Scalable Mobility Management for Content Sources in Named Data Networking

Shuai Gao and Hongke Zhang
School of Electronic and Information Engineering
Beijing Jiaotong University
Beijing, China
{shgao, hkzhang}@bjtu.edu.cn

***Abstract*—As a promising future Internet architecture, Named Data Networking (NDN) naturally enables consumer mobility but leaves source mobility challenging due to the binding between content identifier and locator. Most of source mobility solutions in literature adopt similar idea with the Mobile IP and suffer from several problems, like non-optimal routing, severe scalability, single point of failure etc. To address this issue, we build a distributed scalable mobility management framework based on threefold separation mechanisms to improve the content source mobility management without changing the original NDN's name-based communication paradigm. The proposed scheme supports fast handover and shortest path communication by splitting content locator and identifier as well as isolating content source's dynamics out of the routing plane. Numerical comparisons show that the proposed scheme outperforms the other baseline schemes in terms of handover latency, communication latency.**

I. INTRODUCTION

As a promising ICN architecture in the area of future Internet, Named Data Networking (NDN) [1] replaces the IP addresses with content chunks at the narrow waist of current Internet's hourglass model. In NDN, packets are forwarded based on names instead of traditional IP addresses and the receiver-based service model naturally enables consumer mobility by requesting data from new locations. However, source mobility scenario is more complex and needs to be investigated more precisely [2].

Compared with IP communication, there exists similar mobility problem for NDN mobile sources due to the binding between content's identifier and locator. In NDN, the content name is used to identify each content and also encapsulated into NDN packets for routing. The Locator/ID binding makes source mobility more challenging. First, a mobile content source needs to advertise the name prefixes of the contents at a new location, which brings heavy pressure and severe scalability problem on the routing plane. Second, the content consumers' Interests may go to the old outdated locations which lead to Interest timeout and reissuing.

Recently, content source mobility problem in NDN has been concerned in the literature [3–7]. In general, existing research on source mobility can be classified into two categories: routing-based scheme and MIP-like (Mobile IP) scheme. In general, routing-based mobility management [3, 4] requires more extra nodes involved into mobility management and may bring extra system complexity and management cost. Frequent movement of content sources may cause severe scalability problem to the dynamic routing plane. On the other hand, similar to the mobility solutions (e.g. MIP [8, 9]) in current TCP/IP networks, locator and identity separation is often used to address the source mobility problem in NDN. Based on this, several MIP-like solutions for source mobility are proposed in [5–7].

The solution in [5] suffers from triangle routing problem because all Interests must go to the content source's home domain firstly without consideration about in-network caching. For convenience, we call this scheme as a MIP-like scheme with triangle routing (MIP-TR). And in [6], a location name is added into the Interest message to avoid triangle routing problem. Therefore, we call this scheme as a MIP-like scheme with direct routing (MIP-DR). However, the location name may be outdated in the MIP-DR when the content source moves continuously, thus leading to long handover latency. A solution similar with HMIPv6 [9] is proposed in [7] to improve the performance of intra-domain handover latency. However, it exhibits longer latency for the inter-domain handover and requires more mobility management entities thus increasing the system complexity. In the rest of this paper, we use HMIP-INTRA and HMIP-INTER to denote the intra-domain handover and inter-domain handover for the HMIP scheme in [7]. In the above MIP-like solutions, a centrally deployed mobility anchor, like home agent (HA) is always needed to allow a mobile node to remain reachable, which may suffer from several problems, like non-optimal routing, severe scalability, single point of failure, etc [10].

To address this issue, we build a scalable mobility management (SMM) framework for NDN to support large number of mobile sources, as well as keep the handover latency very low. In the SMM, threefold separation mechanisms and Chord-based [14] distributed mobility management plane are adopted to provide Locator/ID mapping and keep the routing plane stable and immune to source mobility. We make numerical analysis and comparisons, which shows that the proposed SMM scheme significantly outperforms the MIP-like schemes in terms of handover latency, communication latency.

