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MAP-Me : Managing Anchorless Mobility in Content Centric Networking
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Abstract

Mobility has become a basic premise of network communications, thereby requiring a native integration into 5G networks. Despite numerous efforts to propose and standardize effective mobility-management models for IP, the result is a complex, poorly flexible set of mechanisms. The natural support for mobility offered by ICN (Information Centric Networking) makes it a good candidate to define a radically new solution relieving limitations of the traditional approaches. If consumer mobility is supported in ICN by design, in virtue of its connectionless pull-based communication model, producer mobility is still an open challenge. In this document, we focus on two prominent ICN architectures, CCN (Content Centric Networking) and NDN (Named Data Networking) and describe MAP-Me, an anchor-less solution to manage micro-mobility of content producers via a name-based CCN/NDN data plane, with support for latency-sensitive applications.

Status of This Memo

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1. Introduction

With the phenomenal spread of portable user devices, mobility has become a basic requirement for almost any communication network as well as a compelling feature to integrate in the next generation networks (5G). The need for a mobility-management paradigm to apply within IP networks has striven a lot of efforts in research and standardization bodies (IETF, 3GPP among others), all resulting in a complex access-dependent set of mechanisms implemented via a dedicated control infrastructure. The complexity and lack of flexibility of such approaches (e.g. Mobile IP) calls for a radically new solution dismantling traditional assumptions like tunneling and anchoring of all mobile communications into the network core. \changes{This is particularly important with the increase in rates and mobile nodes (IoT), a vast amount of which never moves.}

The Information Centric Network (ICN) paradigm brings native support for mobility, security, and storage within the network architecture, hence emerging as a promising 5G technology candidate. Specifically on mobility management, ICN has the potential to relieve limitations of the existing approaches by leveraging its primary feature, the redefinition of packet forwarding based on _names_ rather than on _network addresses_. We believe that removing the dependence on location identifiers is a first step in the direction of removing the need for any anchoring of communications into fixed network nodes, which may considerably simplify and improve mobility management. Within the ICN paradigm, several architectures have been proposed, as reported in [xylomenos2014survey] and [ahlgren2012survey].

As a direct result of CCN/NDN design principles, consumer mobility is natively supported}: a change in physical location for the consumer does not translate into a change in the data plane like for IP. The retransmission of requests for data not yet received by the consumers takes place without involving any signaling to the network. Producer mobility and realtime group communications present more challenges, depending on the frequency of movements, latency requirements, and content lifetime. The topology does not reflect the naming structure, and we have to preserve key functionalities such as multipath, caching, etc. In all cases, beyond providing connectivity guarantees, additional transport-level mechanisms might be required to protect the flow performance (see [carofiglio2016mwldr] for instance).

MAP-Me aims at tackling such problems by exploiting key CCN/NDN characteristics. Previous attempts have been made in CCN/NDN (and ICN in general) literature to go beyond the traditional IP approaches, by using the existing CCN/NDN request/data packet structures to trace producer movements and to dynamically build a

reverse-forwarding path (see [NDN-survey] for a survey). They still rely on a stable home address to inform about producer movements or on buffering of incoming requests at the producer's previous point of attachment -- PoA --, which prevents support for latency-sensitive streaming applications. We focus on this class of applications (e.g. live streaming or videoconferencing) as they have the most stringent performance requirements: negligible per-packet loss-rate and delays. In addition, they typically originate from a single producer and don't allow for the use of caching.

MAP-Me defines a name-based mechanism operating in the forwarding plane and completely removing any anchoring, while aiming at latency minimization. It has the following characteristics:

o MAP-Me addresses micro (e.g. intra Autonomous Systems) producer mobility. Addressing macro-mobility is a non-goal of the proposal. We are focusing here on complementary mechanisms able to provide a fast and lightweight handover, preserving the performance of flows in progress.

o MAP-Me does not rely on global routing updates, which would be too slow and too costly, but rather works at a faster timescale propagating forwarding updates and leveraging real-time notifications left as breadcrumbs by the producer to enable live tracking of its position. For simplicity, we use the word 'producer' in place of the more correct expression producer name prefixes. The objective being the support of high-speed mobility and real-time group applications

o MAP-Me leverages core CCN/NDN features like stateful forwarding, dynamic and distributed Interest load balancing to update the forwarding state at routers, and relaying former and current producer locations.

o MAP-Me is designed to be access-agnostic, to cope with highly heterogeneous wireless access and multi-homed/mobile users.

o Finally, low overhead in terms of signaling, additional state at routers, and computational complexity are also targeted in the design to provide a solution able to scale to large and dynamic mobile networks.

