Mathematical Modeling of the Scalable LISP-deployed Software-Defined Wireless Network

Eunil Seo, Vyacheslav Zalyubovskiy, and Tai-Myoung Chung
Sungkyunkwan University, Suwon and 16419, South Korea
Email: seoei2@skku.edu; slava@skku.edu; tmchung@skku.edu

Abstract —To improve network and mobility management in the Software-Defined Wireless Network (SDWN), the Locator/Identifier Separation Protocol (LISP) was integrated into the SDWN Controller, which originally controls and manages the OpenFlow routers in an SDWN. In this paper, we propose mathematical models of MIP, HMIP, LISP, the LISP Controller, and LISP-SDWN in order to evaluate the operation cost as a performance comparison analysis. The reference network architecture consists of wireless mobile networks, an operator network, and a public network. The five protocols have their own control messages with different sizes and operation procedures; therefore, the location management cost of one protocol differs from those of others when a mobile node moves from one subnetwork to another subnetwork. Some of them have a longer transmission path, which leads to a higher operation cost. The five protocols are evaluated through two communication scenarios: intra-SDWN communication and inter-SDWN communication. We evaluate the operation costs of LISP, the LISP Controller, LISP-SDWN, HMIP, and MIP based on mathematical models. A comparison of all of these operation costs indicates that the proposed LISP-SDWN is scalable in different communication scenarios and has the lowest cost for updating location information.

Index Terms—SDWN, LISP, mobility management, scalability, SDN, Wireless mobile network, modeling

I. Introduction

The Software-Defined Wireless Network (SDWN) is composed of various wireless mobile technologies (e.g., 3G, LTE, Wi-Fi, small cell, etc.) across heterogeneous mobile edge networks as well as the core network. The SDWN has the structure of a next generation mobile network, which is able to support all mobile gadgets and devices, including IoT devices [1]-[4].

The SDWN architecture, which involves the decomposition of the control plane and data plane, provides service providers with the fast deployment of new services and operators with flexible and vendor-independent management, as shown in Fig. 1. With these strong benefits, it is possible for small-size service providers to run a service business, because only a small amount of CAPEX is required to do so.

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Corresponding author email: tmchung@skku.edu.
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Service providers accomplish the fast deployment of new services, lowered management cost of heterogeneous mobile technologies, seamless operation over multi-vendor network infrastructures, and scalable enhancement of the network operation through the SDWN Controller [5].

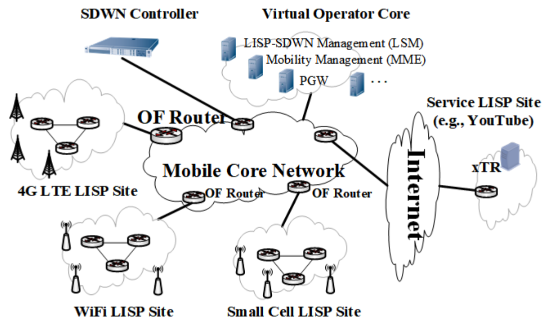

Fig. 1. Network architecture of SDWN

In order to improve the mobility management of an SDWN, we previously proposed LISP-SDWN, where LISP [6] is integrated with the OpenFlow technology [7] into the LISP-SDWN Controller. In this paper, mathematical models of five protocols are proposed for analytic evaluation; the five protocols are LISP, The LISP Controller, LISP-SDWN, MIP, and HMIP.

From the perspective of SDWN technology, the recent LISP-related works, such as routing in the centralized identifier network [8], the network-based host identifier locator separating protocol [9], OpenISMA [10], IDOpenFlow [11], and the LISP Controller [12] successfully achieved a centralized LISP management system in an SDWN. However, the LISP operation and procedure needed to be modified, and extra control messages were required, where scalability is not ensured.

With this discovery, routing scalability became the most important research challenge in our previous works. The main purpose of our research is to specify and realize the technical requirements of an SDWN service provider: centralized LISP management, routing scalability, seamless vertical handover, and traffic-aware management. Moreover, we design a method to deploy LISP in an SDWN according to the specified requirements. In order to evaluate the proposed LISP-SDWN in terms of scalability and operation cost to update location information, we proposed mathematical models of all of the five protocols examined in this paper, including the proposed LISP-SDWN.

In Section II, background information on LISP and the Mapping System (MS) is given. In Section III, the design of the scalable LISP-SDWN is discussed. In Section IV, mathematical models of LISP, The LISP Controller, LISP-SDWN, HMIP, and MIP are suggested. In Section V, performance analysis and results are given. Finally, the conclusion is presented in Section VI.

II. BACKGROUND

In Mobile IP-based protocols, location and identification information are stored in a single field of an IP header. Controlling and maintaining the location management system of mobile IP-based protocols leads to inefficient traffic management cost and extra overhead (i.e., HMIP [13], MIP [14], PMIP [15], and 3GPP mobility [16]).

In an SDWN, Mobility Management (MM) can be improved by utilizing the ID/LOC split scheme, which would support seamless vertical mobility to the Internet [17]-[19]. This is because the current IP-based Internet has suffered from the operation overhead of MM due to an excessively large number of mobile nodes and traffic, which require an extra location management cost to map information between the locations and identities of Mobile Nodes (MNs). Using an LISP could lessen the location management cost and provide seamless mobility management for an SDWN.

LISP is an ID/LOC split scheme that was proposed by CISCO as drafts from the Internet Engineering Task Force (IETF) and implementation on the OpenDaylight controller. LISP consists of Endpoint Identifiers (EIDs) and Routing Locators (RLOCs) as two divided name spaces for the tunneling of data transmission. RLOCs are assigned by network access points belonging to an RAN and are used for packet routing, while EIDs are not related to packet routing and are independent of the network topology; furthermore, EIDs remain unchanged even if mobile devices are roaming around an SDWN. The outer LISP header includes source and destination RLOCs and encapsulates the inner LISP header and data; moreover, the LISP encapsulated packets are transmitted between an Egress Tunneling Router (ETR) and Ingress Tunneling Router (ITR). The inner LISP header includes source and destination EIDs, and data packets are routed to the destination mobile device by the destination EID; moreover, the session connection between devices is built by EIDs. Two xTRs build tunnels between the source and destination devices by RLOCs such as xTR-A with its RLOC a0 and xTR-Y with its RLOC y0 (See Fig. 2).

The referred architecture used to deploy LISP into an SDWN is illustrated in Fig. 1. Each RAN can be operated by different service providers: a 3G UMTS provider, a 4G LTE provider, a Wi-Fi provider, etc. With the use of SDWN technology, a small service provider can own and operate an RAN, and can provide mobile users with various new services with only a small capital investment. Therefore, we predict SDWN will be composed of multiple LISP-sites operated by different RAN technologies, and the proposed scalable LISP-SDWN Controller needs to have the capability of managing multiple LISP-sites in an SDWN.

