ABSTRACT

We propose a novel lightweight cellular wireless network architecture called cell hopping. Unlike traditional cellular networks, cell hopping has base stations interconnected by wireless inter-base station links, WIBLs. WIBLs support all routing and switching in cell hopping networks, obviating the need for costly core networks (or costly switching infrastructure). Cell hopping utilizes unlicensed frequency and presents a low-cost, rapidly deployable solution for mobile communications. We discuss various technical challenges that must be addressed before cell hopping can become a reality. In particular, we concentrate on location management. We propose an on-demand location management technique that completely eliminates the need for location databases and periodic updates by mobile stations. We provide a few variations of the location management scheme, and compare their performance through simulation.

INTRODUCTION

The desire and need of users to be able to communicate and be contacted “anywhere anytime” is increasing every day. The introduction and deployment of cellular networks, such as the Global System for Mobile Communications (GSM), made a revolutionary contribution to fulfilling the anywhere anytime connectivity dream of users. However, cellular networks have a few limitations. Construction of and, as a result, the services from cellular networks still remain expensive. Reasons for the high cost include heavy-weight infrastructure, use of expensive licensed spectrum, and single ownership of the network. Researchers are investigating alternative approaches for low-cost wireless communications. For example, the development of IEEE 802.11b has allowed research into an alternative mobile wireless communication scenario known as mobile ad hoc networks (MANETs) [1]. MANETs address these limitations of cellular networks. However, the absence of any fixed dedicated routing/forwarding agents, and the uncertain and frequent mobility of mobile stations make ad hoc networks unstable. Even if the end nodes are not moving, there can still be routing instability due to intermediate node movement. Numerous research efforts are tackling the routing instability of ad hoc networks, but we have not seen any standard routing protocol that can make ad hoc networks practical. Also, the involvement of user mobile stations in routing/switching of network data is prohibitively expensive in terms of high power consumption and terminal complexity. Users these days want lightweight smaller devices and minimal complexity: most of the complexity should be in the network. The MANET approach involves no infrastructure for network operation.

In this article we propose a new type of architecture that may evolve as a low-cost alternative cellular wireless service by allowing users to play the role of wireless network operator. Some users or organizations of the current Internet may install a low-cost base station based on their needs, and interconnection between these base stations will form a wireless wide area network. We take one step back from MANETs and propose what we call a cell hopping network: a multihop cellular network where there are fixed base stations, which may be contributed by different operators, communicating among themselves via wireless inter-base-station links (WIBLs) to provide network functionality to the mobile stations. Cell hopping allows users to do their own business without worrying about routing/switching, unlike MANETs.

The availability of IEEE 802.11b, 802.11a, and the coming 802.11g standards for wireless LAN (WLAN, also popularly known as Wi-Fi) enabled popular wireless Internet access. Various new kinds of networks are springing up that use this WLAN standard and make use of free unlicensed spectrum. Several food chains, bookstores, hotels, and coffee shops have started offering Wi-Fi services to their customers. Cell hopping networks may be useful for such organizations in building low-cost WANs across their stores in a city with less expensive connections to the Internet backbone.

WLAN technology is one possible candidate for implementing cell hopping networks. Alternatives are also likely to emerge as research in wireless products continues. We envisage that small operators will install base stations in their premises. As WLAN operates in the unlicensed
instrumentation, scientific, and medical (ISM) band at 2.4 GHz, operators will be able to save expensive licensing fees. People with such home wireless networks may choose to become cell hopping service providers. The mobile stations have one-hop wireless connectivity to a base station, and the base stations have multihop wireless connectivity to one another. Some base stations may provide connectivity to the Internet.

The organization of the rest of this article is as follows. We discuss the architecture of the cell hopping network along with some related architectures. We talk about research challenges for cell hopping. We present our proposed on-demand location management schemes for cell hopping, and finally we conclude the article.

