The Graphical Properties of MANETs in Urban Environments

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Abstract

A large portion of MANET research has focused on free-space environments. In this extended abstract, MANETs in urban environments are investigated. Specifically, the graphical properties of the ad hoc topology are investigated. This includes examination of the degree distribution and centrality. The spatial variation of these properties are also investigated. It is found that the graphs for urban MANETs are heterogeneous and far more complex than the ones that arise in a free-space environment.

1 Introduction

Perhaps one of the most difficult challenges of designing network protocols is that networks are heterogeneous. A protocol that performs well in some environments might perform quite poorly in other environments. In the Internet, the environment includes the link speed, the amount and type of competing traffic, as well as the desires of the end user. In MANETs, the situation is even more complex. Not only can the environment vary in the same way as it does in the Internet, but the wireless links and ad hoc topology add a new dimension to the heterogeneity. This new dimension has not been explored, rather it is typically assumed that each node is homogeneous in that it can successfully transmit to nodes within a fixed radius[1]. However, in many realistic settings the wireless link is not homogeneous and a successful transmission in a fixed radius is not possible. The transmission region is heterogeneous and depends on the exact location of the node and the environment.

In mixed indoor and outdoor urban environments, this heterogeneity is extreme. The region of successful transmission does not resemble a disk and rapidly varies with node movement. Figure 1 shows the transmission range in an urban environment with a small displacement of the transmitter. The figure shows how the radio transmission is

[1]When power control is used, the radius is not fixed, when directional antennas are used, the region of transmission is not a disk. However, in both cases, a protocol is responsible for defining the region of successful transmission and it is often assumed that the protocol has unrealistic latitude when selecting a transmission region.

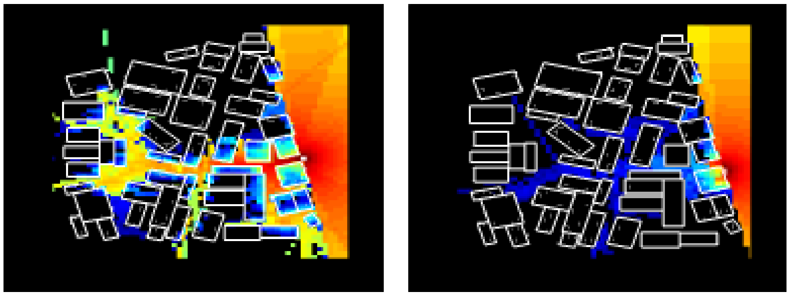

Figure 1. Signal Strength in an Urban Environment. The colors indicate the signal strength from a transmitter on the right-hand side of the modeled area. While the figures show a large variation in coverage, the only difference between the two figures is that the position of the tranmitter has moved 10 meters.

both blocked and reflected by the buildings. Also, it shows the difficulty that radio transmissions have penetrating into buildings. This abstract studies MANETs in urban environments, in particular it focuses on the graph properties of the ad hoc network. This includes an examination of connectivity, the degree distribution, and centrality. Of special interest is the spatial aspects of these properties. It will be shown that there are particular areas where nodes in that area assume certain characteristics. For example, there are areas where nodes in that area will typically have a high degree and other areas where nodes will typically have low degree. These spatial characteristics remain even when the nodes move. It will be seen that the graph from an urban MANET displays far richer properties than the graph produced by the popular free-space/random waypoint model. It is hoped that features of this graph can be exploited to design protocols specially suited for the difficult propagation environment that face an urban MANET.

The abstract is organized as follows. In the next section, some related work is discussed. Section 3 gives a brief explanation of the simulations used. Section 4 begins the analysis of the graph properties of MANETs in urban environments with an examination of the dependence of connectivity on the number of nodes in the population. In Section 5, the duration that a node spends in and out of the largest connected cluster is examined. In Section 6, the degree distribution of nodes is investigated. In Section 7, the distribution of the centrality is found. In Section 8, the spatial aspects of the graph are investigated. Section 9 has concluding remarks.

