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Comparative Analysis of Producer Mobility Management Approaches in Named Data Networking

Lamia Alkwai [1,2], Abdelfettah Belghith [2,*], Achraf Gazdar [2] and Saad Al-Ahmadi [2]

1 King Abdulaziz City for Science and Technology (KACST), Riyadh 12354, Saudi Arabia
2 Department of Computer Science, King Saud University, Riyadh 11543, Saudi Arabia
* Correspondence: abelghith@ksu.edu.sa

Abstract: Seamless management of producer mobility in named data networks (NDNs) has become an inherent requirement to satisfy the ever-increasing number of mobile user devices and the streaming of widespread real-time multimedia content. In this paper, we first classify the various producer mobility management (MM) schemes into four different approaches. Then, we select a representative scheme from each approach and conduct a comparative analysis between them to suggest the most suitable producer MM approach for a broad class of latency sensitive applications, such as video and audio streaming and broadcasting over NDNs. To assess and compare the efficiency and effectiveness of the representative schemes, we implemented them in the NDN defacto NdnSIM simulator and used the same network scenarios and mobility settings. The results show the superiority of the producer MM scheme that follows the data plane-based approach, which yielded lower data loss rates, lower data delivery delays and lower signaling overheads.

Keywords: named data networking (ICN); media streaming; producer mobility management; 5G; NdnSIM

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1. Introduction

The fifth-generation mobile network (5G) is the new global wireless standard, succeeding 1G, 2G, 3G, and 4G networks. With the use of 5G, new network technologies are enabled that connect almost everyone and everything, including machines, objects, and devices. Among the many profound requirements of 5G is delivering ultra low latency, higher peak data speeds, and increased reliability, availability, and network capacity [1]. These improved performance measures are to allow new user experiences and to support the demanded industries. While mobility support requirements are already in the scope of 5G standardization, the ability to meet these requirements in practice is more important than ever in light of the exponential growth in the number of mobile devices [2]. Specifically, providing satisfactory performance for 5G's requirements (such as offering high data speeds for a large number of users) while meeting the high 5G mobility requirements introduces extreme challenges to the underlying Internet design [3], as 5G must enable unrestricted user mobility and effective user mobility management (MM) solutions in order to become the new wireless standard adopted globally [4].

This has motivated the research community to explore clean slate Internet architectures which naturally facilitate user mobility. Specifically, when a user's physical location changes, there should not be an impact on the data plane, as is the case in IP [5,6].

Information-centric networking (ICN), which is intended to replace the current IP Internet architecture, is an umbrella term encompassing a number of important architectures, including the promising Named Data Networking (NDN) architecture [7], which is gaining increasing attention due to its simplicity and efficiency. NDN maintains the efficient hourglass architecture of the current Internet but replaces IP addresses with hierarchal or location-independent names, which has simplified the solution to the mobility problem. The NDN architecture is based on the exchange of two packet types—interest and data—managed by three different data structures present in NDN routers: the content store (CS), forwarding information base (FIB), and pending interest table (PIT) [7]. NDN communication is initiated by a consumer sending an interest packet to acquire data. The interest packet is routed using the interest name until the required data packet is found (at the producer or at a cached copy in the network). The data packet is returned to the consumer by following the reverse path taken by the interest packet, thus decoupling the location of the consumer and producer in the communication process.

Due to the decoupling of locations between the data consumers and producers, the NDN architecture fundamentally realizes the essence of consumer mobility management. Location decoupling means that consumers and producers do not have references to each other, nor do they know about each other's location in the network. Therefore, consumer mobility does not require re-establishment of a connection or reassigning addresses, as in the IP architecture. Despite this, it is not implied that mobility management is entirely handled in the NDN architecture. On the contrary, mobility is seen as one of the most challenging aspects of NDN because of the separation between forwarding decisions and the content identifier. Hence, it is evident that producer mobility in NDN is a reachability problem and requires demanding solutions.

Producer mobility is addressed in the original NDN design by prefix announcement, where the producer floods the network to announce its new location in order to update the FIBs in the network after handoff. This solution causes heavy overhead in terms of signaling and bandwidth consumption. Nevertheless, it results in a large handoff delay. Consequently, producer mobility issues require effective solutions, which have been tackled by the research community wherein different producer mobility management approaches have been proposed. Furthermore, applications that are sensitive to end-to-end packet delays are becoming a primary source of today's Internet traffic (including Internet telephony, video conferencing, and networked gaming) [2,8]. Hence, reducing latency is defined as a basic premise of 5G's requirements. This stringent latency requirement brings even more challenges to proposed producer mobility management approaches in NDN.

In general, based on how producer mobility management is performed, the producer MM schemes proposed in the literature may be classified into two broad categories: an anchor based category, which relies on a central entity to handle producer mobility, and an anchorless category, which does not require any central entity to handle producer mobility. Furthermore, anchor-based schemes may follow a rendezvous (RV) approach, in which a central entity keeps track of the location of the mobile producer in the network, or a proxy-based approach, where all communications with a mobile producer must pass through the proxy. Anchorless schemes, on the other hand, may apply either a routing-based approach, which includes updating of the FIBs along the path from the consumer to the producer, or a data-plane based approach, where the path leading to the producer's new location is re-established using the data plane.

Although many producer MM schemes following these four approaches are proposed in the literature, their suitability for handling producer mobility for latency sensitive traffic has yet to be determined. We are motivated to find the best producer mobility management approach to efficiently accommodate the ever-increasing latency-sensitive traffic of media streaming, videoconferencing, and live video and audio broadcasting. This class of latency-sensitive applications requires the most stringent performance requirements, namely negligible data packet loss and data delivery delay.

The main objective of this article is to specify the best-suited producer mobility management approach to transparently and continuously transport latency-sensitive traffic in NDN. The main contributions of this paper can be summarized as follows: follows:

- Classify the producer MM schemes proposed for NDN into four general approaches;
- Select, according to the defined criteria, a representative producer MM scheme from each approach;

- Implement the selected schemes in the ndnSIM simulator and then conduct a comparative analysis to ascertain their effectiveness and suitability for transporting real-time media streaming traffic under the same network topology and mobility settings;
- Show that the data plane is the most suitable producer MM approach that delivers the best seamless streaming of real-time multimedia content.

The organization of this paper is as follows. First, we review the literature in Section 2. Next, we detail the operation of three promising MM schemes, each representative of a different producer MM approach, in Section 3. In Section 4, the simulation set-up, network topology and parameters, and performance metrics are detailed. Following that, we present and discuss the achieved results in Section 5. Lastly, we conclude our with findings and recommendations in Section 6.

2. Related Work

Producer mobility management in NDN has received extensive attention and investigation. There exists a wide range of surveys and reviews in the literature which have synthesized producer MM approaches with different objectives and goals, such as [9–15].

Some of the related literature aimed to compare different producer MM solutions for a specified functional environment. The authors of [16] compared some producer MM schemes for cloud-based environments, while the authors in [17] focused on comparing a couple of producer MM schemes under different network topologies.

We may classify producer MM approaches into two broad categories: anchor-based and anchorless.

In anchor-based producer MM approaches, mobility is handled by a dedicated network entity (referred to as the anchor). This MM design approach works by binding the anchor content names to their locations.

We may further distinguish two groups of the anchor-based approaches proposed in the literature: rendezvous point (RV)- and proxy-based MM approaches.

In general, anchor-based MM approaches do not fit well with the essence of NDN, tying data to locations and requiring a dedicated network entity (the anchor) through which traffic passes. Aside from that, the anchor is a single point of failure and generates the great memory overhead required during the prefix look-up process.

On the contrary to anchor-based approaches, in anchorless approaches, a mobile producer can announce its mobility to the network and regain connectivity without requiring special role nodes. Compared with anchor-based MM schemes, anchorless MM schemes are distributed and do not have special purpose entities or nodes which might become congestion points or single points of failure. Furthermore, anchorless MM schemes are transparent and do not require tampering the interest packets of the consumer or the data packets of the producer. This is important not only to ensure full compatibility to the NDN specification but also to maintain caching capabilities and avoid security vulnerabilities.

The anchorless producer MM approaches proposed in the literature may be further classified into routing-based and data plane-based approaches.

The taxonomy of producer MM approaches is shown in Figure 1.

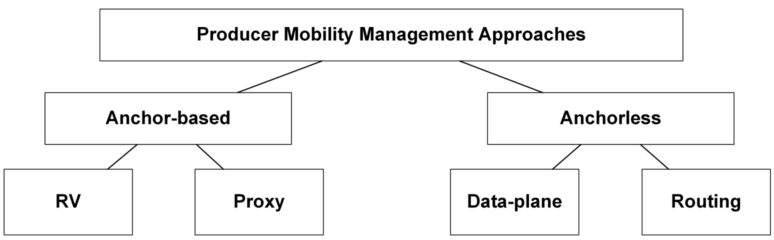


Figure 1. Producer mobility management in the literature.

