Paging in Large-scale Urban Mesh Networks

***Abstract*— While deployments of large-scale urban mesh networks are currently underway, there remain many technical challenges. In particular, due to the scale of these networks, advances in mobility management are required. This paper examines paging (the process of finding a mobile node) in realistic urban mesh networks. The approach finds a trade-off between the overhead due to paging and the overhead due to nodes registering their location with the infrastructure. The approach considers the impact of various network architectures including covering the urban area with a conglomerate of enterprise mesh networks and a large-scale outdoor mesh network. It is demonstrated that the architecture has a substantial impact on paging. This demonstration uses realistic urban mobility and propagation.**

I. INTRODUCTION

As of December 2005, The City of Philadelphia was in the final planning stages of deploying a large-scale urban mesh network (LUMNet) [6]. Several other cities are planning similar LUMNet deployments. While these deployments are meant to enhance city and emergency services communication, one goal is to provide city-wide, low-cost, ubiquitous communication for residents and visitors. These ambitious undertakings demonstrate the immediate need for protocols to overcome the challenges facing LUMNets. Perhaps the most significant of these challenges relate to capacity and scalability. In terms of scalability, an important challenge is mobility management.

When a mobile node within the LUMNet desires to make a connection with a wired host outside of the LUMNet, the node must simply transmit packets to the infrastructure or, if there are multiple hops to the infrastructure, the packets may have to be forwarded by one or several mobile nodes on the way to the infrastructure. Once the packet reaches the infrastructure, the mesh routing protocol and then the wired network will forward the packet to the destination. Thus, in this case, the mobile nodes must only find a infrastructure, which is straightforward since the infrastructure is quite large.

On the other hand, when a wired host desires to initiate a connection with a mobile node, the infrastructure must "find" the mobile node. Since there may be several hundred thousand mobile nodes and the network may span hundreds of square miles (e.g., The City of Philadelphia projects 200,000 users over an area of 135 sq. miles), it is not possible to flood the entire network. Rather, according to protocols such as 802.11f, 802.11 ESS Mesh, Mobile IP, Cellular IP, HAWAII, etc., mobile nodes are required to register with the infrastructure as they move out of range of one infrastructure node and into range of another [8], [13], [9]. This way, when a wired host desires to send packets to a mobile host, its location is already known.

The problem of “finding" nodes also arises in cellular phone networks [14], [5], [4], [3], [1]. In the case of cellular phone networks, it is well known that a large reduction in overhead can be achieved by reducing the frequency that a node registers with the infrastructure. Considering that phone calls are received relatively infrequently, a mobile node may change cells several times before a call is received. In this case, except for the last registration, all registrations that occur between calls will not be used for locate the node. Thus, several schemes have been developed for reducing the frequency of registrations. However, there is a trade-off between the frequency of registration (and its related overhead) and the inexact knowledge of a mobile node’s location, which results in searching overhead when the node must be found.

In the case of LUMNets, the paging problem is similar to the one that arises in cellular phones, but there are important differences. For example, in the case of cellular networks, if a initial page fails, then a page request is sent to one or a set of neighboring base stations, which then transmit the page message. However, in the mesh setting, the neighboring infrastructure node (IN) are not necessarily known. For example, it is quite likely that the coverage of two transmitters overlap, but the transmitters cannot directly communicate. Thus, in the LUMNet setting, each infrastructure node (IN) must learn about its neighboring IN. It should be noted that in the urban setting, the coverage of a IN is quite complex and rarely takes the shape of a disc. Thus, merely knowing the geographic location of the INs does not assist in determining the topology.

Once the INs of neighboring cells is known, an expanding ring type search dictates that if a mobile is not found in one area, the search should be repeated in the neighboring cells. However, unlike the cellular setting, in the LUMNet setting, the cost of such an exploration page is not only the cost of the repeated page broadcasts, but also the cost of delivering the page request to the various other INs. Although the two INs may have overlapping coverage, the path between the nodes may span several wireless hops as well as utilize the wired network. As discussed in section III, the INs could even be in different administrative domains, in which case the page request would travel over the Internet. Hence, careful consideration of the types of transmissions is required. The result is that area searched does not expand in a way that resembled an expanding ring. Rather, the area searched depends on propagation, mobility, and network topology. Furthermore, the area searched depends on whether IN to IN communication uses a shares channel/physical layer with the IN to mobile node communication. And finally, it will be shown that the search area depends on the LUMNet architecture.

Another important difference between paging in LUMNets and paging in cellular networks is that coverage area of a LUMNet IN is much smaller than the coverage area of a cellular base station. For example, in the case of 802.11, a single IN is often not able to cover the entire floor of a moderate sized building. This impacts paging in several ways. First, since the coverage area of LUMNet infrastructure nodes are smaller, mobile nodes will migrate between infrastructure nodes more often. Second, since the smaller coverage areas causes details of mobility to impact the paging. For example, in a cellular network it is common to assume that the cells are homogeneous in that node move between cells nodes according to a Markov process that is independent of the cells. However, in LUMNets, some coverage areas are outdoors and accommodate vehicles and highly mobile pedestrians, while other coverage areas are indoors and accommodate sedentary office workers. By learning the typical migration of mobile nodes, it is possible to optimize the areas where the page is broadcasted. Due to the complexity of propagation, some INs within the set that perform the search might not be in the same building as the business, instead, they might be outside or in a nearby building.

In general, while paging in cellular networks can assume that coverage areas and network architecture are homogeneous, paging in LUMNets is impacted by heterogeneity. One important contribution of this paper is to explore and understand the impact of heterogeneity as it arises in realistic LUMNets and to show how paging can accommodate heterogeneity.

As mentioned above, the paging and registration frequency depends on network topology, as well as on propagation and mobility. In this paper, a framework for paging is developed. The scheme can be applied to a variety of network topologies. This paper also examines the behavior of this paging scheme for several different network architectures that might arise in future LUMNets. This demonstration is performed with a realistic mobility and propagation simulator. As explained in more detail later, the propagation is based on realistic ray-tracing computations performed on a region of downtown Chicago. Infrastructure nodes are placed on lampposts and within buildings. The mobility is based on several surveys on urban mobility including the US Department of Labor Statistics 2003 Time Use Study and recent work in the analysis of office worker use of time and meetings. As a result, the conclusions drawn from the demonstration of this paging scheme are directly applicable to the LUMNets that are currently under development.

The remainder of the paper is as follows. In the next section, some related work is discussed. Next, in Section III, possible architectures of LUMNets are discussed. As mention above, the architecture plays an important role in the behavior of paging. Section IV presents an overview of the paging scheme and provides details on notation. Once the set of INs that will be used to search for the mobile node is determined, the order in which each ID broadcasts the page packet must be determined. A technique to do this is presented in Section V. The paging scheme is based on abstract costs. The factors that make up this cost are defined in Section VII. The scheme presented in this paper minimizes the average cost rate. In Section VII, an expression for the average cost rate is found. Section VIII presents a greedy algorithm to construct the area over which the mobile node is searched. Section IX then examines the behavior of the paging scheme and illustrates the importance of paging in LUMNets. And finally, concluding remarks can be found in Section X.