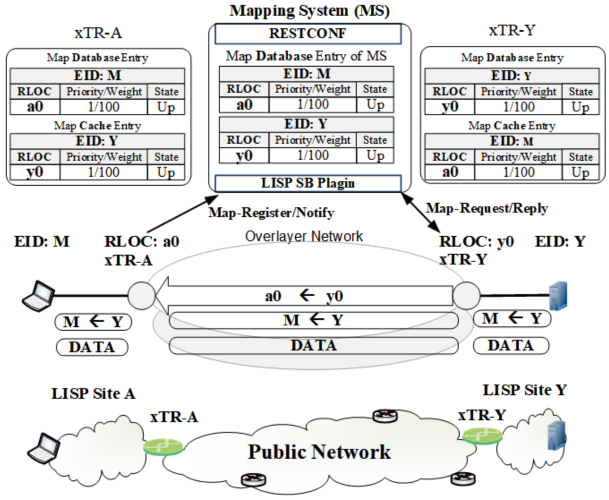

Fig. 2. LISP Operation and Procedure

TABLE I: BASIC NOTATION FOR NETWORK INFRASTRUCTURE COMPONENTS

Name	Description
MS	Mapping System
HA	Home Agent
FA	Foreign Agent
ETR	Egress Tunneling Router
MAP	Mobility Anchor Point
ITR	Ingress Tunneling Router
CN	Corresponding Node
GTR	Gateway Tunneling Router
RAN	Radio Access Network
xTR	Egress/Ingress Tunneling Router
Map Cache	EID-to-RLOC Map Cache
Map Database	EID-to-RLOC Map Database

III. MODELLING OF THE SCALABLE LISP SOFTWARE-DEFINED WIRELESS NETWORK

We proposed LISP-SDWN, where a dual mapping system is chosen to support routing scalability as shown in Fig. 3 previously, so that Mobile Nodes (MNs) associated with the LISP-SDWN Controller are registered in the external standard Mapping System. We have improved our previous work [20] with the detailed mathematical models of all five protocols, and various simulation results.

LISP-SDWN enables an SDWN service provider to deploy the LISP-enabled service and facilities (e.g., xTR in Table I through its own LISP-SDWN Controller. The LISP-SDWN is powered not only with mapping information from a map database, but also with the flow information of an OpenFlow table; moreover, the architecture of the LISP-SDWN Controller is illustrated in Fig. 3.

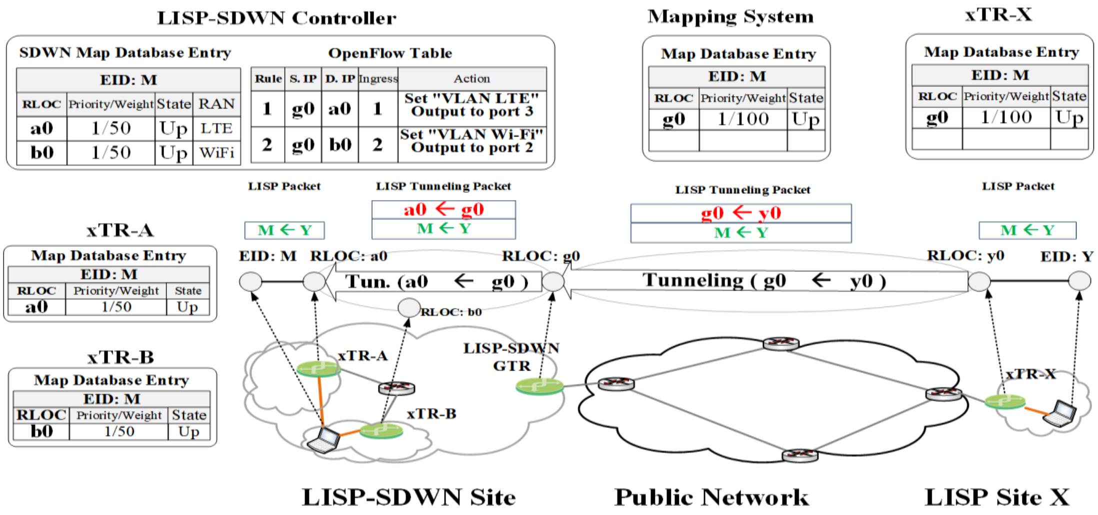

Fig. 3. Architecture and operation procedure of LISP-SDWN

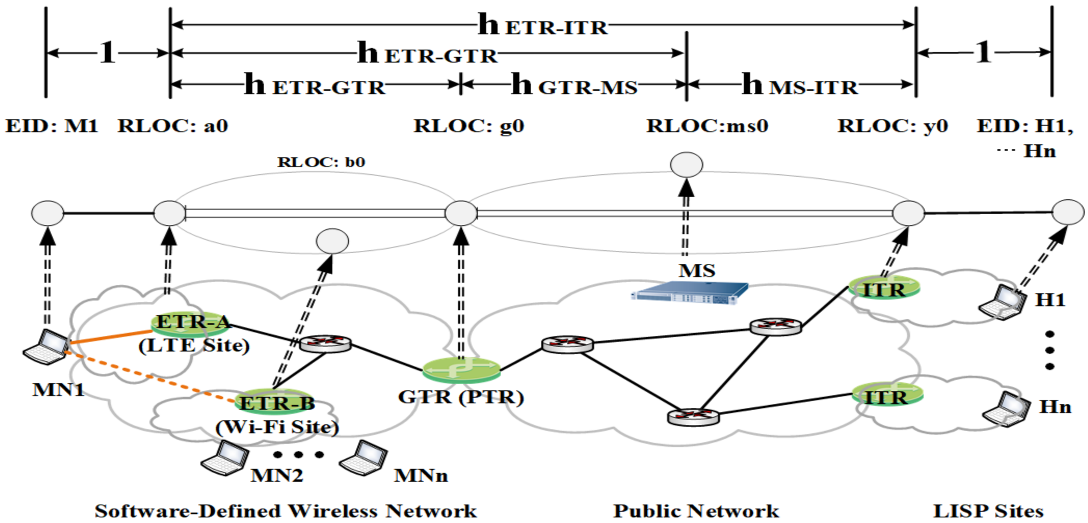

Fig. 4. Control message paths for LISP-based protocols (LISP, The LISP Controller and LISP-SDWN)

The LISP-SDWN Controller is our proposed centralized LISP/OpenFlow management system that was designed based on the SDWN Controller. We design and customize a standard map database to be an SDWN map database, a locally accessible map database for the LISP-SDWN Controller and is also connected with the OpenFlow table, as shown in Fig. 3. The LISP-SDWN Controller adopts a dual Mapping System: an SDWN map database is designed for seamless vertical Mobility Management (MM) among heterogeneous RANs, and a map database of external standard MS is used to connect between the inside SDWN domain and the outside standard LISP sites operated by other domain service providers, as shown in Fig. 3.

The SDWN map database is composed of small pieces of a map database of xTRs and the LISP Mobile Nodes [21]. It is a map database locally accessible only in an SDWN, while a standard map database of MS is a publicly accessible distributed database. An SDWN map database entry consists of the RLOC, priority, weight, state, and type of RAN; moreover, two RLOCs (a0 and b0) indicate two interfaces, as shown in Fig. 3.