2 Related work

There has been a considerable amount of work focused on graph theoretic properties of MANETs. However, the vast majority of this work assumes a free-space environment and neglects the effect of realistic path loss [1], [2], [3]. One exception is [4], where the connectivity is found assuming a random shadowing. The idea behind random shadowing is that the path loss between each link is modeled with an independent random variable. However, this random variable depends on the distance between the two nodes, but not on the path loss between other nodes. We have found that there is a strong dependence between path losses and thus such models are not appropriate. For example, consider three nodes, node A, node B and node C. And suppose we seek a probabilistic model for whether node A is connected to node C. A dependence between path losses means that the connectivity between A and C depends on whether node A and B are connected. This dependence can easily be understood by examining Figures 7 or 8. For example, if a node A is in the street, it degree is typically quite high and hence has a high probability of being connected to some other node. On the other hand, if a node is inside a building, then it is less likely to be connected to other nodes. The fact that node A is connected to node B increases the probability that node A is outside and hence increases the probability that node A can communicate with node C. Thus, random path loss models such as Rayleigh fading models are not appropriate when *networks* are considered (they are only good for point to point communication models, as they are typically used).

There has been some previous work on other path loss models for MANETs in urban areas. In [5] and more recently in [6], 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 [6] this model is called obstruction cone. Of course, in reality, walls reflect wireless transmissions.

3 Simulations

Several types of simulations are presented. These simulations use the urban path loss model and urban mobility model described in [7]. Briefly, the path loss is found using ray tracing and the mobility is a graph constrained random waypoint mobility where mobile nodes move from office to office along a graph defined by stairways, hallways and sidewalks. In these simulations, the nodes select the next office destination at random, and the walking speed was uniformly distributed between 1.7MPH and 4.1MPH (typical walking speeds). The pause time at each office was exponentially distributed with a mean of 1000 seconds. Each simulation was run for 5 hours of simulated time. Note that this paper is mostly focused on the properties of the graph. Thus, the main function of the office pause time is to impose a distribution of the nodes. For example, if the pause time was very small, then the nodes would spend most of the time outside, traveling between offices, and if the pause time was very large, the nodes would spend most of the time inside. As will be seen, the density of nodes indoors and outdoors plays a critical role in the structure of the topology.

Figure 2 shows some of the cities investigated. 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 of Delaware shown on the right of Paddington. 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.

4 Connectivity

Connectivity is perhaps the most basic property of a graph. In the case of MANETs in urban environments, the network is often not connected. The reason for lack of connectivity is that an urban area provides many locations that are well shielded from wireless transmissions. Indeed, mobile phone users are well aware that transmissions are not possible everywhere. The connectivity problem does not necessarily change quickly when the size of the population is increased. The reason for this slow variation is that as the node density increases, the probability of a node residing in a very difficult to reach location (from the propagation perspective) increases. For example, nodes in upper floors

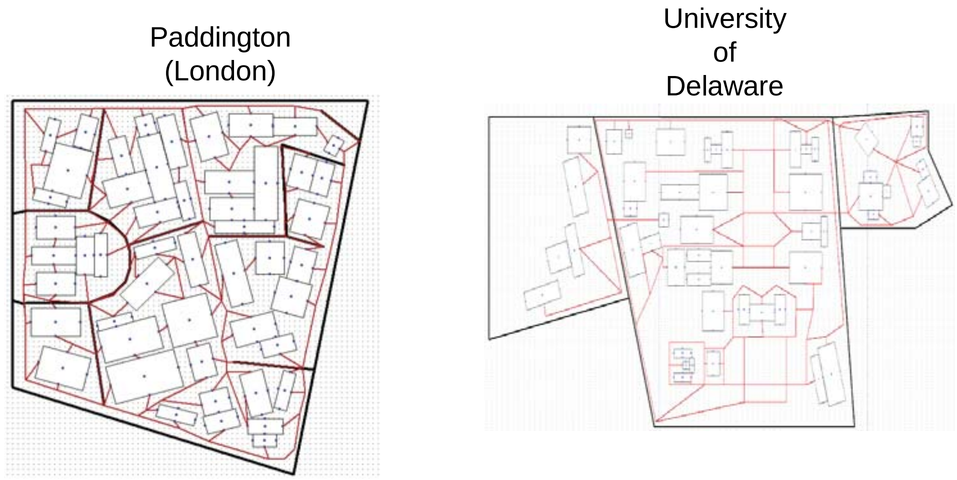

Figure 2. Cities used for Simulation. the rectangles are office buildings with evenly distributed offices and hallways (not shown). Outside sidewalks are shown. The mobile nodes are restricted to sidewalks, offices and hallways.

of corner offices where the corner does not face a popular thoroughfare (e.g. a back alley) are difficult to reach. In order to guarantee connectivity with such locations, there must be a high node density within the building as well as around the building.

