Information Mobility: a New Paradigm for Wireless Content Dissemination

Jose M. Barcelo-Ordinas [1], Claudio Casetti [2], Gunnar Karlsson [3], Susana Sargento [4]

e-mails: joseb@ac.upc.edu, casetti@polito.it, gk@kth.se, ssargento@deti.ua.pt

[1] *Universidad Politecnica de Catalunya (UPC), Barcelona, Spain*

[2] *Politecnico di Torino, Torino, Italy*

[4] *Royal Institute of Technology (KTH), Stockholm, Sweden*

[3] *Universidade de Aveiro, Aveiro, Portugal*

***Abstract*— Content distribution networks are nowadays becoming a mature technology. Nevertheless, content delivery research in ad hoc networks has dealt with overlay applications, information querying and data broadcasting techniques. The aim of this paper is to explore and discuss content delivery in wireless ad hoc networks and to state challenges and reference models for this kind of networks. The concept of *Information Mobility* is introduced to point out that the contents are being stored in mobile nodes and that the contents move and replicate before being accessed. The network considered is a wireless ad hoc network with sparse connectivity and limited infrastructure support.**

I. Introduction

The idea that networks should provide access to contents, rather than to hosts, is currently permeating the research world. This idea is manifested in content distribution networks based on either peer-to-peer networks of hosts where contents are stored and retrieved based on distributed hash tables, or on an infrastructure of large caching nodes located close to edge networks. In this paper, we explore the concept with respect to wireless ad hoc networks. We use the term *information mobility* to highlight both that content is being stored in nodes that move and that the content itself move and is replicated in anticipation of being accessed. The purpose is to re-assess content distribution with respect to ad hoc networks for which member nodes and the topology that interconnects them are changing dynamically. We consider content that both originates within the ad hoc network itself and that is delivered from the Internet through infrastructure nodes (cellular, mesh and hot-spot wireless networks).

Content distribution in wired networks has mainly focused on acceleration techniques that expedite the delivery of content from servers to clients. Web acceleration in wired networks is a mature technology, and now most companies are integrating such techniques for video streaming, particularly for high definition video [1].

If we shift our attention to wireless networks, and specifically to ad hoc wireless networks, we observe that content delivery has mainly been dealt with by bringing overlay applications on top of wireless networks, with information querying (i.e. content lookup) and with data broadcasting techniques. In this context, Wireless Content Distribution (WCD) works as follows: *(i)* a wireless user requests web content from Internet servers by wireless access through a base station; *(ii)* the server sends the reply for the request to a gateway support node (GSN), *(iii)* the GSN issues the content to the base station, which in turn forwards it through the air interface. Wireless data accelerators may be attached to the GSN to improve delivery performance. As such, this system is a wireless extension of the Internet paradigm for content delivery and it does neither leverage the mobile nodes as caches, nor is it optimized for content generated in the wireless network. Besides, it assumes continuous connectivity from the mobile nodes to the infrastructure.

The objectives of this paper are: *(i)* to define the information mobility paradigm, and how it relates to existing paradigms, such as the current content distribution networks; *(ii)* to explain the main issues of this information-centered mobility paradigm when compared to current approaches; and *(iii)* to identify the main challenges we need to address, as posed by content delivery in wireless ad hoc networks with sparse connectivity and limited infrastructure support. Our final goal, which is beyond the scope of this paper, is to design an architecture aiming at coping with this paradigm.

This paper is structured as follows. Section II presents the information mobility paradigm and section III compares the CDN approach with this paradigm, highlighting several issues that gain center stage in our new approach. Section IV describes some reference models for applications that may exploit the information mobility paradigm. Section V depicts the main challenges to be faced when addressing this paradigm. Finally, section VI summarizes and concludes the paper.

II. The Information Mobility Paradigm

The system structure that we assume consists of mobile nodes that may communicate both directly with one another by means of short range radio links (such as Bluetooth and IEEE 802.11 in ad hoc mode) and indirectly with other mobile and fixed nodes through infrastructure based wireless networks (such as UMTS and IEEE 802.11 in infrastructure mode).