The variants of each approach are detailed next, and the advantages and disadvantages of the approaches along with the provided literature are summarized in Table 1.

Table 1. Advantages and disadvantages of producer MM approaches.

Approach	Advantages	Disadvantages	References
Rendezvous point	Low signaling overhead Transparent to the consumer	RV is a single point of failure and congestion points Overhead imposed on the RV Optimizing prefix lookup operation required Possible path stretch depending on RV placement	[18–27]
Proxy	Low signaling overhead Transparent to the consumer	Producer nodes are accessed only through a gateway or home agent Interest packets are modified in the gateway to include location prefix Paths are not optimized	[28–31]
Data plane	Does not require dedicated nodes to have special roles	Higher signaling overhead in comparison with RV and indirection point Path stretch determined by relative locations of producer, consumer, and previous producer's PoA More nodes involved in MM	[32–39]
Routing	Does not require added FIB or PIT structure Does not require dedicated nodes to have special roles Paths are optimal	Great signaling overhead under high-mobility environments A mobile producer remains inaccessible during handoff High handoff delay	[40–42]

2.1. Rendezvous Point

In RV-based approaches, mobility is handled by a location resolution system (LRS) residing within a dedicated node, called a rendezvous point (RV), which binds information between the name prefix provided by a content producer and its current location. A mobile producer must send update notifications to the RV, notifying it of its mobility. The consumer must first contact the RV to learn about the location of the producer, and after that, the consumer may send interest packets directly to the producer. This approach encompasses a low signaling overhead, as only update notifications from the mobile producer to the RV are required. In addition, this approach is transparent to the consumer. However, the dedicated RV node is a single point of failure, and a great memory overhead is imposed on the RV because it should handle location-dependent names for each prefix offered by each mobile node. In addition, RV nodes should be strategically placed, because placement greatly affects the path stretch and hence the performance of the approach. Furthermore, in [15], the authors showed that the reactivity time of RV schemes is greater than the round-trip time (RTT), which is a serious matter and may lead to serving consumers with outdated data packets. Aside from violating core NDN principles by binding data to locations via RV nodes, RV approaches also encompass high latency due to the iterative lookup process and the need for RV synchronization.

Proposals under this approach include that in [18], where each producer is associated with a designated RV. When a producer is about to change its location, it notifies the access router to which it is attached by sending a deregistration message. The access router informs the RV about this situation, and the RV holds the pending interests intended for this mobile producer. When the mobile producer attaches to the new access router, it informs the new access router about its assigned RV in order to retrieve the pending interests waiting to be fulfilled by the mobile producer.

In [19], a similar solution was proposed with a focus on reducing unnecessary bandwidth consumption and the prevention of triangular data routing by proposing coordinator-assisted mobility support solutions.

As an improvement to the RV model, in [20], the locator of the consumers is included in the interest packet for the producer to directly inform the consumer about any future mobility. Therefore, when the mobile producer changes its location, it can update the new locator information to all associated consumers without going through the RV.

Additionally, in [22], an improvement to the RV approach was suggested by means of broadcasting the interest between the producer and RV in search of the required data.

In [21], two types of mobility schemes were presented to support seamless producer handoff. The first scheme follows the RV approach, where an additional network entity exists between a mobile producer and a consumer. A new routable prefix is provided after handoff, or packets may be relayed between a mobile producer and a consumer without renaming. This approach suggests that producers do not have constant prefixes; rather, they acquire an available content name by accessing the RV.

In [23], the authors encouraged learning lessons from IP MM, in which a Domain Name Server (DNS) is a practical solution for handling producer mobility efficiently. The authors suggest that a DNS server stores the binding information between a mobile producer and its location. The prefix announced by the mobile producers contains both the content name and the domain in which it is currently located. Consumer interests are forwarded to the DNS to inform about a specific prefix. The DNS replies with the domain prefix through which the mobile producer is found.

In addition, inspired by IP MM, the authors of [24] proposed using a "forwarding hint" to direct interest packets to the mobile producer. Forwarding hints are maintained by an RV which binds hints to prefixes. Furthermore, forwarding hints are only used in case of a cache miss in the CS and the PIT not having an entry for the prefix already.

In [25,26], producer mobility was handled by specified nodes in the network which announce the prefixes of the mobile producer. However, the scheme proposes a namespace design to avoid path stretch when a consumer interest packet reaches the path between the mobile producer and the gateway node. In this situation, consumer interest packets are forwarded toward the mobile producer instead of the gateway node, thus reducing unnecessary path stretch.

The authors in [27] proposed a scenario-aware handoff technique for the mobile producer. In the proposed scheme, the current router and the new router interchange messages before layer 2 handoff. The new router carries the required information of the mobile producer to the RV to carry location update activity for achieving fast registration.

2.2. Proxy-Based Approaches

In these approaches, each producer is accessed only through an indirection point or proxy node, which is responsible for keeping track of a mobile node. The indirection point acts as a relay and forwards interest packets to producers and data packets to consumers by means of tunneling. Consumers reach the data produced by the mobile producer by specifying its identifier, which does not change during the producer's lifetime. The mobile producer informs its assigned indirection point about its location, and the location information is represented as a prefix that guides the interest packet in the path from the indirection point to the mobile producer.

In essence, the main distinction between RV and proxy-based MM solutions is that in proxy solutions, all traffic to and from the mobile producer must go through the assigned proxy. This is because the proxy acts as a relay, forwarding through tunneling both interests to the producer and the data packets coming back.

On the other hand, the traffic to and from the mobile producer does not necessarily go through the RV. An RV contains mapping information between the prefix and its location. The consumer asks the RV first for the location of a prefix and then it sends interests with this location information directly to the producer.

In proxy-based MM, the mobility of a producer node is transparent to the consumer, and minimal signaling is required (only location information updates from a mobile producer to a proxy are required). However, this approach is only applicable when each producer is assigned to a specified proxy and is only accessible through it. In addition, in most cases, interest packets must be modified in the proxy to include the location prefix.

Furthermore, all interest and data packets must go through an indirection point, and thus paths are not optimized regardless of the relative locations of the producer and consumer nodes in the network.

The authors in [28] presented one of the earliest scheme that uses an indirection point to handle producer mobility in NDN. The authors' motivation was to reduce network resource consumption caused by producer mobility by limiting the range of the required network updates.

A variation of this approach was proposed in [30], where a unique locator is assigned to each access router and content is named based on the locator of the access router the producer attaches to. Unlike in the original NDN, a longest prefix match (LMP) lookup in the FIB is performed with respect to the *locator* instead of the interest name, which is contained in a new field tag proposed for interest packets. Therefore, interest packets will be forwarded to the original access router, which will redirect the interest to the required producer by means of tunneling.

In [29], the authors proposed using a neural network model to predict the new locations of producers and calculate routes before producer handoff. The search algorithm is based on location prediction, given the proxy and the traffic features.

Additionally, the authors in [31] proposed a bind information table (BIT) in a home agent responsible for tracking producer (or network) mobility. The BIT acts as a preliminary FIB, and an interest packet refers to the BIT before FIB lookup. Without referring to the FIB, the interest packet is transmitted if there is a match in the BIT. Otherwise, interests are forwarded using the FIB.

2.3. Data Plane-Based Approaches

The common idea of the proposals following this approach is to re-establish the path leading to the producer's new location using the data plane through the use of special packets.

This requires updating the FIBs of the involved routers in the data plane only. The advantage of this approach is that it is compliant with NDN, but it generally results in stretched paths to the producer.

In [32], the authors proposed a producer MM solution that follows this approach. The approach manages the micro mobility of producers for latency-sensitive applications. A producer announces its mobility by sending a special interest packet message to its previous point of attachment (PoA). The network forwards this packet according to the information stored in the FIBs. All routers in the path update their FIBs to include the new location of the mobile producer.

In addition, a similar approach was followed in the work proposed in [37]. Here, a mobile producers sends an announcement to the previously contacted NDN access router whenever it changes the point of attachment. The link is recovered by treating the exchange of the interest and data pair as a transaction unit and exploiting new face states.

The work in [35] also followed the data plane-based approach and proposed publisher mobility support in CCNs (PMC), in which FIB entries are differentiated to distinguish ordinary FIB entries (which are used for stationary producers) from the mobile entries (which are used for mobile producers). Mobile entries are maintained by the PMC protocol, and a namespace is introduced to report producers' mobility.

