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                    Anchorless mobility through hICN
                     draft-auge-dmm-hicn-mobility-03

Abstract

   This document first discusses the use of locators and identifiers in
   mobility management architectures, and their implication on various
   anchorless properties.  A new architecture is then proposed that is
   purely based on identifiers, and more specifically names as defined
   in Hybrid-ICN (hICN) [I-D.muscariello-intarea-hicn].  The document
   then focuses on two main cases: the end-point sends data (data
   producer) or the end-point receives data (data consumer).  These two
   cases are taken into account entirely to provide anchorless mobility
   management in hICN.

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1.  Introduction

   New usages of the network and the rapid growth of the Mobile Internet
   calls to reconsider the way we deploy and operate IP networks, where
   mobility is not built into the design, but rather added as an
   afterthought.  Notable examples are IETF Mobile IP and its variants
   [RFC3344] and [RFC3775] 3GPP GTP-based architecture [TS29.274], both
   based on tunnelling and encapsulation.

   One identified difficulty in proposing mobility models for IP lies in
   the semantic overloading of IP addresses which are both host
   identifiers, and locators used for routing.  Starting with LISP, the
   identifier/locator split paradigm has shown promising results in
   virtue of its scalability properties with respect to routing tables
   entries, and the possibilities it offers in terms of mobility.
   Several solutions have been proposed around this concept, namely
   ILNP, ILSR, and ILA.  One common facet of these proposals is to
   embrace the current trend of a clear separation between the control
   and data planes, which both allows for distribution of the control
   infrastructure, as well as anchorless operations in the data plane,
   including facilitated local breakout.

   The counterpart of these architectures is an increased dependency on
   the control plane which is responsible for binding the identifiers
   used by the application at the edge to the locators used to forward
   the traffic in the network.  Device mobility will typically induce a
   change of IP address, which makes performance of flows in progress
   dependent on interactions with those control elements which have to
   remain globally consistent.

   In this document, we first propose to clarify protocol descriptions
   by adopting a new terminology of control-plane and data-plane anchors
   to characterize anchorless operations, and show their tight coupling
   with the use of locators and identifiers.  This definition serves to
   position Loc/ID-split architectures with respect to the traditional
   use of tunnels, before advocating to push this step further and
   perform mobility management purely based on identifiers.  We
   introduce a mobility approach based on Hybrid ICN (hICN) as described
   in [I-D.muscariello-intarea-hicn], for which we perform an in-depth
   analysis of mobility considerations.  We show how this proposal can
   help addressing further challenges faced by networks today, such as
   multihoming and multipath, while preserving the simplicity and end-
   to-end design of the current Internet.

2.  Locators, identifiers and anchorless mobility management

2.1.  Terminology

   The consideration of mobility in network design shares the challenges
   raised for routing for instance in [RFC6115], where the terminology
   for locators and identifiers is presented.

   Because they are intrinsically bound to the topological location of a
   node, session established through locators require additional
   mechanisms to support mobility, including the presence of anchor
   points in the network.  The notion of _anchor_ and the resulting
   _anchorless_ properties of mobility schemes are prone to different
   interpretation depending on the context.  The following definitions
   attempt to reconcile those interpretations and propose a unifying
   terminology used throughout this document.

   Anchor  An anchor refers to a specialized node or service, possibly
      distributed, functionally required by a network architecture for
      forwarding or mobility.  This is in contrast to decentralized
      architectures.  Configuration of these anchors, including their
      location, will directly affect the overall scheme performance.  We
      follow the classic distinction between control plane and user (or
      data, or forwarding) plane to distinguish control-plane anchors
      and user-plane anchors.

   User-plane anchor  A user-plane anchor is a node through which
      traffic is forced to pass.  An example of such anchor is the
      indirection point in Mobile IP.

   Control-plane anchor  A control-plane anchor refers to a node that is
      not responsible for carrying traffic, but is needed for the
      operation of the forwarding and/or the mobility architecture.  An
      example of such anchor is the resolution or mapping service of
      LISP.  We remark that while not being on path, such anchors might
      affect the performance of the user-plane due to resolution delays
      or indirection (following a mapping cache miss for instance).

   Anchorless  This term qualifies approaches that do not involve any
      user-plane not control-plane anchor.  The challenge for such full
      anchorless approaches are exacerbated during mobilty of both end
      points at the same time, as they cannot rely on any stable anchor
      point to preserve connectivity.  Nor they can rely on routing
      mechanism that would be the source of overhead and instability.

2.2.  Towards locator-independent network architectures

   We distinguish network architectures based on their use of location
   independent identifiers (or names) and locators for forwarding.

*Locator-based architectures*

As mentioned earlier, IP architectures are typically operated based
on locators corresponding to the IP addresses of the host interfaces
in their respective network attachment, used also as session
identifiers.  This results in a complex mobility architecture built
on top, involving traffic anchors and tunnels to preserve the
identifier exposed to the transport layer: IP/IP or GRE tunnels in
Mobile IP, and GTP tunnels in 3GPP architectures.

The limitations of locator-based schemes in terms of complexity,
overhead and efficiency are well-recognized and led to other
alternatives to be considered.

*Locator-ID separation architectures*

LISP [RFC6830] was the first proposal to distinguish between the
usage of IP addresses as locators or identifiers by explicitly
defining two namespaces, respectively used for endpoint
identification and forwarding.  A mapping service is further used to
bind an identifiers to a given location, and updated after mobility.
From there, several approaches have been defined, either host-based
like SHIM6 [RFC5533] or HIP [RFC4423]), or network-based, like LISP
[RFC6830], ILSR, ILNP [RFC6740] or ILA [I-D.herbert-intarea-ila] to
cite a few.

An overview of these approaches and their use in mobility is
presented in {?I-D.bogineni-dmm-optimized-mobile-user-plane}}.

The main challenge consists in maintaining a (distributed) mapping
service at scale, including the synchronization of local caches
required for scalability and efficiency.

*ID-based architectures*

A third class of approaches exists that redefines IP communication
principles (i.e. network and transport layers) around location-
independent network identifiers of node/traffic.  The interest of
such architectures is highlighted in [I-D.vonhugo-5gangip-ip-issues]
(referred to as ID-oriented Networking) for it removes the
limitations introduced by locators and simplifies the management of
mobility.  The draft however question the possibility to realize such
an architecture where node status and mobility would not affect
routing table stability.

The work done around Information-Centric Networking (ICN) falls into
such class of approaches that we refer to as purely ID-based, also

known as name-based [I-D.irtf-icnrg-terminology], although as we will
see, mobility management often departs from this principle.

## 2.3.  Information-Centric Networking (ICN)

ICN is a new networking paradigm centering network communication
around named data, rather that host location.  Network operations are
driven by location-independent data names, rather than location
identifiers (IP addresses) to gracefully enable user-to-content
communication.

Although there exist a few proposals, they share the same set of core
principles, resulting in several advantages including a simplified
mobility management [RFC7476].  For clarify, this section we focus on
hICN [I-D.muscariello-intarea-hicn] an ICN implementation for IPv6.

