On the Design and Evaluation of Producer Mobility Management Schemes in Named Data Networks

Hesham Farahat
ECE Department
Queen's University
Kingston, ON, Canada
h.farahat@queensu.ca

Hossam Hassanein
School of Computing
Queen's University
Kingston, ON, Canada
hossam@cs.queensu.ca

ABSTRACT

Information-centric Networks (ICNs) offer a promising paradigm for the future Internet to cope with an ever increasing growth in data and shifts in access models. Different architectures of ICNs, including Named Data Networks (NDNs) are designed around content distribution, where data is the core entity in the network instead of hosts. One of the main challenges in NDNs is handling mobile content providers and maintaining seamless operation. Accordingly, attempts at handling mobility in NDNs have been proposed in the literature are mostly studied under simplistic and/or special cases. There is a lack of benchmarking tools to analyze and compare such schemes. This paper introduces a comprehensive assessment framework for mobility management schemes in NDNs, under varying topologies, heterogeneous producers and consumers, and different mobility models. We develop a generic and modular simulation environment in ns-3 that is made available for NDN researchers to evaluate their mobility management proposals. We implement and compare the performance of three mainstream Producer mobility management schemes, namely, the Mobility Anchor, Location Resolution and Hybrid approaches in NDNs. We demonstrate how mobility impacts NDN operation, specifically in terms of latency and delivery ratio. We also argue for the superior operation of the hybrid approach to handling mobility in NDNs, yet highlight its high control overhead.

Categories and Subject Descriptors

C.2.m [**Computer-Communication Networks**]: Miscellaneous; C.4 [**Performance of Systems**]: Design studies

Keywords

Information-Centric Networks; Named Data Networks; Seamless Mobility Management; ndnSIM; ns-3; Simulation Framework

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1. INTRODUCTION

The evolution of social networking, mobile applications and media streaming caused a shift in how the Internet operates. While the Internet was built on a host-to-host model, current usage trends are exhausting network resources in maintaining scalable operation. Consistent attempts at patching up Internet operation to cater for increasing content are bound to fail under the projected increases in data traffic [23]. This includes attempts at supporting Content Distribution Network (CDN) and Peer-to-peer (P2P) overlays on the IP network. In retrospect, the Internet was designed for a mostly client-server architecture. Users, thus, assumed either roles in most scenarios. With an expanding use of the Internet, CISCO's Visual Networking Index (VNI) [1] projects a 2.5 fold increase in global traffic, to reach 132.8 Exabytes per month by 2018 compared to 2013.

Recently, research efforts were directed at developing a paradigm for the future Internet based on content rather than hosts. A promising paradigm, namely Information-centric Networks (ICNs), was presented [5] to address growing challenges with content oriented communication. While considering the strengths and weaknesses of the current Internet design, ICNs are being developed in concerted efforts, and several potential architectures have been proposed. The commonality between all ICN designs is that content is identified by unique names and be cached anywhere in the network. While most of the attention has been directed at addressing challenges such as: routing, naming, and caching [21], while other important challenges remain seldom tackled.

A core property of any future Internet architecture is supporting mobility as a networking primitive. This is exacerbated with a projected increase in mobile entities amounting to 50% of all devices and connections by 2018 [1]. Supporting seamless operation where users can move in the network without service interruptions is core to ICN. This challenge is gaining attention as researchers are attempting to incorporate mobility support in ICN architectures. In the current Internet, the challenge of delivering traffic from or to mobile devices is in how to find the moving hosts in the network. Whereas in ICNs, the challenge is in how to find and track the data [24].

Named Data Network (NDN), formerly known as Content-centric Network (CCN), is one of the pioneering ICN architectures. An implicit assumption of intrinsic mobility "support" inherent to NDN design is realistically impractical due to the late coupling between data and hosts. While recent research efforts addressed mobility challenges in ICNs generally, and NDNs specifically, there remain significant challenges in analyzing the impact of these solutions on the resulting Quality of Service (QoS) and latency measures. We remark that the performance evaluation of mobility management schemes proposed in the literature are mostly performed under simplistic configurations/operations conditions that do not reflect realistic ICN environments. Indeed, there is a lack of comprehensive analysis of the design factors that yield seamless mobility management, and a benchmarking tool to contrast and evaluate mobility management schemes.

In this paper, we address mobility challenges in NDN, as a fundamental functionality in ICNs. Specifically, our contributions are:

1. A detailed analysis of mainstream mobility management scheme in NDN, with insights on design factors that yield seamless mobility.
2. A modular mobility assessment framework, developed within ns-3, to evaluate the performance of mobility management schemes under varying topologies, heterogeneous producers and consumers, and access profiles; to be released for NDN research.
3. An implementation of the three mainstream mobility management schemes in NDN, with contrasted performance evaluation.