In [38], the authors targeted the problem of producer mobility for multimedia applications. They differentiated two application domains. The first is stored media, which can benefit from caching, while the other is real-time media, which does not benefit from caching. For both solutions, they work in the data plane to reduce handoff delay.

In [34], the authors propose an MM approach to handle producer and consumer mobility. During producer mobility, a control packet is sent along the reverse direction of the interest packet's transmission path. A control packet uses the face specified in the PIT to propagate and changes the faces in the FIB. Among consumer mobility, a control packet is sent along the reverse direction of the data packet's transmission path. A control packet uses the face specified in the FIB to propagate and changes the faces in the PIT.

A group of efforts under the data plane-based approaches applies location prediction to handle producer mobility in the data plane. The performance of such approaches relies heavily on the accuracy of the prediction model to anticipate the future location of the producer.

In [33], the PoA acts as an interest buffer for the mobile producer by using a locator field in routers. When a producer predicts that it will change its location, it sends a special interest to its PoA to inform it to reserve all incoming interest packets intended for the mobile producer. When the mobile producer reaches a new PoA, it will send another interest packet to the previous PoA containing the locator of its new PoA. Subsequently, the previous PoA will forward interest packets to the new PoA.

The work in [36] also applies a location prediction mechanism, where the producer is responsible for predicting its new PoA based on its speed and direction. When the old PoA receives the mobility notification associated with the new predicted PoA, it is responsible for establishing a path between the old PoA and new PoA in order to redirect consumer interests.

Additionally, in [39], the authors aimed to solve the producer mobility problem in a remote health monitoring service which requires real-time monitoring of patients. The proposed scheme suggests registering the mobile producer not only into the nearest access point but also multiple neighbors, based on a prediction-based neighborhood registration scheme. Therefore, consumer interests are likely to reach a mobile producer even after handoff to a neighbouring access point.

2.4. Routing-Based Approaches

Routing-based approaches require globally updating FIBs to advertise the new location of a mobile node. This imposes a great signaling overhead under high-mobility environments, and the mobile producer remains inaccessible until convergence of the MM scheme, which introduces high delay. On the positive side, in this approach, direct access to a mobile node is achieved without any redirection or path stretch required. However, the complexity is obvious in propagating the location update information in a minimal time.

In [40], MobiCCN was proposed. This is a greedy routing protocol that supports producer mobility by greedily selecting the candidate routers that a mobile node is likely to be accessible through. The candidate routers were selected based on distance measurements of the neighbors of the current router to the destination.

In addition, in [41], mobility support was achieved through a hierarchical name-based scheme. The proposed architecture allows any meaningful space of the name hierarchy to be mobile. Entities under the name space are accessible anywhere in the network. However, location information is propagated through flooding, which imposes a high signaling overhead.

In [42], the authors proposed a producer MM solution for dynamic IoT environments. The proposal is based on two phases: the FIB construction phase and the link recovery phase. In the FIB construction phase, the FIB is modified to include the faces through which a prefix has been requested to be called (out). In the recovery phase, upon producer mobility, a recovery packet is forwarded from the new PoA of the mobile producer. It propagates by applying LPM operation and using the associated (out) face in the FIB, if any. Otherwise, the recovery packet is broadcasted through all available faces. As it traverses, it adds the new forwarding information to the nodes which it visits.

2.5. Which NDN Producer MM Approach Is Best Suited for Latency-Sensitive Applications?

Since a "one-solution-fits-all" method was not built-in for the producer MM in the original NDN design, there is no agreed upon approach that eliminates all possible disadvantages and meets all performance measures.

As discussed above, each producer MM approach retains some advantages and other disadvantages. Nevertheless, precise evaluation of MM schemes should be considered in the context to which it is intended for. The context includes, for instance, a specific network topology, the application the nodes are running, and the mobility pattern of the nodes. Furthermore, in [43], the authors identified 12 factors that affect the performance of an MM scheme, such as changes in name prefixes and in-network caching.

Additionally, different evaluation metrics were targeted in the literature to determine the achieved performance of the proposed schemes. Therefore, different approaches may enhance specific performance metrics at the cost of others.

Therefore, in this study, we aim to find the best producer mobility management approach to efficiently accommodate the ever-increasing latency-sensitive traffic. This class of latency-sensitive applications requires more stringent performance requirements in terms of reduced data packet loss and data delivery delay.

Hence, we analyze and compare three promising producer MM schemes, each representing a different approach. As followed in the conducted literature review in Section 2, we classified producer MM schemes into four approaches: routing, RV, proxy, and-data plane approaches.

The selection of the three schemes was based on their representation of the intended approach, their reported efficiency performance, and the sufficient description of their design in the published work, which allowed us to implement them in NdnSIM.

In our study, among the routing-based approaches, we chose adaptive forwarding-based link recovery for mobility support (AFIRM) [42]. The main idea is to recover request paths by updating the forwarding information after mobility detection.

We choose Map-Me [32] as a representative of the data plane-based approaches. The main idea in Map-Me is allowing interests to follow the micro-level mobility of a mobile producer to enable faster reach and hence minimize delay.

Due to the similarity between RV- and proxy-based solutions, which both fall under the anchor-based category, we chose Kite [26] as a representative of the anchor-based approaches in general. This similarity is seen in the basic design concept requiring an entity with a special role and the similarity in their design advantages and disadvantages, as summarized in Table 1. The main idea in Kite is to create a hop-by-hop trace between a stationary anchor and a mobile producer.

We compare the three schemes under the stringent requirements of delay-sensitive streaming applications. To the best of our knowledge, there exists no previous work that implemented these three schemes in NdnSim and conducted a comparative analysis between them.

In the following section, we describe the design of each scheme in detail.

3. Analysis of Scheme Designs

3.1. AFIRM

The AFIRM scheme is broken down into two phases. The first is FIB construction, which is initiated during network set-up and executed with data packet arrival at the NDN nodes. The second phase is the link recovery, which is performed when producer mobility occurs. We explain each phase next:

- **Scheme Operation**
  1. FIB Construction
     First, during network set-up, flooding is used to broadcast every interest through each face of all nodes until the interest reaches the intended producer. During this time, PIT tables are populated with requesting the faces of each prefix as usual. However, when a data packet arrives at a node, in addition to recording the incoming face as in normal NDN operation, the FIB is modified to include the face through which the data packet departs.
     In NDN, the data packet follows the reverse path of the interest packets by following the faces in the PIT (which indicate the faces leading to the consumer(s)

who requested this data). Therefore, before deleting the entry in the PIT after request fulfillment, the faces associated with this prefix will be copied from the PIT to a column named (out) in the FIB. Furthermore, not only will an entry be added to the prefix, but all sub-prefixes of the name prefix will be included in the FIB.

2. Link Recovery
Each gateway (or PoA) sends periodic interest packets to the sensors attached to it. If it does not receive a data packet within a defined time interval, then it concludes that this sensor is no longer attached. The gateway should create and send a recovery packet whose purpose is to delete the FIB entries which lead to this gateway. Thus, a recovery packet (which is a modified interest packet) follows the faces specified in the (out) column which leads to the consumer. The recovery packet sent by the old gateway is indicated by a tag with a value of zero.
As soon as a gateway detects the attachment of a new sensor, it should create and send a recovery packet whose purpose is to add FIB entries which lead to this gateway. Therefore, a recovery packet (with flag 1) also follows the faces specified in the (out) column which eventually leads to the consumer.
The recovery packets (zero and one) follow the path to the consumers which requested this prefix earlier. In normal NDN, this information is not known to the routers, whereas due to the FIB out column, the faces leading to the interested consumers are preserved.
In general, the specific out face that the recovery packet must travel through is found by performing an LPM (between the prefix in the recovery packet and the prefixes in the FIB).

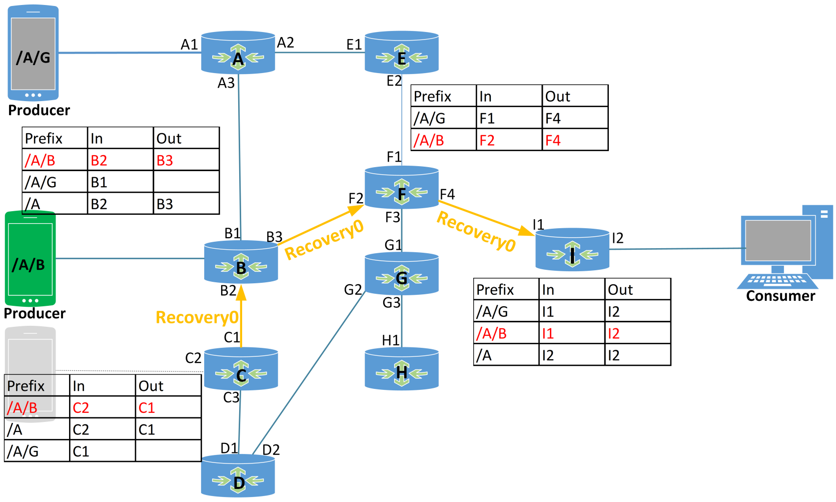
Next, we provide an example of AFIRM operation.

