

令和 元 年度 博士学位論文

**A Study on SDN-based
Inter-domain Node Mobility
Management**

(SDNに基づくドメイン間端末モビリティ管理に関する研究)

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Chapter 1

Introduction

1.1 Background

1.1.1 Internet of Things

The concept of the internet of things (IoT) is connecting any kind of device to the internet and allowing it to interact with other connected devices [1, 2]. The basis of IoT is depicted in Figure 1.1. In recent years, acceleration of the miniaturization and high functionality of communication devices has enhanced the utility of the IoT environment. Therefore, the IoT is adopted in various fields, such as manufacturing [3], agriculture [4, 5], fishery [6], transportation [7–10], supply chain [11–13], smart home, and smart office [14–17].

The spread of IoT promotes the development and use of network services. In 2017, IEEE802.11ai was standardized to have a considerable improvement in connection speed and fast authentication at access points (AP) [18, 19]. This standardization will increase the use of network services in IoT environments. Furthermore, as 5G [20] and local 5G networks [21] are starting to be used in Japan, IoT deployment is expected to spread even further.

1.1.2 Mobility Management

Considering the spread of wireless communication technology and the IoT environment, users of mobile devices, such as tablets and smartphones, can use network services in



Figure 1.1: Internet of Things.

various situations and places, even while moving [1, 2, 18].

However, when a certain network service user in motion connects to a different network, the IP address of the user’s mobile device changes. This may interrupt communication temporarily, making it difficult to use the network service continuously. As a result, the demand for mobility management, which is a mechanism to continue communication even after a mobile node moves, has increased. Approaches like Mobile IP [22–24] has emerged to meet the demand. Especially in recent years, owing to the development of wireless network technology, wireless communication environments—where multiple access networks can be used in multiple layers—have become commonplace, and the importance of mobility management is increasing. However, in conventional mobility management methods, there are issues such as redundancy of a communication route after the movement of a mobile node; moreover, these methods do not address the case where a mobile node moves across domains.

Though there are many studies on inter-domain mobility management in the carrier network environment, most carrier communication providers charge users according to

the traffic volume used or limit their use when it reaches the upper limit. Therefore, many users prefer to maintain low usage. Currently, many facilities have their own Wi-Fi access points; hence, users who want to reduce carrier traffic usage tend to use these access points to communicate. The key to guarantee a user's comfortability in using network services is retaining the same continuity as the carrier network. Therefore, mobility management in Wi-Fi networks is essential.

When a user moves across domains while using Wi-Fi, he/she connects to an access point in a different domain. Consequently, the communication quality deteriorates unless an appropriate communication path is selected. Therefore, mobility management between domains is necessary.

Although communication speed has improved owing to the development of technology, the amount of network service traffic has increased concurrently. As a result, large data and frequent communications still affect communication speed and the communication of other users. To communicate efficiently with a limited network resource, it is necessary to allocate communication routes flexibly, with different available bandwidths and communication delays for requests that differ according to network services and users. In mobility management, it is essential to provide sufficient consideration to selecting communication paths to maintain communication quality even after moving.

1.1.3 Software Defined Networking

Software Defined Networking (SDN) is a network technology that decouples data and the control planes of a network [25]. Figure 1.2 depicts the architecture of SDN. The separation of planes allows centralized control, where an SDN controller has an overview of the entire network under its control. The SDN controller also acts as a centric management entity that operates all the SDN switches in a network using an overview composed of numerous kinds of information. With this entire view, the SDN controller enables dynamic and considerably flexible management and also expands the utility of the network.

The southbound interface, also known as the southbound application programming interface (API), allows communication between SDN controllers and network nodes, such as physical and virtual SDN switches and SDN routers. The first southbound in-

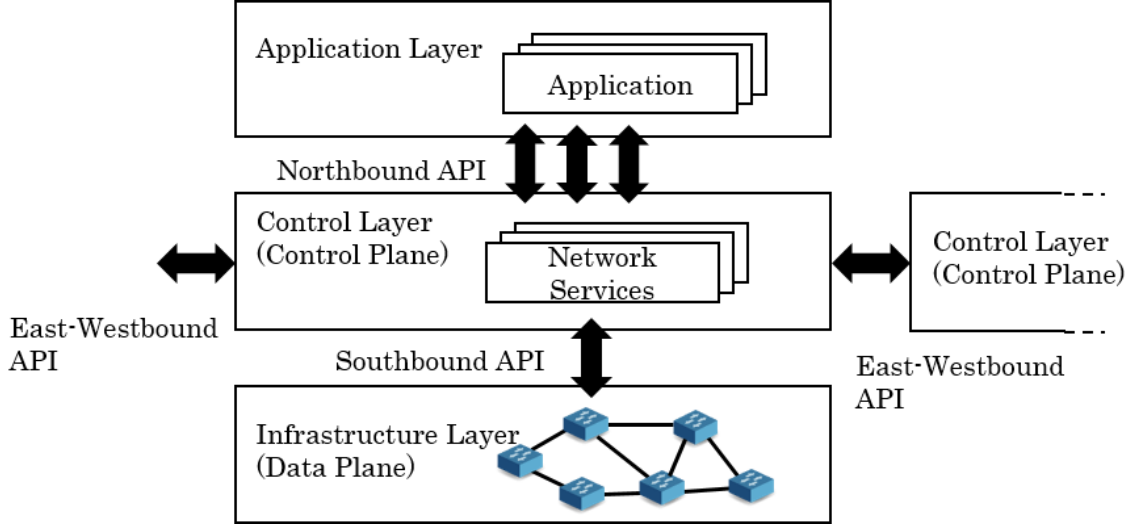


Figure 1.2: Architecture of SDN.

terface was OpenFlow [26]. OpenFlow was developed by Open Networking Foundation (ONF) and is a well-known southbound interface [27]. There are other southbound interfaces, such as OpFlex [28].

The northbound interface, also called northbound API, allows a software to communicate with the SDN controllers and provides the software control of the network.

Furthermore, researchers are struggling to realize the east-west interface of the SDN controllers, which provides a collaboration between the distributed SDN controllers [29, 30].

SDN is now being introduced into vast fields, such as manufacturing [31, 32]; mass media [33]; medical [34–36]; and in the networks of government organizations [37–39].

ny researchers focused on the centralized dynamic control provided by SDN and proposed mobility management approaches using SDN [40–44]. The centralized control of a network renders it extremely easy to manage mobility inside the network. Moreover, it optimizes the communication route after a user ’ s movement. This also is the result of utilizing centralized control.

However, though we need to manage mobility between networks controlled by different administrators, we cannot apply SDN without adding functions since SDN is the technology to manage a network controlled by an SDN controller or collaborated SDN controllers. Currently, as the IoT environment spreads and many networks interconnect to form a larger network, there is a need for collaboration between the SDN

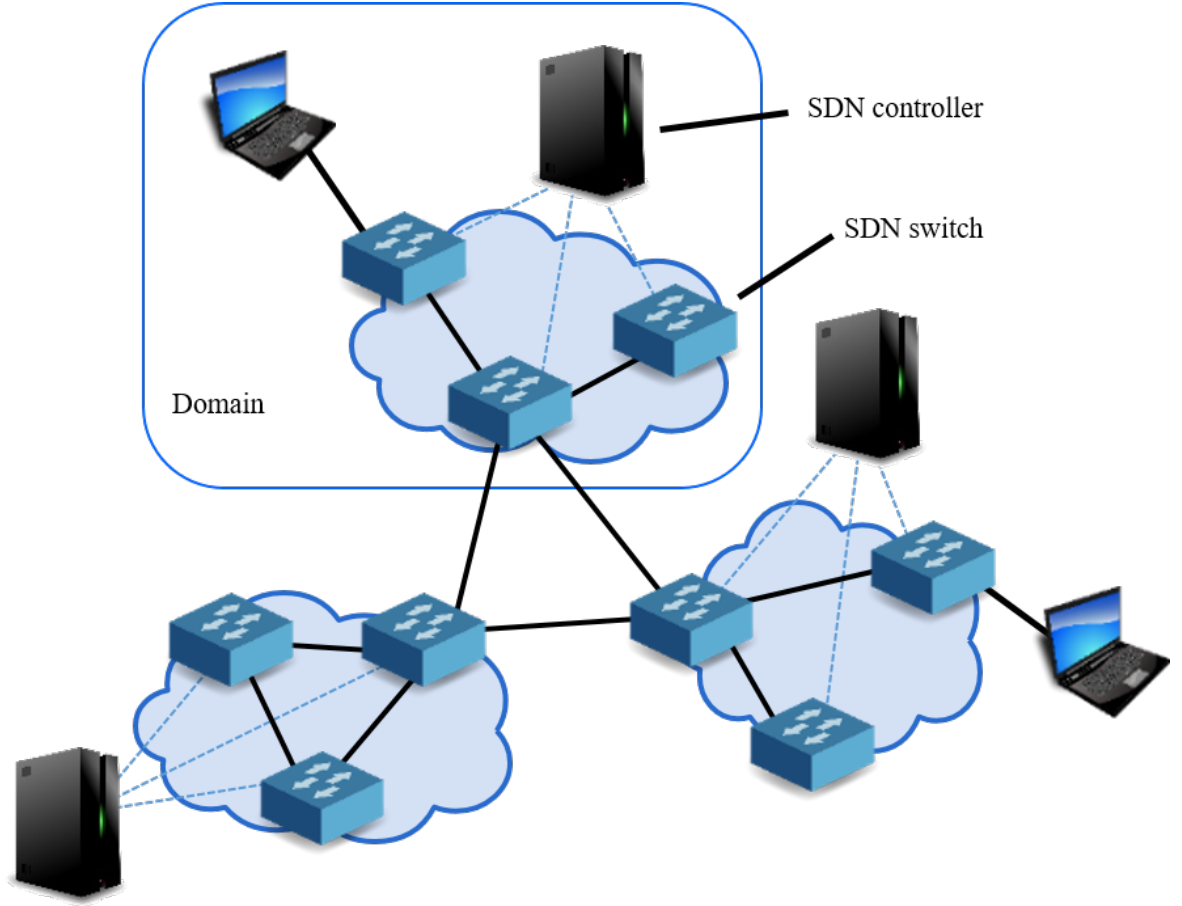


Figure 1.3: Network configuration example.

controllers controlled by different administrators.

Figure 1.3 depicts a sample configuration of a multidomain SDN network we intend to work on. We consider a network within a range managed by each SDN controller an SDN domain and each SDN controller is assumed to be managed by different administrators. Thus, though each SDN domain is able to transfer flows to other SDN domains, the SDN controllers have no visual of other SDN domains.

1.2 Overview of the Study

1.2.1 Objective

The purpose of this research is to construct an inter-domain mobility management framework that continues communication even when a mobile node moves to another

SDN domain. To maintain communication quality, communications on the mobile nodes connected to a network are classified by their characteristics. Moreover, the communication path will be flexibly controlled based on the classification results. This provides users with a seamless and comfortable use of network services.

1.2.2 Challenges

(A) Challenges of the SDN based inter-domain mobility management.

To continue a comfortable communication even after a mobile node moves to another SDN domain, it is significant to share a necessary routing information on the mobile node and also set an inter-domain communication route. This is because it is necessary to set an appropriate communication route between the SDN domains so that the communication quality after movement does not deteriorate. Therefore, we set the following issues.

(A-1) Difficulty in sharing information among SDN domains efficiently.

To grasp the vision of an entire network composed of multiple SDN domains, it is significant to share information, such as mobile node information or information necessary for communication route selection within every SDN controller. This is because SDN controllers only manage the inside of an SDN domain, which they control. However, if all the SDN controllers in a network share an information, the amount of communication for network management increases. As a result, there is a communication delay, causing a likely increment in the network load. Furthermore, the network service quality may be degraded, or even the network service may stop, causing the network service usage to deteriorate.

(A-2) The difficulty of setting an efficient inter-domain communication route.

When a mobile node moves to another SDN domain after transfer of the packet from the home SDN domain, the communication route becomes a redundant triangular routing, which may increase the communication delay. To prevent this, the communication route between a mobile node and its corresponding node has to be controlled after a movement of the mobile

node. However, similar to (A-1), it is difficult to manage an entire network composed of multiple SDN domains. Therefore, it is necessary to collaborate between administrative SDN domains and exchange the necessary information.

(B) Routing challenges after the movement of mobile nodes.

If we set a communication route, after a move of a mobile node to the mere shortest communication route, it may result in a significant reduction in communication quality. It sometimes take time when switching a communication route, ending up disconnecting the communication or dissatisfying the requirements needed for each communication. Therefore, we focus on improving communication quality and set the following issues.

(B-1) The communication quality degradation caused by using only statical information.

To maintain the communication quality, it is necessary to set the communication route properly after a move of a mobile node. In a real network environment, where only one communicating mobile node exists, many mobile nodes often communicate within the same network. Therefore, it is necessary to consider the communication status of other communicating mobile nodes.

(B-2) The difficulty in setting communication routes, satisfying the requirements of communication.

These requirements differ, depending on the type of network service that is communicating. For example, an available bandwidth would likely be plentiful for video streaming and low latency is preferred for network services, such as real-time translation services that frequently exchange small data. If a uniform routing standard is used for all the communication flows, it becomes difficult to respond to different requirements, and the quality of communication may be degraded.

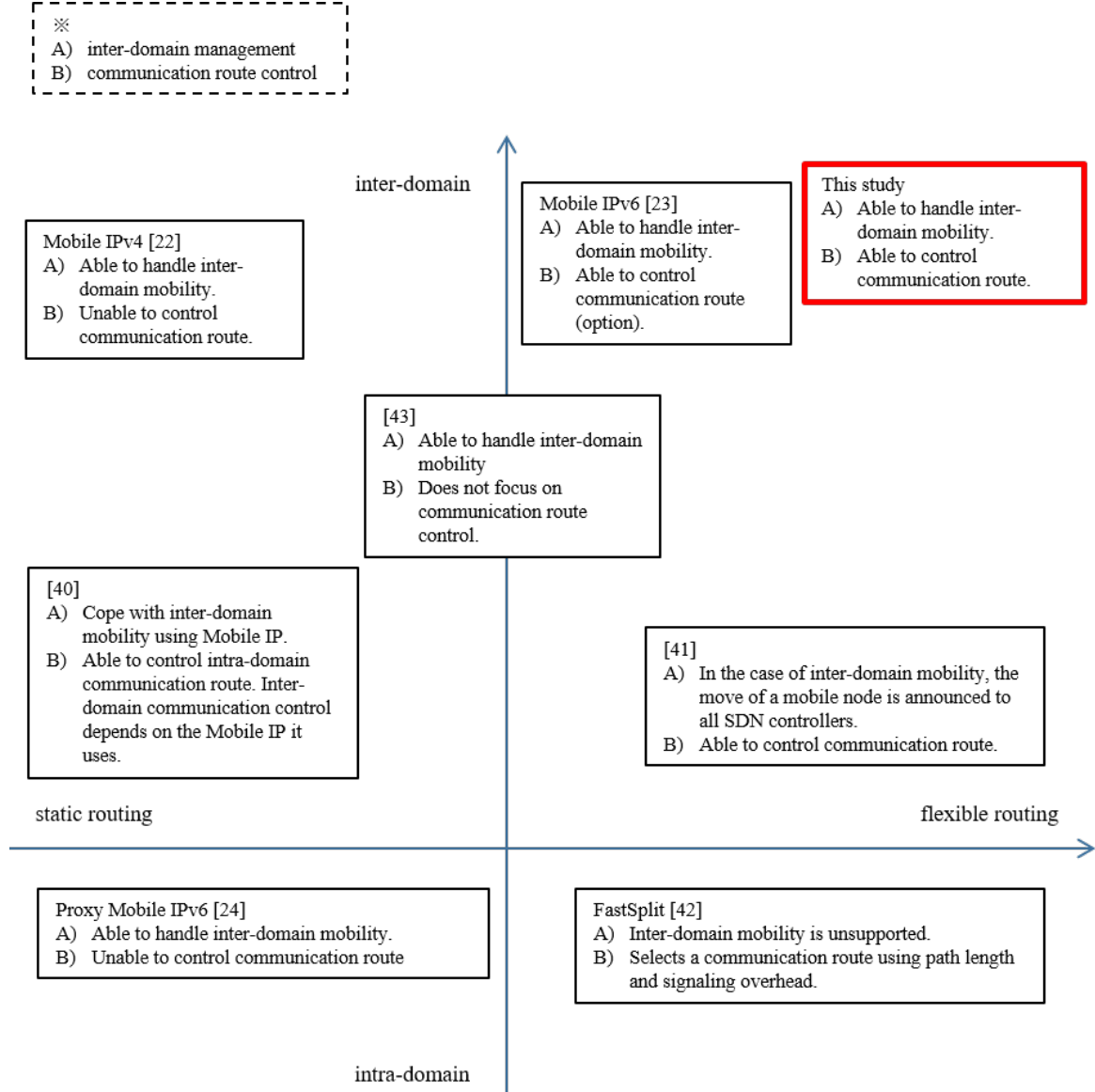


Figure 1.4: The position of this study.

1.2.3 The Position of This Study

Figure 1.4 shows the brief summary of the position of this study.

Conventional SDN based mobility management approaches were proposed to manage communication efficiently when a mobile node moves inside an SDN domain. This is because of the specialty of SDN; SDN can direct a network that is under the control of an SDN controller or a set of SDN controllers that centrally and flexibly collaborate. However, as the IoT environment grew larger, the number of mobile devices that moved across the SDN domains increased. Therefore, it became difficult to cope

with the conventional SDN based mobility management approaches and it has also become necessary to take into account the inter-domain movement of mobile nodes. Hence, there is a need for studying SDN based mobility management that considers inter-domain movements.

I first adopted SDN to the multiple administrative domain network, which made the information exchange efficient. Owing to the characteristics of SDN, an SDN controller can only collect information from the SDN domain it manages. Hence, to perform inter-domain mobility management, an SDN controller needs information from other SDN domains. To attempt to obtain all the network management information from all the SDN domains in a network, we need an enormous amount of communication. In practice, only required information needs to be exchanged among the SDN domains related to mobility management. Hence, the SDN domains to exchange information can be limited to reduce the total traffic load. By achieving this reduction, we can avoid occupying the network resource with communications for mobility management. This is considered to contribute to maintaining a good network environment in the recent IoT environment, where traffic increases.

Also, when setting a communication route after a mobile node moves, it is necessary to select a suitable communication route flexibly to respond to various communication requirements. However, the existing SDN based inter-domain mobility management approaches have difficulty dealing with changing network state. The existing routing methods for SDN networks cannot qualify mobility management requirements while maintaining communication quality.

Therefore, we propose an end-to-end inter-domain routing method specific for mobility management. When selecting a communication route, the proposed method uses the characteristics of the communication and performs dynamic routing, based on them. Currently, there are various network services; however, they require different communication needs, such as wide bandwidth and low latency. If uniform communication route selection criteria are adopted in such a situation, it may be impossible to satisfy the requirements for the comfortable use of network services. Requirements can be roughly categorized and the difference is seen in the characteristics of communications. By classifying the flows based on the characteristics of communication and performing

routing according to the classification, it is possible to assign a communication route that provides network resources, satisfying the bandwidth requests and communication delay. This makes it possible to provide every mobile node with appropriate communication conditions. In addition, there is no other attempt to apply routing methods using the characteristics of communication to mobility management.

In this study, we propose a new SDN based mobility management approach that ensures communication quality. Specifically, we focus on maintaining a high-quality communication after a mobile node moves across the SDN domains. First, we design an architecture for an SDN based inter-domain mobility management framework. Furthermore, we will extend the routing method after the movement of the mobile nodes and also aim for a flexible communication route selection. The effectiveness of the proposed framework and methods are verified through experiments.

The completion of this research will provide comfortable communication for mobile node users aware of mobility management. This will enable ordinary mobile node users to enjoy a comfortable communication environment without being conscious of anything. Currently, with the diversification of network services and increasing opportunities for mobile nodes to communicate, the realization of comfortable communication environments dramatically contributes to the society.

1.3 The Organization of This Thesis

Figure 1.5 shows the outline of this thesis.

In Chapter 1, the background of the study is described first, then the objectives, drawbacks, and the position of this study follow.

In Chapter 2, an SDN based inter-domain mobility management framework is proposed, which facilitates comfortable communication after a mobile node moves. This framework has two key functions: management information sharing function (MISF) and inter-domain routing function (IDRF). The efficiency of the framework is verified through simulation experiments.

in Chapter 3, an end-to-end routing mechanism aware of mobility management is proposed, which considers some information for routing. Also, simulation experiments

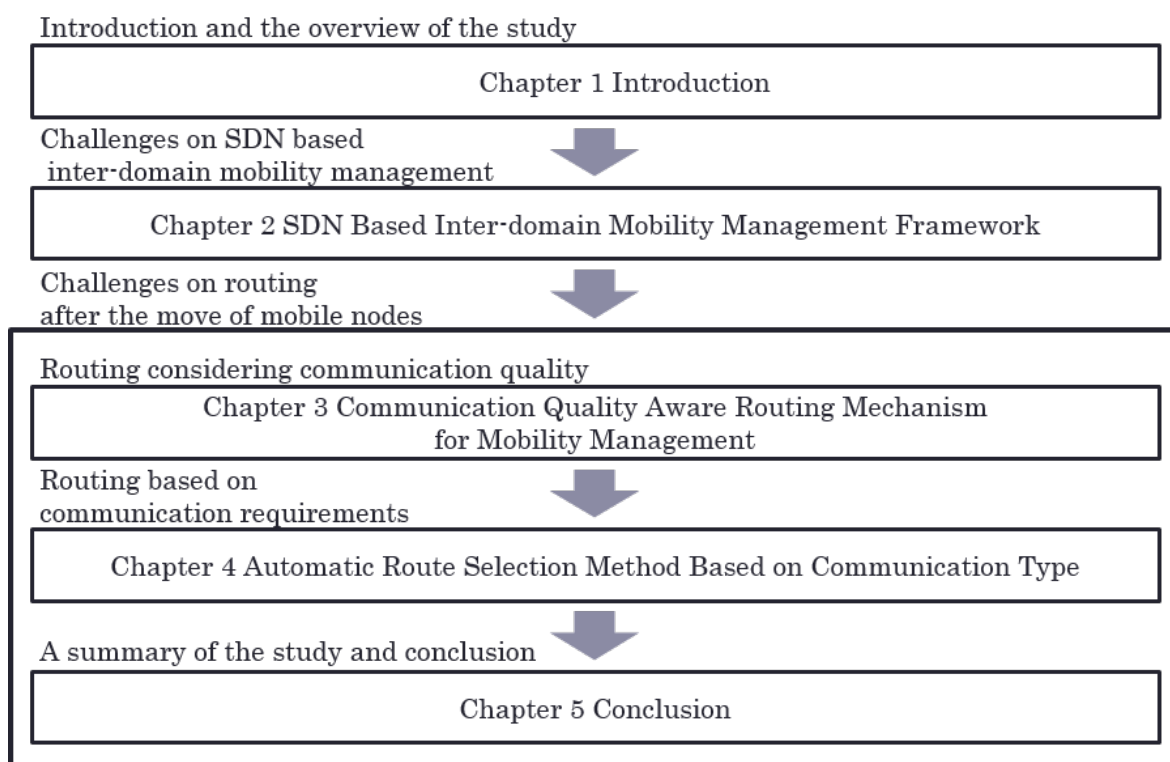


Figure 1.5: Outline of this thesis.

are executed to verify the efficiency of the routing mechanism.

In Chapter 4, the routing mechanism proposed in Chapter 3 is extended to deal with the requirements of various communications flexibly. After automating the flow classification and communication route, setting procedures, the effectiveness of the expansion is assessed through simulation experiments.

Chapter 5 summarizes the research results and presents the conclusions of this study. Future issues are also listed.

Chapter 2

SDN Based Inter-domain Mobility Management Framework

2.1 Introduction

2.1.1 Background and Overview

Owing to the widespread of the wireless network environment, it is now possible to use network services in various places and scenes. Network services, such as file transfer service, remote terminal service, and virtual desktop service are popularly used [1, 2]. Small-sized devices, such as laptop PCs, smartphones, and tablet PCs, capable of wireless communication, use the above mentioned network services. Throughout the rest of the study, we call any of these devices a mobile node (MN). Since MNs are portable devices, users tend to move around while using network services. With the particular case of session continuous network services, continuity of network services during movement becomes a critical problem. When an MN user moves and its device connects to an access point in a different network domain, the IP address of the MN changes. If a communication session is disconnected owing to the change in the IP address, problems such as lack of data and logout from network services emerge, which affect the use of network services. Thus, IP mobility management is essential for enabling the use of network services while moving.

Mobile IP is one of the IP mobility management, standardized by Internet Engineering Task Force (IETF) [22–24]. Mobile IP is a technology that enables continuous

communication when an MN user moves during a communication. If the MN user moves to a different domain, the technology still enables continuous communication, with the IP address used before the move. However, there are cases where the communication route of an MN falls into triangular routing. This might lead to a degrade in the quality of service (QoS), caused by communication delay. Moreover, an MN must be equipped with a Mobile IP function and this is a challenge when applying all MNs.

Some researches apply SDN to IP mobility management to solve the problems mentioned above [40, 41]. SDN is a technology that controls a network dynamically with a software [25]. By using SDN, an SDN controller centrally manages SDN switches in their domain and this enables nodes to communicate with a suitable communication route. However, existing researches focused mainly on the intra-domain move. To cope with the inter-domain move, with SDN, SDN controllers in different SDN domains have to exchange information about the movement of an MN. As a result, communication costs between SDN controllers may increase and might become a problem in practical use. Therefore, it is difficult to maintain an efficient communication when an MN makes an inter-domain move.

There are two major trends in which inter-domain handover with SDN can be handled. One approach is to use a Mobile IP when inter-domain handovers occur [41]. By using a Mobile IP, SDN controllers do not need to search for SDN domains to exchange information of MNs. However, Mobile IP has difficulty in communication route optimization. Another is to announce information of MNs to every SDN controller in the network [40]. This approach allows the communication routes to be optimized. However, with a network that comprises many SDN domains, communication for the announcement might compress the communication bandwidth. These conventional approaches could only realize efficient data exchange or communication route optimization.

To overcome both problems simultaneously, we propose an SDN based IP mobility management framework, focusing on the inter-domain handovers. Our proposed framework comprises two functions: MISF and IDRF. MISF effectively searches for a destination SDN domain of a moved MN and chooses minimum SDN controllers to share minimal information related to the communication of the MN to manage infor-

mation efficiently. IDRF calculates an appropriate communication route to allow the MN to continue effective communication.

We also conducted some experiments to confirm the effectiveness of our proposed framework. The results show that our proposal achieved to optimize the communication route and keep the traffic volume between SDN controllers low.

2.1.2 Novelty and Contribution

To realize efficient inter-domain handovers, we propose a novel framework to efficiently exchange the information of an MN between SDN controllers in each SDN domain and also optimize the communication route between an MN and a corresponding node (CN). Existing approaches do not realize these two requirements simultaneously because these approaches differ in target, purpose, and assumed environment. Therefore, the existing approaches do not match the purpose of what we concentrate on this time. When Mobile IP emerged, communication route optimization had little meaning because there were not too many choices of a communication route, to be selected. Moreover, Mobile IP aimed at easy implementation without any modifications in network infrastructure, as it focused on practical use. Thus, Mobile IP does not have full support on communication route optimization. The SDN based methods do not aim at covering wide-area networks and they are approaches for deprived environments. Hence, they can handle inter-domain handovers; however, not efficiently. Our proposed framework realizes two things simultaneously: efficient information exchange between the SDN controllers and communication route optimization to achieve the inter-domain handovers in a large-scaled wide-area network, efficiently with functional support of network infrastructure.

With this novelty, mobile communication will be more seamless and delay-less. This leads to an improvement in communication quality for users moving around with their communicating MNs. For example, without our proposed mobility management framework, when users with mobile PCs move across SDN domains while downloading data from a cloud server, the disconnection of communication would occur and subsequently lead to packet loss. Moreover, when the users move across SDN domains while using interactive-type applications, such as remote login terminal or remote virtual

desktop environment (VDI), a session would be interrupted. In addition, redundant communication route leads to severe communication delay, especially when users are handling large data. By using the proposed framework, MN users will be able to download or upload their data smoothly and perfectly, while moving around. As for the interactive-type applications, MN users will be able to use the network services without any termination of the process, even without the applications having the function of switching connections when the IP address changes.

2.2 Related Works

2.2.1 Mobile IP

In this section, we introduce related works of IP mobility management and summarize their drawbacks. Internet Engineering Task Force (IETF) standardized Mobile IPv4 to realize IP mobility management [22]. Mobile IPv4 is a protocol that maintains communication between an MN and a CN, which communicates with an MN after the MN moves to other network domains. Figure 2.1 shows its overview. Mobile IPv4 uses a Home Address (HoA) and a Care-of Address (CoA) to continue communication after the move of an MN. HoA is an address an MN uses in the source domain and CoA is an address an MN uses in the destination domain. MN registers its binding-cache to its Home Agent (HA). Binding-cache is a set of HoA and CoA of an MN. The HA transfers the packets sent to HoA to CoA. However, depending on the location of the HA, an MN may communicate with a CN over a redundant communication route, which we refer to as a triangle routing problem.

IETF [23] also standardized Mobile IPv6. In addition to the functions of Mobile IPv4, it also has a communication route optimization function that enables MNs to communicate with the most suitable communication route. However, this is an optional function. Therefore, only the MNs that support communication route optimization can use this function. Moreover, the current IPv6 penetration rate is low, approximately 33% and accordingly, the penetration rate of Mobile IPv6 is low. Therefore, the practical application of Mobile IPv6 is difficult.

To realize IP mobility management, we need to share a variety of information, such

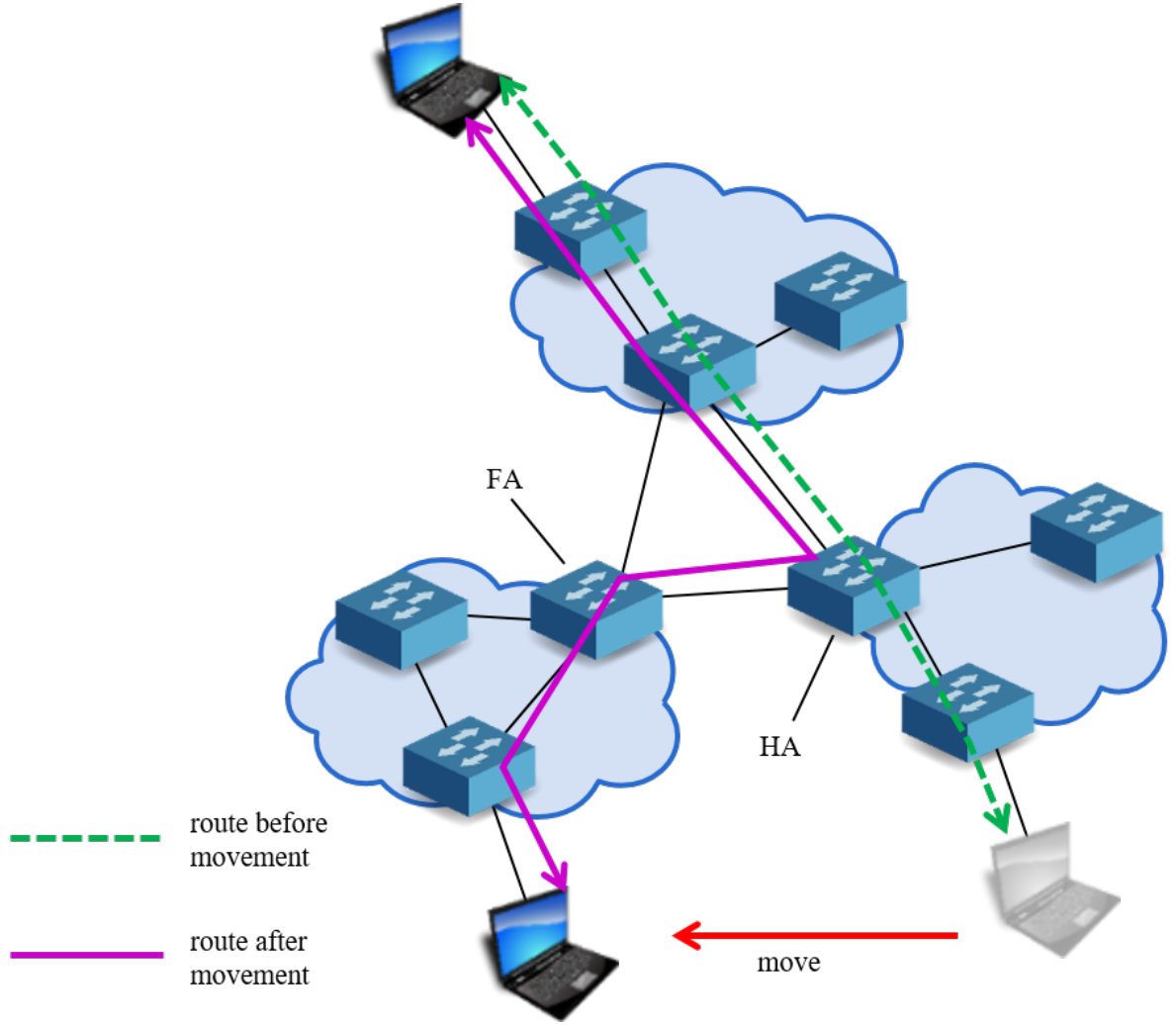


Figure 2.1: Overview of Mobile IPv4.

as HoA, CoA, the lifetime of a Binding Cache, etc., among an MN, an HA, and a Foreign Agent (FA). IETF standardized Mobile IPv6 Management Information Base [45]. MIB defines a large amount of information needed for Mobile IPv6. To realize IP mobility management, it is essential to select a location to share plentiful information efficiently. In Mobile IPv4 and Mobile IPv6, the MN registers its binding cache to its HoA. Thus, there is no need to search for a location to share information.