The remainder of this paper is organized as follows. Section II designs a Chord-based distributed mobility management framework. Some related issues of the proposed SMM are discussed in Section III. Section IV presents numerical com-

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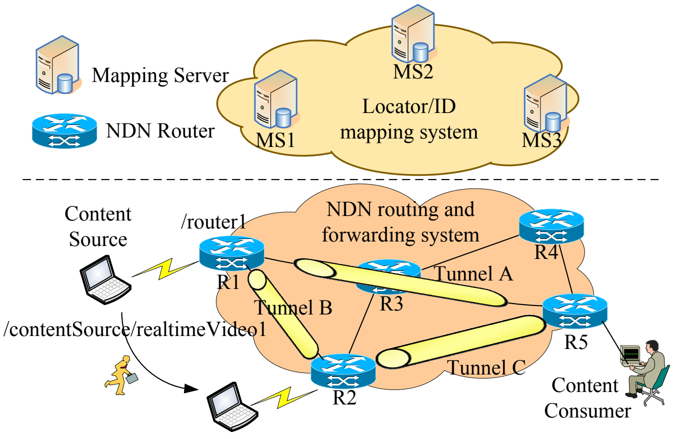

Fig. 1: Scalable Mobility Management Framework for NDN

parisons and Section V concludes the paper.

II. Basic Design

Based on the above analysis about the defects of centralized mobility management in current MIP-like solutions [5–7], a distributed scalable mobility management framework is designed for NDN to address the source mobility problem, illustrated in Figure 1. In the proposed SMM framework, we adopt threefold separation mechanisms, management/routing separation, Locator/ID separation and access/core separation.

In the SMM, the content name is only used for identifying requested data, rather than routing of Interest packets. The content source sets the location name of the contents stored locally as the name of the access router. To support mobility, the content source needs to register the binding between the content name and its location name to the Locator/ID mapping system. Each time a content consumer issues an Interest packet, the access router whose FIB lookup fails will send a special lookup message to query the location name of the requested data and forward the Interest to current location of the content directly.

A. Content Name and Its Locator

In original NDN, the content name is used to identify data as well as forward Interests [1], which brings complexity and obstacles for the content source mobility. Intuitively, we need to separate the double semantics of the content name.

Firstly, the original name of the content stored at the source is only used to represent identifier. Then the name of the content source's access router is used to represent the content's locator. For instance, in Figure 1, the name `/contentSource/realtimeVideo1` is the identifier of a realtime video provided by the mobile content source. In the literature [11], each router is named according to its location characteristics, i.e., `/<network>/<site>/<router>`. Here we borrow this expression and name the routers and mapping servers in a simplified way, i.e., `/<router>`, `/<mappingServer>`. Accordingly, the locator of the content `/contentSource/realtimeVideo1` is `/router1` in Figure 1. Now we have the binding between the content's identifier and its locator which is dynamic with the movement of the content source.

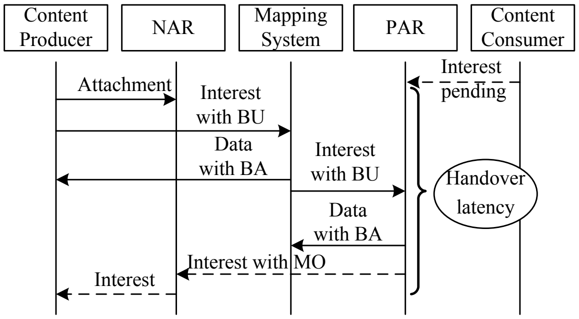

Fig. 2: Basic handover procedure for SMM

With this design, the double semantics of the content name are separated to identifier and locator. Moreover, the locator of the content is represented as the name of the access router and no routing update is needed in the routing plane during the handover, which helps to isolate the dynamics of content sources out of routing system to make the routing plane stable and immune to source mobility.