Our goal is to provide the means (assessment framework) and design parameters for researchers in NDN mobility to evaluate the performance of their frameworks, and to benchmark against the already developed and tested schemes.

The remainder of the paper is organized as follows. In Section 2, an overview of the mobility problem in NDN is introduced. Mainstream NDN mobility management schemes are detailed in Section 3, highlighting their design parameters, and an analysis of design factors that aid seamless mobility (in light of these schemes) is presented in Section 4. The assessment framework is explained in detail in Section 5. We detail our experiments with these approaches in Section 6, and comment on the performance of each under the presented performance metrics. We conclude our findings in Section 7 and present insights into future directions in NDN mobility support.

2. MOBILITY MANAGEMENT IN NAMED DATA NETWORKS

The Named Data Network (NDN) [23] is one of the main ICN architectures that has potential to be the future Internet. Similar to other ICN architectures, content is named in the network. Hence, information can be requested without the need for location information (such as an IP in the current Internet). Additionally, data can be cached in any NDN node, this would decrease the time it takes to request content. A hierarchical *naming* prefix is used in NDN, which makes routing and forwarding process relatively simpler than other architectures.

NDN is designed to be a *Consumer*-driven network, where in order the users to communicate, the requester (referred here as *Consumer*) will send requests packets (*Interests*) for specific data from content provider (referred here as *Producer*) [21,23]. The *Interest* will be forwarded to the nearest copy of the content, and then the *Data* packet holding the content is generated and sent back to the *Consumer*. This process needs three *Data* structures: Forwarding Information Base (FIB), Pending Interest Table (PIT) and Content Store (CS) [23]. Particularly, FIB is used to forward *Interests* to the nearest content location. PITs are used to keep track of the forwarded *Interests* and requested user, so when the *Data* is available, it can be sent to the *Consumer*. Finally, CS is storage for cached data in an NDN node. Moreover, in case of failures, *Consumers* retransmit *Interests* that have not been satisfied for a specific period

In typical NDN, user mobility can be classified to *Consumer* mobility and *Producer* mobility. *Consumer* mobility is handled as if there is a failure in the network where unsatisfied *Interests* will be retransmitted. Consequently, during this process the *Consumer* will experience a long delay to retrieve the data which may affect the QoS of real-time applications [3].

With regards to *Producer* mobility, NDN uses late binding where content is matched to a location in the forwarding process [21]. Consequently, this design complicates *Producer* mobility compared to *Consumer* mobility. When a *Producer* changes its location, the routing tables should be updated with the new location of the *Producer*. However, updating the FIBs is not a scalable solution since the delay of routing convergence will increase with larger networks. Without using any *Producer* mobility management scheme, *Consumers* will not be able to reach the moving *Producer* until the routing protocol updates the routing state with the new location, affecting the *Producer*'s availability and *Consumer*'s Quality of Experience (QoE). The authors in [3,17] have conducted simulations to study the capability of NDN in handling simple mobility events. The results have shown that NDN with its typical architecture fails to provide seamless mobility; thus the use of an effective mobility management scheme is necessary. *Producer* mobility is the focus of this work, since the schemes proposed in the literature is target this type of mobility.

3. MAINSTREAM NDN MOBILITY MANAGEMENT SCHEMES

In this section, we investigate several proposed schemes designed to handle *Producer* mobility in the NDN architecture. Re-applied ideas from current protocols in the Internet such as Mobile IP [6] and Domain Name System (DNS) were at the core of these schemes. We categorize the mainstream NDN mobility management schemes into: Mobility Anchor, Location Resolution and Hybrid approaches. One management scheme from each approach is selected to be a representative scheme, which will be explained and evaluated using the introduced Assessment Framework in Section 5.

3.1 Mobility Anchor Approach

Schemes in this class are based on the Mobile IP protocol [6], which is a proposed standard in the Internet Engineering Task Force (IETF) to support host's mobility in IP networks. In particular, Mobile IP uses fixed nodes called Home Agents that keep track of the location of all mobile hosts originally registered in the home network. While a mobile host is roaming outside of its home network, packets addressed to mobile hosts are tunneled through the Home Agent. Schemes proposed in [11,12,16,18,19] fall into this category with different designs. Generally, the schemes select an anchor node similar to the Home Agent in Mobile IP The methodology used in [16] is based on tunneling. The access router in the home network called "Home Content Router" (CR_h), is the anchor in this scheme. While the *Producer* is roaming, CR_h will forward any *Interest* directed to the former, to the new location. Once the *Data* is received by the CR_h, it will be forwarded to the *Consumer*. The operation of the scheme can be summarized in three steps: 1. *Movement indication*: Once the mobile *Producer* starts the handover it decides on a tentative name prefix that should be unique in the new domain. 2. *Path redirect configuration*: The mobile *Producer* sends a path update (PU) packet to the router to update CR_h with the new location. The router updates the mobile source record in its routing table, and replies with a path update acknowledgment (PACK). The PU and PACK are handled as normal *Interest* and *Data*. 3. *Interest* redirection: When an *Interest* reaches CR_h, it will be encapsulated by a new *Interest* (tunneled *Interest*) and forwards it to the *Producer* using the location information from Step 2. The *Producer* will send the tunneled *Data* back to CR_h, which will extract the *Data* and send it tp the *Consumer*.