## 2.4.  Hybrid-ICN overview

Hybrid ICN (hICN) is an ICN architecture that defines integration of
ICN semantics within IPv6.  The goal of hICN is to ease ICN insertion
in existing IP infrastructure by:

1.  selective insertion of hICN capabilities in a few network nodes
    at the edge (no need for pervasive fully hICN network
    deployments);

2.  guaranteed transparent interconnection with hICN-unaware IPv6
    nodes, without using overlays;

3.  minor modification to existing IP routers/endpoints;

4.  re-use of existing IP control plane (e.g. for routing of IP
    prefixes carrying ID-semantics) along with performing mobility
    management and caching operations in forwarding plane;

5.  fallback capability to tradition IP network/transport layer.

hICN architecture is described in [I-D.muscariello-intarea-hicn].

## 3.  Hybrid-ICN Anchorless Mobility Management (hICN-AMM)

hICN, together with MAP-Me [I-D.irtf-icnrg-mapme], forms the basis
for the mobility management architecture we describe in the rest of
this document.  Due to the pull based nature of hICN architecture, we
distinguish consumer and producer nodes, for which mobility is
handled differently

3.1.  Consumer mobility in hICN

   The consumer end-point is the logical communication termination that
   receives data.  Due to the pull-based and connection-less properties
   of hICN communications, consumer mobility comes natively with ICN.
   It is indeed sufficient that the consumer reissues pending interests
   from the new point-of-attachment to continue the communication.
   Consumer mobility is anchorless by design, and managed without any
   impact on the transport session.  It is however necessary to have an
   appropriate transport layer on top able to cope with eventual
   disruptions and path variations caused by the mobility event.

4.  Producer mobility architectures

   The producer end-point is the logical communication termination that
   sends data.  Producer mobility is not natively supported by the
   architecture, rather handled in different ways according to the
   selected producer mobility management scheme, some of which diverge
   from the concept of pure ID-based architecture through their use of
   locators.  Additional procedures have to be performed to maintain
   reachability as it moves in the network.

   In fact, many schemes proposed for ICN are adaptations to the vast
   amount of work made in IP over the last two decades [RFC6301].
   Surveys for the ICN family, resp. for CCN/NDN-specific solutions, are
   available in [SURVEYICN], respectively [SURVEY1] and [SURVEY2].
   There has been however a recent trend towards anchorless mobility
   management, facilitated by ICN design principles, that has led to new
   proposals and an extension of previous classifications in
   [I-D.irtf-icnrg-mapme] and [MAPME] to the four following categories:

   *  _Resolution based_ solutions rely on dedicated rendez-vous nodes
      (similar to DNS) which map content names into routable location
      identifiers.  To maintain this mapping updated, the producer
      signals every movement to the mapping system.  Once the resolution
      is performed, packets can be correctly routed directly to the
      producer.

   *  _Anchor-based_ proposals are inspired by Mobile IP, and maintain a
      mapping at network-layer by using a stable home address advertised
      by a rendez-vous node, or anchor.  This acts as a relay,
      forwarding through tunneling both interests to the producer, and
      data packets coming back.

   *  _Tracing-based_ 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.

* _Anchorless_ approaches allow the mobile nodes to advertise their
mobility to the network without requiring any specific node to act
as a rendez-vous point.

## 4.1.  Producer mobility in hICN

In an hICN network, regular routing protocols such as BGP, ISIS or
OSPF can be used for propagating all prefix announcements and
populate routers' FIBs.  However, these protocols are not appropriate
and should not be used to manage name prefix mobility, for
scalability and consistency reasons.

The default mobility management for hICN is designed following the
same principles and protocols as MAP-Me, an anchorless producer
mobility management protocol initially proposed for ICN
[I-D.irtf-icnrg-mapme] [MAPME].  It builds on an initial forwarding
state bootstrapped by the routing protocol, and performs a
lightweight path repair process as the producer moves.  For
simplicity, we refer to it as simply MAP-Me in the rest of the
document.

In the rest of this section, we describe the specific realization of
the protocol in an hICN context.  Additional background and details
are available in [I-D.irtf-icnrg-mapme] and [MAPME].  The solution is
based on a path repair mechanism following mobility events, using
dynamic FIB updates.  Using data plane mechanisms for ensuring
connectivity has been previously proposed in [DATAPLANE] to handle
link failures, and has been proven more reactive than relying on
typical control plane messaging.

## 5.  Protocol description

## 5.1.  Signalization messages; acknowledgements and retransmission

Signalization messages follow hICN design principles and use data
plane packets for signalization.  Signalization messages and
acknowledgement are respectively Interest and Data packet (requests
and replies) according to hICN terminology
[I-D.muscariello-intarea-hicn].  Upon processing of those
advertisements, the network will send an acknowledgement back to the
producer using the name prefix as the source and the locator of the
producer as the destination, plus the sequence number allowing the
producer to match which update has been acknowledged.

   Pending signalization interests that are not acknowledged are
   retransmitted after a given timeout.

5.2.  Dynamic face creation and producer-triggered advertisements

   The producer is responsible for mobility updates and should be hICN-
   enabled.  It stores a sequence number incremented at each mobility
   event.

   Faces in the producer are assumed synchronized with layer 2
   adjacencies, upon joining a new point-of-attachment, a new face
   should be created.  Face creation will trigger the increase of the
   sequence number, and per-prefix advertisement packets to be sent to
   the joined network.

   Those advertisements should contain:

   *  the name prefix as the destination address, plus a field
      indicating the associated prefix length;

   *  the locator of the producer as the source address, that will serve
      for receiving acknowledgements;

   *  a sequence number sequentially increased by the producer after
      each movement;

   *  a security token (see Section 7.2).

   Upon producer departures from a PoA, the corresponding face is
   destroyed.  If this leads to the removal of the last next hop, then
   faces that were previously saved are restored in FIB to preserve the
   original forwarding tree and thus global connectivity.

5.3.  Update protocol

   Based on the information transmitted in the packet, and its local the
   network's local policy, the network might decide to update its
   forwarding state to reflect this change.

   The update process consists in updating a few routers on the path
   between the new and a former point-of-attachment.  More precisely,
   this is done in a purely anchorless fashion by sending a signalling
   message from the new location towards the name prefix itself.  This
   packet will be forwarded based on the now-stale FIB entries, and will
   update forwarding entries to point to the ingress interfaces of each
   traversed router.

5.3.1.  Illustration

   {fig-mapme-update}} illustrates the situation of a P moving between
   access routers AR1 and AR2 while serving user requests:

   1.  A first interest towards the producer originates from remote.
       The producer answers with a Data packet.

   2.  Following this, the producer detaches from AR1 and moves to AR2.

   3.  As soon as it is attached to AR2, the producer sends an Interest
       Update towards its own prefix, which is forwarded from AR2
       following the FIB towards AR1 (one of its former positions in the
       general case).

   4.  At each hop, the message fixes the FIB to point towards the
       ingress face, until the message cannot be further forwarded in
       AR1.