The connection between an SDWN map database and a map database is accomplished by registering the RLOC of the LISP-SDWN GTR into a map database of MS. The SDWN map database is in the LISP-SDWN Controller and the map database is in a standard MS. In order to connect these two map databases, the GTR RLOC g0 is registered in the map database of MS, instead of <M, a0> and <M, b0> being stored in an SDWN map database, as shown in Fig. 3. In a standard LISP, both <M, a0> and <M, b0> are originally stored and managed in a standard MS.

IV. Mathematical Models

The total operation costs of LISP, The LISP Controller, LISP-SDWN, HMIP, and MIP are mathematically modeled based on the network architecture, as shown in Fig. 4. The total operation cost, C^{Total}, is defined as the sum of C^L, C^C, and C^D: **C**ost of the **L**ocation update (C^L), the **C**ost of the Dis**C**overy (C^C), and the **C**ost of **D**ata packet delivery (C^D).

The packet delivery cost is considered only in terms of the transmission cost without the processing cost in mathematical models.

A. Analytic Mobility Model

We assume that each LISP is assigned a unique subnetwork, such as a 3G UMTS domain, a 4G LTE domain, a Wi-Fi domain, etc., as shown in Fig. 1. In the fluid flow model, the direction of MN movement in a subnetwork is uniformly distributed in $[0, 2\pi]$, where ω_c is the border crossing rates for MN from the LTE domain to the Wi-Fi domain, as shown Fig. 4.

$$\omega_c = \frac{2V}{\pi R_C} \tag{1}$$

where V is the average speed of MNs. R_C (See Table. II) is the radius of the circular area of a LISP subnetwork.

In an SDWN domain, the MN movement direction is uniformly distributed in $[0, 2\pi]$ as well, where ω_d is the border crossing rates for MN leaving an SDWN domain.

$$\omega_d = \frac{2V}{\pi R_D} \tag{2}$$

where ω_d is defined as the border crossing rate of MN, which remains in the same SDWN domain, and is calculated by subtracting ω_d from ω_c, as shown below.

$$\omega_s = \omega_c - \omega_d \tag{3}$$

The state transition rate ω_c represents the number of handovers while roaming in an SDWN and ω_d represents the transition rate for leaving an SDWN. In order to model the location update process of MN, the Markov chain model is used, as shown in Fig. 5.

TABLE II: NOTATION FOR SIMULATION PARAMETERS

Name	Description
R_C	Radius of a LISP area
R_D	Radius of a SDWN area
ω_c	LISP crossing rate
ω_d	SDWN crossing rate
ω_s	LISP crossing rate within the same SDWN
E_{ω_c}	Average Num. of handovers for LISP crossing
E_{ω_d}	Average Num. of handovers for SDWN mobility
E_{ω_s}	Average handovers for a MN remaining in the same SDWN
E_S	Average session length of packet
α	Weighting factor for the wireless connection
β	Weighting factor for the wired connection
δ	Weighting factor for the tunneling overhead
λ_α	Session arrival rate for each MN
F_{flow}	Number of Flows one MN keeps
$D_{SDWN-size}$	Number of xTR in an SDWN

Based on Eqs (2) and (3), the average number of handovers is calculated during the inter-session arrival. The average number of handovers for a LISP crossing is defined as E_{ω_c} and the average number of handovers for the SDWN crossing is defined as E_{ω_d} in Eqs. (4) and (5).

$$E_{\omega_c} = \frac{\omega_c}{\lambda_\alpha} \text{ and } E_{\omega_d} = \frac{\omega_d}{\lambda_\alpha} \tag{4}$$

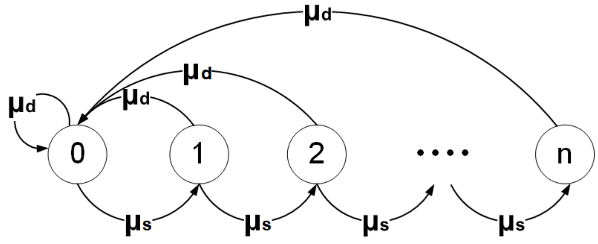

Fig. 5. Markov Chain Model for Mobility

where λ_α is the session arrival rate based on a Poisson distribution. When MN remains in the same SDWN during handovers, the average number of handovers will be as follows:

$$E_{\omega_s} = \frac{\omega_s}{\lambda_\alpha} \tag{5}$$

B. Packet Size and Hop Count of LISP-based Protocols

The packet size used in LISP, the LISP Controller, and LISP-SDWN is defined in Table III, and **Path Hop Count** according to the control paths, the number of hops between two systems, is defined in Table IV.

TABLE III: NOTATION FOR PACKET SIZES OF LISP-BASED PROTOCOLS

Name	Description	Parameter
$P_{Map-Reg}$	Map-Register message size	124 bytes
$P_{Map-Noti}$	Map-Notify message size	128 bytes
$P_{Map-Req}$	Map-Request message size	116 bytes
$P_{Map-Rep}$	Map-Reply message size	120 bytes
$P_{Map-Sol}$	Solicit-Map-Request message	124 bytes
$P_{Map-Up-Req}$	Map-Update-Request message	116 bytes
$P_{Map-Update}$	Map-Update message size	128 bytes

TABLE IV: NOTATION FOR PATH HOP COUNT OF LISP-BASED PROTOCOLS

Name	Description	Parameter
$h_{ITR-GTR}$	Average hop btw ITR and GTR	5 hops
$h_{ITR-LISPCon}$	Average hop btw ITR and the LISP Controller	5 hops
h_{ITR-MS}	LISP crossing rate	13 hops
$h_{ITR-ETR}$	SDWN crossing rate	21 hops
h_{GTR-MS}	LISP crossing rate within the same SDWN	8 hops
$h_{GTR-ETR}$	Average num. of handovers for LISP crossing	16 hops
h_{ETR-MS}	Average num. of handovers for SDWN mobility	8 hops

C. Packet Size and Hop Count of MIP-based Protocols

The packet size used in MIP and HMIP is defined in Table V, and **Path Hop Count** according to the control paths, the number of hops between two systems, is defined in Table VI.

TABLE V: NOTATION FOR PACKET SIZES OF MIP-BASED PROTOCOLS

Name	Description	Parameter
P_{BU-HA}	BU message size for HA	56 bytes
P_{BAck}	BAck message size	56 bytes
P_{BU-MAP}	BU message size for MAP	56 bytes
P_{BU-CN}	BU message size for CN	66 bytes
P_{Data}	Data packet size	51 bytes
P_{HoTI}	Home test initialization (HoTI) msg.	64 bytes
P_{HoT}	Home Test (HoT) message size	64 bytes
P_{CoTI}	Co-test initialization (CoTI) msg.	74 bytes
P_{CoT}	Co-test (CoT) message size	74 bytes

D. Operation Cost of LISP

In order to perform a LISP operation procedure and complete a data delivery of LISP, the Egress Tunnel Router (ETR) cooperates with both MS and the Ingress Tunnel Router (ITR). The total operation cost of LISP is shown in Eq. (6).

$$C_{LISP}^{Total} = C_{LISP}^{L} + C_{LISP}^{C} + C_{LISP}^{D} \tag{6}$$

where C_{LISP}^{L} in Eq. (7) represents the cost of the location update, C_{LISP}^{C} in Eq. (8) represents the cost of the map discovery, and C_{LISP}^{D} in Eq. (9) represents the cost of data delivery.

