MANET performance in urban environments

Abstract

This paper investigates the affect of pathloss and mobility in an urban environment on MANETs. Specifically, this investigation employs mobility and pathloss that resembles the mobility of pedestrians and pathloss in urban environments. We study the behavior of MANETs on a university campus and in the Paddington area of London England. The model utilizes ray tracing to provide realistic radio wave propagation. A constrained random waypoint mobility is used where mobile nodes move from building to building (along sidewalks and through hallways) and then remain in a randomly selected office for a random pause time. The behavior of MANETs in these environments is compared to the behavior provided by the popular random waypoint and free-space models. Several observations are made. These include that the random waypoint/free-space model greatly over estimates the connectivity of a network in an urban environment. Also, it is shown that the distribution of the degree of a node (i.e., the number nodes that a node can directly communicate with) in the urban environment is bimodal and that there are more nodes with large degree as well as more nodes with smaller degree than predicted by free-space pathloss. The dynamics of links is investigated and it is shown that the heterogeneity of the urban environment produces complicated behavior. Lastly, the behavior of DSR in the free-space and urban environments is compared. It is shown that the urban environment is significantly different from the free-space model.

1 introduction

By providing connectivity to mobile users, mobile ad hoc networks (MANETs) are foreseen to be a major extension to the Internet. However, as is well-known, MANETs make use of wireless links that are prone to failure and transmission errors. Furthermore, the mobility of the nodes exasperates the volatility of links. There has been a huge amount of research focused on providing data communication in such environments. The vast majority of this research utilizes simulations to verify claims. Today's simulators provide a large set of the many protocols that have been developed for wireless networking. However, these simulators do not provide a good model of the behavior of the communication links. This is especially the case when communication is in an urban environment.

To the radio waves used in MANETs, walls of buildings reflect most of the energy and allow a small amount of energy to pass through the wall. Thus, to a radio wave, an urban environment is akin to a city built of mirrors[1]. The parts of the city that an transmitter "illuminates" depends on the exact locations of buildings, cars, and other objects. As will be discussed, the presence of buildings can simultaneously limited and expand the transmission range. Furthermore, a slightly movement of a transmitter can greatly alter the ares of the city illuminated. The result is that in urban environments, links between mobile nodes and therefore the topology is volatile.

Clearly, such an environment is different from the free-space models that is typical in MANET research. But it is not known how different free-space and the urban environments are and what these differences imply for the behavior of MANETs. This paper utilizes a set of simulation tools that are compatible with Qualnet and provide a means of building models of cities, generating mobility of nodes in these cities and then determining the pathloss between any two nodes. Pathloss is the degree to which the transmitted signal is attenuted before reaching the receiver. Specifically, this tool uses ray-tracing to determine the pathloss between two nodes and utilizes a constrained random way-point mobility. With this set of tools we compare

[1] Since some energy does pass through walls, it is more accurate say that the city is built of mirrors used in, say, mirror sunglasses or "tinted" windows. However, the "tinting" provided by a wall is far stronger than that provided by sunglasses.

the behavior of MANETs in different settings. Specifically, a university campus and the Paddington area of London are considered. Also, the urban mobility and free-space pathloss are compared and finally the traditional random waypoint and free-space pathloss is investigated.

The conclusions are that urban setting is quite different from the traditional free-space/random waypoint model. This paper examines these differences form three perspectives. First the topology is examined. It is found that the free-space model results in a highly connected topology while the urban setting struggles for connectivity. A mobile phone user is well aware of this behavior as there are many "dead" spots. We find that such dead spots also exist in MANETs, and because of the more limited transmission capabilities of 802.11 as compared to mobile phones, we find that even for over 1000 nodes in a relatively small area, the network remains fragmented. The second direction investigated is the dynamics of topology. In [1], [2] it is suggested that the behavior of links has an important bearing on the performance of MANETs. We find that the links in such urban environments behave quite differently from those in the free-space environments. Furthermore, the dynamics of these links are quite complicated but could be exploited and can produce better performing networks. Finally, network simulations are performed. Specifically, the performance of DSR routing is considered. It is found that the urban environment is quite different from the free-space. These difference are not all bad, but clearly different.

The remainder of the paper proceeds as follows. First we briefly review the basic elements of the simulator and compared it to other simulators. This discussion if divided into two parts, the pathloss model is presented first and is followed by the urban mobility model. Section 3 discusses the simulations performed. Then the three afore mentioned topics are discussed, the urban MANET topology (Section 4), link dynamics in urban environments (Section 5), the performance of DSR in urban environments (Section 6). Concluding remarks follow in Section 7.

2 urban environment simulator

In an urban setting the pathloss is highly volatile and leads to rapid changes in the topology. Furthermore, in the urban environment, buildings and roads play role in the mobility. Thus random waypoint with free-space pathloss is not appropriate. In this section these two aspects of an urban model for MANETs are presented.

There has been some previous work on more realistic pathloss models in urban areas. In [3] and more recently in [4], MANET simulations included some consideration of propagation in the presence of obstacles. The idea in those papers was to model buildings not as reflective, but as perfect absorbing obstacles. In [4] this model is called obstruction cone. Of course, in reality, walls reflect the signal. Figure 8 gives some indication of the problems with such obstruction cone techniques.