3.2 Location Resolution Approach

The approach in Location Resolution schemes is similar to the one used in DNS, where the *Consumer* queries the location of the *Producer* before sending *Interest*s. Location Resolution Servers (LRS) are used to resolve location queries, the servers then should be always aware of the current location of each node. Examples of schemes that use this approach are presented in [4,13,25]. NDN uses late content-to-location binding technique, where the content is matched to a location in the forwarding stage. However, Location Resolution schemes require early binding techniques similar to Data-Oriented Network Architecture (DONA) [14]. This technique will affect content naming used in NDN and will require extra overhead to maintain and query locations.

Kim, et. al have proposed in [13] a mobility management scheme that uses Location Resolution Servers. The operation for both *Consumer* and *Producer* is as follows: 1. *Producer* side: once a handover has occurred, the *Producer* will update its prefix to match the new location (e.g. *Producer* named: /prefix_1 moves from access point 1 (AP_1) to access point 2 (AP_2), the *Producer's* name will change from /AP_1/prefix_1 to /AP_2/prefix_1). This new prefix is then sent to the LRS to update its records. 2. *Consumer side*: a new timeout period L_h is introduced to detect *Producer* mobility. When the *Data* takes longer than L_h to reach the *Consumer*, the latter will query the LRS for the current location of the *Producer*. Once the new prefix reaches the *Consumer*, it will resend all pending *Interest*s with the updated location.

3.3 Hybrid Approach

This approach is considered to be a combination of both Mobility Anchor and Location Resolution approaches, thus it is refereed to as *Hybrid* [20]. The mobile nodes in the Hybrid approach should have a name following this format: *PoA/uniqueID*, where PoA is the Point of Attachment (Access router) that the *Consumer* is directly connected to. A Control Plane is proposed to handle active sessions between a *Consumer* and a mobile *Producer*. The Control Plane has the following components: 1. *Proxy Agent (PA)*: The agent that handles mobility at the point of attachment (Anchor in Mobility Anchor Schemes) 2. *Mobile Agent (MA)*: The agent that handles mobility at the *Consumer* side 3. *Mobility Controller*: Manages the mapping between the client ID and its location in the network (Location Resolution Server)

All communications pass through the domain's PA, which keeps track of all mobile nodes using the Register and Deregister messages sent by the moving node. Furthermore, the Controller will be updated with the new node's location. When the *Consumer* wants to communicate with the *Producer*, first it asks the Controller for the prefix name and appends it to the *Interest* packet. The *Producer*'s PA receives all the *Interest*s (acting as the anchor) and will manage the *Interest* forwarding to the *Producer* by issuing new *Interest* packets.

4. DESIGN OF NDN MOBILITY MANAGEMENT SCHEMES

The three schemes share the same concept where mapping of location to data is needed to support seamless mobility. Specifically, the mapping in Mobility Anchor schemes occurs in the Home Router of the *Producer*; such routers will require extra logic to be added. However, Location Resolution and Hybrid schemes need a new entity (LRS) to handle the mapping. Additionally, these two schemes require the name of the *Producer* (i.e. prefix) to change after the handover to match its current location. Consequently, the same *Data* will be stored in the caches with different names which waste the available resources. In the Mobility Anchor Scheme the change in name should not affect the *Consumer* since the Home Agent will handle the tunneling. On the contrary, the *Consumer*s in Location Resolution Schemes should be aware of the change, thus LRS queries should be sent. As a result, the advantage of late binding strategy proposed in the original NDN will no longer be in use with Location Resolution and Hybrid approaches, which could affect other NDN functionalities such as forwarding and routing.

Typically, the tunneling technique used in Mobility Anchor schemes will cause longer delays, since *Data* packets will take longer paths to reach the *Consumer*. However at the same time, this technique will minimize *Interest*s being dropped during handover. In Location Resolution schemes some *Interest*s will be dropped before querying the LRS but the *Data* packet will take the shortest path to the *Consumer*. The Hybrid scheme takes advantage of both techniques. In particular, regular *Data* will always be sent using the shortest path, while *Data* during handover will be tunneled and will not be dropped.

