the end-users. For use cases like V2X offloading and on-premise industrial deployments, however, MEC hosts need to be placed closer to the vehicles; for example, along the roadside or physically close to the factory etc. (Question answered in interviews 2 and 3)
3. *How do you estimate the normal coverage of a MEC host (with/without virtualization) in the initial stage and 5 years later?*
   Right now, KPN locates MEC hosts at its 4 superior Core location within the Netherlands. Later on MEC hosts may be moved to the 164 Metro Core locations to further reduce the latency. However, as the cost will increase by doing so, therefore further research is required. When a MEC host is co-located with a core/metro core, it will provide MEC services to the UEs that are served by the corresponding core/metro core serving area. In the future, it is hard to predict the serving coverage of a MEC host, which may depend on the usage, development and benefits of MEC as well as the maintenance and other costs of running a MEC host close to the network edge. (Question answered in interviews 2 and 3)
4. *Would you think it is necessary for MEC hosts to always connect to (a) (virtualized) UPF(s)?*
   At least foreseen up to now, it is necessary. A MEC host needs to receive the user data it requires while still under the control of the core network, and UPF is the element that can steer the required data towards a MEC host and get controlled by the core network via control plane signaling. (Question answered in interviews 1, 2 and 3)
5. *How do you estimate the complexity and costs (both time and resource/money-wise) of installing MEC applications and instantiating MEC application instances in MEC hosts?*
   Instantiating a MEC application instance on demand can be done within several milliseconds. However, installing a MEC application in a MEC host can take several seconds. Besides, the transfer of user context data between the old and new MEC hosts for a stateful/dedicated MEC application is the major source of delay during a relocation. (Question answered in interview 2)

6. *Do you think it is possible that one UPF can be connected to CU-UPs from different CUs? Do you think it is possible that one CU-UP can connect to multiple UPFs?*
   The answer to both questions is yes. The number of CUs in a network is much larger than the number of UPFs in a network, so a UPF has to be able to connect to multiple CUs. A UE may have multiple requests to access to different data networks via different UPFs, however, user data may go through the same CU-UP, so it is possible for a CU-UP to connect to several UPFs. (Question answered in interview 3)
7. *Do you agree that service latency between a UE and a MEC host is largely dependent on the locations (physical and/or logical) of MEC hosts in the network?*
   Yes, service latency largely depends on both logical and physical locations of MEC hosts. The logical location of a MEC host determines how many functional entities between the UE and the MEC host are involved in delivering MEC services. Since the optical fiber related transmission time is negligible (especially in small-sized countries such as The Netherlands), the processing and queueing time at each functional entity in between mainly determines the service latency. Besides, the physical location of a MEC host also matters because the transmission nodes in between need time to do coding and decoding as well as transformation of the received data. The closer the physical location of a MEC host is to the UE, the fewer transmission nodes in between and thus the shorter service latency between the UE and the MEC host. (Question answered in interview 1)

Interview 1

Expert: Jan Backman
Position: Expert Packet Core Mobility Architecture
Enterprise: Ericsson
Date: Monday, September 21st, 2020
Time slot: 15:00 – 16:00
Form: Microsoft Teams
Summary:

1. Transmission time on optical fibers is negligible. Sending a packet between the southern part of the Netherlands and the northern part of the Netherlands on optical fibers only takes 1.5 milliseconds back-and-forth. Likewise, sending a packet between the northern part of Sweden and the southern part of Sweden on optical fibers only takes around 2 milliseconds back-and-forth.
2. Transmission time via a 5G New Radio (NR) air interface between a UE and a gNB is around 8 milliseconds back-and-forth. Compared to optical fiber, this delay is much higher, but it is inevitable.
3. Since the transmission time on optical fibers is negligible, one of the major sources of latencies is the processing time and queueing time of functional entities between the UE and the MEC host.
4. Service latency may not be the main driver of MEC deployment, to reduce half of the latency, only 4 times as many MEC hosts are needed. Instead, the population density/UE density of an area may require more MEC hosts in order to fulfill the requirements of all UEs in this area. In large cities, there will be more demands on MEC, hence more MEC hosts needed and maybe some extra MEC hosts used for resiliency. In rural areas,

although the number of UEs is limited, MEC hosts need to be deployed in these locations as well to serve the UEs there, which is costly but there is no better approach.

