Performance of Urban Mesh Networks*

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ABSTRACT

Currently, large-scale deployments of mesh networks are being planned for Philadelphia as well as other cities. The performance of such networks has never been examined through simulation or through any other means. In this paper we perform detailed simulations of mesh networks in several urban environments and evaluate the performance of these networks. The simulations utilize realistic ray-tracing and other propagation models. The mobility of nodes is based on models derived from several movement and time use surveys including the US Department of Labor's recent time use study that includes travel diaries from over 20,000 people. Basic performance issues such as connectivity, capacity, and several application oriented performance metrics as a function of the density infrastructure (base stations and fix wireless relays) are examined. It is found that a high density infrastructure is required to achieve reasonable coverage, in particular, the density must be higher than is currently considered by most deployments. While allowing mobile nodes to act as relays improves coverage, it does not necessarily improve the performance received by the application. It is found that in general, there is a significant difference between the fraction of nodes that are able to communicate with a base station and the fraction of nodes that received acceptable application layer performance.

Categories & Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design - *Wireless communication*
C.4 [**Performance of Systems**]: *Design studies; Modeling techniques; Performance attributes*

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General Terms

Design, Performance

Keywords

Application Performance, Mesh Networks, Propagation, Ray-tracing, Wireless Networks.

1. INTRODUCTION

There has been growing interest in urban mesh networks. Recently, the city of Philadelphia has entered the final planning stages for the deployment of a mesh network that intends to provide coverage to the entire 135 sq. mi. city with 4000 fixed base stations. Several other cities including New York City, San Francisco, and Las Vegas are considering similar massive deployments.

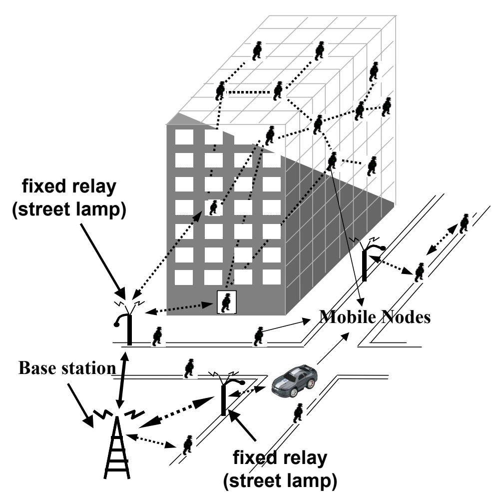

Figure 1: A conceptual visualization of mesh networks.

Market research indicates that the mesh networks will grow to a multi-billion dollar business within the next few years [7]. Applications for ubiquitous Internet access have only begun to be considered. For example, wireless Voice-over-IP phones are currently available [3], [2]. Municipalities such as Las Vegas are considering applications ranging from monitoring and controlling vehicle traffic to assisting emergency response in providing reliable communication and remote situation assessment. Such wireless infrastructure provides a natural conduit for connecting sensor networks to the Internet. The introduction of ubiquitous access to the Internet will surely spawn unforeseen applications.

While the topology and design of urban mesh networks are still evolving, the near-term deployments are expected to be joint public/private ventures that make extensive use of city owned infrastructure. For example, it is expected that city owned lampposts will support much of the infrastructure. This infrastructure will be composed of wired base stations and fixed wireless relays as shown in the Figure 1. Base stations act as gateways between the Internet and the wireless network while the fixed wireless relays act to expand coverage but do not provide a direct connection to the wired Internet. The pilot program in Las Vegas includes about one base station or a fixed relay every 400 m., while Philadelphia's plans call for a density of roughly one base station or fixed relay every 300 m. Another potentially important aspect of mesh networks is the ability of mobile nodes to act as relays. In the Las Vegas program, mobile nodes may act as relays [7], while in the planned Philadelphia deployment, mobile nodes can only act as end-hosts [18].

While the deployment of mesh networks seems imminent, there is little understanding of the performance of such networks. In this paper, the results of large-scale and realistic simulation of urban mesh networks are presented. This paper investigates basic performance issues as a function of the density of the infrastructure. Specifically, densities of one station (base station or fixed relay) every 50m, 75m, 150m, and 300 m and with various fractions of these infrastructure nodes acting as fixed relays are investigated. The performance issues investigated include coverage, an upper bound on capacity, and several application specific performance metrics. Applications considered include web-like file transfer, voice-over-IP, and music streaming.

The goal of this work is to gain an understanding of the performance of different applications over realistic urban mesh networks. To this end, realistic wireless propagation and realistic mobility models are utilized. The propagation is based on 3-D ray-tracing [25] that includes reflection, transmission, and diffraction. Propagation through buildings is modeled with the attenuation factor model [17], [24]. As a result, the propagation simulation is well suited for modeling urban propagation. Indeed, the tool has been validated with propagation measurements in urban areas [25].