- **AFIRM Example**

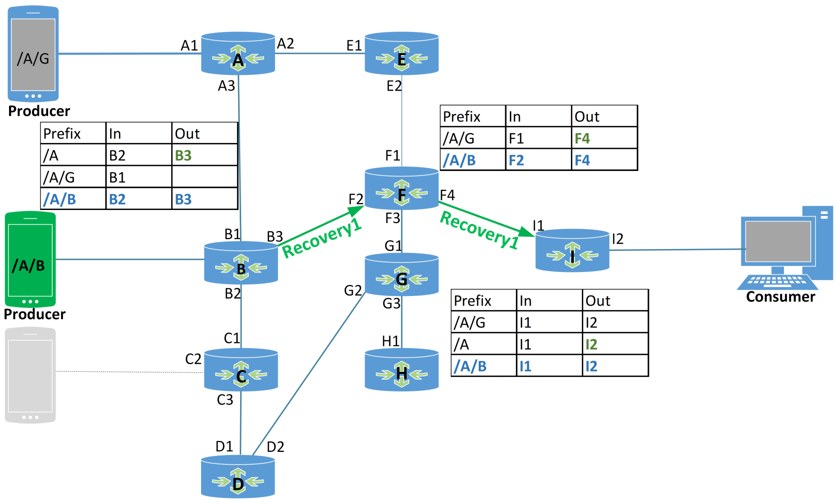
In Figure 2, we show an example of the AFIRM scheme operation among producer mobility. The producer serving the prefix /A/B is attached to PoA C, and the producer serving the prefix /A/G is attached to PoA A. A stationary consumer attached to PoA I is requesting both prefixes. Based on the described FIB construction phase, the FIBs are populated with the prefixes served in the network, and the sub-prefixes (/A) are included in the FIB tables.

As shown in Figure 2a, the out columns are populated with the faces through which the prefix has been requested. Later, the producer of /A/B moves from PoA C to PoA B. As soon as PoA senses the detachment of producer of /A/B, it creates a recovery packet with tag = 0 for the purpose of removing the path leading to the producer at its old PoA. This packet should update the FIB tables of the routers starting at the producer's old PoA reaching the consumer requesting the prefix. As specified in the out column of C's FIB, the face leading to the consumer is C1, so the recovery0 is sent through this face, and the entry associated with /A/B in C's FIB is deleted. Next, the recovery0 reaches PoA B, where the face leading to the consumer is B3, as specified in the out column in the FIB, so the recovery0 is sent through this face, and the entry associated to /A/B is deleted from B's FIB table. This process continues until the recovery0 reaches the consumer, and hence the entries associated with /A/B are removed from the FIBs of the routers in the path from the consumer to the producer's old PoA, as shown (in red) in Figure 2a.

When producer /A/B attaches to PoA B as shown in Figure 2b, B creates a recovery packet with tag = 1 for the purpose of establishing the path between the producer and the consumer. An entry for the prefix /A/B is inserted into B's FIB table, and then a longest prefix match operation between the prefix /A/B and the prefixes in the FIB is performed, which results in the prefix /A. Hence, the out face associated with /A is copied to the out column of /A/B's entry, and the recovery1 is sent through this face (B3) as well. The same operation is performed at routers F and I, leading the recovery1 to the consumer. Thus, an entry associated with prefix /A/B is successfully added in the FIB tables of the routers in the path from the consumer to the producer, as shown (in green) in Figure 2b.



(**a**) AFIRM: recovery0 to delete invalid FIB entry.



(**b**) AFIRM: recovery1 to add correct FIB entry.

Figure 2. Example of AFIRM operation.

3.2. Map-Me

Map-Me is composed of two variant schemes: Map-Me Interest Update (Map-Me-IU) and Map-Me Interest Notification (Map-Me-IN). Map-Me-IU sets the path between the old and new PoA so that any incoming consumer interest packet to the old PoA can be forwarded to the new PoA.

Map-Me-IN includes an additional complementary scheme to IU, which allows for consumer interests to follow a mobile producer as it moves using a "scope discovery" procedure. Map-Me-IN, referred to also as full Map-Me, is based on IN and scope discovery and also deploys the IU technique periodically. An illustrative example of Map-Me operation is shown on Figure 3 and further explained shortly.

- **Scheme Operation**
  Map-Me operations rely on the use of a sequence numbers which is maintained at the producer, initialized to zero, and incremented at each new attachment with a new PoA. Additionally, the sequence numbers are kept in an additional FIB structure within each node, called the temporary FIB buffer (TFIB), to keep a record of the chronological sequence of the mobility of the producer. We describe each of the two schemes next:

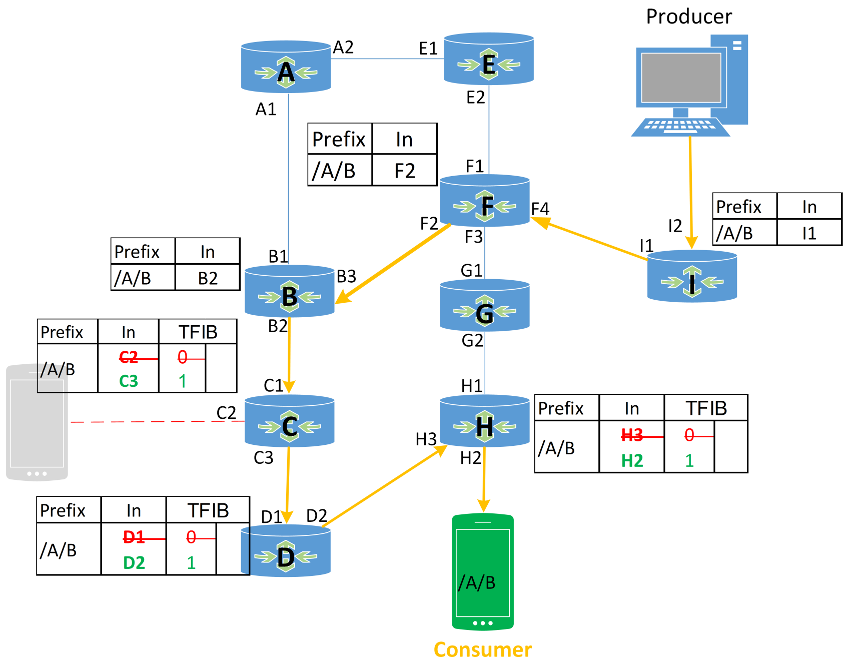
1. Map-Me-IU
   Triggered by producer mobility, and after the attachment of the producer to a new PoA and face creation, a special interest packet called an interest update (IU) is sent from the new PoA to the old PoA by following the name of the prefix advertised by the producer.
   The IU contains a tag field (to recognize it is an IU by the routers) and a copy of the current sequence number at the producer. When the routers receive an IU, the action they take depends on comparing the sequence number of the IU with the sequence number in the TFIB associated with the same prefix.
   If the IU sequence number is greater than the sequence number in the TFIB, then this indicates that the IU is coming from a recent location of the mobile producer. Therefore, the face from which the IU arrived is copied to the FIB, the sequence number is copied in the TFIB, and the IU is further propagated.
   In the second case, if the IU sequence number is smaller than the sequence number in the TFIB, then this indicates that the IU is coming from an older location of the mobile producer, and consequently, the IU is dropped.
   In the third case, if the IU sequence number is equal to the sequence number in the TFIB, the IU is also ignored, as this case may occur as a result of a multicast forwarding.
2. Map-Me (Map-Me-IN)
   Triggered by producer mobility, at each new attachment to an edge PoA, a special interest packet called an interest notification (IN) is sent by the producer. The neighboring PoAs keep a trace of this (a breadcrumb). The IN contains a tag field (to specify it is an IN) and a copy of the current sequence number of the producer. INs are used as breadcrumbs for the ″scope discovery″ process. In this scope discovery, when an interest reaches the old PoA and does not find the producer at the associated face, as indicated in the FIB, the interest is tagged with a "discovery" flag (hence becoming a scope interest) and gets a copy of the sequence number from the TFIB of the old PoA. Then, the scope interest is broadcasted.
   Upon receiving a scope interest, a router first compares the sequence number of the received scope interest and that in its TFIB. In case there is no information about the prefix in the TFIB or a smaller or equal sequence exists in its TFIB, the scope interest packet is dropped. Otherwise, if the TFIB has a higher sequence number than the scope interest packet but there is no valid forwarding information in the FIB, then this means that a recent IN has been attached to this PoA, and the scope interest is moving in the same direction of the producer. Then, the sequence number from the TFIB is copied into the scope interest, which is then further broadcast to the one-hop neighbors. This process is repeated until the producer is found.