II. RELATED WORK

Mobility management is often divided into marcomobility and micromobility. Macromobility accommodates mobile hosts moving between subnets and administrative domains, while micromobility is for movements within subnets, especially when such movement occurs frequently. While a complete discussion of these schemes is outside the scope of this paper, we briefly review mobility management schemes paying special attention to the registration overhead, which greatly impacts paging (See Section IX).

Macromobility is well accommodated by Mobile IP [8]. As shown in Section III, communication ranges in LUMNets may be quite small and hence mobile nodes may frequently move out of range of infrastructure nodes. Mobile IP is not appropriate for such frequent registration changes [8]. An alternative is to use P-MIP, which allows the mobile node to move out of the subnet of the foreign host without registering [15]. When required, the foreign agent finds the mobile node by sending a page request to a set of other foreign agents, which then broadcast a paging packet. While P-MIP does allow for paging, it assumes that the paging is statically configured. This paper presents a method to automatically configure the paging area. While P-MIP does allow paging, the registration overhead is the same as Mobile IP, specifically, the mobile node and the base station (or foreign agent) exchange two packets, and the base station and the home agent exchange two packets.

Micromobility schemes fall into two categories, network layer solutions and layer 2 solutions. Cellular IP [13] and HAWAII [9] are two network layer solutions, while 802.11 is a layer 2 solution. 802.11s, which is still under development, is also expected extend 802.11's support of micromobility. Regardless of the layer the scheme works at, the approach is similar, but there are differences. In the case of 802.11 and HAWAII, when a node moves out of range of its old base station and into range of another one, the registration process includes deregistering with the old base station. HAWAII performs the registration/deregistration by sending a packet from the new base station to the old one, and the old one sending a packet back to the new base station. As these two packets traverse the path between these base stations, the layer 3 routing is updated.

802.11, on the other hand, uses a large number of messages to register (or reassociate) a mobile host. Specifically, according to 802.11i, the mobile must first associate with an IN, requiring 4 packets to be exchanged between the mobile and the IN. Then the mobile node must be authenticated with the authentication server, e.g., a RADIUS server, which typically requires 9 packets exchanged between the mobile and the IN, and 8 packets exchanged between the IN and the RADIUS server. Moreover, the mobile and the IN must generate a temporal key, which requires 4 packet exchanges between the mobile and the IN. Once authenticated, the IN then may employ 802.11F to inform the old IN that the mobile has moved. Since 802.11F uses TCP, this communication requires a minimum of 4 packet exchanges between the old and new IN. However, the IN might not have the IP address of the old IN (the mobile will only provide the BSID). Thus, another two packets must be exchanged with the RADIUS server. Finally, a layer 2 update is required to be transmitted. The number of transmissions that result form the update depends on the details to the distribution system. In summary, 802.11 requires 17 exchanges with the mobile, 10 packet exchanges between the IN and the RADIUS server, and 4 packet exchanges between the old and new IN.

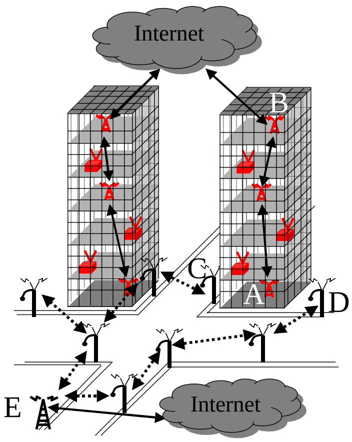
Cellular IP also supports micromobility. However, unlike 802.11 and HAWAII, cellular IP does not require explicit registration and deregistration messages. Rather, Cellular IP relies on the mobile host periodically sending refresh messages. These messages are forwarded to the gateway between the access network and the Internet. While this timer-based provides good performance when mobile hosts are activity sending data, it is difficult to determine the frequency of refresh messages that support rapid mobile host migration and yet do not result in excessive overhead. For example, unless a mobile node generates refresh messages quickly, there will be periods of time where the infrastructure will not be able to find it. In such cases some sort of paging scheme could be applied, however, since the paging area is unbounded, the approach presented in this paper cannot be directly applied.

III. LUMNET ARCHITECTURE

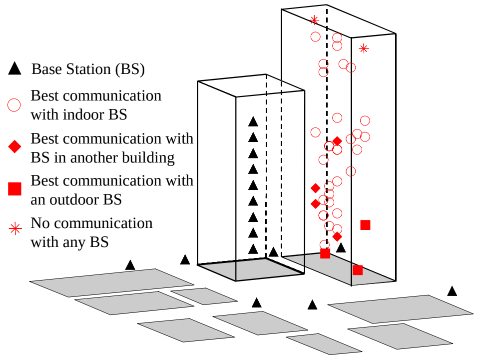
As will be demonstrated in Section IX, the behavior of paging is dependent on the LUMNet architecture. This section includes some discussions of the network architectures that might arise in future LUMNets.

The LUMNet the infrastructure contains two general types of infrastructure nodes (IN), wired base stations (or simply base stations) and fixed wireless relays (or simply fixed relays). Since base stations require wired connections to the wired network, the cost to deploy a base station exceeds the cost to deploy fixed relay. For this reason, it is expected that there will be far more fixed relays than base stations. In Philadelphia, for example, initial estimates were that there would be approximately 30 fixed relays for each base station.

While the outdoor network such as the one being deployed in Philadelphia are reasonably well understood, there is little or no understanding of how to provide coverage within buildings. The challenge indoors is a result of the difficulty in propagating a wireless signal from inside to outside or visa versa. This difficulty increases as the height of the building grows. In this paper, two approaches are considered for reaching indoor nodes. First, we simply assume that the infrastructure of the outdoor mesh network is extended indoors with a large number of INs inside. We refer to this approach as a *flat network*. However, such a flat network would require the mesh provider to have leases and power contracts for each indoor infrastructure node. Due to the overwhelming administrative costs of providing indoor coverage in a flat network, we consider a second approach where the indoor infrastructure nodes are part of a large number of different networks. This network structure is referred to as a *hierarchical network.* In this architecture, we refer to larger network as the dominant mesh network and the several networks as micro-mesh networks. Building residences, landlords, community/neighborhood organization, businesses, etc could operate these micro-mesh networks. If the private mesh does not have a connection to the wired network, then it is assumed that these private INs are integrated into the dominant mesh network. On the other hand, some micro-mesh networks may have direct connection to the wired Internet. In this case it is possible that



1: LUMNet Architecture. This illustrates a possible LUMNet that is comprised of a large outdoor mesh network and several indoor enterprise mesh networks. These networks are not directly connected, but collaborate to support mobility management.



2: Indoor Coverage. The red markers indicate the location of mobile nodes indoors. The type of marker (circle, square, etc.) indicates the IN that provides the best connection (in terms of signal strength) to the mobile node's location. The INs marked with triangles are those that are not in the building under consideration, and yet provide coverage to the mobile nodes in the building under consideration.

the micro-mesh infrastructure does not have any direct wireless connections with dominant mesh infrastructure, in which case, the Internet provides connectivity between the mesh networks. One scenario when this could arise is when the dominant mesh network uses a proprietary physical layer for IN to IN communication. Regardless of the architecture, we refer to the dominant mesh network along with any associated micro-mesh networks as the greater LUMNet (See Figure 1).