MAP-Me performance has been thoroughly analyzed and provides guarantees of correctness, stability and bounded stretch [MAPME].

2. State-of-the-art and benefits of anchorless mobility solutions

Many efforts have been made to define mobility-management models for IP networks in the last two decades, resulting in a variety of complex, often not implemented, proposals. A good survey of these approaches is [RFC6301]. Likewise, within the ICN family, different approaches to mobility management have been presented [tyson2013survey].

When facing high-frequency mobility, those so-called Resolution-Based (RB) approaches present a similar trade-off: for every packet the consumer has to resolve the producer's location or use stale information and run the risk to reach an old position, incurring in timeout, or Nack, etc.

Specifically for the CCN/NDN solutions, several surveys of mobility-management approaches can be found [NDN-survey], [feng2016mobility]. In [NDN-survey] for instance, the authors distinguish three categories of solutions -- routing, mapping, and tracing-based -- depending on the type of indirection point (also called Rendez-Vous, RV). We build on such classification and extend it to distinguish a fifth class of approaches not relying upon the existence of any anchor point as the RV (Anchor-less approaches):

Routing-based (RT) solutions rely on intra-domain routing, and require updating all routing in the AS after a mobile's movement. Scalability of these solutions is widely recognized as a concern which explains why they are usually ruled out, in particular for CCN/NDN where the name space is even larger than IP.

Resolution-based (RB) solutions rely on dedicated RV nodes (similar to DNS) which map content names into routable location identifiers. To maintain this mapping updated, the producer signals every movement to the RV node. Once the resolution is performed, packets can be correctly routed from the consumer along the shortest path, with unitary path stretch (defined as the ratio between the realized path length over the shortest path one). Requiring explicit resolution, together with a strict separation of names and locators, RB solutions involve a scalable CCN/NDN routing infrastructure able to leverage forwarding hints; however, scalability is achieved at the cost of a large hand-off delay as evaluated e.g. in due to RV update and name resolution. To summarize, RB solutions show good scalability properties and low stretch in terms of consumer to producer routing path, but result to be unsuitable for frequent mobility and for reactive rerouting of latency-sensitive traffic, which are key objective of MAP-Me.

Anchor-based (AB) proposals are inspired by Mobile IP, and maintain a mapping at network-layer by using a stable home address advertised by a RV node, or anchor. This acts as a relay, forwarding through tunneling both interests to the producer, and data packets coming back. Advantages of this approach are that the consumer does not need to be aware of producer mobility and that it has low signaling overhead because only the anchor has to be updated. It however inherits the drawbacks of Mobile IP -- e.g. triangular routing and single point of failure -- and others more specific to the CCN/NDN context: potential degradation of caching efficiency, bad integrity verification due to the renaming of content during movement. It also hinders multipath capabilities and limits the robustness to failure and congestion initially offered by the architecture. In contrast, MAP-Me maintains names intact and avoid single point-of-passage of the traffic.

Tracing-based (TB) solutions allow the mobile node to create a hop-by-hop forwarding reverse path from its RV back to itself by propagating and keeping alive traces stored by all involved routers. Forwarding to the new location is enabled without tunneling. Like AB though, this approach assumes that the data is published under a stable RV prefix.

Anchor-less (AL) approaches allow the mobile nodes to advertise their mobility to the network without requiring any specific node to act as a RV. They are less common and introduced in CCN/NDN to enhance the reactivity with respect to AB solutions by leveragingzhang2014kite CCN/NDN name-based routing. The PoA starts buffering incoming Interests for the mobile producer until a forwarding update is completed and a new route is built to reach the current location of the producer. Enhancement of such solutions considers handover prediction. Besides the potentially improved delay performance w.r.t. other categories of approaches, some drawbacks can be recognized: buffering of Interests may lead to timeouts for latency-sensitive applications and handover prediction is hard to perform in many cases. In contrast MAP-Me reacts after the handoff, without requiring handover prediction, and avoids Interests buffering but introduces network notification and discovery mechanism to reduce the handoff latency.

3. Design principles

MAP-Me is an anchor-less, name-based, layer-2 agnostic approach operating at forwarding plane designed according to the following design principles:

- Transparent: MAP-Me does not involve any name nor modifications to basic request/reply operations to be compatible with standard CCN/NDN design and to avoid issues caused by name modifications like triangular routing, caching degradation, or security vulnerabilities.