   5.  A subsequent message from remote will follow the updated FIB and
       correctly reach the producer's new location in AR2.

```
        P (radio link) AR1              AR2             GW         Internet
        |    |          |                |              |              |
   1    |    |          |                |              |<~~~~~~~~~~~~~~
        |    |          |<~~~~~~~~~~~~~~ ~~~~~~~~~~~~~~~ |   Interest
        |<~~~~~~~~~~~~~~ |                |              |              |
        |-------------->|                |              |              |
   2  [] |    Data      |-------------- |-------------->|              |
      /  |              |                |              |------------->|
      |  | (attach to AR2)               |              |              |
     -X].................|...............|              |              |
   3    |===============|==============>o FIB update    |              |
        |    Update     |                |==============>o FIB update   |
   4    |               o<============== |==============|              |
        |    FIB update |                |              |              |
   5    |               |                |              |<~~~~~~~~~~~~~~
        |               |                |<~~~~~~~~~~~~~~|              |
        |<~~~~~~~~~~~~~~ |~~~~~~~~~~~~~~~ |              |              |
        |-------------- |-------------->|              |              |
        |               |                |------------->|              |
        |               |                |              |------------->|
        |               |                |              |              |
```
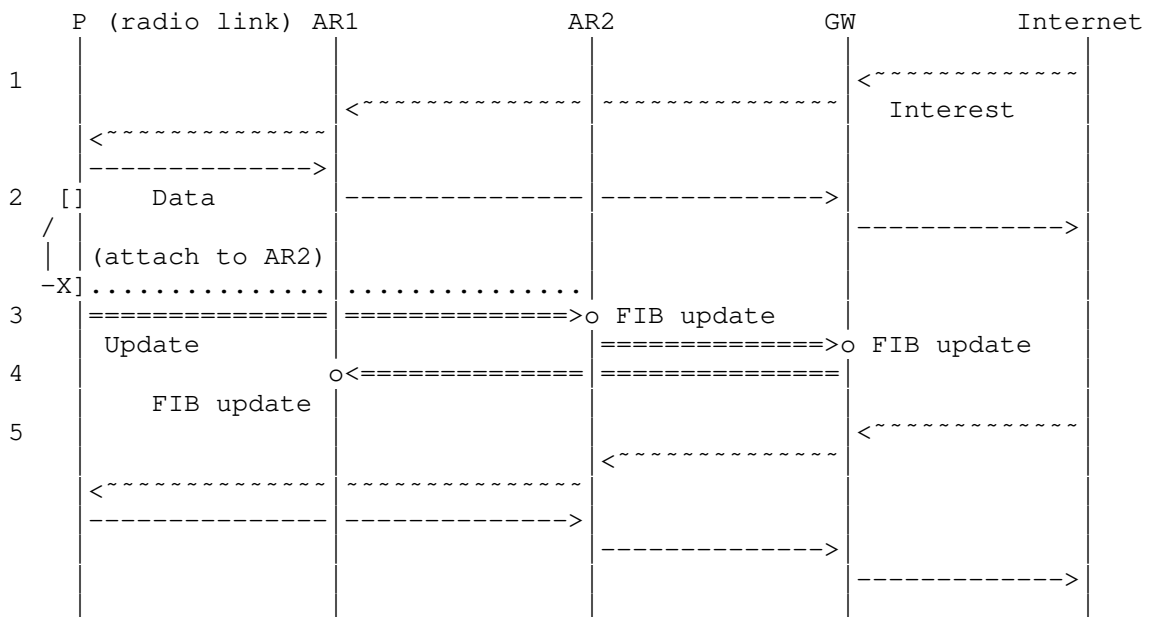
              Figure 1: Signalization during producer mobility (MAP-Me)

   Through this process, MAP-Me trades-off path optimality for a fast,
   lightweight and loop-free forwarding update.  It has been shown in

[MAPME] that stretch is bounded and typically kept low in scenarios
of interest.  This results from the fact that MAP-Me operations
preserve the initial structure of the forwarding tree/DAG (direct
acyclic graph), by only flipping its edges toward the new producer
location.

MAP-Me does not perform a routing update.  The protocol is
complementary to the routing protocol in that it can run in between
routing updates to handle producer mobility, at a faster timescale,
and with a lower overhead.  Routing updates can be performed at a
lower-pace, to re-optimize routes once a node has relocated for
instance.

## 5.3.2.  Message content

The update messages should contain :

*  the name prefix as the destination address, plus a field
   indicating the associated prefix length;

*  the locator of the producer as the source address, that will serve
   for receiving acknowledgements;

*  a sequence number sequentially increased by the producer after
   each movement;

*  an optional security token.

## 5.3.3.  Processing at network routers

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

*  if the packet carries a higher sequence number, the existing next
   hops associated to the lower sequence number in FIB are used to
   forward it further and temporarily stored to avoid loss of such
   information before completion of the acknowledgement process.

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

*  If the 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 packet, this one is re-sent through the
originating face after having updated its sequence number with the
value stored in FIB.

## 5.4.  Notifications and scoped discovery

The update protocol is responsible for reestablishing global
connectivity with minimal changes to the FIBs.  In order to further
improve the reactivity of the scheme and better support QoS
constraints of latency-sensitive traffic, we propose an additional
mechanism named *Notifications*. It assumes hICN-enabled routers at
the edge, and the existence of links between access routers, which
are typically used for handover, and proposes to exploit them during
mobility events, or to delay updates when possible.

## 5.4.1.  Notification processing

Upon receiving a valid advertisement, the point-of-attachment will
remember the presence of the producer, update its corresponding FIB
entry but send no update.  Previous next hops should be saved and
restored upon face deletion so as to preserve the forwarding tree/DAG
structure.

The rationale is that during mobility events, the producer will move
access connected and neighbouring base stations.  It will be then
sufficient to make a scoped discovery around the last position known
to forwarding to find the producer within a few hops.