2.1 urban pathloss

The large majority of MANET simulations use a free-space model to model the behavior of a wireless link. Specifically, it is assumed that the power of the received signal, P_R, is

$$P_r = K \frac{1}{d^r} P_T,$$

where K is a constant that depends on the antennas, the signal wavelength, etc., P_T is the transmitted power, d is the distance between the transmitter and the receiver and r is the *attenuation exponent*. The expression $K\frac{1}{d^r}$ is the *pathloss* and represents the amount that the transmitted signal is attenuated before reaching the reciever. It is often stated that r is between 1.7 and 4. In a real free-space (i.e., no obstacles or objectives for the signal to reflect off of), $r = 2$. It is popular to take $r = 4$ when a ground reflection is considered. However, this should not be done in most MANETs as this effect only comes into play at distances greater than 500m, a range beyond today's 802.11a/b/g technology. While $r = 4$ models a ground reflection, other reflections can be modeled with other exponents. For example, radio waves bounce down a hallway and down city blocks to produce a wave guide effect (consider a light at the end of a mirrored hallway). Such wave guide effects are modeled with $r < 2$. Wave guide effects are prevalent in urban areas [5],

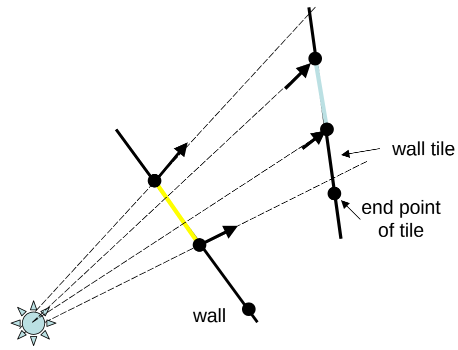


Figure 1: Beam Tracing. Suppose that the (yellow) tile on the lower left has been determined to have been hit by the beam. In particular, this beam hits the end points such that the reflected rays are as shown. From these rays, the virtual source, shown in the lower right is found. The angle at which the beam hits the end points of the (blue) tile in the upper right is found as shown. These rays as translated into reflected rays according to Snell's Law and the process continues.

[6] and results in extending the range of communication along such guides. In the case of random obstacles, a simple model is to take $r > 2$. There are various rules of thumbs that can be used to determine the value.

A more sophisticated approach is to use a fading model. In this case the received power is

$$P_r = HKP_T \frac{1}{d^r},$$

where term H is a random variable that models the effect of time-varying reflections. It is common to model H as a Rayliegh or Rician random variable. However, these models are strictly for narrow band communication such as some cell phones. Such technology is rarely used to data communication and is not appropriate if 802.11 is assumed.

In wideband communication a most reasonable approach to modeling the received signal power is to take H as a long-normal random variable. It has been shown through extensive measurement that the pathloss between two randomly selected locations follows a log-normal distribution (other distributions have also been suggested) [7], [8]. While this model is useful for communication theorist, it is not appropriate for MANET simulation. The problem is that the log-normal distribution is for two randomly selected points. Thus, for every packet sent, the log-normal model assumes that the nodes are at new random points. Since the mobility is a key criteria of MANETs, it makes no sense that the mobile nodes jump randomly between *any* location.

While communication theorists employ various fading models, it is well-known that ray-tracing provides the most realistic model of the communication channel. Thinking of a transmitter as a light source, ray tracing considers each ray emanating from the transmitter and tracks these rays as they bounce from wall to wall and as they past through walls. Such techniques are so accurate that they are sold commercially for the planning of mobile phone networks and wireless LANs. However, accuracy is not the goal of the simulator utilized in this paper, rather the focus is on a realistic model.

The details of the simulator can be found in [9]. However, a brief mention is included for completeness. Strictly speaking, the simulator does not use ray-tracing, but used a related approach known as beam tracing [10]. Thus, instead of following single rays, beams of radio waves are followed. Furthermore, walls are divided into tiles, the beam tracing is performed from tile to tile. Figure 1 depicts the beam tracing.

Beam tracing is useful for outside, but within a building, beam tracing is computationally difficult. Thus we employ an *attenuation factor (AF) model* [11]. In [11], such models are reported to provide loss within 4dB when compared to the actual loss in the building that is modeled.

The beam tracing is for outside and the AF model is for inside. Between inside and outside, the signal propagation is model as follows. When a beam strikes a wall, some of the signal penetrates into the building after suffering around 13dB of loss [11]. The propagation through the building is modeled using beam tracing and the AF model. It is assumed that only the edge walls of the building reflect the signal. From the point of entry into the building, to the point where the signal strikes another edge wall of the building, the signal suffers a loss given by AF model. Similarly, if a beam reaches a destination within the building, the loss from the point of entry to the receiver follows the AF model. It should be noted that in many cases, due to the loss of power as a signal passes through a building, the reflections within a building have a minor effect of the received signal strength.

2.2 urban mobility

Mobility of nodes was been well studied in the "open" environment. For example, ray way-point is extensively used. Indeed, there have been theoretical investigations of the topology resulting from random way-point have been performed. Closely related models have also been developed. For example, Brownian Motion has been used as has the Random Gauss-Markov model [ref]. While these models are simple to simulate, they do not have any relation to specific scenarios. Rather, the hope is that these mobility models provide enough randomness that a protocol that performs well under these models will perform well under more realistic motion.