A key ingredient of realistic propagation is realistic maps (i.e., location and dimensions of buildings). This investigation is based on two urban areas, namely, the University of Delaware Campus and a section of Paddington area of London. Thus, the simulated wireless propagation is based on how wireless signals would propagate through these areas. Due to lack of space, only results for the Paddington area are presented. The performance in University of Delaware Campus was found to be similar, but the Paddington area provides the most interesting scenario.

While propagation in urban areas, has been studied and modeled, urban mobility for wireless networks is a new research area. This investigation focuses on the city-core where, by definition, most of the buildings are assumed to be office buildings, with possibly restaurants and shops on the first floors. Residences are assumed to be on the edge of the simulated area. We focus on the mid-day performance beginning at 11:30 AM, when most people have arrived at work, but some are still arriving, and some those that have already arrived at work are starting to leave for lunch. A similar investigation was conducted for the period beginning at 12:30 PM and 2:00 PM; these investigations produced results similar to those generated by the 11:30 AM time period. Again, 11:30 AM produced the most interesting scenario.

The mobility models used for these simulations are described in some detail in Section 2 and in more detail in [11]. Briefly, the mobility model is based on extensive surveys performed by the US Department of Labor's Bureau of Labor Statistics 2003 time use study, the business research community, and the urban planning research community. These three bodies of work allow realistic modeling of the times people arrive at work and go to lunch, as well as what activities are done during the lunch hour including the distances traveled. They also provides a basis for mobility inside of office buildings, and realistic mobility of people as they navigate congested urban sidewalks.

While this work provides several insights into the performance of urban mesh networks, one important point is that nodes (people) indoors will receive poor coverage unless very high infrastructure densities are used. Specifically, the density must be higher than the currently planned deployments. Furthermore, the planned infrastructure densities for cities such as Philadelphia will not provide adequate coverage outdoors unless mobile nodes are permitted to act as relays. On the other hand, it is also demonstrated that the performance of an application is not the same as the coverage, e.g., the fraction of nodes that receive reasonable application performance is less, sometimes substantially less, than the fraction of nodes that have basic connectivity to the infrastructure. Indeed, in some cases, the coverage achieved without using mobile nodes as relays is a better predictor of performance than coverage achieved when mobile nodes can act as relays. This indicates that while allowing mobile nodes to act as relays improves coverage, it does not improve performance.

The remainder of the paper proceeds as follows. In the next section, the simulation methodology is outlined. In Section 3, the coverage of several mesh network scenarios is investigated. In Section 4, a bound on the capacity achieved in the considered scenarios is discussed. Section 5 investigates the performance of several applications. Specifically, Section 5.1 investigates web-like file transfers, Section 5.2 investigates voice-over-IP, and Section 5.3 investigates music streaming. Section 6 provides a summary and discussion of the results. Finally, Section 7 provides some concluding remarks and scope for further research.

2. SIMULATION METHODOLOGY

Realistic simulation of urban mesh networks requires three components, namely, realistic maps of urban areas, realistic propagation, and realistic mobility. Urban maps provide not only streets, but also the locations and sizes of buildings. The use of realistic maps differs from randomly generated maps that often lack important features such as major thoroughfares. Such thoroughfares are often straight and lined with large buildings. As a result, such streets are able to provide excellent propagation [6]. Indeed, due to the excellent propagation along urban streets, they are often called urban canyons [5]. Furthermore, such thoroughfares have a high density of mobile nodes that provide the opportunity

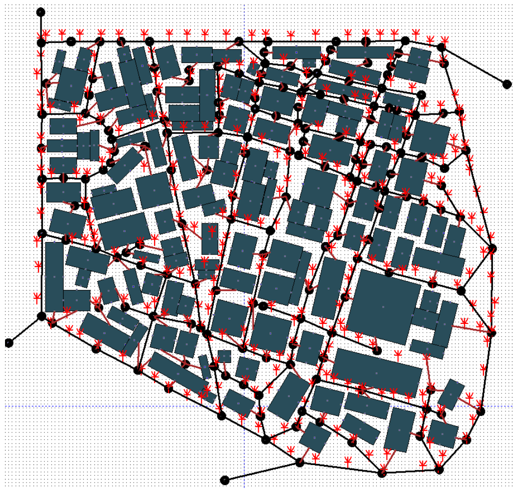

Figure 2: Map of Paddington area of London. Smaller markers along streets indicate possible locations of base stations or fixed relays.

for relaying (if the network permits such relaying). This investigation is based on two urban maps; the University of Delaware, and the Paddington area of London. However, due to lack of space, only the results for the Paddington 2 area are presented.

Realistic wireless propagation in urban areas has been extensively studied. These simulations utilize a technique that uses ray-tracing and vertical plane rays [12] as well as several other techniques to increase the computational efficiency. Detailed discussion of the propagation model along with validation is provided in [25]. In brief, the simulation models the fact that wireless signals may reflect off of buildings and the ground. However, the amount of energy reflected depends on the angle at which the signal strikes the object as well as on the material used in the construction of the object. In these simulations, it is assumed that the exterior walls of buildings are made of 20 cm. concrete (i.e., $\varepsilon_r = 5 - j0.02$) while the earth's dielectric constants are taken as $\varepsilon_r = 15$.