## 5.4.2.  Illustration

Figure 2 illustrate such as situation where an Interest is sent to
the producer before it had the time to complete the update.

```
      P (radio link) AR1              AR2              GW        Internet
      |               |                |                |<~~~~~~~~~~~~~|
   1  |               |<~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~|             |
      |               |                |                |   Interest  |
      |<~~~~~~~~~~~~~~ |                |                |             |
      |-------------->|                |                |             |
   2 []......Data.....-)---------------|--------------->|             |
     / |              |                |    ------------------------->|
     | |(attach to AR2)                |                |             |
    -Y]................|...............+|                |             |
   3  |               |                |                |<~~~~~~~~~~~~~|
   4  |           X-- |<~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~|             |
      |               |                |                |             |
   5  |==============================>o FIB update      |             |
      |  Notification |                |                |             |
      |               |~~~~~~~~~~~~~~~>| (scoped discovery)            |
   6  |<~~~~~~~~~~~~~~ |                |                |             |
   7  |-------------- |--------------->|                |             |
      |               |<--------------                 |             |
      |               |-------------- |--------------->|             |
      |               |                |   ------------------------->|
      |               |                |                |             |
```
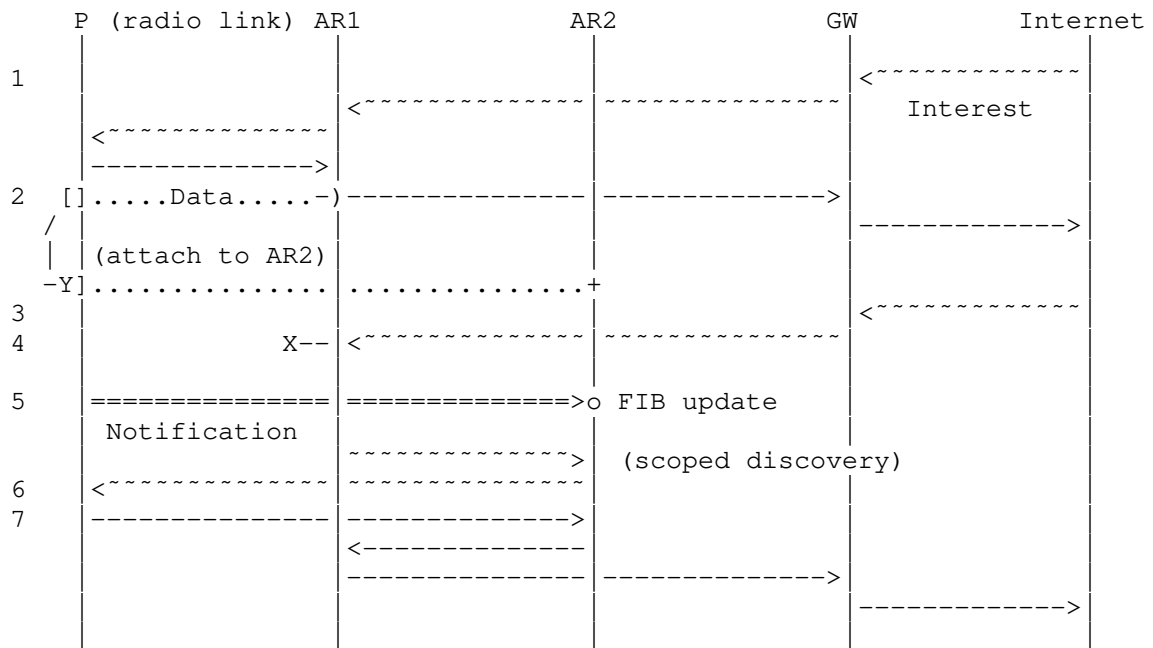
               Figure 2: Scoped discovery during producer mobility

   1.  A first interest towards the producer originates from remote.
       The producer answers with a Data packet.

   2.  Following this, the producer detaches from AR1 and moves to AR2.

   3.  A subsequent message from remote arrives before the update could
       take place, and is thus forwarded to AR1.

   4.  AR1 has no valid face anymore towards the producer, and enters
       discovery mode by broadcasting the interest to neighbours.

   5.  In the meantime, we assume the notification reaches AR2.

   6.  Because the producer is attached to AR2, the producer can be
       directly reachable.  Otherwise, AR2 would iterate the discovery
       to neighbours only if it had more recent information about the
       producer location than its predecessor (based on sequencing of
       regular Interests and Interest Updates).

   7.  The Data packet follows the reverse path to the consumer as
       usual.

6.  Benefits

   We now review the potential benefits of the general architecture we
   have presented using features from the hICN data plane for supporting
   consumer and producer mobility.

6.1.  Overview

   *Native mobility* : This mobility management process follows and
   exploits hICN design principles.  It makes producer mobility native
   in the architecture by preserving all benefits of hICN even when
   consumers and/or producers are moving.

   *Anchorless mobility* : Such approach belongs to the category of pure
   ID-based mobility management schemes whose objective is (i) to
   overcome the limitations of traditional locator-based solutions like
   Mobile IP (conf)using locators as identifiers and requiring tunnels,
   and (ii) to remove the need for a global mapping system as the one
   required by locator-identifier separation solutions.  The result is a
   fully anchorless solution both in the data plane and in the control
   plane.

   *Local and decentralized mobility management* : Mobility updates are
   handled locally and the routers that are affected are those on path
   between successive positions of the producer.  In particular, remote
   endpoints are not affected by the event.  Mobility is managed in a
   fully distributed manner and no third party is required.  This does
   not prevent any centralized control (as discussed in
   [I-D.auge-dmm-hicn-mobility-deployment-options]), but makes the
   network robust to disconnectivity events.

   The next section will discuss more in depth the following advantages

6.2.  Simplicity, scalability, efficiency

   As emerges from the points raised in the previous section, consumer
   mobility is transparently supported by an hICN network in virtue of
   the pull-based model and the way the forwarding path works.  After
   moving, a consumer can just reissue pending interests once attached
   to the new access router at layer 2, without requiring any more
   information from L3 and above.  This ensures a fast and simple
   handover, which can be further enhanced through additional mechanisms
   such as in-network caching.  Consumer mobility is fully anchorless
   with hICN, and does not incur any signalization nor tunneling
   overhead.

   This is particularly interesting considering that most mobile users
   are consumers only (e.g. linear video distribution, or large scale

video conferencing where we typically have few presenters and most
users are simply consumers).

Another aspect of using the unifying hICN architecture in replacement
of the traditional tunnel-based mobile core is that it removes the
need to maintain state for consumers and producers which are not
mobile (eg.  IoT sensors), or not currently moving.

6.3.  Reduced latency through caching

While this is not strictly linked to mobility, we first illustrate
the benefits of caching content close to the edge to reduce user
latencies.  This is particularly important for wireless networks such
as WiFi or LTE which have non-negligible latencies especially during
connection setup, or after an idle period.  The characteristics of
those radio networks are thus of interest for the performance of the
mobility architecture as a whole.

The example in Figure 3 considers a mobile node that can move access
two accesses linked to Access Routers (AR) AR1 and AR2, both
connected to the Internet though a common gateway (GW).  This same
setup will be later used to illustrate the flow of packets during
mobility events, eventually specializing AR into AP or eNB when it
makes more sense.

```
              +-----+                         .-~-.
           _,--+ AR1 +--,              .- ~ ~-(       )_ _
 +-----+  /     +-----+    \ +----+     |                ~-.        +-----+
 |  C  +=                  =+ GW +----+      Internet        \--//--+  P  |
 +-----+ \_    +-----+    / +----+     \                   .'       +-----+
          '--+ AR2 +--'              ~- . _____.-~
              +-----+
```
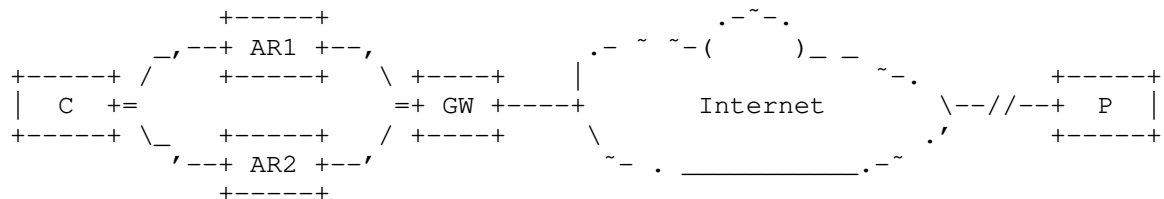
              Figure 3: Simple topology with a multi-homed consumer