5. For telecom operators, investments and benefits are one of their main concerns. At the initial stage, telecom operators may want to reuse their existing data centers.
6. With network function virtualization, functional entities in a 5G network can be placed anywhere where hardware is available. Theoretically, the service latency can be reduced significantly by placing the MEC hosts very close to the UEs. However, from the operators' point of view, although the deployment of MEC hosts is easier and cheaper with the help of virtualization, the operational and maintenance (O&M) costs of software is still high. Therefore, telecom operators do not want too many MEC hosts at the initial stage. As the technology develops, the O&M costs may be reduced in the near future and as more applications/devices require MEC services, by then telecom operators will consider to build more MEC hosts.
7. In Atlantic City in the U.S., in order to save costs, there are only seven integrated base stations in place, located in a circle around the city. Operators use Virtual RAN (V-RAN) technology, a large number of small sites that cover the entire city will send user data towards these seven base stations for aggregated processing, load-balancing management, etc. In this way, the operating cost is significantly decreased.
8. To sum up, at the initial stage of MEC, the number of MEC hosts will be limited, mainly due to the financial consequences for telecom operators. However, in the future, with MEC and other related technology developing, MEC can be needed more widely and the number of MEC hosts will increase at the same time.

Interview 2

Expert: Ir. Geerd Kakes
Position: Advisor
Enterprise: KPN
Date: Friday, October 2nd, 2020 & Monday, October 5th, 2020
Time slot: 13:00 – 14:00 & 11:30 – 12:30
Form: Microsoft Teams
Summary:

1. Distances in the Netherlands are small between radio sites and core location. For instance, when moving a compute node from a Metro Core node (KPN has around 160 MC locations in NL) to the superior level of 4 core locations the latency gains around 1 to 2 milliseconds.
2. KPN will gain more performance from optimizing fiber routes than by bringing the computing resources closer to the user. Some routes with an actual distance of a few kilometers have a fiber length of more than 40 kilometers. This is because service latency was not a main concern in the past and KPN implemented fiber rings which result in a shorter path and a longer path between a UE and computing resources. After the fiber routes are optimized, it can be foreseen that in some local areas the service latency still cannot be satisfied, therefore more MEC hosts closer to the edge will be needed.
3. Four use cases of edge computing are listed below:

a) Increasing the network performance by bringing content closer to the end-user (e.g. with Netflix content servers) or by processing data closer to the end-user (e.g. video processing of surveillance cameras)
b) Decreasing latency for non-mobile users (e.g. gaming), currently the domain of fixed access
c) Decreasing latency and resilience for V2X use cases (relevant after 2025)
d) Enabling factory automation with on premise 5G infrastructure

4. Edge computing locations at the initial stage will be limited to the following situations:
   a) KPN's 4 superior core locations for mobility use cases
   b) Metro Core location to increase network performance
   c) Customer locations to enable factory or logistic use cases
5. On premise deployment of MEC can guarantee a real constant service latency to the customers and end-users, and the MEC hosts will be located closer to the edge than at the metro core locations. Besides, on premise deployment allows the customers to control their own data security.
6. For V2X scenario, the communications between self-driving vehicles can be done by short range communications like Destination-to-Destination (D2D) communication. In this approach, no MEC hosts are needed. A vehicle can communicate with its peers nearby by broadcasting its location and direction information. However, this type of communication cannot be verified. A vehicle which receives the broadcasted information will not send a response to the vehicle that broadcasts the information, therefore the vehicle which broadcasts the information will never know whether the messages are correctly received by all the vehicles within its vicinity or not. To enhance the success rate of message transfers between vehicles, each vehicle will keep broadcasting the same information (maybe with few updates) repeatedly (e.g. 10 times per second).
7. Some information which has a large data volume and is not updated frequently can be transferred via long range communication methods, for example via TCP. TCP guarantees that the data will be received correctly by the receivers and will send a verification to the sender. Although this approach might take longer time, it is suitable for information like map information of the road which contains the overview of the entire road. This type of information will not change frequently and contains a large amount of data, so it is not necessary to broadcast it periodically and create a large volume of redundancy. Therefore, long range communication is the better choice here.
8. For transferring critical information, D2D communication requires the vehicle itself to sign the message and verify the source of the received message, which involves decoding and analyzing procedure that is time-consuming. Some first measurements using a generic processor show an extra latency of around 13ms. In long range communication, however, the network itself will do the verification for the vehicles, consider the much larger amount of computing and processing resources in the network than in a vehicle. Thus, long range communication can be faster than short range communication under this situation.
9. There are debates on where the received information from vehicles nearby should be computed and processed. Some hold the opinion that considering the low cost of