As just mentioned, when a wireless signal strikes a wall, part of the energy is reflected. However, part of the energy is also transmitted into or out of the building (also, part of the energy is absorbed by the wall). In these simulations, when the signal is inside of a building, it propagates according to the attenuation factor model (AF). This model has been shown to provide a realistic model for interior propagation [17], [24].

The last attribute of the propagation model is diffraction. In our and other's work, it has been shown that diffraction plays an important role in wireless communication in urban areas [25]. Diffraction allows the transmission to curve over the top of buildings as well as around corners. The propagation tool used here employs the Uniform Geometrical Theory of Diffraction [14].

While propagation in urban areas has received substantial attention within the communication research community, mobility for mesh networks has received limited investigation. Some work toward realistic mobility includes [22], [4] and [15]. The mobility model used in this paper are based on a three-layer hierarchical model which is described in detail in [11]. The objective of the model is to simulate people in the city-core during the workday. By city-core, we mean that most of the buildings are office buildings and the people are office workers. However, the model also includes some residential buildings along the perimeter of the modeled area. Furthermore, the first floor of the office buildings includes shops and restaurants. This paper focuses on simulations starting at 11:30 AM. By 11:30, most of the people in the city-core have arrived at work, but some are yet to arrive. Furthermore, some of those that have arrived at work, are beginning to go to lunch, while others continue working

This paper utilizes a detailed mobility model for urban pedestrians during a workday. This model is based on three mature research areas, urban planning [21], [27], meeting analysis [23], and time use [26]. The resulting model is a three layer hierarchical model. The highest layer is the activity model that determines the high-level type of activities. Activities considered include working, eating, shopping, and receiving professional services (e.g., visiting a doctor). The activity model determines the time when people start and end various activities. The data used to generate this model is from the recent US Bureau of Labor Statistics (BLS) *time use* study [19]. Such time use studies have been actively performed for the past forty years [26]. The 2003 US BLS study marks the beginning of a yearly study of time use that is based on ten years of planning within the BLS. The 2003 study includes interviews with roughly 20,000 people. Of those, around 5000 resided in metropolitan areas and were used in the activity model utilized here. Furthermore, the BLS determined weightings to account for over and under sampling of some types of people (e.g., unemployed people tend to be at home at the time of the interview call and tend to be over sampled). Hence, the significance of the study exceeds the 20,000 that were actually interviewed.

The second layer of the pedestrian mobility model is the task model. Within an activity, the node may perform a large number of tasks. For example, our model focuses on office workers where there are two types of tasks, working at their desk and meeting with other workers. The significance of these worker tasks is that they model mobility of nodes within the buildings as well as clustering of nodes within the buildings. The basis of this part of the mobility model is several seminal studies of worker meetings performed within the management research community [20], [23], [16]. These surveys include two-people meetings and hence describe much of an office workers activity while at work.

The third layer of the mobility model is the agent model. Such agent models have been investigated within the architecture community [9], [10] and define how the node navigates to its desire destination. The model used here is based on urban planning research, especially the seminal work of Pushkarev and Zupan [21] that includes findings of their own extensive studies as well as results from several other pedestrian mobility studies. The pedestrian chapter of the US Highway Capacity manual [27] is also based on their work. An important aspect of the agent model is that it includes node interactions. For example, a faster walking pedestrian can overtake a slower pedestrian only if there is room. Furthermore, even when there is room, pedestrians do not always overtake slower pedestrians. As recognized by Pushkarev and Zupan, such node dynamics lead to clustering of people, or platoons. Indeed, like in provisioning of networks, it is well known within the urban planning community, that sidewalks must be able to support substantially higher pedestrian flow than indicated by the mean flow rate. We should also mention that traffic lights are also a major source of platooning and are included in the mobility model. Platoons are of interest to mesh networks since they lead to heterogeneous node distribution. The complete methodology for realistic simulation of the mobile Ad-Hoc networks could be found in [25].

3. COVERAGE

Coverage is the first issue that arises when considering the performance of a mesh network. Here we examine the fraction of nodes that are able to communicate with the wired network. We say that a node is able to communicate with the wired network if there is a sequence of communication channels with sufficiently high signal to noise ratio that form a path from the node to a wired base station.

