Mobile Sources in an Information-Centric Network with Hierarchical Names: An Indirection Approach

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***Abstract*—An increasing amount of information is available from mobile devices. We consider the problem of retrieving data from mobile sources in an information-centric network architecture called Named Data Networking. We propose an approach in which indirection points locally map requests for persistent data names to requests for temporary location names that reflects the sources' current network attachment points. The approach does not require cooperation from intermediate routers or requesting nodes, and supports multi-homing, soft hand-overs, and networks of mobile sources. The inherent route stretch problem is mitigated by serving cached data from the indirection points. An initial evaluation shows that our approach reduces retrieval time and load on mobile sources in case of repeated requests, compared to an approach that uses a global distributed naming database to look up mobile sources' locations.**

I. Introduction

Today we are surrounded by a vast number of mobile devices that can be rich sources of information, ranging from mobile phones and laptops to sensors in vehicles and merchandise. Yet, the mobility makes retrieving this information over the Internet a challenging task.

The TCP/IP Internet architecture was influenced by assumptions that the Internet would be primarily used to share resources of few, relatively powerful computers and that nodes were fixed and rarely moved in the topology. In contrast, distribution of content (as opposed to resource sharing) accounts for a large amount of today's Internet traffic [1] and mobile nodes have become ubiquitous. To enable more efficient content retrieval in the network layer, a number of clean-slate, information-centric network architectures have been proposed (see [2] for a survey). In these architectures, each piece of information has a name. Nodes request information merely by its name, without specifying a source. Based on the name, the network obtains the requested information from a suitable source. Information is replicated in the network to reduce the load on the original sources and to reduce retrieval time.

We consider the problem of obtaining information from mobile sources in the recently proposed Named Data Networking (NDN) architecture [3], which has emerged from the earlier Content Centric Networking project [4]. Since NDN is a clean-slate approach envisioned to be independent of IP, we do not regard using an NDN overlay on top of existing mobility solutions such as Mobile IP [5]. Instead, we aim to solve the source mobility problem within the NDN architecture. We argue that frequent source mobility either puts a high load on the routing infrastructure or puts a high load on mobile sources. The latter occurs if location changes have the side effect of unnecessarily invalidating replicated data, as explained in Sec. II-A. We propose to use indirection points for retrieving content from mobile sources. An indirection point locally maps requests for information in one part of the namespace, which contains the requested data, to requests for another part of the namespace, which reflects the sources' current location.

Our approach preserves names of information from mobile sources even as the sources move. In effect, any repeated request can be satisfied from caches in the NDN network, at latest at the indirection point. Serving cached data reduces retrieval times and communication with mobile sources, which is especially important for sources with a limited energy budget. Repeated requests are common for information that is of interest to multiple parties, such as sensor data or other popular data. Our approach is conceptually simple and supports multi-homing and soft hand-overs by decoupling names that identify data from names that identify temporary locations of data. Cooperation from intermediate routers or requesting nodes is not required. The approach is similar in spirit to Mobile IP, but serving cached data mitigates the route stretch incurred by forwarding through indirection points. The approach also handles networks of mobile sources without requiring extensions such as NEMO [10] for Mobile IP.

We evaluate a prototype implementation and compare it to another approach for handling source mobility in NDN, which uses a DNS-style system for translating information names to the source's current location. We find that our indirection-based approach reduces retrieval time and communication with mobile sources in case of repeated requests, while incurring a moderate overhead if all requests are unique.

II. NDN Overview & Problem Description

In this section, we briefly summarize the NDN architecture and describe the problem associated with source mobility.