Since the graph is so often disconnected, there is little point in measuring how often the graph is disconnected. Rather, we compute the connectivity ratio, which is the ratio of the number of nodes in the largest connected component (LCC) to the number of nodes in the entire population. Figure 3 shows the connectivity ratio as a function of the number of nodes in the population. Note that the connectivity ratio for nodes that are inside refers to the ratio of nodes that are inside and in the LCC to the total number of nodes inside. Here the LCC contains both nodes inside and outside. Similarly, the outside nodes case computes the connectivity ratio with nodes that are outside only and the all nodes case includes both inside and outside nodes. We immediately see that the position of the node plays an important role; nearly all nodes that are outside are in the LCC, while only a small fraction of nodes in buildings are in the LCC. However, as there are more nodes added to the population, the connectivity ratio increases. The figure shows that the rate of this increase depends on environment. Nodes within the large buildings in the University of Delaware campus are more difficult to connect to than the nodes in the smaller and densely packed buildings in Paddington.

5 Duration in and out of the largest connected component

While the main focus of this paper is on the graph properties, the dynamic properties of the nodes and the graph are of interest as well. Here we examine the duration that a node spends in the LCC before leaving, as well as the duration spent outside of the LCC before reentering. Figure 4 shows the complementary distribution of these durations. Two distinct behaviors can be observed in the left-hand figure. In the case of Paddington, the distribution of the time within the LCC only depends weakly on the number of nodes in the population. Furthermore, the figure shows that the node is likely to quickly leave

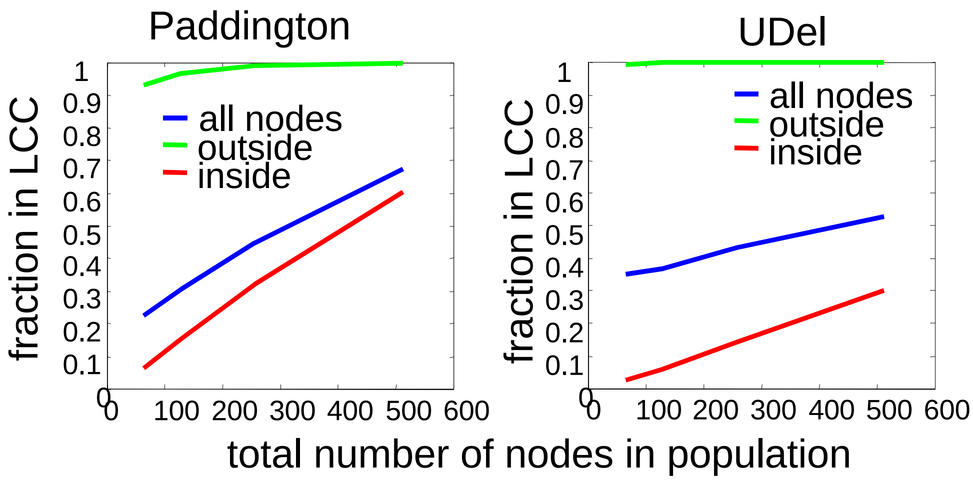

Figure 3. Connectivity Ratio as a Function of the Number of Node in the Population. The upper curve show the connectivity ratio for just the nodes that are outside, the lower curve is of nodes inside buildings and the middle curve is for all nodes (both inside and outside).

the LCC (within the first 50 seconds), but as can be detected by observing the "flatness" of the distribution, if it last longer than 50 seconds, it will likely remain for some time (i.e., the duration suffers from infant mortality). The longer the node stays in the LCC, the more the population size matter, with the largest population leading to the longest lifetime. On the other hand, in the case of the University of Delaware, the distribution strongly depends on the size of the population with the smallest population enjoying the longest durations in the LCC. In the case of large populations on the university campus, the duration in the LCC suffers from a high infant mortality rate. The duration out of the LCC is quite different with both environments showing similar behavior and the larger the population, the shorter the time out of the LCC. 64 nodes on campus has a longest duration not in the LCC and the longest duration in the LCC. 256 nodes in Paddington have the shortest duration not in the LCC and the shortest duration in the LCC. Note that the duration not in the LCC is so short that the nodes, on average, send a significant amount of time in the LCC. This exiting and reentering of the LCC bodes poorly for MANET performance since a node not in the LCC will not be able to receive messages until it returns.