In the hierarchical architecture, ubiquitous access would require some type of advanced mobility management. Considering that the indoor coverage is provided by networks that are under a different administrative control than the dominant mesh network, one might consider using Mobile IP to support user mobility between this mesh network and the micro-mesh networks. However, such a macromobility scheme is not appropriate. Specifically, in a dense deployment of small networks, the coverage of each network will overlap. Furthermore, with such small networks, it is difficult to provide uniform and continuous coverage. In the detailed LUMNet simulated in this paper, it was found that a mobile node might pass through several different networks while moving relatively small distances. For example, indoor propagation is so difficult that a node may have better connectivity to the outdoor network or even a network in a nearby building than it does to the IN that is nearest to it and within the same building. Figure 2 provides a realistic coverage map. As a result, nodes may quickly move between different domains. Macromobility schemes such as Mobile IP are not designed for such high frequency migrations.

Instead, we envision that the indoor networks, regardless of who administrators them, will cooperate with the dominant mesh network to support a cross-domain micromobility. Thus, even when the mobile node moves between different administrative domains, from the macromobility perspective, the node still resides within the greater LUMNet. More simply, the dominant mesh is able to directly interact with the infrastructure nodes of the micro-mesh networks in a way supports micromobility such as paging and hand-off. Thus, when a node external to the greater mesh network desires to make a connection with a mobile node, it contacts the foreign agent that is provided by the dominant mesh. This foreign agent initiates a page/search for the mobile node that may span multiple networks.

IV. Overview of Paging Algorithm

In the scheme proposed here, when a mobile node registers with an IN, the IN provides the mobile node with its *paging area*. The paging area is defined by a set of INs that can only be heard within the paging area. Thus, the paging area is the union of the coverage ares of the INs that define the paging area. The set of INs that define the paging area are referred to as the *paging area INs*. While a mobile node remains in the paging area it does not register. However, when the mobile node leaves the paging area, it registers with the IN that has the strongest received signal strength. The mobile node can detect that it has left the paging area by noticing that it can no longer receive beacons from any of the INs within the paging area INs.

When a message is to be sent to the mobile node, a request is delivered to the IN where the mobile last registered controls the paging process. This IN is referred to as the *initial IN*. The initial IN searches for the mobile node by sending page requests to each IN in the paging area INs. Upon receiving a page request, the IN broadcasts a page. If the mobile node is within the area, its response is delivered back to the initial IN. The initial IN does not transmit a page request to all members of the paging area INs, but sends a page request to one IN, waits for a period of time for a response, and if no response arrives, it sends a page request to another IN. The order of INs that the initial IN sends page request to is referred to as the *paging sequence*. In Section V, shows how the paging order can be determined.

The scheme presented here consists of two processes. In one process, mobility data is collected from the mobile nodes and this is used to determine the paging strategy for each IN. In the second stage, the paging strategy is employed. It is assumed that the mobility data is collected over long periods of time and that the strategy is updated periodically. The mobility data collected consists of the history of INs heard by the mobile node. In this way it is possible to determine the *coverage topology*, which we define to be a mapping from each location in the urban area to the set of INs that are within communication range of a mobile host at that location. From this history it is also possible to determine the average duration that a node spends within the coverage area of a particular IN as well as the probability that a node will move from one coverage area to another. The determination of these probabilities is further discussed in Section VI.

Once these probabilities are known, the paging region must be constructed. This process is described in Section VIII, and requires the computation of the paging cost rate and the paging order, which are discussed in Sections VII and V respectively.

A. Notation

The following notation is required. The set of all infrastructure nodes in the LUMNet are IN_1,..., IN_N. The *coverage area* of the ith IN node is denoted C_i. Let $\mathcal{R} = \{IN_{i_1}, IN_{i_2}, ..., IN_{i_M}\}$ be an ordered list of INs, Specifically, $\mathcal{R}$ will be the sequence of INs that will broadcast pages while searching for a mobile node that last registered with node IN_k. Without loss of generality, we assume that the kth IN's paging sequence is $\mathcal{R} = \{IN_1, IN_2, ..., IN_M\}$. For this $\mathcal{R}$, we denote the *disjoint coverage* of the INs within $\mathcal{R}$ as $\tilde{C}_i = C_i \backslash \cup_{j<i} C_j$, where $A \backslash B$ is the part of A not contained in B.

Mobile nodes move between coverage areas. For shorthand, we denote the probability that a mobile node is in coverage area C with $P(C)$ and, when a mobile node exits the coverage area $\tilde{C}_i$ the probability that the mobile node will move into the coverage area $\tilde{C}_j$ is denoted as $P\left(\tilde{C}_j|\tilde{C}_i\right)$.

V. OPTIMAL PAGING SEQUENCE

Consider a paging area defined by the set of INs, $R = \{IN_1, ..., IN_M\}$. Thus, we assume that it is known that the mobile node is somewhere within the coverage region of at least one $IN \in R$. In the scheme proposed here, one IN in R will broadcast a page, and if that fails, then another IN in R will broadcast a page. This continues until the mobile node is found. Here we address the question as to what order the INs in R should transmit the page. Specifically, we seek to reorder R to $R' = \left\{IN_{O(1)}, IN_{O(2)}, ..., IN_{O(M)}\right\}$, such that, if $i < j$, then $IN_{O(i)}$ should broadcast the page before $IN_{O(j)} = IN_{O(j)}$. The objective of the reordering is to minimize the average cost of the paging process. Thus, IN_i is assigned a paging cost (see Section VII for a discussion of paging costs), denoted D_i. Furthermore, it is assumed that the probability distribution of the mobile nodes is known. We denote $p(C_i)$ as the probability of finding the mobile node in the coverage area of IN_i. If the coverage areas of the INs are disjoint, then the following assists in constructing the paging sequence.

Proposition 1: If the coverage areas of the INs are disjoint, then the paging sequence IN_1, IN_2, ..., IN_M results in the least average cost if and only if for $i < j$,

$$\frac{D_i}{p(C_i)} \leq \frac{D_j}{p(C_j)}. \tag{1}$$

Thus, by ordering the INs according to $D_i/p(C_i)$ yields the lowest average cost. However, if the coverage areas are not disjoint, then the above does not result in the least cost. For example, if several INs have the exact same coverage area, then there is no reason to have each IN broadcast the page. However, assuming that the distribution of the mobile node is known, then the following algorithm can be used to determine a paging sequence, where we assume that $\mathcal{R}$ be the set of INs in the paging area.

As mentioned, in general, this scheme will not provide the optimal paging sequence. However, as mentioned, if the coverage areas are disjoint, then the resulting sequence is optimal.

Proof: [Proof of Proposition 1] We show that if $\frac{D_i}{p(C_i)} > \frac{D_{i+1}}{p(C_{i+1})}$, then the average cost can be improved by reordering IN_i and IN_{i+1}. Thus, the optimal ordering must obey (1).