We represent in Figure 4 a simple data flow between the different
entities involved in the communication between the mobile node M, and
a remote producer available over the Internet.

```
        C              AR1            AR2            GW         Internet
        |~~~~~~~~~~~~~~>|              |              |              |
   1    |              |~~~~~~~~~~~~~~~|~~~~~~~~~~~~~~>|              |
        |   Interest X |              |              |~~~~~~~~~~~~~~>|
        |              |              |              |              |...
        |              |              |              |<-------------|
        |   Data X     |<-------------|--------------|              |
        |<-------------|              |              |              |
        |              |              |              |              |
   2    |~~~~~~~~~~~~~~>|              |              |              |
   3    |   Interest Y |~~~~~~~~~~~~~~~|~~~~~~~~~~~~~~>X Cache hit    |
        |              |<-------------|--------------X              |
        |<-------------|              |              |              |
        |   Data Y     |              |              |              |
```
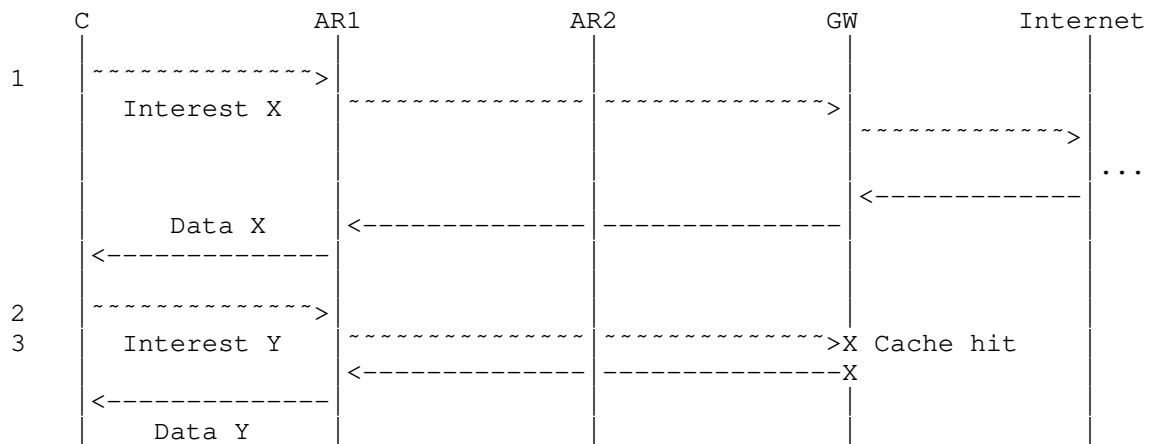
LEGEND:
˜˜˜˜>: Interest      <---- Data      ====> Signalization
....-: L2 detach     .....+ L2 attach        X failure    o event

                 Figure 4: Reduced latency through caching

   Numbers on the left refer to the following comments relative to the
   data flow:

   1.  The consumer issues a first interest towards name prefix X, which
       is transported up to the producer.  A Data packet comes back
       following the reverse path and populating intermediate caches.
       Latency of the exchange can be seen by the distance between lines
       on the vertical axis.

   2.  The consumer now requests content B, which has previously been
       requested by another consumer located on the same gateway.
       Interest B thus hits the cache, refreshes the entry, and allows a
       lower round-trip latency to content both for consumer C and any
       subsequent request of the same content.

6.4.  Improved reliability through caching

   Mobile networks might consist in unreliable access technologies, such
   as WiFi, responsible for packet losses.  Figure 5 considers a similar
   scenario with a lossy channel (eg.  WiFi) between the mobile and the
   first access router.

```
        C (radio link) AR1                AR2            GW          Internet
        |             |                 |               |            |
    1   |˜˜˜˜˜˜˜X      |                 |               |            |
    2   |˜˜˜˜˜˜˜˜˜˜˜˜˜>|                 |               |            |
        |   Interest  |˜˜˜˜˜˜˜˜˜˜˜˜˜˜ ˜˜˜˜˜˜˜˜˜˜˜˜˜˜>|            |
        |             |                 |               |˜˜˜˜˜˜˜˜˜˜˜˜˜>|
        |             |                 |               |            | ...
        |             |                 |               |<------------|
        |     Data    |<-------------|---------------|            |
    3   |         X-------|           |               |            |
        |             |                 |               |            |
    4   |˜˜˜˜˜˜˜˜˜˜˜˜˜˜>X Cache hit     |               |            |
        |<-------------X              |               |            |
        |             |                 |               |            |
```
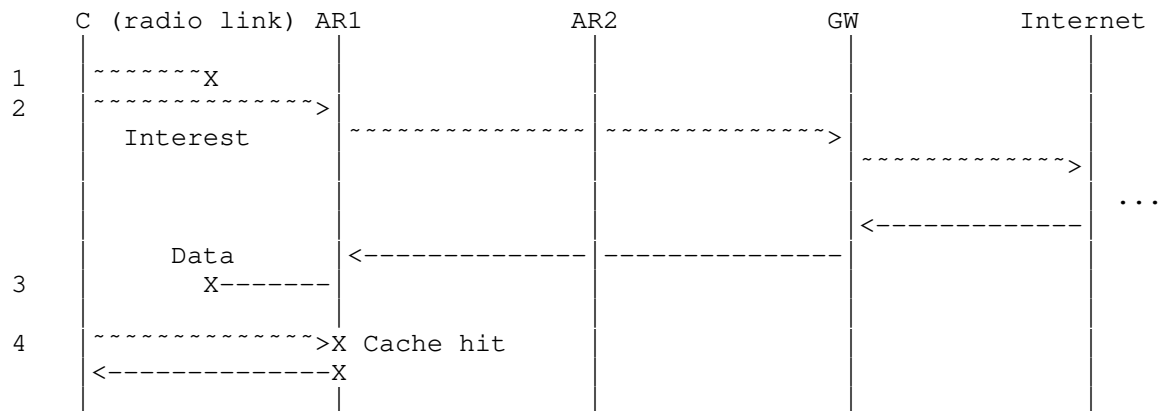
Figure 5: IU propagation example

1.  The first issued interest is lost due to bad radio conditions.

2.  Upon detection (either after a timeout, the consumer can just
    reissue the lost Interest.

3.  This time the remote producer successfully replies but the Data
    packet is lost on the radio link.

4.  Upon a similar detection, the consumer can reissue the lost
    Interest that will hit a locally stored copy at the router where
    the loss occurred (or again use a detection mechanism to
    retransmit the Data packet).

6.5.  Local mobility and recovery from common cache

   The same mechanism can be used to recover from mobility losses after
   the consumer reconnects to the new network as the content will
   already be available in the cache at the junction router between the
   two accesses.  This is particularly interesting in case of micro-
   mobility between access routers that are topologically close in the
   network.