Others have taken a different approach in that more specific scenarios have been developed. For example, group mobility [12] and scenario based models [3] have been utilized.

Another class of models are those that restrict nodes to a graph. Like the random way-point, these graph based random way-point models select a vertex of the graph and constrain the mobile node to move along the arcs of the graph to the selected vertex. Such models include the Manhattan mobility model [13] where nodes are restricted to a lattice. The City Section model is similar to Manhattan [13], but uses random way-point and restricts the speed of the nodes to resemble model traffic moving along city streets. Another graph-based random way-point model is presented in [4]., where the graph was defined by a Voronoi diagram of obstacles. This graph was further extended to include the vertices of the center point of the obstructions and arcs that emanate from the center of the obstruction to the arcs of the Voronoi diagram.

The urban environment restricts the possible types of mobility utilized. For example, it is not reasonable to used random way-point so that nodes are passing through buildings in random locations. Rather, we employ a graph-based random way-point approach. Here a mobile node selects a destination office. The node is constrained to follow the arcs of the graph which represent hallways and sidewalks (see Figure 2). Like the random way-point, upon reaching the destination, the node selects a deterministic or random pause time before selecting the next destination. Furthermore, the nodes select a random speed. In this investigation, the focus was on pedestrian mobility, the speed as was uniformly distributed random variable between 1.7 and 4.1 mph, the typical walking speed. The same buildings that the office reside are used in the pathloss computations. While the layout of the buildings and the roads are similar to the areas modeled (in particular, Paddington and the university), the interior of the buildings is composed of a randomly generated offices. The details of the model are presented [9].

3 simulations

Several types of simulations are presented. The urban simulations use the urban pathloss model and urban mobility model just described. Two urban areas are investigated. These areas are shown in Figure 3. As indicated, the left-hand urban area is a model of the Paddington area in London. This is a tightly packed urban area and provides a good contrast to the University shown in the left. In comparison to Paddington, the University consists of large open areas and large buildings. The images follow different scales, the University covers nearly twice the area as Paddington. These and other cities are available for download as is the tool for constructing the cities. While the simulation packet allows the simulation of cars and aerial vehicles, this paper focuses only on pedestrian networks. Mixed node types with different types of mobility and different transmit and receiver capabilities is opens a large number of areas of investigation that will be reserved for future work.

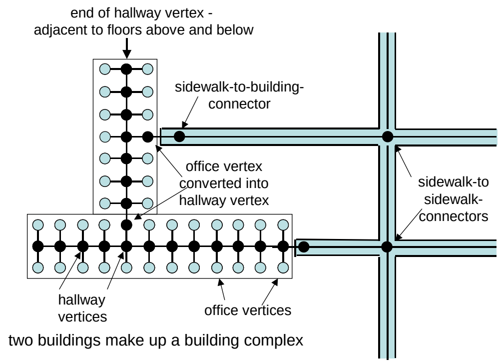


Figure 2: A Building Complex and Sidewalk. The buildings are the large rectangular boxes. Inside the buildings are vertices that represent either offices (pale blue) or hallways (black). Outside of the buildings are sidewalks that connect the buildings together.

Beyond the urban environment, other types of simulations are also presented. Specifically, random waypoint with free-space pathloss and urban mobility with free-space pathloss. As will be discussed, the mixing of free-space pathloss models and urban pathloss is a bit tricky and can easily lead to absurd comparisons. Thus it is necessary to reduce the sensitivity of the receiver. Most of the simulations that involve free-space pathloss use the reduced sensitivity. Besides this reduction in sensitivity, the free-space pathloss model follows the default parameters of Qualnet. The urban pathloss is accommodated with minor changes in Qualnet, the details are available on the web site of urban mobility and pathloss model. The name and location of the simulator will remain anonymous for the review.

The random waypoint model uses mobility speeds that match the urban speeds, specifically, uniformly distributed between 1.7MPH and 4.1MPH, typical walking speeds.

4 urban MANET topologies

In this section the topology of a MANET in an urban environment is investigated and compared to the topology that results from a free-space model for pathloss.

Perhaps the most fundamental characteristic of a graph is whether it is connected or not. In most investigations of MANETs, it is assumed that the network is connected. This assumption typically holds true for the models used; specifically, free-space pathloss with a high enough density of nodes. However, in the case of MANETs in urban areas, we find that this basic assumption rarely holds. To see this intuitively, consider of a mobile phone network. While mobile phones base stations transmit with very high power (up to hundreds or even thousands of Watts) and have very high gain antenna, there are places where there is no connectivity. For example, one will find that in particular locations of a building or in an alley-way between buildings, there is no connectivity.

To quantify connectivity, the fraction of nodes in the largest connected subgraph is considered. Others have used the probability of the graph being connected. We have found such a metric to be misleading since a single disconnect node out of a very large number of connected nodes is counted the same as a network where every node is isolated. Furthermore, considering the mobile phone network, if there are few "dead" areas, then the fraction of nodes that lie outside of these areas will be large. When calculating this metric, the nodes are dispersed according to the mobility model. Thus, if the mobility model stipulates that many nodes are frequently in areas of good connectivity, then this metric will be large.

