Chapter 8

CONCLUSIONS AND FUTURE WORK

It can be reiterated that simulation is one of the main methods for evaluating protocol performance for wireless networks. We have developed an elaborate framework for realistic propagation simulation of urban mesh networks. A general framework for overall simulation of the urban mesh networks, has also been explored. All the developed models have been extended to work with preferred simulators such as NS2 and QualNet. These models and multitude of trace files generated using these models for different urban environments are available for download at [8]. The thesis is aimed at improving the quality of simulations for wireless mesh and mobile ad hoc networks operating in urban environments.

8.1 Propagation simulator

Issues related to propagation simulation for urban wireless networking have been explored. Also, the design of a propagation simulator has been discussed. This propagation simulator is integrated with a mobility simulator discussed in [52]. This simulation package, which is available for download [8], demonstrates that it is possible to include realistic propagation into simulation of urban wireless networks such as the ones being deployed in several cities. As has been shown, traditional simulators that use random way-point mobility and the 2-ray propagation model are not suitable for urban environments. It is important to note that the simulation strategies discussed here and implemented in the simulation tools focus on realistic simulation, not accurate prediction. Thus, they are suitable for understanding the
performance of urban wireless networking protocols, but not for planning specific networks. However, as computational resources increase, we expect that more complicated and accurate techniques will be integrated into the simulation packages, and will, perhaps, allow for accurate prediction as well.

8.2 Graphical properties of urban mesh and mobile ad hoc networks

The urban environment brings many new problems and possibilities. In Chapter 3 heterogeneity of an urban mesh graph is explored. Various graphical properties such as degree distribution, duration in and out of largest connected component and centrality are examined for indoor and outdoor nodes operating in two contrasting environments. It is shown that the behavior of nodes inside and outside is quite different. Efficient protocols for urban mesh networks will have to cope with this disparity in the quality of communication depending on the position of the nodes. 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 act as high bandwidth data communication paths. For example, they may be a natural backbone.

8.3 Variation in propagation characteristics

Chapter 4 is dedicated to examining the channel variability in a crowded environment. While the variability of the channel is often attributed to the mobility of the receiver or transmitter, it is also possible that objects in the environment are partly responsible for the channel variability. This work verifies that hypothesis. It was found that the standard deviation of the received signal strength is affected by the density of the mobile objects in the environment. A four-parameter, diffusion process was developed that approximates the observed variability of the signal.
strength. To fully characterize the system, transition probabilities are investigated and modeled. It was demonstrated that a realistic variation can be synthetically generated using the developed diffusion model. Thus this model can be incorporated into high fidelity simulators and test beds alike to introduce realistic variations in channel.

8.4 **Effect of interference on performance of 802.11b/g**

Chapter 5 explores the effect of signal to interference ratio (SIR) on the packet success probability. Specifically this work explored the behavior of 802.11b/g in the interference limited regime through a large number of laboratory experiments. Two observations were made. First, in the scenarios considered, synchronization error plays a critical role in the performance. As a result, in many cases, lowering bit-rate will not improve tolerance to interference. The implications that this observation has on bit-rate selection was investigated. A second observation is that during a collision, the probability of a bit error is independent of the frame size. This differs from the noise limited case where the probability of bit-error grows exponentially with the frame size.

8.5 **Simulation framework**

Chapter 6 presented simulation framework for urban mesh networks. Various aspects including number of nodes to be used in the simulation have been discussed. These techniques include methods to realistically simulate propagation and mobility. While realistic propagation modeling is computationally expensive, the propagation matrix needs to only be computed once for each urban map. Based on the findings from urban planning and traffic engineering research community, realistic mobility models can be developed. It is evident that these models are far more realistic than the random waypoint open-space propagation models that are widely used in current simulations. One challenge in realistic simulation is to keep the usage complexity
low. The methods, models, and model parameters developed reduce the complexity of use while still maintaining realistic simulation.

8.6 Insights gained from realistic simulations

The impact of using the realistic propagation simulator and the insights gained from these simulations has been discussed in Chapter 7. Specifically the issues relating to coverage and topology were investigated. While large-scale urban mesh networks (LUMNets) are being deployed around the world, there remain substantial challenges related to coverage and scalability. The coverage in terms of regions and achievable bit rates are investigated. The disparity in coverage of indoor and outdoor nodes is evident from this study. As mentioned earlier successful protocols will have to cope with this disparity in coverage and quality of communication. The study also investigates the coverage criteria when the mobile nodes are allowed/not allowed to act as relays. It was found that allowing mobile nodes to act as relays adds very less to the coverage when the infrastructure node densities are high. On the other hand it was seen that when the infrastructure density is low, coverage can be enhanced if mobile nodes are permitted to act as relays. In this case, traditional mobility management techniques are not applicable. While coverage is one aspect that dictates the performance of a network, quality of coverage is the one that is of more interest. By quality of coverage, we mean the achievable bit rates. A brief investigation on the achievable bit rates was conducted for nine different infrastructure node density scenarios. It was found that the average bit rate that can be achieved for an infrastructure node densities of 300 m. (scenario 9 in 7.1 which is the planned density for Philadelphia as of December 2006.) is around 4 Mbps. By increasing the density of the infrastructure nodes, bit rates of 10 Mbps can be achieved. It was found in [91] that these bit rates do not necessarily translate into application performance. However further work is required to ascertain
this fact whether good coverage and high achievable bit rates translate into network performance.