   This is also the opportunity to manage those losses on behalf of the
   transport protocol, so that only losses due to congestion are exposed
   to it, and don't perturb the feedback loop by unnecessarily reducing
   the transfer rate.

```
   C (radio link) AR1              AR2            GW         Internet
        |                |          |              |            |
   1    |~~~~~~~~~~~~~~~~>|          |              |            |
        |    Interest    |~~~~~~~~~~~~~~~~~~~~~~~~~~~~>|         |
        |                |          |              |            |
        | (detach fm AR1)|          |              |~~~~~~~~~~~~~>|
   2 ...|.............._  |          |              |<------------|
        |                |<-------------------------|            |
   3    |    Data X-     |          |              |            |
        |                |          |              |            |
        | (attach to AR2 |          |              |            |
   4 ...|................|...............+          |            |
   5    |~~~~~~~~~~~~~~~~|~~~~~~~~~~~~~~~~>|          |            |
   6    |                |          |~~~~~~~~~~~~~~~>X Cache hit  |
        |                |          |<-------------X|            |
        |----------------|---------------|          |            |
        |                |          |              |            |
```
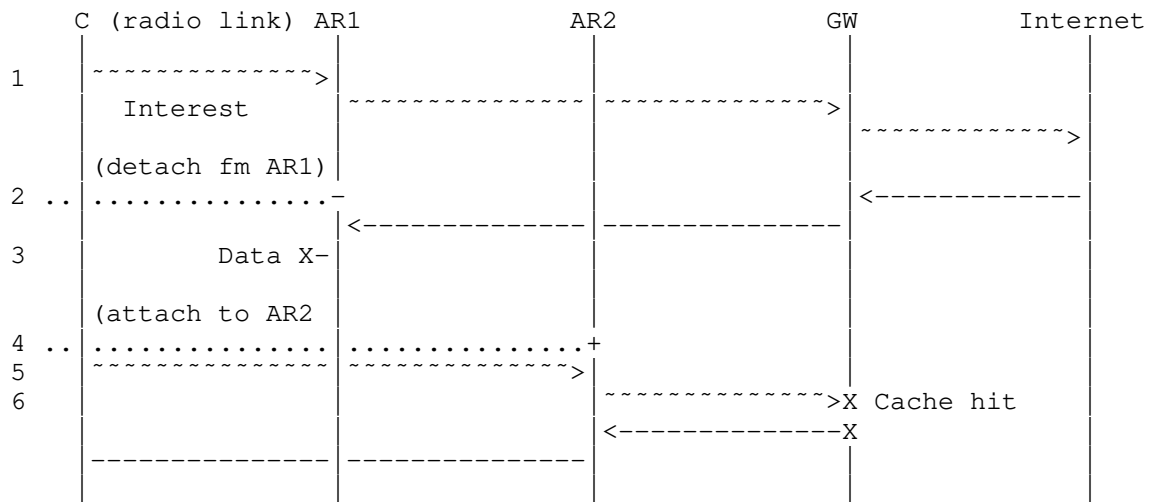
Figure 6: IU propagation example

1.  The consumer issues an interest before moving to a new location

2.  It detaches from the first Access Router AR1

3.  This causes the returning data packet to be lost as there is no
    more a valid face towards the consumer.

4.  The consumer has finished attachment to the new access router
    AR2.

5.  It can retransmit pending interests immediately.

6.  The interests will hit the cache at the first junction point
    between AR1 and AR2 which have previously seen the data packet
    coming back.

6.6.  Additional reliability through consumer multihoming

   Because mobility is implemented at layer 3 and is thus agnostic to
   the physical layer, this allows a mobile consumer to seamlessly
   switch to a different access layer, eg.  WiFi to LTE, following the
   unreachability of the preferred radio access.

   Figure 7 illustrates a fallback to LTE which can be performed
   transparently for the application.

```
        C           WiFi           GW          LTE enB        PGW         Internet
        |            |             |            |             |            |
    1   |~~~~~~~~~~~>|             |            |             |            |
        |           |~~~~~~~~~~~>  |            |             |            |
        |           |            ~~~~~~~~~~~~|~~~~~~~~~~~~|~~~~~~~~~~~>     |
        |           |             |            |             |            |
        |           |             |<-----------|------------|------------ |
        |           |<----------- |            |             |            |
        |<----------|             |            |             |            |
    2   |            X            |            |             |            |
    3   |~~~~~~~~~~~~X~~~~~~~~~~~|~~~~~~~~~~~>   |             |            |
        |            X            |            |~~~~~~~~~~~>  |            |
        |            X            |            |             |~~~~~~~~~~~> |
        |            |            |            |             |            |
        |            |            |            |             |<---------- |
        |            |            |            |<----------- |            |
        |<-----------|------------|------------|             |            |
    4   |~~~~~~~~~~~>|...          |            |             |            |
        |            |            |            |             |            |
```
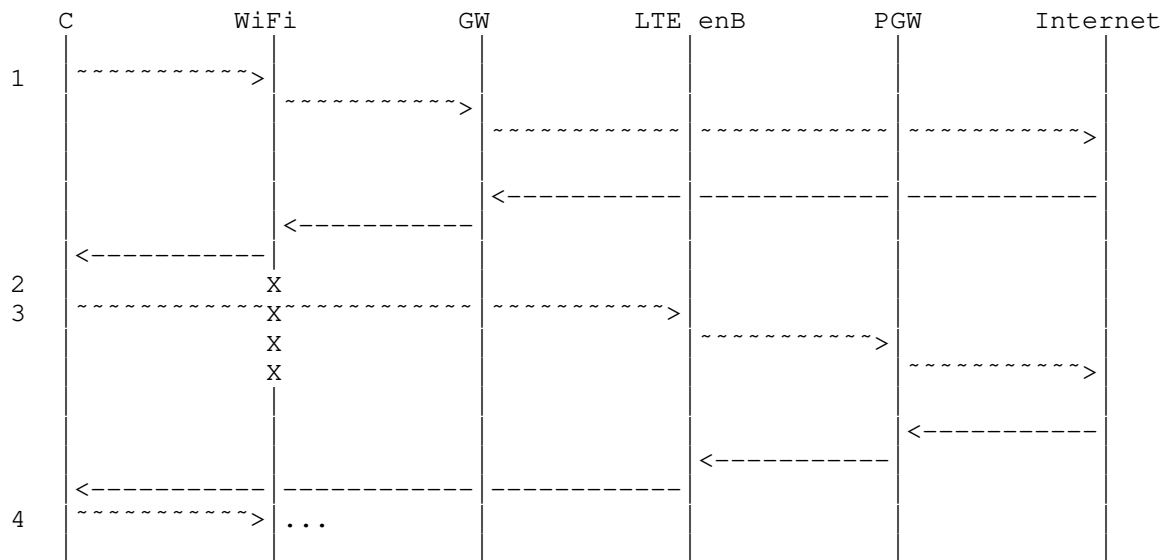
                            Figure 7

1.  First interest is sent on the WiFi link.

2.  WiFi unavailability due to failure for instance.

3.  The application seamlessly switches to the LTE link.

4.  Upon recovery, the traffic can be brought back on the WiFi
    interface.

hICN handles consumer mobility from one access to the other (e.g.
WiFi to LTE or vice-versa) without any a-priori knowledge of the
multiple networks to use as it is the case of MPTCP or QUIC
approaches.  Moving rate and congestion control at the receiver end
results to be a significant advantage w.r.t. all existing
alternatives in controlling dynamically multiple and new discovered
network accesses in presence of mobility.