B. Locator/ID Binding Update

Figure 2 shows the basic handover procedure for the proposed SMM. Here, we consider the worst case that Interests are issued continuously to analyze the handover performance. In Figure 2, once a mobile source attaches a new access router (NAR), it will send a special Interest message as binding update (BU) to the corresponding mapping server. The BU Interest message will be forwarded to the mapping server based on normal NDN forwarding process. Upon receiving the Interest message with binding update, the mapping server will store the bindings and return a special Data message to make a binding acknowledgement (BA). To support better handover, the mapping server should inform the previous access router (PAR) to update the binding relationship with the BU Interest message. Upon receiving the binding update from the mapping server, the old access router will reply a BA Data message for acknowledgement and update local binding cache, so that the corresponding Interest for the mobile content can be intercepted and transferred to the new location.

Note that, the above BU and BA messages still use the format of Interest and Data packets defined in original NDN. New packet type is unnecessary in the proposed SMM framework. And the content name is kept unchanged during the BU and BA interactions, which guarantees the compatibility with original NDN.

C. Locator/ID Mapping System Design

The mapping system shown in Figure 1 needs to store global Locator/ID mapping and handle global binding update and lookup. Considering the huge amount of contents in the Internet (Google has indexed $> 10^{11}$ webpages [1]), we adopt a distributed hash table (DHT) [14] consisting of multiple

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[1] <http://www.worldwidewebsize.com>

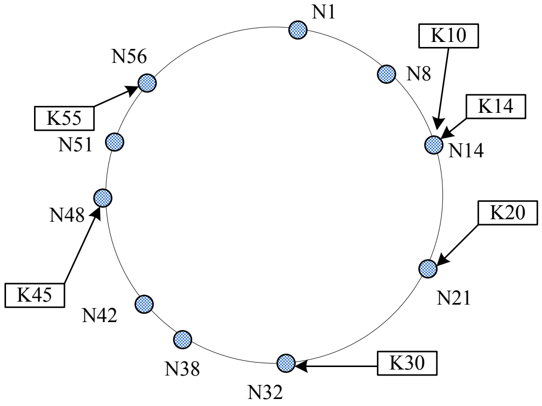

Fig. 3: A Chord-based DHT mapping system for SMM

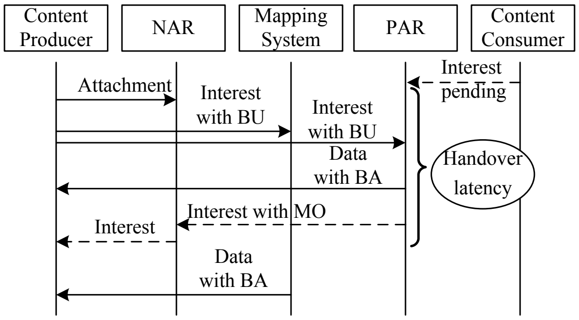

Fig. 4: Fast handover procedure for SMM

mapping servers to support scalable and robust mapping system. Figure 3 shows an example of the Chord-based DHT mapping system which is created using hashing over names of mapping servers. And the DHT key and DHT value are the content name' hash and the content locator respectively. The mapping relationship $< key, value >$ pairs are stored at the mapping servers. For a given content name, the corresponding content locator should be stored at the mapping server that is a successor of the content name's hash. In the example of Figure 3, if the hash value of the content name is 20, the $< key, value >$ pair will be stored at the mapping server corresponding to N21.

With the deployment of the Chord-based DHT mapping system, the basic handover procedure in Figure 2 may incur long handover latency since the special Interests with binding update sent to the mapping server may be forwarded in the Chord-based mapping system over several hops . In order to address this issue, we propose a fast handover for the SMM illustrated in Figure 4 to improve the handover process. The difference with the basic procedure is the content source sends an extra Interest with BU to the PAR to inform the location change immediately after handover. So that the Interests from the content consumer can be forwarded to the NAR without waiting for the BU from the mapping system.