Topology of node connectivity has a very strong influence on the kind of protocols that can be developed. It was shown that using realistic simulations gives rise to realistic topologies. This topology information has been used to develop a new protocol that operates with low overhead in such scenarios. In particular, paging or searching for a mobile node in urban mesh networks has been addressed. Flooding, which is used in MANET routing protocols cannot be used since it does not scale to the size of the large scale urban mesh networks being developed. This work presents a scalable technique to page nodes in such networks. The scheme leverages the topology that arises in urban areas. Specifically, the fact that wireless propagation is good outdoors, but greatly restricted indoors produces a topology with highly connected core that is composed of outdoor nodes, and weakly connected tendrils made up of indoor nodes. The scheme presented restricts the flooding to the tendril where the mobile node resides and thus is more energy efficient and has very low overhead when compared to the other popular MANET routing protocols.

8.7 Future work

While the propagation simulation discussed above is significantly more realistic than the 2-ray and the open space models commonly used in mobile wireless network simulation, there are several areas that require further effort. For example, as discussed in Chapter 2 and Section 2.2.7, propagation is time-varying, and is linked to the mobility of objects, specifically people and vehicles. Since the integrated mobility and propagation simulator include the locations of people and vehicles, these locations can be included into the propagation calculations. However, more effort is required to model the impact of people and other mobile objects. One approach is to incorporate stochastic models. In this case, the simulation strategy would be site-specific and mixed deterministic and stochastic. See [106] for
mixed deterministic and stochastic propagation modeling.

Modeling propagation from indoors to outdoors and visa versa is an area of ongoing research [43]. One difficulty is that accurate propagation through non homogeneous walls is difficult to compute. As shown in Sections 2.2.3 and 2.2.4, propagation is greatly influenced by the material. However, these sections only considered propagation through walls made from a single material, whereas most walls are made of several types of material. While [107] develops a technique to model propagation through complicated walls, it is computationally complex. Furthermore, even if more computational power is available, there remains the difficulty of determining the materials and wall structure of realistic urban buildings which adds to complexity of simulation.

Throughout the thesis, it was assumed that transmitter and receiver antennas are vertically polarized. Furthermore, we also assumed that they are ideal. While it is straightforward to include the model of an ideal dipole antenna, in many cases the antenna is not an ideal dipole and is not vertically positioned. For example, see [108] for an example where the angle of inclination the antenna played a critical role in connectivity. Further work is required to get realistic models of antennas.

Capacity estimation is an other area which can utilize these models. While coverage and achievable bit rates have been addressed, further work is necessary to estimate the capacity of urban mesh networks.

In the work involving the investigation of time varying nature of propagation in crowded environments, it was found that the model parameters are closely related to one another and appear to follow a deterministic relationship. Thus, the only independent variable is the variance of the channel gain, which seems to be highly correlated to the pedestrian density. This prompts for further investigation to determine the relationship between them. A single parameter (pedestrian density) diffusion model can be developed once the relationship between variance in signal
strength and the pedestrian density is established.

Another important aspect of channel variation is the variation induced by small movements of transmitter or receiver. Currently due to computational constraints the resolution of a position in propagation simulation is unreasonable to be less than 0.5 m for large urban areas such as downtown Chicago (2km x 2Km). It is necessary to investigate the variations induced by movements that are less than the minimum resolution. These models can be incorporated into the packet simulator in conjunction with mobility simulator which can provide much smaller resolution in terms of node movement by correlating with the propagation characteristics at a coarse resolution provided by the propagation simulator.

Signal to interference plus noise ratio is one of the factors that affects the channel quality to a large extent. Due to the deployment of large and dense mesh networks, it has been receiving a lot of attention in recent times. Our work on the characterization of interference’s impact on the packet error probability gave a lot insights into the way it differs from that of the impact of SNR. While this work examined the effect of a single interferer, more work needs to be done to model the effect of SIR on performance of wireless mesh networking protocols. Also further work needs to be done on making the rate fall back mechanisms to cope up with the interference.

While there can be no limit to the extent to which the quality of simulations can be extended, this concluding section addresses some of the issues that are of interest in the near future.