TABLE VI: NOTATION FOR PATH HOP COUNT OF MIP-BASED PROTOCOLS

Name	Description	Parameter
h_{MN-FA}	Average hop btw MN and FA	1 hop
h_{MN-MAP}	Average hop btw ITR and the LISP Controller	6 hops
h_{MN-HA}	Average hop btw MN and HA	14 hops
h_{MN-FA_CN}	Average hop btw MN and CN	22 hops
h_{MN-CN}	Average hop btw MN and Host	23 hops
h_{MAP-HA}	Average hop btw MAP and HA	8 hops
h_{MAP-FA_CN}	Average hop btw MAP and CN	16 hops
h_{FA_CN-HA}	Average hop btw CN and HA	8 hops
h_{FA_CN-FA}	Average hop btw CN and FA	21 hops

Location Update Cost: In order to perform the map registration of LISP, a Map-Register message and a Map-Notify message are required. MS is registered with a new MN1 RLOC and is informed of any changes of MN1 RLOC, as shown in Fig. 4. The location update cost of LISP is as follows:

$$C_{LISP}^{L} = E_{\omega_s}(P_{Map-Reg} + P_{Map-Noti})\beta h_{ITR-MS} \tag{7}$$

where E_{ω_s} is the average number of handovers for MN1, which is still in the same SDWN. $P_{Map-Reg}$ is the message size of a Map-Register and $P_{Map-Noti}$ is the message size of a Map-Notify, which are transmitted along the path between ITR and MS: h_{ITR-MS}.

Map Discovery Cost: ITR sends a Solicit-Map-Request message to ETR so as to inform it of a change of MN1 RLOC, which is defined as $P_{Map-Sol} \times h_{ITR-ETR}$. Thus, the Solicit-Map-Request message triggers ETR to send a Map-Request message, and MS replies to ETR with a Map-Reply message, which is defined as $(P_{Map-Req} + P_{Map-Rep}) \times h_{ETR-MS}$. The map discovery cost of LISP is shown in Eq. (8).

$$C_{LISP}^{C} = E_{\omega_s}P_{Map-Sol}\beta h_{ITR-ETR} + E_{\omega_s}(P_{Map-Req} + P_{Map-rep})\beta h_{ETR-MS} \tag{8}$$

Data Delivery Cost: After the map registration and the map discovery have been successfully completed, the data packets are delivered from ETR to ITR by a tunneling connection; moreover, ITR decapsulates and forwards the packets to MN1. The data packet delivery cost of LISP is defined by Eq. (9).

$$C_{LISP}^{D} = \lambda_\alpha E_S h_{H1-MN1} \tag{9}$$

where λ_α is the average session arrival rate of MN1, E_S is the average session length of data packets, and h_{H1-MN1} is the number of hop counts between H1 and MN1 (See Fig. 4) for the data packet path, which is defined by Eq. (10).

$$h_{H1-MN1} = \alpha h_{H1-ETR} + \beta\delta h_{ETR-ITR} + \alpha h_{ITR-MN1} \tag{10}$$

where δ is the weighting factor for the tunneling overhead of data transmission and α is the weighting factor for the wired link. Because the path between ITR and ETR is set up by the tunneling connection, δ was used for the tunneling overhead of data transmission.

E. Operation Cost of LISP Controller (L-Con)

The LISP Controller achieves the centralized LISP management system from the perspective of an ISP and performs the fast convergence of the map database among xTRs using the push-based method; however, the LISP Controller does not support the inter-domain handover in the same way as the Proxy Mobile IP (PMIP). Consequently, the LISP Controller must depend on the Proxy Tunneling Router (PTR), as shown in Fig. 4. The total operation cost of the LISP Controller is as follows:

$$C_{L-Con}^{Total} = C_{L-Con}^{L} + C_{L-Con}^{C} + C_{L-Con}^{D} \tag{11}$$

where C_{L-Con}^{L} on Eq. (12) represents the cost of the location update, C_{L-Con}^{C} on Eq. (13) represents the cost of the map discovery, and C_{L-Con}^{D} on Eq. (14) represents the cost of data delivery.

Location Update Cost: In order to perform the map registration of the LISP Controller, a Map-Update-Request message and a Map-Notify message are required.

The LISP Controller does not support inter-domain handover; therefore, when MN1 exits an SDWN, the map registration follows the standard LISP map registration. The location update cost of the LISP Controller is as follows:

$$C^{L}_{L-Con} = E_{\omega_d}(P_{Map-Reg} + P_{Map-Noti})\beta h_{ITR-MS} + E_{\omega_s}(P_{Map-Up-Req} + P_{Map-Noti})\beta h_{ITR-LISPCon} \quad (12)$$

where E_{ω_d} is the average number of handovers for inter-domain mobility and E_{ω_s} is the average number of handovers, while MN1 remains in the same SDWN domain, as shown in Fig. 4.

As for the intra-SDWN handover, Map Registration requires a Map-Update-Request message and a Map-Notify message between the ITR and the LISP Controller. The average map registration cost for the movement of MN1 within an SDWN is defined as follows: $E_{\omega_s}(P_{Map-Up-Req} + P_{Map-Noti})\beta h_{ITR-LISPCon}$.

As for the inter-SDWN handover, a Map-register message and a Map-Notify message are required between ITR and MS according to the standard LISP, and the average map registration cost for MN1 moving outside of an SDWN is as follows: $E_{\omega_d}(P_{Map-Reg} + P_{Map-Noti})\beta h_{ITR-MS}$

Map Discovery Cost: unlike a standard LISP, the Solicit-Map-Request message is not needed, and is replaced by Map-Update messages sent to all of the ETRs inside of an SDWN. The Proxy Tunneling Router (PTR) is used to communicate with Mobile Nodes outside of an SDWN.

$$C^{C}_{L-Con} = E_{\omega_d}(P_{Map-Req} + P_{Map-rep})\beta h_{ETR-PTR} + E_{\omega_s} P_{Map-Update}\beta h_{ITR-LISPCon} D_{SDWN-size} \quad (13)$$

where the first term represents the cost of the map discovery carried out by CN when MN1 moves outside of an SDWN; moreover, the second term represents the cost of the Map-Update carried out by the LISP Controller according to $D_{SDWN-size}$, which indicates the number of xTRs in an SDWN. The LISP Controller transmits Map-Update messages to all xTRs.