Let $q_i = 1 - P(C_i)$, the probability of node finding the mobile node in the coverage area of IN_i. Thus, the probability of not finding the mobile node in the first j coverage areas is $\prod_{k=1}^{j} q_k$. Then we compare the cost or the sequence $\{IN_1, IN_2, ..., IN_i, IN_{i+1}, ..., IN_M\}$ to $\{IN_1, IN_2, ..., IN_{i+1}, IN_i, ..., IN_M\}$. In the first case,

Algorithm 1 Determine paging sequence

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1:  Set $\mathcal{R}'_0 = \varnothing$ and $m = 0$.
2:  for all $IN_i \in \mathcal{R}\backslash\mathcal{R}'_m$ do
3:      set $\tilde{C}_i(\mathcal{R}_m) = C_i \backslash \cup_{IN_j \in \mathcal{R}'_m} C_j$, i.e., $\tilde{C}_j(\mathcal{R}'_m)$ is the coverage area that is disjoint from the area covered by the INs in $\mathcal{R}'_m$.
4:  end for
5:  for all $IN_i \in \mathcal{R}\backslash\mathcal{R}'_m$ do
6:      set $p\left(\tilde{C}_i(\mathcal{R}'_0)\right)$ to be the probability that the mobile node is in $\tilde{C}_i(\mathcal{R}'_0)$
7:      if $p\left(\tilde{C}_i(\mathcal{R}'_0)\right) = 0$ then
8:          remove $IN_i$ from $\mathcal{R}$
9:      end if
10:     if $\mathcal{R}\backslash\mathcal{R}'_{m+1} = \varnothing$ then
11:         stop, the paging order is $\mathcal{R}'_{m+1}$
12:     end if
13: end for
14: Find $i^*$ such that $IN_{i^*} \in \mathcal{R}\backslash\mathcal{R}'_m$ and $D_{i^*}/p\left(\tilde{C}_{i^*}(\mathcal{R}'_m)\right) \leq D_j/p\left(\tilde{C}_j(\mathcal{R}'_m)\right)$ for all $IN_j \in \mathcal{R}\backslash\mathcal{R}'_m$.
15: Set $\mathcal{R}'_{m+1} = \{\mathcal{R}'_m, IN_{i^*}\}$.
16: if $\mathcal{R}\backslash\mathcal{R}'_{m+1} = \varnothing$ then
17:     stop, the paging order is $\mathcal{R}'_{m+1}$
18: else
19:     set $m = m + 1$ and go to step 2
20: end if
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the average cost is

$$
\begin{aligned}
cost_1 \quad = \quad & D_{i_1} + \sum_{j=1}^{i-2} \prod_{k=1}^{j-1} q_k \cdot D_{i_{x+1}} + \prod_{j=1}^{i-1} q_j \cdot D_i \\
& + q_i \cdot \prod_{j=1}^{i-1} q_j \cdot D_{i+1} + \sum_{j=i+2}^{M} \prod_{k=1}^{j-1} q_k \cdot D_j
\end{aligned}
$$

and the average cost when reordered is

$$
\begin{aligned}
cost_2 \quad = \quad & D_{i_1} + \sum_{j=1}^{i-2} \prod_{k=1}^{j-1} q_k \cdot D_{i_{x+1}} + q_{i+1} \prod_{j=1}^{i-1} q_j \cdot D_i \\
& + \prod_{j=1}^{i-1} q_j \cdot D_{i+1} + \sum_{j=i+2}^{M} \prod_{k=1}^{j-1} q_k \cdot D_j .
\end{aligned}
$$

Thus,

$$
\begin{aligned}
& \text{cost}_1 - \text{cost}_2 \\
= \quad & \prod_{j=1}^{i-1} q_j \cdot D_i + q_i \cdot \prod_{j=1}^{i-1} q_j \cdot D_{i+1} \\
& - \left(q_{i+1} \prod_{j=1}^{i-1} q_j \cdot D_i + \prod_{j=1}^{i-1} q_j \cdot D_{i+1} \right) \\
= \quad & \left(\prod_{j=1}^{i-1} q_j \cdot D_i \right) (1 - q_{i+1}) + (q_i - 1) \prod_{j=1}^{i-1} q_j \cdot D_{i+1} \\
= \quad & \prod_{j=1}^{i-1} q_j \cdot \left(D_i p\left(C_{i+1}\right) - p\left(C_i\right) D_{i+1} \right) > 0
\end{aligned}
$$

where the last inequality follows from $\frac{D_i}{p(C_i)} > \frac{D_{i+1}}{p(C_{i+1})}$. Thus, unless (1). holds, the cost can be reduced by reordering. ■

Remark 2: Paging sequences have also been examined in the context of cellular phones [11]. However, in that context it is assumed that the coverage areas do not overlap and that the paging cost is independent of the base stations that broadcasts the page, i.e., $D_i = D_j$.

VI. Learning the Coverage Topology and Mobility Model Parameters

To learn the coverage topology and mobility parameters, each IN broadcasts beacons and each mobile node records history of INs heard. Specifically, the mobile node records the initial time when the IN is heard and the last time it is heard. The IN beacons include the beacon period so the mobile nodes declares that an IN is no longer heard when several (e.g., 3) beacons have been missed. Mobile nodes occasionally upload their history of heard INs to INs.

With the histories collected, the probability of a mobile node moving from one coverage area to another can be determined. Of specific interest is $P\left(\tilde{C}_j|\tilde{C}_i\right)$, the probability of a mobile node moving from $\tilde{C}_i$ to $\tilde{C}_j$ and $\tilde{\lambda}_i$, rate that a mobile node exits $\tilde{C}_i$, where the $\tilde{C}_i$ are the disjoint coverage areas for a given paging sequence $\mathcal{R} = \{IN_1, ..., IN_M\}$. While the discussion below focuses on computing $P\left(\tilde{C}_j|\tilde{C}_i\right)$ and $\tilde{\lambda}_i$,it is straightforward to extend it to compute the statistics for other coverage areas.

There are several ways to estimate $P\left(\tilde{C}_j|\tilde{C}_i\right)$ and $\tilde{\lambda}_i$. One simplistic approach is for each IN to examine the various mobile nodes histories and compute number of times mobile nodes move from one coverage region to another. For example, the kth IN, can determine $N^k\left(\tilde{C}_j|\tilde{C}_i\right)$, the number of times a mobile host reported moving from $\tilde{C}_i$ to $\tilde{C}_j$. These values can then be distributed to other INs in the LUMNet when the paging is recomputed, e.g., during the early morning hours. >From such counts, it is straightforward to compute the probability of moving from one coverage area to another. The value of $\tilde{\lambda}_i$ can be determined in a similar fashion.

It is also possible to compute the necessary statistics in a distributed fashion (i.e., without INs exchanging N^k). For example,

$$p\left(\tilde{C}_j|\tilde{C}_i\right) = \frac{N^i\left(\tilde{C}_j|\tilde{C}_i\right)}{\sum_k N^i\left(\tilde{C}_k|\tilde{C}_i\right)}, \tag{2}$$

or more generally

$$p\left(\tilde{C}_l|\tilde{C}_k\right) = \frac{N^i\left(\tilde{C}_l|\tilde{C}_k\right)}{\sum_j N^i\left(\tilde{C}_j|\tilde{C}_k\right)}. \tag{3}$$

Thus, the ith IN can determine all probabilities by observing the histories from mobile nodes. On drawback of this approach can be seen in (2), where the ith IN must collect observations about nodes leaving the coverage range of i. Assuming ergodicity, mobile nodes that leave the coverage of the ith IN will eventually return and relay the history of heard INs allowing (2) to be computed. However, this requires that mobile nodes keep an extended history of the heard INs.

If the mobility process is reversible, then it is possible to compute $p\left(\tilde{C}_j|\tilde{C}_i\right)$ without requiring mobile nodes to record lengthy histories.