Content recipients are mainly mobile nodes that are interested in accessing some piece of information. These nodes are, for example, carried by pedestrians or vehicles, and they may pass through areas covered by infrastructure wireless networks, such as Wi-Fi hot spots and the blanket coverage of 3G. Mobile nodes have then opportunity to download content, and they may lose connectivity when they leave the coverage area. Other examples are mobile nodes (e.g., vehicles) collecting data from parking sensors that advertise free parking slots, or information disseminated by vehicular traffic authorities. In order to capture these different cases, we make a simple distinction between the geographic *relevance* and *availability* of an information item. An item might, for instance, be of interest to users anywhere in the world, but it might only be available to a closed group. This distinction is not important in the (wired) Internet, where every content item can be retrieved anywhere, but it makes a compelling case for harnessing the power of information mobility in wireless ad hoc networks.

There are three cases to consider for the discussion, figure 1.

- **General relevance, general availability** Contents created anywhere that are distributed over large geographical areas by using a fixed infrastructure (e.g. a cellular or mesh network). The fixed infrastructure coverage might not necessarily be spatially continuous.
- **Local relevance, local availability** Contents created by stand-alone providers (e.g. shops, gas stations, restaurants) with the aim of *directly* publishing contents or promoting services to passer-by nodes. This includes also fixed nodes, such as parking sensors, that disseminate their information to passing cars.
- **General relevance, local availability** Contents that originate from mobile nodes and stand-alone providers, which might be of general interest but are only locally distributed.

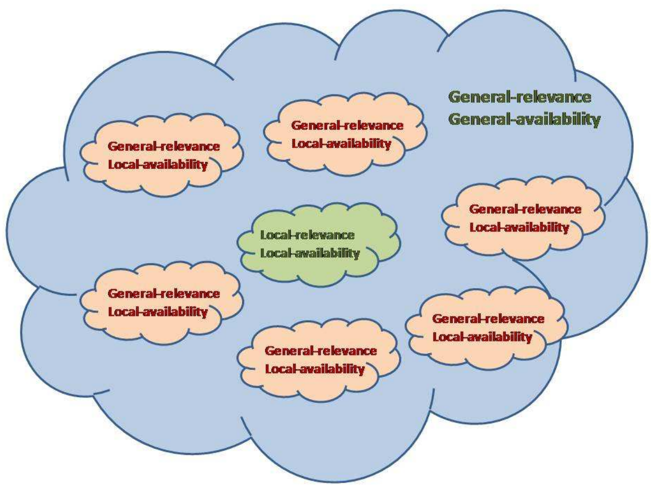

Fig. 1. Content Distribution Scenarios

The aims of information mobility in an ad hoc network are twofold:

- to bridge gaps in content availability due to the lack of coverage of infrastructure networks, for information travelling from the ad hoc domain to the infrastructure domain and viceversa;
- to make content of local relevance available in a designated area with arbitrarily high probability over any time period.

The first aim requires a protocol for information exchange, based on some consistent, unique naming of content items. The naming issue is common to any content distribution system and any appropriate solution might be equally applicable in the wireless as in the wired networks. The information exchange depends on the connectivity of the ad hoc network. A particular challenge is posed by sparse networks, addressed by several proposals in recent years. While some suggest the use of explicit routing, other proposals focus on general dissemination based on replication of data [2], [3]. The main issue is when and to whom to forward a content item. Note that this includes replication where a node forwards multiple copies of the item in order to hedge against uncertainty in forwarding decisions.

The second aim of the information mobility requires two additional functions. First, the forwarding has to be geographically scoped in order to limit the availability of a content item to within its geographic scope of relevance. The second function is to provide custody of the contents in order to make them available also over time (see [4] for some work on custodianship in delay-tolerant networks).

In brief, information mobility means that information is provided in a wireless domain at the locations where it is requested, irrespective of where it originated and of how the nodes of the network are moving. We will explore the challenges that arise from this concept in more depth in the following sections.

III. CDN in Wireless Networks

As previously stated, our scenario can be viewed as a special case of CDNs in wireless networks. Infrastructure CDNs are provided by several companies, e.g. Akamai, to avoid congested parts of the Internet, and they consist of edge servers deployed at several ISP access locations and network exchange points. The purpose is to improve the response time of an Internet site. Even in these networks, there are several issues and challenges that need to be addressed, such as efficient mechanisms to keep data consistency, autonomic mechanisms for distribution, configuration and management, and security.