D. Message Format Extension with Mobility Option

We modify the format of original NDN's Interest and Data packet with mobility option (MO) extension. The forwarding process of Interest packet with MO is illustrated in Figure 5.

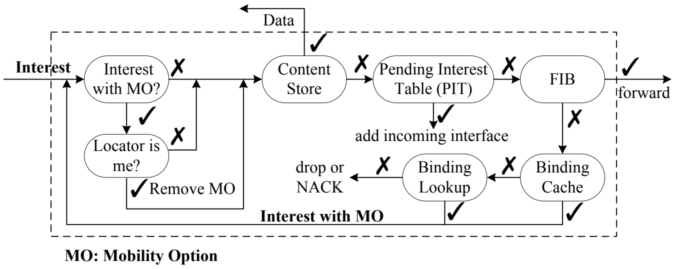

Fig. 5: Forwarding Process for Interest Packet with Mobility Option

When a router receives an Interest with MO, it will firstly check whether its name is the locator name in the MO or not. If yes, the MO will be removed and normal NDN Interest process will be performed. Otherwise, the locator name will be checked with higher priority than the content name during the FIB lookup. In addition, a special flag is used in the Interest packet to indicate the access router of the content source whether triangle routing exists during the Interest delivery.

Regarding the Data packet, a mobility option is optionally included to carry the latest locator name of a content. Thus the special Data packet may indicate the routers along the reverse path to update the local binding cache to avoid triangle routing problem and speed up handover process.

III. DISCUSSION

In this section, we discuss some issues of the proposed mobility solution.

A. Scalability

The SMM framework operates under cooperations among the following three planes: 1) mobility management plane; 2) routing plane; 3) forwarding plane. Here, we discuss the scalability of them respectively.

1) Mobility management plane: Regarding the mobility management plane, an important question is how to store all the Locator/ID mappings and handle global mobility management. Fortunately, there have been some literatures [12, 13] which have done in-depth research on how to build global name resolution system based on distributed hash table for information-centric networking and reached a conclusion that DHT schemes exhibit significant scalability due to their inherent load balancing and meet the scalability requirements imposed by the huge amount of content mappings.

Therefore, we suggest to use a DHT consisting of multiple mapping servers here to support scalable and robust mapping system. According to [14], the Chord system resolves all lookups via $O(logm)$ messages to other nodes. Here, m is the number of Chord nodes. Therefore, the binding update and binding lookup messages may be forwarded over multiple hops in the Chord ring, thus incurring long delay. For better binding update and lookup delay performance, one-hop DHT [15] can be created to support one-hop lookup. Note that, there are other DHT creation methods that can be used to design the scalable Locator/ID mapping system, which details are out scope of this paper.

2) Routing Plane: As mentioned in Section II, the SMM adopts Locator/ID separation and access/core separation. With the help of these twofold separation mechanisms, the dynamics due to source mobility are isolated out of the core network and the routing plane just needs to keep the reachability to core routers and fixed terminals. Thus, the size of routing table and the number of routing updates can be reduced greatly. The conclusion of the literature [16] is helpful to support our point, even if the routing plane of NDN is different from traditional Internet. According to [16], 35%-40% of total routing prefixes and 50%-60% of total routing updates will be separated from the global routing system if locator/identifier separation is used to isolate the customer networks from the core network.

3) Forwarding Plane: Regarding the forwarding plane, the FIB size in the SMM is independent of the number of mobile content sources, because the routing plane only needs to keep the reachability to core routers and fixed end hosts. Apart from FIB lookup specified in original NDN, the SMM needs to perform local binding cache lookup, which brings extra cost on the forwarding plane. With suitable choice of binding cache timeout and the aggregatable attribute of hierarchical naming, the size of local binding cache can be limited to a reasonable value to keep good scalability of forwarding plane in the SMM.