In Mobile IPv4 and Mobile IPv6, the MN needs to conduct IP mobility management. However, Proxy Mobile IPv6 (PMIPv6) executes IP mobility management on network equipment [24]. Figure 2.2 shows its overview. The network equipment executes the process for IP mobility management in PMIPv6. Therefore, there is no need for an MN to involve in IP mobility management. Local Mobility Anchor (LMA)

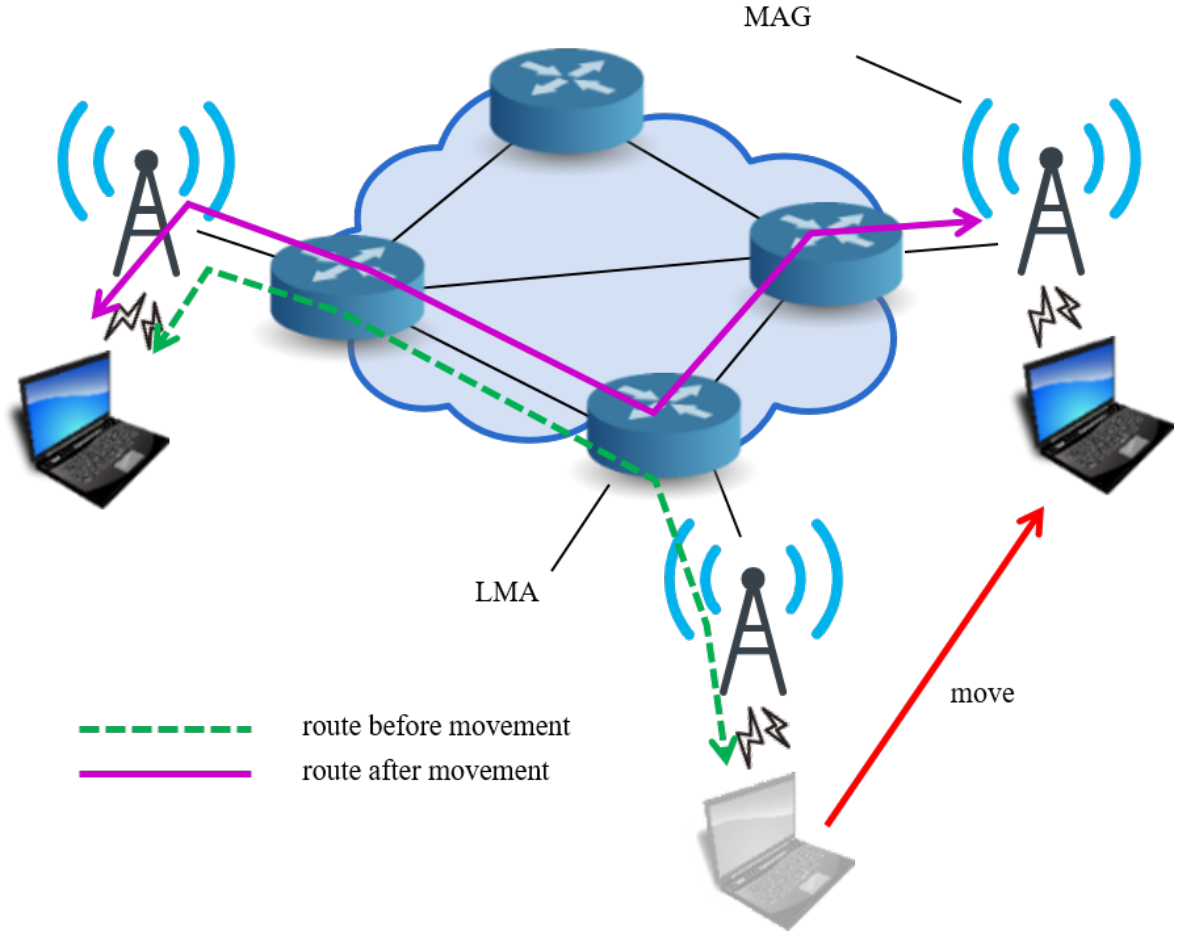


Figure 2.2: Overview of Proxy Mobile IPv6.

keeps bindings of HoA and Proxy-CoA. Mobile Access Gateway (MAG) detects MNs and registers bindings to LMA. After an MN moves, MAG registers the HoA and the Proxy-CoA binding of the MN to LMA. Packets sent to the HoA of an MN are transferred to the MN via LMA. Like Mobile IPv4 and Mobile IPv6, PMIPv6 also has the triangular routing possibility.

2.2.2 SDN based IP mobility management

SDN enables us to control networks intensively and flexibly. Therefore, as a means to solve the communication route optimization problem, SDN has attracted attention. Using SDN, network devices execute all the IP mobility management processes. Thus, unlike Mobile IPv4 and Mobile IPv6, the MN does not need to be equipped with IP mobility management functions. For this reason, there are some IP mobility management

Table 2.1: Summary of related works.

Approaches	Mobile IPv4 [22]	Mobile IPv6 [23]	PMIPv6 [24]	Paper [40]	Paper [41]
Intra-domain routing	×	△	△	○	○
Inter-domain routing	×	△	×	○	△
Domain selection to share information	○	○	○	×	○

approaches using SDN. Studies, [40] and [41], show communication route optimization mechanisms in the case when intra-domain handover occurs. However, in the case of an inter-domain handover, the mechanism in [40] uses a Mobile IP. Therefore, MNs need to be equipped with communication route optimization function to optimize communication route after handover. The mechanism in [41] regards inter-domain handover as infrequent and broadcasts this event to all other SDN controllers. Therefore, the amount of traffic increases when inter-domain handover occurs frequently in a network that comprises many SDN domains.

2.2.3 Problems of related works

We summarized the drawbacks of the related works in Table 2.1. We confirm that existing works cannot realize an efficient selection of the SDN domain to share information, intra and inter-domain communication route optimizations, all together. The studies, [40] and [41], applied SDN to solve the Mobile IP problem, communication route optimization. However, SDN controllers can only control the SDN domain they manage. This means that these approaches focus on the intra-domain communication route. Nonetheless, in recent network environments, users move freely to various SDN domain networks while using network services. Therefore, we have to consider the IP mobility management in multiple SDN domain networks. To realize this, we need an SDN controller in each SDN domain to share information of MNs. However, if an SDN controller broadcasts the information to all other SDN controllers, it might cause large amount of traffic in a situation where inter-domain handover occurs frequently.

Hence, we need a mechanism to share information efficiently in multiple SDN domain networks.

2.3 SDN Based Inter-domain Mobility Management Framework

2.3.1 Overview

In this section, we propose an SDN based IP mobility management framework, considering inter-domain handovers, to solve the problems explained in section 2.2. We first show the overview of our proposed framework and discuss the details of composed functions later. Figure 2.3 depicts the overview of our framework. This framework realizes inter-domain communication route control while sharing information efficiently with two functions: MISF and IDRF.

MISF searches for the source domain (the MN ' s SDN domain before movement) and decreases the number of SDN domains to exchange MN information, to reduce traffic load between SDN controllers. IDRF calculates an end-to-end communication route between an MN and a CN in the destination domain (the SDN domain the MN moved into) and announces this communication route only to the SDN domains in the selected route, to optimize inter-domain communication routes.

We assume that inter-domain topology changes do not occur frequently. Therefore, the SDN controllers have an inter-domain topology information. Inter-domain topology information consists of the following.

- IP address of an SDN controller in each SDN domain.
- The network address of each SDN domain.
- The inter-domain link information.

The functions mentioned above use this inter-domain topology information to search SDN domains and also calculate communication routes.

We show the components of our proposal in Figure 2.4. The components include SDN controllers, SDN switches, an MN, and a CN. Our framework supports two layers

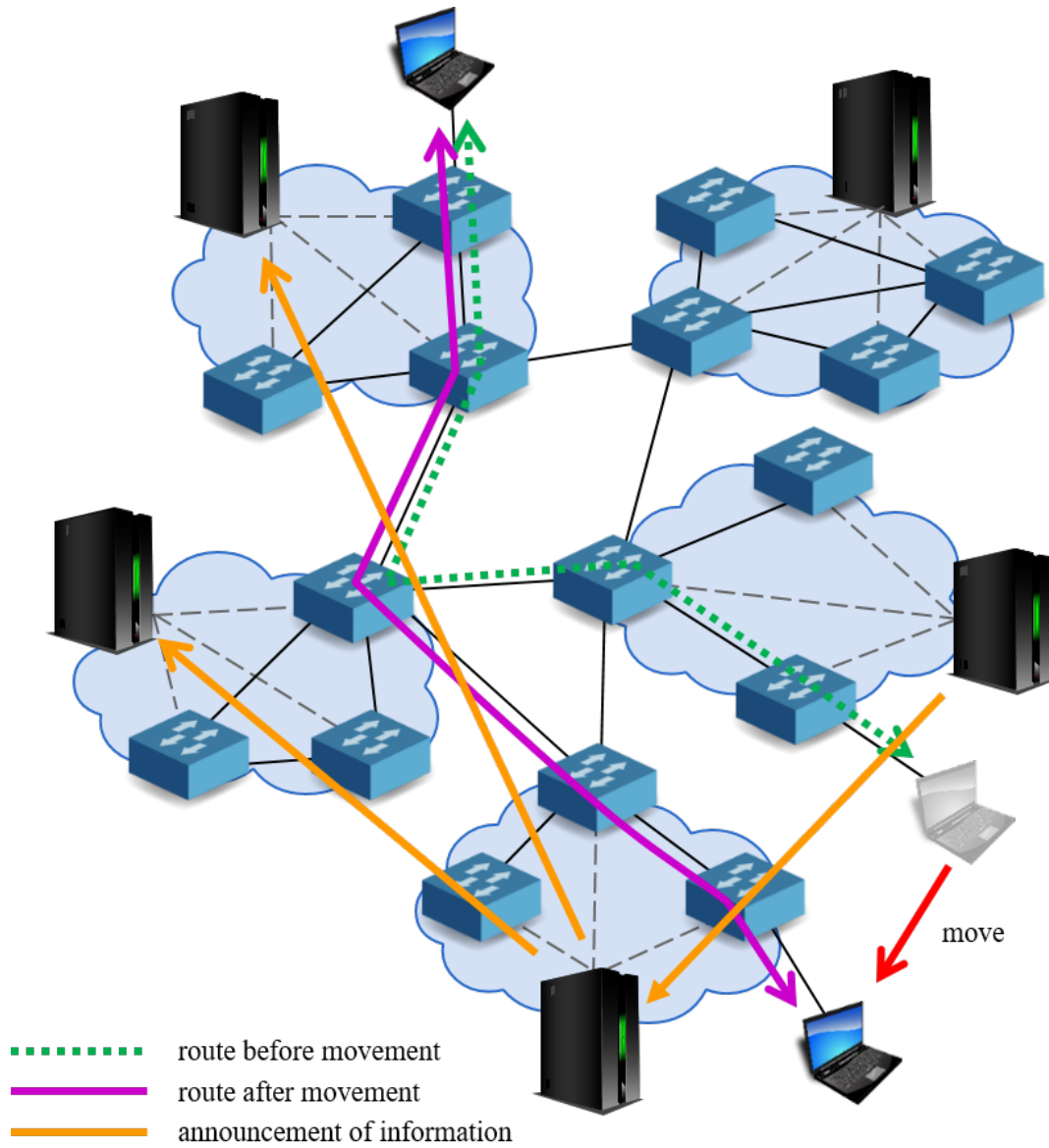


Figure 2.3: Overview of SDN based IP mobility management considering inter-domain handovers.

of a network: an SDN controller network and an SDN switch network. SDN controller network consists of SDN controllers in each SDN domain. This network is used to exchange information to optimize the MN-CN communication route. SDN switch network consists of SDN switches.

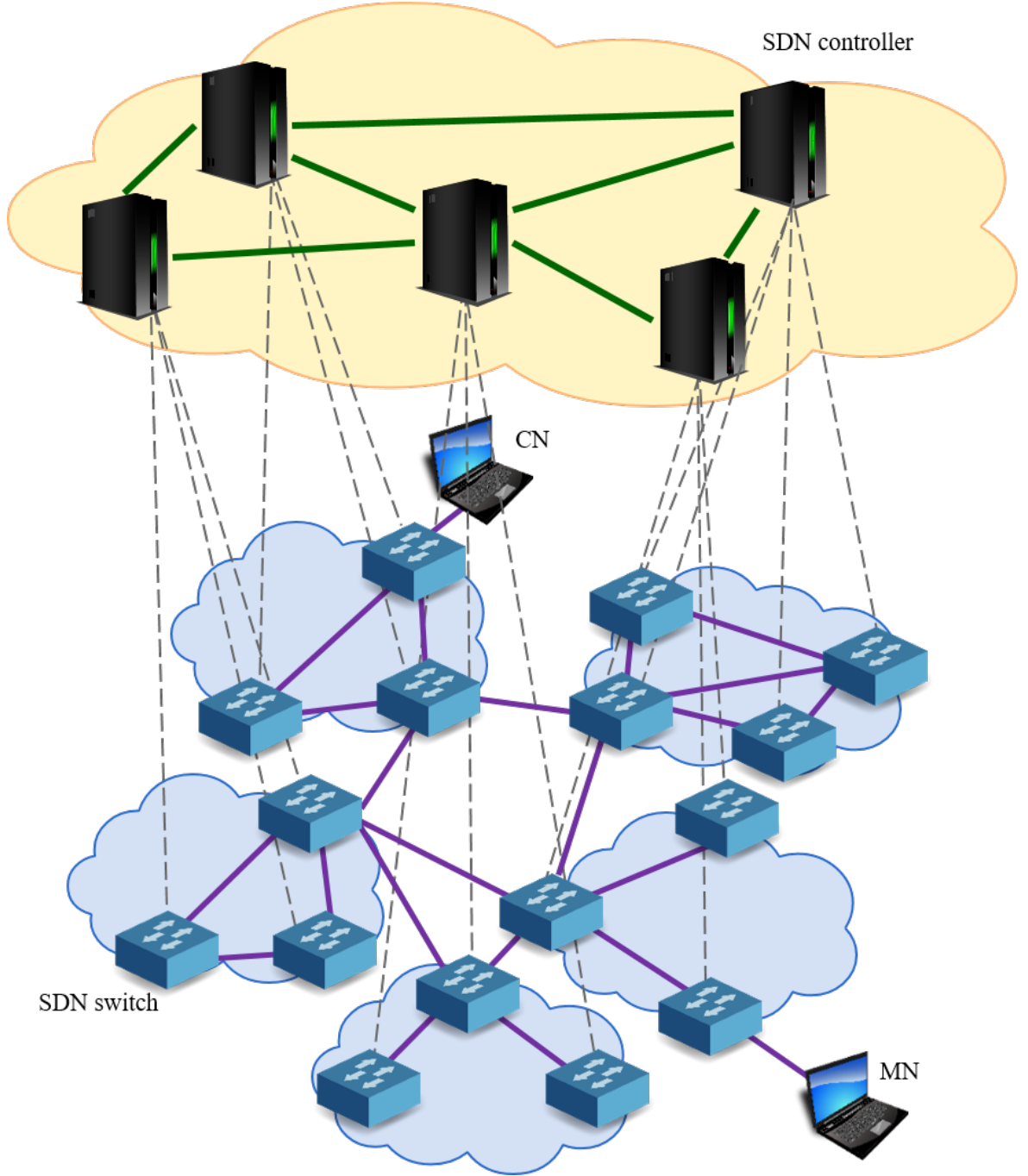


Figure 2.4: Network configuration.

2.3.2 Management Information Sharing Function

We describe the detailed design of MISF with an example. The network used for the explanation is shown in Figure 2.3. We assume that an MN moves from a source to a destination domain during communication with a CN and an SDN controller of the destination domain, which detects the connection of an MN in the destination domain

(attachment of the MN). The IP address of the MN changes after this move. Below is the MAC address, the IP address that the MN used in the source domain (former IP address), and the IP address that the MN is currently using in the destination domain (current IP address).

- MAC address: 00:00:00:00:00:11
- former IP address: 10.0.1.1
- current IP address: 10.0.2.1

We define the names of the SDN domains and the SDN controllers that involve in the MN handover as below:

- SDN domains
 - D_d : The SDN domain MN belongs to, after a move
 - D_s : The SDN domain MN belongs to, before a move
 - D_c : The SDN domain CN belongs to
- SDN controllers
 - C_d : The SDN controller that manages D_d
 - C_s : The SDN controller that manages D_s
 - C_c : The SDN controller that manages D_c

Now we describe the MISF procedure, step by step. The Sequence diagram of MISF is depicted in Figure 2.5.

1. C_d searches for D_s , based on the MAC address of MN.

C_d sends queries in order, from neighboring SDN domains, as depicted in Figure 2.6. SDN controllers of the SDN domains that received the query search their SDN domain to check if the MN belonged to it, and send the result to C_d , for a reply. When an MN was not in their SDN domain, they return the absence of the MN. However, when an MN was in their SDN domain, they return the IP address the MN used.

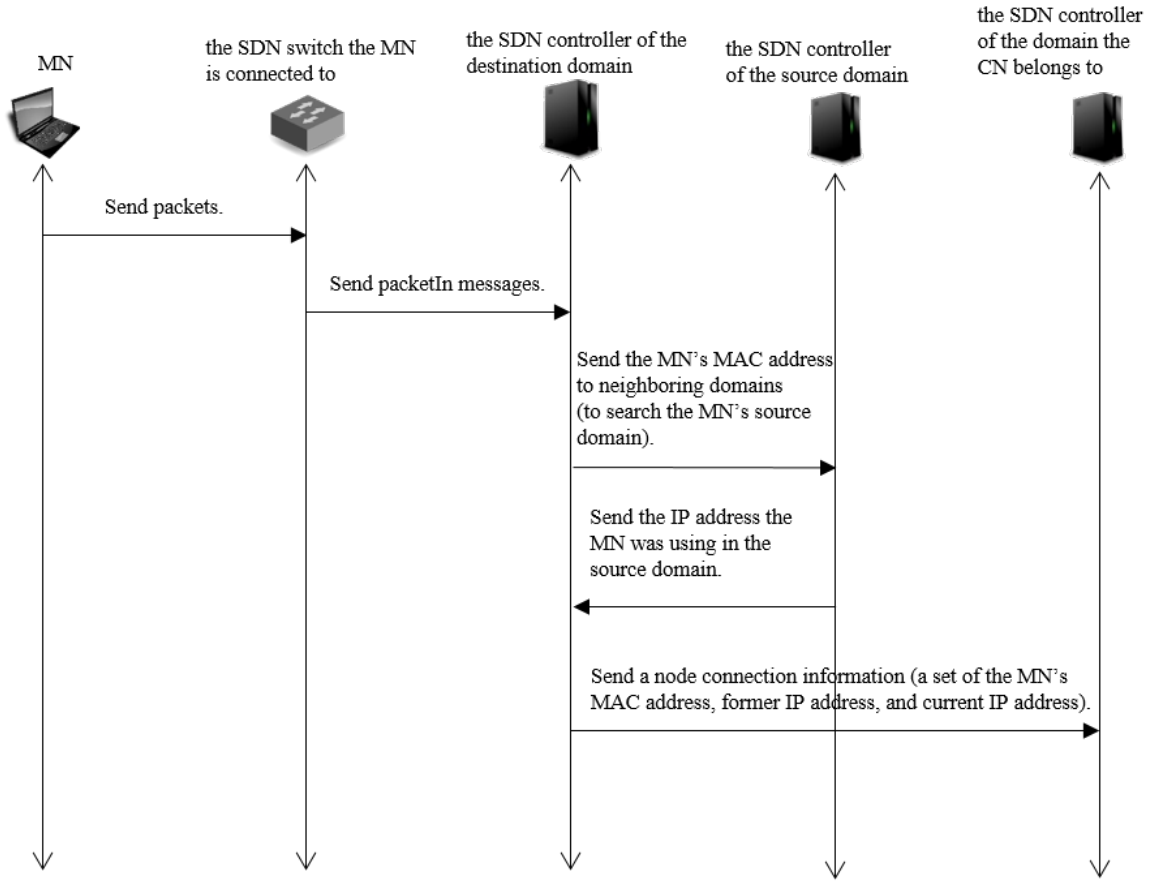


Figure 2.5: Sequence diagram of MISF

2. C_d generates node connection information from the IP address sent from C_s .

Node connection information consists of the following information.

- MAC address of an MN
- former IP address
- current IP address

In this example, the node connection information is as follows.

- MAC address: 00:00:00:00:00:11
- former IP address: 10.0.1.1
- current IP address: 10.0.2.1

3. C_d sends node connection information to C_c .

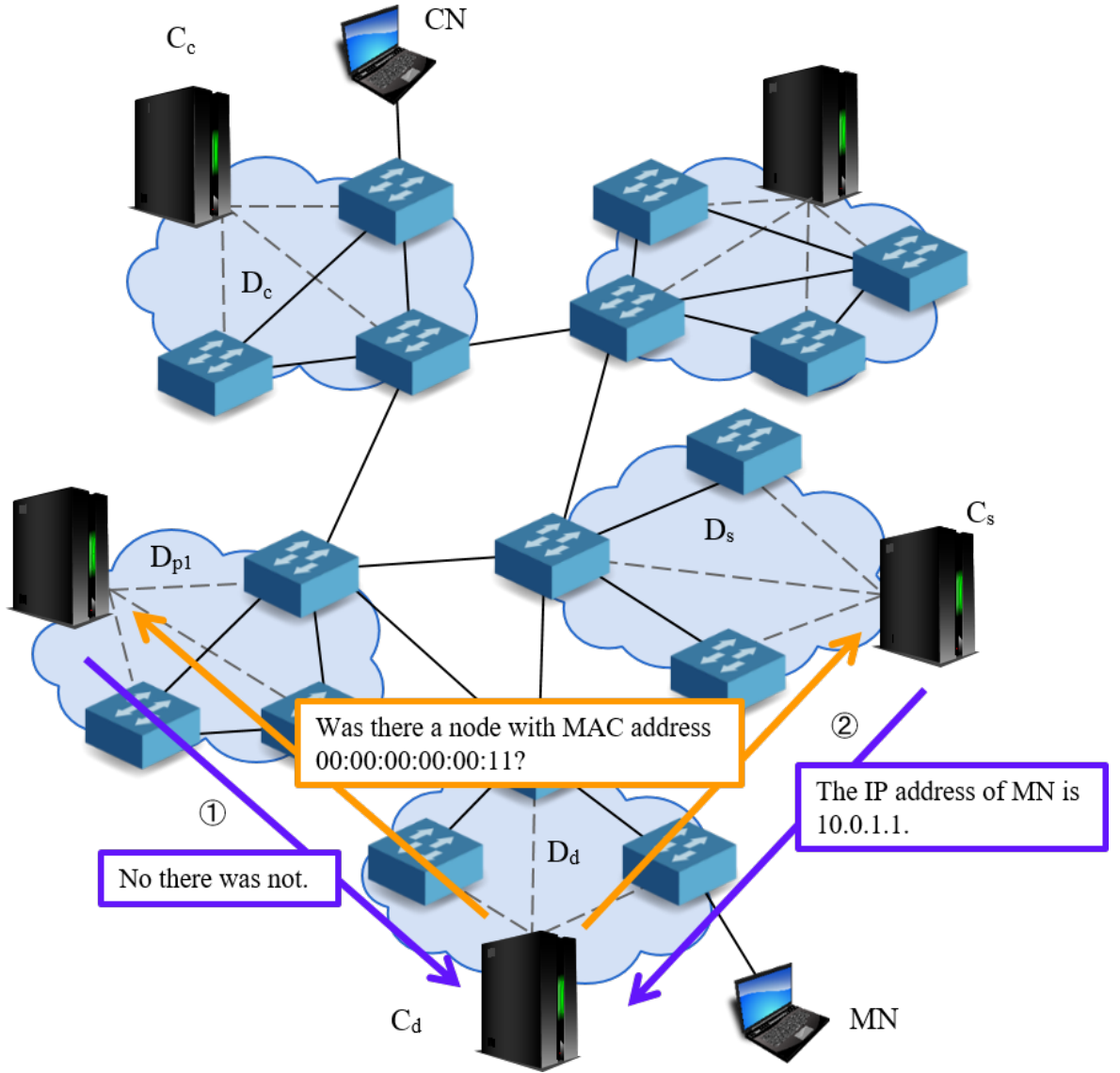


Figure 2.6: Search for D_s .

C_d sends the information as shown in Figure 2.7. To send a node connection information to a CN, C_d needs to know where the CN is, and the IP address of C_c . C_d obtains the IP address of CN from the header of the packet sent from the MN to the CN, and subsequently, derive the C_c information from the inter-domain topology information that each SDN controller possesses.

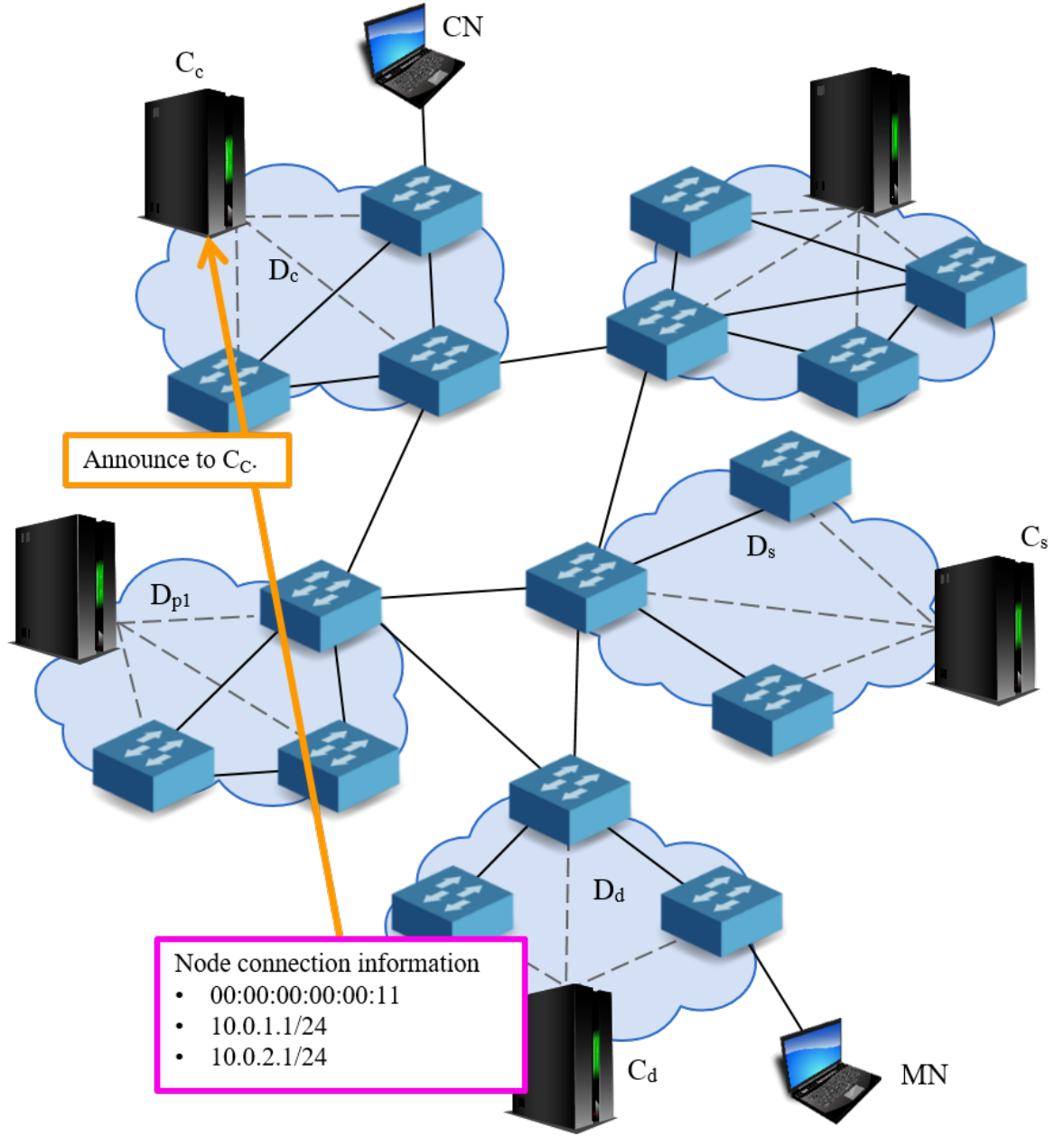


Figure 2.7: Announcement of node connection information.

2.3.3 Inter-domain routing function

Next, we explain the detailed design of IDRF following the example we used in the explanation of MISF in section 2.3.2. The Sequence diagram of IDRF is depicted in Figure 2.8.

1. C_d calculates the MN-CN inter-domain communication route.

We regard each SDN domain as a node and calculate the inter-domain commu-

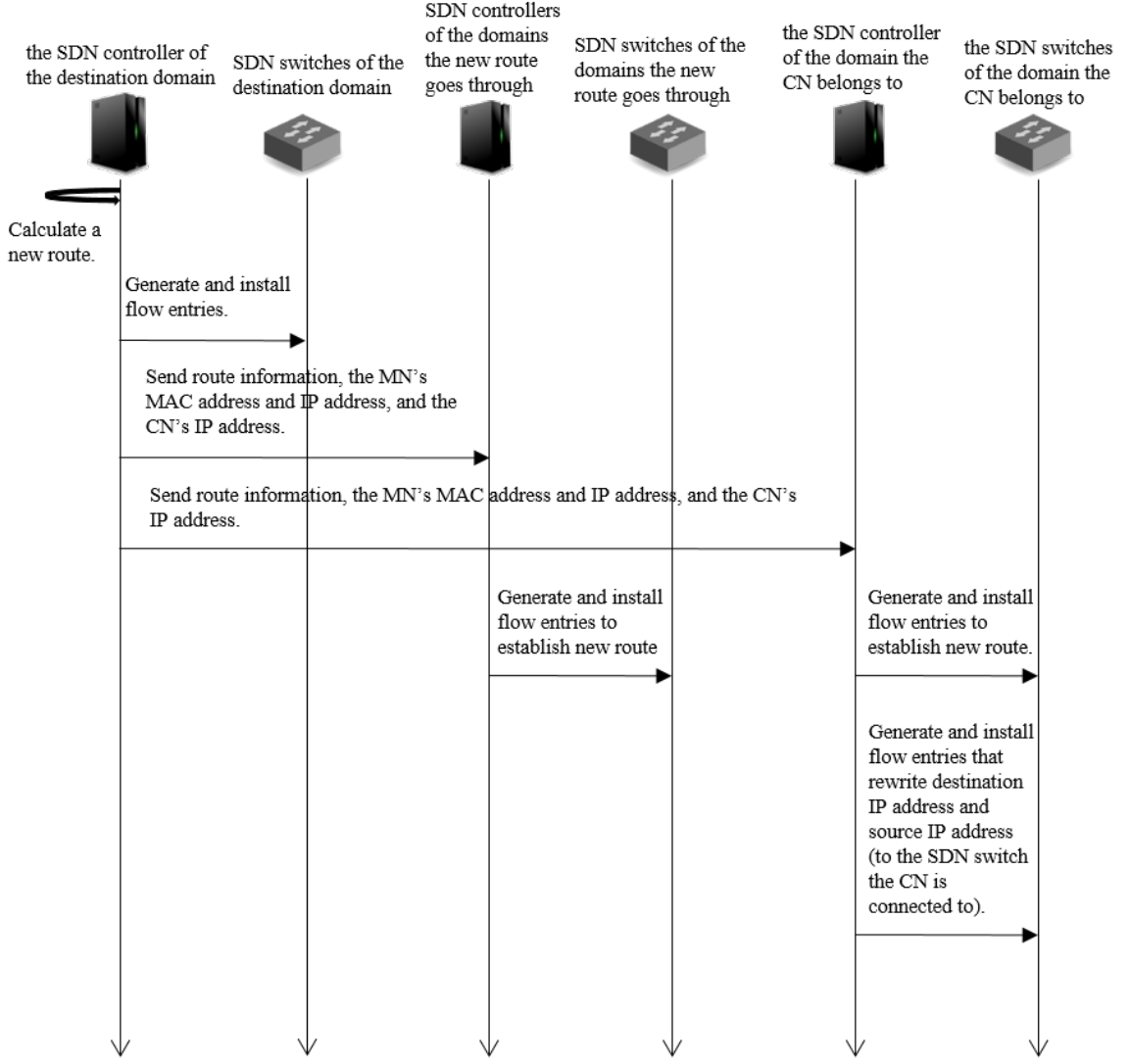


Figure 2.8: Sequence diagram of IDRf

nication route. We consider the number of inter-domain hops (N_{hop}) and the total number of flow entries that need installation in SDN switches (N_{flow}). This is performed to select the shortest communication route that can suppress the resource consumption of the SDN controllers. C_d performs all the querying and calculation in this procedure.

2. C_d announces the communication route information to the SDN controllers of the SDN domains that the selected route goes through.

In this example, C_d announces a bundle of information needed for establishing the new communication route to the SDN domains shown in Figure 2.9: information,

such as the node connection information, the IP address of the CN, and the communication route information that indicates where the packets are to be transferred.

3. Each SDN controller generates flow entries based on the received communication route information and installs them to their corresponding SDN switches.

In particular, it checks flow entries and rewrites the packets sent between the MN and the CN based on the node connection information at the SDN switch that the CN connects to. This keeps the MN IP address, seen from the CN, the same as before, while the actual IP address the MN is using is the current IP address. Hence it enables the communication to continue between the MN and the CN, just as before. Concretely, we set the flow entries, as shown below.

- Rewrite the destination IP address of the packets, sent from the CN to the MN, from the former IP address to the current.
- Rewrite the source IP address of the packets, sent from the MN to the CN, from the current IP address to the former.

We would explain the details of Step 1 above. We choose the communication route with minimum N_{flow} among the communication routes with minimum N_{hop} , in the following steps.