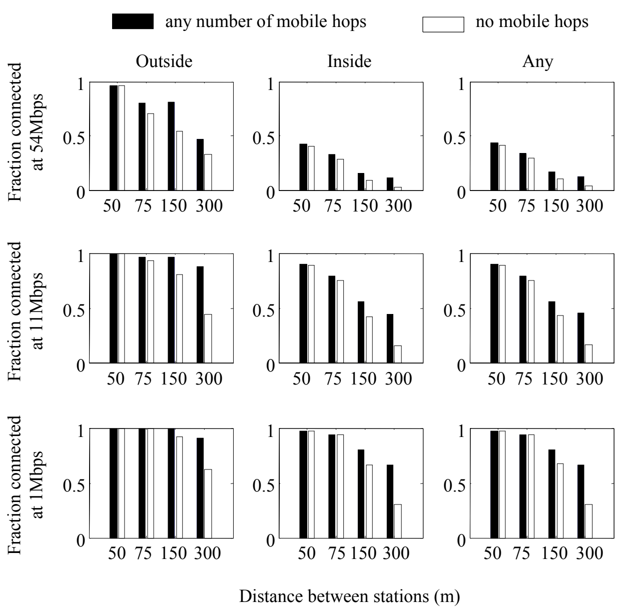

Figure 3: Coverage. These plots show the fraction of people that can communicate with the base station in different scenarios. The left hand column considers only nodes that are outside, the middle column only considers nodes that are inside, while the right hand column includes all nodes. The upper row is for coverage at 54 Mbps with 802.11g (-69 dBm signal strength). The middle row is for 11 Mbps (-85 dBm), while the bottom row is for 1 Mbps (-93 dBm). The x-axis indicates the distance between the infrastructure nodes. Within each infrastructure scenario, the right most bar indicates the coverage when mobile nodes are not allowed to act as relays, while the left column shows the coverage when mobile nodes may act as relays.

In urban areas, coverage is complicated by the fact that buildings can reflect wireless signals while allowing small amount of energy to penetrate into or out of the building. As a result, communication from within a building to outside is severely impacted to the point that nodes that are indoors may not be able to directly communicate with nodes that are outdoors even when the nodes are relatively close. Similarly, wireless propagation indoors must pass through many interior walls. While interior walls typically result in less loss than exterior walls, interior propagation is also impacted to the point that communicating nodes must be closer when they are inside as compared to when they are outside. Thus, we expect that an outdoor mesh network will provide significantly better coverage to nodes that are outside than to those that are inside.

The physical layer used also impacts the coverage of a mesh network. Typically, high bit-rate physical layers require less loss (stronger received signal power) than lower bit-rate physical layers. Thus, a mesh network that uses high bit-rate physical layer schemes will typically provide worse coverage than one that allows lower bit-rates. Here we assume the bit-rates that are achievable with 802.11g with transmission power of 15 dBm.

The density of the infrastructure plays an important role in the coverage; more the base stations, more the nodes that will be in range with at least one base station. On the other hand, if each fixed relay is able to communicate with at least one base station directly or indirectly (i.e., via other fixed relays), then the fraction of the infrastructure nodes that are wired base stations does not impact the coverage. Thus, when considering coverage, there is no need to consider the fraction of the infrastructure that is made up of base stations or fixed relays.

Another feature of a mesh network that may affect the coverage is whether mobile nodes may act as relays. As mentioned in the introduction, the current plans (as of Spring 2005) of the Philadelphia mesh network is to not allow the mobile nodes to act as relays. However, the Las Vegas pilot project does allow mobile relays.

The degree to which these five issues impact coverage is shown in Figure 3. This figure is based on the behavior averaged over 20 observations over the period from 11:30 AM to 11:35 AM.

The difference between the coverage of nodes inside versus those that are outside is obvious and as expected; an outdoor infrastructure provides better coverage of nodes outside. However, note that when all nodes are considered, the coverage is nearly the same as the coverage of nodes that are inside. This is due to the fact that people are mostly inside. Even when considering the lunch time, e.g., 12:30 PM, we find that most nodes are inside (either in their work place, a restaurant, a shop, etc.).

Figure 3 shows that nodes that are indoors or nodes in general (i.e., when a node is selected at random) can expect "*spotty*" coverage from networks built with infrastructure nodes spaced at 300 m, even when only low bit-rates are desired. While, if infrastructure nodes are placed every 150 m, then 75% of nodes will be able to connect to the infrastructure at 1 Mbps. At high infrastructure densities, low bit-rate coverage of indoors is possible. Bit-rates of 54 Mbps to nodes indoors appears to be not possible even when there is only 50 m between base stations.

The impact of allowing mobile nodes to act as relays depends on the scenario. In general, higher the density of the infrastructure, lower the impact. Thus, when base stations are 300 m apart, the impact of allowing mobile nodes to act as relays is significant. For example, for general nodes, al-

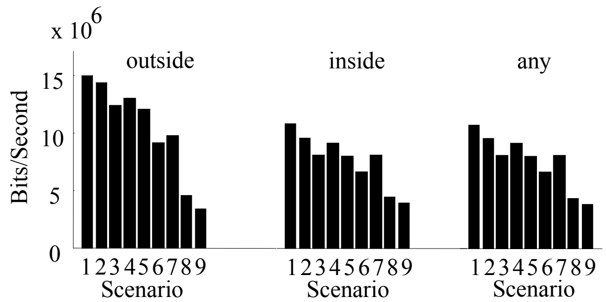

Figure 4: Achievable bit rates.

lowing mobile nodes to act as relays increases the coverage from 30% to 65%. On the other hand, when the base stations are less than 150 m apart, allowing mobile nodes to act as relays provides only moderate improvements in coverage. It should be noted that in these simulations we assumed that about 12% of the population was participating in the network. Future work will examine the impact of a larger and smaller fraction of users.