hardware, it is possible to do the computing and processing inside a vehicle, while others think this approach is not reliable. With the help of MEC, the computation of a vehicle can be offloaded to the MEC host physically close to the vehicle, which can speed up computation and possibly enhance reliability. In this case, the MEC hosts should be deployed very close to the vehicles and the MEC service continuity should be guaranteed.

10. If the trajectory of a vehicle is fully predictable, the MEC application instance in the target MEC host can be instantiated in advance, so the vehicle can connect to the new MEC host before it loses the connection towards the current MEC host. However, in real situations, accurate predications cannot be guaranteed sometimes, if a vehicle connects to a new MEC host before the required MEC application instance in the new MEC host is ready, it can still connect to the previous MEC host via the new one. In this case, the service latency mainly comes from the latency between two MEC hosts instead of the latency between the UE and the new MEC host.
11. Launching a MEC application (instantiating a MEC application instance) on demand can be done easily and quickly with current technology within several milliseconds. However, installing a MEC application in a MEC host can take several seconds. Although the MEC application image can be easily pre-loaded in a MEC host with almost no cost at all, loading a container is rather time-consuming.

Interview 3

Expert: Dr. ing. Frank Mertz
Position: Designer
Enterprise: KPN
Date: Monday, October 5th, 2020
Time slot: 13:00 – 13:30
Form: Microsoft Teams
Summary:

1. The current possible locations for MEC at KPN is at the four superior core locations in the Netherlands. Later, MEC hosts may be moved to the Metro Core locations that KPN has in place in the Netherlands, 161 in total, if the benefits have been proved. Besides, the on-premise deployments will put the MEC host physically close to the place where MEC services are required by the customer, for example, a factory. In the future, it is hard to say where possible locations of MEC hosts can be, but it is always the case that telecom operators want to maximize their benefits and currently, running and maintaining a MEC host is costly, hence the number of MEC hosts needs to be limited, unless the maintenance cost decreases and the profits provided by MEC increases in the future.
2. Up to now, a MEC host is always collocated with at least one (local) UPF, because the user data required by a MEC hosts needs to be steered by UPFs. Besides, traffic steering should always under the control of the core network, using UPF can make sure MEC applications do not fiddle with the traffic rules, because traffic rules followed by a UPF is controlled by PCF via SMF instead of the MEC application itself.

3. A UPF can connect to multiple CU-UPs that are controlled by different CU-CPs at the same time. In this sense, a 5G network is similar to a 4G network. In the Netherlands, KPN has only 4 P-Gws but around 5000 base stations in the current 4G network. This means that one P-Gw should be able to serve multiple base stations. Even though in 4G technology, an eNodeB is not split into multiple DUs, one CU-CP and multiple CU-UPs, the basic concept is the same; one P-Gw can serve multiple base stations which means that it can be connected to multiple user planes that are controlled by multiple control planes in different base stations.
4. A CU-UP can be connected to multiple UPFs at the same time. Nowadays, one single UE may have multiple requirements to different data networks. Take mobile phone as an example, a user may require for Internet connection and IMS connection at the same time. To connect to multiple data networks, the UE may be connected to multiple UPFs, but on the radio side of the network, all the user data may be transferred via the same CU-UP, therefore, one single CU-UP should be able but not necessarily to connect to multiple UPFs. Theoretically, it is possible to build one CU-UP for each UPF, but consider the high cost of implementing and maintaining one functional element even with the help of network virtualization, connecting one CU-UP to multiple CU-UPs seems to be the better option at present.