Any communication in NDN is based on requesting named data. Two types of packets are used: *Data packets* and *interest messages*. A data packet is a named sequence of bytes. A name is a sequence of arbitrarily many components. E.g., a picture could be identified by the name `/isp1/bob/pics/z.jpg`, which contains the four components `isp1`, `bob`, `pics`, and `z.jpg`. An interest message (or interest for short) represents

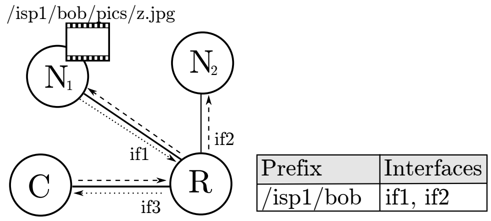


Fig. 1: Node C wants to retrieve data located at N_1. Both N_1 and N_2 serve data for the prefix `/isp1/bob`, as seen in router R's FIB. Dashed arrows depict how C's interest is propagated, dotted arrows depict how the data flows back.

a request to retrieve a data packet. It contains a name, and if the name of an interest is a prefix of a data packet's name, then the data packet is said to satisfy the interest.

Communication is strictly pull-based. A node may only send a data packet in response to an interest it received. Routers propagate interests towards (potential) sources of data by consulting their *forwarding information base* (FIB) table. A FIB entry maps a name prefix to a set of network interfaces over which sources of data for the prefix may be reached. If an entry specifies multiple interfaces for one prefix, the so-called *strategy layer* defines the order in which the interfaces are tried. If a node receives an interest message that it can satisfy, it sends out the satisfying data packet and does not further propagate the interest. The data packet is forwarded along the reverse path of the interest towards the original requester. This is exemplified in Fig. 1.

To leverage storage in the network, nodes may cache any data packets they receive. Nodes satisfy interests from their cache whenever possible.

FIB tables are populated as follows: If a node wants to receive interests for a given name prefix (and thus be able to publish data for this prefix), it announces the prefix to its next routers. A router that receives such a *prefix announcement* updates its FIB table accordingly and propagates the announcement to other routers if needed. The exact mechanisms of prefix announcements are not defined yet, but it has been suggested that they can be inspired by the BGP protocol.

Since names are hierarchical, FIB entries can be aggregated if they refer to the same prefix. Small FIBs enable low lookup times, which is required for scalability of the network. To ensure that names are well-aggregable, it is suggested to use provider-assigned names for data. The top-level components of a provider-assigned name reflect the provider to which the original data source is connected. Requesting nodes query a DNS-style distributed database to translate user-friendly names (e.g., `bob.ndn`) from a separate namespace to provider-assigned names in the data namespace (e.g., `/isp1/bob`). We refer to such a translation system as a *distributed naming database* from now on.

For a detailed description of the NDN architecture, including the aspects of consumer mobility (as opposed to source mobility), security and determining freshness of cached data, the reader is referred to [4] and [3].

A. Problem description: Source mobility

Consider a mobile source, i.e., a mobile node that wants to serve data for a given name prefix. As the mobile source moves, it changes its attachment points to the NDN network. For example, it may connect to a local WiFi network at first, then switch to a 4G connection, and then connect to a WiMAX network. The NDN network needs to be informed of these changes to ensure that interests are still forwarded to the mobile source.

The mobile source could issue a prefix announcement at each new attachment point to trigger FIB updates in routers so that interest messages are delivered to the mobile source's new attachment point. However, there are three issues associated with this approach. (1) If a mobile source switches from one provider to another, many routers may be affected by the resulting prefix announcement, putting considerable load on the routing infrastructure. (2) If prefix announcements are allowed from arbitrary topological locations, then the name of an interest cannot be used to efficiently propagate the interest towards the potential sources. Consider some prefix X that is announced from many different provider networks. An interest in data under X needs to be propagated to all sources announcing X, until eventually one of the sources can satisfy the interest. In such a situation, forwarding of interests puts considerable load on the whole network. (3) A provider may restrict the propagation of prefix announcements.