B. Robustness

The MIP-like mobility schemes [5–7] for NDN adopt fixed anchor device to perform mobility management. As we know, centralized anchoring design is vulnerable to a single point of failure and attacks [10], thus leading to poor robustness and severe security threats. In the SMM scheme, a distributed mapping system is constructed to perform mobility management and avoid single point-of-failure. Firstly, a Chord-based DHT system with suitable successor list size is robust and Chord lookup is not likely affected even by massive simultaneous failures [14]. Secondly, the failure of a mapping server only affects a very limited number of mapping lookups in the Chord system. In addition, the backup method [17] of the mapping relationships can be used to improve the robustness of the mapping system.

IV. PERFORMANCE EVALUATION

A. Handover and Communication Latency Analysis

To make comparisons, we refer three MIP-like mobility schemes proposed in [5–7] as the baseline schemes.

1) Analytical Model: For handover and communication latency analysis, we consider an analytical model like to the one used in [18, 19] shown in Figure 6. The following notations are used:

- The delay between the HA and the access router (AR) is t_a, which is the time required for a packet to be sent between the HA and the AR. Without loss of generality, we assume that the time to send a packet from one server in the mapping system to the AR is also t_a.

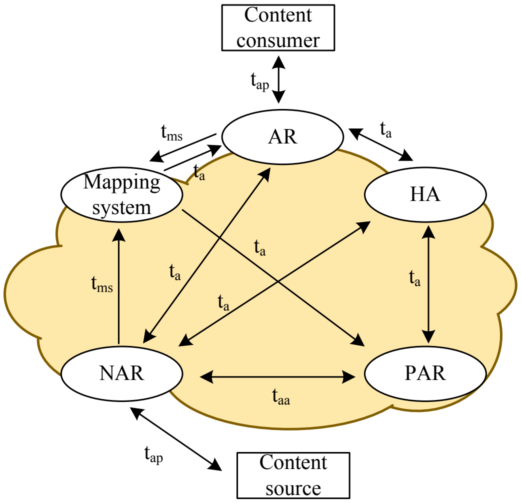

Fig. 6: A simple model for handover latency analysis

- The delay between the content source to the AR is t_{ap}, which is the time required for a packet to be sent between the content source and the AR via a wireless link.
- The delay between the AR and the mapping server is t_{ms}, which is the time required for a packet to be sent from the AR to the mapping server that is the successor of the content name's hash, as mentioned in Section II-C. Without loss of generality, we assume that $t_{ms} = h \cdot t_a$, where h is the number of hops that a binding update or binding lookup traverses in the Chord mapping system. According to [14], the average hops h is $\frac{1}{2}log_2m$ and m is the number of nodes in the Chord ring.
- The delay between the NAR and the PAR is t_{aa}.

2) Handover Latency: In this section, we borrow the conception in [20] and define the handover latency as the time duration when L2 handover begins to when the mobile content source can receive the first Interest packet from new access router.

For basic handover of the proposed SMM shown in Figure 2, the handover latency d_{basic} can be simply expressed as follows:

$$\begin{aligned} d_{basic} &= t_{ms} + t_a + t_{aa} + 2t_{ap} \\ &= (h+1) \cdot t_a + t_{aa} + 2t_{ap} \end{aligned} \tag{1}$$

For fast handover of the SMM shown in Figure 4, the handover latency d_{fast} can be simply expressed as follows:

$$d_{fast} = 2t_{aa} + 2t_{ap} \tag{2}$$

For the MIP-TR handover procedure [5], the handover latency d_{mip_tr} can be simply expressed as follows:

$$d_{mip\_tr} = t_{DND} + 2t_a + 2t_{ap} \tag{3}$$

where, t_{DND} is the duplicate name detection time during the handover.

For the MIP-DR handover procedure [6], the handover latency d_{mip_dr} can be simply expressed as follows:

$$\begin{aligned} d_{mip\_dr} &= t_{timeout} + t_{ap} + t_a + t_a + t_{ap} \\ &= t_{timeout} + 2t_a + 2t_{ap} \end{aligned} \tag{4}$$

where, $t_{timeout}$ is the Interest loss detection timer because the Interest reissuing is initiated by the expiration of loss detection timer in the mobility management scheme proposed in [6].