1. C_d checks for communication routes with minimum N_{hop} based on inter-domain topology information. We use a breadth-first search algorithm for this search.
2. If there is only one communication route with minimum N_{hop} , the framework chooses it as the shortest communication route. If there are two or more communication routes with a minimum N_{hop} , the N_{flow} of each communication route are compared. C_d asks SDN controllers of each SDN domain to obtain the number of flow entries needed for the installation of each communication route, as seen in Figure 2.10. The SDN controllers return the number of flow entries to C_d and C_d calculates the N_{flow} of each communication route.
3. C_d chooses the communication route with minimum N_{flow} as the final decided communication route.

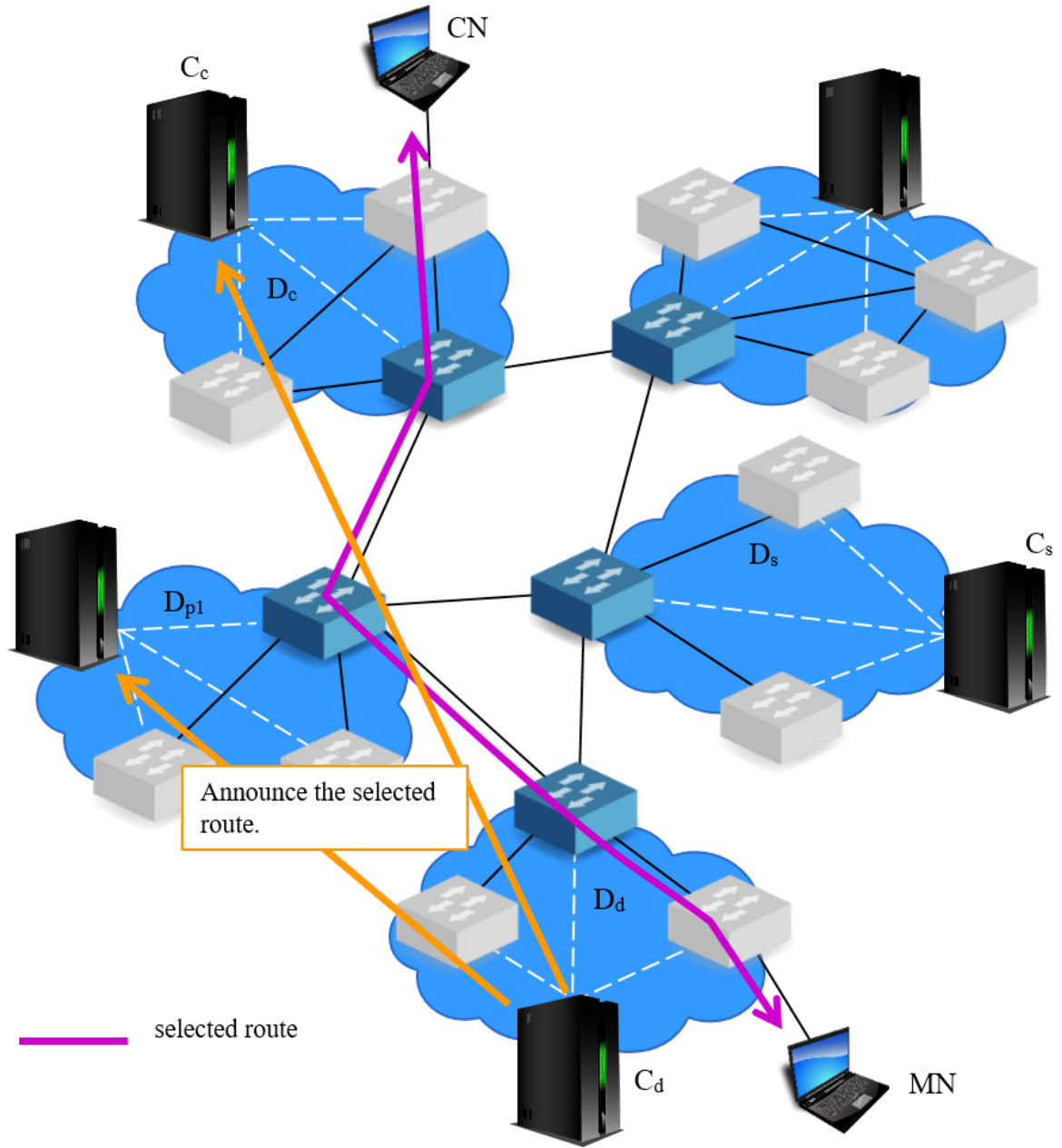


Figure 2.9: Announcement of inter-domain communication route.

2.4 Implementation

We indicate the implementation of the basic architecture of our framework, based on SDN networks. Figure 2.11 is its architecture. In this architecture, we introduce the two modules described above into the SDN controllers.

All the SDN controllers in a network have an inter-domain topology information. The inter-domain topology information consist of the network address of each SDN

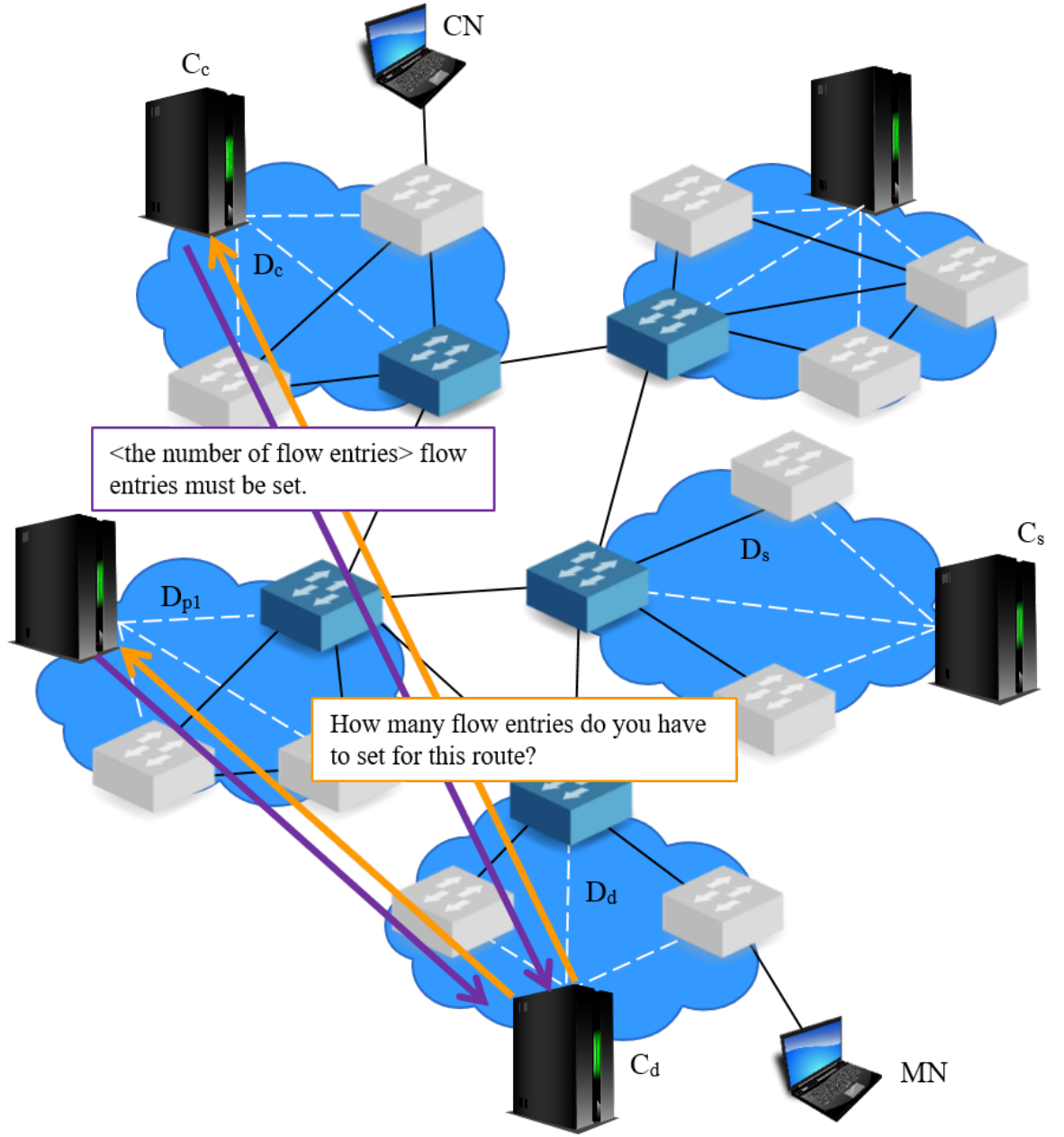


Figure 2.10: Inquiring N_{flow} .

domain in the network, the IP address of the SDN controllers in each SDN domain, and the inter-domain link information. MISF and IDRf use this inter-domain topology information to search SDN domains and also calculate communication routes.

The MISF shares information on MNs and inter-domain topology information among the SDN controllers. The SDN controllers exchange this information for inter-domain handover processes. The IDRf exchanges communication route information and calculates a new communication route according to the proposed routing mechanism.

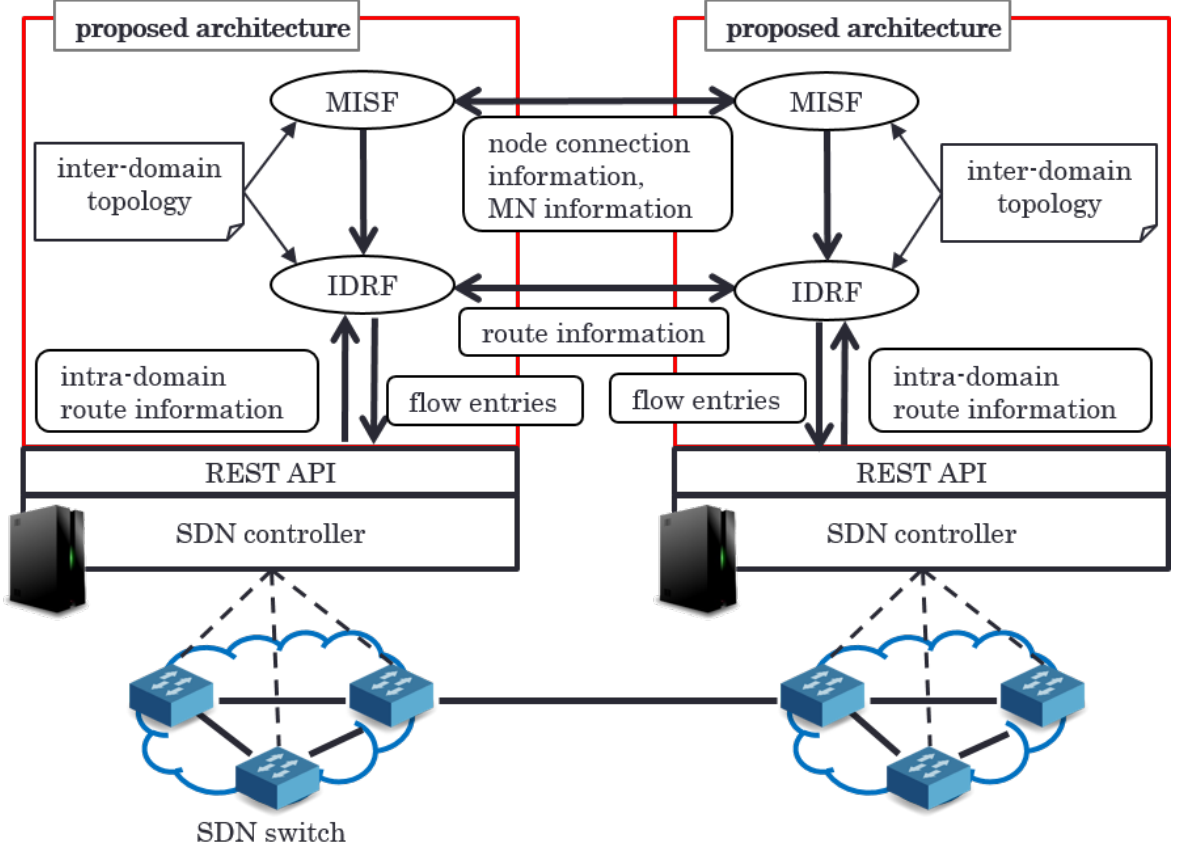


Figure 2.11: Basic architecture of our proposal.

For SDN controllers, we use OpenDaylight [46], and Open vSwitch [47] for the SDN switches. OpenFlow Protocol ver.1.3 [26] is used for communication between SDN controllers and their switches. We installed the two functions we introduced in section 2.3 into the SDN controllers. The IDRF obtains flow entry information from the SDN controllers via REST API.

2.5 Evaluation

2.5.1 Overview

We conducted experiments to validate the effectiveness of our proposed framework. We confirmed the reduction effect in the total communication amount, among the SDN controllers caused by MISF and the reduction effect on communication delay between an MN and a CN caused by IDRF.

We equipped two approaches for comparison with our proposed framework.

- Approach 1: announces the movement of an MN to all SDN domains.

We replaced MISF with a function that announces the move of an MN to all the SDN controllers, which behave similarly to those in [8].

- Approach 2: transfers packets sent to the MN from the source domain.

We replaced IDRF with a function that sets a communication route that transfers packets sent to the MN from the source domain. This approach sets a communication route similar to that of the Mobile IPs [22–24, 40].

We constructed a virtual network as an experimental network with Mininet 2.2.1 [48]. The bandwidth capacities of the links between the SDN switches are all set to 1 Mbps and the delay of each link is set to 10 ms.

The experiments are conducted in the following manner:

1. An MN moves from D_s to D_d , five seconds after it starts a communication with a CN.
2. C_d searches for the source domain and retrieves the former IP address of the MN.
3. C_d generates the node connection information and announces it to C_c .
4. C_d calculates a new communication route between the MN and the CN.
5. C_d announces the new communication route to the SDN controllers of the SDN domains involved in the route. Subsequently, the SDN controllers install flow entries in their SDN switches.

In this evaluation, we conducted three experiments.

- Experiment 1: Evaluation of MISF
- Experiment 2: Evaluation of IDRF
- Experiment 3: A comprehensive evaluation of the proposed framework

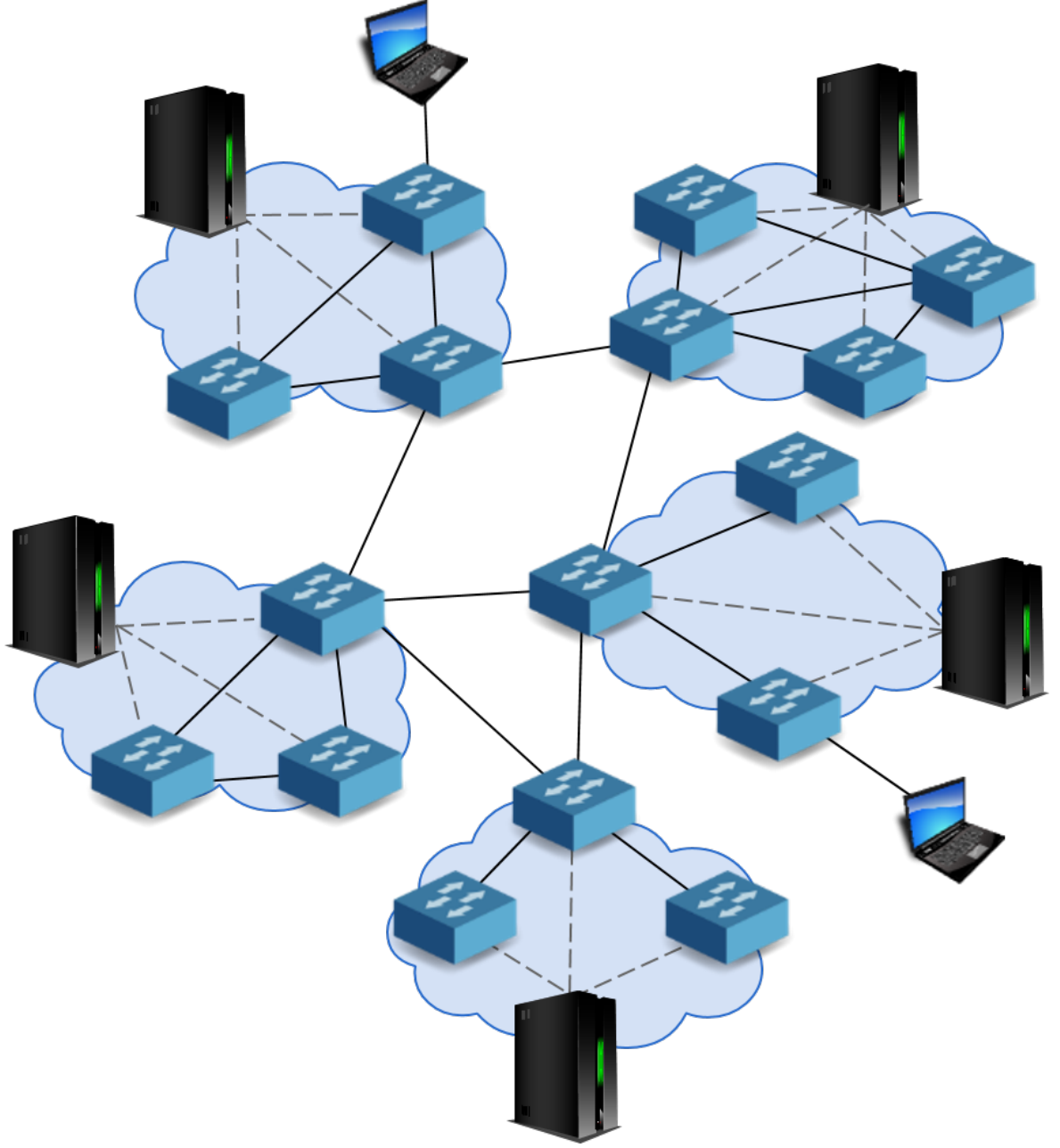


Figure 2.12: Experimental network topology (5 SDN domains).

2.5.2 Experiment 1: Evaluation of MISF

In Experiment 1, we focused on the total communication amount between the SDN controllers. We arranged three networks, consisting of 5, 10, and 15 SDN domains. The number of inter-domain hops between the source domain and the destination domain is 1. The SDN domains increase concentrically as shown in Figures 2.12, 2.13, and 2.14.

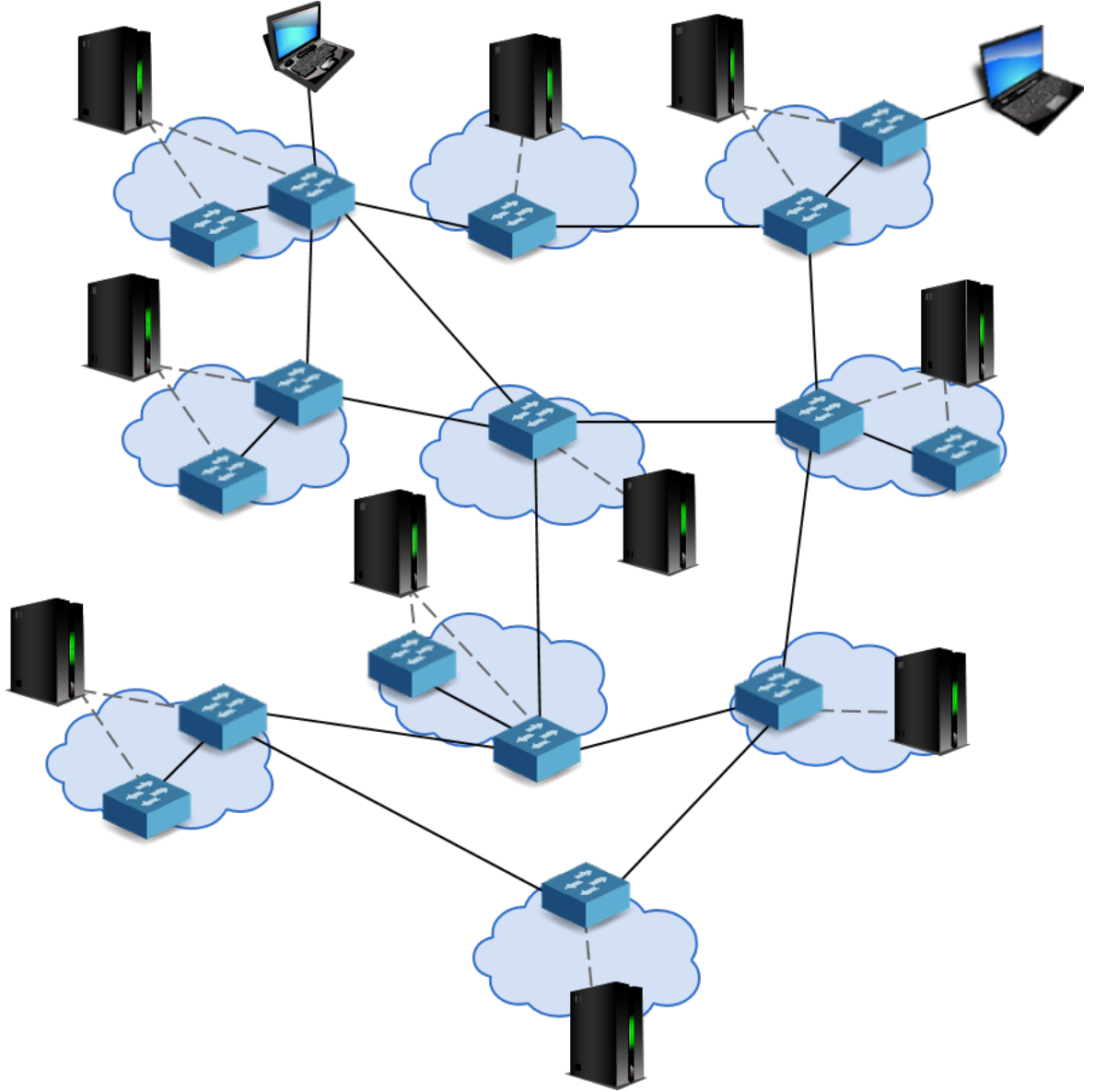


Figure 2.13: Experimental network topology (10 SDN domains).

Figure 2.15 shows how the total amount of communication changed as the number of SDN domains changed. In approach 1, the total communication amount increased as the number of SDN domains increased. In contrast, the total communication amount in the case of the proposed framework remained constant even though the number of SDN domains increased.

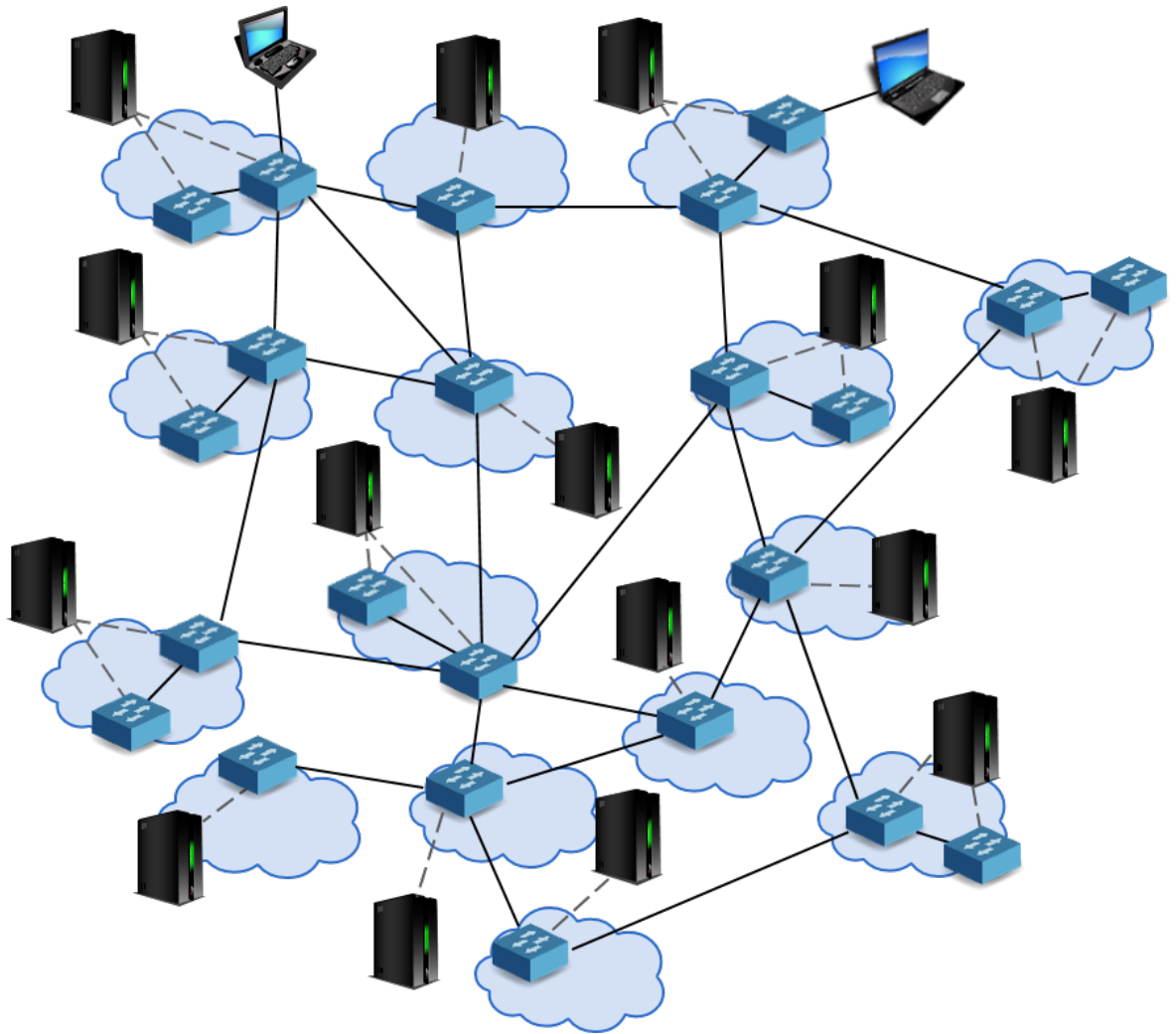


Figure 2.14: Experimental network topology (15 SDN domains).

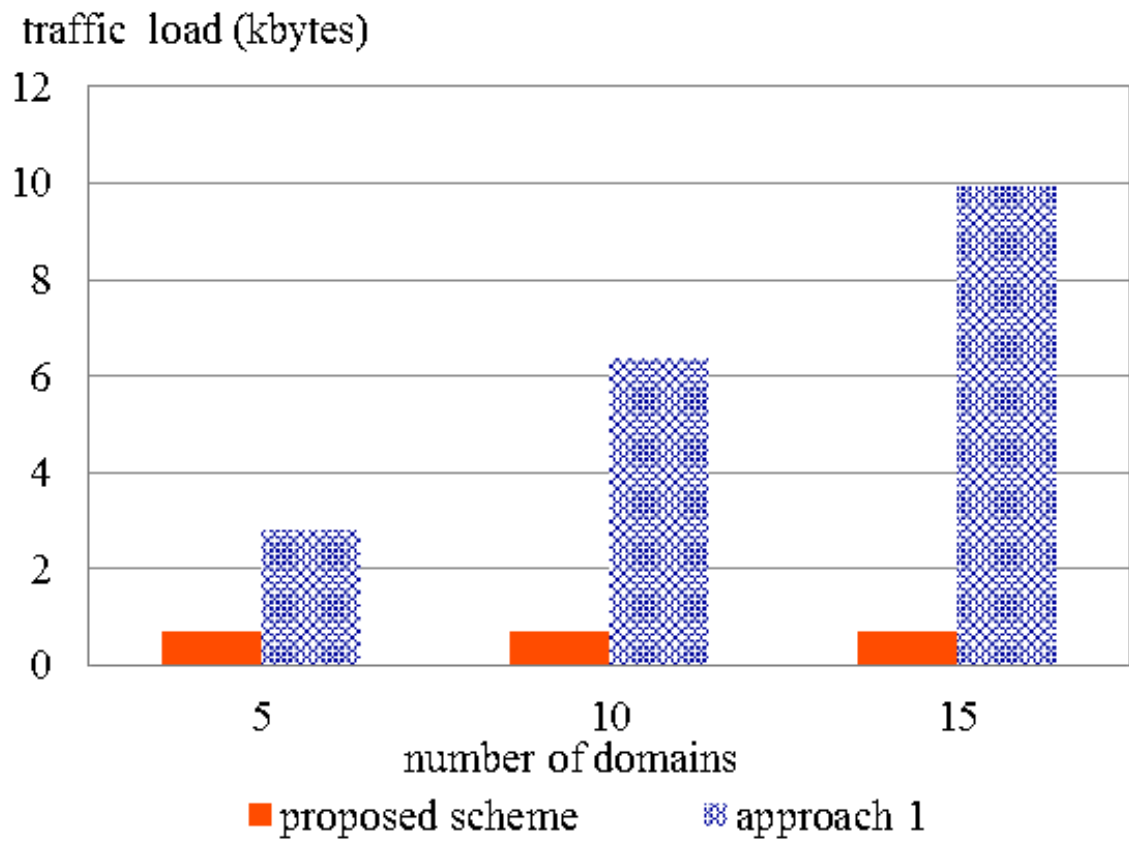


Figure 2.15: Experimental result 1: Traffic load of communication between SDN controllers.

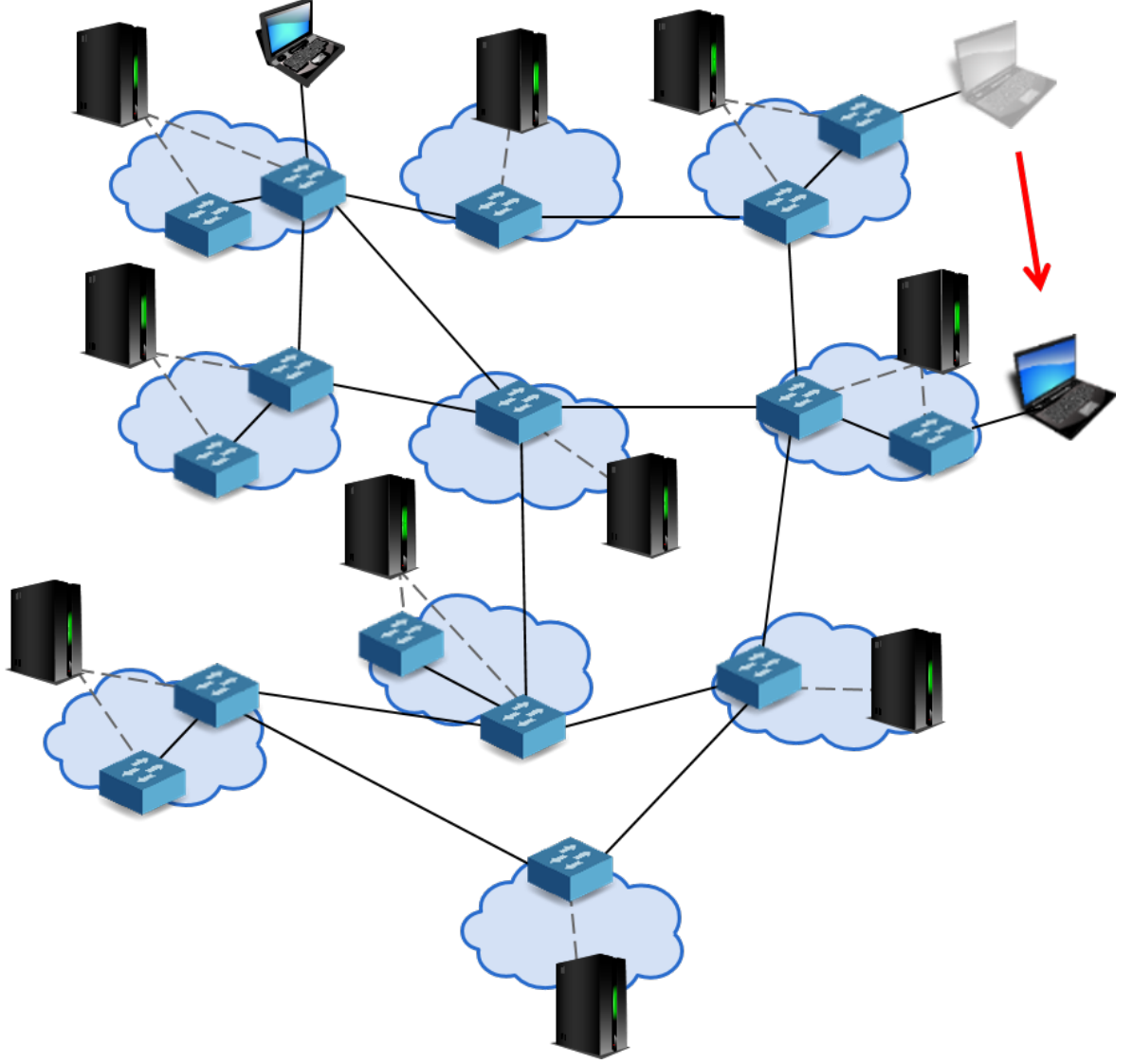


Figure 2.16: Experimental network topology (1 hop between D_d and D_s).

2.5.3 Experiment 2: Evaluation of IDRf

In Experiment 2, we focused on the communication delay (round trip time (RTT)) between an MN and a CN, communicating with a newly selected communication route after the move of the MN. We arrange a network with 10 SDN domains and set the number of inter-domain hops between D_d and D_s to 1 hop, 2 hops, and 3 hops, as shown in Figures 2.16, 2.17, and 2.18.