Figure 3 is the only instance where mobile nodes are not permitted to act as relays. In the remainder of the paper, mobile nodes are always permitted to act as relays.

4. BIT-RATE ACHIEVABLE OVER MESH NETWORKS

It is common to use achievable bit-rates as a performance metric for wireless networks. While total capacity is computationally difficult, a simple estimate of the achievable bit-rate can be found as follows. We assume that the data originates at base stations and flows to mobile nodes. Also, the data that flows to a mobile node originates only at its nearest base station. The nearest base station and the routing to the mobile nodes is found using least cost routing where the cost is the path loss (i.e., the reciprocal of the channel gain). Hence, data flows along links with the highest quality. No load balancing is attempted.

It is assumed that a node receives and transmits data at the maximum bit-rate possible with the 802.11b/g physical layer. Transmissions are assumed to be at 15 dBm.

An upper bound on the bit-rate achieved by a single flow is given by the lowest link bit-rate along its path from base station to destination. Figure 4 shows the bit-rate averaged over all mobile nodes that are able to communicate with a base station. These bit-rates were further averaged over 20 time points as was done in the previous section. The x-axis denotes the mesh network scenario where the scenarios are defined in Table 1.

Figure 4 shows that when a node is able to communicate with the base station, the achievable data rates are quite high. For example, even when the base stations are 300 m apart, if communication is possible, then the average data rate is approximately 4 Mbps. As more base stations and fixed relays are added, average bit-rates reach 10 Mbps. However, achievable bit-rates should be treated with care. As will be seen in the next section, the high achievable bit-rates shown in Figure 3 do not translate into good performance of an application as experienced by the average user.

5. APPLICATION PERFORMANCE

The previous two sections indicate that if the density of the infrastructure is high enough, then the nodes both inside and outside are able to connect to the wired network. However, the performance of network-based applications requires not only that the connectivity is achieved, but is also maintained throughout the life of the application. Such connectivity not only depends on the locations of node and resulting channel gain between nodes, but also on the underlying routing protocol. For example, if the channels between nodes allow connectivity, but the routing protocol is unable to find a route, then end-to-end communication is not possible. Furthermore, if a route is found, the end-to-end performance may still not be sufficient to support a particular application. For example, TCP file transfers demand loss probabilities below 10% or else transfer rates will be exceeding slow. In this section, the performance of three applications is considered, web-like file transfers, voice-over-IP, and music streaming. While each application demands that the routing protocol find a route, the requirements of each application differs.

As will be shown, these applications perform significantly worst than would be expected by considering the coverage and capacity plots shown in Figure 3 and Figure 4 respectively. While poor performance may be expected when coverage is at 75%, poor performance can also be observed when nearly all nodes are able to communicate with the wired network. This is especially the case for Voice-Over-IP where the performance outdoors is rather poor even at high infrastructure densities. On the other hand, it will be shown that coverage is a useful predictor of performance when web-like file transfers are considered.

While there are a large number of routing protocols that are suitable for multiple hops over mobile node, the most popular protocols (DSR, AODV, OLSR) are not well suited for routing over a mixed wired and wireless network. Specifically, these protocols treat wired links in the same way that wireless links are treated. However, considering that wired links are more stable and often faster than wireless links, these simulations made use of a modified version of AODV that finds the minimum number of *wireless* hops. Thus, hops over wired links do not affect the cost of the route. Furthermore, the base stations do not need to invoke route discovery to find routes to other base stations. These simulations assumed a very high bit-rate wired network upon which the base stations are attached. No distinction was made between fixed relays and mobile relays except that the infrastructure nodes were assumed to be on lampposts, and hence the higher elevation provided better propagation by decreasing the impact of the ground reflection

Nine mesh network scenarios are considered. The details of these scenarios are provided in Table 1.

As noted above, the quality of service received by a node that is inside greatly differs from the quality of service received by an outside node. Thus, the performance of the application on end-hosts that are outside is considered separately from the performance of applications on end-hosts that are inside. Nodes that are outside are typically moving, unless they are waiting at a traffic light. On the other hand, nodes that are inside do not move for considerable amount of time. The average time between the movements of nodes that are inside is approximately 20 minutes. The average duration of a trip outside is around 4 minutes.