- Distributed: MAP-Me is designed to be fully distributed, to enhance robustness w.r.t. centralized mobility management proposals subject to single point-of-passage problem.

- Localised: MAP-Me updates affect the minimum number of routers at the edge of the network to restore connectivity. The goal is to realize effective traffic off-load close to the end-users.

- Lightweight: MAP-Me mobility updates are issued at prefix granularity, rather than content or chunk/packet granularity, to minimize signaling overhead and temporary state kept by in-network nodes;

- Reactive: MAP-Me works at forwarding layer to enable updates in FIBs at network latency, i.e. round-trip time scale. Specific mechanisms are defined, referred to as network notifications and discovery, to maximise reactivity in mobility management in case of real-time producer tracking and of latency-sensitive communications;

- Robust to network conditions (e.g. routing failure, wireless or congestion losses, and delays), by leveraging hop-by-hop retransmissions of mobility updates.

4. MAP-Me description

As a data plane protocol, MAP-Me handles producer mobility events by means of dynamic FIB updates with the objective of minimizing unreachability of the producer. It relies on the existence of a routing protocol responsible for creating/updating the FIB of all routers, possibly with multipath routes, and for managing network failures [NLSR].

MAP-Me is composed of:

an Update protocol (MAP-ME-IU) (Section Section 5), which is the central component of our proposal;

a Notification/Discovery protocol (Section Section 6), to be coupled with the Update protocol (the full approach is referred to as MAP-ME) to enhance reactivity in mobility management for realtime/latency-sensitive application.

5. Update protocol

5.1. Rationale

The rationale behind MAP-Me is that the producer announces its movements to the network by sending a special Interest Packet, named Interest Update (IU) to "itself" after it reattaches to the network. Such a message looks like a regular Interest packet named with the prefix advertised by the producer. As such, it is forwarded according to the information stored in the FIBs of traversed routers towards previous locations of the producer known by router FIBs. A special flag carried in the header of the IU enables all routers on the path to identify the Interest as a mobility update and to process it accordingly to update their FIBs (a detailed description of the IU processing is provided in Sec. Section 8.

The key aspect of the proposal is that it removes the need for a stable home address (present in Tracing-Based approaches for instance) by directly leveraging name-based forwarding state created by CCN/NDN routing protocols or left by previous mobility updates. FIB updates are triggered by the reception of mobility updates in a fully distributed way and allow a modification on-the-fly to point to the latest known location of the producer.

5.2. Update propagation

MAP-ME-IU aims at quickly restoring global reachability of mobile prefixes with low signaling overhead, while introducing a bounded maximum path stretch (i.e. ratio between the selected and the shortest path in terms of hops).