All schemes will require control packets to be sent in order to support seamless mobility. Such control packets are considered as overhead traffic on the network. In particular, the Mobility Anchor scheme will require a pair of *Interest*/*Data* (prefix update) to be sent for every mobility event to update the Home Agent. On the other hand, Location Resolution Scheme will require two types of overhead. First, prefix update packets which are similar to the mobility Anchor Scheme but will be directed to the LRS. Second, a prefix fetch pair will be requested by the *Consumer* once a timeout period is expired. However, this timeout can occur as result of other events, unrelated to mobility, in the network such as congestion, which will cause the scheme to send unnecessary packets. Since the Hybrid scheme uses both techniques, causing the overhead to be higher than the other two schemes.

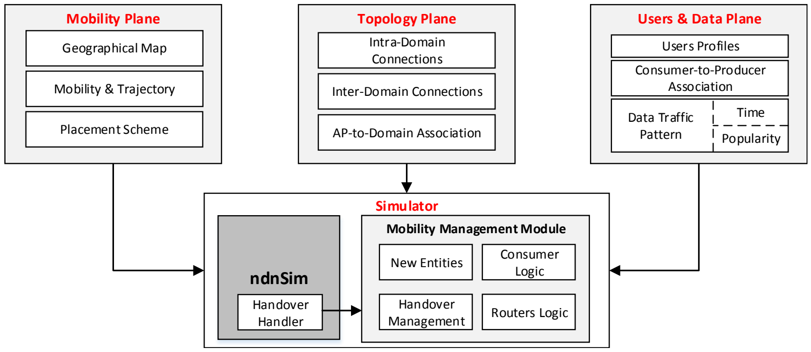


Figure 1: The main components of the Assessment Framework

5. ASSESSMENT FRAMEWORK

The proposed framework is designed to be a benchmarking tool for existing and future mobility management schemes. Hence, the tool will be used to evaluate and compare the schemes using selected performance metrics. The inputs to the Assessment Framework will be varied to study the performance of the mobility management schemes under different scenarios. The components of the framework are shown in Figure 1 and are explained below. The simulator used in the assessment framework is ndnSIM [2] which is an NDN simulator for Network Simulator 3 (ns-3).

5.1 Topology Plane

This component generates various network topologies to be used in the Assessment Framework. The topologies are designed to be hierarchal with multiple domains such as Transit-stub topologies [22], and will allow Intra-domain and Inter-domain communications. Moreover, with hierarchal topologies two different mobility scenarios will be investigated: moving to a new Access Point (AP) within the same domain (Intra-domain mobility) and moving to another domain (Inter-domain mobility). Studying both scenarios will emphasize the advantage of data caching during mobility events, since the effect of Intra-domain mobility are reduced by the available caches in the domain.

The Topology Plane will generate the network in three steps. First, the domains will be generated based on the number of routers and number of distinct domains required. Second, the domains will be connected to form the transit network. Third, the APs will be associated with the different domains.

Once the user leaves the communication range of one AP and enters another, a handover event occurs. Specifically, the user will dissociate from the current AP and associate with the new AP. With this in mind, APs that are geographically neighbors, are not necessarily neighbors in the network topology (i.e. within the same domain).

5.2 Mobility Plane

The positions and movements of users on the map are the outputs of this component. The map may consist of streets, sidewalks and/or buildings. An example of a geographical map that can be used is urban areas which are characterized by having higher densities of users and Wi-Fi APs. This component will also place the APs on the map in addition to the fixed users such as PCs and servers.

Users' trajectory can be generated using analytical random mobility models, simulation models or real mobility traces. Random Waypoint, Random Walk and Gauss-Markov are examples of analytical models that use mathematical calculations to determine the next position of a node. Simulation models such as traffic simulators provide more realistic user movements within a given map. Simulation of Urban MObility (SUMO) [15] is widely used to generate such trajectories for vehicles and pedestrians moving at various speeds. Mobility traces of real user's movements can be captured and used in the Assessment Framework similar to the dataset published in [8].

5.3 Users and Data Plane

This component determines the traffic profile of each user, what data the *Producers* can generate and what (and when) the user requests data. Specifically, *Consumers*' *Interest* patterns are generated which will include the time of request, the *Producer*'s name and the data name. To create realistic request patterns, data will be requested with different popularity (i.e. some data are requested more frequently than others). To model data popularity, distributions such as the Zipf's law [10] can be used. The distribution is controlled by parameter α, where lower values give more uniform-like distributions (i.e. if $\alpha = 0$ then all data has the same probability).

