An Identifier-Based Approach to Internet Mobility: A Survey

You Wang, Jun Bi, and Athanasios V. Vasilakos

Abstract

This article surveys one Internet mobility approach that is highlighted by the employment of an identifier namespace. This approach uses identifiers other than traditional IP addresses to name mobile hosts, contents, or other entities, and introduces a mapping function to locate the entities in the global scope. Although this approach has been adopted by many Internet mobility solutions and is also considered as a promising way to support mobility in the future Internet, there lacks a comprehensive review and analysis of this approach together with related solutions, especially the ones proposed in recent years. This article describes the emergence, evolution, and state of the art of the approach, and gives a classification, a review, and a comparison of typical solutions related to the approach. This article also presents discussions of open issues, challenges, and research trends on designing future Internet mobility solutions.

Internet mobility has been an active research topic for over two decades. Along with the evolution of the Internet, especially the growing of mobile data due to more and more mobile devices and applications, much research effort has been paid to addressing Internet mobility. However, so far there is no consensus on how we should provide mobility support in the Internet; hence, it remains an open issue.

Generally, the main challenge in supporting Internet mobility is to deliver data to an entity with a location in the network topology that changes dynamically [1]. Internet mobility is difficult to realize because Internet design in its early stages did not take mobility support into account, which leaves a contradiction between the current Internet architecture and mobility support. Specifically, since Internet routing requires aggregation of IP addresses to scale, a host needs to change its IP address after moving to a new network. However, due to the tight coupling of TCP and IP, changing IP addresses causes interruption of transport layer sessions, which then seriously impacts the experience of mobile users.

Basically, Internet mobility solutions can be divided into routing-based and mapping-based approaches [1]. Routing-based approaches make a mobile entity use the same address while roaming, and thus require dynamic routing to maintain reachability of the mobile entity. On the contrary, mapping-based approaches allow a mobile entity to change addresses but keep a piece of stable information, known as an *identifier*, which does not change during movement. To reach the mobile entity using its identifier, a *mapping function* is introduced to resolve the identifier to the mobile entity's current location(s), which is usually represented by one or several locators (normally IP addresses). With identifiers and up-to-date mappings, data senders can always make data reach a moving receiver regardless of its locations.

As discussed by Zhang *et al*. [1], a routing-based approach is not suitable to provide mobility support in the global Internet, because the whole network needs to be informed of each mobile entity's movement, which may not scale well in large networks. Therefore, this article focuses on mapping-based and hybrid approaches, which we call *identifier-based approaches* [2] because their fundamental common principle is the employment of identifiers instead of IP addresses to name and reach mobile entities.

Identifier-based Internet mobility support is not a new topic. On one hand, the concept of an "identifier" comes from earlier research on Internet naming and addressing, which defined that an identifier names an entity in the Internet, and the relationship between the identifier and the entity does not need to change when the entity changes its location in the network topology. On the other hand, identifier-based Internet mobility solutions have kept coming out over the last two decades, keeping this research area active.

However, our understanding on this topic is also evolving. In light of several emerging ideas and related proposals in recent years, we feel it necessary to give an updated survey of this topic. To this end, this article summarizes the evolving process of identifier-based Internet mobility approaches, and presents a new taxonomy and a comprehensive review of related solutions, including the state of the art in this research area. This article also gives in-depth comparisons of identifier-based Internet mobility solutions in terms of both their diversified identifier features and mapping functions, together with discussions on open issues, challenges, and research trends related to this topic.

In the following sections, we first give a classification and an overview of related Internet mobility solutions. Particularly, we spend another section to describe the mobility concept and solutions in information-centric networking (ICN) [3, 4], which

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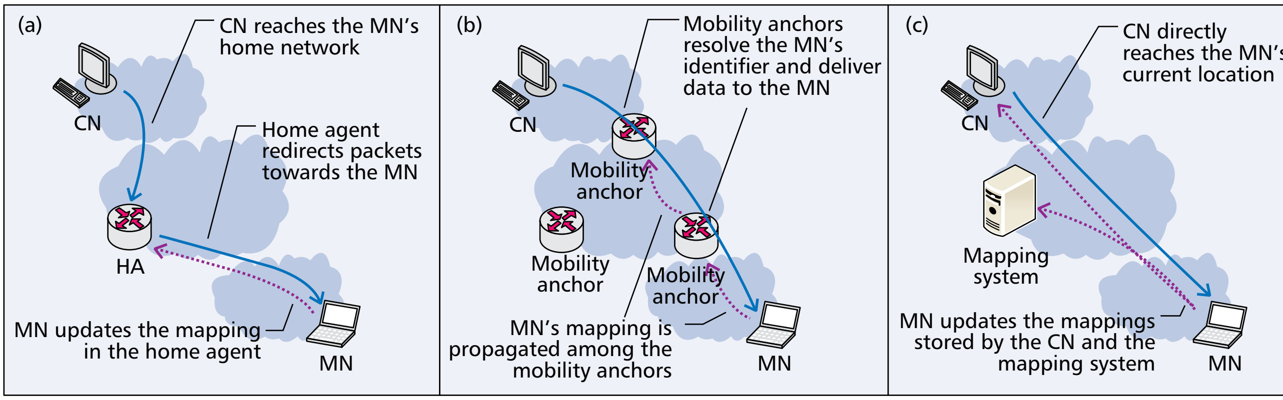

Figure 1. Illustration of a) Mobile IPv6; b) distributed mobility management solutions; c) ILS designs.

differ from our traditional understanding of mobility management based on end-to-end sessions. Then, since identifiers and mapping functions are the two most important components introduced by identifier-based approaches, we use two sections to discuss identifier features and mapping function designs of the reviewed solutions. Finally we summarize this article.