Table 1: Mesh Network Scenarios

Scenario #	Distance between infrastructure nodes	Fraction of infrastructure nodes that are wired
1	50 m	1.0
2	50 m	0.50
3	50 m	0.25
4	75 m	1.0
5	75 m	0.50
6	75 m	0.25
7	150 m	1.0
8	150 m	0.50
9	300 m	1.0

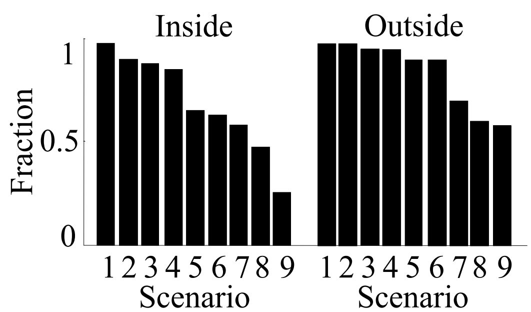

Figure 5: Fraction of file transfers connections completed

The applications tested on outside nodes start after the node is outside and stop before it returned indoors.

The primary goal of this investigation is not to determine the capacity of mesh networks. Hence, only a small number ($\leqq 10$) of flows are active at any moment. In all cases, the simulation ran for 20 minutes and 100 trials in each scenario were conducted. The application implementations are those that are provided in QualNet v3.7 [1]. The 802.11b physical layer is used with bit-rates ranging from 1 Mbps to 11 Mbps. 15 dBm transmission power is assumed.

5.1 Web-like File Transfer

Web browsing is one of the "killer apps" that lead to the explosive growth of the wired Internet. It is likely that web-browsing will be an important application on mesh networks as well. Hence, web-like file transfers provide the most basic test of the performance of an application on a mesh network. The simulations described here assume that the file sizes are distributed according to a log-normal distribution as described in [8]. It is assumed that the mobile hosts download files from the wired network.

The most elementary network performance metric is the fraction of file transfers completed. Figure 5 shows the fraction of files that were successfully transferred in each scenario. Comparing this performance to the coverage plots in Figure 3, we see that coverage and the probability of successful file delivery are highly correlated (the correlation coefficient is 0.84). However, the relationship between coverage and performance is not perfect. For example, consider the probability of successful file delivery experienced by nodes that are indoors in scenarios 4-6 to the probability experienced by nodes that are outside in scenario 9.

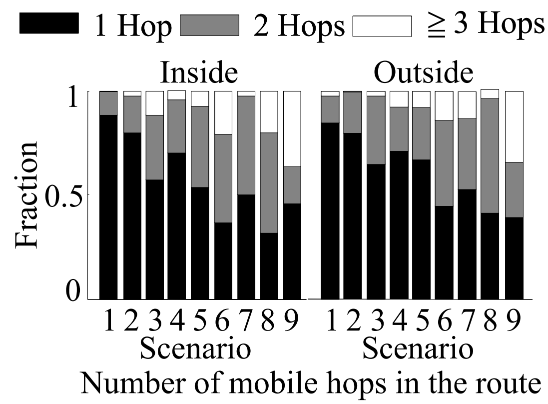

Figure 6: Number of mobile hops in the route. There is always one mobile hop to a mobile end host. If there is more than one mobile hop, then the route contains a mobile-to-mobile link.

These three scenarios have approximately the same coverage of around 85%. However, the probability of successful file delivery varies from 55% to 85%. On the other hand, there is a stronger correlation between the connectivity achieved when mobile nodes are *not* permitted to act as relays and the probability of successful file delivery; the correlation coefficient was found to be 0.91. This correlation can also be seen by noting that the indoor coverage in scenario 7 and 8 is approximately the same as the outdoor coverage in scenarios 9. Furthermore, in these three cases, the probability of successful file transfer is approximately 0.5.

Similarly, Figure 5 also indicates that in general, the fraction of nodes that can communicate with the wired network is higher than the fraction of successful file transfers. On average, the fraction of successful file transfers is 25% less than the fraction of nodes that can communicate with the wired network. On the other hand, the fraction of successful file transfers is only 15% less than the fraction of nodes that can communicate with the wired network without mobile nodes acting as relays.

Thus, it seems that the availability of mobile nodes acting as relays does not improve the performance of short file transfers as much as might be suspected by considering the coverage. Next we further investigate the impact of mobile nodes acting as relays. Figure 6 shows the number of hops over links where at least one end has a mobile node. Since all end-hosts are mobile nodes, all routes have at least one hop where one node is a mobile node. However, Figure 6 shows that some routes have more than one hop where one end is a mobile node. These extra hops are over links between two mobile nodes (i.e., mobile-to-mobile links). As expected, in scenarios where the coverage is poor, connections require more mobile-to-mobile links. However, Figure 6 also shows that even in cases where the infrastructure is so dense that no mobile hops are needed (e.g., outdoor nodes in scenario 1-6), routes may still have a number of mobile-to-mobile links.