Instead of using prefix announcements to inform routers of a mobile source's new attachment point, the mobile source could update the distributed naming database. It changes the entry for the user-friendly name under which it serves data to map to the provider-assigned name that reflects its new attachment point. This approach does not suffer from the above-mentioned issues, but it reduces the efficiency of in-network caching: As the mobile source moves, data changes its provider-assigned name even though the data does not change. In the previous example, the data name may change from `/isp1/bob/pics/z.jpg` to `/isp2/bob/pics/z.jpg`. Subsequent interests will be expressed using the new data name (`/isp2/bob/...`), and all data cached under the old name (`/isp1/bob/...`) becomes useless, since a router cannot tell that the names refer to identical data. Furthermore, maintaining a consistent distributed database that supports fast lookups adds additional complexity to the architecture.

III. An Indirection Approach to Source Mobility

We suggest to use indirection points to handle source mobility in NDN. Each indirection point maintains a set of bindings between persistent data names and temporary names dependent on the mobile sources' current attachment points. An indirection point tunnels interests for persistent data names towards the sources' by sending out corresponding interests for the temporary names.

Consider an indirection point deployed in the network of some provider ISP_X. The indirection point, which we refer to as the *home repository*, is a node that is permanently connected to ISP_X's network and does not move. It maintains a binding table, and each entry of this table represents a binding of a target prefix to a set of source prefixes.

- A *target prefix* is a prefix beginning with `/ispX` that a mobile source wants to serve data for. Names under the target prefix identify data permanently. They do not change as the mobile source changes its attachment point.
- A *source prefix* is a prefix that a mobile source can currently receive interests for and that reflects its current attachment point within some other provider's network.

The home repository announces each target prefix once so it receives interests for the target prefixes. These announcements do not need to leave ISP_X's network, since they can be aggregated at the border routers.

When the home repository receives an interest i for any target prefix, it first tries to satisfy it from its cache. If this is not possible, it performs a longest-prefix matching of the interest's name against the target prefixes in the binding table. Assume that the best-matching entry specifies the source prefix set S. The home repository creates a new interest i_s for each $s \in S$ that encapsulates the original interest i. The new interests are sent out according to the home repository's strategy layer. When a mobile source receives an interest i_s, it decapsulates the original interest and tunnels back a satisfying data packet if possible. The home repository decapsulates the data packet and sends it to the original requester.

When a mobile source connects to the NDN network the first time, it sends a binding request to the home repository. In the binding request it specifies the target prefix it wants to serve data for, as well as the source prefixes it currently can receive interests for. If the mobile source has a single connection to the network, it may have just one source prefix, but if it is multi-homed, it may specify multiple source prefixes. As the mobile source moves and changes its attachment points, it sends new binding requests, and also requests the home repository to delete obsolete bindings. This way, the mobile source ensures that the binding at the home repository is always correct. The home repository furthermore periodically checks the reachability of source prefixes. If a source prefix is unreachable, it is removed from the affected binding.

The approach can handle networks of mobile sources. Since an interest only denotes the requested data name and does not denote a specific source node, a mobile router can simply forward decapsulated interests to other nodes in its mobile network. If it receives a data packet in response, this data packet is tunneled back towards the home repository. The other nodes in the mobile network need not be aware of the mobility.

Our approach requires the following changes to the network: Mobile sources have to run a software that sends binding messages to a home repository as it moves. If a mobile source wants to bind a target prefix, a home repository needs to be deployed in the network to which interests for the target prefix are propagated. Home repositories could be dedicated nodes operated by providers, but a user's desktop machine with permanent connectivity could also serve as a home repository. Intermediate routers and nodes requesting data from mobile sources do not need to be changed.

A. Discussion

In contrast to using prefix announcements, our approach only requires an update to the home repository's binding table if a mobile source changes its attachment point. Other nodes in the network need not be aware of whether data sources are mobile. Since data names are preserved even as mobile sources roam between networks, more requests can be satisfied from cached data than when updating the distributed naming database to handle source mobility.

The key advantage of forwarding interests and data through the home repository is that the home repository can serve cached data for repeated requests. This is especially desirable if the mobile source is connected wirelessly, as wireless connections are prone to high bit error rates, strong variations in bandwidth, high round trip times, and often require major amounts of the energy budget of battery powered devices.