Data Delivery Cost is as follows:

$$C^{D}_{L-Con} = \lambda_\alpha E_S h_{H1-MN1} \quad (14)$$

where λ_α is the average session arrival rate in MN1, E_S is the average session length of data packets, and h_{H1-MN1} is the number of hop counts between H1 and MN1 (See Fig. 4) for the data packet path, which is defined by Eq. (15).

$$h_{H1-MN1} = \alpha h_{H1-ETR} + \beta\delta h_{ETR-PTR} + \alpha h_{PTR-MN1} \quad (15)$$

where δ is a weighting factor for the tunneling overhead of data transmission and α is a weighting factor for the wired link. Because the path between ETR and PTR is set up by the tunneling connection, δ was used for the tunneling overhead of data transmission.

F. Operation Cost of LISP-SDWN (L-SDWN)

The LISP-SDWN Controller and MS are the location management systems in an SDWN.

The intra-SDWN handover involves only the LISP-SDWN Controller; the inter-SDWN handover involves both the LISP-SDWN Controller and MS.

The total operation cost of LISP-SDWN is as follows:

$$C^{Total}_{L-SDWN} = C^{L}_{L-SDWN} + C^{C}_{L-SDWN} + C^{D}_{L-SDWN} \quad (16)$$

where C^{L}_{L-SDWN} in Eq. (17) represents the location update cost, C^{C}_{L-SDWN} in Eq. (18) represents the map discovery cost, and C^{D}_{L-SDWN} in Eq. (19) represents the data delivery cost.

Location Update Cost: An intra-SDWN handover requires a Map-Request message and a Map-Notify message between the ITR and the LISP-SDWN Controller as the map registration. An inter-SDWN handover requires a Map-Request message and a Map-Notify message between ITR and MS as the map registration. The location update cost is defined as follows:

$$C^{L}_{L-SDWN} = E_{\omega_s}(P_{Map-Req} + P_{Map-Noti})\beta h_{ITR-L\_SDWN} + E_{\omega_d}(P_{Map-Reg} + P_{Map-Noti})\beta h_{ITR-MS} \quad (17)$$

where p_0 in Eq. (4) is the state probability of an inter-SDWN handover and p_i in Eq. (5) is the state probability of an intra-SDWN handover, while MN1 remains in the same SDWN.

An intra-SDWN handover requires a Map-Register message and a Map-Notify message between ITR and the LISP-SDWN Controller, and is defined as follows: $E_{\omega_s}(P_{Map-Reg} + P_{Map-Noti})\beta h_{ITR-L\_SDWN}$.

An inter-SDWN handover requires the exchange of a Map-register message and a Map-Notify message between ITR and MS through the LISP-SDWN Controller, and is defined as $E_{\omega_d}(P_{Map-Reg} + P_{Map-Noti})\beta h_{ITR-MS}$, where $h_{ITR-MS} = h_{ITR-GTR} + h_{GTR-MS}$, as seen in Table IV.

Map Discovery Cost: The control messages of the map discovery are exchanged between the ETR and the LISP-SDWN Controller as follows:

$$C^{C}_{L-SDWN} = (P_{Map-Req} + P_{Map-rep})\beta h_{ETR-L\_SDWN} \quad (18)$$

During inter-SDWN communication between MN1 and H1, a handover does not invoke the Map Discovery between ETR and MS, due to the LISP-SDWN Controller. Only the LISP-SDWN Controller is informed of any handovers within an SDWN. In this sense, LISP-SDWN does not generate control messages in the public network including MS.

Data Delivery Cost is as follows:

$$C^{D}_{L-SDWN} = \lambda_\alpha E_S h_{H1-MN1} \quad (19)$$

where h_{H1-MN1} is the hop count number between H1 and MN1 (See Fig. 4) for the data delivery path, E_S is the average session length of the data packets, and λ_α is the average rate of sessions received by MN1, and is defined by Eq. (20).

$$h_{H1-MN1} = \alpha h_{H1-ETR} + \beta\delta h_{ETR-GTR} + \beta\delta h_{GTR-ITR} + \alpha h_{ITR-MN1} \quad (20)$$

where α is a weighting factor dedicated by the wired link and δ is a weighting factor for the tunneling overhead caused by data transmission. Both the path between GTR and ITR and that between ETR and GTR are set up by the tunneling connection, thus δ is used for the tunneling overhead caused by data transmission.

G. Operation Cost of HMIP

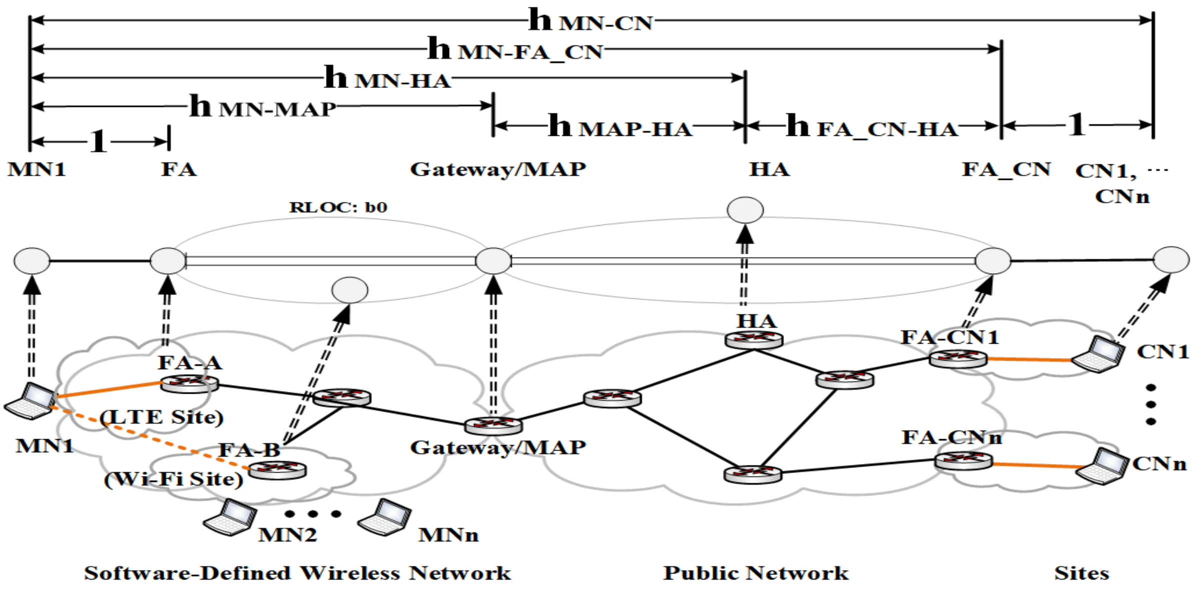

Fig. 6. Control message paths for the operation cost of MIP-based Protocols (MIP and HMIP)

HMIP employs two location management systems: Home Agent (HA) and Mobile Anchor Point (MAP). In order to perform the operation procedure and data delivery, the Mobile Node needs to cooperate with the three systems shown in Fig. 6: HA, MAP, and Corresponding Node (CN). HMIP needs to have binding to HA, CN, and MAP during the handover. With the benefits of MAP, HMIP does not require a binding update while roaming in the MAP domain, while LISP needs to update its new RLOC for every handover. The total operation cost of HMIP is as follows:

$$C_{HMIP}^{Total} = C_{HMIP}^{L} + C_{HMIP}^{C} + C_{HMIP}^{D} \quad (21)$$

where C_{HMIP}^{L} in Eq. (22) represents the cost of the location update, C_{HMIP}^{C} in Eq. (23) represents the cost of the route optimization, and C_{HMIP}^{D} in Eq. (24) represents the cost of data delivery.