Note that in all cases the probability decays exponentially. This can be easily seen by the "straight line" of the semilog plot. Analysis shows that these durations can be modeled as a mixture of two exponential, one exponential for the initial infant mortality and one exponential for longer lifetimes.

6 Degree distribution of nodes in an Urban MANET

It is well known in wired networks that the degree distribution plays an important role in the topology. Specifically, nodes with large degree often play an important role in forwarding packets. Also, nodes with a large degree are likely to be well connected to the other nodes. Figure 5 shows the degree distribution for the two different urban environments and different population sizes. Here a degree of one implies that the node can only communicate with itself. Again, there is an obvious difference between nodes that are inside and those that are outside; the degree of outside nodes is much higher.

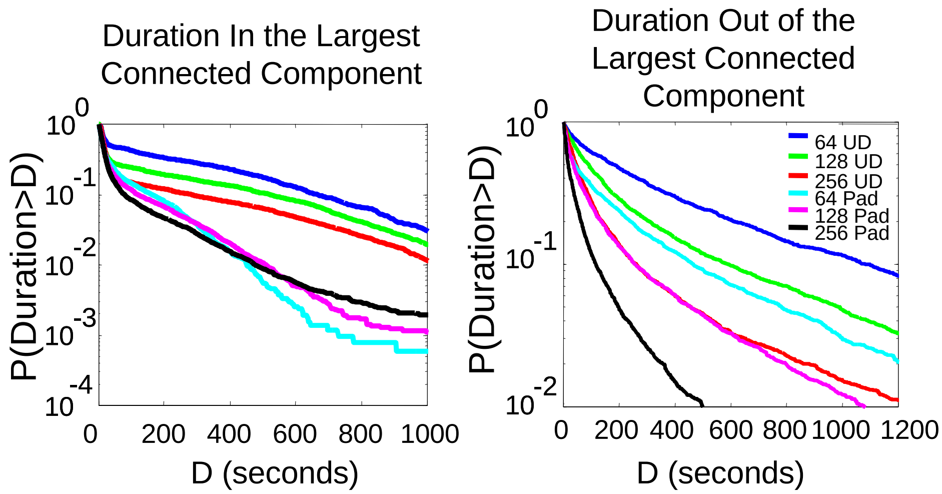

Figure 4. Left-hand figure. The Complimentary Distribution of the Duration that a Node Spends in the LCC. Right-hand figure. The Complimentary Distribution of the Duration that a Node Spends out of the LCC.

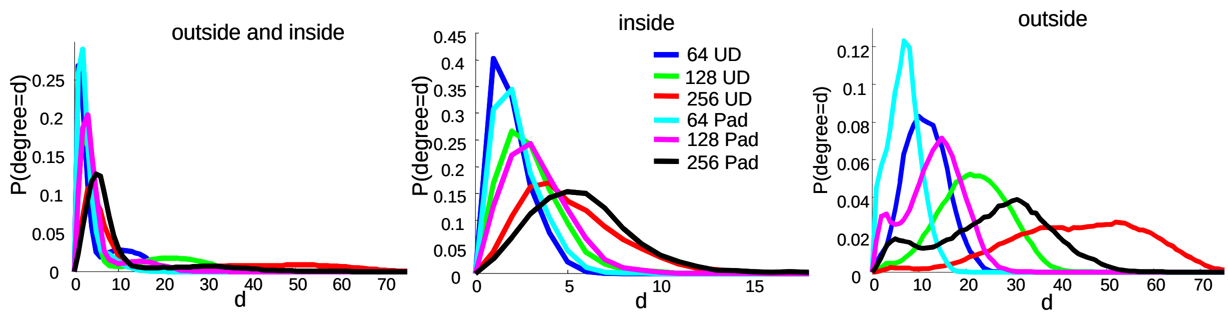

Figure 5. Degree Distribution.