Next, we provide an example of Map-Me operation.

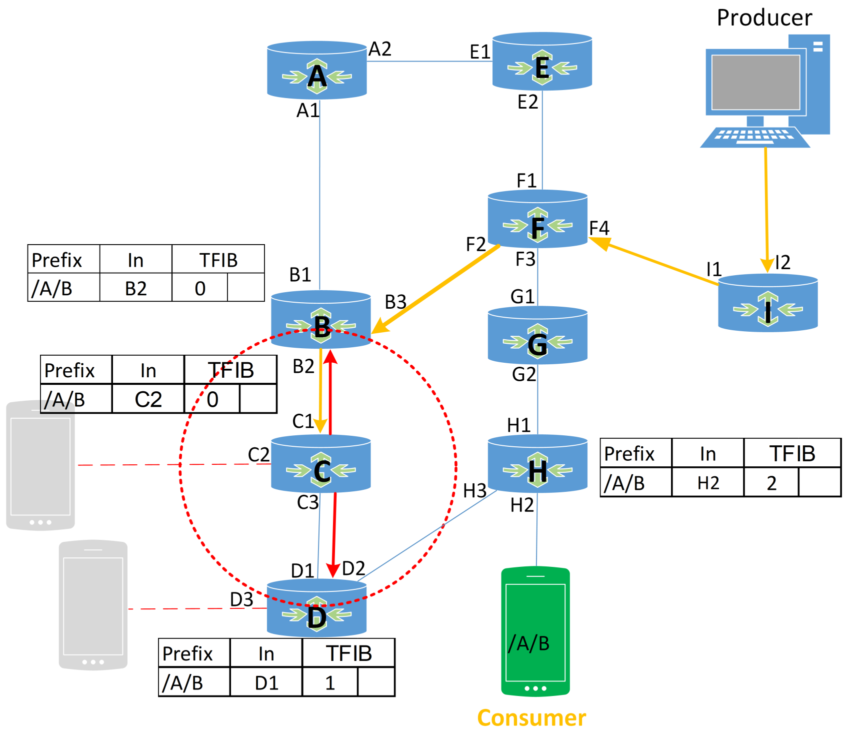
- **Map-Me Example**

An illustrative example of the operation of Map-Me-IU is shown in Figure 3a. The producer moves from PoA C to PoA H. When the producer attaches to PoA H, it first increments the sequence number (from 0 to 1) and then sends an IU using its prefix (/A/B). Therefore, the IU will travel from the producer at its new location (PoA H) to PoA C, as directed by the FIBs.

The reception of the IU at PoA H induces the change in the face associated with the producer's prefix (/A/B) to the incoming face of the IU (H2). The same is performed at PoA D, which changes the face to D2 and finally at C, which changes the face to C3. All these changes are performed after comparing the sequence number in the IU (1) to the sequence number in each PoA's TFIB and finding that the IU indeed holds a higher sequence number. As a result, the path between the old PoA and new PoA is now established, and new incoming consumer interests can reach the producer by following the path I-F-B-C-D-H and finally the producer.



(**a**) Triangular path in Map-Me.



(**b**) Scope discovery in Map-Me.

Figure 3. Example Map-Me operation.

We depict an example of the scope discovery operation in Figure 3b. Here, the producer moves from PoA C to H, passing by PoA D. The producer increments the sequence number and transmits an IN at each attachment to a new PoA. When the consumer's interest reaches C, it finds that the face associated with the required prefix (/A/B) is unavailable (face C2), which indicates that the producer has disassociated from this PoA. Therefore, this interest is tagged as a "scope discovery interest" with a sequence number 0 (as indicated by the TFIB of C) and is broadcast to one-hop neighbors B and D.

When the scope discovery interest reaches PoA B, the sequence number of the scope interest (zero) is compared to the sequence number associated to this prefix in B's TFIB (zero). Therefore, the scope interest is dropped at B. Indeed, the producer did not attach to this PoA during its mobility. However, when the scope discovery interest reaches PoA D, the sequence number of the scope interest (zero) is compared to the sequence number associated to this prefix in D's TFIB (zero). Therefore, the scope interest sequence number is changed to one, and the scope interest further propagates and is broadcast to the one-hop neighbors. The same behavior is pursued at PoA H. The received scope interest has a sequence number of one, which is smaller than the one found in the TFIB of PoA H (two).

As a result, the scope discovery is broadcast after incrementing its sequence number to two. This way, the scope interest reaches the producer at its new PoA (H).

3.3. Kite

The Kite scheme works by setting up a forwarding path from an immobile anchor to a mobile producer. The Kite scheme uses a specific namespace design to make sure interests which cross paths with the trace path (the path between the anchor and the mobile producer) are directed to the mobile producer instead of the anchor to eliminate path stretch. A namespace design was proposed to implement the logic required for scheme operation as described below:

- **Scheme Operation**
  1. Namespace Design
     The prefix announced by the anchor is in the form /routingPrefix, and it notifies the network that this prefix is only reachable through this anchor. The prefix of the data packet generated by the mobile producer is /routingPrefix/tracingPrefix.
     The control packets (trace interest (TI) and trace data (TD)) have the prefixes /routingPrefix/"trace"/tracingPrefix/verificationInfo. The routing prefix is used to direct TIs toward the anchor, and the trace tag is used to differentiate the TI or TD from ordinary interest and data packets. Furthermore, they are easily detected and removed by the routers as necessary, and the verification information is for authenticating the communication between the anchor and the mobile producer.
  2. Trace Set-up
     Every producer is associated with a dedicated anchor which announces the mobile producer's routing prefix in the routing plane. After handoff, the mobile producer sends a TI to its assigned anchor. A TI is an interest packet with a special "/trace" tag in the name field. This TI will be directed to the anchor based on the LPM.
     The anchor responds with a TD, which travels back to the mobile producer following the reverse path of the TI. The TD serves as an acknowledgment to the TI, since it has the same prefix of the earlier TI. In addition, in intermediate routers between the anchor and mobile producer, upon receipt of a TD, a forwarder treats it as a regular data packet, matches it against the PIT entries, and forwards it downstream if a match is found. The routers then search for the "/trace" tag in the TD's name field. If the tag is found, then the "/trace" prefix is extracted from the name.
     The router then updates the FIB using the prefix and the incoming face of the corresponding TI. The trace is in a soft state and will be purged if not refreshed, so the mobile producer needs to actively keep the trace alive by resending TIs.
     Consumers' interests are forwarded toward the anchor, unless they have reached a node in the trace path. In this case, the router's FIB will have two entries for the prefix: one for the announced prefix of the anchor and the other resulting from the TI or TD exchange. The entry set by the anchor announcement leads toward

the anchor, and the entry set during the TI or TD exchanges leads toward the mobile producer, but since the latter will result in a longer prefix match, the consumer interest will be forwarded toward the mobile producer, thus eliminating unnecessary path stretch.

After producer mobility from its current PoA, the intermediate routers in this trace will lead to the old location of the mobile producer (thus called a stale trace), which will result in a NACK sent back to the consumer. To avoid going to the stale trace again, a forwarding strategy is proposed to forward an interest to a face indicated by the shorter prefix match instead of the LPM, unless it results in the face from which the interest arrived to avoid looping. This will forward the interest to the anchor, which will direct the interest to the correct location of the mobile producer.

Next, we provide an example of Kite's operation:

- **Kite Example**

  We show an example of Kite's operation in Figure 4. We assume two consumers: consumer1 attached to PoA C and consumer2 attached to D, as shown in Figure 4a. The anchor advertises for prefix /A, which is the routing prefix. Therefore, all routers in the network add an entry for /A in their FIB tables leading to the anchor.

  The producer of prefix /A/B is at PoA B and has established a verified trace via the exchange of TI or TD with the anchor. Thus, the routers in the branch from the anchor to the producer have the entry /A/B in their FIB tables associated with the face from which the TI arrived, "which is the face leading to the producer". If consumer2 is interested in /A/B, then it issues an interest with the name /A/B. This interest reaches router D, which preforms LPM and results in forwarding the interest through face D1, as specified in the FIB.