The challenges of this type of networks are exacerbated if they are provided through wireless networks, and in particular mobile ad hoc networks: mobility leads to node churn and to dynamically changing available bandwidth; security is also more easily compromised. Developing edge servers in wireless nodes requires an intelligent mechanism to determine the best location of the servers, which should be dynamically updated according to network conditions, users mobility and access patterns to contents. User preferences and context-based decisions can be leveraged to increase the efficiency of these systems. Moreover, the error-prone, shared medium of wireless networks complicates the support of a reliable network with reliable delivery of services, and the secure access and transmission of these services.

The scenario addressed in this paper is even more challenging since it considers a wireless peer-to-peer scenario, where mobile nodes act as edge servers that cache and deliver the information to the intended users, who may be several hops away. This scenario adds to the previous challenges all issues related to the support of mobile edge servers, such as information survivability, reliable distribution, information spreading according to desired distributions and network performance, and security.

The next items further explain each of these issues in comparison to wired and wireless CDN networks:

- **Information survivability:** Regardless of the initial information distribution, and of the density of nodes, information should never be allowed to die out due to node isolation, transmission malfunctions or incorrect distribution. Related to the information survival is the evaluation of the minimum number of copies of a specific information that can satisfy users' needs (i.e., in terms of information retrieval time or response rate).
- **Reliable distribution of information:** Mechanisms are needed to increase the efficiency of the transmission in a wireless medium, as well as the support of information mobility mechanisms to spread the information to the required places according to receiver nodes' mobility. Node mobility patterns and user behaviors are key factors if the network has to cache information. In order to define a general framework, there is a need for more detailed user behaviors and realistic mobility patters.
- **Information spreading according to a desired distribution:** Regardless of how the information is distributed at the outset, the system should be able to identify if and how frequently the information should be replicated and spread to neighboring nodes, while guaranteeing that the provider role is taken up by all of the nodes in a fair manner. It may also be required that an information object be kept within a limited geographical area to provide localized services.
- **Information spreading according to network performance:** the performance of the network in terms of bandwidth availability and information retrieval delay is also a key factor. For a given mobility pattern, the information placement in the network should be chosen by taking into account the congestion level of the path it will need to traverse in order to reach the receiver. Both mobility patterns and available network resources should be used to determine the pattern of information mobility.
- **Security:** this is a common issue to all scenarios, since the authenticity of the edge servers, as well as the authenticity of the end-users, are strong requirements. In our scenario, many more security issues arise: guaranteeing the authenticity of the nodes that cache information, information change and/or corruption as it travels in a multi-hop fashion, and intruder nodes compromising correct information.

To illustrate the spatial spreading of contents, see figure 2. We show a part of an actual downtown area (left) and the spatial distribution of the contents in a corresponding network of street segments (right) (from [5]). Darkened areas denote the percentages of pedestrian nodes with the contents in steady state; the average availability is 77.5% in the grid. The underlying analysis assumes Poisson arrivals of rate 5 nodes per 100 seconds on each inlet to the area. Each node selects a speed randomly at arrival and at each intersection from a uniform distribution over the interval $[0.5, 1.5]$ m/s. Nodes turn left or right at intersections with probability 0.25 and continue straight with probability of 0.5 (or turn with equal probabilities at T-intersections). Only 5% of the nodes on one inlet carry the contents into the area (marked p_{in} on the left). The transmission range of the nodes is 10 m and minumum useful contact time is 20 s.

IV. Reference Models

Applications that exploit the information mobility paradigm can be designed along several reference models.