This use case highlights the importance of having a compatible
transport, as the WiFi and LTE paths will have much different
characteristics in terms of delay, jitter and capacity.

Evaluations of the scheme have shown this scheme to preserve the
performance of flows like mobile video distribution up to very high
switching rates in the order of a second, not even considering
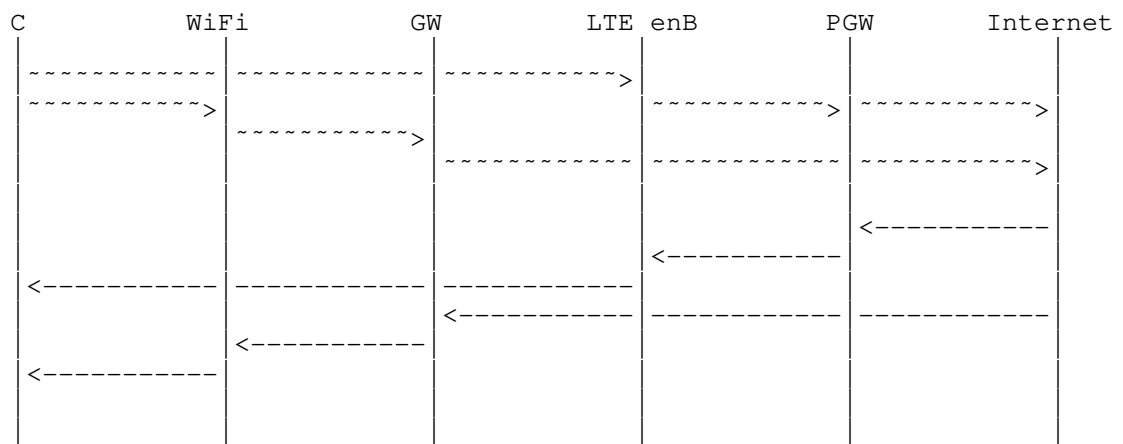optimization occurring from network support.

Mobility is handled transparently at the network layer with very fast
handover times, due to the connection-less property of hICN.  This
makes it possible to offer reliable WiFi connectivity, besides its
lossy nature as observed in previous use case and besides the
frequency of mobility from one network access to the other.

6.7.  Bandwidth aggregation with consumer multihoming

Bandwidth aggregation can be realized dynamically through a
congestion-aware load-balancing forwarding strategy at the client,
with no a priori knowledge of paths.  This is done similarly in the
network by hICN forwarders, allowing a combination of multi-homing,
multipath and multi-source data transfers.  As all the paths are used
at the same time, hICN offers the full network capacity to the users
and tends to smooth fluctuations due to the radio channels.

Over an heterogeneous network access, hICN also offers a simple and
cost-effective realization of heterogeneous channel bonding allowing
an user to seamlessly roam across different radios or fixed lines
(for increased reliability or reduced costs), or aggregate their
bandwidth for high-throughput applications such as video streaming.

We illustrate a simplified data flows with one mobile consumer C
alternating interests between a WiFi and LTE access points.  The load
balancing strategy would in that case optimize the split ratio
between the two access to realize an optimal split.  Note that in
that case the relative distances on the vertical axis have not been
respected here for readability.

```
    C            WiFi           GW           LTE enB          PGW         Internet
    |             |             |             |    |           |             |
    |~~~~~~~~~~~~~|~~~~~~~~~~~~~|~~~~~~~~~~~~~>|    |           |             |
    |~~~~~~~~~~~~>|             |             |    |~~~~~~~~~~~>|~~~~~~~~~~~~>|
    |             |~~~~~~~~~~~~>|             |    |           |             |
    |             |             |~~~~~~~~~~~~|~~~~~~~~~~~~~|~~~~~~~~~~~~>|     |
    |             |             |             |    |           |             |
    |             |             |             |    |           |<-----------|
    |             |             |             |    |<----------|             |
    |<------------|------------|------------|     |           |             |
    |             |             |<-----------|-----------|------------|------------|
    |             |<-----------|             |    |           |             |
    |<-----------|             |             |    |           |             |
    |             |             |             |    |           |             |
```

Fine grained control from the application allows fully exploiting
available bandwidth, resulting in an aggregated throughput equal to

the sum of access throughputs, which is hard to achieve with existing
solutions.

6.8.  Traffic and signalization offload

As a natural consequence of its anchorless behavior, an hICN network
can continue to operate in disconnected mode, for local mobility,
even though no upstream entity is available.

In order to illustrate this, we slightly extend the previous topology
in Figure 8 with an additional access network.  To show that local
mobility induces no traffic on upstream links, we further assume a
failure on the link between the gateway (GW) and the Internet.

```
                  +-----+
                _,--+ AR1 +--,
 +-----+ /      +-----+    \                       .-~~~-.
 |  P   +=                    \           .- ~ ~-(       )_ _
 +-----+ \_    +-----+    +----+          |              ~   -.
          '--+ AR2 +-----+ GW +----X----+      Internet       \
             +-----+     +----+   FAIL   \                      .'
                      /                    ~- . _____ . _~
 +-----+      +-----+  /
 |  C  +------+ AR3 +-'
 +-----+      +-----+
```
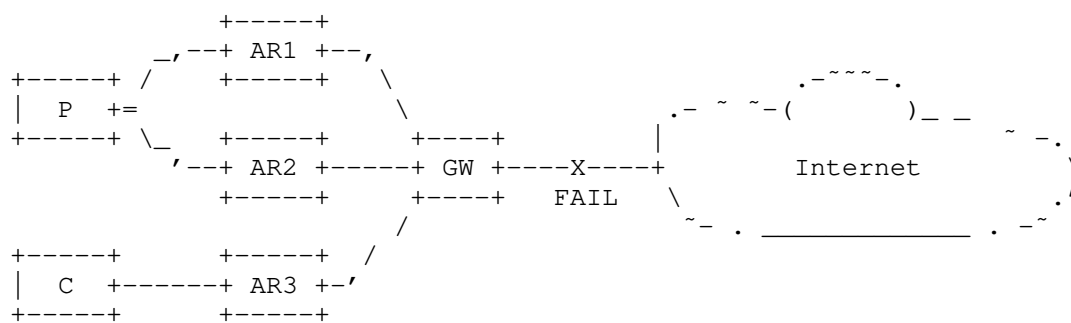
Figure 8: Access network disconnected from core