5.4 Mobility Management Schemes Implementation in ndnSIM

The existing ndnSIM (and ns-3) does not provide Wi-Fi handover between access points, nor a mobility management scheme. Therefore, two main updates are done to the current ndnSIM: AP handover handler and a base for mobility management schemes. A new class called `HandoverHanlder` is created and added to the Mobility Module of ns-3. For each mobile node, an object of this class will be instantiated and aggregated to class Node. The handler is responsible for detecting the handover event based on the power received from the AP or the AP-to-user distance. Specifically, it will dissociate the mobile node from the old serving AP and associate it to the new AP. The class will trigger two events in the mobility management scheme by calling the function `PreHandover` before dissociating from the old AP and `PostHandover` after associating with new AP.

`MobilityManagement` is a base class for any mobility management scheme to be implemented in ndnSIM. This abstract class contains two pure virtual functions (the derived class required to implement this function) `PreHandover` and `PostHandover`. In particular, these functions will implement

Table 1: Simulation Parameters

	Parameter	Value
General	Simulation Duration	1000s
	Transit Period	80s
	Map size	$1400m \times 1400m$
	Number of Blocks	7×7
	Number of Users	100
	Producers	50
	Consumers	50
Application	*Interest* Rate	50-80 I/s
	Zipf α	0.2
	Content per *Producer*	$1000 \times 1KB$
Topology	APs	49
	AP Range	200m
	Number of Routers	40
	Core router's links	10Mbps
	Access router's links	5Mbps
	Propagation delay	10ms
Mobility	Model	Manhattan
	Handover delay	0.5s
	Speed	70 km/h
NDN	Forwarding Scheme	BestRoute
	Cache replacement	LRU
	Cache Size	1000 objects

the required actions to be done by the mobile node before and after the handover. Moreover, the class may include any extra logic to be added to the *Consumer*s, routers and/or new entities. For example, Location Resolution Schemes need a new timeout period to be added to the *Consumer* application and the logic of the LRS. `MobilityManagmentHelper` is a class that will be used to aggregate the `MobilityManagement` on all nodes for handling *Producer* mobility. The source code of our modules in ndnSIM is available for the public [9].

5.5 Performance Metrics

In order to provide a seamless experience during mobility in NDN, the management scheme needs to keep the delay experienced by the *Consumer* maintained, avoid *Interest* retransmissions and minimize the overhead. Measuring the following metrics will provide a complete picture of the scheme's performance which covers the effect on both the user and network:

1. *Consumer* Delay (CD) is the total delay the *Consumer* experiences to request an *Interest* and receive the corresponding *Data*. Specifically, it is the time difference between the first attempt of sending the *Interest* and receiving the *Data*. This includes the total timeout and the delay of retransmitted *Interest* and *Data* packets
2. Delivery Ratio (DR) is the proportion of successful *Data* packets received by the *Consumer* to the total number of *Interest*s sent. This metric is a measure of how successful is the scheme in avoiding both *Interest*s and *Data* drops.
3. Scheme Overhead (OH) is the total number of control messages sent by the scheme for the purpose of supporting mobility. For example, in Location Resolution schemes, the overhead includes the prefix update and prefix query packets.

6. EXPERIMENTS, RESULTS AND DISCUSSION

In this section, we present one instance of the Assessment Framework, where the aforementioned mobility management schemes are implemented and tested. The details of the experiments and select results are shown and discussed.

6.1 Experimental Setup

Table 1 summarizes the simulation parameters used for this experiment. The topology used is Transit-stub network that consists of 40 core routers and 5 domains. Core routers are connected with links of 10Mbps capacity, while access routers are connected to the core routers with 5Mbps links, and the propagation delay in all links is 10ms.

The map where the users will move on is assumed to be a street grid plan (e.g. Manhattan) where users are either pedestrians on sidewalks or riding vehicles (private cars or public transit). Moreover, a Wi-Fi AP will be installed at every intersection to provide Internet access within its communication range which is assumed to be 200m. Wi-Fi 802.11g is used as a standard for the wireless medium. The handover delay (AP dissociating and associating) is assumed to be 0.5s.

Each *Producer* provides 1000 unique *Data* objects (1KB each), and content popularity is modeled using Zipf's law distribution with $\alpha = 0.2$. *Consumer*s request *Data* by sending *Interests* (frequency = 50-80 *Interest*/s) with random inter-*Interest* gap that follows exponential distribution with $mean = 1/frequency$.

The main functionalities of NDN are assumed to have the default values in ndnSIM. In particular, ndnSIM uses an opportunistic scheme named as "Cache Everything Everywhere" for object caching [7]. NDN nodes using this scheme will cache any *Data* passing through it. In case of full cache, Least Recently Used (LRU) replacement policy is used. The cache size in the simulation environment is designed to be 2% of the total content in the network, therefore the cache size = 50 (*Producer*s) $\times$ 1000 (content per *Producer*) $\times$ 2% = 1000 *Data* objects. Best Route is used as the forwarding strategy in ndnSIM where the next hop is decided on the best-calculated metrics such as number of hops, delay and congestion.