Solution Classification and Review

One of the earliest identifier-based mobility solutions is Mobile IP. The first Mobile IP Working Group in the Internet Engineering Task Force (IETF) was formed in June 1992. Since then, various derivatives have been proposed to improve the baseline protocols of Mobile IP. Although Mobile IP does not explicitly propose a new identifier namespace, it employs a special IP address type to identify each mobile node (MN), the role of which is essentially the same as an identifier. The research related to Mobile IP is still active at this stage.

Some other efforts have been spent on addressing Internet mobility which can be classified into *identifier/locator split* (ILS) designs. ILS is an architectural model which points out that an IP address has both host identifier and locator semantics embedded, and a split of the two is necessary. ILS has also been discussed many times during the past two decades and recently has received wide acceptance.

In recent years, more and more future Internet architecture proposals have integrated the concept of identifiers and made mobility handling one of their goals. Compared to Mobile IP and ILS designs, such proposals are more revolutionary. However, the core idea of mobility support using identifiers remains the same.

Accordingly, we review typical Internet mobility solutions in the following three subsections. Due to space limitations, we do not touch on every protocol detail, but focus on explaining their basic concepts as well as how they realize packet delivery to MNs.

Mobile IP and Its Derivatives

Mobile IP derivatives are based on two baseline protocols: Mobile IP (MIP) [5] and Mobile IPv6 (MIPv6) [6]. We take MIPv6 as an example shown in Fig. 1a: the protocol uses a special IP address called the home address (HoA) to identify an MN. When an MN moves to a new network, it obtains a care-of address (CoA), which can be used to reach the MN. Then the MN communicates with the home agent (HA) located in its home network to update the binding cache, which maps the MN's HoA to its current CoA. A correspondent node (CN) sends packets to the MN using its HoA; thus, the packets are forwarded to the HA. With an up-to-date binding cache, the HA can encapsulate and redirect packets toward the MN's current CoA. To reduce mobility signaling cost when the MN moves away from the HA, some MIPv6 extensions such as Hierarchical Mobile IPv6 (HMIPv6) and Proxy Mobile IPv6 (PMIPv6) have been proposed.

The major drawback of Mobile IP is that all the packets from CN to MN have to take a detour to pass the HA, which is known as the *triangle routing* problem. Triangle routing can result in routing path stretch, which means the actual routing path is longer than the shortest one, as well as heavy load on the HA. MIPv6 has offered a route optimization (RO) mode to address triangle routing by directly sending a binding cache from MN to CN. However, RO mode is less than ideal due to some drawbacks in security and efficiency.

In recent years, a series of Mobile IP derivatives, which follow the *distributed mobility management* (DMM) architectural paradigm [7], arise to address the problem. As shown in Fig. 1b, DMM solutions distribute the functionality of the HA to multiple mobility anchors deployed in the network so that the MN can always choose a nearby mobility anchor to maintain its binding cache and perform packet redirection. Thus, the MN's HoA never represents a fixed location, and triangle routing can be alleviated or even eliminated. DMM research is still in the early stage, but it is considered as a promising way to evolve Mobile IP networks and is currently under standardization in the IETF DMM group.

ID/Locator Split Designs

Host Identity Protocol (HIP) [8] and Identifier-Locator Network Protocol (ILNP) [9] are typical solutions that fall into this category. Note that in a broad sense, core-edge separation designs also belong to ILS, which focus on improving global routing scalability and are not within the scope of this article.

Compared to Mobile IP, which places identifier-to-locator mapping functions at the network side, most mobility management functions in ILS designs are implemented at the host side. Figure 1c shows how these solutions work: before sending packets to the MN, the CN obtains and stores the current IP address of the MN by querying a global mapping system (usually DNS plays this role), which always maintains up-to-date identifier-to-locator mapping of each MN. After the MN moves to a new network, it keeps its identifier unchanged and obtains a new IP address as its locator; then the MN updates its new identifier-to-locator mapping in the mapping system. The MN also notifies all the CNs of its new IP address so that they can directly reach its current location. Therefore, mobility handoff in such solutions is achieved in an end-to-end way.