The data flow represented in Figure 9 illustrates the communication
between a consumer connected to AR3, and a mobile producer moving
from AR1 to AR2.

```
 C          P          AR1         AR2         AR3        GW  X    Internet
 |          |          |           |           |          |  X        |
 |~~~~~~~~~~|~~~~~~~~~~~|~~~~~~~~~~~|~~~~~~~~~~~>|          |  X        |
 |          |          |           |           |~~~~~~~~~~>|  X        |
 |          |          |<~~~~~~~~~~|~~~~~~~~~~~|~~~~~~~~~~~|  X        |
 |          |<~~~~~~~~~~|           |           |          |  X        |
 |          |--------->|           |           |          |  X        |
 |          |          |-----------|-----------|--------->|  X        |
 |          |          |           |           |<---------|  X        |
 |<---------|----------|-----------|-----------|          |  X        |
 |          |          |           |           |          |  X        |
 |          |..........‾          |           |          |  X        |
 |          |..........|..........+           |          |  X        |
 |          |==========|=========>o           |          |  X     NO  |
 |        Update       |           |===========|=========>o  X  TRAFFIC|
 |          |          o<==========|===========|==========|  X        |
 |          |          |           |           |          |  X        |
 |~~~~~~~~~~|~~~~~~~~~~~|~~~~~~~~~~~|~~~~~~~~~~~>|          |  X        |
 |          |          |           |           |~~~~~~~~~~>|  X        |
 |          |          |           |<~~~~~~~~~~|~~~~~~~~~~~|  X        |
 |          |<~~~~~~~~~~|~~~~~~~~~~~|           |          |  X        |
 |          |----------|--------->|           |          |  X        |
 |          |          |           |-----------|--------->|  X        |
 |          |          |           |           |<---------|  X        |
 |<---------|----------|-----------|-----------|          |  X        |
 |          |          |           |           |          |  X        |
```
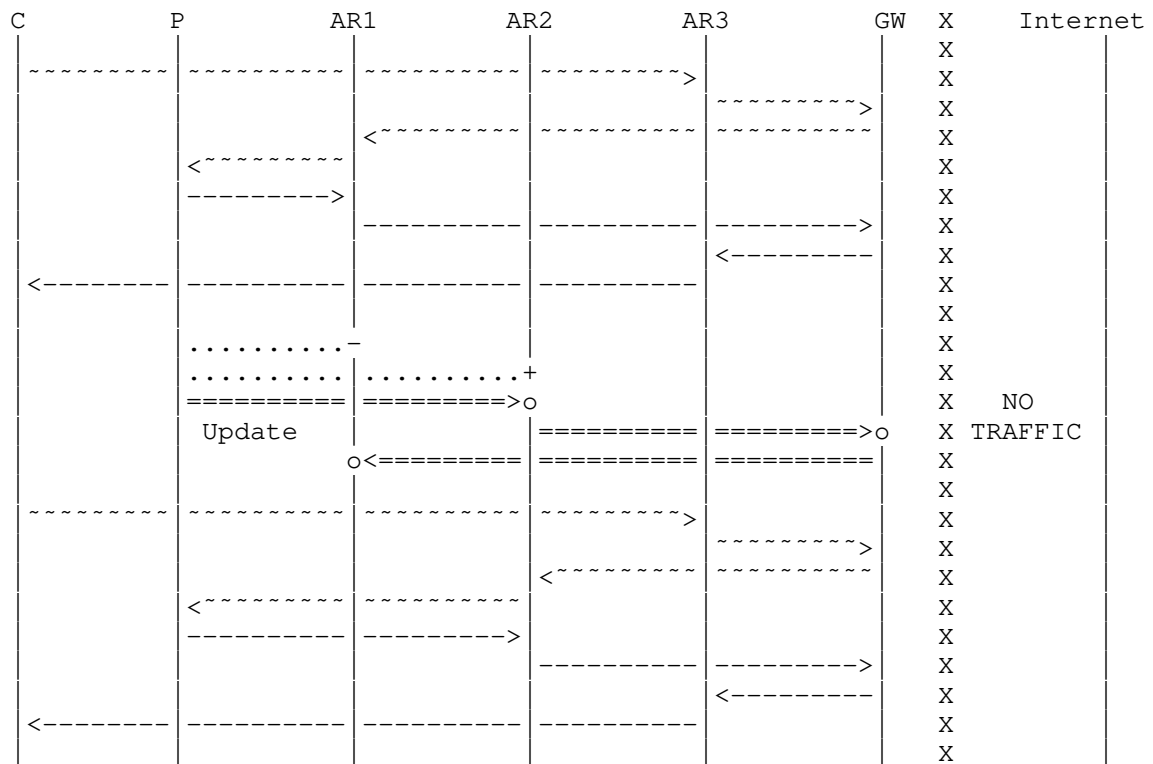
Figure 9: Anchorless mobility in network disconnected from core

We see that both the data and the signalization remain local to the
zone where the mobility occurs, and that communications during
mobility are not affected by the failure of the link upstream.  This
is a sign that the mobile core is not loaded with unnecessary
traffic, and that communications remain local, thus improving user
flow latencies.  The offload of both data and signalization allows
reducing the cost of the infrastructure by increasing the diversity
of resources used at edge, mutualizing their capacity, and lower
requiring network and compute capacity in the mobile core.  A direct
consequence is also a more robust and reliable network.

7.  Implementation considerations

7.1.  Interaction with non-hICN enabled routers

   The realization of the architecture in a partial hICN deployment
   where some routers are not extended to support hICN mechanisms
   requires either to introduce additional functionalities or protocol
   support, or to reuse existing protocols achieving similar objectives
   (following hICN design).

   One such example is the combination of ICMP redirect messages and
   Neighbour Discovery Proxies (NDProxy), that partially realizes the
   objectives of the update process:

   *  ICMP packets do not include sequence numbers however they can be
      transported as part of the payload; verification is deferred to
      the next hICN node which should send the packet backwards in case
      of verification failure to fix the incorrect path update.

   *  multipath is not supported in the pure-IP part of the network
      (which is the expected behaviour)

   Identified concerns might be about the unexpected use of such
   protocols, the lack of available implementation for NDProxy, and
   security aspect related to redirect messages.  The latter shares the
   fate of source routing, which has long been advocated against, and
   has recently gained popularity within the SPRING context.  A proper
   security scheme is certainly the right way to address this problem,
   and we believe the set of benefits that we have listed are worth
   reconsidering such aspects.

7.2.  Security considerations

   As indicated in previous sections, signalization messages transmitted
   across trust boundaries must be secured.  The choice of the solution
   will intimately depend on the selected protocols.

   The use of ICMP packet might allow reusing existing security schemes
   such as AH headers [RFC4302], or SEND [RFC3971] (and its proxy
   extensions [RFC6496], [RFC5909]).

   Alternatively, [SEC] has reviewed standard approaches from the
   literature and proposes a fast, lightweight and distributed approach
   that can be applied to MAP-Me and fits its design principles.

7.3.  Discussion

   Both consumer and producer mobility support multiple paths, however
   the support of mobility for a multihomed producer, is left for future
   updates of the present document.

   Similarly, the proposed producer mobility solution is appropriate for
   the management of micro-mobility; its extension to multiple domains
   is out of scope.

8.  IANA Considerations

   This memo includes no request to IANA.

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