Proposition 3: If the mobility of the nodes can be described by a reversible Markov process, then

$$p\left(\tilde{C}_j|\tilde{C}_i\right) = \frac{N^i\left(\tilde{C}_i|\tilde{C}_j\right)}{\sum_k N^i\left(\tilde{C}_i|\tilde{C}_k\right)} \tag{4}$$

That is, the probability of moving from $\tilde{C}_i$ to $\tilde{C}_j$ can be determined by observing the history of mobile nodes as they arrive into $\tilde{C}_i$.

Proof: Recall that reversibility implies that $\tilde{\pi}_i\tilde{\lambda}_i P\left(\tilde{C}_j|\tilde{C}_i\right) = \tilde{\pi}_j\tilde{\lambda}_j P\left(\tilde{C}_i|\tilde{C}_j\right)$, where $\tilde{\pi}_i$ is the stationary probability of a mobile node being in $\tilde{C}_i$, and $\tilde{\lambda}_i$ is mean rate that a mobile node exit from $\tilde{C}_i$. Applying reversibility twice yields the following equalities,

$$\begin{aligned}
&\tilde{\pi}_i\tilde{\lambda}_i P\left(\tilde{C}_j|\tilde{C}_i\right) = \tilde{\pi}_j\tilde{\lambda}_j P\left(\tilde{C}_i|\tilde{C}_j\right) \\
= \;& \frac{\tilde{\pi}_i\tilde{\lambda}_i}{\sum_k \tilde{\pi}_i\tilde{\lambda}_i P\left(\tilde{C}_k|\tilde{C}_i\right)}\tilde{\pi}_k\tilde{\lambda}_k P\left(\tilde{C}_i|\tilde{C}_j\right) \\
= \;& \frac{\tilde{\pi}_i\tilde{\lambda}_i}{\sum_k \tilde{\pi}_k\tilde{\lambda}_k P\left(\tilde{C}_i|\tilde{C}_k\right)}\tilde{\pi}_k\tilde{\lambda}_k P\left(\tilde{C}_i|\tilde{C}_j\right)
\end{aligned}$$

or

$$P\left(\tilde{C}_j|\tilde{C}_i\right) = \frac{\tilde{\pi}_k\tilde{\lambda}_k P\left(\tilde{C}_i|\tilde{C}_j\right)}{\sum_k \tilde{\pi}_k\tilde{\lambda}_k P\left(\tilde{C}_i|\tilde{C}_k\right)}. \tag{5}$$

Furthermore, $\tilde{\pi}_k\tilde{\lambda}_k P\left(\tilde{C}_i|\tilde{C}_j\right)$ is the average rate that mobile nodes move from $\tilde{C}_i$ to $\tilde{C}_j$, and hence, during T seconds, $N\left(\tilde{C}_i|\tilde{C}_j\right)$, the total number of mobile nodes that move from $\tilde{C}_i$ to $\tilde{C}_j$, is $T \times \tilde{\pi}_k\tilde{\lambda}_k P\left(\tilde{C}_i|\tilde{C}_j\right) = N\left(\tilde{C}_i|\tilde{C}_j\right)$. The fact that IN_i observes a random sample of histories can be expressed via $\rho N\left(\tilde{C}_i|\tilde{C}_j\right) = N^i\left(\tilde{C}_i|\tilde{C}_j\right)$, where ρ is the fraction of nodes that upload their histories of heard INs to the ith IN. Multiplying the numerator and dominator of (5) by ρ yields (4). ■

In the same manner, it can be shown that

$$p\left(\tilde{C}_l|\tilde{C}_k\right) = \frac{N^i\left(\tilde{C}_k|\tilde{C}_l\right)}{\sum_j N^i\left(\tilde{C}_k|\tilde{C}_j\right)}. \tag{6}$$

Therefore, IN i can use either (3) or (6) to compute $p\left(\tilde{C}_l|\tilde{C}_k\right)$. Since the accuracy of the estimate increases with the number of observations, if $\sum_j N^i\left(\tilde{C}_j|\tilde{C}_k\right) > \sum_l N^i\left(\tilde{C}_k|\tilde{C}_j\right)$, then (3) should be used, and otherwise (6) should be used.

It is a little bit more difficult to compute $\tilde{\lambda}_i$. In general, $\tilde{\lambda}_i = \frac{1}{\rho_i}\frac{1}{T}\sum_j N^i\left(\tilde{C}_j|\tilde{C}_i\right)$ where T is the length of the time period over which the observations have been made and ρ_i is the fraction of mobile nodes that come into $\tilde{C}_i$ and provide i with there history of heard INs. If the process is reversible, then $\tilde{\lambda}_i = \frac{1}{\rho_i}\frac{1}{T}\sum_j N^i\left(\tilde{C}_i|\tilde{C}_j\right)$. It is possible set ρ_i by requiring all mobile hosts to select to upload their INs heard history with probability ρ when changing coverage regions. To minimize overhead, ρ should be selected to be quite small.

During the numerical examples that follow, the first approach was taken (where INs exchange the counts of mobile node movements). However, this is due to the lack of observations (1 hour). If an IN is continuously online, a large number of observations can be made distributed schemes can be used.

VII. EPOCH COST AND DURATION

A. Costs

The critical issue in paging is how often the mobile node should register. On the one hand, if a node registers frequently, then the registration overhead is large, but the location of the mobile node is accurately known and hence can be paged with generating little overhead. On the other hand, if the frequency of registration is decreased, the overhead of registration decreases, but, since the location of the node is known with less accuracy, the paging of the node results in more overhead. Thus, a balance between registration overhead and paging overhead must be achieved. This balance is found by assigning costs to various types of communication. While costs are abstract, they typically encapsulate delay, congestion, as well as monetary costs.

Paging and registration both require various types of transmissions, namely, exchanges between mobile nodes and INs, exchanges between neighboring INs, and exchanges between INs via wired links or the Internet. Consider the network shown in Figure 1. Note that IN A and IN D are quite close, and may have overlapping coverage areas. However, if IN A desires IN D to broadcast a page, the page request must pass through the network within the building to IN C, through the Internet to the base station E, and then over several wireless hops to IN D. Furthermore, the cost of each type of transmission varies, and also depends on whether it is for a page, page request, or a registration.

The paging cost includes the cost of delivering a page request from the initial IN to a destination IN, and the cost of the destination IN broadcasting the paging packet. The cost for broadcasting a paging packet could depend on the average utilization or congestion of the channel where the broadcast would occur. This cost is denoted by PBC_i, where i denotes the IN that broadcasts the packet. The cost of delivering a page request from the initial IN to another IN is the sum of the costs of the wireless IN to IN transmissions, along with the cost of wired IN to IN transmissions. In case that the wireless IN to IN communication does not interfere with the mobile to IN communication, the cost of IN to IN communication is different (e.g., lower) than PBC. The cost for wired IN to IN communication depends on if the INs are on the same wired network (e.g., on the same Ethernet in the same building), in which case the cost is quite low and could reasonably be neglected, or if the INs are in different networks and so the packet must travel over the Internet. In this case, the delay could be quite high and significantly impact the cost. We call the cost for delivering a packet across the Internet as the Inter-AS cost. Thus, we denote the cost for delivering a paging packet between the ith and jth In as $PRQ_{i,j}$.