The experiments were executed for 28 runs on 7 different topologies where different random seeds are used in every run. Accordingly, the averages of the performance metrics were calculated to be used in the evaluation. For every metric, the same simulation parameters are used to evaluate pure NDN with no mobility management scheme and NDN with the aforementioned three schemes.

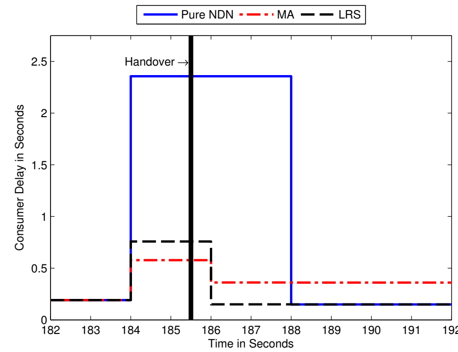
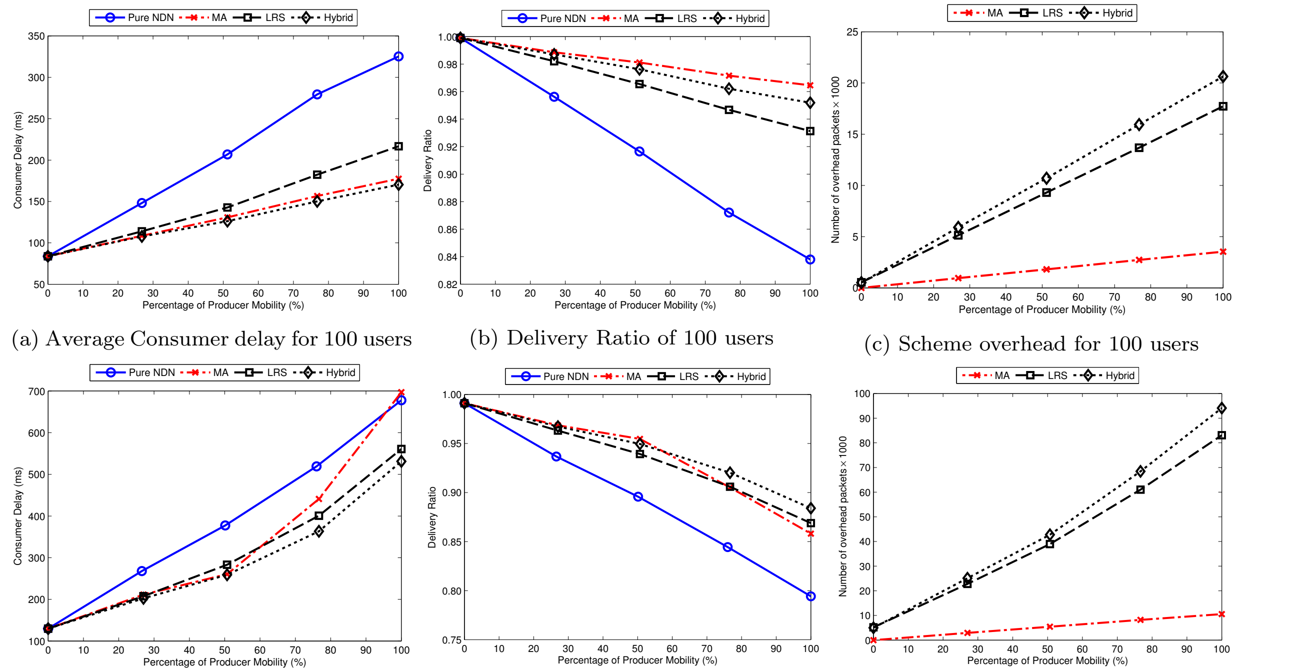


Figure 2: Delay for one *Consumer* during *Producer* mobility event at time=185.5s

6.2 Impact on a One Consumer

Figure 2 shows the effect of *Producer* mobility on the delay experienced by one *Consumer* using no mobility management scheme (pure NDN), Mobility Anchor scheme and Location Resolution scheme. The *Consumer* Delay (y-axis) is measured for every *Interest* sent by the *Consumer* (x-axis ordered by *Interest* sending time) with handover event



(a) Average Consumer delay for 100 users (b) Delivery Ratio of 100 users (c) Scheme overhead for 100 users

(d) Average Consumer delay for 300 users (e) Delivery Ratio of 300 users (f) Scheme overhead for 300 users

Figure 3: Comparison between the four schemes in two scenarios: 100 and 300 users, using the three performance metrics

occurred at time 185.5s. As shown in the figure, the *Consumer* experiences long delays with pure NDN more than a network with a mobility management scheme. Moreover, the affected period in which the *Interests* could not reach the *Producer* is longer (approximately 4s compared to 2s). During the handover, the CD reached 2.35s from time 184s to 188s, and once the routing protocol finished updating the FIBs at time 188s, CD was back 0.15s. Using a mobility management scheme mitigated this delay problem. In particular, the two schemes have shortened the affected period, and a shorter delay is experienced. Mobility Anchor scheme had less delay during the handover compared to the Location Resolution scheme. However, the delay after the handover in Mobility Anchor scheme is higher than the other scheme and pure NDN due to the tunneling process in which *Interest-Data* path becomes longer.