Almost all interests in data from a mobile source have to travel via the home repository. This may be a detour if the home repository is not on the path between a requester and a mobile source. However, this detour has to be taken only once for each requested data, since the data can be served from the home repository's cache afterwards. Furthermore, if requester and mobile source are in the same broadcast domain, then NDN enables the requester to obtain data directly from the mobile source, without any involvement of the home repository. Roughly speaking, this works by leveraging the broadcast nature of many (especially wireless) link layer networks: any node that overhears another node's request that it can satisfy may send back the satisfying data immediately. Thus, a mobile source can directly respond to requests from its link layer neighbors, without involvement of the home repository.

The use of a home repository requires some additional security considerations. A node that requests data from a mobile source via a home repository needs to be able to verify the authenticity and integrity of the received data. In the NDN architecture, each data packet is signed by its producer, and furthermore contains information on how to obtain the producer's public key to validate the signature of a packet. Therefore, by design of NDN, a requesting node is able to determine the producer of a data packet (by looking at who signed it) and its integrity (by validating the signature). Another consideration regards the validity of binding requests. To this end, a binding request sent by a mobile source must not only include the source and target prefix, but must also enable the home repository to establish the identity of the source of the request. Using this information, a home repository can decide whether it will accept a binding request or not.

IV. Evaluation

We aim to verify the expected caching benefits by comparing the performance of our prototype implementation against the distributed naming database approach. We refer to our approach as HR (since it involves home repositories) and refer to the distributed naming database approach as described in II-A as DND. In DND, requesting nodes resolve the user-friendly name of data from the mobile source to the current provider-assigned name prior to each retrieval.

Retrieval time (time to obtain content from a mobile source) and amount of data sent from and to a mobile source were chosen as metrics. The latter is an indicator of the amount of energy a mobile source needs to spend on communication.

A. Scenario and Method

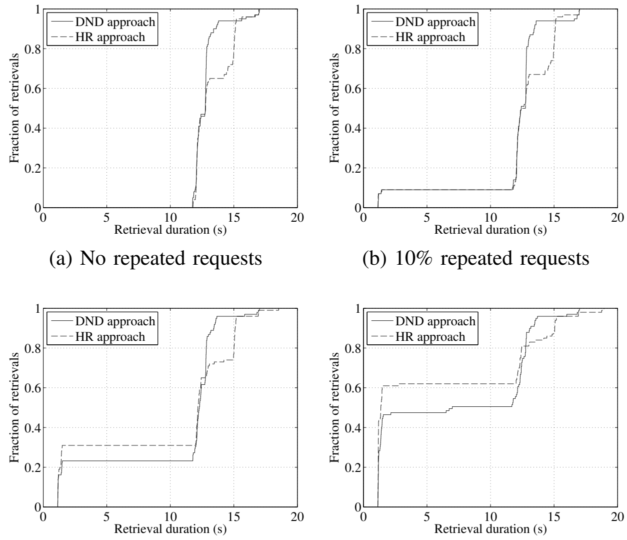
All nodes and links were emulated using Xen virtualization technology. The evaluation scenario consists of two networks and a mobile source that roams between the networks. Each network consists of two stationary hosts and a router, and the routers are connected over a dedicated link. The router of the first network serves as the home repository for the mobile source. To mimic the characteristics of a wireless link, the mobile source's uplink is limited to 1 MBit/s and the round-trip time is set to 100 ms. The mobile source hosts 10 files, each 1 MB in size. In each experiment run, the stationary hosts request 10 of these files. In case a request can be satisfied from a cache, the requesting host checks with the mobile source to ensure that the cached copy is up-to-date. The files to be requested were chosen according to a Zipf distribution. Changing the skewness of the distribution allows us to control the amount of repeated requests and see the effects on caching. The requests are distributed uniformly at random over the stationary hosts, and are distributed uniformly over time. Each experiment run lasted 4:10 minutes, and half-way through each experiment the mobile source performed a hand-over from the first to the second network. No network stabilization time was required in our scenarios. Every experiment was repeated ten times with different random seeds and we present averages and distributions of the obtained results.