Figure 2.19 shows the result of Experiment 2. In the case of approach 2, RTT increased according to the increase in the number of inter-domain hops between D_d and D_s . In contrast, the proposed framework succeeds in maintaining lower RTT than

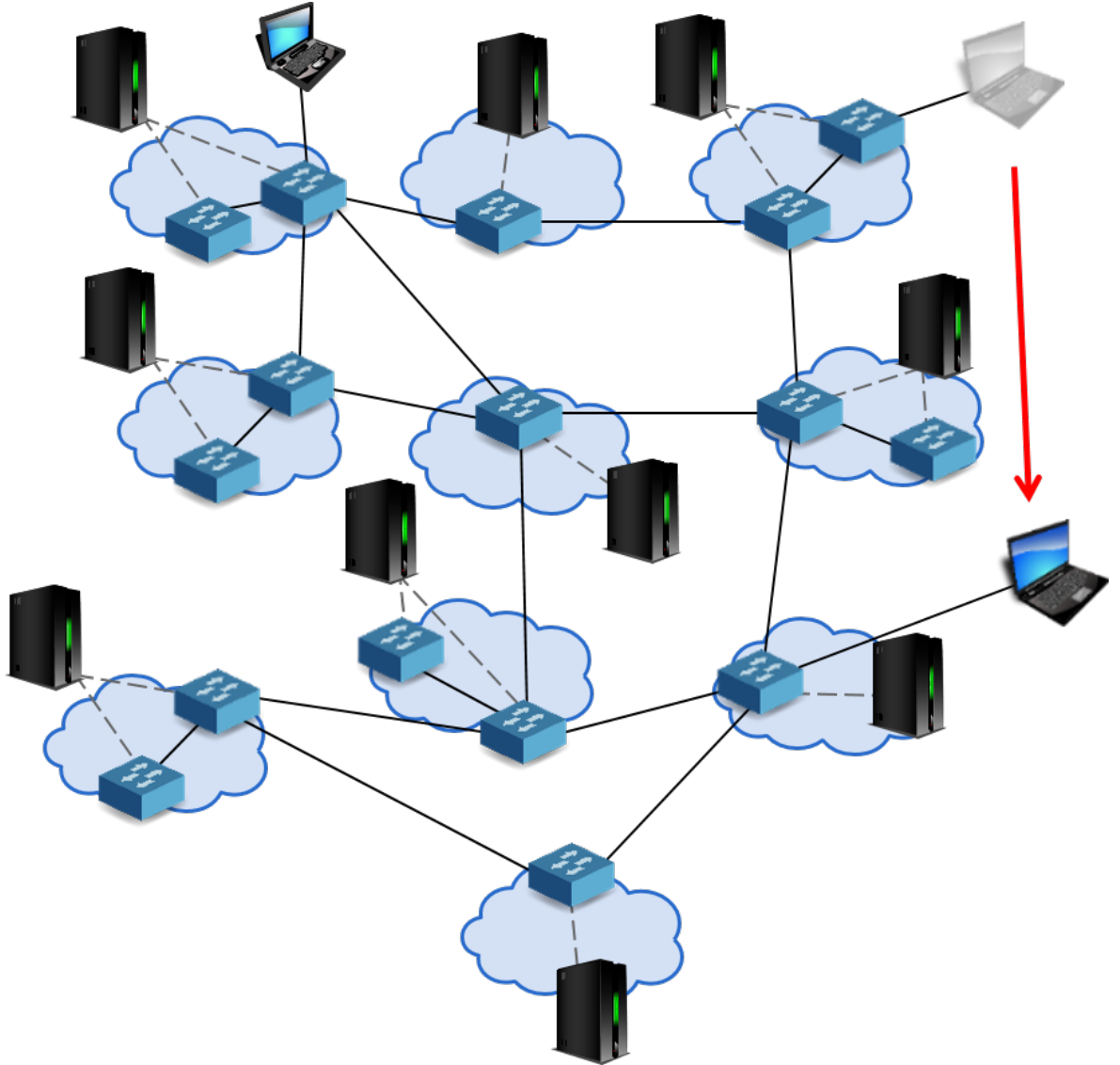


Figure 2.17: Experimental network topology (2 hops between D_d and D_s).

that of approach 2 in every case.

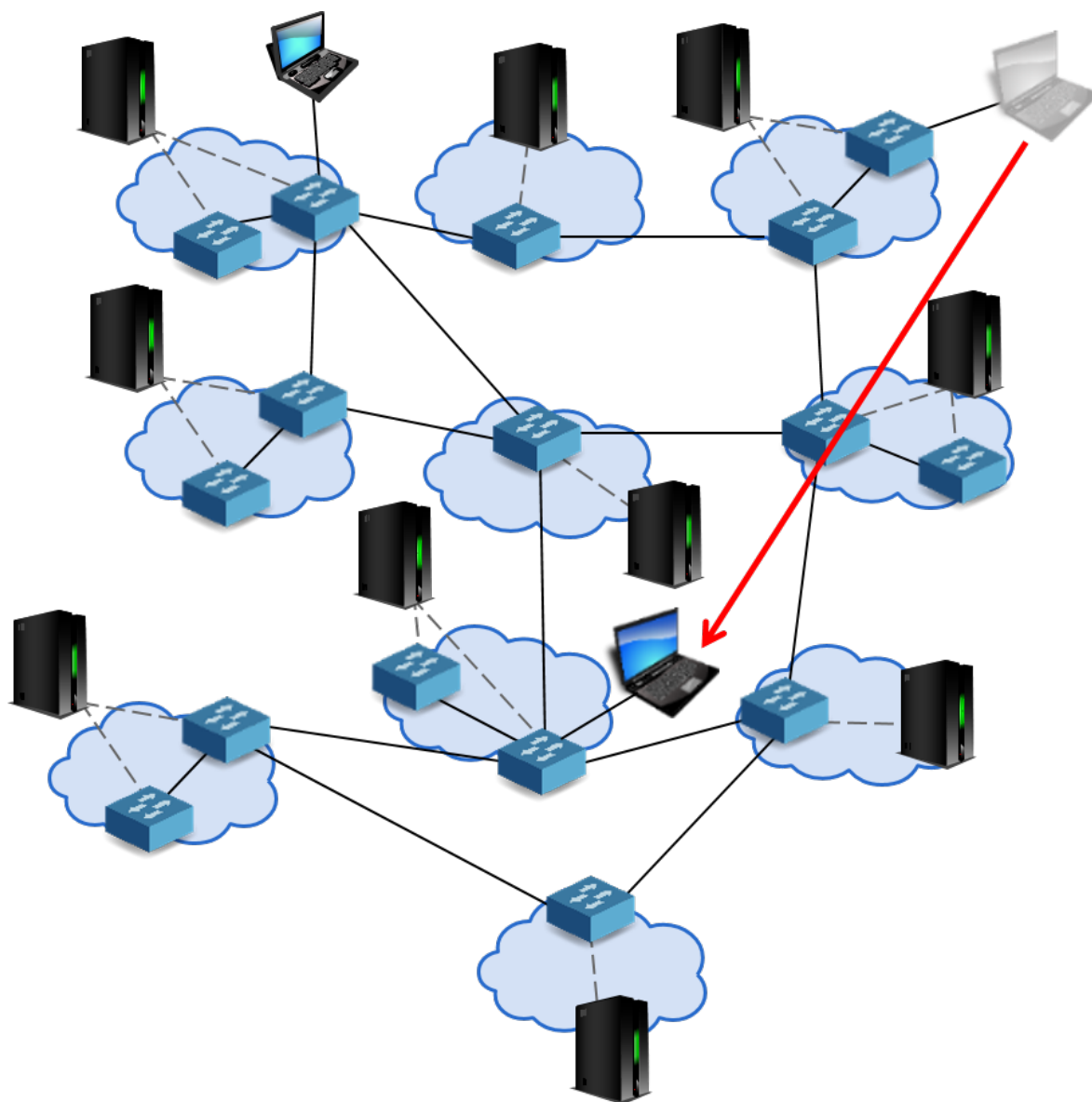


Figure 2.18: Experimental network topology (3hops between D_d and D_s).

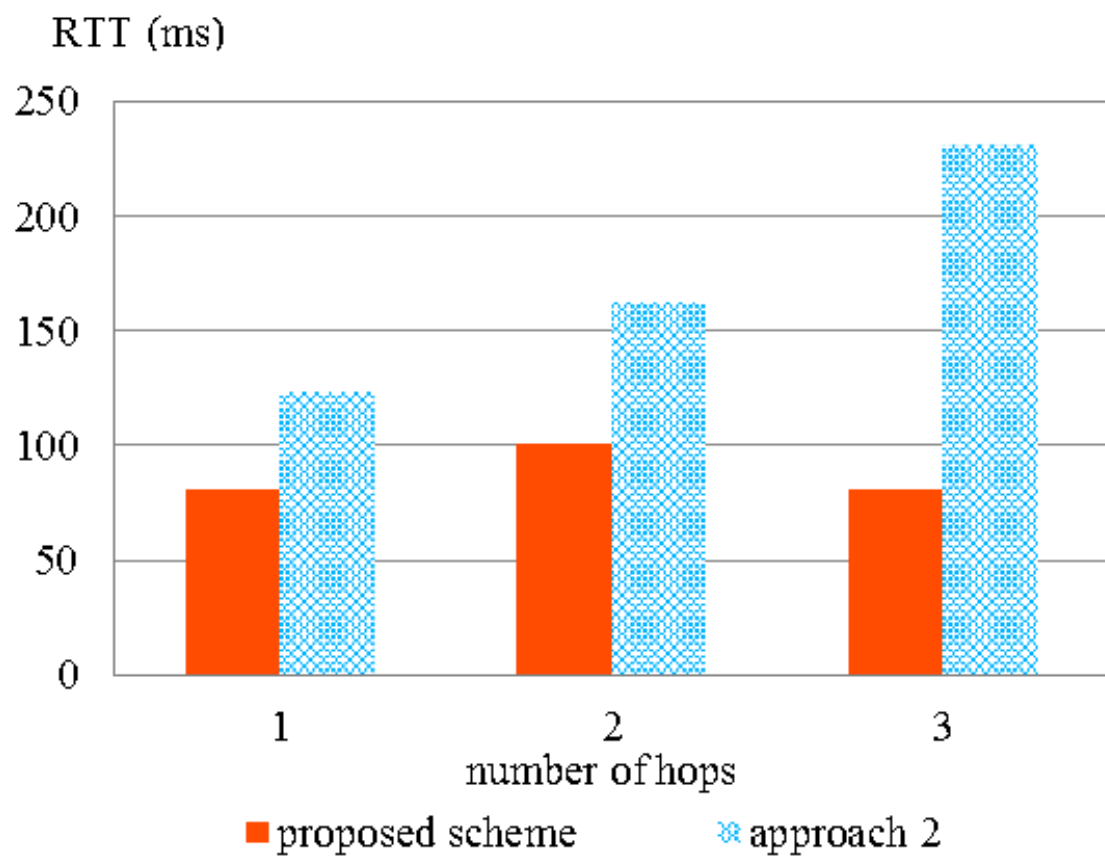


Figure 2.19: Experimental result 2: RTT between the MN and the CN.

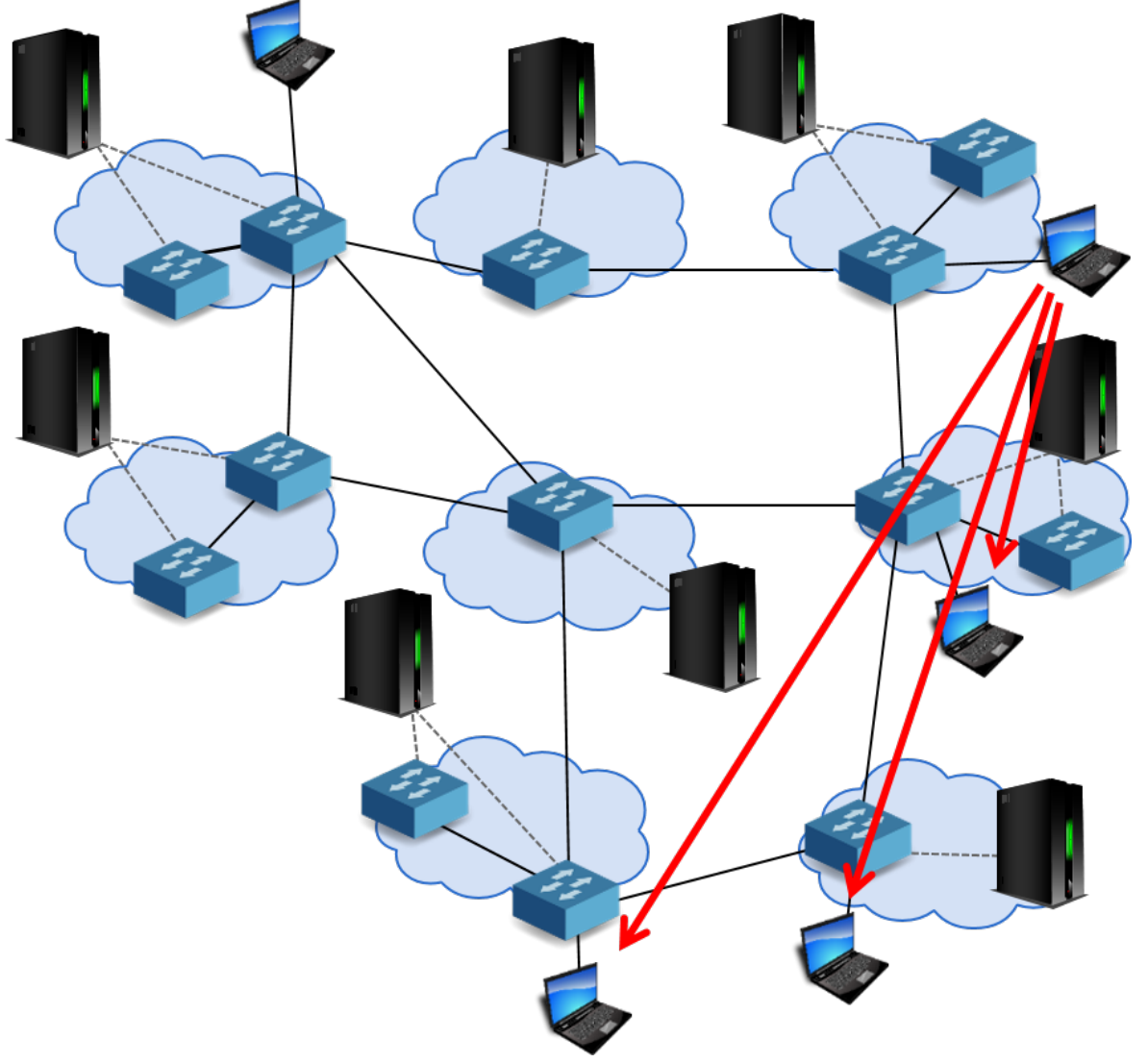


Figure 2.20: Experimental network topology (8 SDN domains).

2.5.4 Experiment 3: A comprehensive evaluation of the proposed framework

In Experiment 3, we compared the total communication amount between the SDN controllers and the RTT between the MN and the CN of the proposed framework: approach 1, and approach 2. We set the parameters as below:

- The number of inter-domain hops between the MN and the CN: 1, 2, 3.
- The number of SDN domains that compose an experimental network: 8, 9, 10.

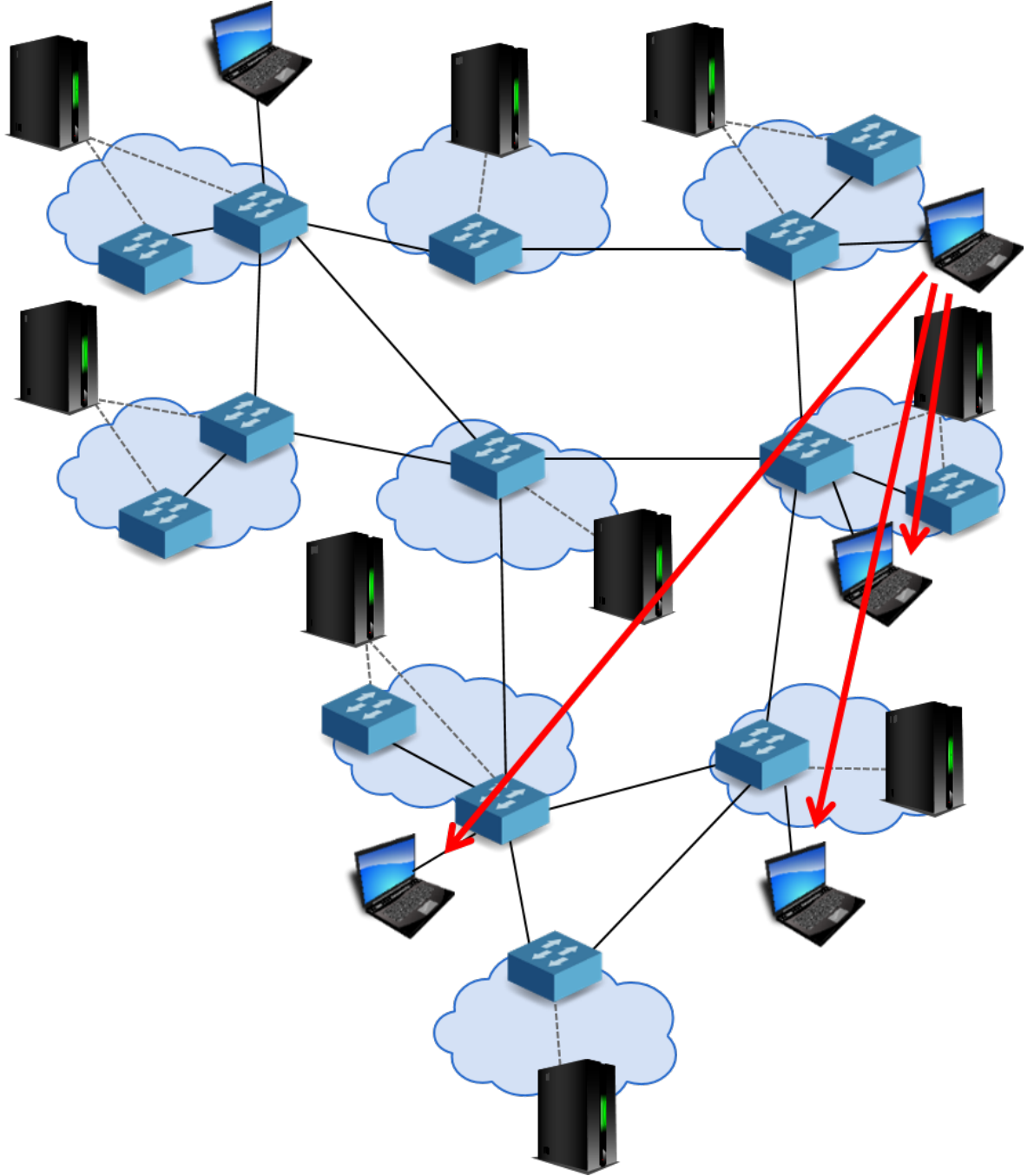


Figure 2.21: Experimental network topology (9 SDN domains).

Figures 2.20, 2.21 and 2.22 shows the topology of networks when the numbers of SDN domains are 8, 9, and 10, respectively. The MN moves as indicated by the arrows in the figures.

We show the total communication amount between the SDN controllers, for each number of hops between the MN and the CN, in Figure 2.23. The total communication

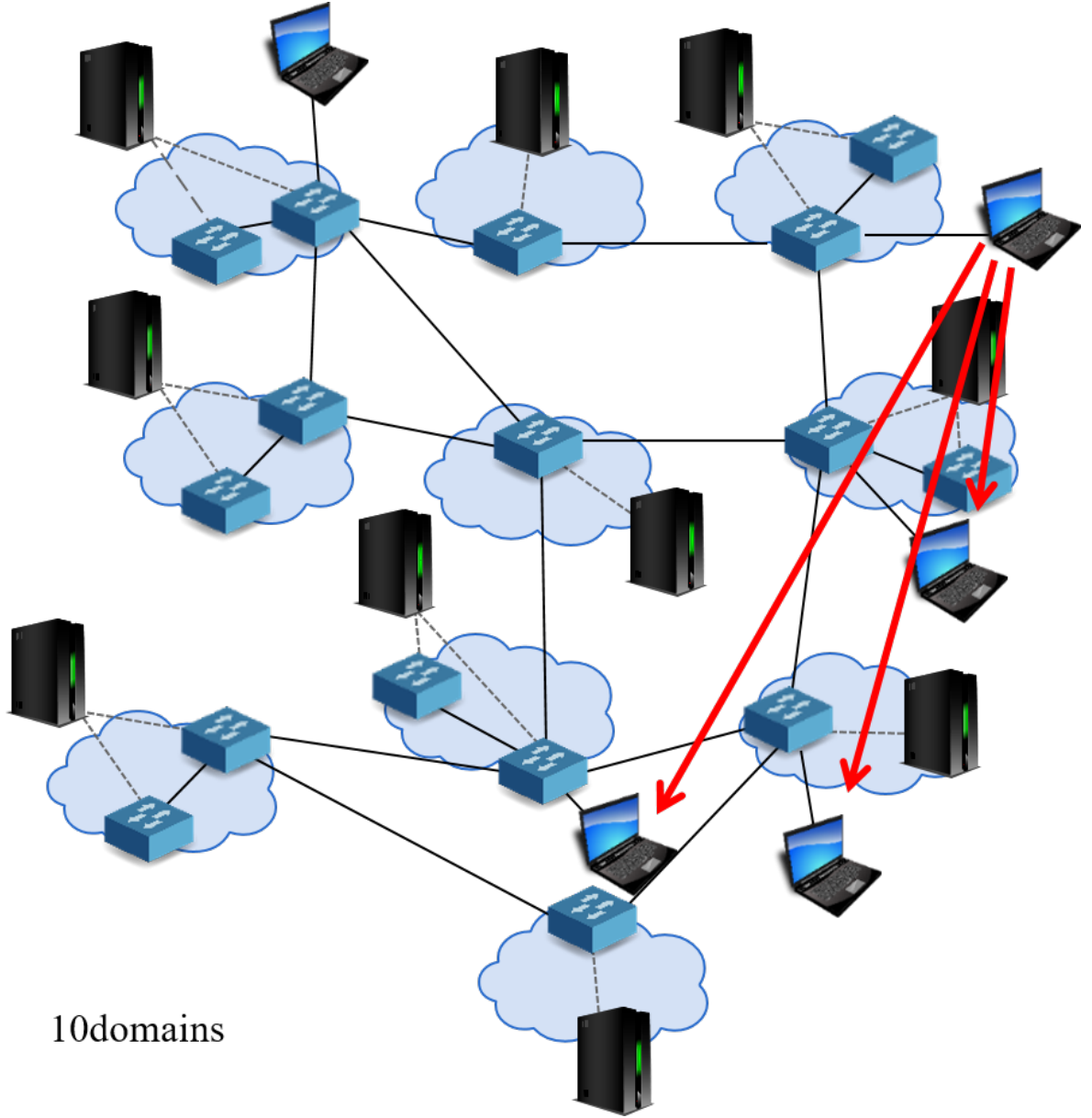


Figure 2.22: Experimental network topology (10 SDN domains).

amount increases as D_s goes farther from D_d in the cases of the proposed framework and the approach 2. Nonetheless, in the case of the approach 1, the total communication amount was not affected by the number of hops; however, it was influenced by the number of SDN domains.

Figure 2.24 shows the RTT of the communication between the MN and the CN for each number of SDN domains. In the case of the proposed framework and approach 1, RTT differs by the number of hops; however, it is always smaller than that of approach 2 in any case. In the case of approach 2, RTT increased as the number of hops between

D_s and D_d increased. Nevertheless, the results of the proposed framework and approach 1 showed no relevance to the number of hops between D_s and D_d .

2.5.5 Summary of evaluations

First, we discuss the results of Experiment 1. In the case of the proposed framework, the closer the source domain was to the destination domain, the smaller the traffic load because our framework queries from neighboring SDN domains.

However, the total communication amount of approach 1 increased as the number of SDN domains increased. This is because approach 1 announces the move of the MN to all the SDN domains in the network, regardless of the position of the source domain.

Next, we discuss the results of Experiment 2. In the case of the proposed framework, the number of the inter-domain hops does not become greater than the number that can be taken by approach 2. Therefore, the communication delay in the proposed framework becomes smaller, compared with approach 2. This is because the longest communication route the proposed framework chooses is the same communication route chosen by approach 2.

Finally, we analyze the results of Experiment 3 according to the following view-points: the total communication amount among the SDN controllers and the RTT of communication between an MN and a CN after a move of the MN.

- The total communication amount among the SDN controllers.

The proposed framework had lower total communication amount than approach 1 in all cases. Approach 2 also had lower total communication amount than approach 1 in the case where D_s and D_d were 1 and 2 hops away. However, as the number of inter-domain hops between the source and the destination domains became bigger, the total communication amount of the proposed framework and approach 2 increased. When D_s and D_d were 3 hops away, the total communication amount of the proposed framework was pretty similar to that of approach 1 from Figure 2.23 (c). In view of the fact that D_s was 3 hops away from D_d , C_d ended up searching all the SDN domains. Furthermore, when D_s and D_d were 2 hops away, the total communication amount of approach 2 was the biggest of

all the approaches and the proposed framework marked a larger total communication amount than that of cases with 1 and 3 hops. Approach 2 used MISF, the proposed framework function, for obtaining and announcing the move of the MN. Thus, the communication amount of this part was the same as that of the proposed framework. The difference came from the communication amount of IDRf. The difference in the way to select a new communication route caused the change in the amount of communication among the SDN controllers and this affected the total communication amount. Figure 2.23 (b) shows when D_s and D_d were 2 hops away, the total communication amount of the proposed framework and approach 1 greatly exceeded that of approach 2. In this case, there were several communication routes with minimum inter-domain hops. Therefore, IDRf queried other SDN controllers for the number of flow entries that was needed to be installed for each communication route. This querying caused the increase in the communication amount. This fact shows that by querying the number of needed flow entries, the total communication amount among the SDN controllers increases.

- The RTT of communication between the MN and the CN after the move of the MN.

The results show that in the case of approach 2, the RTT increased as the number of hops between D_s and D_d increased. In approach 2, packets sent to the MN are first sent to D_s . Thus, the communication route becomes longer as the MN moves farther. In contrast, the proposed framework and approach 1 selected the shortest communication route regardless of the position of D_s . Therefore, the RTT did not get too large. Besides, the transferring communication route that approach 2 selected is the longest communication route that could be chosen in the proposed framework and approach 2. Thus, these approaches could maintain RTT like approach 2 or make it smaller.

From the results mentioned above, we can say that approaches 1 and 2 can only hold back either the RTT of communication between an MN and a CN after the move of the MN or the total communication amount among the SDN controllers. In contrast,

the proposed framework is able to deal with both.

2.5.6 Discussion

These quantitative experimental results mentioned above reveal the contribution of our proposed framework in practical use. This achievement enables the suppression of the consumption of limited network resources while enabling users of MNs to move around, maintaining seamless and fast communication even if they moved across SDN domains. For example, consider the situation where many users work with a laptop PC or a tablet PC to download data from cloud servers or to upload data. The users can smoothly download/upload large data from/to cloud servers while they are moving (e.g. during transit time). Concerning interactive-type applications, such as remote login terminal or VDI environment, the users can use the network services continuously when the connecting SDN domain changes.

Generally speaking, to avoid the termination of network services or processes when MNs move across SDN domains, application-level handover function is usually implemented in the applications. When the IP address of an MN changes according to the move of the MN, the handover function terminates the transport connection on the previous IP address and then establishes a new transport connection on the new IP address. By this function, the data communication sessions seem to continue transparently and also application logic can handle the sessions seamlessly. However, not all applications have this feature implemented. This is because the mechanism is relatively complicated and it is necessary to deal with the server-side as well. Our framework enables this functionality at the network level. It means that all the Internet applications can utilize their network-dependent functions seamlessly, in situations where the MNs move across SDN domains.

Furthermore, when a user is at a place where the service areas of different access points overlap, the MN shifts its connecting access point back and forth, depending on the link condition even when the user is stationary. The proposed framework currently does not cover this kind of handovers; however, it has the potential to manage the handovers and keep communication quality high. Meanwhile, a standardization activity of a fast-initial setup of Wi-Fi links is progressing like IEEE802.11ai [15]. This function

would enable a Wi-Fi client to establish a secure link setup within 100 ms. If this standard will widely be used in the above environment, switching of access points may occur very rapidly and frequently in the near future. There are no modern technologies available to deal with such situations and we anticipate our proposed framework will work effectively in such situations.

2.6 Conclusion

This chapter aimed at realizing seamless connections and selecting suitable communication routes in SDN based IP mobility management on inter-domain handovers. It is difficult to realize efficient information exchange between the SDN controllers and communication route optimization together. To solve this problem, we proposed the SDN based mobility management framework, considering inter-domain handovers. As the evaluation results show, we were able to optimize the communication route while retaining the total amount of communication among SDN controllers that was needed to manage low mobility management.

IDRF needs improvement in future works. By extending the algorithm to introduce metrics of paths, we can take more kinds of information into account, such as the bandwidth of inter-domain links and network usage.

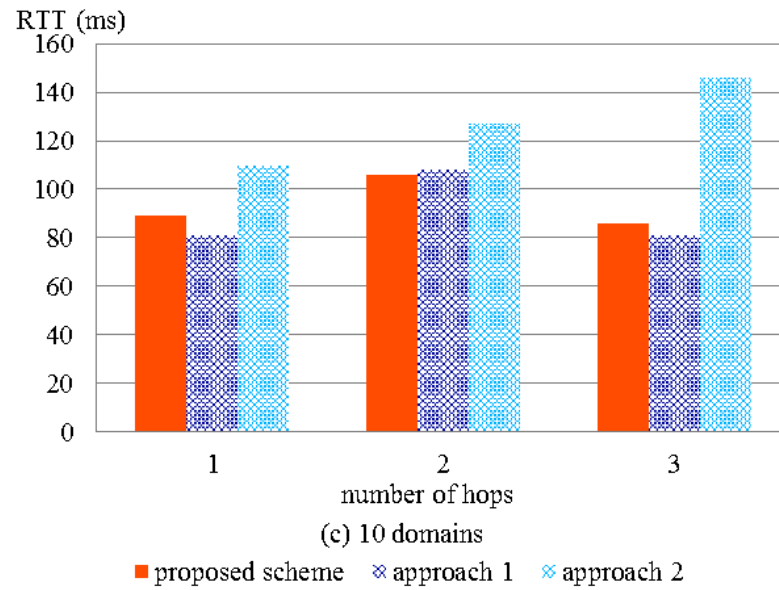
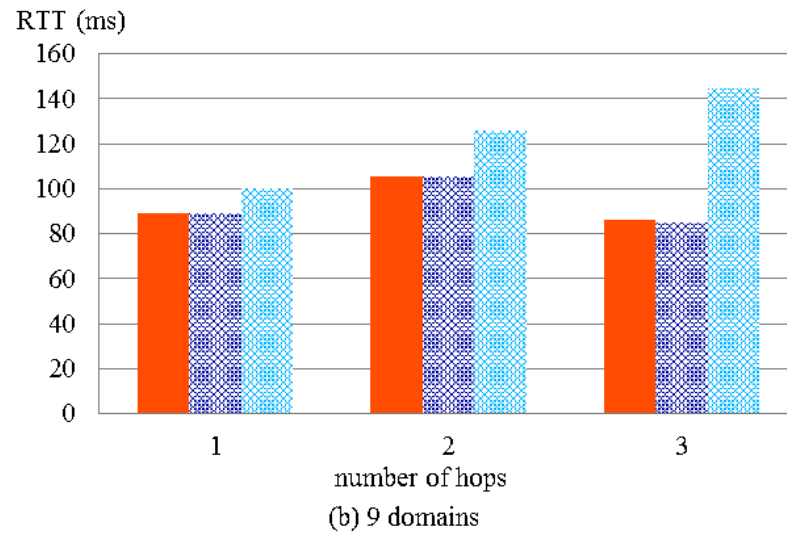
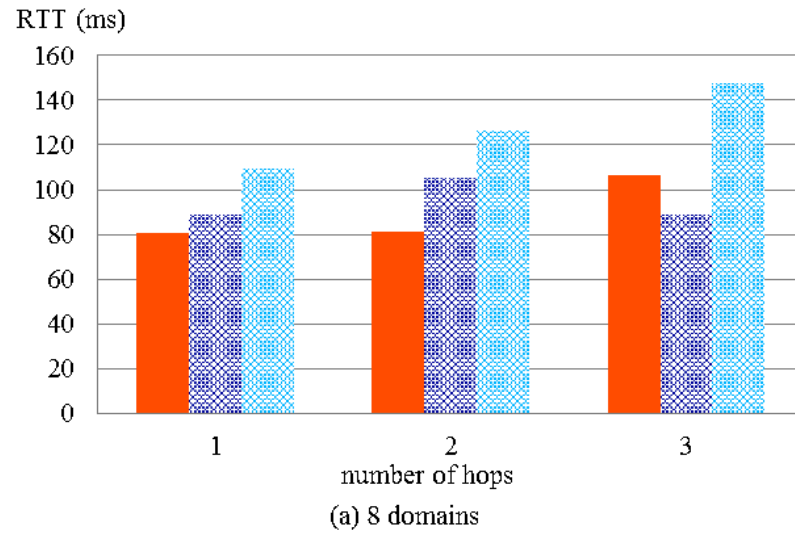


Figure 2.23: Experimental result 3-2: RTT between the MN and the CN.