Appendix E. Location Service

Location Service provides services including UE Location Lookup, UE Information Lookup, UE Location Subscribe, UE Information Subscribe, Subscribe Cancellation, Radio Node Location Lookup, UE Tracking Subscribe, UE Distance Lookup, UE Distance Subscribe and UE Area Subscribe. Only a few relevant services are further introduced.

UE Location Lookup

The UE Location Lookup can provide the current location information of a single UE or a group of UEs. The Location Service will report the lookup result once on each request. Figure E.1 illustrates the procedure of UE Location Lookup.

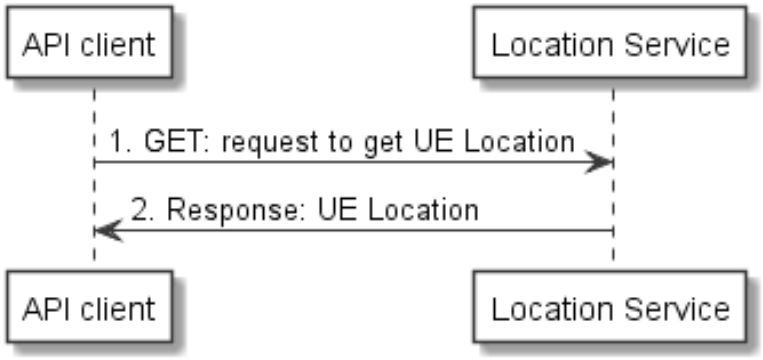

Figure E.1: Flow of UE Location Lookup [32].

1. The MEC application/MEC platform which wants to look up one or more UE locations sends a request with the identifier for each UE (e.g. UE IP address). The request includes one or more query parameters to specify the interested UE(s).
2. The Location Service returns a response with the location information of the requested UE(s).

Radio Node Location Lookup

The Radio Node Location Lookup is to retrieve the radio nodes that are currently associated with a MEC host. Figure E.2 illustrates the procedure of Radio Node Location Lookup.

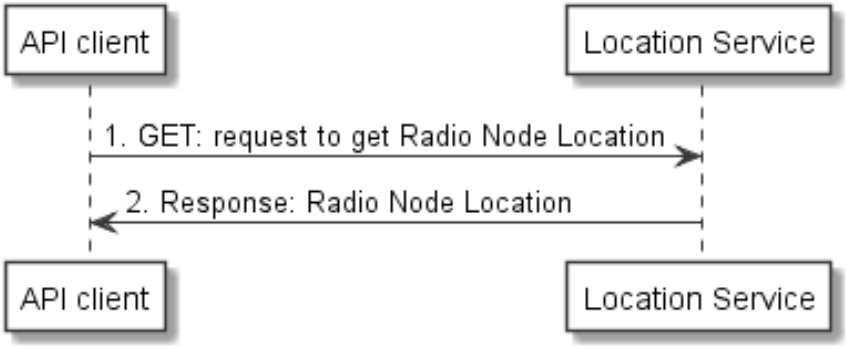

Figure E.2: Flow of Radio Node Location Lookup [32].

1. The MEC application/MEC platform makes an enquiry about the radio nodes currently associated with the MEC host which the MEC application/MEC platform located in.
2. The Location Service returns a response with the list of radio lists currently associated with the MEC host as well as the location information of each radio node.

UE Distance Lookup

The UE Distance Lookup is the procedure for MEC applications/MEC platforms to acquire the current distance between a specific UE and a geographical location, or another UE. Figure E.3 illustrates the procedure of UE Distance Lookup.

