Models and Methodologies for Simulating Mobile Ad- Hoc Networks*

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Abstract

It is a truism that simulations of mobile ad hoc networks (MANETs) are not realistic. Today, simulations typically model propagation with either the free-space model or a "two-ray" model. Such models are valid only in open space where there are no hills and buildings. Since wireless signal at the frequencies used for MANETs is partly reflected off of buildings and is partly transmitted into the building, the presence of buildings greatly influences propagation. Consequently, these open-space propagation models are not accurate in outdoor urban areas. When propagation for Indoors is considered, the open-space models are not even applicable. There has been little effort in developing realistic mobility models. In urban areas, the mobility of vehicles and pedestrians is greatly influenced by node interaction. Furthermore, the location of streets, sidewalks, hallways, etc. restricts the position of nodes. Traffic lights also have a direct impact on the flow of nodes. We discuss the models and methodologies for realistically modeling the propagation and mobility of MANETs in urban environment. The techniques of simulation, models, model parameters and accuracy are all examined. The techniques for propagation are validated against propagation measurements.

1 Introduction

Mobile ad hoc networks (MANETs) will likely be deployed in the future military operations. Cities such as Philadelphia are planning to deploy ad hoc networks to provide wireless access to the entire 135 square mile city [21]. Las Vegas has a pilot project already deployed for use by public safety organizations which is capable of supporting applications such as monitoring and controlling vehicular traffic for emergency response and remote situation assessment [4]. Over two hundred other local governments are considering similar projects. In such networks, end-hosts will certainly be mobile. Thus, large-scale deployment of multi-hop wireless ad hoc networks appears imminent.

It is well known that the variability of node-to-node communication is a major challenge facing MANETs. For example at one moment, high quality communication between two nodes may be possible while a short time later, communication between the nodes may not be possible. In the case of wide bandwidth communication, such drastic changes in link quality are typically the result of node mobility. Thus, a combination of node mobility and complex propagation due to the environment results in rapid variability of communication links. However, while great strides have been made in protocols for MANETs, there has been very little effort devoted to understanding how to best simulate MANETs, specifically, how to best simulate the node mobility and signal propagation.

At the frequencies used in today's wide band communication, wireless signals may undergo reflections off of buildings and ground, transmissions through walls, and diffractions over and around buildings. Wireless communication extends far beyond what line-of-sight (LOS) communication will offer. Indeed, our simulations show that majority of a node's neighbors (i.e., the nodes with which a node can communicate) are not within LOS. As will be discussed in Section 4.2, the variation of the signal strength under LOS propagation is significantly different from the variation of the signal strength in reality. Goals of realistic propagation simulation include simulating realistic coverage and realistic variation of the signal strength.

When propagation in urban environments is considered, mobility must also be addressed. Specifically, the mobility model must take into account the structure of the urban environment such as streets, sidewalks and buildings. It is important to note that the locations of the nodes are correlated. This is due to the reason that in reality pedestrians and vehicles tend to move in clusters [22], [28]. Since the spatial distribution of nodes has an important impact on the behavior of MANET protocols, mobility models must be realistic.

It is important to note that the objective is realistic

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simulation, not accurate simulation. By this we mean that the simulation should provide mobility and propagation similar to what *could* occur in an urban environment, not necessarily what *would* occur in a particular urban environment. As will be discussed, accurate prediction requires knowledge of the intricate details of modeled urban environment. Realistic simulation, on the other hand, merely needs realistic dimensions and locations of buildings, building materials, and realistic trip generation for vehicles and pedestrians. The motivation for realistic simulation rather than accurate prediction is to reduce the complexity of simulation. There are two types of complexity that are relevant here, computational complexity and usage complexity. The latter refers to the difficulty in defining the simulated environment. This paper provides models and parameter values, and discusses tools to develop simulated environment that satisfy the goal of realistic simulation.

The remainder of the paper is organized as follows. In the next section, previous work related to simulation of propagation and mobility for MANETs is discussed. Section 3 provides a short overview of the steps involved in simulating MANETs. Section 4 discusses characteristics and simulations of propagation. Section 4.1 discusses the impact of reflections and diffractions in propagation in urban areas. Section 4.2 provides validation of the propagation models. Section 5 discusses mobility models for realistic MANET simulation. This discussion is broken down into the following sections. Section 5.1 deals with the dynamics of nodes and section 5.3 discusses trip generation. Finally section 6 provides concluding remarks.

2 Related work

Currently, open-space propagation (i.e., free-space and the two-ray model) is the most popular propagation model for MANETs research. For example, ns-2 [17] only supports open-space propagation models. On the other hand, QualNet [25] supports open-space propagation as well as stochastic propagation models such as Rayleigh, Rician and Lognormal fading. QualNet also supports path loss trace files. Furthermore OPNET [20] supports open-space propagation models as well as an enhanced open-space model that accounts for hills, foliage and atmospheric affects.

While less popular, stochastic models such as Rayleigh, Rician and Lognormal fading [23] have been used by several investigators. While such propagation modeling is useful to compare physical layer techniques, they have limited use in MANETs. The drawback of stochastic propagation models is that they fail to model the propagation structure found in urban areas.