**CELL HOPPING ARCHITECTURE**

Cell hopping is a wireless multihop packet switching cellular network operating in the unlicensed spectrum. Cell hopping is a coreless network where there are only wireless access points, but no switching infrastructure. Fixed base stations, possibly but not necessarily contributed by many small operators, make up the network. Base stations communicate with each other to route packets for mobile users using WIBLs. The coverage by each provider can be as little as just one cell, and the set of cells belonging to all the providers can make up the network. The users roam around freely; there is no notion of a “home network” in cell hopping. The reason there is no home network or home agent in cell hopping is that there is no core network. In home agent or home network based systems, home and foreign networks or agents use signaling over the core network. In the case of cell hopping, because there is no core network, when the mobile user moves to a different segment of the network that is not connected to the previous segment, signaling cannot occur. This is referred to as the problem of disjoint graphs in the network, which does not exist in core-centric networks. Therefore, the technical challenge here is to deliver data to mobile users that do not have any home network without going through any core network.

Cell hopping offers new business opportunities and enables low-cost basic services for common users. Base stations contributed by small wireless operators can provide access to the Internet; however, the main focus of the network is to facilitate communication among users within the cell hopping network. User devices do not take part in such operations of the network as routing and location management, unlike ad hoc networks. When there is a packet to be sent from a user device, it sends it to its host base station for forwarding. The base stations perform hop-by-hop routing of the packets, while all the user devices need to do is register themselves with the current nearest base station.

With the development and deployment of cell hopping networks, small operators can enjoy a slice of revenue from the wireless provisioning business. Cell hopping also offers low-cost services to users, as huge infrastructure setup costs and license fees for spectrum usage such as that in GSM are not required. The presence of the base stations separates the cell hopping architecture from the MANETs mentioned above [1]. Cell hopping is also different from current infrastructure-based cellular networks such as GSM, because there are no hierarchical entities such as mobile switching centers (MSCs) or base station controllers (BSCs). In cell hopping, the base stations communicate and cooperate with each other to route packets hop by hop without going through any kind of hierarchical wired entity. Differences between cell hopping, GSM, and ad hoc networks are shown in Fig. 1.

**RELATES ARCHITECTURES**

In this section we briefly discuss some of the proposed alternate architectures, and their similarities and differences with the cell hopping model.

CarNet [2] and Terminode [3] are examples of large-scale wireless ad hoc networking. They work on the same basic idea as MANETs, but their main emphasis is on scalability. Both avoid the need for costly infrastructure. However, because the terminals do all the tasks usually done by routers/switches, terminal complexity is high and so is the terminals’ use of battery power. Handheld devices must be lightweight and small to be practical. This poses a great challenge for large-scale use of such devices in ad hoc networks. As well, it should not be the users’ job to run a network, as they have their own tasks to do. In contrast, cell hopping puts no extra load on the terminals, as the terminals do not perform network operations.

Frenkiel et al. [4] have proposed a network infrastructure consisting of infostations operating in the unlicensed spectrum bands. Infosta-
proprietary. However, the protocols used are entirely proprietary.

One of the most commonly mentioned products for providing this style of networking functionality is the Nokia Rooftop system. This system makes it extremely easy to deploy a rooftop network with nodes separated by up to 10 miles (16 km). However, the protocols do not provide continuous coverage, but provide pockets (hot spots) of high-speed coverage. For the remaining coverage, the users must still use the cellular services from the big providers. Boingo Wireless operates in a similar way [5]. On the other hand, Metricom set up Ricochet networks [6], a wireless access network for Internet connectivity for mobile users. Metricom had its own access points installed in streets in areas it covered. Although Ricochet operated in the unlicensed free spectrum, the cost of installing access points in dense city streets and other related costs were very high for one company to bear. Therefore, despite the exciting service provided by Ricochet, Metricom went bankrupt [7], and Ricochet was taken over by another company.

Undedicated High Altitude Aeronautical Platform (Undedicated-HAAP) [8] uses undedicated aircraft to support mobile coverage. The aircraft (e.g., commercial planes) act as satellites to provide city-wide high-speed coverage while they are appropriately positioned (location and altitude). This scheme uses licensed spectrum (47.2–48.2 GHz). The coverage is limited to the area near the flight path. The implication of using licensed bandwidth and airplanes as base stations is that the system is going to be expensive, prohibiting small businesses from taking part in it.