As discussed in Section II, the cost of registering depends on the mobility management scheme used. Given the ith IN's paging area, and the mobility model statistics, it is possible to determine the probability that a mobile node that registered with the ith IN will next register with jth IN. We denote the cost of such a registration as $RC_{i,j}$, and denote the average registration cost for nodes that registered with the ith IN to be RC_i.

Depending on the mobility management used, $RC_{i,j}$ includes the cost between two and six packet exchanges between the jth IN and the mobile node. This cost could depend on the average congestion in the jth IN's mobile to IN channel. A registration also requires between two and four packet exchanges between INs, and these exchanges may include traversing the Internet. However, since registrations are not delay sensitive, the cost of registration accounts for the impact on congestion caused by registering; only the wireless IN to IN communications are included in the cost. Thus, $RC_{i,j}$ includes the cost of exchanging between two and four packets between the ith IN and the jth IN. This cost also includes the cost of the jth IN exchanging packets with the RADIUS server, and thus depends on the number of hops from the nearest base station to the jth IN. Finally, registration includes the cost of updating the routing. HAWAII and Cellular IP use the IN to IN transmissions to adjust the routing, and hence require no further packet deliveries. 802.11 does not specify how the routing is updated. One drawback of HAWAII and Cellular IP is that they assume a tree-like routing. However, in a LUMNet, it may be advantageous to have some other routing topology that supports efficient mobile to mobile communication. In this case, since updates may need to be flooded throughout the LUMNet, the cost of updating the distribution service could be quite high. Some specific examples of costs are provided in Section IX.

B. *Epoch Cost*

After a mobile node registers with an IN, the network will incur a cost due to either the paging of the mobile node or due to the registration of the mobile node with another IN. We refer to the period from after the one registration to the next page or registration as an epoch. It is assumed that once a page is successful, and the desire message is delivered, the mobile node has registered with it nearest IN. Thus, after a connection completes, a new epoch begins.

If the size of the paging area is increased, then the registration cost remains the same, but since it takes longer for the mobile node to exit the paging area, the time between registrations increases. As a result, the average cost per second due to registration decreases. We refer to the cost per second as *cost rate*. The objective of the paging scheme is to minimize the cost rate. Note that while the cost rate due to registration may decrease with the paging area, the cost rate due to paging could increase or decrease; it may decrease if epoch duration grows faster than the paging cost. The average cost rate is found as follows.

Let the paging area INs be denoted as IN_1, IN_2, ... , IN_M, where the subscripts also denotes the paging order (i.e., IN_1 broadcasts the page first). Let $\widetilde{C}_i$ denote the disjoint coverage area of IN_i as explained in Section

IV. It is assumed that the mobile node moves between coverage areas according to a Markov jump process. Specifically, a mobile node exits area $\tilde{C}_j$ at rate $\tilde{\lambda}_j$ (or, equivalently, the mean duration in area $\tilde{C}_j$ is $1/\tilde{\lambda}_j$). Once a node exits area $\tilde{C}_i$, if moves into area $\tilde{C}_j$ with probability $P\left(\tilde{C}_j|\tilde{C}_i\right)$, or more succinctly, $p_{i,j}$. Similarly, we denote the probability that the mobile node exits the entire paging area as $p_{i,M+1}$.

Finally, we assume that calls (i.e., requests for connections) arrive according to a Poisson process with mean interarrival time of $1/\lambda$.

With these definitions, we have the following

Proposition 4: Let the paging sequence be $\mathcal{R} = \{IN_1, IN_2, ..., IN_M\}$ and assume that the mobile node last registered with IN_m (i.e., IN_m is the initial IN). Then, the average cost rate incurred is

$$V(\mathcal{R}) = \frac{1}{\int_0^\infty \left(1 - P_t(M+1)\right) \exp(-\lambda t)\, dt} \times$$
$$\left(\int_0^\infty \sum_{i=0}^{M} P_t(i) \sum_{k \leq i} \left(PBC_k + PRQ_{m,k}\right) \lambda \exp(-\lambda t)\, dt \right.$$
$$\left. + RC_m \int_0^\infty P_t(M+1)\, \lambda \exp(-\lambda t)\, dt \right)$$

where

$$P_t = \exp(tQ)\, e_m,$$

e_m is the vector of all zeros, and a one in the mth location, and

$$Q_{i,j} = \begin{cases} -\tilde{\lambda}_j \text{ if } i = j \neq M+1 \\ \tilde{\lambda}_j p_{j,i} \text{ if } i \neq j \text{ and } j \neq M+1 \\ 0 \text{ if } j = M+1 \end{cases}.$$

Proof: Since the mobile is initially in $\tilde{C}_m$ with probability 1, the probability distribution of the mobile node over the coverage area is where $P_t(i)$ is the probability of being in $\tilde{C}_i$ after t seconds has elapsed since the node registered (See [12] for details).

Thus, the cost of paging a mobile node t seconds after registration is

$$\sum_{i=0}^{M} P_t(i) \sum_{k \leq i} \left(PBC_k + PRQ_{1,k}\right). \tag{7}$$

Thus, the event that the mobile node is within $\tilde{C}_i$ results in sending page request and page transmissions to IN$_m$ to IN$_i$. However, this cost is only incurred if the call occurs at time t. Under the assumption that call arrive like a Poisson process with rate λ, the probability of incurring the cost given in (7) is $\lambda \exp(-\lambda t)\, dt$. Thus, the average cost due to paging is

$$\int_0^\infty \sum_{i=0}^{M} P_t(i) \sum_{k \leq i} \left(PBC_k + PRQ_{1,k}\right) \lambda \exp(-\lambda t)\, dt.$$

On the other hand, the epoch might end not with a call, but with a registration. The probability of call arriving at time t and the mobile node having already exited the area is $P_t(M+1)\, \lambda \exp(-\lambda t)\, dt$. Thus the cost due to registering is

$$RC_m \int_0^\infty P_t(M+1)\, \lambda \exp(-\lambda t)\, dt. \tag{8}$$

The total average cost is the sum of (7) and (8).

The epoch ends when either a call arrives of the node exists the paging area. Using the formula $E(T) = \int_0^\infty P(T > t)\, dt$, we find the the average epoch duration is given by

$$\int_0^\infty \left(1 - P_t(M+1)\right) \exp(-\lambda t)\, dt$$

The average cost rate is the average cost, divided by the average time between incurring the cost (we neglect the duration covered by the data communication). ■

VIII. PAGING AREA CONSTRUCTION

Once the paging area is known, then the optimal paging sequence can be determined as shown in Section V, and the cost that results can be determine by using Proposition 4. This section demonstrates how the paging area can be found. It appears that the construction of the optimal paging area is computationally difficult. Instead, a greedy algorithm is used to iteratively expand the paging area.