For the HMIP-INTRA handover procedure [7], the handover latency d_{hmip_intra} can be simply expressed as follows:

$$d_{hmip\_intra} = t_{ap} + 2t'_a + t'_a + t_{ap} = 2t_{ap} + 3t'_a \tag{5}$$

where, t'_a denotes the delay between the AR and mobility management entities in local domain, like RP or RH in [7]. Without loss of generality, we assume that $t'_a = \frac{1}{2}t_a$.

For the HMIP-INTER handover procedure [7], the handover latency d_{hmip_inter} can be simply expressed as follows:

$$\begin{aligned} d_{hmip\_inter} &= t_{ap} + 3t'_a + 2t_a + t'_{aa} + t'_a + t_{ap} \\ &= 2t_{ap} + 4t'_a + 2t_a + t'_{aa} \end{aligned} \tag{6}$$

where, t'_{aa} denotes the delay between the NAR and the PAR located in different domains. Without loss of generality, we assume that $t'_{aa} = 2t_{aa}$.

3) Communication Latency: In this section, we are concerned about the initial connection setup time (CST) which can reflect the communication latency to some extent. Let's assume that there are 100 content consumers attached at a access router and each content consumer initiate connection establishment with single remote content source.

As analyzed earlier, the MIP-TR scheme has triangle routing problem and the MIP-DR support routing optimization to avoid triangle routing. However, in both the MIP-TR and MIP-DR, the initial packets for connection setup would go to the HA at first before arriving at the foreign location of mobile source. Therefore, the average CST of the MIP-TR and MIP-DR can be expressed as follows:

$$t_{mip} = t_{ap} + t_a + t_a + t_{ap} = 2t_{ap} + 2t_a \tag{7}$$

Similarly, even though the HMIP scheme supports direct routing without detouring at the HA, in both the HMIP-INTRA and HMIP-INTER, the initial packets would go to the HA at first and then go to the rendezvous point (RP) in the domain where mobile source locates. Therefore, the average CST of HMIP-INTRA and HMIP-INTER can be expressed as follows:

$$t_{hmip} = t_{ap} + t_a + t_a + t'_a + t_{ap} = 2t_{ap} + 2.5t_a \tag{8}$$

In the SMM, no all initial packets would go to the DHT-based mapping system due to the binding cache in each content router. If local binding cache lookup hits successfully, the initial packets would go to the location of mobile source directly. Otherwise, remote binding lookup at the mapping system is performed. The probability of local binding cache lookup failing is denoted as α, which is dependent on the setting of binding cache timeout. Therefore, the average CST of the SMM can be expressed as follows:

$$\begin{aligned} t_{smm} &= t_{ap} + \alpha \cdot (t_{ms} + t_a) + t_a + t_{ap} \\ &= 2t_{ap} + (1 + \alpha \cdot h + \alpha) \cdot t_a \end{aligned} \tag{9}$$

4) Numerical Results: In this section, we show the numerical results based on the handover and communication latency analysis in the previous subsection. For our analysis, the basic delay parameters are set as follows in default: $t_{aa} = 5ms$, $t_a = 10ms$, $t_{ap} = 12ms$ and $t_{DND} = 20ms$. All these values are chosen based on the parameter settings given in [18, 19]. As discussed in [3], the lower bound of the Interest loss detection timer $t_{timeout}$ is dependent on the lifetime of PIT entry and the latter should be slightly larger than the RTT of the network. According to the literature [21], we set the $t_{timeout}$ is $500ms$ in our numerical analysis.