Future Internet Architectures

The list of future Internet architecture proposals is long and growing. Due to space limitation, in this article we pay more attention to the proposals that emphasize Internet mobility support and have presented detailed mobility solutions in

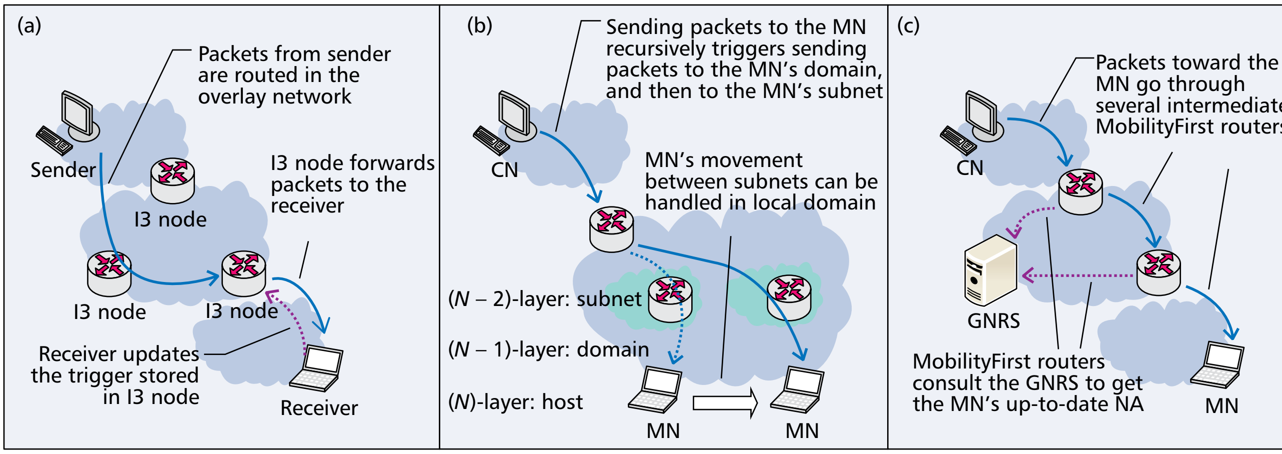

Figure 2. Illustration of a) I3; b) RINA; c) MobilityFirst.

their current designs, including Internet Indirection Infrastructure (I3) [10], Recursive InterNetwork Architecture (RINA) [11], and MobilityFirst [12], as well as ICN proposals such as Data-Oriented Network Architecture (DONA) [13], Named Data Networking (NDN) [14], NetInf [15], and Publish-Subscribe Internet Technologies (PURSUIT) [16].

In I3, data receivers insert triggers into the network in the form of (*id*, *addr*), which is analogous to an identifier-locator mapping. When data senders send packets toward an existing identifier *id*, the trigger of the *id* causes the packets to be delivered to *addr*, which represents the location of the receiver. Packet delivery in I3 is realized by an overlay network consisting of I3 nodes, as shown in Fig. 2a. Each trigger is stored in an I3 node, and packets toward an *id* are routed though the overlay network and reach the specific I3 node, which then redirects the packets to the receiver. Receivers can choose nearby I3 nodes to store their triggers and avoid triangle routing. Receiver-to-I3 node relationships can also be cached by other I3 nodes to reduce the routing overhead in the overlay.

The RINA model consists of several layers realized by recursively repeating a single inter-process communication (IPC) layer. In this model, (N)-layer entities (e.g., applications) use identifiers of (N – 1)-layer entities (e.g., hosts) as addresses. Thus, sending packets to (N)-layer identifiers implies first resolving the identifiers to addresses that are actually (N – 1)-layer identifiers, and then sending packets to (N – 1)-layer identifiers recursively. Figure 2b demonstrates a mobility case in RINA: an (N)-layer MN moves to another subnet in the same domain, and it only needs to change its (N – 1)-layer address (e.g., subnet prefix) but keep its (N)-layer address (e.g., domain index). Since one movement usually takes place in a limited area and thus has a greater possibility to cause lower-layer address changes, RINA facilitates handling mobility events within a local scope.

MobilityFirst uses globally unique identifiers (GUIDs) to name network attached objects and employs a Global Name Resolution Service (GNRS) to dynamically map GUIDs to network addresses (NAs). Packets sent toward an MN in MobilityFirst may go through several intermediate MobilityFirst routers, each of which can consult the GNRS to get the NA(s) of the MN's GUID, as shown in Fig. 2c. Therefore, MobilityFirst can perform both "early binding" and "late binding" when forwarding packets to an MN. The late binding feature is beneficial to mobile scenarios, since MobilityFirst routers on the path towards an MN are able to rebind the MN's GUID to new NAs in order to adapt to movements of the MN.

It is worth noting that so far we are discussing identifying and locating MNs. However, a large number of future Internet architectures, especially the ICN proposals, identify not only MNs but also mobile contents (or mobile data/information; we use them interchangeably in this article). Although dealing with mobile contents differs from dealing with MNs in many aspects, we argue that they share essential similarities. We discuss mobility in ICN in the following section.

Discussion on Mobility in ICN

Normally, ICN architectures overlay a resolution system on a routing system. The routing system routes packets based on locators, while the resolution system may provide an identifier-to-locator resolution service, or a route-on-identifier service. NDN is an exception that completely relies on identifier-based routing. NetInf also provides a similar alternative mechanism.

ICN proposals focus on content distribution and employ a publish/subscribe model to replace the current connection-oriented model. Content providers (or publishers/sources) register content identifiers into the resolution/routing system, and content consumers (or subscribers/clients) send requests with content identifiers to the system, which then triggers retrieval of the contents.

Content Request and Retrieval

ICN mobility is highly related to the content request and retrieval processes. We briefly summarize related mechanisms in Table 1. Note that some proposals provide alternative mechanisms and thus appear multiple times in the table.