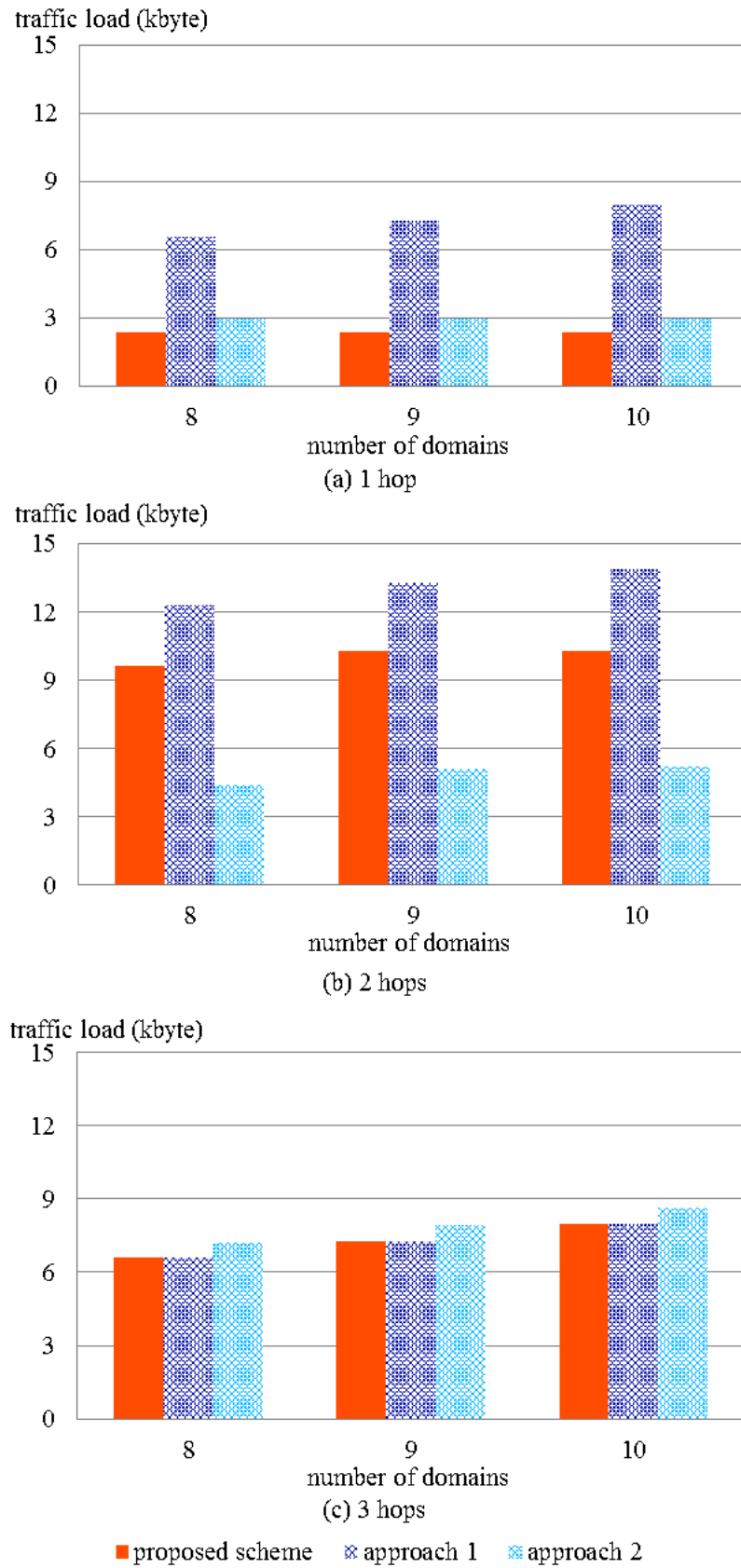


Figure 2.24: Experimental result 3-1: The total communication amount between SDN controllers.

Chapter 3

Communication Quality Aware Routing Mechanism for Mobility Management

3.1 Introduction

In Chapter 2, we tackled the challenges that hindered the application of SDN to inter-domain mobility management. We proposed an SDN based inter-domain mobility management framework as the first step to provide MN users, seamless and comfortable communication while moving around. The proposed framework selects the shortest communication route as the new route applied to the communication after the move of an MN.

Thanks to the growth of network services, there are many kinds of network services today, such as video streaming services, chat services, online games, and etcetera. They have different requirements for communication, depending on what they do and how they communicate. Hence, selecting a proper communication route will ensure or even increase the comfortability of communications.

Many researchers have proposed the SDN based mobility management approaches that handle inter-domain handovers [40,42,43]. However, they do not control the communication route after an inter-domain handover or the information used for selecting a communication route is insufficient. Routing approaches to optimize inter-domain

communication routes in an SDN environment are also proposed [49–52]. Though they are capable of inter-domain routing, they are not designed for mobility management and do not nicely fit with mobility management.

As a result, we propose an SDN based end-to-end routing mechanism, specified for mobility management. The inter-domain routing function selects a suitable end-to-end communication route for communication between an MN and a CN after the MN has moved across the SDN domains, based on parameters selected for mobility management. We have designed a basic inter-domain routing mechanism and showed its effectiveness. However, this mechanism mainly considers only the number of SDN domains a new route goes through. Lack of information for selecting a new route causes problems in the QoS after switching the route; moreover, this affects the time it takes to switch an old communication route to a new one. Therefore, we extend our routing mechanism by introducing new parameters, such as the number of inter-domain hops, real-time bandwidth availability of the links between the SDN domains, and the number of flow entry operations.

In this chapter, we extend the IDRF of the SDN based inter-domain mobility management framework and confirm the efficiency of our new routing mechanism, through evaluations. The evaluation results show that our routing mechanism can reduce communication delay and data transfer time. Therefore, it realizes the comfortable use of network services. The contribution of this study is to show the evaluation and effectiveness of our new routing mechanism.

3.2 Related Works

3.2.1 SDN based mobility management

We introduce some approaches that apply SDN to mobility management. M. Idri uses the routing header to keep communication without using IP tunneling mechanism [43]. However, his work does not focus on communication route selection. Thus, we might end up with a lengthy communication route and we also need a master SDN controller to manage the SDN controllers, leading to an additional cost. P. Shrivastava et al. presents FastSplit that reuses the previous communication route to reduce signaling

overhead while it retains the new route near optimal [42]. FastSplit method uses the length of paths and signaling overhead to select a new route; however, it does not take real-time information into account. Y. Wang et al. proposed a Mobile IP based mobility management that copes with inter-domain handovers [40]. This approach uses Mobile IP for inter-domain handovers. Thus, MNs need Mobile IPv6's route optimization function to realize route optimization. However, not all MNs support Mobile IPv6 or its route optimization function.

In Chapter 2, we proposed an SDN based mobility management framework that focuses on inter-domain handovers. Its overview is shown in Figure 3.1. Each SDN controller manages its own SDN domain and communicates with other SDN controllers to exchange necessary information. Although we succeeded in reducing communication delay, we had a few problems in the routing mechanism. This is because we did not consider route switching costs, such as the time needed to calculate a route and its flow entry installation time. To avoid disconnection, communication routes are updated before a TCP session disconnects. Therefore, we need to consider the calculating time of the communication route and the time an SDN controller needs to add, change, or delete flow entries to SDN switches, which we refer to as flow operation, real-time network usage, and processing time. Not considering these features might result in a low throughput communication route or session disconnection, which lead to serious QoE degradation. Moreover, the framework we proposed in Chapter 2 targets a situation with only one communication in a network. Especially, our previous algorithm does not consider the bandwidth availability affected by other communications. In usual networks, many MNs communicate with their CNs. Thus, we have to take other communications into consideration to avoid using low bandwidth links.

3.2.2 Routing approach in SDN networks

There are several inter-domain routing mechanisms that use SDN. In [49], the authors show a routing mechanism based on path cost and the number of flow operations. However, this mechanism focuses on link failure owing to disasters or accidents. Thus, it is not suitable for mobility management because it does not consider the move of an MN.

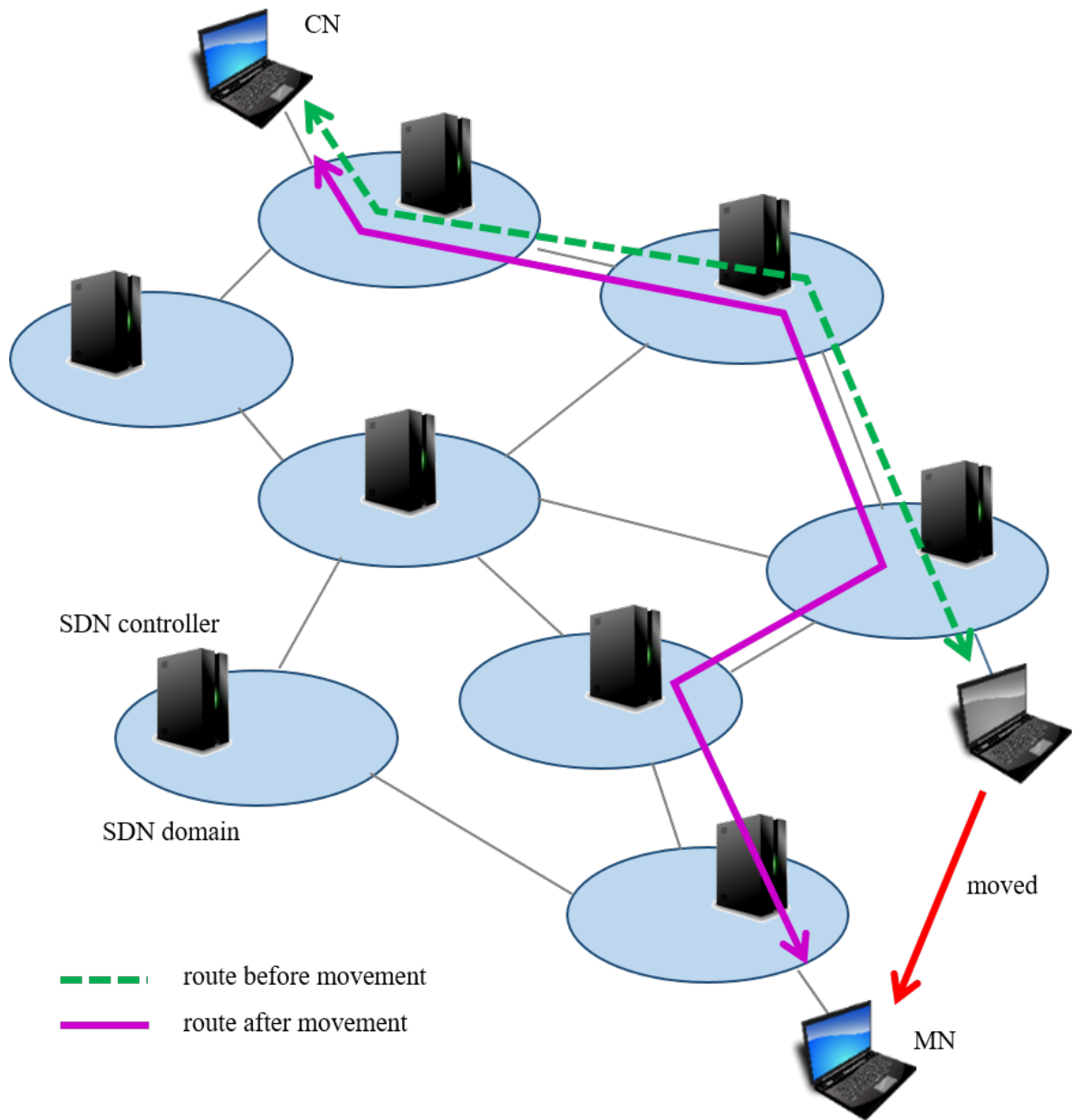


Figure 3.1: Overview of the SDN based mobility management proposed in Chapter 2.

In [50], the authors show a network model for an end-to-end QoS provisioning in inter-domain cases. This model selects a route, mainly focusing on bandwidth. Thus, there are problems with communication delay and the time taken for changing the communication route for mobility management.

K.Phemius et al. [51] propose architecture for the distributed SDN controllers. Since the routing in this approach is not made for a specific use, it is hard to apply it to mobility management.

N. Figueira et al. [52] indicate a hierarchical multi-domain SDN Controllers' framework. It requires a master SDN controller to manage other SDN controllers. Thus, this leads to an additional cost.

3.3 Communication Quality Aware Routing Mechanism for Mobility Management

3.3.1 Overview and Design

To solve the problems we mentioned above, we propose a mobility management specific end-to-end routing mechanism. Our basic concept of routing mechanism is to consider a balance between the quality of communications and the operation costs. For example, if we select a communication route with the fewest inter-domain hops, it may reduce the communication delay. However, there is a risk of selecting a very low throughput communication route. On the other hand, if we focus on high throughput, communication delay might become large. Requirements vary depending on the kind of network service an MN user is using. If the user is using a network service like video streaming, it requires high bandwidth. Also, if the user is using a network service like chat application that requires high performance and real-time communication, it ought to require a low communication delay. Moreover, most importantly, we have to avoid session disconnection. Thus, the entire processing time for a handover cannot exceed the total time-out limit. According to the mentioned concepts, we defined the parameters for the calculation of communication routes.

- The number of SDN domains each route candidate goes through (the number of hops)
- The number of flow operations for each route candidate
- Real-time bandwidth usage information

The values of each information are normalized and added individual importance to the values to be used for calculating routes.

We use the SDN based inter-domain mobility management framework proposed in Chapter 2 as the base and change the routing mechanism used in IDRf to the one proposed in this chapter. The components and the architecture of the framework are the same as in Chapter 2, depicted in Figure 2.4 and Figure 2.11. Each SDN controller manages its own domain and they also hold inter-domain topology information. SDN controllers communicate with one another in the controller network and also the SDN switches are connected with one another via the data network.

The process of the proposed end-to-end mechanism is explained in Figure 3.2. The SDN controller of the destination domain calculates the switching route and subsequently, other SDN controllers send the required information to it.

$$M_k = M_{F_k} + M_{D_k} + M_{B_k} \quad (k = 1, 2, \dots, K) \quad (3.1)$$

Equation (3.1) is used for calculating the total metric of each listed route. M_k stands for the total metric of route k . M_{F_k} stands for the metric for flow operations, M_{D_k} stands for the metric for the number of inter-domain hops, and M_{B_k} stands for the metric for the bandwidth availability of the communication route.

$$M_{D_k} = \frac{D_k}{D_{max}} \alpha \quad (3.2)$$

$$M_{F_k} = \frac{F_k}{F_{max}} \beta \quad (3.3)$$

$$M_{B_k} = (1 - \frac{B_k}{B_{max}}) \gamma \quad (3.4)$$

Equation (3.2) defines the calculation of the metric, for the number of inter-domain hops, Equation (3.3) defines the calculation of the metric, for the flow operations and equation (3.4) defines the calculation of the metric, for the available bandwidth of each route. D_k indicates the number of SDN domains route k goes through, F_k indicates the number of flow operations to the switch communication route, k , and B_k shows the minimum bandwidth of route k . D_{max} indicates the number of SDN domains in the network and B_{max} is the largest bandwidth in the network. F_{max} becomes $2N$ when we set the number of SDN domains in a network as N . This is because we need to set the flow entries for both ways of communication between an MN and a CN. α , β , and γ are the importance of each piece of information that is added to achieve balance

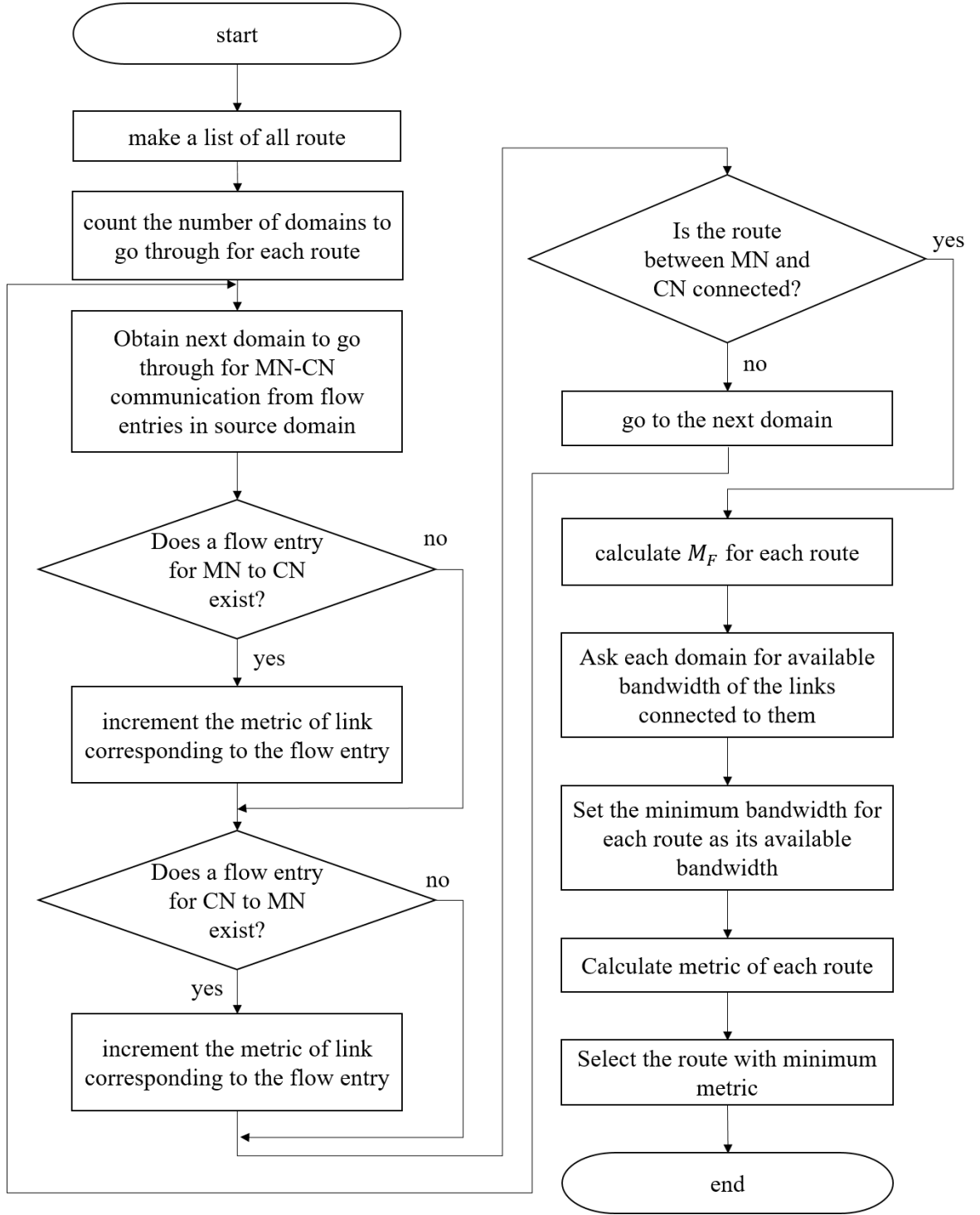


Figure 3.2: Flowchart of route calculating process.

among parameters. The values of importance can be set differently for each network to enable a network administrator to set its own importance according to the conditions of the network.

Our routing mechanism calculates M_k for every possible communication route without loops and selects route k when M_k is minimum. Based on this process, our routing mechanism can select an effective route for mobility management, to keep seamless and comfortable communication.

3.3.2 Example of a Routing Process

We would show an example of a routing process following the flowchart (3.2). Figure 3.3 indicates the network used to explain the routing process. The numbers near the links are their bandwidths. When an MN, communicating with a CN, moves to another SDN domain, the SDN controller of the destination domain detects the movement. Afterwards, the SDN controller creates a list of all possible routes from the MN to the CN. Figure 3.4 shows part of the route list. There are many possible routes from the MN to the CN; however, for convenience, we list up just three routes: route 1 ($r1$) to route 3 ($r3$). The proposed routing mechanism calculates the metric, M_k , for each route. In this case, F_{max} is 16; D_{max} is 8; and B_{max} is 5. We set the importance, α , β , and γ , to 1 for a simple calculation.

$$M_1 = M_{F_1} + M_{D_1} + M_{B_1} = \frac{6}{16} + \frac{5}{8} + (1 - \frac{1}{5}) = 1.80 \quad (3.5)$$

$$M_2 = M_{F_2} + M_{D_2} + M_{B_2} = \frac{8}{16} + \frac{5}{8} + (1 - \frac{4}{5}) = 1.33 \quad (3.6)$$

$$M_3 = M_{F_3} + M_{D_3} + M_{B_3} = \frac{10}{16} + \frac{5}{8} + (1 - \frac{4}{5}) = 1.45 \quad (3.7)$$

In this example, M_2 is the minimum metric; thus, the routing mechanism selects route 2. As mentioned in the example, our routing mechanism can select an effective route, balanced among the number of SDN domains, to go through the number of flow operations and available bandwidth.

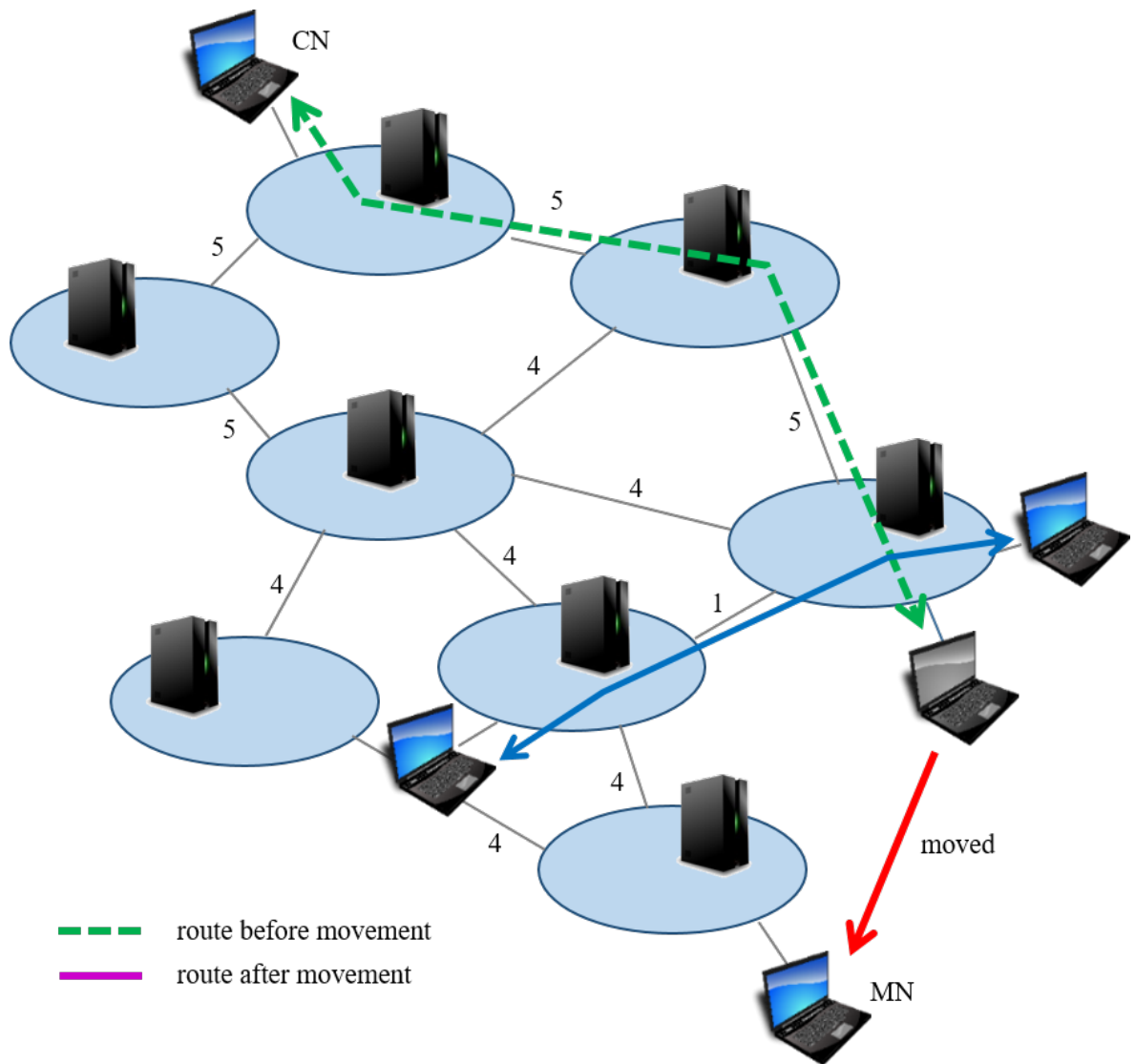


Figure 3.3: Example of network.

3.4 Evaluation

3.4.1 Overview

We conducted experiments to verify two things: the effectiveness of our mobility management approach, using the renewed routing mechanism compared with other approaches and the effects of various importance on network throughput and the communication delay between an MN and a CN. We also measured the time needed to calculate a new communication route and set flow entries (processing time) for the proposed approach and the approach in Chapter 2, which will be called previous ap-

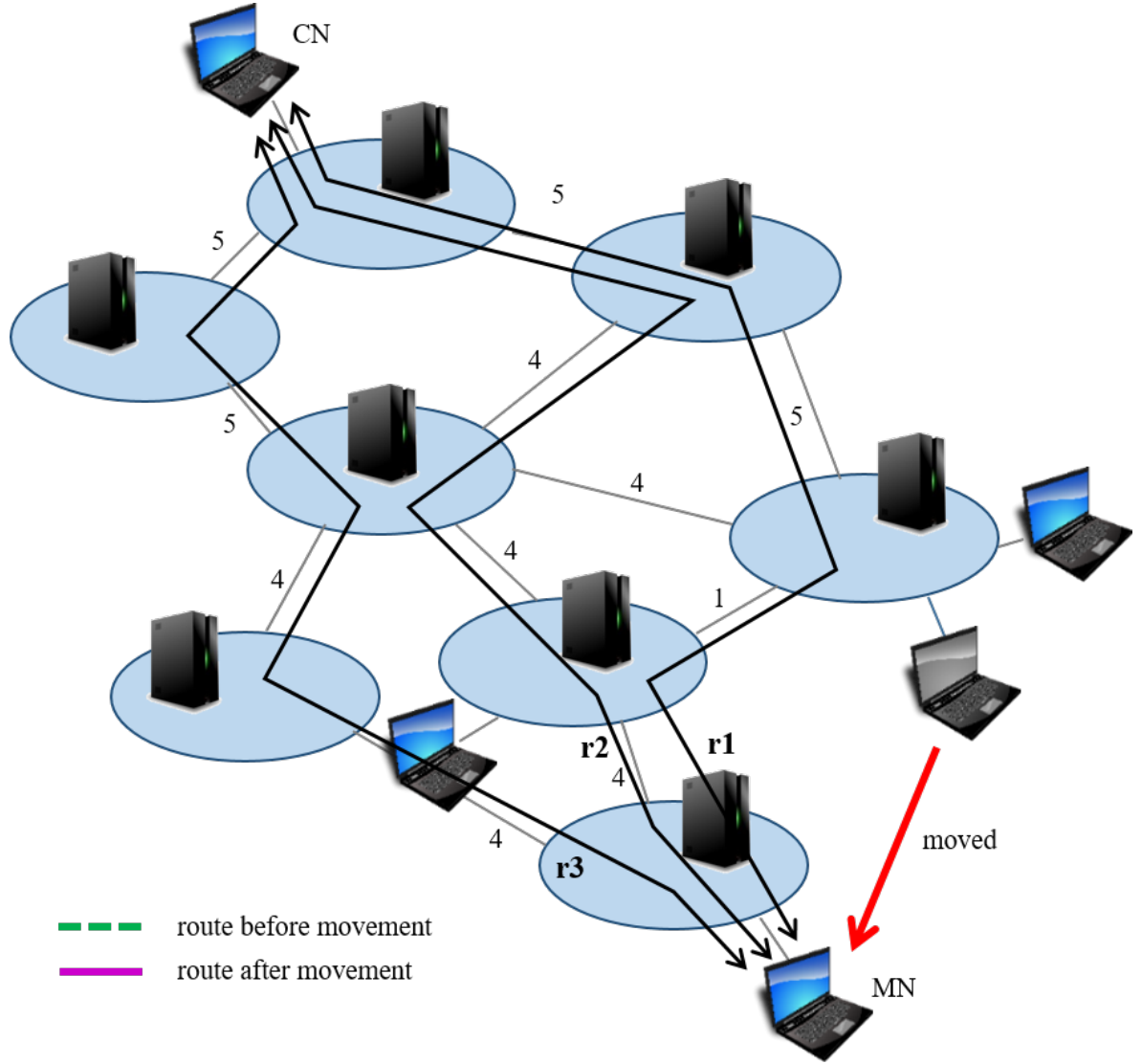


Figure 3.4: Lists of routes.

proach in the rest of the chapter.

To evaluate our new approach, we compared the previous approach with a Mobile IP-like approach. Mobile IP-like approach sets a route from the source domain to the destination domain. As its process is different from Mobile IP, the processing time was not measured for the Mobile IP-like approach.

We built a virtual network with Mininet 2.2.1. The bandwidth capacities of each link, in the grid part, are set randomly from 100 Mbps, 200 Mbps, 300 Mbps, and 400 Mbps. Appearance ratio of each bandwidth is 10%, 20%, 30%, and 40% relatively. This means that 10% of all the links have 100 Mbps bandwidth; 20% of them have 200

Mbps; 30% have 300 Mbps; and 40% have 400 Mbps. We also set every link, except the ones connected to the MN and the CN, 0.5 ms delay. The links connected to the MN and the CN have a bandwidth of 1000 Mbps and 0 ms delay. In the experiments, we aim to explore the characteristics of our routing mechanism. Thus, we do not provide a detailed limitation range of each importance. Each importance is a positive integer.

The experiments are conducted in the following scenario:

1. An MN, communicating with a CN, moves to its neighboring SDN domain.
2. Select a new route and set flow entries.
3. After changing the route, send 1000 MB data from the MN to the CN and measure the data transfer time.
4. Subsequently, send 50 pings from the MN to the CN and measure the average RTT that represents communication delay.

We executed 4 trials in each experiment. In each trial, the experimental network is generated automatically with random bandwidths.

3.4.2 Experiment 1: comparison with legacy approaches

In the first experiment, we verified the effect of the proposed approach compared to the Mobile IP-like and the previous approaches in various sized networks. We prepared three networks: 3 by 4, 4 by 5 and 5 by 6 grid networks. They are shown in Figures 3.5, 3.6, 3.7 respectively. In this experiment, we set the values of α, β, γ , in the proposed approach, as the default values ($\alpha = 1, \beta = 1, \gamma = 1$), which put no importance on specific features.

The results are shown in Figure 3.8 and Figure 3.9. The proposed approach had the shortest data transfer time in every network size. The communication delay for the proposed approach was lower than that of the Mobile IP-like approach; however, the delay was approximately the same as that of the previous approach. The route of the Mobile IP-like approach cannot be the shortest in this case because, although the MN moves nearer to the CN, the communication route has to go through the source domain. The previous approach first considers the number of hops, and hence

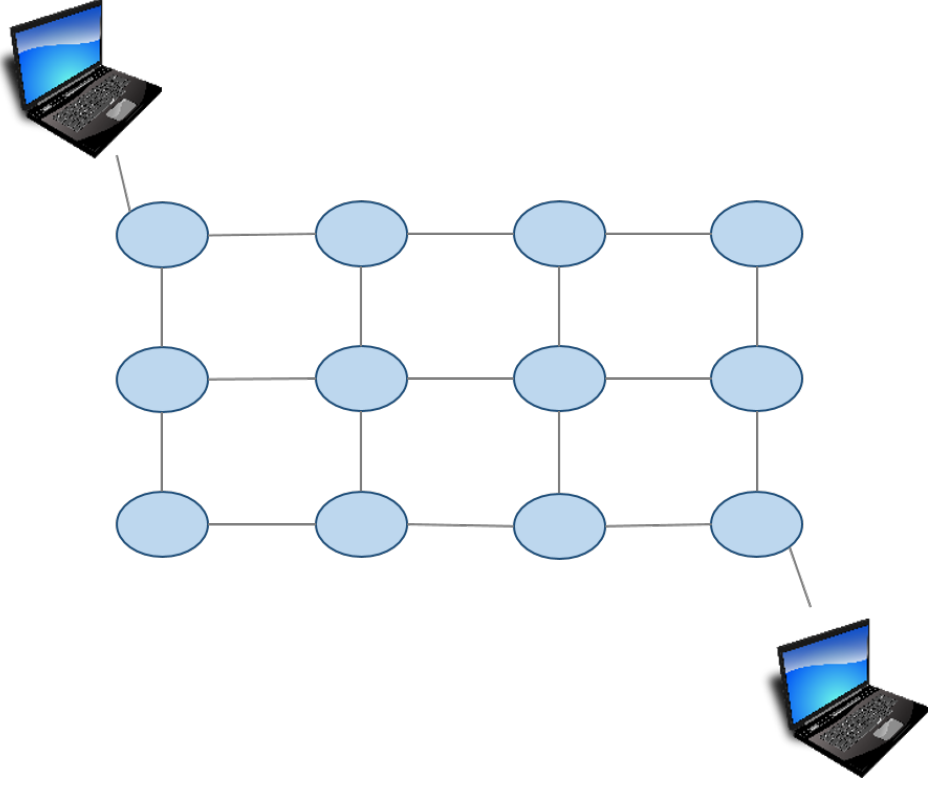


Figure 3.5: Experimental network (3 by 4).

selects the route with the least hops, which results in the least communication delay. However, the previous approach does not consider bandwidth. In view of this, if there is any link with a small bandwidth in the chosen route, the approach ends up having a low throughput. Both the Mobile IP-like approach and the previous approach do not consider bandwidth. Therefore, even if there is a link with a small bandwidth in the chosen communication route, the communication route cannot be avoided.

3.4.3 Experiment 2: Effects of importances

In the second experiment, we changed the three importance and investigated how the changes affected throughput, communication delay, and processing time. We used the 5 by 6 grid network shown in Figure 3.7, in this experiment. The importance, α, β, γ , are two-valued in this experiment. We set 5 for higher importance and 1 for lower importance.