However, in both cases, the mean degree increases as the population grows. But in the case of outside nodes, the degree distribution shows that there is a lower tail with a significant number of nodes with small degree. The reason for this is that while outside does provide good connectivity, there are small regions that are not well connected. As mentioned in Section 4, as more nodes are added, it is more likely that a node is in a hard to reach situation. Note that the behavior as more nodes are added depends on the environment. Outside, the degree is larger for the University of Delaware campus, while inside, the degree is larger for Paddington. The reason is that the University's buildings are large and difficult to penetrate, but the outside region is spacious with few buildings to block the signal.

The result of a mixed topology (i.e., one that has nodes both inside and outside) is a diverse degree distribution. Specifically, the degree distribution is bimodal with the modes sometimes a factor of 10 apart (e.g., the university campus with 256 nodes). While today's protocols do not make use of such information, an intelligent network could treat nodes with very high degree different than it treats the nodes with low degree.

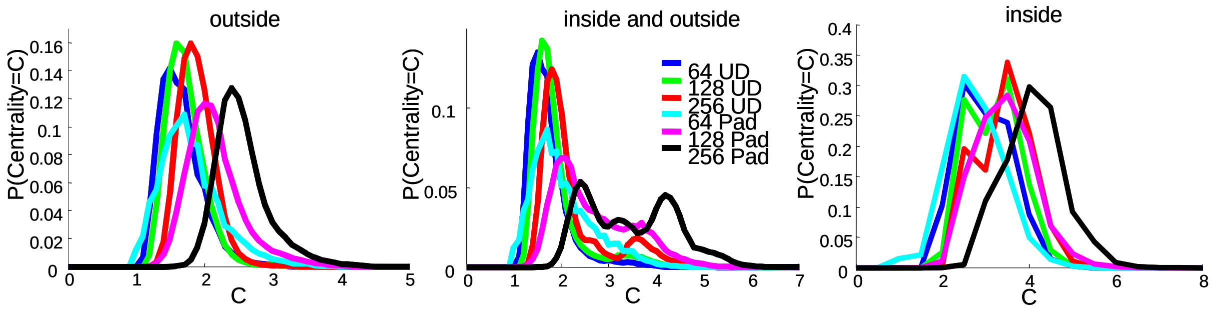

Figure 6. Centrality Density (Histogram).

7 Centrality distribution of node in an urban MANET

Centrality is a useful measure to determine the extent to which a node is connected to the other nodes in the population. While there are many possible definitions of centrality, a common definition is the mean distance, in hops, to all other nodes. A well connected node would have a low centrality and a node on the "edge" of the network would have a larger centrality. Since the graph is not connected, we speak of the centrality to nodes within the largest connected component and neglect the impact of nodes not in the LCC. Figure 7 shows the distribution of the centrality. The plot labeled "outside" is the distribution of the centrality from the nodes that are outside while the plot label "inside" is the centrality form nodes inside. In both cases, the centrality measures the distance to all nodes, both inside and outside nodes. Again the impact of outside and inside is clear. The centrality of nodes inside is roughly the same, independent of the environment. Specifically, the distribution of the centrality of indoor nodes when there are 64 nodes in the environments is rough the same, as is the distribution when there are 128 nodes. There is a larger difference between the university and Paddington for 256 nodes. On the other hand, the centrality of nodes outside show clear a distinction between the environments. Specifically, as nodes are added to the population, the centrality in the Paddington environment increases much faster than it does in the university campus environment. The reason that the centrality grows as nodes are added is that as more nodes are added, the nodes within buildings are included into the LCC. However, it often takes a few hops to reach nodes within buildings (typically one hop just to pass from just outside of the building to just inside). Thus, as the graph becomes more connected, the centrality of the outside nodes grows. This growth is faster for the Paddington environment as is shown in Section 4.