As for requesting content, a content request can be routed to the provider or some in-network cache using the identifier of the content in the resolution/routing system. As for content retrieval, the requested content can be routed back to the consumer using a reverse path in the resolution/routing system, which is constructed in the routing process of the corresponding content request, or directly using the locator of the consumer to route back the content in the routing system.

Mobility of Content Providers and Consumers

Since ICN distinguishes content request and retrieval, we have to consider mobility support for content providers and consumers separately. However, their goals remain the same, that is, ensuring data (can be content or content request) can reach a moving entity. As for mobile content providers, the goal is to make sure that content requests can be delivered to them. As for mobile content consumers, the goal is to successfully get requested content back to them.

We also present current solutions for both content provider and consumer mobility in Table 1. Normally, mobility of con-

<table>
<tr><th>ICN proposals</th><th>Content requesting</th><th>Content retrieval</th><th>Content provider mobility</th><th>Content consumer mobility</th></tr>
<tr><td>NetInf</td><td rowspan="3">Route content request according to the identifier of the content in the resolution system.</td><td rowspan="2">Route content back according to the locator of the consumer in the routing system. (PURSUIT uses Bloom-filter-based source routing)</td><td rowspan="3">Update the content's location in the resolution system.</td><td rowspan="4">Make the consumer resend content requests. (Handling interruptions of ongoing content retrieval may also be required)</td></tr>
<tr><td>DONA, PURSUIT</td></tr>
<tr><td>DONA</td><td>Route content back according to the reverse path in the resolution system.</td></tr>
<tr><td>NDN, NetInf</td><td>Route content request according to the identifier of the content in the routing system.</td><td>Route content back according to the reverse path in the routing system.</td><td>Update the content's location in the routing system.</td></tr>
</table>

Table 1. Different mechanisms employed by ICN proposals for content requesting and retrieval as well as mobility handling.

tent providers is achieved by updating the contents' new locations in the resolution/routing system so that they can still be reached by consumers. As for the mobility of content consumers, due to the receiver-driven nature of ICN, consumers can simply resend the requests for contents that are not received due to movement.

However, we must notice that the above mobility solutions are aimed at the publish/subscribe model, and further consideration of the content retrieval process is missing in most cases. Actually, since the content objects employed by most ICN proposals are not packet-sized, content transmission in the routing system is unavoidable and may still rely on end-to-end sessions or other mechanisms. In such cases, if the provider or consumer moves during the content retrieval process, additional mechanisms may be required to handle interruption of content transmission.

Open Issues and Challenges

The research on mobility in ICN is still in its early stage with a number of open issues and challenges. First, as mentioned above, interruptions of the content retrieval process due to mobility should also be considered, especially in proposals with large granularity of content chunks. Although resending content requests can finally get the contents back to moving consumers, it may be an inefficient method to retransmit large content objects.

Reducing the size of content objects may alleviate the retransmit problem, but leads to another dilemma. A smaller content object implies more frequent content requests sent to the resolution system, which then demands more efficient resolution and thus requires the contents' location information to be distributed to more nodes in the system. As a result, content provider mobility brings considerable overhead since all location information of the provider's content stored in the network may become outdated and need updating.

As an extreme case, the baseline NDN protocol adopts packet-sized content objects and stores routing states for each content in the routing system. Thus, it can effectively route each content request but has to support provider mobility using a routing-based approach, which is considered unscalable. Recently, some NDN extensions have been proposed to address the problem by applying "identifier-locator split" in NDN, but this makes NDN more similar to other ICN proposals. Other novel solutions are also encouraged to solve the mobility problem in an NDN way. Since the baseline NDN mobility solution is more of a routing-based than identifier-based approach, we do not include it in our following discussions on mapping functions.

Other ICN features for mobility support we have not touched on include caching, multicasting, and so on. Due to ICN's particularity, mobility in ICN can be regarded as an independent research topic from traditional mobility studies, and this article only involves its most basic ideas and mechanisms. We refer readers to ICN surveys for more information [3, 4, 17].

Discussion on Identifier Features

In this section, we discuss the diversified features of identifiers employed by the solutions reviewed above, including how the identifiers are defined, formatted, and implemented. A summary of these features can be found in Table 2.

Identifier Definition

The definition of identifiers is also evolving. In earlier proposals, such as Mobile IP and its derivatives, identifiers are still bound to network-layer interfaces and addresses. Then in ILS designs, such as HIP and ILNP, the identifier becomes completely independent of the network layer and is explicitly defined as names of hosts (or endpoints) in the Internet. Future Internet architectures do not restrict the definition of identifier. For instance, MobilityFirst is fundamentally designed to be compatible with multiple identifier definitions simultaneously, including hosts, services, contents, contexts, and other possible future definitions. Although ICN proposals emphasize identifying Internet content, they usually claim to be compatible with other identifiers.

Identifier Format

The format of identifiers can be structured or flat. Typical structured identifiers include IP addresses used by Mobile IP and URL-like hierarchical names used by NDN. Other proposals employ flat identifiers. Most of them, including HIP, MobilityFirst, and other ICN proposals, explicitly employ self-certifying identifiers by making an identifiers hash of the public key of a key pair.