The NDN prototype implementation package does not yet include the distributed naming database as described in Sec. II and [3], as its design is still in progress. To enable a fair comparison, we mimic the use of a distributed naming database as follows: in the DND experiments, the stationary nodes are assumed to have instantaneous and perfect knowledge of the mobile source's current attachment point. Thus, the results for the DND approach are idealized, because query and update costs of the database are not included. In contrast, the stationary nodes in the HR experiments do not have this knowledge. Since our evaluation is concerned with the relative performance of the HR approach to the DND approach, we believe that such an idealization on behalf of the DND approach is acceptable.

B. Results

Figure 2 shows the empirical cumulative distribution functions (ECDFs) of retrieval times. Both approaches perform comparably for only distinct requests (Fig. 2a), but the ECDF of our HR approach features an additional "step" around 15 s. This is due to retrievals that are handled by the home repository software, which adds approximately 2 additional seconds of delay. The other steps present in both ECDFs are due to the distance between requester and source. Results are similar for 10% repeated requests (Fig. 2b).

Figure 2c shows ECDFs when 40% of the requests are repeated. Notice that using DND, around 24% of all requests are satisfied from a cache in the network (taking around 1.5 s), whereas using the HR approach, around 31% of the requests



(a) No repeated requests (b) 10% repeated requests

(c) 40% repeated requests (d) 70% repeated requests

Fig. 2: Cumulative distribution function of retrieval times for varying redundancy in requests.

are satisfied from caches. Figure 2d shows ECDFs when 70% of the requests are repeated. Again, the HR approach is able to satisfy more requests from cached data (around 62% of all requests) than DND (around 50%).

The amount of data sent to and from the mobile source for the two approaches is shown in Tab. I.

As expected, our approach increases the amount of requests that can be served from cached data since data names are preserved and repeated requests can be satisfied at latest at the home repository. For repeated requests, our approach lowers the average retrieval time, whereas for non-repeated requests the increase in retrieval time is moderate.

Repeated requests	DND approach	HR approach	Overhead of DND
0%	6.28 MB	6.48 MB	−3.23%
10%	5.72 MB	5.95 MB	−4.02%
40%	4.81 MB	4.62 MB	4.08%
70%	3.25 MB	2.60 MB	19.90%

TABLE I: Total number of bytes sent from and to the mobile source for different amounts of repeated requests.

V. Related Work

Wang et al. propose a system based on NDN to collect data from cars [6]. They suggest that car manufacturers reserve special prefixes and ask network providers to announce these prefixes from road-side base stations. We believe that such agreements may be impractical given a large number of car manufacturers and network providers. Meisel et al. study the use of NDN in an ad-hoc network scenario [7]. Their approach uses flooding of interests. Lee et al. describe a proxy-based scheme for increasing efficiency of mobile retrievals as opposed to mobile sources [8].

Ahlgren et al. review how various information-centric architectures handle source mobility [2]. Similar to the approaches in NetInf and PSIRP, our home repository effectively is a rendezvous point for a requester and a mobile source.

Much research has been conducted on handling mobility in the TCP/IP Internet architecture [9]. Our approach is similar to Mobile IP [5], which also uses an indirection point (called a home agent) to tunnel packets towards mobile nodes. In contrast to Mobile IP, our approach allows to mitigate the route stretch problem by serving cached data from the home repository. Furthermore, Mobile IP requires additional protocols such as NEMO [10] to handle mobile networks.

VI. Conclusion

We presented an indirection approach to handling source mobility in the Named Data Networking architecture. In our approach, home repositories locally map interests from persistent data names to temporary names dependent on the mobile source's location. Any repeated request can be satisfied at latest at a mobile source's home repository, reducing retrieval time and communication with mobile sources. If a mobile source changes its attachment point to the network, it only needs to inform its home repository. The mobility is transparent to other nodes in the network.

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