Multihop cellular [9] allows the mobile terminals within a cell to take part in routing. The authors claim that throughput is increased this way. However, this scheme still depends on infrastructure-based cellular networks, and involves user devices in packet forwarding.

None of the proposals mentioned provide business opportunities for small operators to create a network together. Table 1 summarizes these proposals.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Frequency</th>
<th>Base station</th>
<th>Switching center</th>
<th>Hop</th>
<th>Self-organizing</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ricochet</td>
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<td>Access points</td>
<td>Yes</td>
<td>Multi</td>
<td>No</td>
<td>Medium</td>
</tr>
<tr>
<td>Multihop cellular</td>
<td>Licensed</td>
<td>Required, fixed</td>
<td>Yes</td>
<td>Single/multi</td>
<td>No</td>
<td>Large</td>
</tr>
<tr>
<td>Infostations</td>
<td>Unlicensed</td>
<td>Required, fixed</td>
<td>No</td>
<td>Single</td>
<td>No</td>
<td>Small</td>
</tr>
<tr>
<td>CarNet</td>
<td>Unlicensed</td>
<td>No</td>
<td>No</td>
<td>Multi</td>
<td>Yes</td>
<td>Large</td>
</tr>
<tr>
<td>Terminate node</td>
<td>Unlicensed</td>
<td>No</td>
<td>No</td>
<td>Multi</td>
<td>Yes</td>
<td>Large</td>
</tr>
<tr>
<td>U-HAAP</td>
<td>Licensed</td>
<td>Has, mobile</td>
<td>No</td>
<td>Single</td>
<td>No</td>
<td>Small</td>
</tr>
</tbody>
</table>

Table 1. Comparison of various approaches.

There are various research issues in cell hopping that must be addressed before this network model can become a reality. Below we list some of the challenging areas, and present details of our solution for one particular challenge that is the focus of this work: location management.

**Commercial/Proprietary Efforts**

On the commercial front, one of the most commonly mentioned products for providing this style of networking functionality is the Nokia Rooftop system [10]. This system makes it extremely easy to deploy a rooftop network with nodes separated by up to 10 miles (16 km). However, the protocols used are entirely proprietary. This product provides rooftop connection with wireless routing capability, wireless Ethernet bridging capability, and the Nokia AIR Operating System, a specialized suite of IP and wireless networking protocols targeting improved efficiency and robustness for IP-based networking in multihop wireless mesh networks.

UC Wireless produces the WinRouter 2050 Wireless DSL System with a maximum data transfer rate of 1.678 Mb/s and node connections up to 10 miles. It can be set up on rooftops to provide wireless network access. It can also be configured as a virtual Ethernet, that is, a bridge (at the medium access control [MAC] level).

Tropos Networks [11] have launched their cellular Wi-Fi access product line. These devices allow for creation of indoor and outdoor cells based on the 802.11 standard. The Tropos Wi-Fi cells use a proprietary Tropos Control Protocol, which provides a cellular Wi-Fi mesh routing algorithm for intercell communication.

**Research Challenges**

Different routing algorithms and protocols serve different types of networks. For the fixed Internet, there are link state and distance vector protocols that suit the relatively less dynamic nature of the Internet. However, these protocols cannot readily be used in more dynamic networks such as ad hoc wireless networks because the traditional protocols will not be adequate to address the frequent and unpredictable changes in network topology.

In cell hopping, the base stations are fixed and fairly stable. Routing protocols that are used in the Internet can be utilized in cell hopping. We use shortest path table-based routing. However, we cannot perform packet forwarding just by using the routing table; the user terminal IDs do not have any relation to their current point of attachment to the network as the terminals are mobile and change their position often. Therefore, we require a mechanism to incorporate user location with the routing.

We incorporate user location information (i.e., which base station the user is listening to at the moment) in the packet header before the packet is forwarded further by the source base station. We call this cell-membership binding. Location management, detailed next, is used to
find the current location of the destination terminal. When a next hop is selected for packet forwarding, the destination base station is used as the destination address instead of the destination terminal address. The routing table used contains the next hop toward the shortest path from a base station to all other base stations in the network.