6.3 Varying Percentage of Producer Mobility

In able to study the effect of mobility on the performance metrics mentioned above, the number of mobile *Producers* is varied from 0% (no mobility) to 100% (all *Producers* are mobile).

6.3.1 Consumer Delay

For 100 users, the average *Consumer* delay of the different schemes as a function of the number of mobile *Producers* is shown in Figure 3a. In pure NDN, the average *Consumer* delay in case of full mobility is 4 times longer than no mobility scenarios. This increase is avoided with the use of a mobility management scheme which will reduce the *Consumer* delay by at least 33%. As for comparing the schemes, the Hybrid approach outperformed the other two schemes just after 25% mobility. This is the result of avoiding *Interest* drops using the Anchors, in addition to the path update using the Location Resolution server. Moreover, the delay in MA is lower than LRS. This is due to the longer *Data* paths in Mobility Anchor after the handover (a relatively small delay but occurs for all *Interest*). On the other hand, the delay in Location Resolution scheme is due to the value of L_h (location change detection period) and the time needed to query the LRS (a long delay but for short periods just after the handover).

To clarify, Figure 4 shows the Cumulative Distribution Function (CDF) for full mobility scenario (100% *Producer* mobility) for all the schemes. From the figure, we see that the Mobility Anchor scheme has the longest delay (300ms) upon all schemes in 92% of total *Interests*. Furthermore, the delay in this scheme is longer than Location Resolution scheme 95% of total *Interests*, after that the latter's delay exceeds with larger values. To illustrate this, Figure 5 shows the standard deviation (SD) of the *Consumer* delay of each scheme. The SD of Location Resolution scheme reached 0.6, while the SD of Mobility Anchor is maintained below 0.2 which confirms that the variance in delay in Location Resolution scheme is larger than the Mobility Anchor.

To analyze the performance of the schemes in a dense user environment, the number of users is increased to 300 (150 *Producers* and 150 *Consumers*). As shown in Figure 3d, the delay of the schemes increased 4 times where it was 2.5 times in case of 100 users. More interestingly, the delay in Mobility Anchor scheme increases much faster and bypasses the delay in the Location Resolution scheme after 60%. This is due to the increase of number of events requests which will take longer paths.

6.3.2 Delivery Ratio

Figure 3b shows the average delivery ratio of *Consumers* as a function of mobility percentage. The delivery ratio decreased from 100% to 85% without any mobility manage-

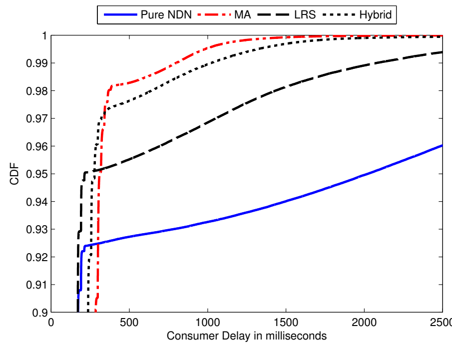


Figure 4: CDF of Delay in 100% *Producer* mobility

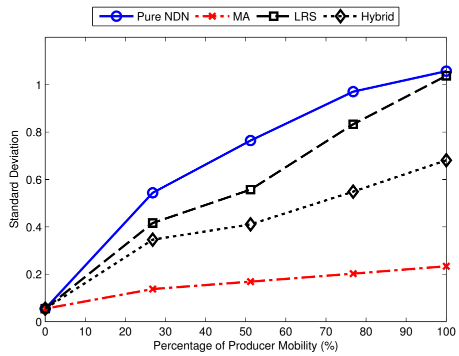


Figure 5: Standard Deviation of *Consumer* Delay

ment scheme. This is a result of *Interests* retransmissions and packets drops. On the other hand, using a mobility management scheme will reduce this drop to 95%. In particular, Mobility Anchor scheme has the best delivery ratio among other schemes due to the anchors which forward *Interests* to the new location of the *Producer*, thus no *Interest* dropping occurs.

The result of 300 users scenario is shown in Figure 3e. The same performance degradation of the Mobility Anchor scheme happened after 60%.