The results are shown in Figure 3.11 and Figure 3.12. As we can see from Figure 3.11, the proposed approach achieved better results compared with the Mobile IP-like

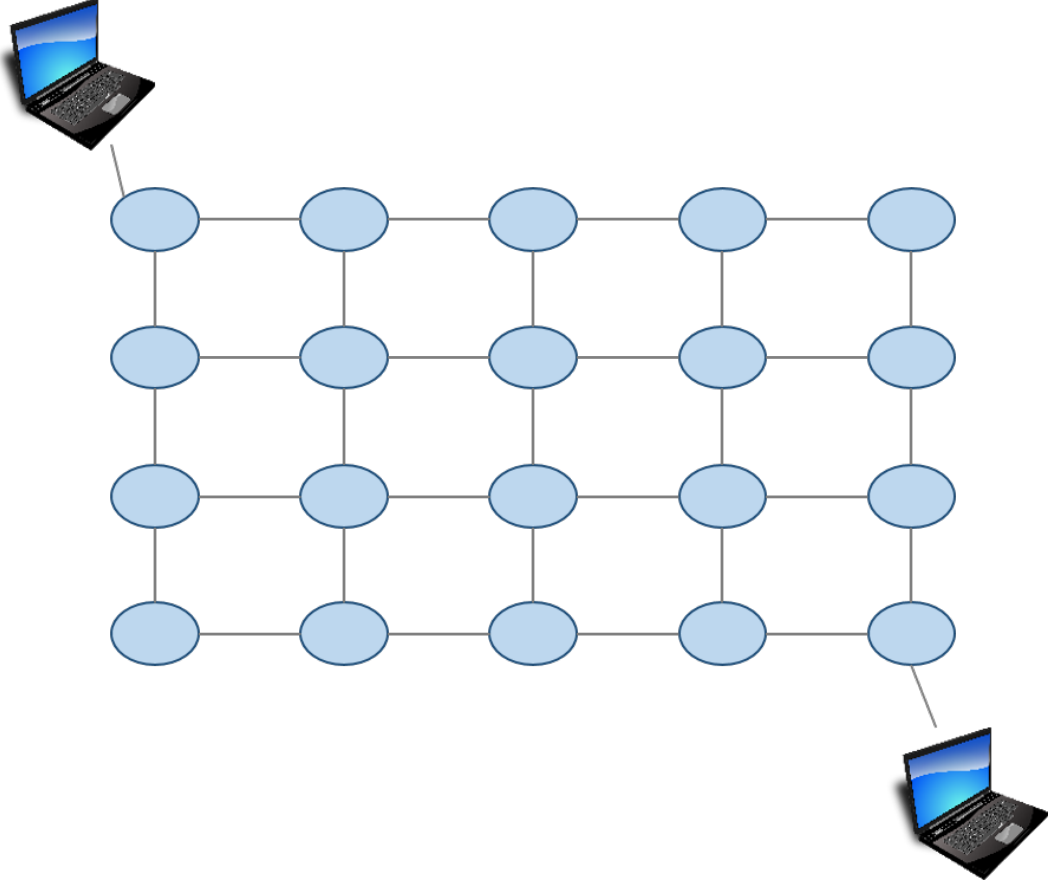


Figure 3.6: Experimental network (4 by 5).

approach and the previous approach, with any combination of importance. Though the communication delay seems to differ a bit, it was mostly the same when we independently investigated each trial. However, there was a particular network with which the communication delay differed greatly depending on the combination of importance.

In Figure 3.13, we show the processing time of the communication route calculation. If the network size is under 20 SDN domains (4 by 5 network), our proposed approach is able to select a communication route within a short time. However, as the network size increases, the processing time also increases, and when the network size is 30 SDN domains (5 by 6 network), it takes approximately 10 s to select a communication route, which is excessively long and might lead to a communication disconnection. Thus, the routing algorithm needs to be revised to reduce calculation time.

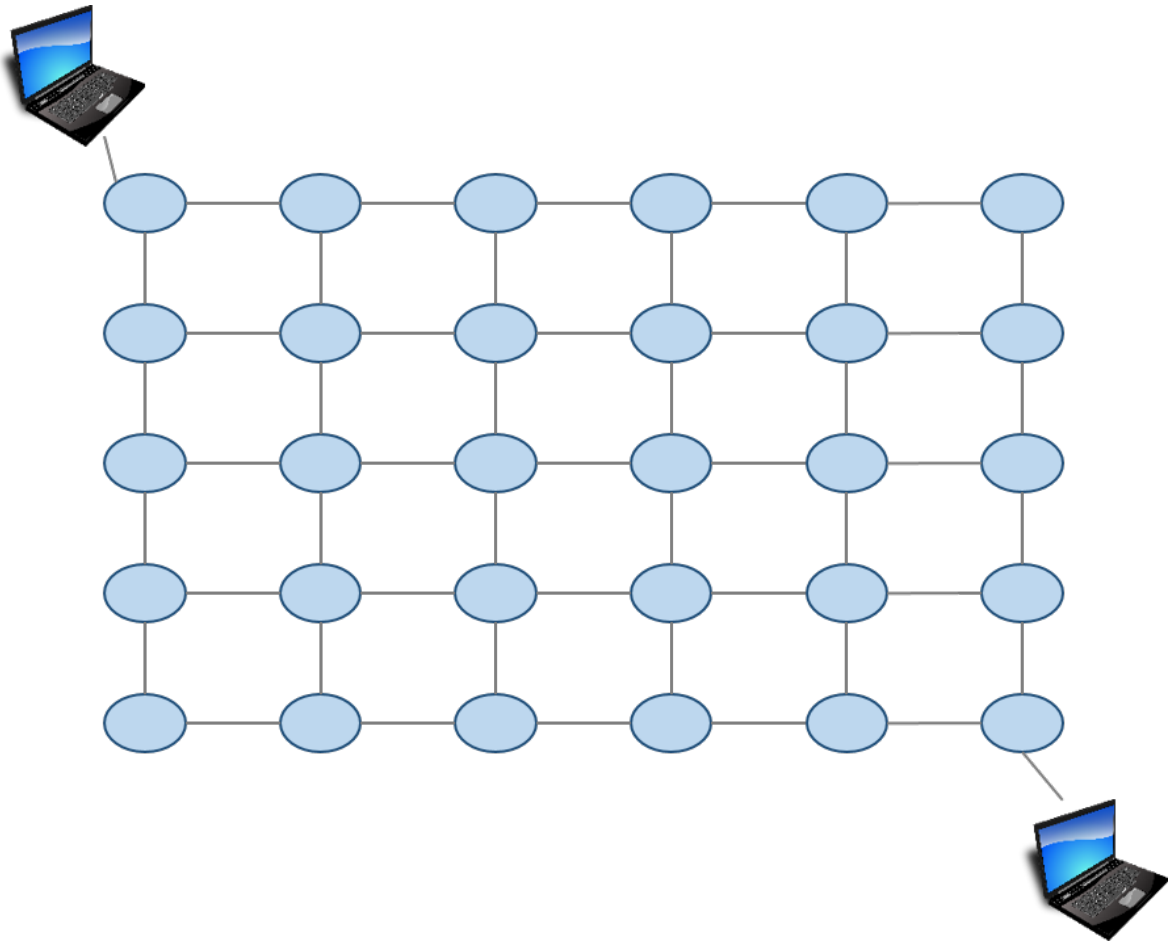


Figure 3.7: Experimental network (5 by 6).

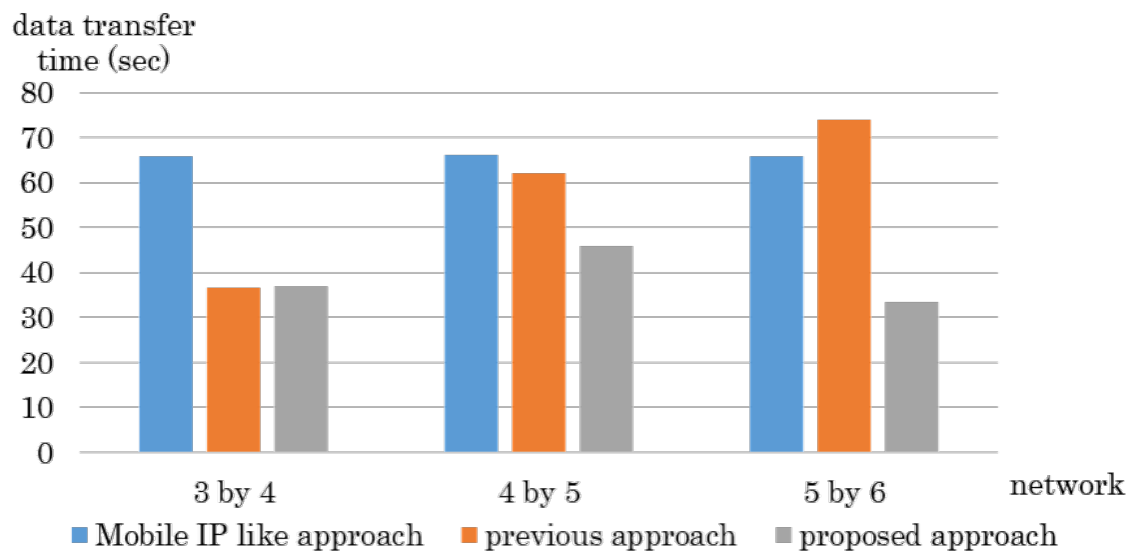


Figure 3.8: Experiment result: Data transfer time in Experiment 1.

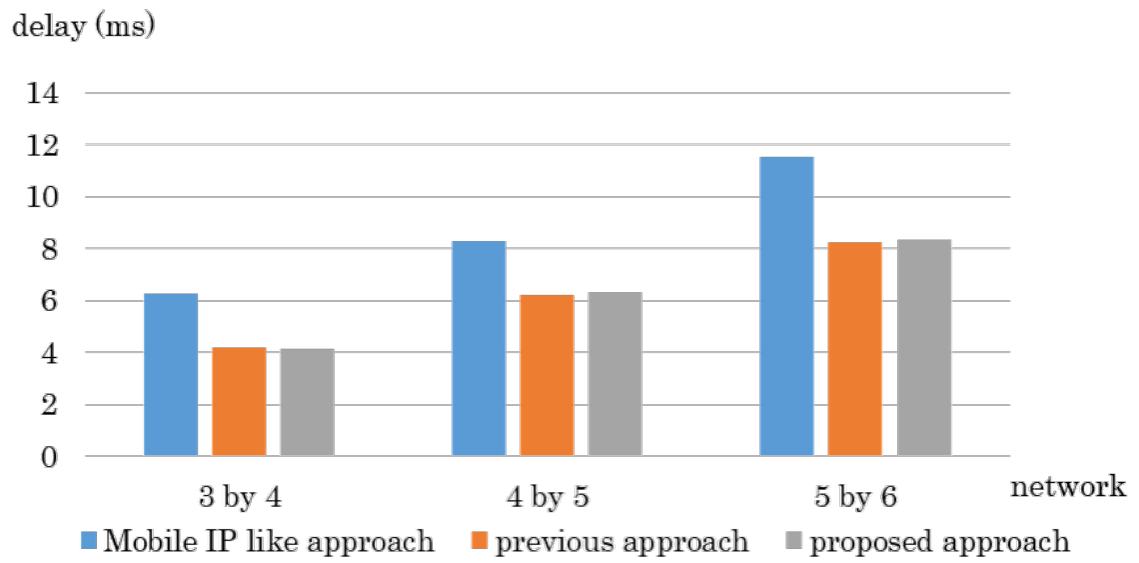


Figure 3.9: Experiment result: Communication delay in Experiment 1.

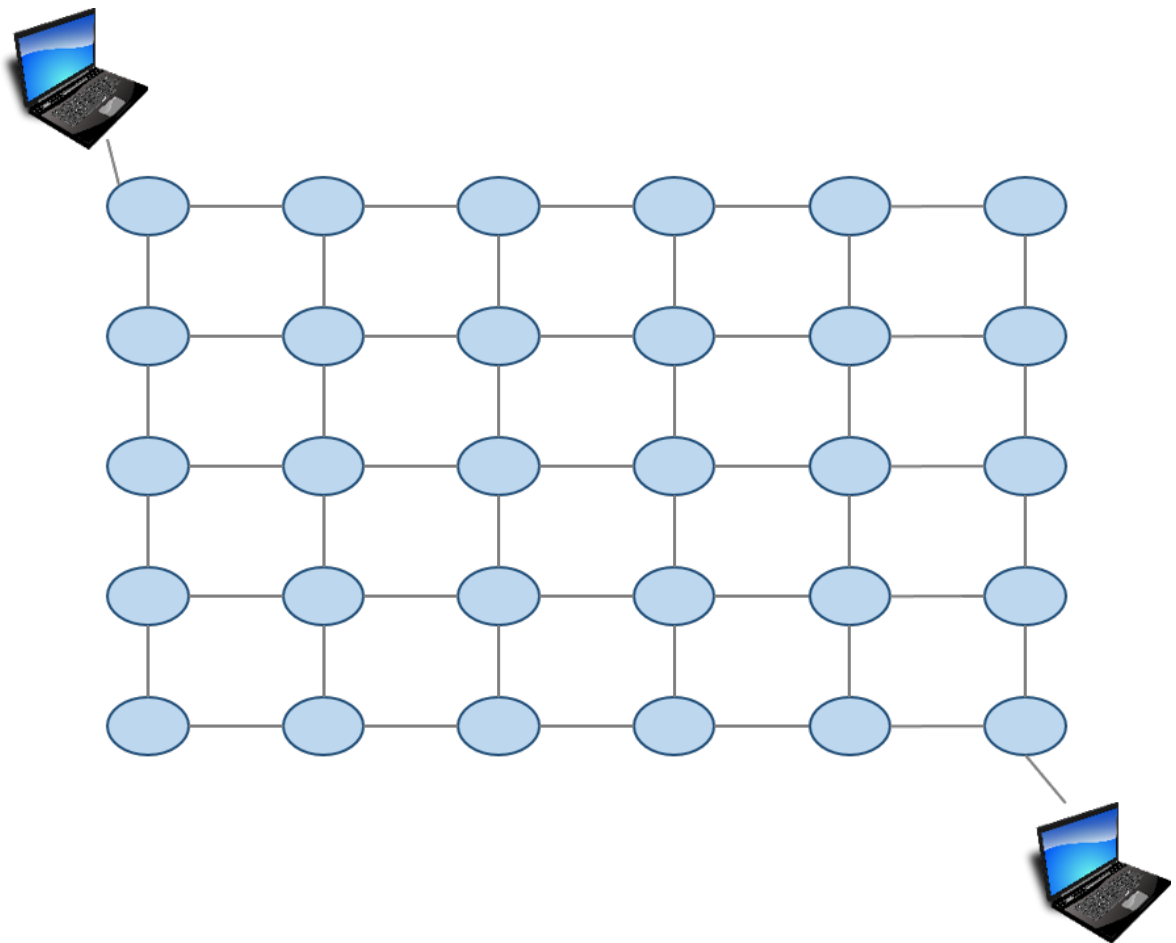


Figure 3.10: Experimental network used in Experiment 2.

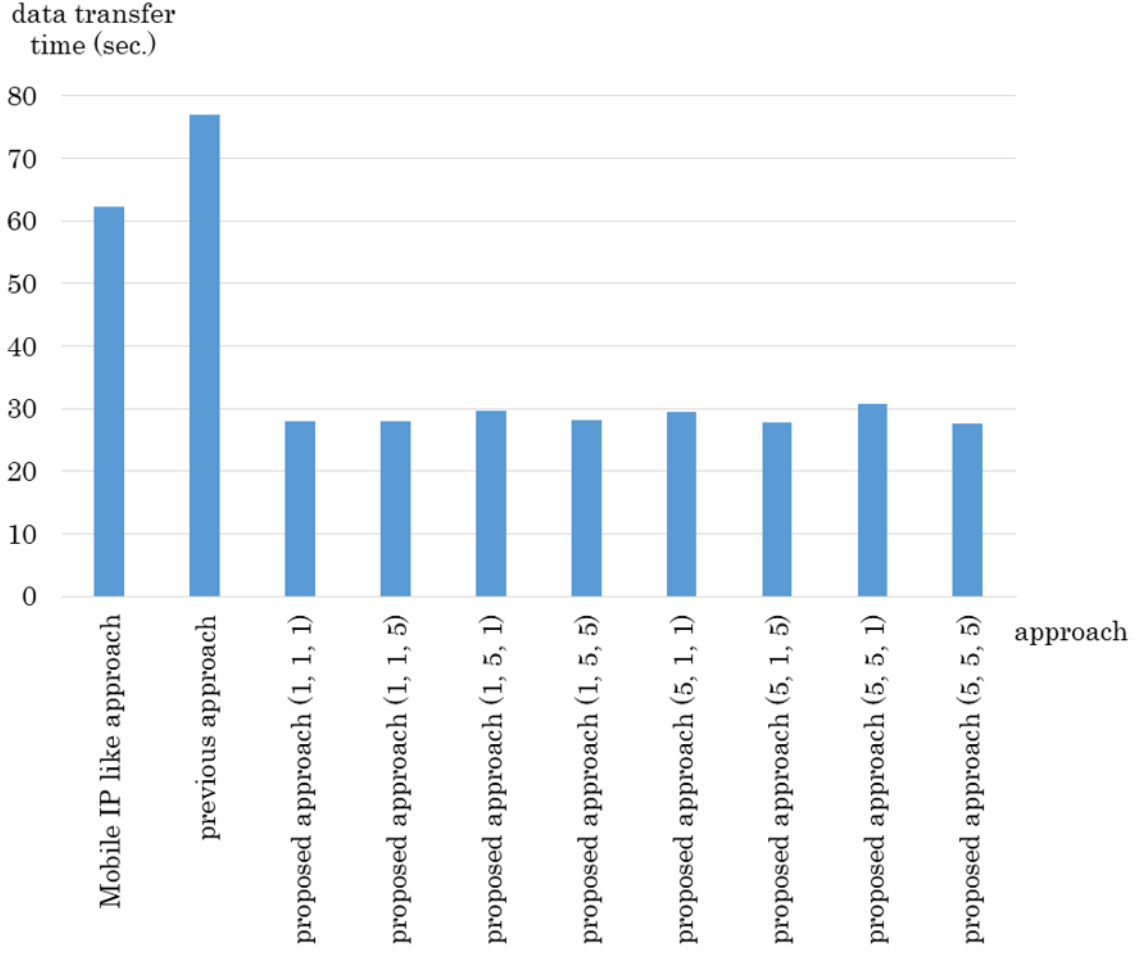


Figure 3.11: Experiment result: Data transfer time in Experiment 2.

3.4.4 Discussion

The number of flow entries had almost no effect on the results. In the experimental networks used in this evaluation, there were no overloaded or low-performance SDN controllers or switches. However, in practical environments, there are possibilities of using low-performance or overloaded SDN controllers or SDN switches. In such a network, the number of flow entries greatly affects the processing time because it takes much time to calculate and install necessary flow entries, with such devices.

As a reference, the default number of times TCP retries to retransmit a data before it disconnects its session is five and the minimum Retransmission Time Out (RTO) is 0.2 s for Linux OS. RTO is doubled after each retransmission; hence, the time limit for changing a route is approximately 6 s, minimum. As this is the default and theoretical

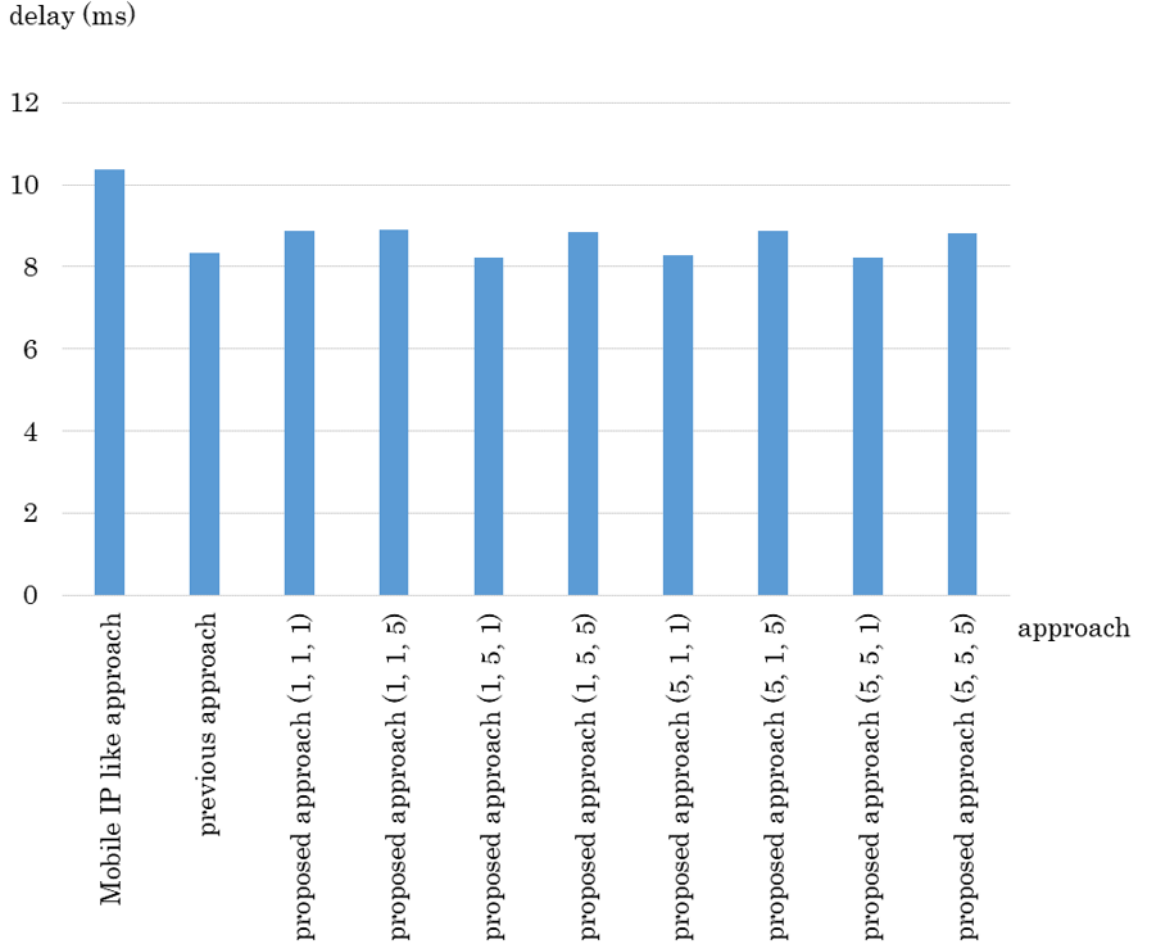


Figure 3.12: Experiment result: Communication delay in Experiment 2.

value, not a real one, we take it for reference. In a situation where the time-out limit is 6 s, the proposed approach cannot finish changing the communication route before 6 s in the 5 by 6 network.

Note that the processing time we measured does not include the time the SDN controller takes to detect the attachment of an MN or the time it takes for the SDN controllers to install flow entries into SDN switches, in a practical network environment. We focused only on the processing time of the communication route calculation and the announcement of the flow entries, in this chapter. In the future, we would like to do the evaluation in a practical network environment so as to measure the time for the entire process. Thus, from the start of a movement of an MN to the end, where all flow entries are installed and the MN starts communicating with a new communication route.

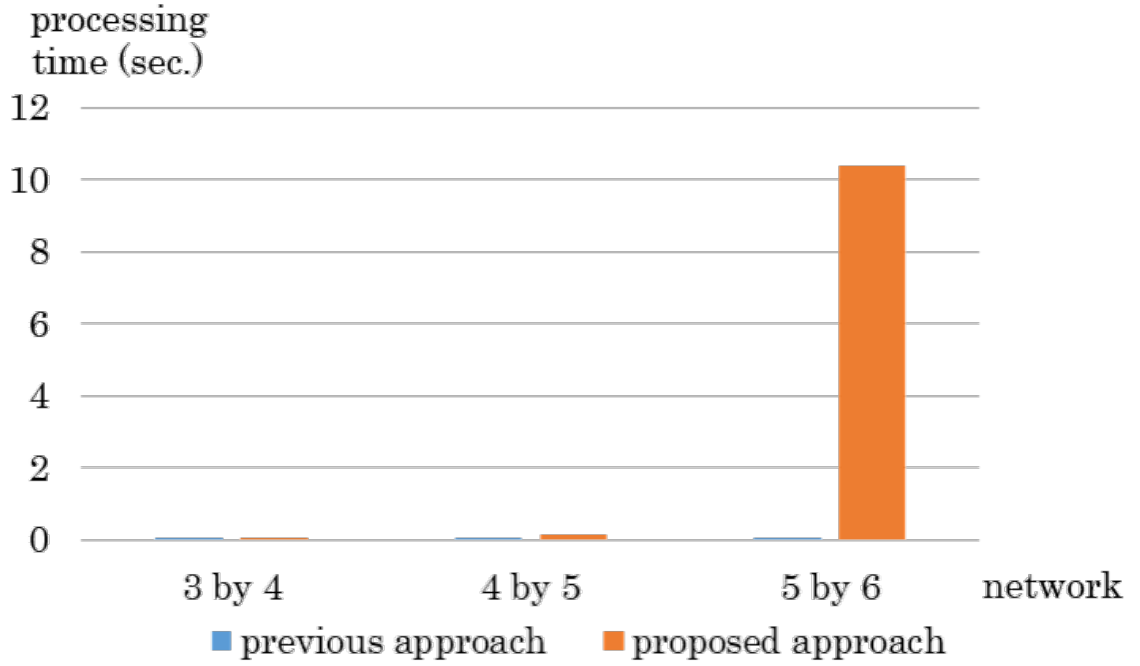


Figure 3.13: Experiment result: Processing time.

3.5 Conclusion

In this chapter, we proposed a routing mechanism for mobility management and showed the detailed design of it. This routing mechanism enables MNs to communicate with low-delay route after the inter-domain handovers and avoids disconnection that might occur when switching the communication route. We also conducted experiments to show the effectiveness of our routing mechanism.

For future works, we would extend our routing mechanism further to apply it to bigger networks with more SDN domains. Furthermore, we will attempt to update it to the lexicographic approach based on the study, [53]. Furthermore, we would like to conduct experiments in practical network environments.

Chapter 4

Automatic Route Selection Method Based on Communication Type

4.1 Introduction

Currently, there are many network services, and the requirements for maintaining their high QoS varies depending on their function. For example, while video streaming services require high throughput, chat services require a low communication delay. As described above, the requirement for communication is different for each network service and in a real network environment, communications with different requirements coexist, as shown in Figure 4.1. Thus, there are cases where a unified resource allocation rule remarkably deteriorates the communication quality. Therefore, to realize a comfortable communication, it is necessary to flexibly assign routes according to the communication requirements.

This is also the same for routing when MNs move and require mobility management. By considering the different requirements of each flow and maintaining the communication quality even after the MNs move, it is possible to prevent degradation of communication quality. Though the routing mechanism for mobility management we proposed in Chapter 3 can change the importance of routing information, it can only apply importance unified per network. Thus, we need a system in which we can apply individual importance to each flow.

We focused on flow classification to automatically decide on the kind importance to

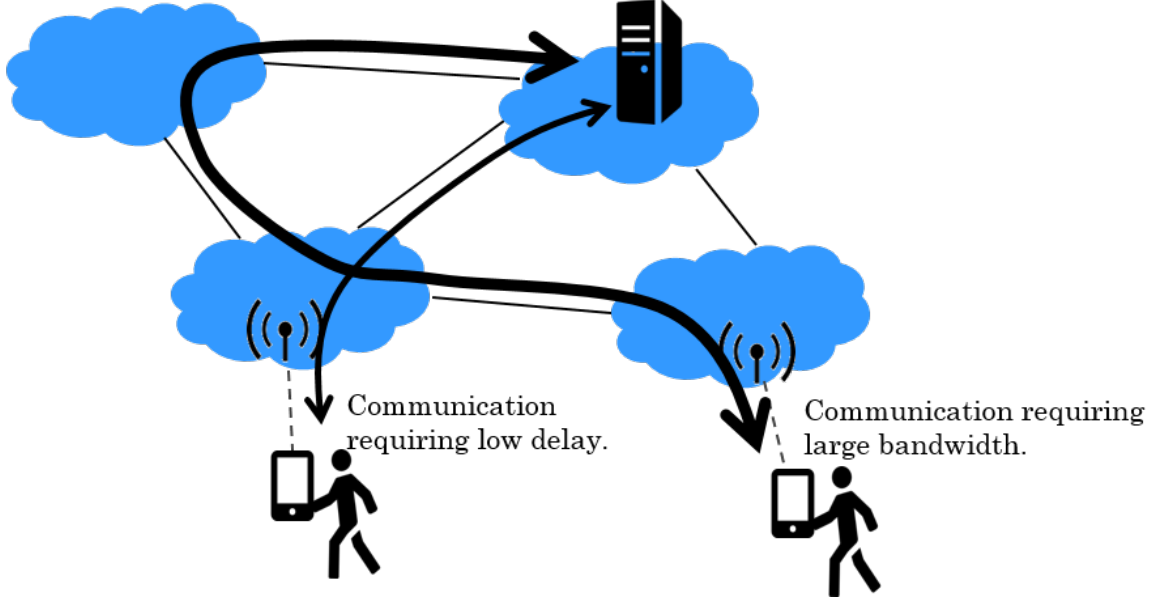


Figure 4.1: Actual network environment.

be set for the different communication flows. If we succeed in classifying the communication flows automatically, all we have to do to apply individual importance to each flow is to prepare sets of importance for each class. Therefore, we first sorted network services into four classes and then defined sets of importance that suit the classes. Moreover, with respect to mobility management, the classification must be executed in a short time. This means we cannot use the entire flow for the classification; however, a part of the flow can be used.

4.2 Related Works

4.2.1 Legacy communication flow classification

In the early days of the internet, most protocols used well-known ports. In this case, port-based classification could perfectly classify communication traffics. However, in these days, many of the protocols and the network services use unknown ports. Thus port-based classification methods are no longer useful now [54].

Deep packet inspection (DPI), also known as payload based classification, emerged to overcome the problem of port-based methods [55–57]. DPI methods classify traffics using payload data. Although DPI method can gain high accuracy, it leads to a high

computational cost and also, it finds it difficult working with encrypted data.

4.2.2 Communication flow classification combined with SDN

In recent years, flow classification, combining SDN with machine learning or deep learning, has also been proposed. M. R. Parsaei et al. proposed a method using information gained by an SDN controller that executes the training in offline phase and the actual classification in online phase [58]. A. S. d. Silva et al. extracted 33 flow features, which they used for classification [59]. Both studies utilized features made available by SDN and achieved high accuracy in coarse-grained classification. However, these methods require the entire communication flow to classify flows. In other words, the classification can only be performed after the communication is over. This is a fatal drawback considering their application to mobility management, which requires real-time classification.

Atlas realized fine-grained mobile application detection with the first few packets in a flow; however, it can only be applied to Android devices [60]. We are aiming for a mobility management that is not limited by OS or the type of MN. Therefore, this method is unsuitable for our mobility management method.

M. Hayes et al. assured scalability by separating the classifier from the SDN controller and placed it in another component [61]. Owing to the installation of an additional component for the classifier, additional cost is needed for managing the component.

4.3 Automatic Route Selection Method Based on Communication Types

4.3.1 Overview

In Chapter 3, we proposed a mobility management specific end-to-end routing mechanism. This approach takes the quality of communications and the operation costs into account and takes a balance between them. This mechanism is able to select a new communication route, depending on the requirements of a network. However, this ap-

proach cannot cope with individual communications with different requirements. The importance of considering information can only be manually set per network.

Therefore, there is a need for automatically deciding the requirements of each communication and applying an appropriate communication route. However, existing approaches are not appropriate for mobility management. Below are the terms needed for mobility management.

1. Ability to classify flows by using packets during a communication. Because we are attempting to select an appropriate route when an MN moves, we need to make a judgement based on the packets during communication.
2. Ability to classify flows with a few packets. We classify the flow observed when an MN moves into an SDN domain and calculate a new route so that the MN's communication is not disconnected. Therefore, it is impossible to use the entire flow for classification. We have to classify the flows with only a few packets.

We propose an automatic route selection method based on communication types, which classifies flows based on the concepts above. Furthermore, we add importance to route selection information according to the classification results. First, we built a classifier to classify flows by their communication types. Then, we extended the routing mechanism proposed in Chapter 3 to automatically set the importance of route selection information based on the classification results.

4.3.2 Communication type based flow classification

Though there are many network services, the demands for their communication quality can be sorted into several groups. Thus, we first sorted network services into the following 4 classes.

- Large bandwidth recommended.

Network services, such as video streaming service, that send large data unilaterally are sorted into this class.

- Low delay recommended.

Network services that need to send small data, frequently and interactively with low communication delay, are sorted into this class; e.g., chat service.

- Large bandwidth and low communication delay recommended.

Network services that need to send large data, frequently and interactively with low communication delay, are sorted into this class; e.g., online games.

- No requirement

Network services with no specific requirements except maintaining a connection are sorted into this class, e.g., e-mails.

By classifying communication flows into these classes, the routing mechanism can assign the appropriate routing information importance.

We decided to use the following features for classification.

- source port
- destination port
- payload length

Because the classification method we are aiming for is a coarse-grained classification with 4 classes and requires a real-time classification, we reduced the number of features used, to a small number.

In figure 4.2, we show the outline of the model training and classification system.

4.3.3 Automatic importance setter

Once a flow is classified, we set the routing information importance that suits the class it is classified into. Referring to the results in Chapter 3, we made sets of routing information importance for each class.

- Large bandwidth recommended.
 - The importance of the number of SDN domains each route candidate goes through: low.