Location Update Cost: In order to perform a binding of HMIP, a Binding Update (BU) message and a Binding Ack (BAck) message are exchanged between MN1 and HA, between MN1 and MAP, and between MN1 and CN1. The location update cost of HMIP is defined as follows:

$$C_{HMIP}^{L} = E_{\omega_s}(P_{BU-MAP} + P_{BAck})(\alpha h_{MN1-FA} + \beta h_{FA-MAP}) + E_{\omega_d}(P_{BU-MAP} + P_{BAck})(\alpha h_{MN1-FA} + \beta h_{FA-MAP}) + E_{\omega_d}(P_{BU-HA} + P_{BAck})(\alpha h_{MN1-FA} + \beta h_{FA-HA}) \quad (22)$$

where E_{ω_s} is the state probability of an intra-domain handoff while MN1 remains in the same SDWN domain, and E_{ω_d} is the state probability of an inter-domain handover, as shown in Fig. 5; α is a weighting factor for the wired link and β is a weighting factor for the wireless link.

Route Optimization: In order to avoid the triangular routing problem, Regional Care of address (RCoA) and Local Care of Address (LCoA) of MN1 are registered in a Corresponding Node1 (CN1). The route optimization cost of HMIP is classified into one of two cases: CN1 is located either inside of an SDWN or outside of an SDWN. In the case of CN1 located outside of an SDWN, the path of BU is from MN1 to CN1 through MAP in order to inform CN1 of the newly obtained RCoA; therefore, the route optimization is as follows:

$$C_{HMIP}^{C} = E_{\omega_d}(P_{BU-CN1} + P_{BAck})(\alpha h_{MN1-FA} + \beta h_{FA-CN1}) \quad (23)$$

where P_{BU-CN1} contains RCoA, α is a weighting factor for the wired link, and β is a weighting factor for the wireless link.

In contrast, in the case of CN1 located inside of an SDWN, the path of BU is from MN1 to CN1 within an SDWN; therefore, CN1 is informed of the newly obtained Local Care of Address (LCoA) and the path is shorter. The cost of HMIP route optimization is as follows:

$$C_{HMIP}^{C} = E_{\omega_s}(P_{BU-CN1} + P_{BAck})(\alpha h_{MN1-FA} + \beta h_{FA-CN1}) \quad (24)$$

where P_{BU-CN1} contains LCoA, α is a weighting factor for the wired link, and β is a weighting factor for the wireless link.

Data Delivery Cost is as follows:

$$C_{HMIP}^{D} = \lambda_{\alpha} E_S h_{H1-MN1} \quad (25)$$

where λ_α is the average session arrival rate in MN1, E_S is the average session length of the data packets, and h_{H1-MN1} is the number of hop counts between H1 and MN1 (See Fig. 4) for the data packet path, and is defined by Eq. (26).

$$h_{H1-MN1} = \alpha h_{H1-CN1} + \beta h_{CN1-MAP} + \delta(\beta h_{MAP-FA} + \alpha h_{FA-MN1}) \quad (26)$$

where δ is a weighting factor for the tunneling overhead of data transmission. The path between MAP and FA are set up by the tunneling connection, thus δ was used for the tunneling overhead of data transmission. The path between H1 and CN1 is a wireless link, and the path between FA and MN1 is a wireless link as well.

H. Operation Cost of MIP

MIP employs a location management system: Home Agent (HA). In order to perform the operation procedure and data delivery, the Mobile Node needs to cooperate with the three systems shown in Fig. 6: HA, FA, and Corresponding Node (CN). MIP needs to have a binding to HA and CN during the handover. The total operation cost of MIP is as follows:

$$C_{MIP}^{Total} = C_{MIP}^{L} + C_{MIP}^{C} + C_{MIP}^{D} \quad (27)$$

where C_{MIP}^{L} in Eq. (28) represents the cost of the location update, C_{MIP}^{C} in Eq. (29) represents the cost of the route optimization, and C_{MIP}^{D} in Eq. (30) represents the cost of data delivery.

Location Update Cost: In order to perform the binding of MIP, a Binding Update (BU) message and a Binding Ack (BAck) message are exchanged between MN1 and HA. The location update cost of the MIP is defined as follows:

$$C_{MIP}^{L} = E_{\omega_s} \mu_c^i (P_{BU-HA} + P_{BAck}) \alpha h_{MN1-FA} + E_{\omega_s} \mu_c^i (P_{BU-HA} + P_{BAck}) \beta h_{FA-HA} \quad (28)$$

where α is a weighting factor for the wired link and β is a weighting factor for the wireless link.

Route Optimization: In order to avoid the triangular routing problem, the return routability (RR) is carried out by a Home Test initialization (HoTI) message, a Home Test (HoT) message, a Co-test initialization (CoTI) message, and a Co-test (CoT) message. The route optimization cost of the MIP is defined as follows:

$$C_{MIP}^{C} = E_{\omega_s} P_{HoTI}(\alpha h_{MN1-FA} + \beta h_{FA-HA} + \beta h_{HA-CN1}) + E_{\omega_s} P_{HoT}(\alpha h_{MN1-FA} + \beta h_{FA-HA} + \beta h_{HA-CN1}) + E_{\omega_s} P_{CoTI}(\alpha h_{MN1-FA} + \beta h_{FA-CN1}) + E_{\omega_s} P_{CoT}(\alpha h_{MN1-FA} + \beta h_{FA-CN1}) \quad (29)$$

where α is a weighting factor for the wired link and β is a weighting factor for the wireless link.

Data Delivery Cost is as follows:

$$C_{MIP}^{D} = \lambda_{\alpha} E_S h_{H1-MN1} \quad (30)$$

where λ_α is the average session arrival rate in MN1, E_S is the average session length of the data packets, and h_{H1-MN1} is the number of hop counts between H1 and MN1 (See Fig. 4) for the data packet path, and is defined by Eq. (31).

$$h_{H1-MN1} = \alpha h_{H1-CN1} + \delta \beta h_{CN1-FA} + \alpha h_{FA-MN1} \quad (31)$$

where δ is a weighting factor for the tunneling overhead of data transmission. The path between MAP and FA is set up by the tunneling connection, thus δ was used for the tunneling overhead of data transmission.

V. Performance Evaluation

We carry out a performance evaluation based on the mathematical models of the five protocols: LISP, The LISP Controller, LISP-SDWN, HMIP, and MIP. In order to evaluate the scalabilities of the five protocols, two different scale communication scenarios are designed in this work: intra-SDWN communication for a relatively short distance, and inter-SDWN communication for longer distance. The metric for performance evaluation is the operation cost when handover occurs within an SDWN or beyond an SDWN.