  We can see that router D only has an entry for the routing prefix /A advertised by the anchor. The interest reaches the anchor and thus is forwarded through F1. Eventually, this interest reaches the producer by traversing routers A and B.

  It can be seen that since consumer2 is not in the same sub-tree of the producer (rooted at the anchor), the interest must go through the anchor to find the producer.

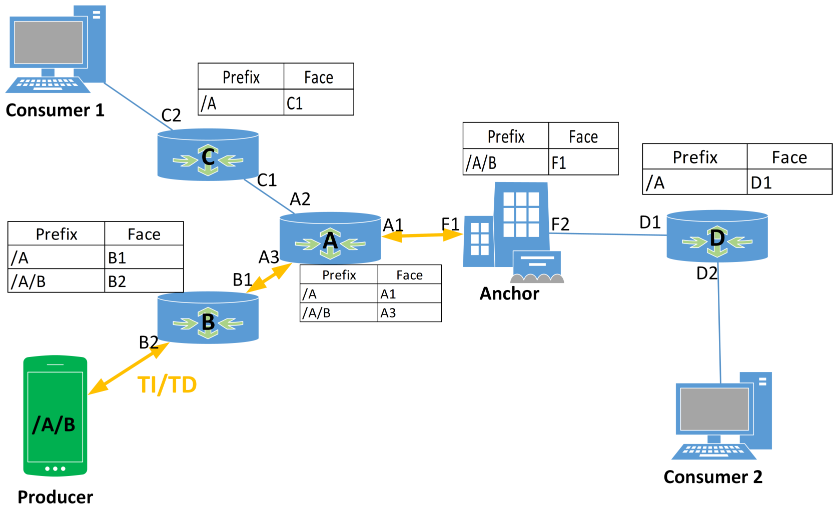
  On the other hand, consumer2 is in the same sub-tree as the producer (rooted at the anchor), and therefore, the interest path intersects with the established trace path leading to the producer. Specifically, as the interest /A/B reaches router A, it is forwarded through face A3, because it resulted from the LPM. It is also forwarded through face B2 at router B by the same logic, eventually reaching the producer.

  In Figure 4b, the producer has relocated from router B to router D. Since the previous trace path was not refreshed by the periodic TI/TD exchange, the entry associated to /A/B expired and was thus removed from the FIBs of routers A and B. Therefore, the interests of consumer2 are correctly directed toward the anchor rather than the producer's old location.

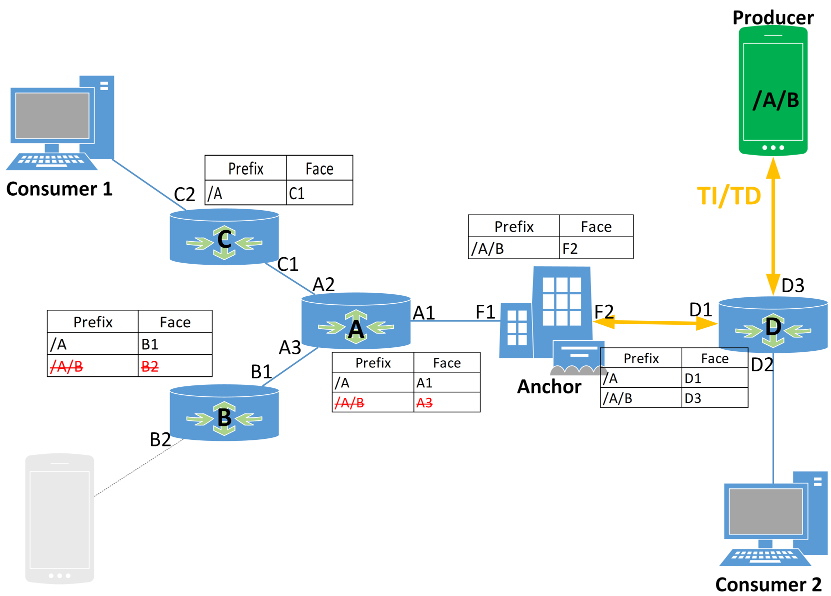
  However, if consumer1's interest arrives before the expiry of the entry /A/B at router A, then it will be led to the producer's old location, thus resulting in a NACK at routers A, B, and C.

  Upon the arrival of NACK, and based on the forwarding strategy, A should resend the interest to face A1 this time, which leads to the anchor, and then to the producer at its new location.

  In addition, the producer establishes a trace path from its new location to the anchor. Hence, consumer2's interests are now directly forwarded to the producer without going through the anchor.



(**a**) Path shortcut in Kite to mitigate triangular route.



(**b**) Forwarding strategy in Kite to mitigate stale trace issue.

Figure 4. Example Kite operation.

4. Simulation Set-Up and Evaluation Metrics

For the purpose of evaluating the different schemes considered in this study, we used the ndnSIM 2.1 simulator [44,45], as ndnSIM is a modular NDN simulator that implements all basic NDN operations and is based on the NS-3 network simulator. We implemented AFIRM, Map-Me, Map-Me-IU, and a relaxed version of Kite (which we refer to as R-KITE) to compare their performances using the same network scenarios and mobility settings.

We evaluated all three schemes in the exact same settings to guarantee evaluation fairness.

We relaxed some specifications of Kite to represent the general anchor-based solutions. Our decision was based on the following observations and considerations:

- Kite's trace-based mechanism is useful in situations where the consumer interest arrivals are sparse and the producer is moving at a low mobility speed. However, when these conditions are not met (either high consumer interest arrival rates or a high producer mobility speed), the consumer interest may arrive before expiry of the old trace. Hence, the trace-based mechanism downgrades the scheme's operation. This can be seen in the case where consumer interests are mistakenly forwarded to the producer's old PoA instead of the anchor. Retransmitted interests will continue to be mistakenly forwarded until the old trace expires [46].

- Even when new routing information to the producer's new PoA is available at the anchor and a new trace is established, the aforementioned situation still holds. Specifically, for all consumers in the same sub-tree of the producer's old PoA (rooted at the anchor), interests are mistakenly forwarded to the old PoA until the associated trace expires. This is a direct result of Kite's design choice in passively managing stale traces and leaving it up to the expiry of the trace, instead of providing an active mechanism to remove the stale traces upon producer dissociation.
- Although a forwarding strategy was proposed to reduce the negative affect of the described situation, we aim to provide a fair comparison of the schemes, where the default NDN strategies and setting are applied.

Therefore, the relaxed version of Kite is indeed a general representative of anchor-based solutions which require a special node to handle producer mobility. Consequently, this allowed us to make general conclusions about the performance of the broader anchor-based category.

We describe the simulation topology, applied parameters, and evaluation metrics in the following sections.

4.1. Topology and Parameters

We considered a real-time streaming application where the producers broadcasted a sequence of data packets to requesting consumers. We conducted a comparative analysis between the three producer MM schemes using a fat tree network topology while considering different producer mobility speeds. The producers were set to keep streaming a video medium at a constant bit rate of 1 Mbps. The data packets were assumed to be 1024 bytes in length. This amounted then to a constant traffic rate of 128 data packets per second emanating from the producer.

The used topology in our scenario was a fat-tree back-haul network, shown in Figure 5. The tree had three levels of routers: 1 core (router 1), 4 backhaul (routers 2–5), and 8 access (routers 6–13). Two PoAs (or base station (BSs)) were connected to each edge router, with a total of 16 PoAs (PoAs 0–15).

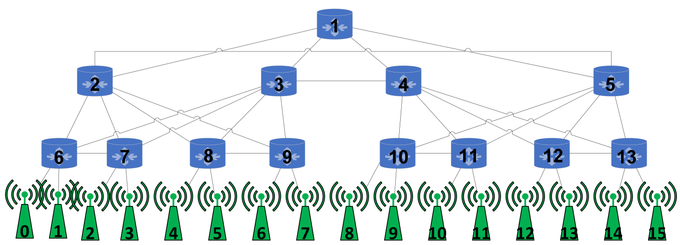


Figure 5. Simulation topology.

The BSs operated on 5GHz frequencies and used the IEEE 802.11n access network. As shown in Figure 6, they were placed in a 4 × 4 grid with one BS in each cell and the size of the cell being 80 × 80 m. The random waypoint (RWP) mobility model [47] implemented in the NS-3 simulator was the applied mobility model. In this model, a mobile producer randomly selects a destination point (a way point) from the 320 × 320 m global grid and then moves in a straight line at a constant speed in that direction. After arriving, the mobile producer pauses for a period before choosing a new location and speed and continuing in the same direction. Hence, the mobile producer relocates from one PoA (BS) to another while moving in accordance with the RWP model.