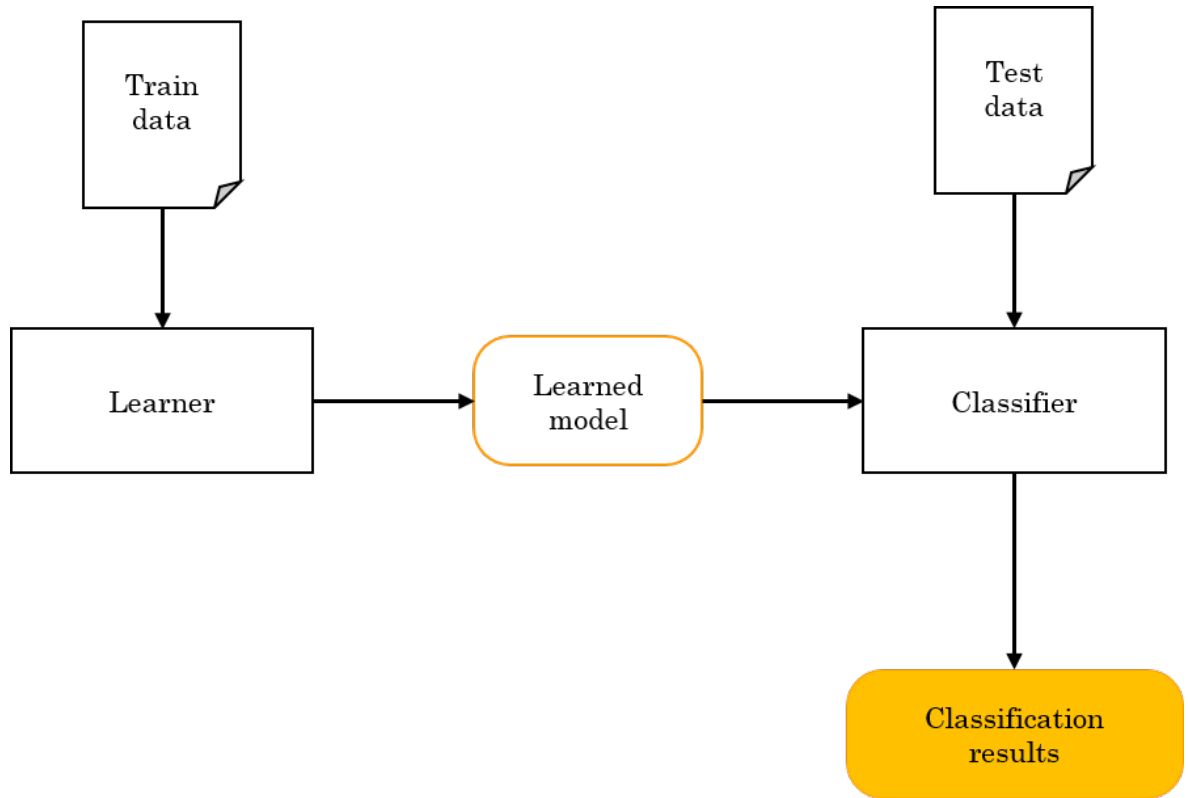


Figure 4.2: Outline of model training and classification system.

- The importance of the number of flow operations for each route candidate: low.
- The importance of real-time bandwidth usage information: high.
- Low delay recommended.
 - The importance of the number of SDN domains each communication route candidate goes through: high.
 - The importance of the number of flow operations for each communication route candidate: low.
 - The importance of real-time bandwidth usage information: low.
- Large bandwidth and low delay recommended.
 - The importance of the number of SDN domains each communication route candidate goes through: high.

- The importance of the number of flow operations for each communication route candidate: low.
- The importance of real-time bandwidth usage information: high.
- No requirement.
 - The importance of the number of SDN domains each communication route candidate goes through: low.
 - The importance of the number of flow operations for each communication route candidate: high.
 - The importance of real-time bandwidth usage information: low.

When the classifier hands the classification result to the routing mechanism, the routing mechanism automatically sets the routing information importance, as shown above. The routing mechanism then calculates a new communication route with the importance.

4.4 Evaluation

4.4.1 Overview

We conducted two experiments to show the validity of our flow classification method and the inter-domain routing, based on the classification results. The experiments are conducted in the following scenario:

1. An MN communicating with a CN moves to its neighboring SDN domain.
2. The mobility management framework extracts data from the detected communication flow between the MN and the CN and classifies the flow.
3. The routing mechanism calculates a new communication route between the MN and the CN, based on the classification result.
4. The MN and the CN continue communication with the new communication route.

In this experiment, we verified the flow classifier we made and compared the new

communication route, selected by our approach, with the communication routes selected by other approaches.

4.4.2 Experiment 1: Flow classifier

In the first experiment, we trained and evaluated the flow classification model.

The dataset used in this experiment is generated from captured traffics of a specific computer in our laboratory. Figure 4.3 shows the network we collected the traffic data from. We activated network services, one at a time, at Target PC and mirrored traffic data from the router to the data server. We collected traffic data of the following network services: YouTube [62], Google Docs [63], Skype [64], online game and E-mail.

Each data is composed of the information below.

- label
- source IP address
- source port
- destination IP address
- destination port
- average payload length

We used 10 packets per a data to take the average of the payload lengths. Furthermore, we monitored traffics for each network service we captured and labeled each data according to the monitored results.

We separated the dataset to train data and test data for evaluation and also performed 10-fold cross 验证 alidation, using 90% of the dataset for training and 10% for testing.

The classifier was trained and tested for all combinations of the three features mentioned in 4.3.2. These are the evaluated combinations :

- source port
- destination port

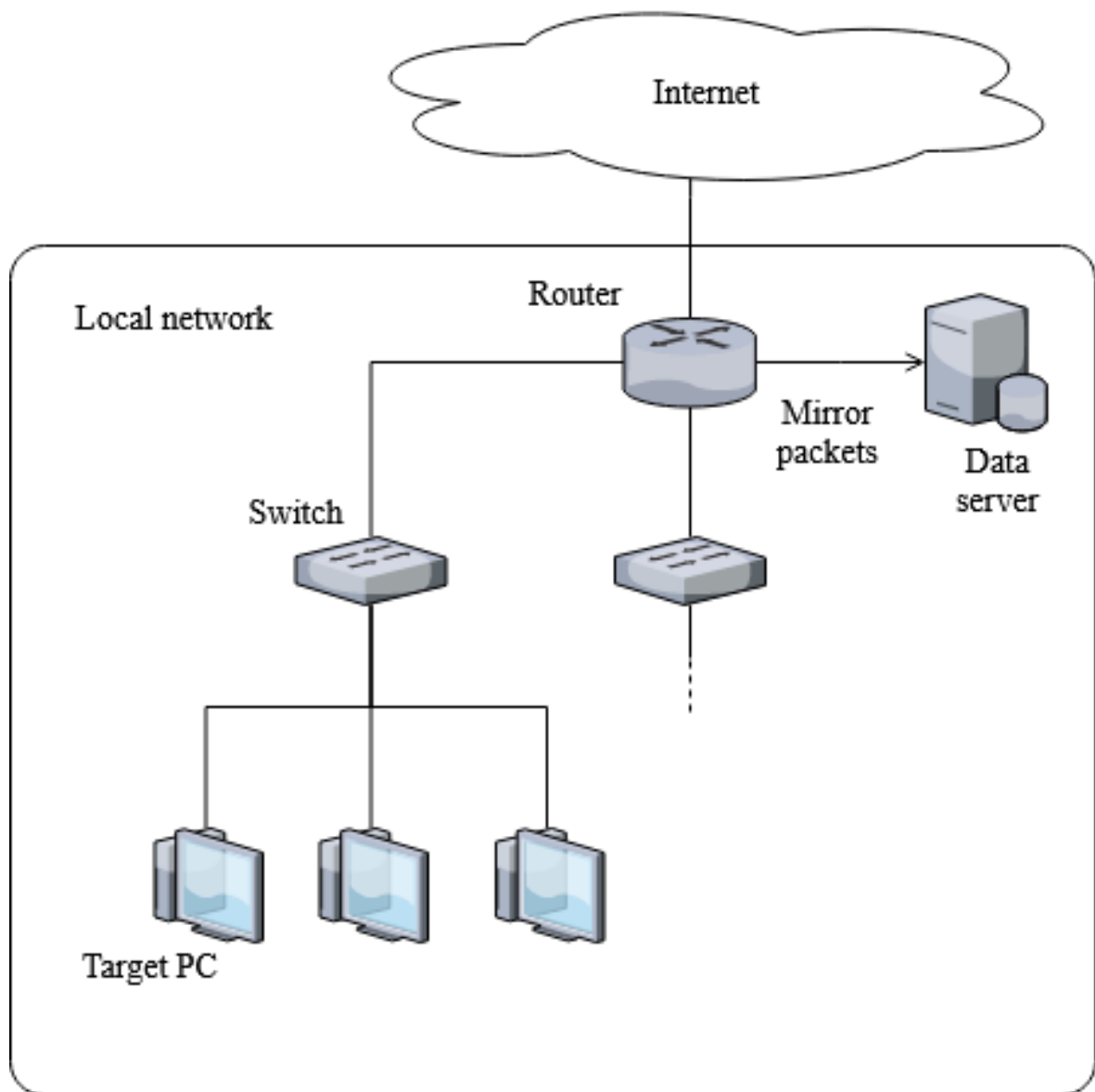


Figure 4.3: Configuration of the network used for making the dataset.

- payload length
- source port and destination port
- source port and payload length
- destination port and payload length
- source port, destination port, and payload length (all features)

Figures 4.4 to 4.10 and Tables 4.1 to 4.7 show the results of the classification

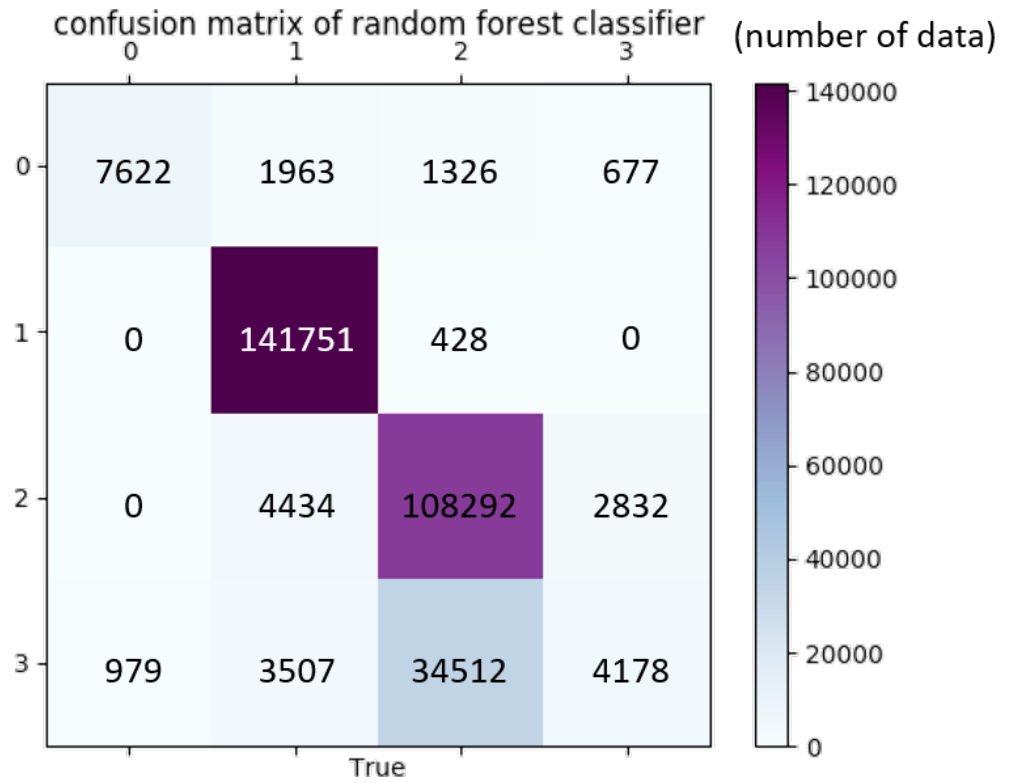


Figure 4.4: Confusion matrix of classification result (source port).

experiments. The labels 0 3 stands for each class and the mapping is as shown below.

- 0: no requirement
- 1: low delay recommended
- 2: large bandwidth recommended
- 3: large bandwidth and low delay recommended

The numbers in the graph represent the number of data.

Table 4.1: Classification result (source port).

Class	precision	recall	F-score
no requirement	0.89	0.66	0.76
low delay recommended	0.93	1.00	0.96
large bandwidth recommended	0.75	0.94	0.83
large bandwidth and low delay recommended	0.54	0.10	0.16

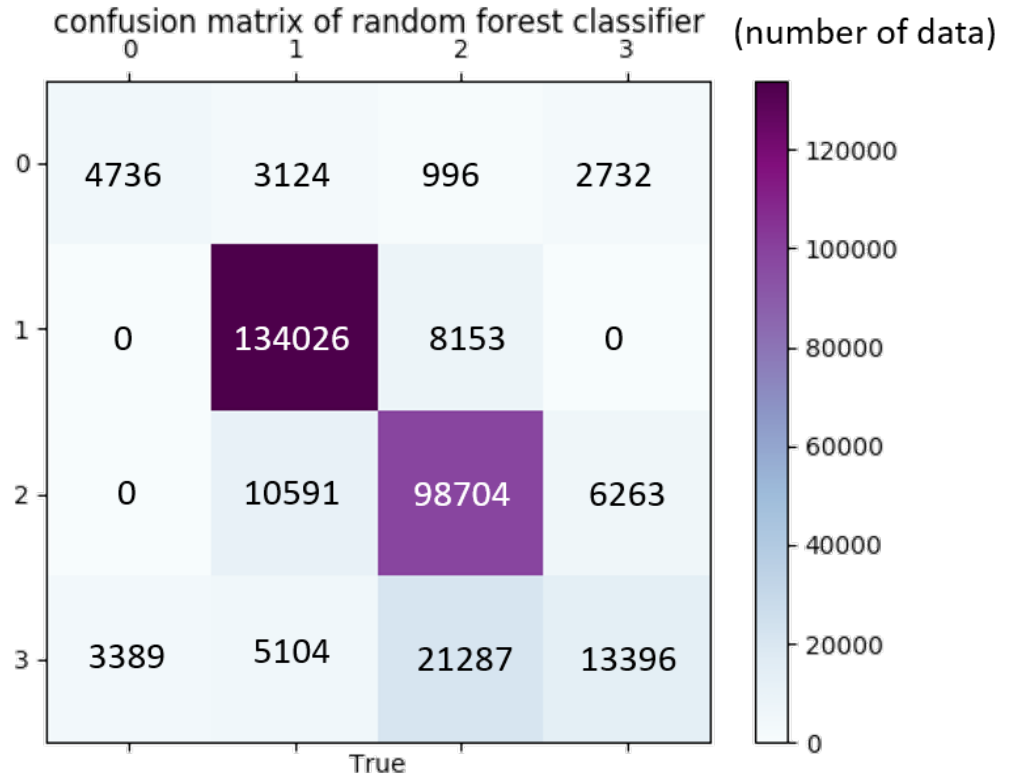


Figure 4.5: Confusion matrix of classification result (destination port).

Table 4.2: Classification result (destination port).

Class	precision	recall	F-score
no requirement	0.58	0.41	0.48
low delay recommended	0.88	0.94	0.91
large bandwidth recommended	0.76	0.85	0.81
large bandwidth and low delay recommended	0.60	0.31	0.41

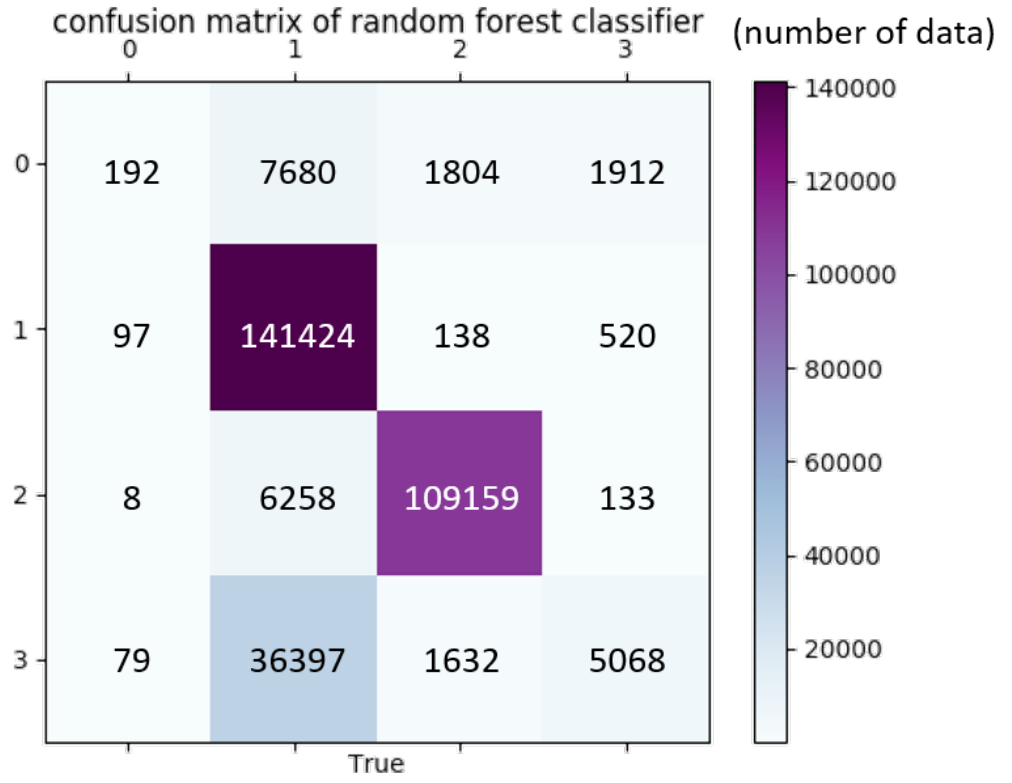


Figure 4.6: Confusion matrix of classification result (payload length).

Table 4.3: Classification result (payload length).

Class	precision	recall	F-score
no requirement	0.51	0.02	0.03
low delay recommended	0.74	0.99	0.85
large bandwidth recommended	0.97	0.94	0.96
large bandwidth and low delay recommended	0.66	0.1212	0.20

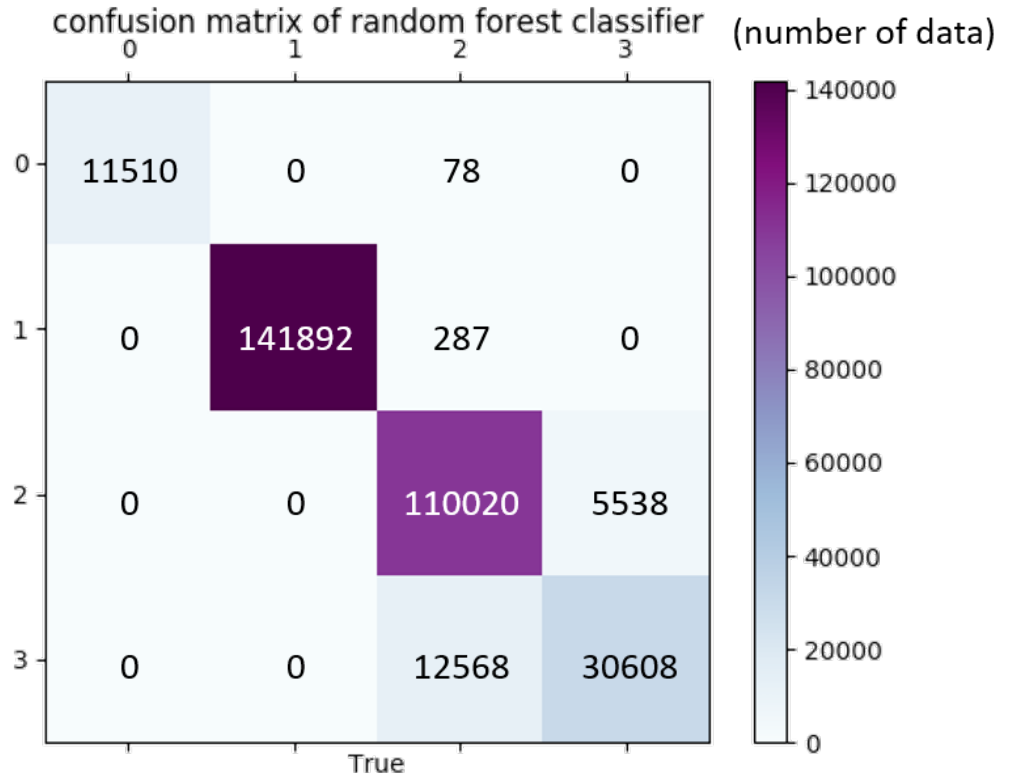


Figure 4.7: Confusion matrix of classification result (source port and destination port).

Table 4.4: Classification result (source port and destination port).

Class	precision	recall	F-score
no requirement	1.00	0.99	1.00
low delay recommended	1.00	1.00	1.00
large bandwidth recommended	0.89	0.95	0.92
large bandwidth and low delay recommended	0.85	0.71	0.77

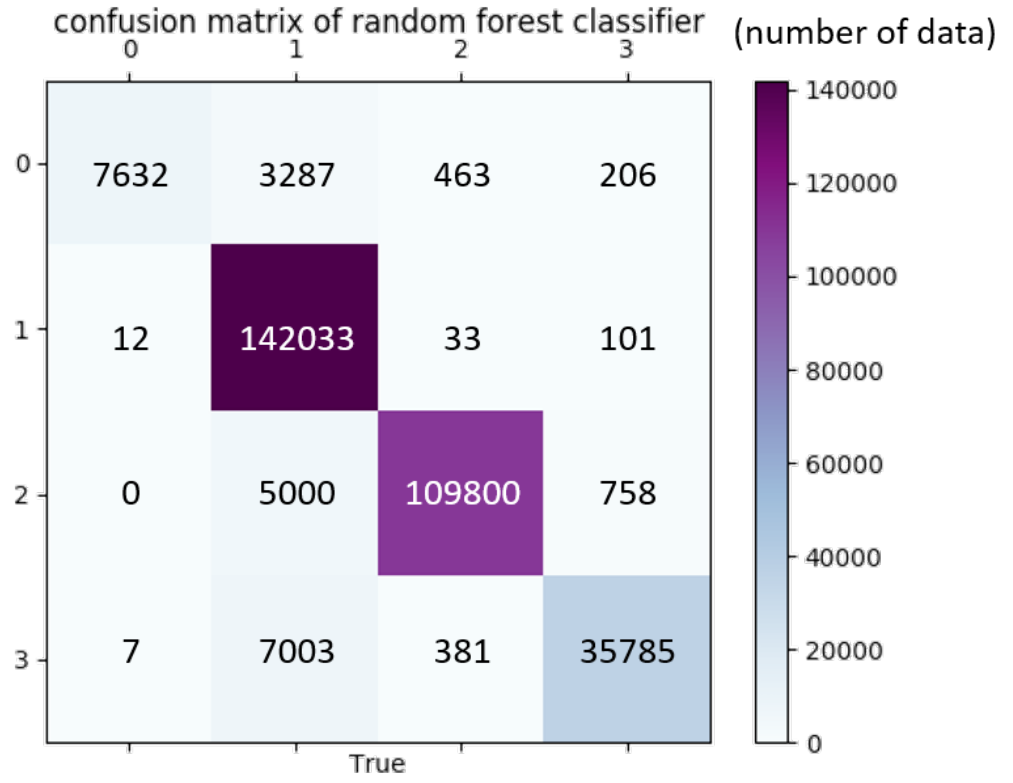


Figure 4.8: Confusion matrix of classification result (source port and payload length).

Table 4.5: Classification result (source port and payload length).

Class	precision	recall	F-score
no requirement	1.00	0.66	0.79
low delay recommended	0.90	1.00	0.95
large bandwidth recommended	0.99	0.95	0.97
large bandwidth and low delay recommended	0.97	0.83	0.89

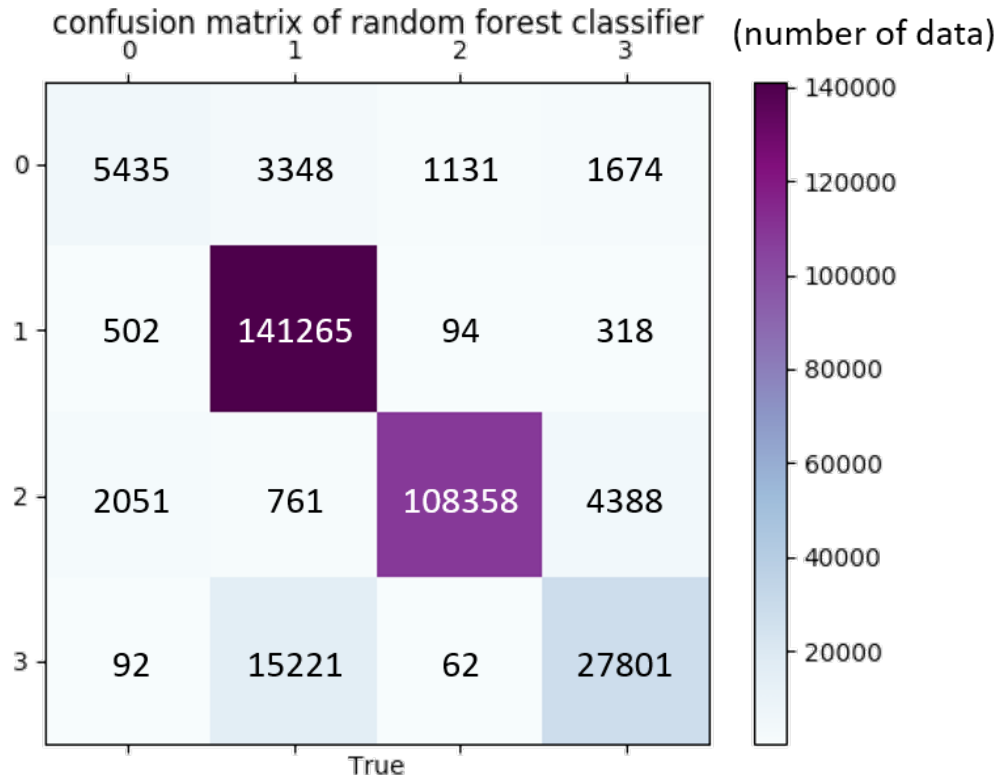


Figure 4.9: Confusion matrix of classification result (destination port and payload length).

Table 4.6: Classification result (destination port and payload length).

Class	precision	recall	F-score
no requirement	0.67	0.47	0.55
low delay recommended	0.88	0.99	0.93
large bandwidth recommended	0.99	0.94	0.96
large bandwidth and low delay recommended	0.81	0.64	0.72

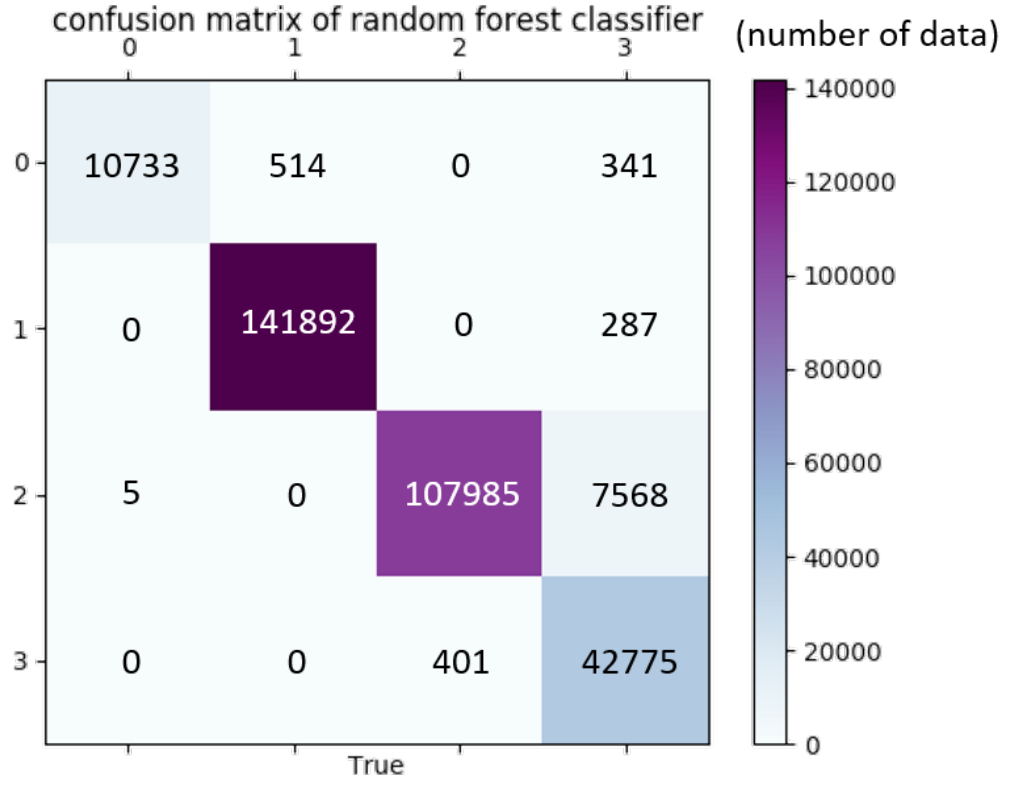


Figure 4.10: Confusion matrix of classification result (all features; source port, destination port and payload length).

Table 4.7: Classification result (all features; source port, destination port and payload length).

Class	precision	recall	F-score
no requirement	1.00	0.93	0.96
low delay recommended	1.00	1.00	1.00
large bandwidth recommended	1.00	0.93	0.96
large bandwidth and low delay recommended	0.84	0.99	0.91

Comparing the results of seven combinations, the F-score of the classifier, which used all the three features, was high. However, the other combinations are too inaccurate to be useful. The no requirement class and the large bandwidth and low delay recommended class have particularly low scores with respect to the results of classifiers using only one feature. Though the low delay recommended class have relatively high scores, many data are misclassified according to the number of data, leading to the degradation of the communication 交互 comfortability.

Basically, the scores tend to rise along with the number of features used. However, the scores of the classifiers, using both the source port and the destination port, were higher than the classifiers using only one of the ports with payload length. Hence, the feature used also affects the scores and the feature selection is a key to suppress classification costs.

Also, in this experiment, we treated the packets, with reversed source and destination ports, as different flows. In view of the fact that classifiers using both ports had higher F-score than the others, we infer that treating packets with reversed source and destination ports as the same flow yields different results. We will evaluate again, treating the packets with reversed source and destination ports as the same flow, in the future.

According to the above results, we decided to use all the three features to classify flows. Nonetheless, the rest of the experiment is conducted with the classifier that uses the three features.

From the result of the classifier using the three features, we can say that we obtained correct classification results for most of the data.

However, the misclassification of large bandwidth and low delay recommended data is noticeable. This is because the features of flows recommending large bandwidth and low communication delay are similar to those recommending only large bandwidth. To correctly classify these data, either time-oriented features are taken into account, to distinguish flows that require a low communication delay or IP addresses are used to identify network services.

4.4.3 Experiment 2: routing information importance adjustor

In the second experiment, we examined the communication delay and the throughput of the communication using the selected communication route by our approach, based on the classification results. To evaluate the new approach, we compared it with Mobile IP-like approach that sets a new communication route similar to the communication route the Mobile IP without route optimization would set, and our previous approach proposed in Chapter 3. As for the previous approach, we assumed the network administrator did not set importance to any specific routing information. All the importance is set to low.

We built a 30 SDN domain-virtual network with Mininet 2.2.1. The network topology is shown in Figure 4.11. The bandwidth capacities of links in the grid network are set randomly from 100 Mbps, 200 Mbps, 300 Mbps and 400 Mbps. The appearance ratio of each value is 10%, 20%, 30%, and 40% respectively. Except the links connected to the MN and the CN, we set every link to 0.5 ms delay. The bandwidth and the delay of the links connected to the MN and the CN are 1000 Mbps and 0 ms respectively. After changing to a newly selected communication route, we send 1000 MB data from the MN to the CN to measure the transfer time and send 50 pings from the MN to the CN to measure the average RTT.

In this experiment, we attempted six trials. In each trial, the experimental network is generated automatically with random bandwidths, following the appearance ratio mentioned above.