In Figure 7, we compare the handover latency of the previously mentioned six handover procedures by varying the delay t_a between a AR and a HA. It can be observed clearly that the average handover latency of the fast handover SMM is the lowest, because binding update messages are exchanged between two access routers directly. The handover latency of the HMIP-INTRA can also be kept very low due to the hierarchical mobility management in which location updates caused by intra-domain mobility are not reported to the remote HA. On the other hand, since inter-domain mobility requires more entities (e.g. remote HA) involved into mobility management, the HMIP-INTER scheme exhibits longer handover latency. The MIP-TR has a little longer handover latency than the fast handover SMM and HMIP-INTRA, because duplicate name detection is needed and the communication delay t_a between a AR and a HA is generally larger than the one t_{aa} between a NAR and a PAR. The handover latency of the basic handover SMM is dependent on the average hops h, which is consistent with previous analysis. And the basic handover SMM with larger h is more affected by the t_a because the binding update will traverse more hops in the Chord mapping system. The MIP-DR has the longest handover latency, since it lacks necessary notification method about location change to remote content consumers and the Interest loss detection timer needs to be waited for expiration before reissuing a new Interest to the HA.

Figure 8 shows the results of average connection setup time of different mobility management schemes by varying the delay t_a between a AR and a HA. As analyzed earlier, the binding lookup probability α in the SMM is dependent on the setting of cache timeout T. According to statistical results of the literature [17], $\alpha \approx 3\%$ when T is set as 3 minutes and $\alpha \approx 0.7\%$ when T is set as 30 minutes. In Figure 8, the HMIP scheme needs longest time to establish initial connection for the communication because there is an extra mobility management entity, named rendezvous point in each mobility domain. Thus, initial connection request would detour at not only HA but also rendezvous point, even though the HMIP scheme support routing optimization for subsequent traffic. The MIP-TR and MIP-DR schemes exhibits better performance than the

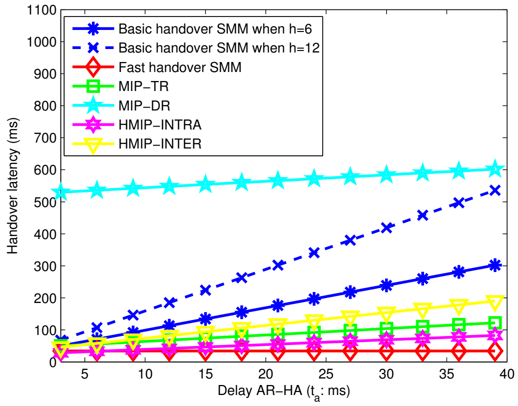

Fig. 7: Handover latency vs. delay between a AR and a HA

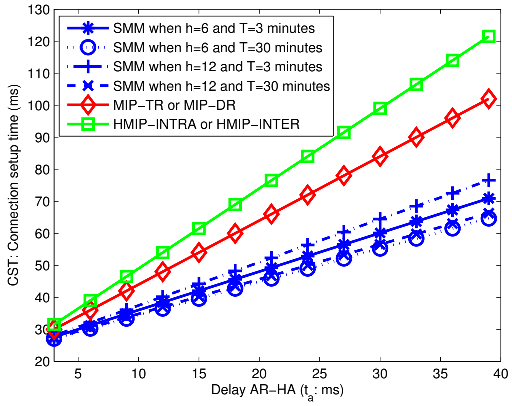

Fig. 8: Connection setup time vs. delay between a AR and a HA

HMIP scheme in terms of CET comparison, since only HA is asked for the current location of mobile source. It can be observed that the CET results of the SMM scheme is related with the scale of mapping system and the choice of binding cache timeout. Less mapping servers and longer cache timeout would help reduce the initial connection establishment time and improve the communication efficiency. Even with more mapping servers (2^{24})and shorter cache timeout (3 minutes), the SMM still outperforms other baseline schemes in terms of average connection setup time.

V. CONCLUSION

In this paper, we build a Chord-based distributed mobility management framework into the NDN architecture to solve the content source mobility problem without changing the original NDN communication paradigm. In detail, the proposed SMM framework adopts threefold separation mechanisms to split the double semantics of the content name as well as keep the routing plane stable and immune to source mobility. Numerical analysis and comparisons show that the proposed SMM scheme outperforms the other MIP-like schemes in terms of handover latency, communication latency.

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