Let us illustrate its behavior through the example in Figure Figure 1, where a single producer serving prefix /p moves from position P0 to P1 and so on. Figure Figure 1 (a) shows the tree formed by the forwarding paths to the name prefix /p where IU initiated by the producer propagates.

```
                     +---+                        +---+
                     | 0 | P0                      | 0 | P0
                     +---+                         +---+
                      ^ ^                           ^ ^
                     /   \                         /   \
                 +---+    +---+                +---+    +---+
                 | 0 |    | 0 |                | 0 |    | 0 |
                 +---+    +---+                +---+    +---+
                  ^ ^                           ^ ^
                 /   \                         /   \
```

```
                    +---+    +---+                +---+    +---+
                    | 0 |    | 0 |                | 0 |    | 0 |
                    +---+    +---+             A  +---+    +---+
                     ^ ^                  IU1 /    ^ ^
                    /   \                    /    /   \
                +---+    +---+          .... .+---+.   +---+
                | 0 |    | 0 |         .   P1 | 1 | .  | 0 |
                +---+    +---+        .       +---+ .  +---+
                 ^ ^                  .        ^ ^    .
                /   \                 .       /   \     .
            +---+    +---+            .   +---+    +---+  .
            | 0 |    | 0 |            .   | 0 |    | 0 |  .
            +---+    +---+            .   +---+    +---+ .
                                       ..................

                     (a)                       (b)

                                                   .................
                            +---+               ...       +---+     ..
                            | 0 | P0           .          | 1 | P0    .
                            +---+             .        A  +---+       .
                             ^ ^             .  IU(1) /    / ^        .
                            /   \            .       /    V   \       .
                        +---+    +---+      .        +---+    +---+  .
                        | 0 |    | 0 |     .         | 1 |    | 0 |  .
                        +---+    +---+    .       A  +---+    +---+  .
                         ^ ^              . IU(1) /    / ^           .
                        /   \            .       /    V   \         .
            ........+---+.   +---+      .         +---+    +---+   .
           .        | 1 | .  | 0 |     .          | 1 |    | 0 |   .
          .  FIB    +---+ .  +---+    .        A  +---+    +---+   .
         . updated   / ^   .          . IU(1) /    / ^            .
         .          V   \   ....      .      /    V   \          .
         .      +---+    +---+  .     .       +---+    +---+   .
         .  P1  | 1 |    | 0 |  .     .    P1 | 1 |    | 0 |   .
         .      +---+    +---+  .     .       +---+    +---+   .
         .       ^ ^            .     .        ^ ^            .
         .      /   \          .       .      /   \         .
         .  +---+    +---+    .        .  +---+    +---+  .
         .  | 0 |    | 0 |   .         .  | 0 |    | 0 |  .
         .  +---+    +---+  .          .  +---+    +---+  .
          ..................            ..................

                     (c)                       (d)

                            +---+
                            | 1 | P1
                            +---+
```

```
                           ^  A  ^
                         /    |    \
                    +---+   +---+   +---+
                    | 0 |   | 0 |   | 1 |
                    +---+   +---+   +---+
                                     ^ ^
                                    /   \
                                +---+    +---+
                                | 0 |    | 1 |
                                +---+    +---+
                                          ^ ^
                                         /   \
                                     +---+    +---+
                                 P0  | 1 |    | 0 |
                                     +---+    +---+
                                      ^
                                     /
                                 +---+
                                 | 0 |
                                 +---+

                              (e)
```

Figure 1: IU Propagation example

Network FIBs are assumed to be populated with routes toward P0 by a name-based routing protocol. After the relocation of the producer from P0 to P1, once the layer-2 attachment is completed, the producer issues an IU carrying the prefix /p and this is forwarded by the network toward P0 (in general, toward one of its previous locations according to the FIB state of the traversed routers).

Figure Figure 1 (b) shows the propagation of the IU. As the IU progresses, FIBs at intermediate hops are updated with the ingress face of the IU (Figure Figure 1 (c) and (d)). IU propagation stops when the IU reaches P0 and there is no next hop to forward it. The result is that the original tree rooted in P0 becomes re-rooted in P1 (Figure Figure 1 (e)). Looking at the different connected regions (represented with dotted lines), we see that IU propagation and consequent FIB updates have the effect of extending the newly connected subtree (represented as a red cloud): at every step, an additional router and its predecessors are included in the connected subtree. The properties of the update propagation process in terms of bounded length and stretch are studied in [MAPME].

5.3. Concurrent updates

Frequent mobility of the producer may lead to the propagation of concurrent updates. To prevent inconsistencies in FIB updates, MAP-Me-IU maintains a sequence number at the producer end that increases at each handover and identifies every IU packet. Network routers also keep track of such sequence number in FIB to verify IU freshness. Without detailing the specific operations in MAP-Me to guarantee update consistency (whose description is provided in Section Section 8, we can say that modification of FIB entries is only triggered when the received IU carries a higher sequence number than the one locally stored, while the reception of a less recent update determines a propagation of a more recent update through the not-yet-updated path.