A drawback of employing mobile nodes as relays is that the nodes may move and a new route will be required. Figure 7 shows the average number of route failures that occurred during file transfers. Visual inspection of Figures 6

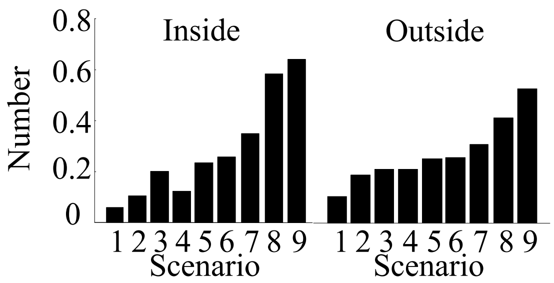

Figure 7: Average number of route changes

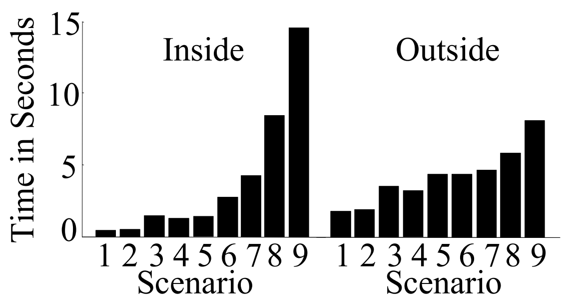

Figure 8: Time taken to establish route

and 7 indicate a strong correlation between the fraction of routes that use at least one mobile-to-mobile links and the number of route failures. Indeed, the correlation coefficient was found to be -0.81.

Thus, utilizing mobile-to-mobile links increases the probability of experiencing a route failure. One drawback of route changes is that packets are often lost when routes break. In these simulations, the only packet losses observed were due to route failures. Another problem with route errors is that it may take a significant amount of time to find a new route. Figure 8 shows the average time required to find a route in each scenario. Again, coverage is closely related to this metric. However, significant differences between indoor nodes and outdoor nodes are apparent.

5.2 Voice-over-IP

The second application examined is voice-over-IP. Today, handheld voice-over-IP mobile phones are available. Ubiquitous Internet access could provide low cost mobile phone service, provided, of course, that the quality is sufficiently high. A challenging aspect of VoIP is that while the quality only slightly decays with a few lost packets, high loss probability results in unacceptable quality. Extensive work has examined the conditions under which the quality is sufficient to support for voice communication (e.g., see [13] and the references therein). When considering the quality for VoIP, the relevant metric is the mean opinion score (MOS); a MOS value less than 3.6 indicates that the call quality is not acceptable to most people. While the MOS is a subjective measure, studies have provided relationships between MOS and delay and loss probability. Following the techniques developed in [13], this investigation uses the Emodel under the assumption that losses are bursty and that the G.711 standard is used. Once a route is found, the end-to-end delay is small and does not impact the MOS. However, significant delay results from the initial route search and any subsequent route searches that result from broken routes. Such momentary delays are not included into the Emodel. Here, a one time delay of up to 5 seconds is allowed for call set-up or route repair. Thus, if either the MOS drops below 3.6 or a delay of above 5 seconds is experienced the call is marked as unacceptable.

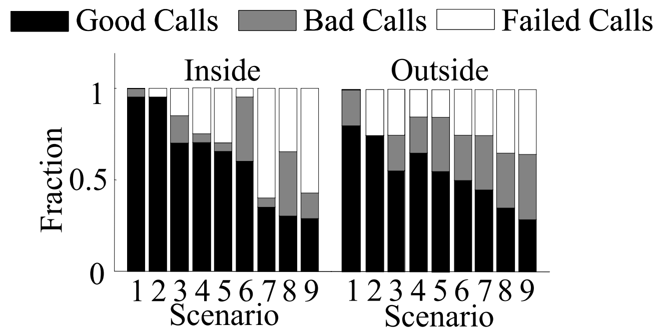

Figure 9: Performance of VoIP indicating the fraction of good, bad and failed calls.

While it is possible that two mobile nodes may call each other, this experiment focused on the case the caller or callee is a wired host. It is also assumed that call durations are exponentially distributed with mean of 100 sec.

Figure 9 shows the fraction of the total calls that were either good quality (i.e., MOS $\geq$ 3.6 and delay always less than 5 seconds), bad quality (MOS<3.6 or delay greater 5 seconds), or failed to be successfully initiated before a 10 seconds time limit. As in the case of file transfer, better coverage leads to an increase in the quality of calls. However, even when the stations are closer than 150 m, the fraction of good calls is significantly smaller than the fraction of nodes able to communicate with the wired part of the network. This is especially the case when outside nodes are considered. Figure 9 also shows that once the infrastructure nodes are spaced less than 150 m. apart, nodes that are inside receive better quality of service than outside nodes. The reason for the poor performance experienced by outdoor nodes is that the mobility of the nodes leads to route failure, which can cause packet loss, excessive delay, or both. On the other hand, nodes that are inside are more likely to be stationary and hence, route failure occurs less frequently.

5.3 Music Streaming

Ubiquitous multimedia streaming is another possible application for urban mesh networks. Unlike VoIP, music streaming is able to handle relatively long outages during which no data is received. The maximum duration of an outage that is not noticeable to the user depends on the size of the receiver buffer and on the stream bit-rate. On the other hand, while VoIP calls may be quite short, music streaming is typically much longer, making them more vulnerable to extended outages. Thus, the performance of VoIP and music streaming, while related, are not exactly the same. Another difference between VoIP and music streaming is that music streaming requires high bit-rate communication.