6.3.3 Scheme Overhead

To support seamless mobility, schemes need to send control messages to different entities in the network. This overhead is shown in Figure 3c and 3f . Mobility Anchor scheme has very low overhead compared to the two other schemes, since the *Consumers* in the Location Resolution scheme query the LRS. The Hybrid approach has the worst overhead since it needs both types of control messages as discussed in Section 4. Nonetheless, this control overhead is found to be lower than the amount of FIB update messages for all mobility events. For instance, the number of FIB update packets sent is 22 times more than the control overhead of the Hybrid scheme in 100% mobility. Notice that the Location Resolution and the Hybrid schemes has a significant overhead (1000 to 5000 packets) with 0% of *Producer* mobility. This is due that the *Consumers* will query the LRS after the timeout period L_h even though there are no mobility events.

Increasing the number of users was found to have no effect on the trend of overhead. However, the total number of packets is increased by 250% in Mobility Anchor scheme and 450% in the other two schemes.

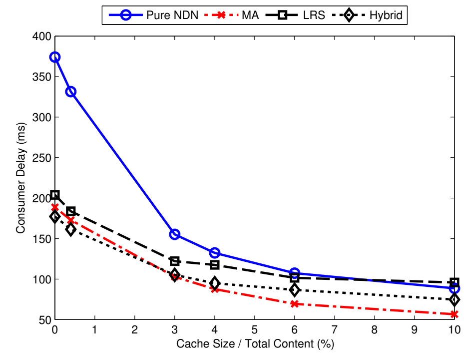


Figure 6: Effect of Cache size with 50% *Producer* Mobility

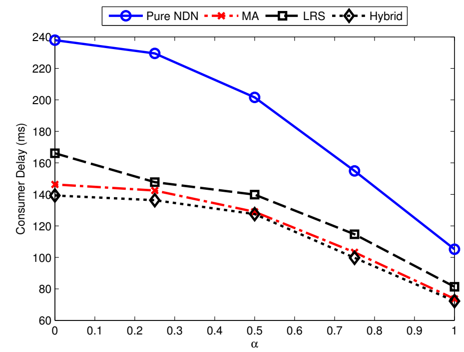


Figure 7: Effect of popularity with 50% *Producer* mobility

6.4 Impact of the Cache Size and Content Popularity

To study the effect of caching on the schemes, another experiment was conducted where the cache size varies from 0 (no caching) to 5000 objects (10% from the total content of all *Producers*) and the mobility ratio is fixed to 50%. The results are shown in Figure 6. Generally, the *Consumer* delay is decreasing with the increase of cache size. Notice that Mobility Anchor is the best scheme to utilize large cache sizes. Specifically, any cache size larger than 4%, Mobility Anchor scheme outperforms all other schemes. As a matter of fact, with larger cache sizes Location Resolution scheme has a very close performance level to pure NDN. The reason behind this is the renaming process in Location Resolution schemes (and Hybrid). For instance, after a mobility event of a *Producer*, it will provide the same content but with a different name, which makes the content with the old name stored in the caches obsolete.

Finally, we investigate the effect of content popularity on *Producer* mobility. As mentioned in Section 5, the Zipf distribution can be used to model the popularity of data requests. To test different content popularities, the parameter α is varied while fixing *Producer* mobility to 50% as shown in Figure 7. Starting with $\alpha = 0$, which means all content has the same popularity, and ending with $\alpha = 1$ (The larger α is, the more popular is some content). As shown in the figure, the delay decreases with the increase of content popularity. This is because the caches in the network will store more popular content. It has the same effect of increasing the cache size.

7. CONCLUSION

Supporting seamless mobility in NDN is a challenge. As shown in this study, and several others, that the development of a mobility management scheme for NDN is inevitable. There are existing *Producer* mobility management schemes in the literature that claim to support seamless mobility, but never investigated or compared to one another. Therefore, we designed and implemented a novel Assessment Framework to be used as a benchmark tool and made available to NDN researchers to investigate existing and future mobility management schemes. The framework was used to compare three main classes of *Producer* mobility management schemes; Mobility Anchor, Location Resolution and Hybrid approaches.

Simulations results show that in the case of low mobility, the three schemes have close *Consumer* delay. However, with mid to high mobility, the Hybrid approach has lower delay than other schemes but at a cost of extra overhead. Mobility Anchor approach has a close *Consumer* Delay and higher Delivery Ratio compared to the Hybrid approach. However, with dense user environments the Mobility Anchor scheme has lower performance than all other schemes. Investigating the effect of cache size on mobility has shown that with larger cache sizes the Mobility Anchor scheme has a shorter *Consumer* delay than the Hybrid approach. Finally, the experiments have shown that the Location Resolution scheme has the lowest performance in all metrics; thus it cannot be used without combining it with another scheme.

Our next step is to design an optimal mobility management scheme to be used as a benchmark solution in the Assessment Framework. In addition to extending the framework to evaluate and compare *Consumer* mobility management schemes.

8. ACKNOWLEDGMENT

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