An example of reconciliation of concurrent updates is illustrated in Figure Figure 2 (f), when the producer has moved successively to P1 and then to P2 before the first update is completed.

```
                            +---+                         +---+
                            | 0 | P0                      | 2 | P0
                            +---+                      A  +---+
                             ^ ^                IU(2) /    / ^
                            /   \                    /    V   \
                        +---+    +---+                +---+    +---+
                        | 0 |    | 0 |           <!>  | 2 |    | 0 |
                        +---+ A  +---+             A  +---+ A  +---+
                         ^ ^   \            IU(1) /    ^ \   \
                        /   \   \  IU(2)         /    /   V   \ IU(2)
                    +---+    +---+                +---+    +---+
                    | 0 |    | 2 | P2             | 1 |    | 2 |
                 A  +---+    +---+             A  +---+    +---+
          IU(1) /    ^ ^                  IU1 /    / ^
               /    /   \                    /    V   \
                +---+    +---+                +---+    +---+
             P1 | 1 |    | 0 |             P1 | 1 |    | 0 |
                +---+    +---+                +---+    +---+
                 ^ ^                            ^ ^
                /   \                          /   \
            +---+    +---+                +---+    +---+
            | 0 |    | 0 |                | 0 |    | 0 |
            +---+    +---+                +---+    +---+

                     (f)                       (g)

                            +---+                      +---+
                            | 2 | P0                   | 2 | P2
                            +---+                      +---+
```

```
                             / ^                         ^
                            V   \                        |
                        +---+    +---+                 +---+
                    <!> | 2 |    | 2 |                 | 2 |
             IU(2)  /   +---+    +---+                 +---+
                   /     ^ \                           ^   ^
                  V     /   V                         /     \
                    +---+    +---+                +---+     +---+
                    | 2 |    | 2 | P2         P0  | 2 |     | 2 |
          IU(2)  /  +---+    +---+                +---+     +---+
                /    / ^                           ^         ^ ^
               V    V   \                         /    P1   /   \
                +---+    +---+                 +---+    +---+   +---+
             P1 | 1 |    | 0 |                 | 0 |    | 2 |   | 0 |
                +---+    +---+                 +---+    +---+   +---+
                 ^ ^                                     ^ ^
                /   \                                   /   \
            +---+    +---+                          +---+    +---+
            | 0 |    | 0 |                          | 0 |    | 0 |
            +---+    +---+                          +---+    +---+

                     (h)                                 (i)
```

Figure 2

Both updates propagate concurrently until the update with sequence number 1 (IU(1)) crosses a router that has been updated with fresher information -- that has received IU with higher sequence number (IU(2)) as in Figure Figure 1 (g). In this case, the router stops the propagation of IU(1) and sends back along its path a new IU with an updated sequence number (Figure 1 (h)). The update proceeds until ultimately the whole network has converged towards P2 (Figure 1 (i)).

MAP-Me-IU protocol reacts at a faster timescale than routing -- allowing more frequent and numerous mobility events -- and over a localized portion of the network edge between current and previous producer locations. We thus expect MAP-Me-IU respectively to minimize disconnectivity time and to reduce the link load, which are the main factors affecting user flow performance, as show in [MAPME] evaluations.

6. MAP-Me Notification/Discovery protocol

IU propagation in the data plane accelerates forwarding state re-convergence w.r.t. global routing (GR) or resolution-based (RB) approaches operating at control plane, and w.r.t. anchor-based (AB) approaches requiring traffic tunneling through the anchor. Still,

network latency makes IU completion not instantaneous and before an update completes, it may happen that a portion of the traffic is forwarded to the previous PoA and dropped because of the absence of a valid output face leading to the producer.

Previous work in the Anchor-Less category has suggested the buffering of Interests at previous producer location to prevent such losses by increasing network reactivity. However, such a solution is not suitable for applications with stringent latency requirements (e.g. real-time) and may be incompatible with IU completion times. Moreover, the negative effects on latency performance might be further exacerbated by IU losses and consequent retransmissions in case of wireless medium. To alleviate such issues, we introduce two separate enhancements to MAP-Me-IU protocol, namely (i) an _Interest Notification_ mechanism for frequent, yet lightweight, signaling of producer movements to the network and (ii) a scoped _Producer Discovery_ mechanism for consumer requests to proactively search for the producer's recently visited locations.

6.1. Interest Notification

An Interest Notification (IN) is a breadcrumb left by producers at every encountered PoA. It looks like a normal Interest packet carrying a special identification flag and a sequence number, like IUs. Both IU and IN share the same sequence number (producers indistinctly increase it for every sent message) and follow the same FIB lookup and update processes. However, unlike IU packets, the trace left by INs at the first hop router does not propagate further. It is rather used by the discovery process to route consumer requests to the producer even before an update process is completed.

It is worth observing that updates and notifications serve the same purpose of informing the network of a producer movement. \changes{The IU process restores connectivity and as such has higher latency/ signaling cost than the IN process, due to message propagation. The IN process provides information to track producer movements before update completion when coupled with a scoped discovery. The combination of both IU and IN allows to control the trade-off between protocol reactivity and stability of forwarding re-convergence.