The left-hand figure of Figure 4 shows how this metric varies for different *normalized receiver sensitivities.*

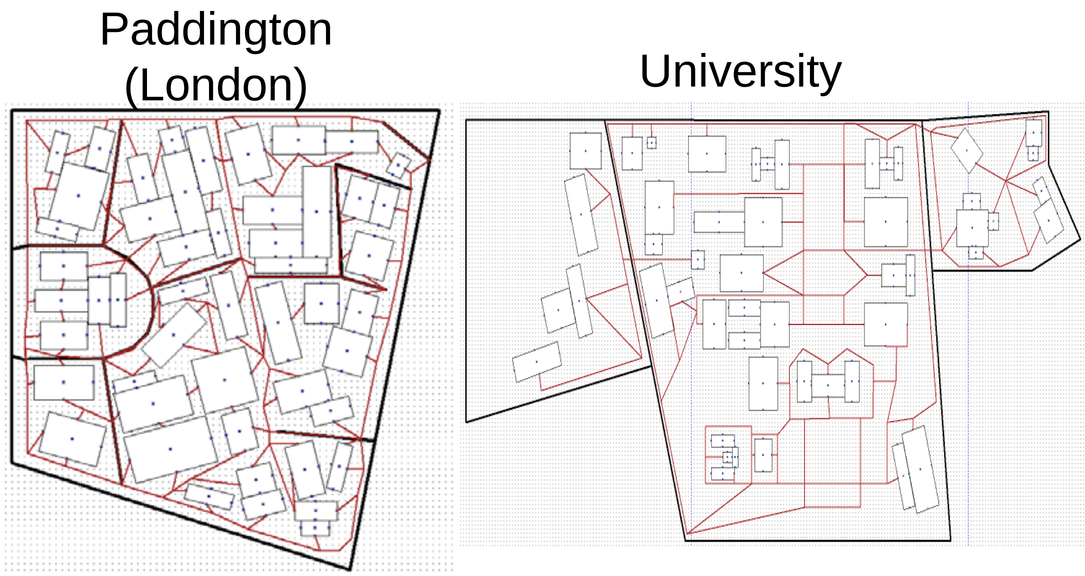


Figure 3: Cities used for Simulation.

By normalized sensitivity we mean that the threshold for receiving a packet is

$$10 \log_{10} \left(\frac{1}{d^2} \right) < \text{Sensitivity}^*.$$

Of course, if this condition is true, there is still the possibility of bit-error[2]. In Qualnet, the default value of Sensitivity* is 56. The dotted lines in Figure 4 shows fraction of nodes in the largest connected subgraph for 40, 128, and 512 nodes in the population and various values of Sensitivity* when the urban model and its associated pathloss is considered The solid lines show the same quantities but assuming free-space pathloss model. The difference between the free-space model and urban pathloss model is obvious; the free-space model indicates that the graph is completely connected for very small values of Sensitivity*. This plot alone indicates that no further comparisons between this two models are reasonable as the free-space pathloss is far more connected. Any further comparisons will simply provide different manifestations of this difference in connectivity. This difference in connectivity should not be understated. It shows that for when even a small number of nodes are present, the free-space model indicates that data communication is possible. However, if the environment is urban, then such conclusions are false.

Considering this problem with connectivity, we attempt to rectify the situation by greatly reducing the Sensitivity* of the free-space model and carry on the comparisons. In order to make the comparisons fair, we hand tuned the Sensitivity* as follows. The Sensitivity* of the urban pathloss model is fixed at 56, the default value in Qualnet (we have found that other values yield qualitatively the same results). Then, considering the fraction of nodes in the largest connected subgraph, we select the Sensitivity* for the free-space model so that for a particular number of nodes in the total population, the fraction of nodes in the largest connected subgraph matches the fraction that results when the same total population is used with urban pathloss. The left-hand plot in Figure 4 includes thin lines that show how these Sensitivity* are determined. Specifically, following values were used.

# node	Sensitivity* for University	Sensitivity* for Paddington
40	39.9	34.1
128	35.5	32.6
512	34.3	29.4

[2] These simulations use Qualnet's default relatiionship for bit-error and receiver signal strength.

Note that the different environments, University and Paddington, required different values of Sensitivity*.

While these values of Sensitivity* can be used for better comparison between the free-space model and the urban pathloss model, the left-hand of Figure 4 shows some other difference beyond the value of the curves. specifically, we see that the slope of the free-space model curves are far steeper than the one generate by the urban path-loss. This lead to the problem of how one might determine these hand selected values of Sensitivity* if the free-space model is used without the urban path-loss model. For example, one approach might be to perform a large number of simulations with various values of Sensitivity*. In this way, one can hope that a simulation with a value of Sensitivity* that matches the urban path-loss is covered. However, the steepness of this curve shows that a fine gridding of the Sensitivity* is necessary. For example, in the topologies explored here, step of 3dB are too large. Nonetheless, we still consider the utility of free-space simulations with the Sensitivity* indicated.

Another look at the difference in connectivity is provided by Figure 5 where the relationship of fraction of nodes in the largest connected subgraph and the number of nodes in the population is explored. This figures show that the urban pathloss is better connected for small numbers of nodes, but less connected for larger populations. Note that even for 1000 nodes, the topology is still not connected, with typically more than 200 nodes not part of the largest connected subgraph. While not shown, it was found that the nodes not in the largest cluster where not connected in a second largest cluster, but mostly isolated or perhaps member of small clusters. These nodes and clusters typically resided in buildings.