A. Test Scenarios and Metrics

Two communication scenarios are considered as follows:

- **Inter-SDWN communication**: when MN1 moves from one LISP site to another LISP site while communicating with hosts in the **outside** of an SDWN.
- **Intra-SDWN communication**: when MN1 moves from one LISP site to another LISP site while communicating with hosts in the **inside** of an SDWN.

In Fig. 4, inter-SDWN communication indicates that MN1 moves from an LTE LISP site to a Wi-Fi LISP site while communicating with stationary hosts: H1, H2 ... Hn outside of an SDWN, intra-SDWN communication indicates that MN1 moves around while communicating with other stationary mobile nodes: MN2, MN3 … MNn within the same SDWN. In these two scenarios, we evaluate five protocols in terms of the following metrics:

- **Location Update cost**: Caused by Map request and Map reply for LISP-based protocols or by binding update and binding acknowledge for MIP-based protocols.
- **Route Optimization cost**: Caused by the discovery of a shorter route between the source and destination.
- **Data Delivery cost**: Caused by delivering data between the source and destination.

B. Inter-SDWN Communication

The total operation costs of the five protocols are evaluated in terms of four variables: the session arrival rate, the flow number of MN1, the velocity of MN1, and the radius of the cell area while MN1 communicates with stationary hosts (E.g., H1, H2, etc.) outside of an SDWN, as shown in Figs. 4 and 6. The four variables and other simulation parameters are defined in Table VII.

TABLE VII: SIMULATION PARAMETERS FOR INTER-SDWN COMMUNICATION

Items	Parameters
The Number of cells in an SDWN	30
Radius of the Cell area	200 to 650 meters
The Session arrival rate for each MN	0.1 to 1
The Number of flows which MN handles	1 to 10
Velocity of a MN	10m to 100m/sec
The Average session length of a packet	51 bytes
A weighting factor for the wireless Link	1.5
A weighting factor for the wired link	1
A weighting factor for the tunneling overhead	1.1
The Number of xTR	5

The total operation costs of LISP, The LISP Controller, the LISP-SDWN, HMIP, and MIP are evaluated based on Equations (6), (11), (16), (21), and (27), respectively.

As the session arrival rate increases, the total operation costs of LISP, the LISP Controller, LISP-SDWN, HMIP, and MIP increase accordingly and are shown in Fig. 7a. LISP-SDWN and HMIP have the lowest location management cost of the five protocols. During the intra-SDWN handover of LISP-SDWN and HMIP, the control messages are suppressed outside of an SDWN due to a domain-level location management entity, which is the LISP-SDWN Controller or MAP. Even though the LISP Controller is a domain-level location management entity, it has a higher operation cost than the LISP-SDWN and HMIP. This is because the LISP Controller uses the pushing method to update a map entry whenever a handover occurs, while LISP-SDWN uses the pulling method to update a map entry in a basic manner.

As the velocity of MN1 increases, the total operation costs of LISP, the LISP Controller, LISP-SDWN, HMIP, and MIP increase accordingly and are shown in Fig. 7c. The proposed LISP-SDWN shows the lowest operation cost of the five protocols. In comparison with LISP-SDWN, HMIP generates more control messages during the inter-SDWN mobility, where a location update is carried out in both MAP and HA as well. Furthermore, similar operation costs are shown during the intra-SDWN mobility for both LISP-SDWN and HMIP.

As the number of flows handled by MN1 increases, the total operation costs of LISP, the LISP Controller, LISP-SDWN, HMIP, and MIP increase accordingly and are shown in Fig. 7e. The metric, a flow number, will be a key factor for evaluating network performance, because many applications running on high-computing personal devices will require a high number of flows; therefore, the required location management entity needs to handle a large number of flows in future network.

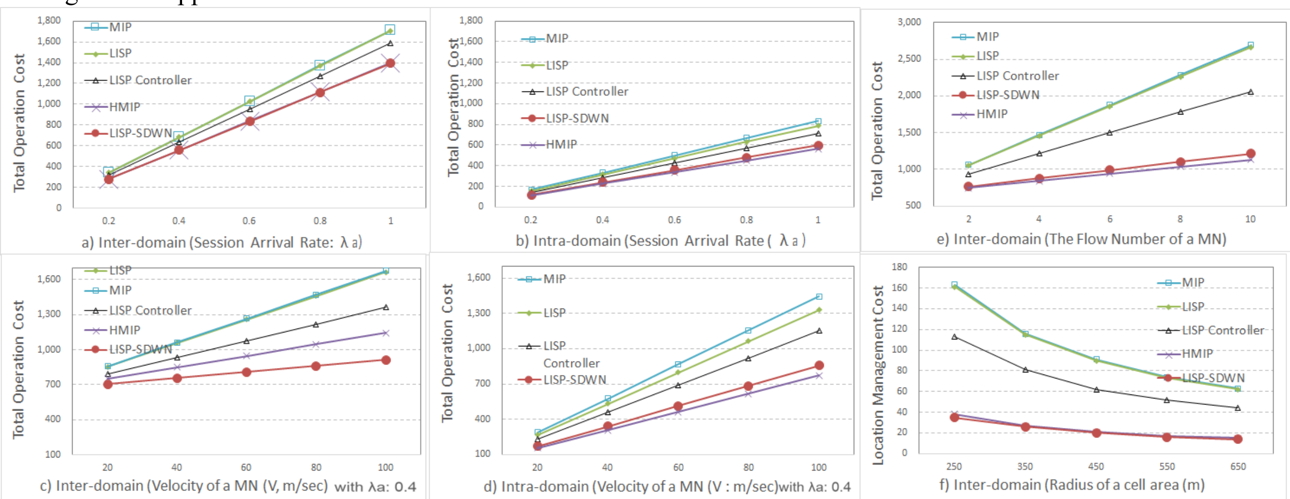

Fig. 7. Total operation cost of inter- domain and intra-domain communication

As the radius of a cell area increases, the total operation costs of LISP, the LISP Controller, LISP-SDWN, HMIP, and MIP decrease accordingly and are shown in Fig. 7f. Clearly, as the radius of a cell size increases, the total operation cost decreases due to fewer handovers. Note that LISP-SDWN and HMIP show steady location management costs in all ranges; the other protocols are steady after 550 meters.

C. *Intra-SDWN Communication and Comparison*

The total operation costs of the five protocols are evaluated in terms of two variables: the session arrival rate and the velocity of MN1 while MN1 communicates with other MNs in the same SDWN. During a handover, as shown in Figs. 4 and 6, the total operation costs caused by intra-SDWN communication and inter-SDWN communication are compared and analyzed in terms of the session arrival rate and the velocity of MN1.

The two variables and other simulation parameters are defined in Table VIII.