Using self-certifying identifiers, the identified entities are able to prove ownership of their identifiers via cryptographic methods. In contrast, structured identifiers need other ways to ensure their validity. However, structured identifiers such as URLs are easy to read, while flat identifiers cannot embody any human-friendly meaning. Therefore, sometimes it is necessary to leverage another level of indirection to map human-readable names to flat identifiers.

Moreover, we have experience in dealing with structured names in the Internet, such as IP addresses and domain names. Structured identifiers are easier to organize hierarchically and become aggregatable, which helps to scale in large networks. Proposals using IP addresses or domain names as identifiers can directly make use of the global routing infrastructure or

Solutions	Definition of ID	Format of ID	Implementation of ID
Mobile IP and its derivatives	Network-layer concept: has difficulty in supporting cross-device mobility	IP address: can utilize IP routing infrastructure; need additional security mechanisms	Network-based: require network change; compatible with legacy correspondent nodes
ILNP	Identify Internet hosts (endpoints): has difficulty in supporting cross-device mobility	IP address suffix: can be self-authenticating; needs additional resolution mechanism	Host-based: requires host change; compatible with legacy applications
HIP		Flat identifier: can be self-certifying, but need additional resolution mechanism	
I3, MobilityFirst, ICN proposals	Allow multiple definitions (hosts, services, contents, etc.)		Clean slate: require both host and network-change; hardly compatible with legacy routers, hosts, or applications
NDN		URL-like identifier: can utilize DNS for resolution; needs additional security mechanisms	

Table 2. Comparison among the solutions in terms of identifier definition, format, and implementation.

DNS to resolve identifiers to their locations. In comparison, flat identifiers always require additional mechanisms such as a distributed hash table (DHT) to maintain the identifier-to-locator mappings. Besides, one can embed more semantics into structured identifiers to help routing/forwarding. For example, content identifiers can be defined to contain priority, propagation scope, time to live, and other information that can help to realize a more flexible routing system [18].

Identifier Implementation

The identifier namespace together with the mapping functions can be implemented at the network or host side. Mobile IP and its derivatives belong to network-based implementation, which only requires changing the network and mobile sides, and thus is compatible with legacy CNs.

Most ILS solutions adopt host-based implementation. HIP and ILNP modify the TCP/IP stack on hosts to handle identifier-to-locator mappings. They make transport-layer sessions only see identifiers, while the network layer only deals with IP addresses. They also propose new application programming interfaces (APIs) while still keeping the original socket API, so stale applications benefit from the new mobility feature.

Future Internet architectures are usually clean slate and demand large modifications at both the network and host sides. Although they propose backward-compatible workarounds, their main application scenario is the future Internet, and most of their features are not compatible with legacy routers, hosts, or applications.

Open Issues and Research Trends

First, there is no consensus on what we should identify in the future Internet. We can observe diversification of identifier definition in future Internet research, which may imply that, based on our current understanding, one identifier definition alone is inadequate to satisfy various requirements in the future Internet, and proposals with different identifier definitions are all worth further study.

At least from the perspective of mobility support, identifying hosts is not enough to handle all mobility scenarios in the future Internet. This is because one user owning multiple devices is becoming common nowadays, and a new mobility scenario may arise when users prefer to switch ongoing communications among different devices. A host identifier alone is unable to support such scenarios, and identifying some higher-level entities (e.g., users and services) is required in the future Internet.

Second, as discussed above, structured and flat identifiers are both desirable but conflict with each other. Recent proposals such as MobilityFirst and ICN have a tendency to employ both kinds of identifiers to utilize their advantages and thus need additional mechanisms to secure the binding of the two identifiers. Such mechanisms can be achieved by utilizing search engines, social networks or new global directory services.

Third, large-scale deployment of the solutions are difficult to realize, no matter whether they require host change or network change. In contrast, some industrial solutions, such as Back to My Mac (BTMM) [19] service, have been widely used in the Internet. One of the reasons for its rapid popularization is that all BTMM functionalities are based on existing protocols. Although currently BTMM still lacks handoff management functionalities, it serves as a positive example of deployment of Internet mobility solutions.

Note that mobility can also be implemented in the application layer. However, one application cannot unify the market, and the same functionality needs to be repeated in each mobile application. Also, implementations in the application layer may get poorer performance than those in the lower layers. To keep our focus, application-layer mobility solutions are not covered in this article.

Discussion on the Mapping Function

To ensure data delivery to a mobile entity, the key mapping function is to distribute the mobile entity's up-to-date identifier-to-locator mapping, both actively and reactively, to the mapping servers, intermediate routers, end hosts, or other entities in the network in order to keep the mobile entity reachable for both ongoing and upcoming data transmission. Active mapping distribution includes registering the mobile entity's mapping into the network and updating stale mapping states stored in the network, while reactive mapping distribution involves sending mapping states in the form of response messages to the requesters. The mapping distribution mechanism varies in the reviewed proposals, and each leads to different ways to deliver packets to a mobile entity.