**Location Management**

A network must be able to discover the physical location of a terminal to forward messages to it. There are various location management proposals in the literature for core-centric networks. The techniques used in cellular networks [12, 13] involve the use of a home location register (HLR) database, stored and managed centrally in the fixed wired infrastructure. Variations of this scheme use distributed databases acting as location registers. These registers must be highly available and reliable. As cell hopping has no wired fixed infrastructure or central controlling entity, the use of a location database is not practical. Also, the coreless feature of the network does not allow any of the signaling done in core-centric networks for location update/query. In the traditional Internet, there are Mobile IP and related protocols [14], which operate on the hierarchically organized core-centric Internet. Cell hopping does not have the notion of a home agent; mobile nodes roam about all the time and do not belong to any particular cell. Therefore, we require a location management technique that has no dependence on any cell for location finding/management, and the users will also not be involved in the process. We propose COLM: Cell-Based On-Demand Location Management for Cell Hopping, which does not involve any location database and works in an on-demand fashion. We discuss COLM in more detail in a later section.

**Business Model**

As mentioned before, the cell hopping network model brings about a paradigm shift in the business of wireless service providers. At present, customers of wireless services enter into a fixed term contract with one major service provider. Some options for implementing trust and disincentives against cheating are important aspects of the cell hopping architecture, but they are not a major focus of our current research. For instance, billing and charging are complex issues that deserve greater attention. Future research is required in the area of billing and charging for the cell hopping network.

**Radio Resources Management/Frequency Overlapping Control/Self-Configuration**

The base stations in a cell hopping network are to operate at an unlicensed frequency. Adjacent base stations must self-configure and reconfigure their operating frequencies to avoid frequency overlapping. Self-configuration is also necessary when the topology changes, because of the change in the number of operating base stations. This will ensure that network connectivity is maintained.

**Authentication and Security**

Wireless network security requires protection against eavesdropping, unauthorized participation as a network node, and unauthorized access as a user. We note that authentication and security are important aspects of the cell hopping architecture, but they are not a major focus of our current work. Some form of automated trust management is required for a loose confederation of small providers. Some options for implementing trust and disincentives against cheating that may be useful in cell hopping are discussed in [15].

**On-Demand Location Management for Cell Hopping**

Before we show how COLM works for cell hopping, let us state why we designed an on-demand location management protocol. As mentioned before, there is no fixed wired entity in cell hopping to manage a central location database that requires periodic updates. Also, the absence of a core network makes it impossible to use any signaling that is needed for home agent/network/register based schemes and normally done over the core network. Therefore, we require a scheme that does not depend on periodic updates, and signaling over the core. On-demand schemes are well suited to such situations. To our best knowledge, the on-demand approach has not previously been explored in the realm of location management. COLM works for any addressing scheme that uses unique IDs for each
In Cell-Hopping, the locations of the users keep changing as they roam about. Therefore, we must be able to flush the MR-c entries so that we have fresh information in the cache.

In COLM, when a base station has a packet to forward from a node it is serving, a membership resolution query (MRQ) is generated and flooded through the network using reverse path forwarding (RPF), if the destination and source are not connected to the same base station. When this query is received by the base station serving the destination node, it generates a membership resolution reply (MRR) containing the destination base station address, and unicasts the reply to the originating base station of the MRQ. Upon receipt of this reply, the query-originating base station performs membership binding in the data packet by adding the destination base station address and then forwards the data packet to the next hop by consulting its shortest path routing table. The routing tables at each base station contain shortest paths to the other base stations, but no information about mobile nodes’ locations is stored. In the simplest form, MRQ is performed for each data packet. This variation of COLM is named FLOOD. This databaseless scheme has the advantage that there will be no signaling cost for central database update because of node movement. A possible improvement would be to send some data with the initial MRQ packet.

To reduce MRQ flooding and the increased packet delay caused by location finding for each packet, we propose cached COLM, where FLOOD COLM is enhanced by introducing a membership resolution cache (MR-c) at each base station to store MRP-resolved membership information. When no location entry for a destination can be found in the MR-c, only then does the base station initiate the MR query-reply process. Location caching provides a mechanism for location reply from an intermediate base station en route to the destination base station. Location reply from caches reduces locating time, which affects the packet delivery time or end-to-end delay.