TABLE VIII: SIMULATION PARAMETERS FOR INTRA-SDWN COMMUNICATION

Items	Parameters
Radius of the Cell area	200 meters
Number of cells in an SDWN	30

Session arrival rate for each MN	0.1 to 1
Average session length of packet	51 bytes
Velocity of MN	10 to 100 m/sec
Number of xTR	5

During the intra-SDWN communication, as the session arrival rate received by MN1 increases, the total operation costs of LISP, the LISP Controller, LISP-SDWN, HMIP, and MIP increase accordingly are shown in Fig. 7b. Even though HMIP has longer control paths than those of LISP-SDWN, HMIP has a slightly lower cost than LISP-SDWN due to the smaller control message size; specifically, the Map-Register message (for LISP-SDWN) is 124 bytes and the Binding Update (for HMIP) is 56 bytes. The larger size of the control messages for LISP-SDWN is caused by tunneling technology. The LISP Controller has a larger operation cost than the LISP-SDWN and HMIP; as expected, the higher control cost is caused by the use of a pushing method to update the entire Map Database of xTRs in an ISP domain.

The total operation costs shown in Fig. 7a are generally higher than the total operation costs shown in Fig. 7b. The total operation costs shown in Fig. 7a are those associated with inter-SDWN communication and the total operation costs shown in Fig. 7b are those associated with intra-SDWN communication. During Intra-SDWN communication, when the LISP-SDWN Controller (or MAP) carries out location management, the control messages are suppressed outside of an SDWN; this is why the total operation cost shown in Fig. 7a is smaller than that shown in Fig. 7b.

During intra-SDWN communication, as the velocity of MN1 increases, and the total operation costs of LISP, the LISP Controller, LISP-SDWN, HMIP, and MIP increase accordingly and are shown in Fig. 7d. HMIP and LISP-SDWN have outstanding performance in terms of the operation cost.

Note that the total operation costs of the five protocols have a steeper gradient shown in Fig. 7d than those of the five protocols shown in Fig. 7b.

According to the total operation costs as shown in Fig. 7b and Fig. 7d, LISP-SDWN and HMIP show better operation costs in terms of the session arrival rate and velocity; therefore, the velocity of MN1 is a bigger factor that causes more control messages.

D. *Scalability of LISP-SDWN*

Fig. 8 shows the total operation costs of the three LISP-based protocols (LISP, the LISP Controller, and LISP-SDWN) in two communication scenarios with simulation parameters, as shown in Table IX.

TABLE IX: SIMULATION PARAMETERS FOR TWO COMMUNICATION SCENARIOS

Items	Parameters
Radius of the Cell area	200 meters
Number of cells in an SDWN	30
Session arrival rate for each MN	0.5
Velocity of MN	20 m/sec
Number of xTR	5
Average session length of packet	51 bytes
Weighting factor for the wireless Link	1.5
Weighting factor for the wired link	1
Weighting factor for the tunneling overhead	1.1

The total operation costs are measured in terms of two variables: the velocity of MN1 and the session arrival rate. When the velocity of MN1 is 20 meters per second, the total operation costs of LISP, the LISP Controller, and LISP-SDWN are drawn as dotted lines; when the average session length of packet is 51 bytes, the total operation costs of LISP, the LISP Controller, and LISP-SDWN are drawn as dotted lines in Fig. 8. The total operation of LISP-SDWN has the lowest cost and is steady in all cases, which means that the proposed LIPS-SDWN is scalable and requires the lowest operation cost in both intra-SDWN communication and inter-SDWN communication.

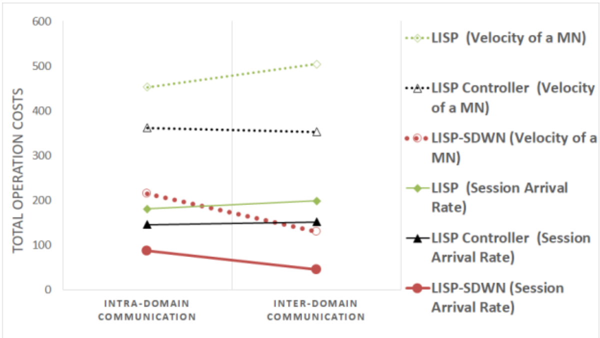

Fig. 8. Scalability Evaluation while the communication coverage varies from Intra-SDWN to Inter-SDWN

VI. CONCLUSION

In this paper, we propose mathematical models of LISP, the LISP Controller, LISP-SDWN, HMIP, and MIP in order to show the scalability of the proposed LISP-SDWN. The performance evaluation is carried out by comparing the total operation costs caused by one handover in both intra-SDWN communication and inter-SDWN communication. In most cases, LISP-SDWN showed the lowest and steady total operation cost, based on the mathematical models of the five protocols. The proposed LISP-SDWN is thus proven to be an efficient and practical method for a next generation Network. Furthermore, the scalability of the proposed LISP-SDWN is confirmed in both different scale communications: intra-SDWN communication and inter-SDWN communication.

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Eunil Seo received the B.S. degree from the Sungkyunkwan University, Korea, in 1997 and the M.S. degree from the University Southern California (USC), Los Angles, USA, in 2002. Over 18 years, he has a cross-functional career as a research staff in the Mobile IP, IPv6, User Centered Network, Ad-hoc and sensor network for Samsung Advance Institute of Technology (SAIT), a technical member in Network WG of ZigBee Alliance, a chair in RIA WG of OMG, and a project manager for the several control related projects of International Thermonuclear Experimental Reactor (ITER). He is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering, Sungkyunkwan University, Korea. His research interests include machine learning based Traffic Engineering (TE), LISP-based SDWN, and SDN&NFV-based Mobility Management (MM).

Dr. Vyacheslav Zalyubovskiy received the M.S. degree in Mathematics from Novosibirsk State University, Russia, and the Ph.D. degree in Mathematics for the Sobolev Institute of Mathematics of the Siberian Branch of Russian Academy of Sciences. Since 1984, he has been a Scientific Researcher with the Sobolev Institute of Mathematics. In 2007, he joined the College of Information and Communication Engineering, Sungkyunkwan University, as a Research Professor. His resent research focuses on design and analysis of optimal and approximation algorithms for combinatorial optimization problems and their applications, particularly in the areas of networking, planning, and scheduling.

Dr. Tai-Myoung Chung received his first B.S. degree in Electrical Engineering from Yonsei University, Korea in 1981 and his second B.S. degree in Computer Science from University of Illinois, Chicago, USA in 1984. He received his M.S. degree in Computer Engineering from the University of Illinois in 1987 and his Ph.D. degree in Computer Engineering from Purdue University, W. Lafayette, USA in

1995. He is currently a professor of Information and Communications Engineering at Sungkyunkwan University, Korea. He is now a vice-chair of the Working Party on IS \& Privacy, OECD, and a senior member of IEEE. He also serves as a Presidential committee member of the Korean e-government, the chair of the information resource management committee of the e-government. He is an expert member of Presidential Advisory Committee on Science & Technology of Korea, and is chair of the Consortium of Computer Emergency Response Teams (CERTs). His research interests are in information security, network, information management, and protocols on the next-generation networks such as active networks, grid networks, and mobile networks