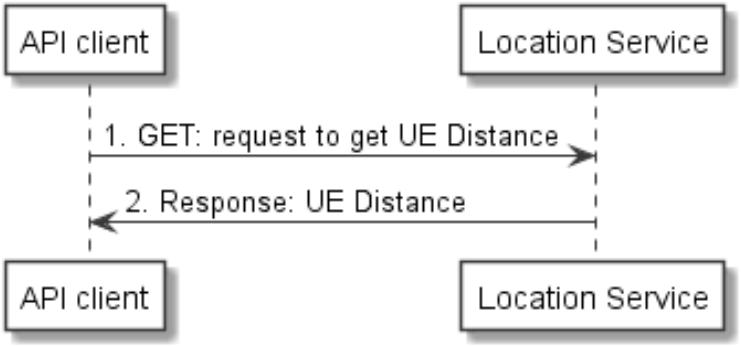

Figure E.3: Flow of UE Distance Lookup [32].

1. The MEC application/MEC platform looks up the distance between the UE and another UE or a geographical location by sending a request including the two UE identities (e.g. UE IP address), or a single UE identifier and the coordinates of the geographical location.
2. The Location Service returns a response including the distance information.

Appendix F. Functional Entities in 3G, 4G and 5G Networks

Table F.1 is an informative comparison table and it gives a global reflection of how functional entities have evolved from 3G to 5G. Further information about mobile communications network architecture can be found in [29] and [45].

Table F.1: Functional entities in 3G, 4G and 5G

<table>
<tr><th></th><th>3G</th><th colspan="2">4G</th><th>5G</th></tr>
<tr><td rowspan="11">Core Network</td><td>Home Location Register (HLR)</td><td colspan="2" rowspan="2">Home Subscriber Server (HSS)
* HSS may utilize the AuC that is functionally connected to the HLR, instead of using an HSS-internal AuC</td><td>Authentication Server Function (AUSF)</td></tr>
<tr><td>Authentication Center (AuC)</td><td rowspan="2">Unified Data Management (UDM)</td></tr>
<tr><td rowspan="2">Serving GPRS Support Node (SGSN)</td><td colspan="2" rowspan="2">Mobility Management Entity (MME)</td></tr>
<tr><td>Access and Mobility Management Function (AMF)</td></tr>
<tr><td rowspan="4">Gateway GPRS Support Node (GGSN)</td><td rowspan="2">Serving Gateway (S-Gw)</td><td>Control Plane (S-Gw-C)</td><td rowspan="2">Session Management Function (SMF)</td></tr>
<tr><td>User Plane (S-Gw-U)</td></tr>
<tr><td rowspan="2">Packet Data Network Gateway (P-Gw)</td><td>User Plane (P-Gw-U)</td><td rowspan="2">User Plane Function (UPF)</td></tr>
<tr><td>Control Plane (P-Gw-C)</td><td>Session Management Function (SMF)</td></tr>
<tr><td>Mobile service Switching Center (MSC)
*Related to circuit-switched networks only</td><td colspan="2">N/A</td><td>N/A</td></tr>
<tr><td>Gateway MSC (GMSC)
*Related to</td><td colspan="2">N/A</td><td>N/A</td></tr>
</table>

<table>
<tr><td rowspan="2"></td><td>circuit-switched networks only</td><td></td><td colspan="3"></td></tr>
<tr><td>N/A</td><td>Policy and Charging Rules Function (PCRF)</td><td colspan="3">Policy Control Function (PCF)</td></tr>
<tr><td rowspan="3">Radio Access Network</td><td>NodeB (NB)</td><td rowspan="3">E-UTRAN NodeB (eNB)</td><td rowspan="3">Next Generation NodeB (gNB)</td><td colspan="2">Distributed Unit (gNB-DU)</td></tr>
<tr><td rowspan="2">Radio Network Controller (RNC)</td><td rowspan="2">Centralized Unit (gNB-CU)</td><td>Control Plane (gNB-CU-CP)</td></tr>
<tr><td>User Plane (gNB-CU-UP)</td></tr>
</table>