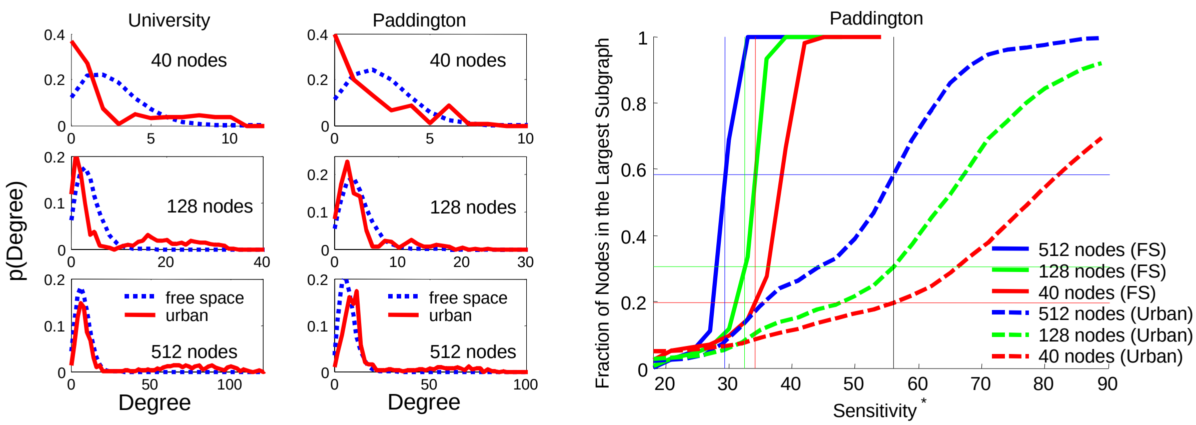
Figure 5 shows that a slight variation in the number of nodes (say from a power saving "sleep" mode) will affect the free-space topology far more significantly than the urban pathloss case.

The right-hand of Figure 4 shows the degree distribution (histogram) for the different scenarios. Note that in each case, the values of Sensitivity* given in the table above are used. These distributions indicate the heterogeneity that results when an urban path-loss is used. It is not hard to show that if the nodes are uniformly distributed and a free space path-loss is utilized, then the degree distribution is Poisson and tends to Gaussian as the number of nodes in the population increases. Here the nodes are not uniformly distributed, but it can be seen that if the free-space path-loss is used, and if as the number of nodes is increased (but the Sensitivity* is also decreased), the degree distribution appears to tend towards Gaussian. On the other hand, the degree distribution resulting from the urban path-loss model, does not appear to tends toward Gaussian. Rather, it can be seen that the degree of nodes in the urban setting is both higher and lower. For example, in 40 node case on the University environment, there are more nodes with a smaller degree than the free-space model predicts and there are more nodes with a larger degree. In the case of 512 nodes, the University environment, a budge in the distribution can be seen indicating a significant number of node having very large degree (over 100), while the free-space model predicts that the degree of a node is never more than 25. The impact of these high degree nodes is yet to be fully understood. However, in general such nodes act to reduce the diameter of the graph. For example, in graphs such as the routers of the Internet and the WWW the high degree nodes are known to play an important role. Specifically, the high degree nodes are considered to comprise a highly connected core, while the edges are the weakly tendrils. It appears that such a model is appropriate when an urban pathloss is used. It is easy to see how such a model arises. Roads and open areas provide high connectivity with line-of-sight or perhaps wave-guide effect. Nodes in these areas make up the connected core. The path-loss into and within a building is very high. The nodes within a building have low degree and make up the weakly connected tendrils.

The implication of such a model on routing and interference remains to be understood.

5 link dynamics in urban environments

The dynamics of links has not attracted much attention. However, several routing mechanism attempt to estimate link stability in order to exclude routes that are likely to break. For example, [14] and [15] suggested incorporating signal strength into routing decisions, while [16] suggests using the age of the link (the time the link has been active). Several methods advocate using GPS to discern proximity as well as relative velocity [17], [18], [19]. Gerharz et al. [20] study the stability of links in under different types of mobility (specifically,



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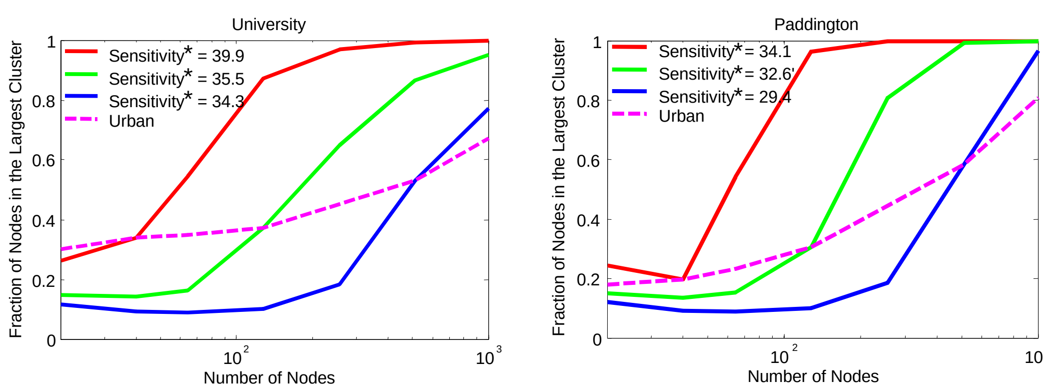