8 Spatial aspects of the graph

While the preceding clearly shows the heterogeneity of inside versus outside nodes, urban environments also have heterogeneity among the outside nodes as well as among the inside nodes. Figure 7 and 8 show the spatial properties of a MANETs. Four metrics are shown. Three metrics have already been mentioned, the probability of being in the LCC, the mean degree, and the mean centrality. The fourth metric shows how often nodes occupy each spatial location. Specifically, the frequency plot shows the probability that a node would be in each location. These figures use colors to indicate the value of metric at each spatial location. For example, a dark area in the mean degree plot indicates that when

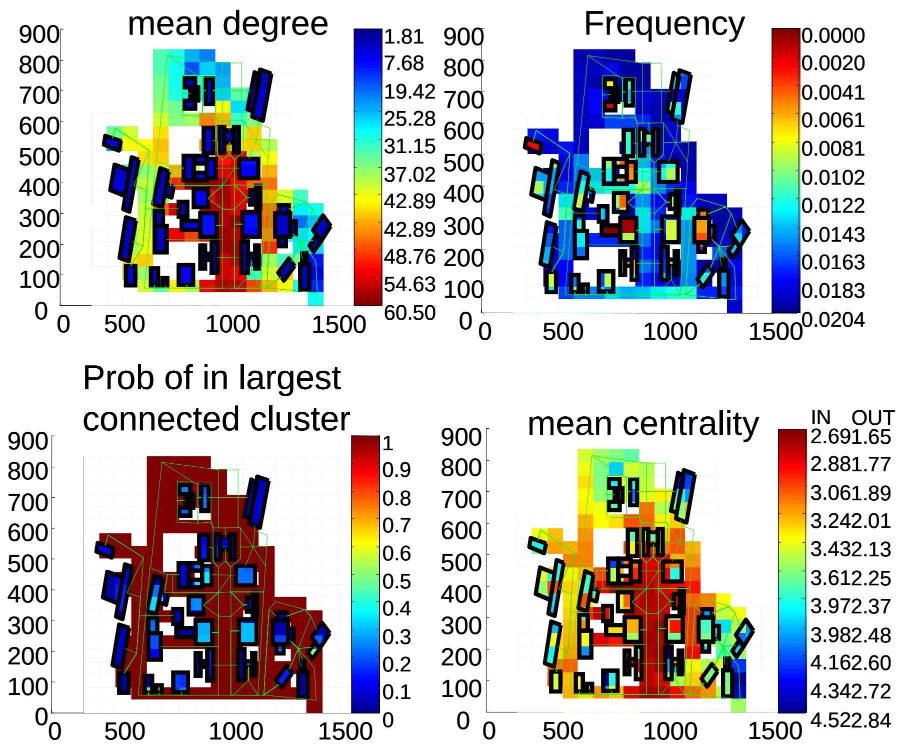

Figure 7. Spatial Graph Properties of the University of Delaware. The upper right figure indicates the mean degree at each location. If a node never entered a particular region, the region is left uncolored. The upper left plot shows the probability that a node in a location is in the largest connect component. However, two color scales are applied, one for inside locations and one for outside locations. The lower left shows the centrality of nodes in each position. Again, two different color scales are used, one for inside and one for outside. The lower right figure indicates the frequency or proportion of time a node was in each location.