Given $\mathcal{R}$, a series of M INs, it is important to not consider expanding $\mathcal{R}$ to include INs with coverage regions such that a mobile node will never visit before exiting the paging region $\mathcal{R}$ (e.g., INs with coverage area that is disjoint from any other IN in $\mathcal{R}$). The addition of such a IN would not impact the cost rate, and hence, is a trivial expansion of the paging area. For a given $\mathcal{R}$, the set of INs that can be added to $\mathcal{R}$ in a non-trivial way is denoted by $NT(\mathcal{R})$. Whether an IN belongs to $NT(\mathcal{R})$ can be determined by defining the $(M+2) \times (M+2)$ matrix

$$Q_{i,j} = \begin{cases} -\tilde{\lambda}_j \text{ if } i = j \neq M+1 \text{ and } j \neq M+2 \\ \tilde{\lambda}_j p_{j,i} \text{ if } i \neq j,\ j \neq M+1, \text{ and } j \neq M+2 \\ 0 \text{ if } j = M+1 \text{ or } j = M+2 \end{cases}.$$

where $p_{j,i}$ is as in Proposition 4, and $p_{j,M+2}$ is the probability of a node moving from $\tilde{C}_j$ to the coverage area of IN_*. Then, the probability of entering the coverage area of IN_* before exiting the paging region is $(M+2)$th element of $\lim_{t \to \infty} Q^{-1} \exp(Qt)\, e_1$, where e_1 is the vector of zeros except with the first element being one.

Let $\mathcal{R} = \{IN_1, IN_2, ...\}$ be a given set of INs. Then, following the approach of Section V, the paging sequence can be constructed from $\mathcal{R}$. We denote this sequence with $\mathcal{O}(\mathcal{R})$. Next, Proposition 4 provides the average cost rate due to this paging sequence. This cost rate is denoted $V(\mathcal{O}(\mathcal{R}))$. Lastly, let $\tau > 0$ be first time that a mobile node exits the paging region. Letting IN_0 be the initial IN where the mobile node has registered, the algorithm to construct the paging area can be described as follows.

Algorithm 2 Paging Area Construction

```
   Set $\mathcal{R} = \{IN_0\}$
2: Set $\text{IN}^* = \arg\min (V(\mathcal{O}(\mathcal{R} \cup IN_j)) : IN_j \notin \mathcal{R}$ $and IN \in NT(\mathcal{R}))$
   if $V(\mathcal{O}(\mathcal{R})) < V(\mathcal{O}(\mathcal{R} \cup IN^*))$, then
4:     set $\mathcal{R} = \mathcal{R} \cup IN^*$ and return to step 2.
   else
6:     stop, the paging area is $\mathcal{R}$.
   end if
```

Thus, in brief, given a paging area, $\mathcal{R}$, a new IN is added if the addition of this IN leads to the least cost rate as compared to the addition of any other IN, and if the addition of this IN reduces the cost rate as compared to not adding any IN. In the case that the addition of any IN results in a greater cost rate, the process is stopped.

IX. NUMERICAL RESULTS FOR REALISTIC URBAN MESH NETWORKS

A. Simulation Methodology

A distinguishing feature of LUMNets is the complicated propagation and mobility. Propagation is greatly impacted by buildings. On the one hand, complicated propagation can lead to two geographically close locations not being able to communicates (e.g., a mobile node that is indoors and a IN that is outdoors), and on the other hand, it can cause two geographically distance locations to be able to communicate (e.g., a mobile and an IN on the same straight boulevard). Thus, propagation has a substantial impact on paging and the relationship between paging and network architecture. For this investigation, considered the core downtown region of Chicago. Specifically, the region bounded by W. Lake St., N. Clark St., W. Madison St., and N. Franklin St. was examined. A GIS map of the buildings in this region along with a ray-tracing tool was used to determine realistic urban propagation (e.g. [2]). This investigation focused on pedestrian mobility. The two tiered hierarchical mobility model was used. The upper layer models the basic activities, e.g., at work, at home, at lunch, etc. This model is based on US Dept. of Labor and Statistics survey of how people spend their time [7]. The second tier models the tasks performed during a particular activity, particularly, the at work activity. This part of the mobility model used results from several surveys on meetings, e.g., how long meetings are, how many people attend meetings, the time between meetings, etc [10]. This part of the model is important for modeling the movement of people within a business.

Within the simulated region, 52 INs were distributed outside and 301 INs were distributed indoors. The result was that every location was in communication of at least one IN. Four one-hour simulations were run, two for the morning rush hour, from 8 AM to 9 AM, and two for the lunch hour, from 11:30 to 12:30. In each trial, the mobility and resulting propagation of 2400 mobile nodes was used. With this data, the paging algorithm was used to compute paging regions for each IN.

B. Numerical Results

This section demonstrates that in most cases, the paging region would consist of more than a single IN. Hence, it is inefficient for a mobile node to register whenever it moves out of range of the IN it last registered with. This section also examines how the topology and costs impact the paging.

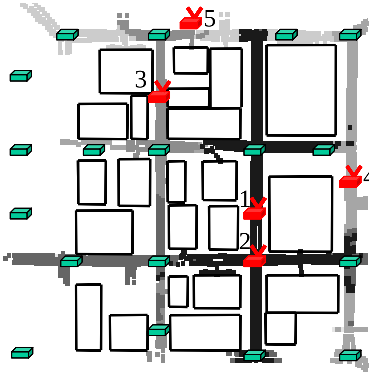
Section VII-A discussed how various factors such as congestion, delay, and mobility management protocol influences the costs, the costs also depend on the congestion, delay, and mobility management protocols used. In general, the congestion and delay can be measured, in which case the costs due to congestion would depend on the transmitter. However, here we assume that the congestion and delay is the same for all links of the same type. Thus, we define

1) `INToMNCC` - IN to Mobile node congestion cost
2) `INToINCC` - IN to IN congestion cost (via a wireless link)
3) `INToMNDC` - IN to mobile node delay cost
4) `INToINDC` - IN to IN delay cost (via a wireless link)
5) $\texttt{SNDC}_{i,j}$ - subnet to subnet delay cost

If these nodes reside in the same subnet, then $\texttt{SNDC}_{i,j} = 0$. Furthermore, here we assume that communicating between subnets only impacts delay, not congestion. Note that we do not consider the congestion cause by communicating between subnets.

With these constants, the costs defined in Section VII-A become

$$\begin{aligned}
&PBC_i = \texttt{INToMNCC} + \texttt{INToMNDC},\\
&PRQ_{i,j} = \texttt{SNDC}_{i,j}\\
&+NumHops_{i,j} \times (\texttt{INToINCC} + \texttt{INToINDC}),\\
&RC_{i,j} = \text{NumHops}_{i,j} \times\\
&(\texttt{NumOldToNewINForReg} \times \texttt{INToINCC}\\
&+\texttt{NumINToRadiusForReg} \times \texttt{INToINCC})\\
&+\texttt{NumINToMNForReg} \times \texttt{INToMNDC}_i,
\end{aligned}$$



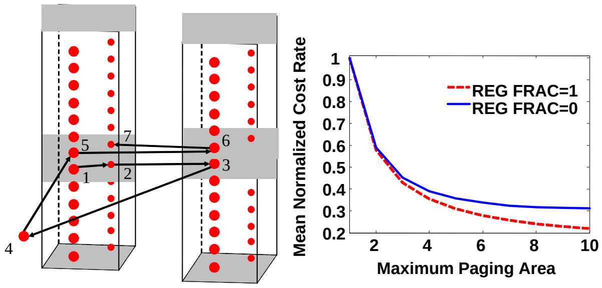
3: Evolution of Paged Area. A five IN paging area is shown. The paging sequence is as indicated. The darkest regions are those covered by the first IN in the paging sequence, while the lightest gray is the region covered by the fifth IN in the paging sequence and not covered by any of the first four INs. The rectangular boxes are the INs that are not in the paging area. Note, only coverage along sidewalks is shown.