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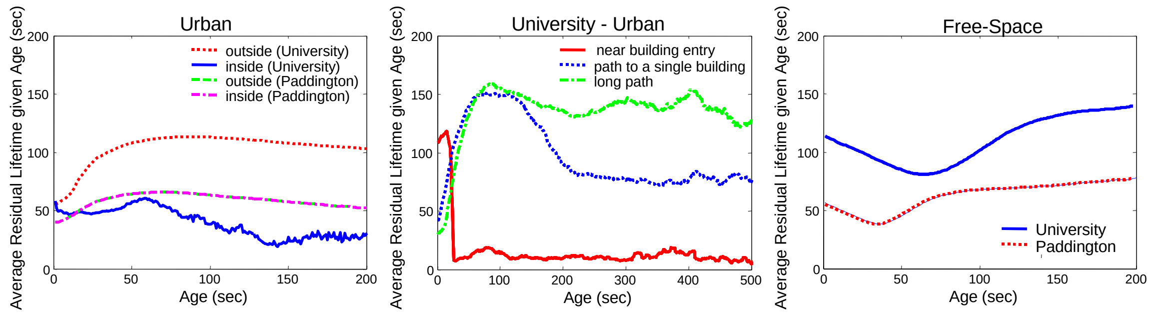

Figure 6:

Random Waypoint, Manhattan, Gauss-Markov). More recently, it was shown how the dynamics of links and paths plays a key role in the performance of routing protocols [1], [2].

In this section we compare various aspects of the dynamics of links. Specifically, we examine the conditional expectation of the residual lifetime. Figure 6 shows the expect residual lifetime conditioned on the age and, in some cases, on some position information. These simulations used 40 nodes and the free-space Sensitivity* is given in the table in Section 4. By residual lifetime, we mean the remaining life of the link. The expected lifetime given the age is a useful way to understand the distribution of the lifetime process. For example, if the conditional expectation of the residual lifetime was flat, then the process is memoryless, and hence the lifetime is exponentially distributed. Figure 6 shows that in no case is the lifetime exponentially distributed. However, the left most plot appears to indicate that, once a certain infant death age has surpassed, the residual lifetime tends to exponential. However, the slight decay implies that a Weibull distribution is more appropriate (as it the typical case when considering residual lifetimes [21]). The left most figure shows the lifetime averaged over the entire outside or inside as indicted. The middle figure show a more detailed plot where the residual lifetime is examined at different locations. A very strong dependence on location is clearly scene. These curves are due to the heterogeneity of the environment. Consider the solid red curve denoted by "near building entry." This curve shows long residual lifetime is the link is less than 20 seconds old, but a short remaining lifetime if the link life time is greater than 20 seconds. This behavior is repeated in front of every building entry. to see why this is so consider a node that has just left the building. In the University map, once outside, there are large areas that must be crossed (taking a long time) and allow excellent signal reception. Thus, if a node has just left the building, any link is has just made is a link with another node that is also outside. This link is likely to have a longtime. On the other hand, if a node is in the same location, but its link is older than 25 seconds, thent his node could not have just left the building. Rather, this node is on the sidewalk that leads to the building. Upon entering the building, these old links with nodes outside are likely to be severed. Thus, the residual life of these links is short. The other curves have similar explanations. The right most plot shows the residual lifetimes in the free-space path-loss. This plot is similar to those found in [20] for several different mobility models. Thus, none of these models reflects the behavior found in the urban setting. Furthermore, the homogeneity of the free-space path-loss does not allow for the diverse behavior found in the urban environment. Interestingly, the Paddington environment does not display the same behavior as the University. The reason for this is that Paddington is far more homogeneous than the University. Note that the left most plot show that the behavior inside and outside of buildings is the same in the case of Paddington.

A second view of the difference between the urban path-loss and the free-space path-loss is illustrated in Figure 7. Here we see the residual lifetime conditioned both on the age and the signal strength. As mentioned, some routing protocols attempted to take advantage of the dependence between signal strength and lifetime. these figures show that the behavior in the urban settings, regardless if it is the University or Paddington, behave similarly, while the behavior in the free-space settings behave similarly, but the free-space and the urban setting behave quite differently. For example, the strong and medium signal strengths behave exactly the same in the free-space setting. Thus, the free space setting seem to indicate that routing that