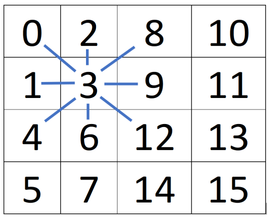


Figure 6. Layout of base stations.

Five pairs of producers and consumers were used. The links had a capacity of 10 Mbps and end-to-end delay of 5 ms.

Table 2 summarizes the various simulation parameters.

Table 2. Simulation parameters.

Category	Parameters	Value
Mobility	Mobility model Number of producer Number of consumers	Random waypoint 5 5
NDN	Streaming rate Packet size Request rate Application	1 Mbps 1024 bytes 128 request/s Streaming audio or video
Network	4 × 4 fat tree Link delay Bandwidth	80 × 80 m cell size 5 ms 10 Mbps
Set-up	Simulation duration Warm-up duration	3000 s 100 s

4.2. Evaluation Metrics

To evaluate the performance of the different MM schemes, several evaluation metrics which measured their effectiveness from different perspectives were used. We explain the evaluation metrics next.

- Average Data Packet Retrieval Delay

The data packet retrieval delay is the time delay between the consumer issuing the interest packet and the arrival of the requested data packet to the consumer. This delay is measured for each associated interest-data pair and then averaged over the total number of received data packets. Shorter delays indicate faster handoff management of the MM scheme because the route to the mobile producer was re-established successfully in shorter time. The data retrieval delay obviously affects the QoS perceived by the consumer application and should be minimized as much as possible.

- Average Hop Count

The ratio between the optimum potential path through the network and the actual path taken by traffic is known as the path stretch. The optimal path is the shortest possible path between two nodes in the network (the producer and the consumer in our case). The hop count represents the path length and is measured by the average number of (router) hops a data packet traverses from the producer to the consumer.

After producer mobility, an effective MM scheme would assure reachability to the mobile producer by a path that has a low stretch. We used the average hop count as one of the metrics to assess the performance of an MM scheme, as it is an important metric and has a direct impact on other evaluation metrics, such as the delay. Specifically, a certain delay in data delivery may result from the increase in the path length caused by the underlying MM scheme.

- Data Loss Rate

The streaming producers generated data packets with a constant rate, such as 128 packets per second. A data packet that was generated but did not arrive at its requesting consumer was considered a lost data packet. The data loss rate is then the number of data packets that have not arrived at their requesting consumers over the total number of data packets sent by the producers. Packet loss is the number of unfulfilled interest packets, which in the simulation was equivalent to the number of interest packet retransmissions.

A packet may be lost due to either producer mobility, network congestion, or wireless collisions. Due to producer mobility, some interest packets may not find the mobile producer, because the FIB tables may lead interest packets to the old location of the producer. A producer MM scheme should react to producer mobility promptly and update the network to make the mobile producer reachable. Fast reachability of a mobile producer guarantees replying with the requested data packet and thus reducing packet loss.

- Signaling Overhead

This is the additional signaling packets per handoff required by the MM scheme to complete its operations. Although the signaling overhead does not really describe the effectiveness and efficiency of an MM scheme, it should be rather minimized to better utilize the network resources. What is more, the signaling overhead may sometimes have an inverse relationship with other evaluation metrics. This is because more messages may help a scheme to perform better in a targeted evaluation metric at the expense of additional network traffic.

5. Results

The resulting data retrieval delay from the producer mobility as a function of speed are shown in Figure 7 when handled by the AFIRM, Map-Me-IU, Map-Me-IN, and R-Kite schemes.

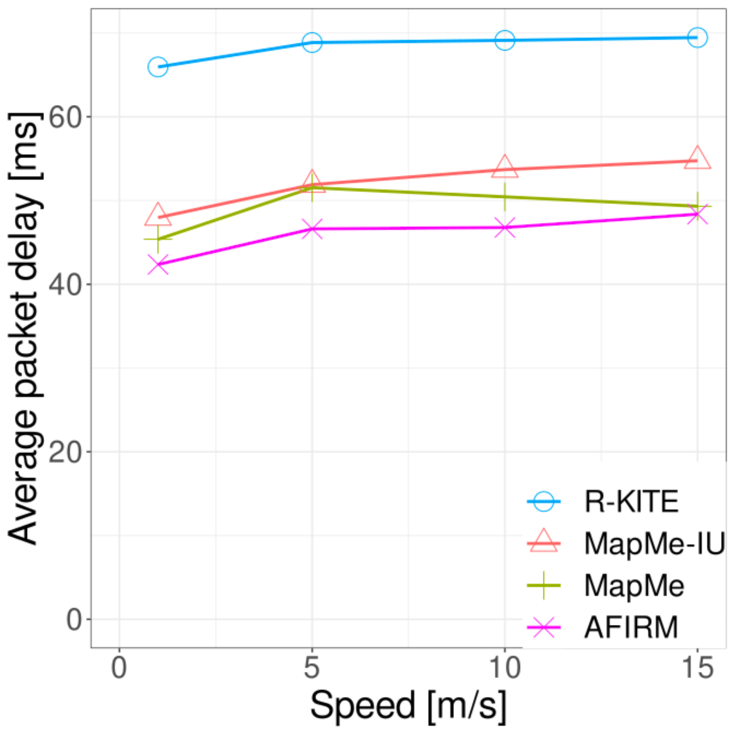


Figure 7. Data retrieval delay.

As we can see, the highest delay was for R-Kite. This was due to the existence of an anchor, and all interest packets had to pass through this central entity in order to reach the producer. This was required regardless of the relative geographical location of the producer and consumer in the network. In the worst cases, the consumer was near the producer, but both were far away from the anchor. In such situations, the interest packet must travel all the way from the consumer to the anchor, and the data packet follows the reverse of this same long path.

We must note that producer mobility had little affect on the resulting data retrieval delay in the case of the R-Kite scheme, and this was because a consumer had to query the anchor about the location of the producer upon every request. Although the mobile producer needed to only propagate a mobility notification to the central anchor, the consumer interest had to go through the anchor regardless in all communications.

The variations of Map-Me (Map-Me and Map-Me-IU) both caused lower data delays of about 50 ms, whereas Map-Me achieved a slightly lower delay. This was due to the fast reactivity of the Map-Me variations, which were operating on edge PoAs instead of propagating mobility notifications to a central anchor as in R-Kite.

AFIRM achieved the lowest delay, indicating its having the fastest reactivity to producer mobility in addition to the advantage of the followed optimal paths.

Furthermore, we noticed that the slopes of all schemes were not affected much by the mobility speed of the producer. This was because the data retrieval delay was calculated for every interest-data pair for data packets that arrived at the consumer only. Although producer mobility may cause interest loss (as we will show shortly), this does not affect the calculation of the data retrieval delay.

Figure 8 shows the average hop count taken by data packets from a mobile producer to a consumer when the producer mobility was handled by the different schemes as a function of the producer mobility speed.

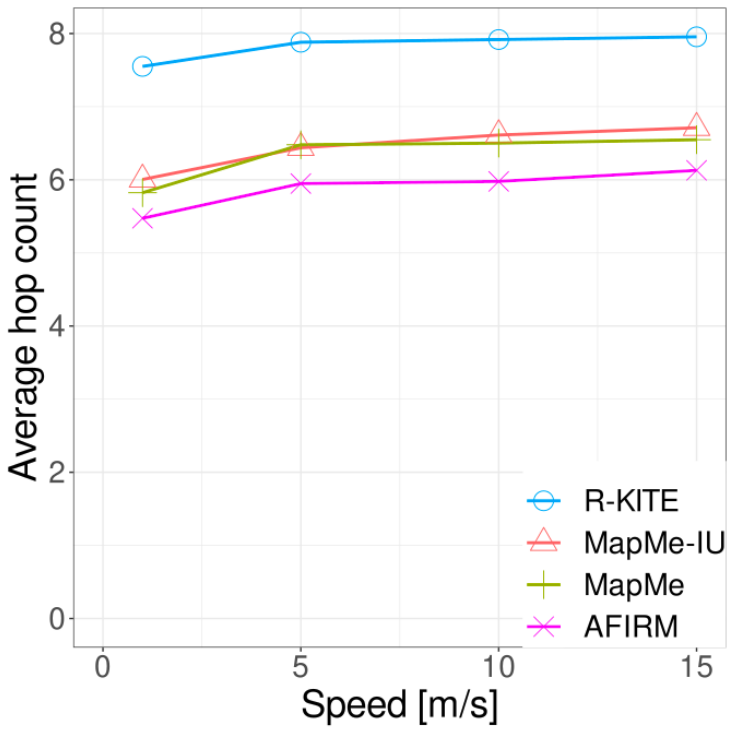


Figure 8. Average hop counts.