6.2. Discovery

The extension of MAP-Me with notifications relies on a local discovery phase: when a consumer Interest reaches a PoA with no valid output face in the corresponding entry, the Interest is tagged with a _discovery_ flag and labeled with the latest sequence number stored in FIB (to avoid loops). From that point on, it is broadcasted with hop limit equal to one to all neighbors and discarded unless it finds

the breadcrumbs left by the producer to track him (notifications). The notifications can either allow to forward consumer Interests directly to the producer or give rise to a repeated broadcast in case of no valid output face. The latter is the case of a breadcrumb left by the producer with no associated forwarding information because the producer has already left that PoA as well. A detailed description of the process is reported in Section 8.

The notification/discovery mechanism proves important to preserve the performance of flows in progress, especially when latency-sensitive.

6.3. Full approach

The full approach is a combined update and notification/discovery approach consisting of sending a IN immediately after an attachment and a IU at most every Tu seconds, referred to as MAP-Me, to reduce signaling overhead especially in case of high mobility. The update-only proposal, denoted as MAP-Me-IU, is equally interesting on its own and might be a fit depending on the use case.

7. Implementation

In this section we describe the changes to a regular CCN/NDN architecture required to implement MAP-ME and detail the above-described algorithms. This requires to specify a special Interest message, additional temporary information associated to the FIB entry and additional operations to update such entry.

7.1. MAP-Me Messages

Two new optional fields are introduced in a CCN/NDN Interest header:

- a special _Interest Type_ (T) to specify four types of messages: Interest Updates (IU), Interest Notifications (IN), as well as their associated acknowledgment (Ack) messages (IU_Ack and IN_Ack). Those flags are recognized by the forwarding pipeline to trigger special treatment;

- a _sequence number_ to handle concurrent updates and prevent forwarding loops during signaling, and to control discovery interests' propagation;

7.2. MAP-Me additional Network Information

FIB entries are enriched with a sequence number, initialized to 0, say, by routing protocol and updated by MAP-Me upon reception of IU/IN messages. The Data about not-yet-acknowledged messages are temporarily stored in what we denote as _Temporary FIB buffer, or

TFIB_, to ensure reliability of the process, and removed upon reception of the corresponding acknowledgement.

As sketched in Figure Figure 3, each TFIB entry is composed of an associative array (F -> T) mapping a face F on which IU has been sent with the associated retransmission timer T (possibly Null). Note that the update mechanism is a constant delay operation at each router and is performed at line rate.

```
         IU (IN) input face(s)            IU (IN) output face

   +-----------+------------------+.......+.......................+
   |  /prefix  |  { next hop(s) }  |  seq  |  { face : rx_timer }  |
   +-----------+------------------+.......+.......................+
    \______________ ________________/ \______________ ______________/
                  V                                 V
             original FIB                      TFIB section
```

Figure 3: MAP-ME FIB/TFIB description

8. Algorithm description

8.1. IU/IN transmission at producer

MAP-Me operations are triggered by producer mobility/handover events. At the producer end, a mobility event is followed by a layer-2 attachment and, at network layer, a change in the FIB. More precisely, a new face is created and activated upon attachment to a new PoA. This signal triggers the increase of MAP-Me sequence number and the transmission of an IU or IN for every served prefix carrying the updated sequence number.

To ensure reliable delivery of IUs, a timer is setup in the temporary section of the FIB entry (TFIB). If an acknowledgement of the IU/IN reception is not received within t seconds since the packet transmission, IU is retransmitted.

We define the SendReliably(F, type, E) function fpr sending Special Interests of a given type on faces F based on FIB entry E. It schedules their retransmission through a timer T stored in TFIB: E.TFIB = E.TFIB U (F -> T) and removed on Ack.

8.2. IU/IN transmission at network routers

At the reception of IU/IN packets, each router performs a name-based Longest Prefix Match lookup in FIB to compare sequence number from IU/IN and from FIB}. According to that comparison:

- o if the IU/IN packet carries a higher sequence number, the existing next hops associated to the lower sequence number in FIB are used to forward further the IU (INs are not propagated) and temporarily copied into TFIB to avoid loss of such information before completion of the IU/IN acknowledgement process (in case of IN, such entries in TFIB are set with a $\bot$ timer to maintain a trace of the producer recent attachment). Also, the originating face of the IU/IN is added to FIB to route consumer requests to the latest known location of the producer.

- o If the IU/IN packet carries the same sequence number as in the FIB, the originating face of the IU/IN is added to the existing ones in FIB without additional packet processing or propagation. This may occur in presence of multiple forwarding paths.