The results are shown in Figure 4.12. The left graphs present the transfer time and the right graphs present the communication delay. As seen from the results, data transfer time and the communication delay of the Mobile IP-like and the previous approach do not differ in spite of different requirements. However, the new routing mechanism chose the communication routes that satisfy the requirements. Especially for the flows with requirements, it performed well. The low delay recommended flows took more time than other classes to transfer data; however, they had lower communication delay than others, which was required. The large bandwidth recommended flows had shorter transfer time, which means the proposed approach classified the flows to the large bandwidth recommended class (the right class) and assigned a new communication

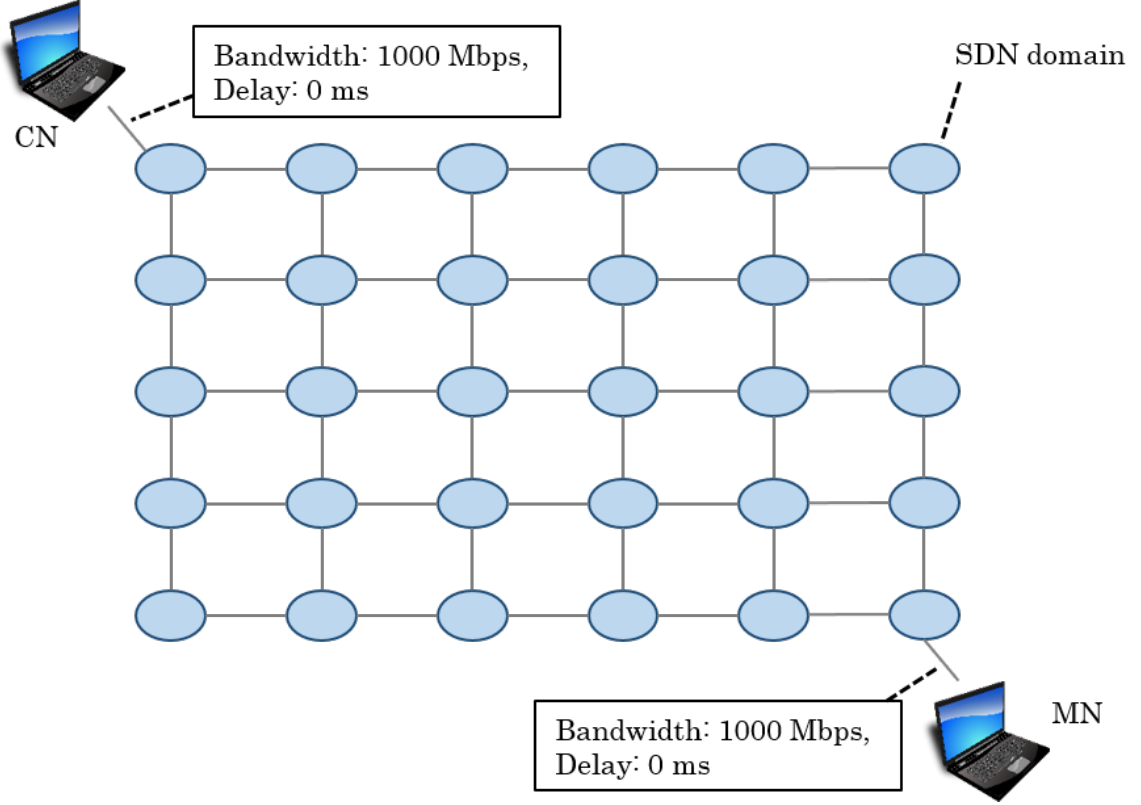
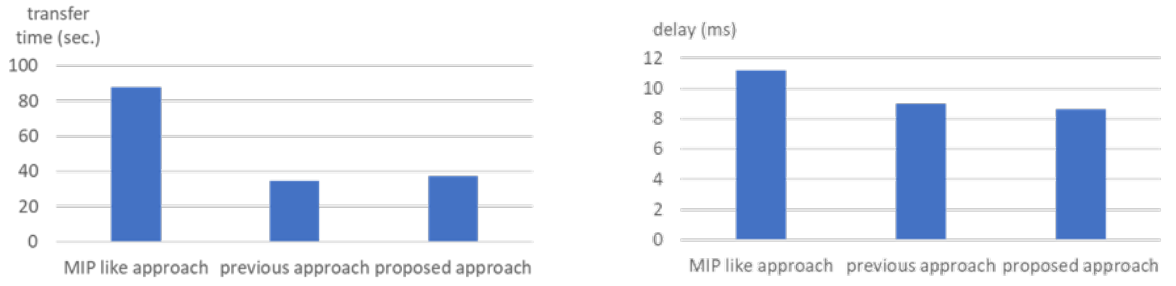


Figure 4.11: Experimental network configuration.

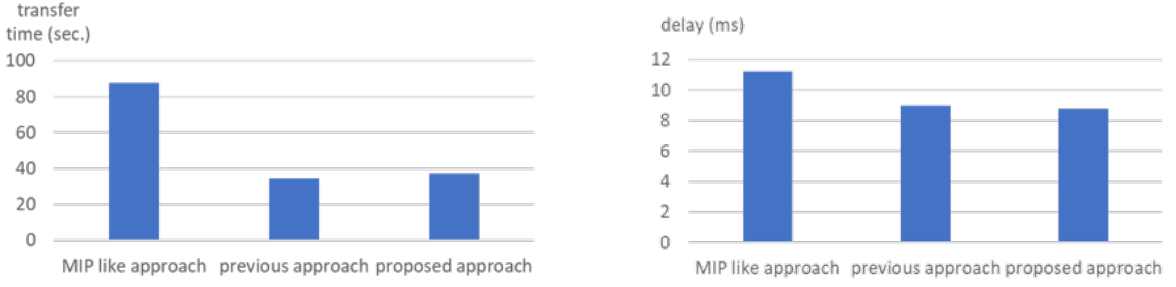
route that fit the requirement. For the low delay and large bandwidth recommended flows, both requirements were met without bias towards either high bandwidth or low communication delay, though the communication delay was slightly higher than the low delay recommended flows.

We noticed that the importance of bandwidth had a strong influence and the proposed approach tends to allocate more bandwidth than expected. Because there would be other flows in a real environment, we prefer not to allocate excessive bandwidth to flows that do not require large bandwidth. It is considered that by adjusting the given importance, a more appropriate communication route may be selected.

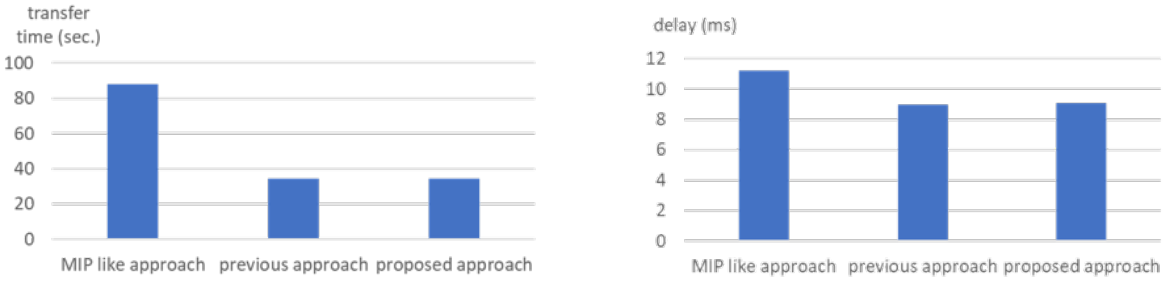
This time, we set the importance, high or low, based on the results in Chapter 3. However, there is a possibility that the importance that provides a good result may differ depending on the network topology. In the future, we would like to verify the effect by changing the network topology and the values of importance.



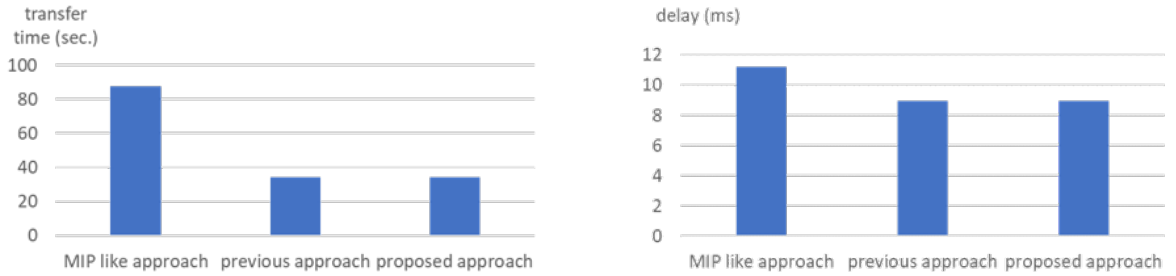
(a) No requirement traffic



(b) Low delay recommended traffic



(c) Large bandwidth recommended traffic



(d) Low delay and large bandwidth recommended traffic

Figure 4.12: Experimental result: data transfer time and communication delay.

4.5 Conclusion

In this chapter, we proposed an automatic communication route selection method, based on communication types. This communication route selection method classified

flows by communication types and decided on what to automatically prioritize. From the evaluation, we confirmed the effectiveness of our method. This automation expands the use of the routing mechanism we presented in Chapter 3. Networks can deal with each communication requirement that varies.

For future works, we would like to adjust the approach to select communication routes that fit the requirements perfectly, with no over-allocation of resources. Afterwards, we will apply and evaluate the proposal with other network traffics. Furthermore, we would consider a finer flow classification, whether a fine-grained classification is necessary for mobility management in the first place.

Chapter 5

Conclusion

5.1 Objective and challenges

Today, with the spread of wireless communication technology and the IoT environment, mobile node users can now use network services in various places and situations even while moving. The objective of this study is to construct an inter-domain mobility management framework that enables communication to continue when communicating mobile nodes move between SDN domains. We also extend the routing mechanism of the mobility management framework to enable flexible routing, based on communication type and control communication after the move of an MN.

With the completion of this study, users will be able to continue comfortable communication, after moving to another SDN domain. In this study, we set the issues below.

(A) Challenges of the SDN based inter-domain mobility management.

To continue comfortable communication after an MN user moves to another SDN domain, it is worthwhile to share MN information and other information, necessary for routing. Also, we have to set the inter-domain communication routes and it is also necessary to set an appropriate communication route between SDN domains so that the communication quality does not deteriorate after an MN moves. Therefore, we set the following issues.

(A-1) Difficulty in sharing information among SDN domains efficiently.

To execute inter-domain mobility management and avoid the degradation of communication quality, SDN controllers need to share information without excess or shortage.

- (A-2) The difficulty of setting an efficient inter-domain communication route.

The control of the communication route after the move of an MN is necessary to keep communication quality.

- (B) Routing challenges after the movement of mobile nodes.

Equally selecting a mere shortest communication route as the new communication route, after the move of an MN, may result in a significant reduction in communication quality. Therefore, we focused on maintaining communication quality with a new communication route and set the following issues.

- (B-1) The communication quality degradation caused by using only statical information

To maintain the communication quality, it is necessary to set the communication route properly after an MN moves. Many MNs communicate in a real network. Therefore, it is necessary to consider the communication status of other communicating MNs.

- (B-2) The difficulty in setting communication routes, satisfying the requirements of communication.

The requirements of communication differ, depending on the type of network service. Using a uniform routing standard for all communication flows makes it difficult to respond to different requirements and also the quality of communication may be degraded.

5.2 Achievements of each Chapter

- Chapter 1: Introduction

In this chapter, we provided the research background and set the purpose and drawbacks.

- Chapter 2: SDN Based Inter-domain Mobility Management Framework

In this chapter, we worked on the challenges of SDN based inter-domain mobility management and proposed its framework. This framework provides efficient information exchange and communication route management, after an MN moves between SDN domains. We succeeded in selecting communication routes with lower communication delay, compared to legacy approaches.

- Chapter 3: Communication Quality Aware Routing Mechanism for Mobility Management

In this chapter, we tackled the degradation of communication quality: by using only static information for routing when an MN moves. The proposal is an end-to-end routing mechanism specified for a mobility management that considers communication quality. This routing mechanism takes real-time information, such as available bandwidth, into account. As a result, we succeeded in selecting new communication routes, following the communication quality demands of a network.

- Chapter 4: Automatic Route Selection Method Based on Communication Type

In this chapter, we extended the routing mechanism to apply individual routing information importance to communication flows. The proposal is an automatic communication route selection method based on communication type, which classifies the flows into several classes and automatically applies routing information importance to each flow. We succeeded in classifying flows and applying routing information importance that meet the requirements of each flow. The new communication route selected, using this method, satisfied the requirements of the flows.

5.3 Achievements of This Study

First, we presented a case of applying SDN to multiple domain environments. When we started working on this study, there were only a few cases where SDN was applied to multiple domain environments. We believe this study helped stimulate this field of

research. Simultaneously, we showed a new approach to realize inter-domain mobility management. Our approach can be used by all kinds of users, MNs, or network services. This allows everyone to communicate comfortably, even while moving. We managed to reduce what an MN has to do to make mobility management available for MNs with very limited computational resources. By realizing to select new communication routes, after the move of MNs considering the requirement of the communication, we can support the use of wide range network services.

Moreover, we managed to restore the proper state of networks by performing mobility management on the network side. Owing to the inconvenience of the current mainstream mobility management techniques, mobility management is often performed on the network service side; for example, partitioning data and sending them independently. This should be unnecessary in network service development. Our mobility management framework resolves this problem by performing mobility management on the network side and freeing developers from mobility management consideration.

Furthermore, it can also reduce the use of MN resources. In addition to the adaptability to small computation resource MNs, it enables MNs to use their resources on other things.

With the completion of this study, the growth of wireless communication technology, the spread of the IoT environment, and the use of network services can be accelerated.

5.4 Future Works

Here we discuss the future direction of this study.

- Chapter 2: SDN Based Inter-domain Mobility Management Framework

The proposed framework only works when an MN has moved just once, during its communication. In real situations, users may move across multiple SDN domains. Thus, it is better to be applicable to multi-stage moves. I have an idea of coping with the multi-stage move by sharing the history of an MN's move among SDN domains.

Although we evaluated the framework with only one MN-moving environment, many MNs communicate and move in a real environment. To apply the frame-

work to a real environment, we have to guarantee the quality of all communications. We believe that it can be handled by performing overall optimization.

- Chapter 3: Communication Quality Aware Routing Mechanism for Mobility Management

We concluded that the routing mechanism could not be applied to networks with 30 or more SDN domains. This is because of the part listing the communication route candidates, which lists all possible communication routes without loop, ending up with high computational complexity.

Improving the listing part is the best way to let this routing mechanism apply to bigger networks. We assume that performing overall optimization is the breakthrough.

- Chapter 4: Automatic Route Selection Method Based on Communication Type

We would like to adjust the approach to select communication routes that fit the requirements perfectly, with no over-allocation of low communication delay or large bandwidth links so that other MNs can also communicate comfortably.

In this study, we classified the network flows into four classes. We would like to consider much fine-grained classification and control, such as per-application control. First, it is important to consider whether such a classification is necessary or not.

We would like to make a deeper investigation on how we set the routing information importance, the granularity, and the actual values we apply to the routing algorithm. Furthermore, we will examine if the sets of routing information importance can be applied to all kinds of networks or the rules, depending on what network we use the approach in, can be changed.

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Publications

Journals

- (1) Kosuke Gotani, Hiroyuki Takahira, Misumi Hata, Luis Guillen, Satoru Izumi, Toru Abe, and Takuo Suganuma, “A Proposal of Control Method Considering the Path Switching Time of SDN and Its Evaluation,” *Advances in Science, Technology and Engineering Systems Journal*, Vol.4, No.4, pp.388-393, August 2019.
- (2) 高平寛之, 畑美純, ギリエ ルイス, 和泉諭, 阿部亨, 菅沼拓夫, “災害発生直後における被災の影響とデータ伝送量を考慮したネットワーク制御手法の提案とその評価,” *情報処理学会論文誌*, Vol.60, No.3, pp.738-749, March 2019.
- (3) Misumi Hata, Mustafa Soylu, Satoru Izumi, Toru Abe, and Takuo Suganuma, “SDN Based End-to-End Inter-Domain Routing Mechanism for Mobility Management and Its Evaluation,” *Sensors* 2018, Vol.18, Issue 12, 4228, December 2018. (IF: 3.031)
- (4) Misumi Hata, Mustafa Soylu, Satoru Izumi, Toru Abe, Takuo Suganuma, “A Design of SDN Based IP Mobility Management Considering Inter-Domain Handovers and Its Evaluation,” *Advances in Science, Technology and Engineering Systems Journal*, Vol.2, Issue.3, pp.922-931, June 2017.
- (5) Satoru Izumi, Misumi Hata, Hiroyuki Takahira, Mustafa Soylu, Asato Edo, Toru Abe and Takuo Suganuma, “A Proposal of SDN Based Disaster-Aware Smart Routing for Highly-available Information Storage Systems and Its Evaluation,” *International Journal of Software Science and Computational Intelligence* Vol.9, No.1, pp.68-82, January-March 2017.

International Conferences

- (6) Hayato Abe, Misumi Hata, Muhammad Alfian Amrizal, Satoru Izumi, Toru Abe, and Takuo Suganuma, “Estimation of Power Consumption of ICT Devices Based on Network Traffic,” Proc. of the IEEE 8th Global Conference on Consumer Electronics (GCCE 2019), October 2019 (to appear).
- (7) Kosuke Gotani, Hiroyuki Takahira, Misumi Hata, Luis Guillen, Satoru Izumi, and Toru Abe, “OpenFlow Based Information Flow Control Considering Route Switching Cost,” Proc. of the 2nd IEEE International Workshop on Information Flow Oriented Approaches in Internet of Things and Cyber-Physical Systems (InfoFlow 2019, COMPSAC Workshop), pp.527-530, July 2019.
- (8) Satoru Izumi, Hiroyuki Takahira, Kosuke Gotani, Misumi Hata, Luis Guillen, Toru Abe, and Takuo Suganuma, “Basic Design of Network Control Method Based on Disaster Risk of OpenFlow C/M-Plane,” Proc. of the IEEE 43rd Annual Computer Software and Applications Conference (COMPSAC 2019, Fast Abstract), pp.958-959, July 2019.
- (9) Kosuke Gotani, Hiroyuki Takahira, Misumi Hata, Luis Guillen, Satoru Izumi, Toru Abe, and Takuo Suganuma, “Design of an SDN Control Method Considering the Path Switching Time Under Disaster Situations,” The 5th International Conference on Information and Communication Technologies for Disaster Management (ICT-DM2018), pp.1-4, December 2018.
- (10) Satoru Izumi, Hiroyuki Takahira, Kosuke Gotani, Misumi Hata, Luis Guillen, Toru Abe, and Takuo Suganuma, “A Proposal of Network Control Method Based on Disaster Risk of OpenFlow Control Channel,” The 5th International Conference on Information and Communication Technologies for Disaster Management (ICT-DM2018), (Poster/Demo session), December 2018.
- (11) Satoru Izumi, Misumi Hata, Hiroyuki Takahira, Asato Edo, Toru Abe and Takuo Suganuma, “Proposal of Dynamic Information Flow Management Method Under Disaster Situations,” Proc. of the 1st International Workshop on Information Flow of Things (IFoT2016), pp.18-23 November-December 2016.

- (12) Misumi Hata, Mustafa Soyly, Storu Izumi, Toru Abe, Takuo Suganuma, “Design of SDN based End-to-end Routing over Multiple Domains for Mobility Management,” The 4th International Workshop on Management of SDN and NFV Systems (ManSDN/NFV2017, CNMS2017 Workshop), pp.1-4, November 2017. (FWCI: 3.12, Top 9%)
- (13) Misumi Hata, Satoru Izumi, Toru Abe and Takuo Suganuma, “A Proposal of SDN Based Mobility Management in Multiple Domain Networks,” The 18th Asia-Pacific Network Operations and Management Symposium (APNOMS2016), pp.1-4 October 2016.
- (14) Misumi Hata, Mustafa Soyly, Satoru Izumi, Toru Abe and Takuo Suganuma, “Data Flow Control With SDN Based Mobility Management,” Proc. of the AEARU 11th Web Technology and Computer Science Workshop 2016 (WTCS2016) - Computer Science and Data Science, pp.31-32 September 2016.

National Conferences

- (15) 阿部隼斗, 畑美純, Muhammad Alfian Amrizal, 和泉諭, 阿部亨, 菅沼拓夫, “ネットワークトラフィックに基づく ICT 機器の消費電力の分析に関する一検討,” 第 81 回情報処理学会全国大会, 1W-08, pp.3-119-3-120 March 2019.
- (16) 後谷浩輔, 高平寛之, 畑美純, Guillen Luis, 和泉諭, 阿部亨, 菅沼拓夫, “OpenFlow における経路切り替え時間を考慮したネットワーク制御手法の設計と実装,” 電子情報通信学会技術研究報告, Vol.118, No.206, NS2018-104, pp.95-100, September 2018.
- (17) 和泉諭, 高平寛之, 後谷浩輔, 畑美純, Luis Guillen, 阿部亨, 菅沼拓夫, “OpenFlow 管理回線の災害リスクを考慮したネットワーク制御手法の設計,” 第 80 回情報処理学会全国大会予稿集, 2D-03, pp.3-17-3-18, March 2018.
- (18) 後谷浩輔, 高平寛之, 畑美純, Luis Guillen, 和泉諭, 阿部亨, 菅沼拓夫, “OpenFlow における経路切り替えコストを考慮したネットワーク制御手法の一検討,” 第 80 回情報処理学会全国大会予稿集, 3U-03, pp.3-279-3-280, March 2018.

- (19) Misumi Hata, Mustafa Soylu, Satoru Izumi, Toru Abe, Takuo Suganuma, “SDN Based End-to-end Inter-domain Routing Mechanism for Mobility Management and Its Implementation,” IEICE Technical Report, Vol.117, No.299, IA2017-46, pp.71-76, November 2017.
- (20) 高平寛之, 畑美純, 和泉諭, 阿部亨, 菅沼拓夫, “災害発生直後における災害リスクとデータ転送時間を考慮したネットワーク制御手法の提案,” 電子情報通信学会技術研究報告, Vol.117, No.205, IN2017-23, pp.67-72, September 2017.
- (21) 高平寛之, 畑美純, 和泉諭, 阿部亨, 菅沼拓夫, “OpenFlow 管理回線の災害リスクを考慮したネットワーク制御,” 2017 年電子情報通信学会通信ソサイエティ大会通信講演論文集, Vol.2, p.52, September 2017.
- (22) Misumi Hata, Mustafa Soylu, Satoru Izumi, Toru Abe, Takuo Suganuma, “A Study on SDN Based End-to-end Routing Mechanism for Mobility Management in Multiple Domain Networks,” 平成 29 年度 電気関係学会東北支部連合大会, 2B04, August 2017.
- (23) 畑美純, Mustafa Soylu, 和泉諭, 阿部亨, 菅沼拓夫, “SDN 型モビリティマネジメント手法の設計と実装,” 電子情報通信学会技術研究報告, Vol.116, No.231, IN2016-45, pp.53-58 September 2016.
- (24) Misumi Hata, Mustafa Soylu, Satoru Izumi, Toru Abe and Takuo Suganuma, “Basic Design of SDN Based Mobility Management for Multiple Domain Networks,” 平成 28 年度 電気関係学会東北支部連合大会, 1A19, August 2016.
- (25) 畑美純, 和泉諭, 阿部亨, 菅沼拓夫, “SDN を用いたモビリティマネジメントに関する一考察,” 第 78 回情報処理学会全国大会予稿集, 5R-03, pp.3-77-3-78 March 2016.

Bibliography

- [1] D. Giusto, A. Iera, G. Morabito, and L. Atzori, Eds., *The Internet of Things*. Springer-Verlag GmbH, 2010.
- [2] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, “Internet of things (IoT): A vision, architectural elements, and future directions,” *Future Gener. Comput. Syst.*, vol. 29, no. 6, pp. 1645–1660, 2013.
- [3] “中小ものづくり企業 iot 等活用事例集,” https://www.meti.go.jp/meti_lib/report/H28FY/000279.pdf, 2017.
- [4] “スマート iot 推進フォーラム :: 広域無線による低コストで安定したスマート農業実現に向けたトライアル — ntt 西日本「産地経営支援システム」,” <https://smartiot-forum.jp/iot-val-team/iot-case/case-ntt-west>, 2020 (accessed on Feb. 03).
- [5] “スマート iot 推進フォーラム :: データ活用によって大規模農業の効率化と品質向上を実現する — ja めむろの「農産物適期収穫支援システム」,” <https://smartiot-forum.jp/iot-val-team/iot-case/case-jamemuro>, 2019 (accessed on Feb. 03).
- [6] “スマート iot 推進フォーラム :: Iot/ai を活用した「大規模沖合養殖システム」の開発,” <https://smartiot-forum.jp/iot-val-team/iot-case/case-nssmceng>, 2018 (accessed on Feb. 03).
- [7] “スマート iot 推進フォーラム :: 24 時間路面を見張り続ける路面センサー「ロードアイ」,” <https://smartiot-forum.jp/iot-val-team/iot-case/case-yamada-giken02>, 2018 (accessed on Feb. 03).

- [8] “スマート iot 推進フォーラム :: 日本版 gps みちびきを活用したオンデマンドバスロケーションシステム「孝行デマンドバス locator」,” <https://smartiot-forum.jp/iot-val-team/iot-case/case-kogasoftware>, 2018 (accessed on Feb. 03).
- [9] “スマート iot 推進フォーラム :: タイヤセンシング技術「cais」によるソリューションビジネスの提供,” <https://smartiot-forum.jp/iot-val-team/iot-case/case-bridgestone>, 2018 (accessed on Feb. 03).
- [10] “スマート iot 推進フォーラム :: 運行データ・生体データの分析による自動車事故防止をめざして,” <https://smartiot-forum.jp/iot-val-team/iot-case/case-sompo-japan>, 2018 (accessed on Feb. 03).
- [11] “活用事例：アパレル・小売業における棚卸や商品管理 | rfid room,” <https://rfid.tss21.co.jp/ex/solution/shop.html>, (accessed on Feb. 04).
- [12] S. Azevedo, H. Carvalho, and V. Cruz-Machado, “A cross-case analysis of rfid deployment in fast fashion supply chain,” vol. 280, 2014.
- [13] M. Abdel-Basset, M. Gunasekaran, and M. Mohamed, “Internet of things (iot) and its impact on supply chain: A framework for building smart, secure and efficient systems,” *Future Generation Computer Systems*, vol. 86, 2018.
- [14] “スマートホーム検討資料,” <https://www.meti.go.jp/press/2017/05/20170523004/20170523004-1.pdf>, 2017.
- [15] “A’s smart home solutions,” [urlhttps://smarthomesolutionsas.com/](https://smarthomesolutionsas.com/), (accessed on Feb. 04).
- [16] “Smart office iot solution — avnet,” <https://www.avnet.com/wps/portal/us/solutions/iot/software/smart-applications/smart-office/>, (accessed on Feb. 04).
- [17] “Nimway – a smart office solution by sony,” <https://nimway.com/>, (accessed on Feb. 04).
- [18] “Ieee p802.11 - task group ai - meeting update.” http://www.ieee802.org/11/Reports/tgai_update.htm, (accessed on Feb. 04).

- [19] “Ieee announces significant enhancements available with release of ieee 802.11aiTM and ieee 802.11TM wireless standards,” <https://standards.ieee.org/news/2017/ieee-802-11.html>, 2017 (accessed on Feb. 06).
- [20] “5gの特徴,” <https://www.soumu.go.jp/johotsusintokei/whitepaper/ja/h30/html/nd133420.html>, (accessed on Feb. 03).
- [21] “ローカル 5g の概要について,” https://www.soumu.go.jp/main_content/000644668.pdf, 2019.
- [22] C. E. Perkins, “RFC 5944 - IP mobility support for IPv4, revised,” <https://tools.ietf.org/html/rfc5944>, 2010.
- [23] C. E. Perkins, D. B. Johnson, and J. Arkko, “RFC 6275 - Mobility support for IPv6,” <https://tools.ietf.org/html/rfc6275>, 2011.
- [24] S. Gundavelli, K. Leung, V. Devarapalli, K. Chowdhury, and B. Patil, “RFC 5213 - Proxy mobile IPv6,” <https://tools.ietf.org/html/rfc5213>, 2008.
- [25] “Software-Defined Networking (SDN) definition,” Open Networking Foundation, <https://www.opennetworking.org/sdn-resources/sdn-definition>, (accessed on Feb. 06).
- [26] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, and J. Turner, “OpenFlow: enabling innovation in campus networks,” *ACM SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 2, pp. 69–74, 2008.
- [27] “Open networking foundation,” <https://www.opennetworking.org/>, (accessed on Feb. 04).
- [28] M. Smith, R. Adams, M. Dvorkin, Y. Laribi, V. Pandey, P. Garg, and N. Weidenbacher, “Opflex control protocol,” <https://tools.ietf.org/html/draft-smith-opflex-03>, 2016.
- [29] P. Lin, J. Bi, and Y. Wang, “East-west bridge for sdn network peering,” in *Frontiers in Internet Technologies. Communications in Computer and Information Science*, vol. 401. Springer Berlin Heidelberg, pp. 170–181, 2013.

- [30] F. Benamrane, M. B. mamoun, and R. Benaini, “An east-west interface for distributed sdn control plane: Implementation and evaluation,” *Computers & Electrical Engineering*, vol. 57, pp. 162–175, 2017.
- [31] “ものづくりの未来へ！竹内製作所がめざすスマート工場: Nec online tv — nec,” <https://jpn.nec.com/ad/onlinetv/takeuchi-mfg.html>, (accessed on Feb. 06).
- [32] “村田機械株式会社様: 事例紹介 — nec,” <https://jpn.nec.com/case/muratec/>, (accessed on Feb. 06).
- [33] “関西テレビ放送株式会社様: 事例紹介 — nec,” <https://jpn.nec.com/case/ktv/>, (accessed on Feb. 06).
- [34] “京都岡本記念病院様: 事例紹介 — nec,” <https://jpn.nec.com/case/okamoto-hp/index.html>, (accessed on Feb. 06).
- [35] “慶應義塾大学病院様: 事例紹介 — nec,” https://jpn.nec.com/case/hosp_keio/index.html, (accessed on Feb. 06).
- [36] A. Volkov, A. Muthanna, R. Pirmagomedov, and R. Kirichek, “Sdn approach to control internet of thing medical applications traffic,” pp. 467–476, 2017.
- [37] “新宿区様: 事例紹介 — nec,” <https://jpn.nec.com/case/city.shinjuku/>, (accessed on Feb. 06).
- [38] “伊豆の国市様: 導入事例 — nec,” https://jpn.nec.com/sdn/case/city_izunokuni/, (accessed on Feb. 06).
- [39] “Why disa has embraced sdn for the pentagon,” <https://fedtechmagazine.com/article/2018/09/why-disa-has-embraced-sdn-pentagon-perfcon>, (accessed on Feb. 06).
- [40] Y. Wang and J. Bi, “A solution for IP mobility support in software defined networks,” in *23rd Int. Conf. Comput. Commun. Networks*, pp. 1–8, 2014.
- [41] Y. Wang, J. Bi, and K. Zhang, “Design and implementation of a software-defined mobility architecture for IP networks,” *Mob. Network Appl.*, vol. 20, no. 1, pp. 40–52, 2015.

- [42] P. Shrivastava and K. Kataoka, “Fastsplit: Fast and dynamic ip mobility management in sdn,” in *2016 26th International Telecommunication Networks and Applications Conference (ITNAC)*, pp. 166–172, 2016.
- [43] M. Idri, “Mobility management based sdn-ipv6 routing header,” in *2017 Fourth International Conference on Software Defined Systems (SDS)*, pp. 150–155, 2017.
- [44] M. Karimzadeh, L. Valtulina, H. v. d. Berg, A. Pras, M. Liebsch, and T. Taleb, “Software defined networking to support ip address mobility in future lte network,” in *2017 Wireless Days*, pp. 46–53, 2017.
- [45] G. M. Keeni, K. Nagami, K. Koide, and S. Gundavelli, “RFC 4295 - Mobile IPv6 management information base,” <https://tools.ietf.org/html/rfc4295>, 2006.
- [46] “The OpenDaylight platform,” Linux Foundation, <https://www.opendaylight.org/>, (accessed on Feb. 06).
- [47] “Open vSwitch,” Linux Foundation, <https://openvswitch.org/>, (accessed on Feb. 06).
- [48] “Mininet: An instant virtual network on your laptop (or other pc) - mininet,” Mininet Team, <http://mininet.org/>, (accessed on Feb. 06).
- [49] S. A. Astaneh and S. Shah Heydari, “Optimization of sdn flow operations in multi-failure restoration scenarios,” *IEEE Transactions on Network and Service Management*, vol. 13, no. 3, pp. 421–432, 2016.
- [50] Q. Duan, “Network-as-a-service in software-defined networks for end-to-end qos provisioning,” in *2014 23rd Wireless and Optical Communication Conference (WOCC)*, pp. 1–5, 2014.
- [51] K. Phemius, M. Bouet, and J. Leguay, “Disco: Distributed sdn controllers in a multi-domain environment,” in *2014 IEEE Network Operations and Management Symposium (NOMS)*, pp. 1–2, 2014.

- [52] N. Figueira and R. R. Krishnan, “Sdn multi-domain orchestration and control: Challenges and innovative future directions,” in *2015 International Conference on Computing, Networking and Communications (ICNC)*, pp. 406–412, 2015.
- [53] M. G. Gouda and M. Schneider, “Maximizable routing metrics,” *IEEE/ACM Transactions on Networking*, vol. 11, no. 4, pp. 663–675, 2003.
- [54] A. W. Moore and K. Papagiannaki, “Toward the accurate identification of network applications,” in *Passive and Active Network Measurement*, C. Dovrolis, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 41–54, 2005.
- [55] S. Sen, O. Spatscheck, and D. Wang, “Accurate, scalable in-network identification of p2p traffic using application signatures,” in *Proceedings of the 13th International Conference on World Wide Web*, ser. WWW ’04. Association for Computing Machinery, pp. 512–521, 2004.
- [56] Young-Hoon Goo, Kyu-Seok Shim, Su-Kang Lee, and M. Kim, “Payload signature structure for accurate application traffic classification,” in *2016 18th Asia-Pacific Network Operations and Management Symposium (APNOMS)*, pp. 1–4, 2016.
- [57] Z. Fu, Z. Liu, and J. Li, “Efficient parallelization of regular expression matching for deep inspection,” in *2017 26th International Conference on Computer Communication and Networks (ICCCN)*, pp. 1–9, 2017.
- [58] M. R. Parsaei, M. J. Sobouti, S. R. khayami, and R. Javidan, “Network traffic classification using machine learning techniques over software defined networks,” *International Journal of Advanced Computer Science and Applications*, vol. 8, no. 7, pp. 220–225, 2017.
- [59] A. S. d. Silva, C. C. Machado, R. V. Bisol, L. Z. Granville, and A. Schaeffer-Filho, “Identification and selection of flow features for accurate traffic classification in sdn,” in *2015 IEEE 14th International Symposium on Network Computing and Applications*, pp. 134–141, 2015.

- [60] Z. A. Qazi, J. Lee, T. Jin, G. Bellala, M. Arndt, and G. Noubir, “Application-awareness in sdn,” *SIGCOMM Comput. Commun. Rev.*, vol. 43, no. 4, pp. 487—488, 2013.
- [61] M. Hayes, B. Ng, A. Pekar, and W. K. G. Seah, “Scalable architecture for sdn traffic classification,” *IEEE Systems Journal*, vol. 12, no. 4, pp. 3203–3214, 2018.
- [62] “Youtube,” <https://www.youtube.com/>, (accessed on Feb. 13).
- [63] “Google docs,” <https://www.google.com/intl/ja-jp/docs/about/>, (accessed on Feb. 13).
- [64] “Skype,” <https://www.skype.com>, (accessed on Feb. 13).