The results shown here are in agreement with the average packet delay results in Figure 7. We can see that the hop count for the R-Kite approach was the highest, and the hop count for AFIRM was the lowest. Although Map-Me is known to generate triangular paths, the seen path stretch was not high, given that the topology was a fat tree and a producer attached to PoAs which were leaves of the tree.

In Figure 9, the resulting data loss rates as a function of the producer mobility speed are shown. Although packet loss may be caused by either producer mobility, network congestion, or wireless collisions, fixing the simulation parameters (streaming rate, link delay, etc.) for all producer MM schemes allowed us identify the performance of the producer MM schemes.

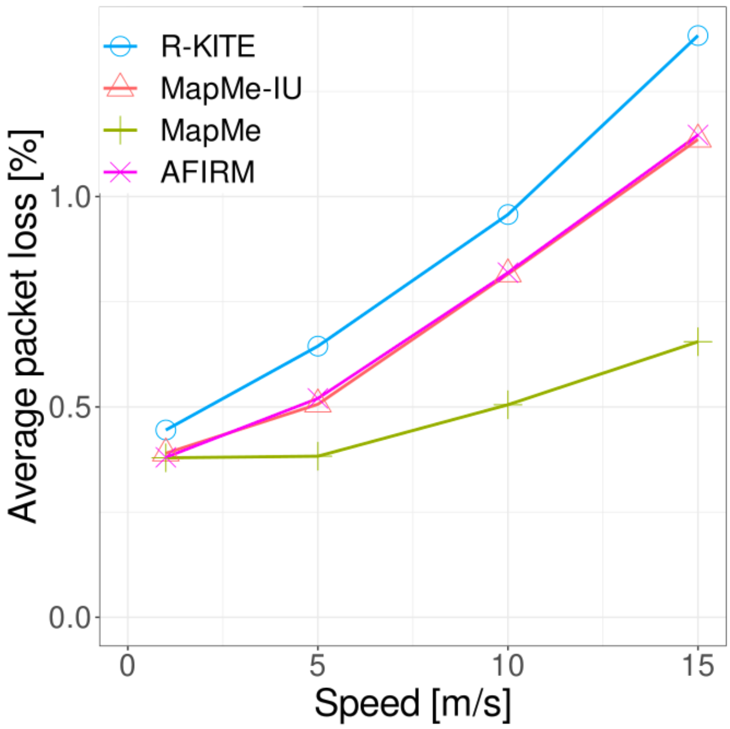


Figure 9. Data loss rates.

We can observe that the loss rate for all schemes increased with the producer speed, which was due to the decreased ability of the producer MM scheme to handle the more frequent mobility events.

Indeed, the producer-chasing nature of the full Map-Me variant yielded the lowest loss rate but certainly with the expense of the overhead caused by the broadcast of IN packets in scope discovery. AFIRM and Map-Me-IU resulted in higher loss rates than Map-Me, and the justification is obvious in the case of Map-Me-IU, given that scope discovery and producer chasing were not performed.

However, for AFIRM, the loss rate was higher than that for Map-Me because the producer was only reachable once the recovery1 packet reached a router that resided in the path from the producer's old PoA to the consumer. If the path between the consumer and the mobile producer's new location does not cross with the path leading to the mobile producer's old location, then no sub-prefix exists in the FIB that may guide the forwarding process. Therefore, the recovery1 packet may require more propagation to update the FIBs to the producer's new PoA in order to make the producer reachable again.

R-Kite resulted in the highest loss rate because, upon every producer handoff, a producer was inaccessible until the mobility notification reached the central anchor.

Figure 10 portrays the required signaling overhead for each producer handoff, which is shown for each node class (as explained in the simulation topology). This means that the shown overhead was calculated as the ratio of the number of messages over the number of routers in each class. Certainly, this was averaged for all handoff events during the simulation.

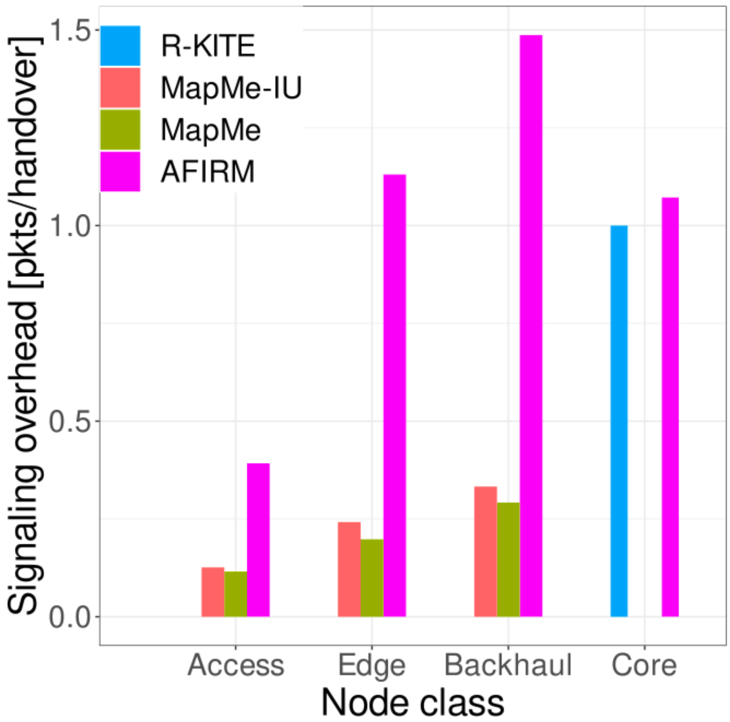


Figure 10. Signaling overheads.

Indeed, the signaling overhead for the Map-Me variations was lower than AFIRM in the access, edge, and backhaul classes. Map-Me-IU only requires IU packets to traverse between the producer's new PoA and its old PoA. In addition, no Map-Me-IU signaling overhead propagates to the core router because the scheme works on edge routers. However, although it was foreseen that Map-Me-IN would generate a higher overhead than Map-Me-IU, due to the use of IN packets, this did not hold in the shown figure. The reason for this was that IN packets were excluded from counting, as they did not propagate further than the access routers and thus it did not generate overhead in the network. Additionally, the scope discovery interest broadcasting was performed in a specific situation where the consumer interest reached the old PoA before the IU packets. Therefore, only a few instances of the scope discovery process were performed during the simulation duration, and thus the amount of signaling overhead caused by scope discovery was negligible.

AFIRM noticeably generated the highest overhead. The high overhead seen here was a result of the naming scheme applied in our simulation, which drastically degraded AFIRM's performance in the signaling overhead metric.

The AFIRM scheme was proposed for IoT sensors, where the name prefixes have many common sub-prefixes (to indicate a common site of the IoT sensors for example). This naming scheme was not applied in our simulation, and the name prefixes of the producer are of one syllabus (*/prefix0* for instance). Therefore, the flooding process in the "FIB construction phase" would not generate any sub-prefixes. Thus, no additional hints about the producer would exist in the FIBs other than the original one-syllabus prefix. Furthermore, upon recovery0 propagation, the only hint associated with the producer was deleted from the path. Thus, recovery1 was broadcasted in most routers due to lack of any matching prefix in the FIB.

As for R-Kite, the overhead seen in the figure was in the core router only. Although a mobility notification packet must propagate from the producer's new PoA all the way to the anchor, the number of messages (=1) averaged over the the number routers in each class yielded a negligible value. This held for all node classes except for the core class, where there existed only one core router, resulting in a signaling overhead value of exactly one.

6. Conclusions

In this paper, we conducted a comparative analysis between three promising producer MM schemes, each representing a different approach: AFIRM (routing-based), Map-Me (data plane-based), and Kite (anchor-based).

We ascertained and compared the performance of the schemes to accommodate latency-sensitive and real-time applications. These applications generate traffic classified according to its sensitivity to latency and do not benefit from network caches due to their real-time nature. We evaluated, using NdnSIM, all three schemes with the same network, traffic, and mobility settings.

The results showed that the data plane-based approach represented by the Map-Me scheme held the right balance to handle producer mobility in delay-sensitive applications. The routing-based approach yielded a negligible, slightly lower data retrieval delay at the cost of a much higher overhead.

Further investigations can be conducted using different network topologies and for various specific environments. One such environment is that of vehicular ad hoc networks (Vanet) where road side units (RSU) act as central entities, and hence the anchor-based category may prevail. The question arises, however, of the conformity of the NDN specifications and the implementation in ndnSIM.

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