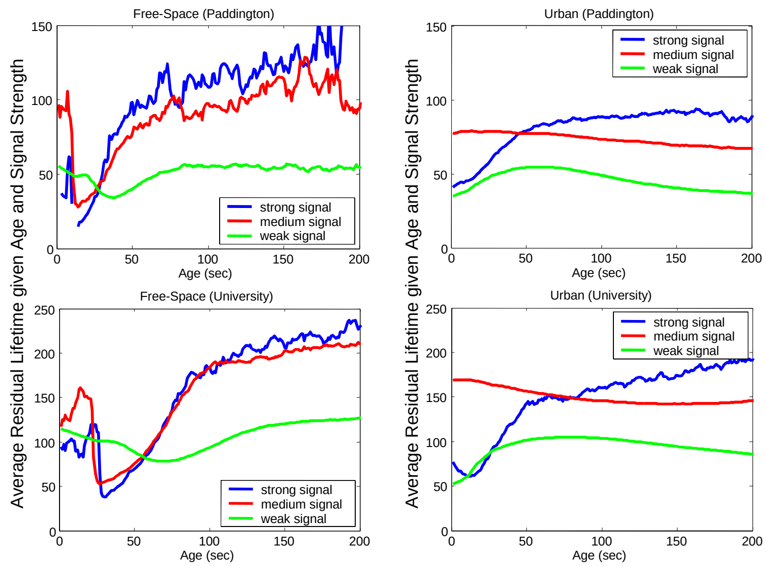

Figure 7:

distinguished between strong signals and medium signals will have no better performance than methods that only distinguish between weak and non-weak signal strength. However, in the urban setting, this conclusion is false with each signal strength having a unique profile.

To gain more insight into the dynamics of the pathloss and the connectivity, consider the sequence of path-loss snap-shots shown in Figure 8. These figures show the signal strength generated by a single transmitter that is on the right side of the modeled area. This tightly packed region models the Paddington area in London. The brighter color indicates a higher signal strength. Communication is possible only if the color is at least The different between the two images is that in transmitted has moved 10 meters. Such a movement takes a pedestrian about ten seconds. Notice the drastic change in the signal propagation. When the node is directly in front of the street, the nodes is able to transmit to the far side of the modeled area. However, when the node moves slightly, such transmissions are not possible. Note that the narrow roads of Paddington provide a wave-guide effect. The free-space path-loss cannot model these wave-guide effects. Note that during the period when the node is able to transmit across the modeled area, this node will provide connectivity to many nodes. Hence, if the area was well populated, this node have a very high degree. Thus it would be a member of the connected core. On the other hand, this node's signal does not penetrate into buildings. However, when the node moves directly in front of a building, it is able to transmit deep into the building and provides a communication to the nodes within the building, i.e., the tendrils. Figure 8 also shows how quickly and drastically the topology can change.

6 performance of DSR in urban environments

While the properties of the topology and the behavior of the links is interesting and likely relevant to the performance of the network, network simulations provide a direct view of the performance of the MANET protocols. While a through study is justified, we restrict the discussion to the performance of DSR [22]. Several situations are considered. Specifically, the urban mobility with urban pathloss, urban mobility with free-space pathloss but with the Sensitivity* adjusted so that the average fraction of nodes in the largest connected subgraph is the same is as it is in the case with urban pathloss. This adjustment is discussed in Section 4. Note that the urban mobility in both cases is exactly the same (same trace files). The experiments also include random waypoint and free-space pathloss, again, with Sensitivity* adjusted to

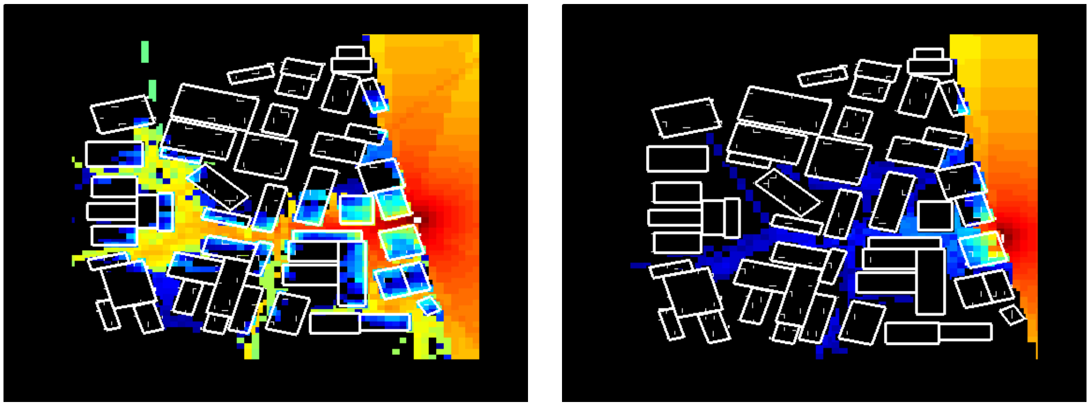

Figure 8:

make the comparison fair. And finally, the experiments included random waypoint and free-space pathloss but with Qualnet's the default Sensitivity*. Recall that the urban pathloss also uses Qualnet's default Sensitivity*.

Figures 9 and 10 show the results from ten trials each 900 seconds long. As mention DSR was employed, however, the *Cache Timeout Value* was varied. All other parameters were left as their default values. The varying of Cache Timeout Value is well studied and provides a useful benchmark for exploring the implications of the urban pathloss and mobility. While many simulations were performed, only the results for the University with 128 nodes environments are shown. The other environments gave the same qualitative results. These simulations represent a wide array of environments so analysis must proceed with care.