- **Peer-to-Peer model**. In a pure peer-to-peer system, nodes may simultaneously act as both "clients" and "servers" to other nodes in the network. Information dissemination should second the spatial distribution of nodes, with peers selected not only according to their position in the overlay network, but also with the notion that the overlay hides a highly mobile, volatile physical network.
- **Publish & subscribe model**. These type of applications hinge on an asynchronous, many-to-many communication model designed to distribute information to a large number of users using either content-based or topic-based routing. According to the publish-subscribe messaging paradigm, users can be both information providers (publishers) and information consumers (subscribers). Consumers subscribe to the system, i.e., through a *broker* and specify the type of information that they are interested in, while providers publish data to the system. The broker disseminates the information to all of the consumers that are interested in receiving it. In a highly mobile scenario, brokers should be aware not only of the content carried by nodes, but also of their position. Thus, a better matching between offer and demand is possible.
- **Beaconing model**. With the term "beaconing", it is usually denoted the periodic transmission of packets containing public safety/public utility messages by means of a single-hop, link-layer broadcast to all neighboring nodes. Beaconing applications may or may not cover multiple hops (in the latter case, the message includes a time-to-live value, decremented at each hop).
- **Synchronized downloading model**. Assuming all infrastructure nodes in an area are under the same centralized control, portions of a message may be preemptively

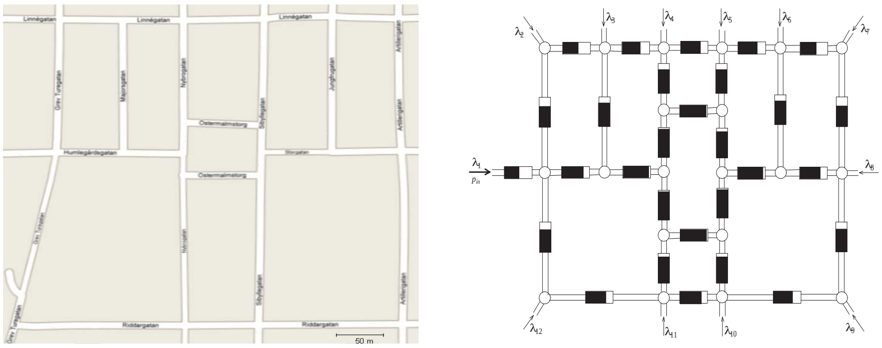

Fig. 2. A Stockholm downtown area (left) with spatial distribution of contents (right).

downloaded to the infrastructure nodes along the (presumed) path followed by the mobile node.

V. Challenges

In order to make the information mobility concept a reality, there are several research challenges that need to be overcome.

- Content that is designated for local availability requires that the geographic scope be described so as to be passed along with the content item itself. In addition, nodes must be able to determine their own position in order to know whether they are within or outside the defined scope; the content item should not be forwarded in the latter case.
- The decision to forward some content, including its replication, requires the knowledge of where the content should go. Hence, content may be opportunistically forwarded in hope of being requested; alternatively, requests could be forwarded in search for contents; finally, both content and requests could be opportunistically forwarded. When a request meets the matching content item, the identity of the source node of the request can then be attached to the content item for delivery. How to determine a strategy for opportunistic forwarding that is less resource demanding than flooding is an open problem.
- The decision to forward some content, including its replication, also requires knowledge of network performance. Hence, the information should be forwarded through non-congested paths, and replication of information should be performed with the aim of lowering the probability of network overload. Both mobility patterns and available network resources should be used to determine the pattern of information mobility.
- The forwarding of a content item to a specific node whose past locations are known would need estimates both of the forwarding node's movement trajectory as well as of the trajectory of the node it peers with [6]. Replication might be used to hedge against uncertainty in the information that is used for the forwarding decisions. The representation and estimation of movement trajectories is not solved, and how to take decisions for replication is also open.
- Cache management and garbage collection are both necessary in the network nodes. The cache management has to weigh content availability in the network against conservation of nodal storage [7]; garbage collection weighs opportunistic forwarding of requests and contents for increasing the probability of matching against the cost in terms of communication resources. Both processes are vital and difficult, especially in view of the long-term availability of content in the network that might exceed any node's sojourn time in the area.

VI. Conclusions

This paper has defined the *information mobility* paradigm and how it relates to wireless content distribution networks. Information mobility addresses the paradigm of considering how nodes storing content move while at the same time their contents move in geographical areas in order to provide global or local relevance and availability. The paper identifies main challenges in wireless content delivery assuming sparse connectivity and limited infrastructure support.

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