When an MR query is received by a base station with an identical entry in its cache for the destination, the query is quenched by that base station and an MR reply is unicast to the query-originating base station. When base stations forward MR replies, they cache the location information found in the replies. When an MR query-originating base station receives an MR reply with location information that already exists in its cache, the reply is simply discarded.

The essential fields in the MR-c are the mobile node address, and the host base station address. A timer value field is required for the timer-based approach, as discussed in the next section.

There may be cases when the destination station moves out of the base station before the message reaches the base station it was residing in after the location was resolved by the query-reply process or from the cached entry. This results in packet drop. The base stations do not do anything special in such cases; it is up to the higher layer protocols, such as TCP, to handle such situations.

### Variations of Cached COLM

In cell hopping, the locations of the users keep changing as they roam about. Therefore, we must be able to flush the MR-c entries so that we have fresh information in the cache. The timer value selection is a trade-off: it should be long to minimize MRQs, but short to minimize stale information. Below we describe variations of cached COLM where we use different flushing techniques.

**Timer-based flushing [TIMER-CACHE]:** We use a fixed timer to flush out the cache entries. Whenever a cache entry is made, the station activates a purge timer. The entry is flushed once the timer expires. Because of user mobility, the cache entry should be flushed often to maintain the freshness of the cached location information. Careful selection of the timer value will minimize stale information in the cache.

**Notification-based flushing [NOTIFY-CACHE]:** When a stale entry is detected by the destination base station because the target mobile node has moved out of its previous coverage area:
- The packet is dropped.
- A location error notification message is sent to the source base station (unicast).

When the source base station receives this notification message, it removes the stale cache entry from its cache. This means that when the next packet is ready to send out, there will be no cache entry for the destination and the sender base station must generate an MR query to find the new location of the destination. This avoids using a stale entry from the cache when the timer has not expired and a new packet is ready to send out, but the destination has moved away from the cached base station. Base stations forwarding the failure notification also update their caches if they had an entry for the destination terminal and destination base station pair in their MR-c.

**Optimum flushing [OPTIMUM-CACHE]:** This is the ideal approach for location cache entry expiration: location information cached for a destination will expire when the destination terminal changes its serving base station, making the entry in the cache stale. Although it is not feasible to implement this policy in an on-demand location management scheme where there is no central knowledge base keeping location information, this can be used as a benchmark for comparison. The closer the performance of a scheme is to this case, the better the scheme.

Figure 2 shows steady-state values for average locating time and end-to-end packet delay for the location caching schemes discussed above. The simulator was written in C using the discrete event simulation technique. The area simulated is a 10 × 10 mesh topology, with each cell having a radius of approximately 500 m. The average cell-residence time (1000 s) used in our simulation is for pedestrian mobility speed. The average cell residence time is assumed to have exponential distribution. User mobility is simulated using the random walk mobility model. Mean message arrival rate is 1 message/min; it is also assumed to be exponentially distributed.
The FLOOD scheme results in the highest delay, as expected. Using the location cache substantially reduces the time involved in locating the destinations, and as a result packet end-to-end delay. As the hop delay increases, there is more saving achieved by using cached COLM. For smaller networks, or where the hop delay (which includes queuing and processing delay) is smaller, the FLOOD scheme performs well, and one may choose to use it as it does not involve extra overhead from having to maintain the cache. However, for larger networks, or networks where the hop delay is quite large, cached COLM is a better choice. Detailed study is required to investigate the influence of various timer values and the adaptive timer selection process. We are unable to present detailed simulation results because of space constraints; however, Fig. 2 highlights the basic performance trade-offs of various location management schemes for cell hopping as presented in this article.

**CONCLUSION AND FUTURE WORK**

We present a lightweight cellular wireless communication model called cell hopping. Cell hopping requires significantly less infrastructure than traditional cellular (e.g., GSM, 3G) networks, yet provides much superior routing stability than emerging infrastructureless ad hoc networks.

We believe cell hopping has enormous potential to emerge as a low-cost alternative wireless network access solution. Our conjecture is that cell hopping as presented in this article.

**REFERENCES**