The curves marked RT/Urban correspond to the urban pathloss and urban mobility while the curve marked FS/RW2 corresponds to the free-space pathloss model and random waypoint with the default values of Sensitivity*. As mentioned in Section 4, these two environments are quite different, for example in the free-space simulation, the graph is connected whereas in the urban pathloss model, the graph is not connected. The effect of the connectivity is clear from the simulation results. For example, the free-space gives far better performance than the urban pathloss model. Perhaps most notable is the end-to-end delay that is measured in tens of seconds in the case of urban pathloss. while it cannot be determined from the graph, the free-space simulation gives an end-to-end delay of around 100 ms. The reason the delay in the free-space case is so large is that there with 128 nodes, free-space and the default value of the Sensitivity*, the graph is so well connected that there is considerable interference.

The curve marked FS/Urban represents the results with urban mobility discussed in Section 2.2 but free-space pathloss. The curves marker FS/RW depict the results for free-space pathloss and random waypoint. However, in this case the Sensitivity* is set as suggested in Section 4. Note that the urban mobility and pathloss yields more packets delivered and a shorter path length. However, we see that the end-to-end delay is far larger. These three observations are related. Recall the dynamics of links discussed at the end of the pervious section. We saw that when a node moves into a position that is along a road, this node is able to communicate with nodes that are far away. These nodes have a large number of neighbors degree as indicated by the upper tail in the distribution of the degree shown in Figure 4. This connectivity continues while the node remain in such a position. Such nodes are able to act as intermediaries for a large number of pending transfers and are able to complete a large number of transfers. Since these nodes are so well connected, the transfer often takes two hops, as shown in the left most plot of Figure 9. As also shown in Figure 8, these nodes that provides such good connectivity may slightly move and lose connectivity with a large number of nodes. On the other hand, a node can also just as easily move into position and provide good connectivity. Thus, the presence of these nodes is not continuous, but intermittent. The end-to-end delay demonstrates this intermittent nature of the communication.

The simulations that used free-space but with the Sensitivity* is set as suggested in Section 4 have these

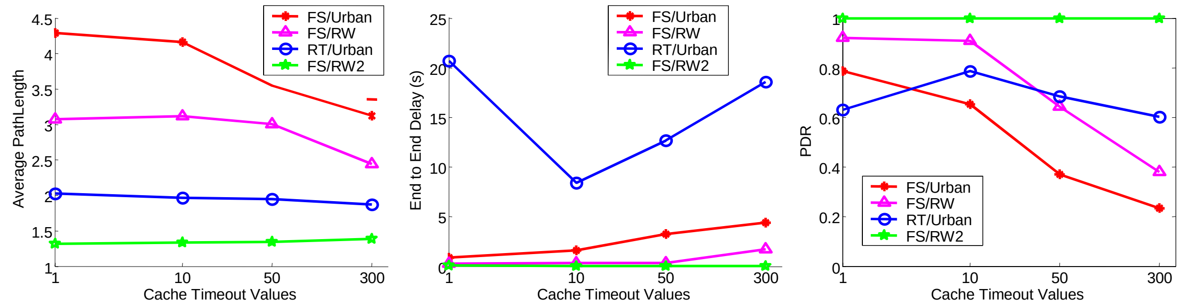

Figure 9: Simulation Results I.

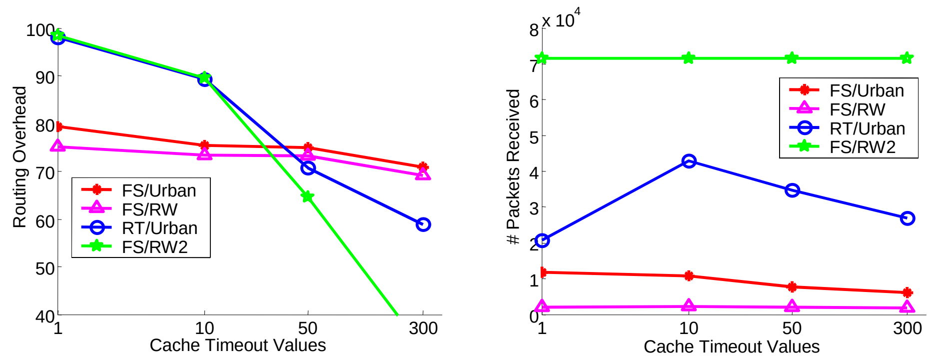

Figure 10: Simulation Results II.

intermittent well connected nodes. Hence these simulations show a smaller delay but fewer packets are delivered. Furthermore, while these two simulations have quite different mobility patterns, the performance is similar. Thus we can conclude that it is the pathloss, not the mobility that plays a major role in the difference between the free-space/random waypoint and the urban mobility/urban pathloss.

7 conclusions

The impact of an urban environment on the performance of MANETs is investigated. Specifically, the results provided by a random waypoint/free-space pathloss model are compared to an urban model that models both mobility and pathloss. It is found that the behavior of MANETs is greatly impacted by this model. For example, the random waypoint/free-space pathloss model indicates that the urban area network would be connected, while the model suited for simulating urban environments indicates that the network is not connected. Furthermore, it is found that the dynamics of the links is quite different and that the performance of DSR is quite different.

Clearly this work is just the tip of the iceberg in the area of MANETs in urban areas. Specifically, since previous work with free-space models provide little insight into the performance of MANETs in these areas, there are many new areas requiring investigation. For example, the discussion in Section 5 indicates that the dynamics of links is quite different in urban areas as oppose to free-space areas. It remains to be scene to what degree MANET routing can accommodate or even take advantage of this behavior.

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