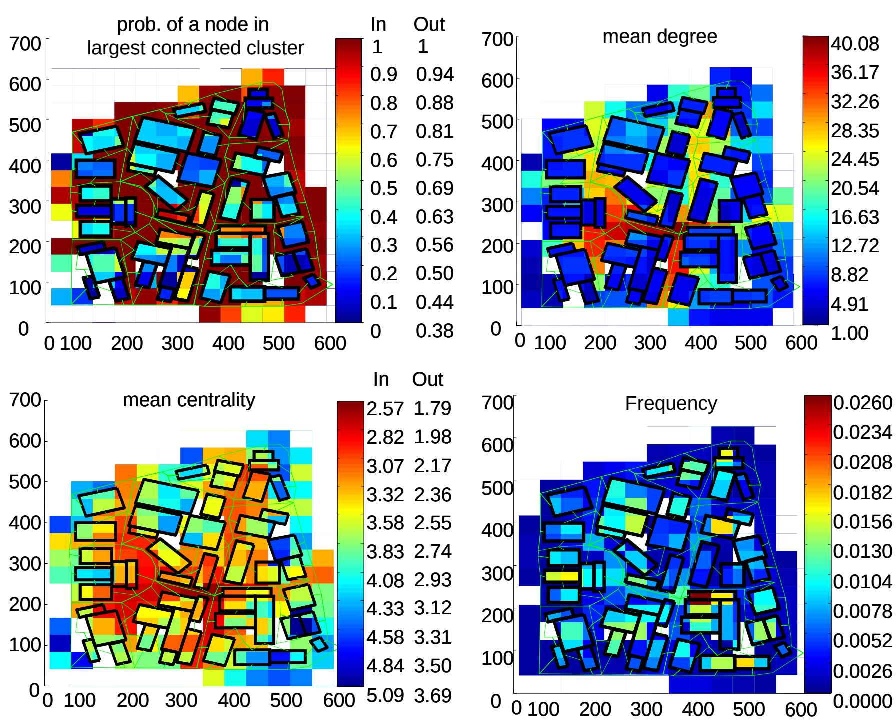

Figure 8. Spatial Graph Properties of the Paddington Environment

a node is in that location, the degree of the node is typically high. The color bar along the right indicates the correspondence between the color and the value of the metric. The values of the probability of being in the LCC and the mean centrality greatly varies when the location is inside versus when it is outside. Thus, two different correspondences between color and the value of the metric are used, one for inside and one for outside. In these cases, the color bar shows both correspondences. Note that a white area indicates that no nodes were in the location and hence no value of the metric is given.

The spatial heterogeneity of urban MANETs is clear. The figures show that along major roads or open areas, the nodes are well connected (high degree and low centrality). However, in regions where there is no major roads, nodes are poorly connected. For example, in Paddington, consider the region near the point $(300, 200)$, or more generally, the regions along the major roads that pass through Paddington along points $(50, 200) \to (500, 250)$, $(375, 550) \to (275, 50)$, and $(150, 500) \to (150, 350) \to (200, 250) \to (150, 200) \to (150, 50)$. Nodes along these roads are well connected. As a comparison, consider the region North of $(300, 200)$ where there are fewer roads and no major roadways. Nodes that find themselves in this region would be poorly connected (until they move). The lower right figure shows the fraction of time that a region is occupied by a node. Note, as can be observed by examining the occupancy, these major roadways also carry a significant amount of pedestrian traffic. However, it is not true that a region where nodes are well connected always has high occupancy. For example, the region near $(375, 500)$ is not particularly highly occupied, but nodes in this area would be well connected. The reason is that this region is on a roadway and has line-of-sight with the major intersection at $(300, 200)$. Note that this intersection has high occupancy. It should be noted that the roadways in the Paddington area are so narrow that they act like a waveguide, thus the radio is transmitted down these road very efficiently.

In these figures, the upper left figure shows the probability of a node in each location being in the LCC. As mentioned, the color scales for inside and outside are different. The connectivity into a building is affected by several factors. We see that small buildings near well connected and highly occupied regions are relatively likely to be in the largest connected cluster. The parts of the buildings near $(300, 450)$ are far from any major roadway and are hence unlikely to have nodes in the LCC. Recall that the communication through buildings is difficult, so it is difficult to communicate via several inside hops. Rather, in order for an inside node to be in the LCC, it must be near an outside node, or the population of nodes must be extremely large. This gives some indication as to the difficulty of constructing an operational MANET in an urban environment.

9 Conclusion

MANETs in urban environments have largely been unexplored, however, if MANETs are to be used for civilian or military situations, it is likely that they will be used in urban environments. The urban environment brings many new problems and possibilities. Here the heterogeneity of a MANET graph is explored. It is shown that the behavior of nodes inside and outside is quite different. Successful protocols will be forced to grapple with these differences. Also, MANETs in urban environments are quite heterogeneous. For both inside and outside nodes, the graph properties depend on the spatial position of the node. For example, nodes in some areas are well connected while nodes in other areas others are not. We see that these areas of well connected nodes are along major pedestrian thoroughfares. Thus, it seems likely that these thoroughfares will not only be used to transfer people and cars, but data as well. For example, they may be a natural backbone.

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