Classification of the Mapping Function

As shown in Table 3, we classify the mapping functions according to how the mappings are distributed. In Mobile IP (without RO), the MN's mapping state is only distributed to the HA, and in extensions of Mobile IPv6 such as HMIPv6 and PMIPv6, the mappings are distributed to a local anchor point instead. These solutions adopt local-scope mapping, which

Mapping function classification	Typical proposals	Packet routing overhead	Mobility signaling delay	Mobility signaling overhead
Local-scope mapping	Mobile IP without Route Optimization, content provider mobility of NetInf and PURSUIT	High	Medium	Low
Global-scope mapping	HIP, ILNP, Mobile IPv6 Route Optimization, content consumer mobility of DONA, NetInf and PURSUIT	Low	High	High
Hybrid mapping	DMM solutions, I3, RINA, MobilityFirst, content provider mobility of DONA	Medium	Medium	Medium

Table 3. Comparison among the mobility solutions in terms of the mapping function and related performance metrics.

means a mobile entity's up-to-date location information is only locally distributed to a fixed rendezvous node. Thus, data packets always have to first get to the specific rendezvous node and then reach the mobile entity. Besides Mobile IP and its extensions, content provider mobility in some ICN proposals such as NetInf and PURSUIT also falls into this category. This is because, based on their current design, they propose to distribute contents' locations to specific DHT nodes in the resolution system, and content requests go through a routing/resolution process in DHT before being received by the provider or intermediary nodes that have cached the content.

On the contrary, ILS designs adopt global-scope mapping by distributing a mobile entity's mapping state to all corresponding data senders over a global scope. For instance, in HIP and ILNP, CNs always get the MN's location via both active and reactive mapping distribution. In the reactive case, an MN's mapping is cached by the CNs after they query the mapping system when sessions are initiated; while in the active case, the MN pushes its new mapping to all CNs after it moves to a new location. Mapping distribution on a global scope ensures that packets can be routed directly from senders to mobile receivers in the routing system. MIPv6 with RO also employs global-scope mapping. Besides, the solution to content consumer mobility in ICN can be regarded as another form of global-scope mapping distribution. Recall that ICN proposes to rely on the consumer-driven nature to solve consumer mobility; that is, making consumers resend the requests to content providers is actually equivalent to informing the data senders (providers) of the mobile receivers' (consumers') new location after movement.

DMM solutions and future Internet architectures such as I3, RINA, and MobilityFirst belong to neither of the above categories but employ a hybrid approach. The similarity of their mapping functions is that they all perform multiple levels of mapping resolutions to reach one mobile entity. For instance, a two-level mapping function can first map the identifier of a mobile entity to a rendezvous node, and then to the mobile entity's exact location. When such a mapping function is deployed, a mobile entity's movement in a limited scope (e.g., within a domain) can be handled by only changing the local-level mapping, that is, updating the mobile entity's location on the rendezvous node. If the mobile entity moves away from one rendezvous node and gets close to another, changing global-level MN-to-rendezvous mapping is necessary. Using a combination of local and global-scope mapping, data packets can always be forwarded to a rendezvous node that is close to the MN and then redirected to the MN's exact location. As for ICN proposals, since DONA enables multi-level dynamic resolution when routing a content request in the resolution system, its content provider mobility solution is also a hybrid approach.

Open Issues and Challenges

One of the earliest problems related to the mapping function is to deal with the triangle routing of Mobile IP. The challenge lies in the fact that although many approaches have achieved small or even no routing path stretch, they all bring non-ignorable side-effects. Actually, existing efforts expose a trade-off between the efficiency of routing packets toward a mobile entity and handling movements of the mobile entity. Specifically, for one mobile entity, if we limit the scope of mapping distribution, packets may have to take a detour to reach the mobile entity, which causes path stretch and thus brings down routing efficiency of data packets; while if we employ global-scope mapping distribution, we may have to deal with heavy signaling overhead and large signaling delay caused by the distribution, because it may take a large number of messages and a long distance to distribute the mobile entity's mapping to all data senders.

We give an explanation of the trade-off by drawing an analogy to Internet routing. One common understanding in the routing research area is a fundamental trade-off between the routing table size and routing path stretch in a static network. This trade-off implies that a node in the network must store one routing table entry for each of the other nodes in the worst case to achieve shortest path routing. Otherwise, we can only trade off an increase of the routing path stretch for a drop of the routing table size, as once a node loses the routing table entry for some remote node, it may not be able to forward packets to that node via the optimal path. The situation in identifier-based mobility support is analogous: to ensure an optimal routing path, up-to-date mapping must be propagated to all data senders in the worst case; otherwise, the signaling overhead and delay can be reduced, but data senders may lose the information about the mobile entity's exact location and have to reach the mobile entity via indirection, which leads to potential inefficient routing.

Internet mobility solutions use different ways to make the trade-off, and have their own pros and cons. Mobile IP gains higher routing path stretch but lower mobility signaling delay and overhead; HIP and ILNP always get no routing path stretch but may suffer from large mobility signaling delay and overhead; DMM solutions and future Internet architectures including I3, RINA, MobilityFirst, and so on, are seeking a balance between the two.

The trade-off also applies to mobility in ICN. NetInf and PURSUIT may experience inefficient content request routing but easier mapping update when handling content provider mobility; DONA trades off a drop of content request routing overhead for an increase in the mapping update delay and overhead when dealing with content provider mobility. As for content consumer mobility, existing proposals share the same problem; that is, resending content requests after the consumer moves may be costly, especially when the movement interrupts ongoing content transmission. It worth further evaluating resending-based consumer mobility in ICN proposals particularly in real-time communication scenarios, and researching additional mechanisms to avoid long interruption of active content transmission if necessary.