- o If the IU/IN packet carries a lower sequence number than the one in the FIB, FIB entry is not updated as it already stores 'fresher information'. To advertise the latest update through the path followed by the IU/IN packet, this one is re-sent through the originating face after having updated its sequence number with the value stored in FIB.

8.3. Hop-by-hop IU/IN acknowledgement

The operations in the forwarding pipeline for IU/IN processing are reported in Figure 4.

```
| Algorithm 1 : ForwardSpecialInterest(SpecialInterest SI, Ingress face F)
|
|  CheckValidity()
|  // Retrieve the FIB entry associated to the prefix
|  e, T <- FIB.LongestPrefixMatch(SI.name)
|  if SI.seq >= e.seq then
|  .   // Acknowledge reception
|  .   s <- e.seq
|  .   e.seq <- SI.seq
|  .   SendReliably(F, SI.type + Ack, e)
|  .   //Process special interest
|  .   if F in e.TFIB then
|  .   .   // Remove outdated TFIB entry (eventually cancelling timer)
|  .   .   e.TFIB = e.TFIB \ F
|  .   if SI.seq > s then
|  .   .   if SI.type == IU then
|  .   .   .   // Forward the IU following the FIB entry
|  .   .   .   SendReliably(e.NextHops, SI.type, e
|  .   .   else
|  .   .   .   // Create breadcrumb and preserve forwarding structure
|  .   .   .   e.TFIB = e.TFIB U {( f -> NULL) : for all f in e.NextHops}
|  .   .   e.NextHops = {}
|  .   e.NextHops = e.NextHops U { F }
|  else
|  .   // Send updated IU backwards
|  .   SI.seq = e.seq
|  .   SendReliably(F, SI.type, e)
```

Figure 4

8.4. Face removal at producer/network nodes

Upon producer departures from a PoA, the corresponding face is destroyed. If this leads to the removal of the last next hop, then faces in TFIB with Null timer (entries generated by notifications) are restored in FIB to preserve the original forwarding tree and thus global connectivity.

8.5. Consumer request forwarding in case of producer discovery

The forwarding of regular Interests is mostly unaffected in MAP-Me, except in the case of discovery Interests that we detail in Figure 5. The function SendToNeighbors(I) is responsible for broadcasting the Interest I to all neighboring PoAs.

```
| Algorithm 2:  InterestForward(Interest I, Origin face F)
|
|  // Regular PIT and CS lookup
|  e <- FIB.LongestPrefixMatch(I.name)
|  if e = 0 then
|  .   return
|  if I.seq = 0 then
|  .   // Regular interest
|  .   if hasValidFace(e.NextHops) or DiscoveryDisabled then
|  .   .   ForwardingStrategy.process(I, e)
|  .   else
|  .   .   // Enter discovery mode
|  .   .   I.seq <- e.seq
|  .   .   SendToNeighbors(I)
|  else
|  .   // Discovery interest: forward if producer is connnected
|  .   if hasProducerFace(e.NextHops) then
|  .   .   ForwardingStrategy.process(I, e)
|  .   // Otherwise iterate iif higher seq and breadcrumb
|  .   else if e.seq >= I.seq and EXISTS f | (f -> NULL) in e.TFIB then
|  .   .   I.seq <- e.seq
|  .   .   SendToNeighbors(I)
```

Figure 5

When an Interest arrives to a PoA which has no valid next hop for it (because the producer left and the face got destroyed), it enters a discovery phase where the Interest is flagged as a Discovery Interest and with the local sequence number, then broadcasted to neighboring PoAs.

Upon reception of a Discovery Interest, the PoA forwards it direcly to the producer if still attached, otherwise it repeats the one-hop brodcast discovery to neighboring PoAs if it stores a recent notification of the producer presence, i.e. an entry in TFIB having higher sequence number than the one in the Discovery Interest. Otherwise, the Discovery Interest is discarded.

It is worth observing that the discovery process is initiated only in the case of no valid next hop, and not every time a notification is found in a router. This is important to guarantee that the notification/discovery process does not affect IU propagation and completion.

9. Security considerations

All mobility management protocols share the same critical need for securing their control messages which have a direct impact on the forwarding of users' traffic. [compagno2017secure] reviews standard approaches from the literature before developing a fast, lightweight and distributed approach based on hash chaining that can be applied to MAP-Me and fits its design principles.

10. Acknowledgements

11. Contributors

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12. IANA Considerations

This memo includes no request to IANA.

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