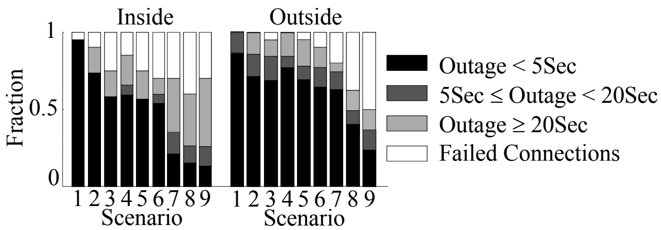

Figure 10: Fraction of connections undergoing outages

Here we consider music streaming connections that last an average of four minutes[1] and use the duration of the longest outage as a metric for the connection.

Figure 10 shows the performance of music streaming in different scenarios. As opposed to VoIP and like file transfer, nodes outdoors receive better quality of service than nodes inside. This is due to the better coverage outside. Assuming that the receiver buffer is large enough, the mobility of nodes and resulting route errors do not impact the performance since new routes can be found before the receiver buffer empties. It should be noted that in many cases, the fraction of connections that have outages that last longer than 5 seconds, but less than 20 seconds is rather small. Thus, it appears that increasing the size of the receiver buffer from 5 seconds to 20 seconds will not provide significantly better performance.

Figure 10 also shows that a significant fraction of connections experience outages that last longer than 20 seconds. While some data is successfully received over these connections, many of these connections failed to deliver a majority of their data. Hence, from the application performance perspective, these connections should be counted as failed connections. The connections marked as failed in Figure 10 are those that failed to send any packets.

6. DISCUSSION

The above results indicated some of the challenges facing ubiquitous Internet access via mesh networks. For example, at the infrastructure densities planned for Philadelphia, the applications considered here will not work most of the time. This contrasts the coverage, which indicates that most outdoor nodes will be able to communicate with the wired network. It also contrasts the bit-rate plots in Figure 4.

It is our opinion that acceptable application performance less than 75% of the time will not be acceptable to most users. Thus, when the typical user is considered, the acceptable performance will only be achieved if infrastructure densities of 50 m between stations are deployed. Such a deployment is approximately 35 times denser than what is currently planned by Philadelphia.

When comparing the performance of different applications, file transfer provides the best performance. This is expected since today's file transfer protocols are robust to extended outages and moderately high packet loss. Indeed, we see that if infrastructure densities of 150 m between stations are used, nearly 90% of connections will succeed when users are outdoors. However, indoor users will not receive reliable performance unless densities are above 75 m between stations.

This poor performance is partly due to the poor coverage that such mesh networks provide in urban areas where propagation of wireless signal is impeded by numerous buildings. However, the difficulties are not entirely due to propagation. For example, if mobile nodes are allowed to act as relays, then 300 m between base stations results in coverage of nearly 85% of outdoor nodes. However, such a deployment scenario does not provide adequate application performance to 85% of the outdoor nodes. While more work is required to fully understand why coverage exceeds application performance, routing is a possible cause. While these simulations used a slightly modified version of AODV to accommodate the wired part of the network, more research is required to develop protocols that are able to provide application performance that meets the bounds imposed by coverage.

It is also possible to improve performance of physical layer algorithms to expand coverage. For example, directional antenna, MIMO, and cooperative networking are all a promise to increase coverage. Future work will investigate performance under these advanced physical layer schemes.

7. CONCLUSIONS AND FUTURE WORK

Utilizing advanced simulation tools and mobility models, realistic performance evaluation of urban mesh networks was conducted. First, the performance in terms of coverage was investigated. It was found that infrastructure densities currently proposed for cities such as Philadelphia will provide adequate coverage to nodes that are outdoors. However, coverage to indoor nodes requires significantly higher infrastructure densities. Second, the performance of applications was investigated. It was found that the fraction of nodes that experience acceptable performance is lower than the fraction of nodes that are able to communicate with the wired infrastructure. In general, it was found that infrastructure densities proposed for urban mesh networks will not provide acceptable performance, even in the limited case of outdoor nodes.

The results presented here justify further work into the development of protocols for mesh networks and examining the performance of mesh networks. Furthermore, the impact of recently developed multi-antenna physical layer algorithms needs to be understood. The investigation presented here did not examine in detail the impact of congestion on the performance of applications. Further work is required to assess the capacity of urban mesh networks. Finally the impact of the node density on the performance of these mesh networks need to studied when non-infrastructure nodes are allowed to act as intermediate hosts or routers.

Disclaimer

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U. S. Government.

9[1] While music streaming connections may have a longer average duration than what is assumed here, the average duration of a walking trip outside is four minutes. Since connections to outdoor nodes end once they return inside, the average music streaming duration was also four minutes. The duration for nodes that are inside was selected to match that of outdoor nodes.

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