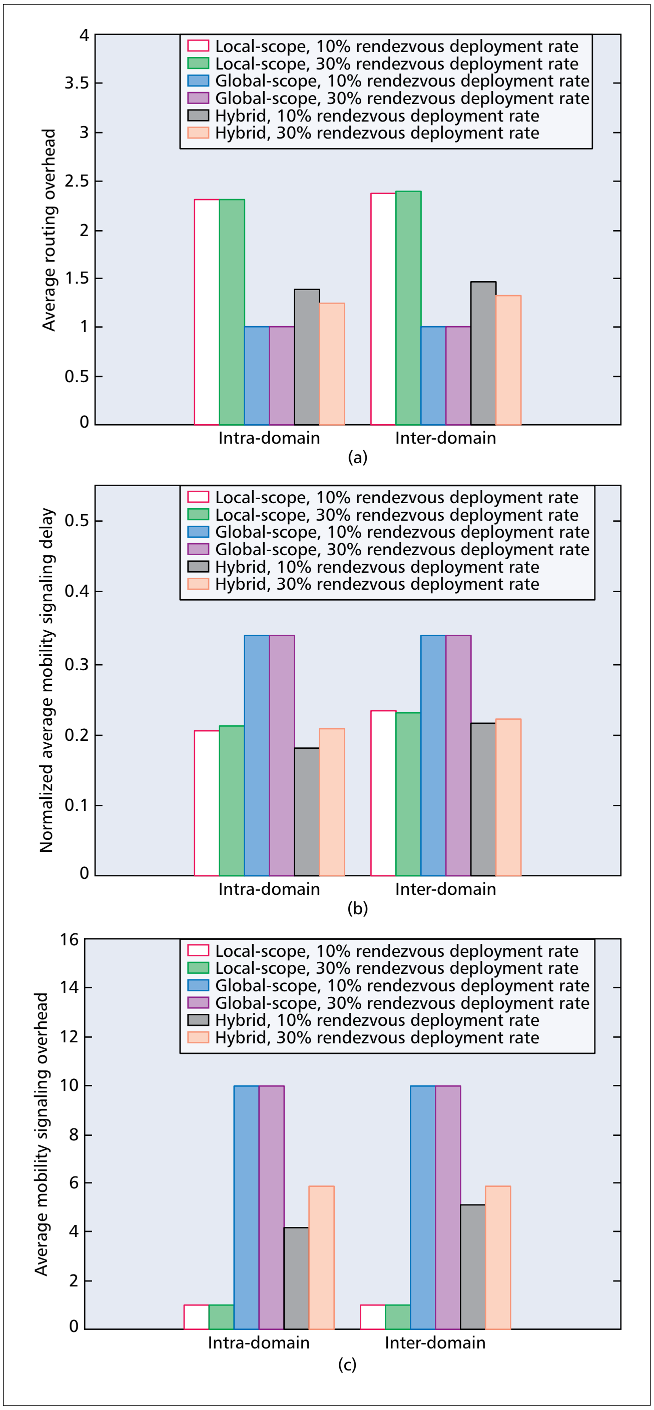

Figure 3. Quantitative analysis on performance metrics of different mapping functions.

Quantitative Analysis

We provide a quantitative analysis on different mapping functions by simulating stationary data senders and mobile data receivers as well as rendezvous nodes in real network topologies. We collect an all-pairs router-level hop count from the Rocketfuel Project [20] and Border Gateway Protocol (BGP) data from the Route Views Project [21] to form intra- and inter-domain topologies, respectively. Based on each topology, we randomly choose one node as a data receiver, 10 nodes as data senders, and several nodes (with a specific percentage) as rendezvous nodes. Each movement of the data receiver is simulated by choosing a neighbor node of the receiver's current location as the movement destination.

In each simulation turn, we estimate three performance metrics including packet routing overhead, mobility signaling delay, and overhead according to the locations of the data senders, data receivers, and rendezvous. Routing overhead is represented by path stretch calculated by dividing the length of the actual sender-to-receiver path by that of the shortest path between them in the topology. Mobility signaling refers to the message exchanges for distributing the mobile receiver's mapping to rendezvous nodes or data senders, which we call anchor points in this simulation. We use normalized average distance between the receiver and the anchor points to approximate mobility signaling delay, and use the number of anchor points to approximate mobility signaling overhead.

Specifically, for local-scope mapping, a packet routing path is divided into two sub-paths: one from data senders to a fixed anchor point, and the other from the anchor point to the data receiver. The role of the anchor point is played by the rendezvous node nearest to the data receiver at the beginning of each simulation. For global-scope mapping, the routing path is always the shortest, while all data senders serve as anchor points. Finally, we simulate hybrid mapping using a two-level mapping function as described previously. In this case, the packet routing path also consists of two sections, and the turning point is the rendezvous node located nearest to the receiver's current location. The set of anchor points is dynamic: if the receiver's nearest rendezvous node remains after one movement of the receiver, the anchor point is the specific rendezvous node; otherwise the anchor points become all data senders.