where, considering the registration overhead of the protocols discussed in Section II, we set $\texttt{NumOldToNewINForReg}= 4\cdot\texttt{RegFac}+2\times(1-\texttt{RegFac})$, $\texttt{NumINToRadiusForReg}= 10\cdot\texttt{RegFac}$, and $\texttt{NumINToMNForReg}= 17\cdot\texttt{RegFac}+2\cdot(1-\texttt{RegFac})$. Thus, if $\texttt{RegFac}=1$, then the registration cost is as in 802.11i and if $\texttt{RegFac}=0$, then the registration cost is as in HAWAII. Note that we assume that paging is delay sensitive and registration is not. Throughout these examples, $\texttt{INToMNCC}=1$ and we assume that all indoor INs are base stations (i.e., they have wired connections) and are not able to directly communicate with outdoor INs (they must use the Internet). Outdoors, it is assumed that there is only one BS and least-hop routing is used. Furthermore, it is assumed that node can communicate if the channel gain between the nodes is better than -50 dB.

To get an understanding of this the paging process, consider Figure 3. Note that the INs that define the paging area are not necessarily the INs that are closest to the first IN in the sequence. For example, the third IN is further from the first IN than the fourth IN and the INs between the first and third are excluded from the paging sequence.

Figure 4 provide another view of paging. Specifically, it shows how the paging area may include INs in different buildings and outdoors.

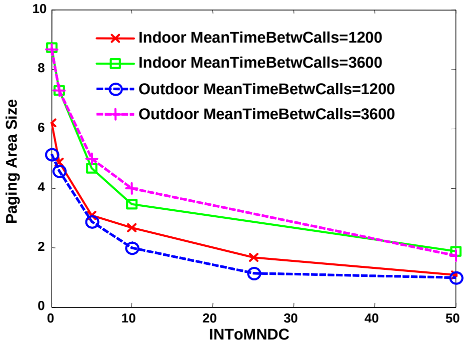
We begin by analyzing the case where $\texttt{INToMNDC}=0$, $\texttt{INToINDC}=0$, $\texttt{SNDC}_{i,j}=0$ (no delay is considered), $\texttt{INToINCC}=1$ (the congestion cost for IN to IN communication is the same as congestion cost for IN to mobile node communication), and the mean time between calls is 3600 sec. For these parameters, right hand plot of Figure 4 shows how the average cost rate decreases as the size of the paging area is allowed to grow. The cost rate is normalized, so that the cost rate is normalized to one when only one IN is in the paging region (i.e., paging is not used and the mobile registers whenever it moves out of range of the last IN it registered with). Note that the cost rate (which, in this case, is purely due to overhead) is reduced by factor between 3 and 5, depending on the cost of registration.



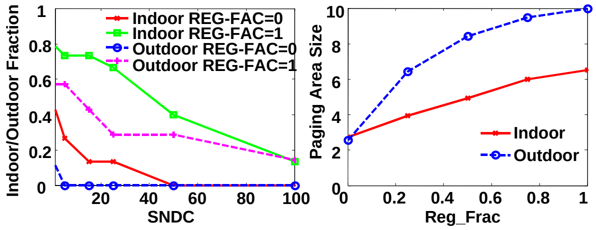
4: Left; The paging sequence is as indicated. Note that since nearby INs may provide coverage (see Figure 2), the paging sequence may span nearby buildings and outdoors. Right; Cost Rate vs. Number of IN in Paging Region.

Right hand plot of the Figure 4 shows that on average and for the parameters given above, the smallest cost rate is achieved by allowing the paging area to include many INs. Next we examine the in the paging area that results in the smallest cost rate, i.e., the best paging area size. Figure 5 shows this best paging area size when averaged over all INs. Furthermore, Figure 5 shows the behavior of the paging area as a function of $\texttt{INToMNDC}$ and for the average time between calls set of 3600 sec. and to 1200 sec. Furthermore, the results are divided into the cases where the initial IN is indoors and where the initial IN is outdoors. Figure 5 indicates that as the delay incurred from the broadcasting of the page packet by each IN becomes more expensive, the paging area size decreases. However, even for very large delay costs, the paging region is above one, indicating some utility to paging.

As indicated in Figure 4, the paging area may span both indoors and outdoor. However, here we assume that the communication between the INs indoors and the INs outdoors are not directly connected and must communicate via the Internet. The cost of this communication is reflected by the parameter SNDC. Figure 6 shows the fraction of INs that include both indoor and outdoor INs in their paging area as a function of SNDC. This relationship is shown for indoor and outdoor nodes and for $\texttt{RegFac}$ equal to zero and one. It can be seen that in general, a smaller fraction of indoor INs require paging



5: Average Value of the Best Paging Area Size vs. the INtoMNDC, the IN to Mobile Delay Cost.



6: Left, Fraction of INs that have both indoor and outdoor INs in their best paging area. Right, Average of the Best Paging Area Size vs. RegFrac. As registration cost increases, the paging region increases.

regions that spanned to indoors as compared to indoor INs. Indeed, for small registration cost such as HAWAII, if even a small cost is incurred when communicating between the outdoor mesh and the indoor INs, then there is not need to include indoor INs. However, for indoor nodes, especially if the registration cost is expensive, then the best paging region will include outdoor nodes, even if the cost to communicate between the indoor INs and outdoor INs is quite high. This indicates the importance of allowing cross subnet paging, as is done in P-MIP.

The cost of registering has a significant impact on the paging. This can be seen in Figure 6 where the size of the paging area grows as the registration becomes more expensive. The calculations use top produce this figure assumed `INToMNDC`$= 25$. It can be seen that for this value of `INToMNDC`, if the registration is inexpensive, then the average best paging area is rather small, indicating that there may be little utility to allowing paging. On the other hand, if registration is expensive, then the average best paging area is quite large. Since authentication, authorization, and accounting (AAA) is likely to be required in any LUMNet, the registration may be expensive, necessitating large paging areas.

It is important to note that the average best page area size depends on the costs in a complicated way. For example, when `INToMNDC`$= 25$, and `RegFac`$= 0$, we find that changing `INToINCC` from 1 to 0.1, results in the average page size for indoor nodes to change from 6.5 to 6.8. However, if `INToMNDC`$= 25$, and `RegFac`$= 0.25$, we find that changing `INToINCC` from 1 to 0.1, results in the average page size for outdoor nodes to change from 6.4 to 4.8, a change in the opposite direction.

X. CONCLUSION

As the number of mobile nodes in a large-scale urban mesh networks (LUMNets) increases, the problem of finding a particular mobile node becomes more challenging. Here a paging techniques that is specialized for LUMNets was developed. It was shown that integrating paging into the mobility management could provide a substantial reduction in the overhead. Furthermore, the impact of the LUMNet architecture on the paging was investigated. It was shown, for example, that in many cases, the best performance is achieved when the paging for a single mobile node is allowed to span both indoors and outdoors. It is important to note that the conclusions developed here result from computations using realistic propagation and mobility. Hence, they can be directly applied to LUMNets currently under development.

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