We calculate the average value of three performance metrics during 1000 simulation turns, and in each turn the data receiver performs 100 movements. Figure 3 shows the simulation results at a two rendezvous deployment rate (10 percent and 30 percent) from both intra- and inter-domain topologies. The results are also summarized in Table 3, which is consistent with our analysis: local-scope mapping has both high packet routing overhead and mobility handling efficiency, while global-scope mapping is just the opposite. Although it seems that the hybrid approach can reduce packet routing overhead without bringing severe mobility signaling delay and overhead, considering that our simulation settings are simple, we still need to investigate how this approach behaves when applied to more complex and real mobility scenarios.

In our opinion, to fit into various mobility scenarios in the future Internet, using local or global-scope mapping alone may be inadequate since they are relatively fixed and difficult to further improve. In comparison, DMM solutions and future Internet architectures adopt a more flexible approach, which we regard as a promising way to seek an ideal balance for the performance trade-off and provide better mobility support in future Internet.

Summary

In this article, we provide a survey on identifier-based Internet mobility approaches, the key idea of which is to introduce a new namespace to identify a mobile entity and leverage a mapping function to track the location of the mobile entity. We show that an identifier-based approach emerged in Mobile IP research, then matured and achieved wide acceptance in ILS research, and has currently become a common part of proposals in future Internet research. We review several typical identifier-based solutions and provide comparisons in terms of identifier features and mapping functions. We point out that each category of solutions has its pros and cons, and can be employed to meet diverse requirements in the future Internet. We also discuss open issues and challenges, and present our suggestions for future research on this topic.

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References

[1] Z. Zhu, R. Wakikawa, and L. Zhang, "A Survey of Mobility Support in the Internet," IETF RFC 6301, Jul. 2011.
[2] Y. Wang, J. Bi, and X. Jiang, "Mobility Support in the Internet Using Identifiers," *Proc. ACM CFI*, 2012, pp. 37–42.
[3] B. Ahlgren et al., "A Survey of Information-Centric Networking," *IEEE Commun. Mag.*, vol. 50, no. 7, July 2012, pp. 26–36.
[4] G. Xylomenos *et al.*, "A Survey of Information-Centric Networking Research," *IEEE Commun. Surveys & Tutorials*, vol. 16, no. 2, July 2013, pp. 1024–49.
[5] C. Perkins, "IP Mobility Support for IPv4, Revised," IETF RFC 5944, Nov. 2010.
[6] C. Perkins, D. Johnson, and J. Arkko, "Mobility Support in IPv6," IETF RFC 6275, Jul. 2011.
[7] J. C. Zuniga *et al.*, "Distributed Mobility Management: a Standards Landscape," *IEEE Commun. Mag.*, vol. 51, no. 3, Mar. 2013, pp. 80–87.
[8] P. Nikander, A. Gurtov, and T. R. Henderson, "Host Identity Protocol (HIP): Connectivity, Mobility, Multi-homing, Security, and Privacy over IPv4 and IPv6 Networks," *IEEE Commun. Surveys & Tutorials*, vol. 12, no. 2, Apr. 2010, pp. 186–204.
[9] R. Atkinson and S. Bhatti, "Identifier-Locator Network Protocol (ILNP) Architectural Description," IETF RFC 6740, Nov. 2012.
[10] S. Zhuang *et al.*, "Host Mobility Using an Internet Indirection Infrastructure," *Wireless Networks*, vol. 11, no. 6, Nov. 2005, pp. 741–56.
[11] V. Ishakian et al., "On Supporting Mobility and Multihoming in Recursive Internet Architectures," *Comp. Commun.*, vol. 35, no. 13, JulY 2012, pp. 1561–73.
[12] A. Venkataramani *et al.*, "Design Requirements of a Global Name Service for a Mobility-Centric, Trustworthy Internetwork," *Proc. IEEE COMSNETS*, Jan. 2013, pp. 1–9.
[13] T. Koponen *et al*, "A Data-Oriented (and Beyond) Network Architecture," *ACM SIGCOMM Comp. Commun. Rev.*, vol. 37, no. 4, Oct. 2007, pp. 181–92.
[14] L. Zhang *et al.*, "Named Data Networking," tech. rep. NDN-0019, Revision 1: 10, Apr. 2014.
[15] C. Dannewitz *et al.*, "Network of Information (NetInf) — An Information-Centric Networking Architecture," *Comp. Commun.*, vol. 36, no. 7, Apr. 2013, pp. 721–35.
[16] D. Trossen and P. George, "Designing and Realizing an Information-Centric Internet," *IEEE Commun. Mag.*, vol. 50, no. 7, July 2012, pp. 60–67.
[17] G. Tyson *et al.*, "A Survey of Mobility in Information-Centric Networks," *Commun. ACM*, vol. 56, no. 12, Dec. 2013, pp. 90–98.
[18] I. Psaras *et al.*, "Name-Based Replication Priorities in Disaster Cases," *Proc. IEEE Wksp. NOM*, Apr. 2014.
[19] S. Cheshire *et al.*, "Understanding Apple's Back to My Mac (BTMM) Service," IETF RFC 6281, June 2011.
[20] Rocketfuel: An ISP topology mapping engine: http://www.cs.washington.edu/research/networking/rocketfuel/.
[21] Univ. Oregon Route Views Project: http://www.routeviews.org/.

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