In [11] and [10] obstacles were included in the simulated environment and propagation was limited to line-of-sight. In [10] the obstacles were randomly placed buildings. As will be shown most of the communication in an urban area is not line-of-sight. Since streets play an important role in MANET topology, the random placement of buildings will result in non-realistic topologies.

There has been limited work that includes accurate propagation modeling along with MANET simulation. For example, [5] suggests using ray tracing indoors to enhance ns-2's propagation model.

There are several mobility models used for MANET simulation (see [3] for details and references). However, most models do not attempt to be realistic, but rather focus on ease of implementation and analysis.

3 MANET simulation overview

There are several stages to MANET simulation. The first step is to define the simulated city map. This can be done by utilizing the GIS datasets [8], which includes 3-dimensional maps and coordinates of the buildings, streets and other objects. The interiors for the buildings are automatically generated with predefined dimensions for the offices, rooms, hallways etc. The second step is to determine the propagation matrix for the city. The propagation matrix includes channel characteristics such as path loss, delay spread and angle of arrival for each source-destination in the city. This is discussed in Section 4. Next, the city map is used to generate one or more mobility trace files. This step is discussed in Section 5. From the mobility trace file and the propagation matrix, the propagation trace file is computed; the propagation trace file provides the propagation statistics between all pairs of nodes at every moment (The definition of *moment* depends on the desired resolution). The propagation trace file can then be used by the protocol simulator.

4 Propagation modeling

The main factors that affect the probability of a packet error are signal strength, delay spread, Doppler spread, and noise, which include interference. Of these, current simulators only consider signal strength and interference. The section focuses on estimating the signal strength[1] in urban environments. The simulator discussed here is also capable of estimating the delay spread.

The signal strength at the receiver is given by $P_{\text{Received}} = P_{\text{transmitted}} \times C \times \textit{Path Loss}$, where C is

[1]Note that signal strength is also used to determine interference.

a constant that depends on the antennas and the frequency, and is often on the order of -30dB to -40dB. Assuming that C is known, and if the transmitted power is known, then knowing the path loss is equivalent to knowing the signal strength. Thus, the terms path loss and received signal strength are used interchangeable.

A large volume of research has shown that at the distances and frequencies considered here, the propagation of electromagnetic waves can be modeled as rays (see [24] and reference therein). These rays reflect off of the ground and walls, are transmitted through walls, and diffract around corners. While traveling through free-space, the ray's signal strength decays like $1/d^2$ where d is the distance. When the ray makes a reflection, transmission, or diffraction, it experiences an additional decrease in signal strength and a change in the phase. Thus, the path loss for a particular ray is given by $1/d^2 \times \mathit{Attenuation}$where $\mathit{Attenuation}$ is a complex number that depends on the details of each reflection, transmission, and diffraction. The received signal strength can be calculated by determining the length and the attenuation experienced by each ray that hits the receiver. Determining the received signal strength at a particular frequency requires the addition of signal strength provided by each ray. For wide band communication, the signal strength is the average power of the signal averaged over the entire bandwidth.

The attenuation and change in phase due to a reflection or transmission depends on the frequency and polarization of the signal[2], the angle of incidence, and the type and the thickness of the material that the signal is reflecting off of or transmitting through. If the material is known and is homogeneous, the loss and change in phase can be found in a straightforward manner (e.g., [13]).

Besides reflection and transmission, diffraction plays an important role in propagation. Diffraction allows wireless transmissions around the corners and over the buildings. Whether a signal is more easily diffracted over the building or transmitted through the building depends on the size and height of the building. The Uniform Geometrical Theory of Diffraction has been shown to provide a realistic model for diffraction.[15].

Once the map, bandwidth, and building materials have been defined, propagation can be determined. However, extreme care must be taken to reduce the computation. Assuming that all walls are vertical significantly decreases computational complexity. Specifically, the 3-D ray tracing problem reduces to a 2-D ray tracing problem that finds vertical plane paths. The 2-D ray tracing problem is illustrated in the right-hand plot in Figure 1, where two vertical plane paths are

[2]It is typical to assume vertical polarization.

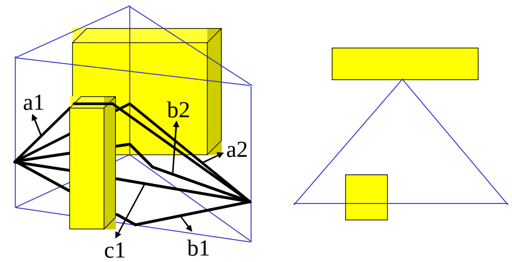


Figure 1. Left: Two vertical plane paths and 5 ray paths. Right: a top-view of the scene on the left.

shown. Once the vertical plane paths are found, the 3-D ray paths restricted to the vertical plane paths can be computed easily. The left-hand figure in Figure 1 shows the paths of a ray in the vertical plane. One vertical plane path has three ray paths, (a1) one that diffracts over a building, (b1) one that reflects off of the ground and passes through a building, and (c1) the one that passes straight through a building. The other vertical plane path has two ray paths, (a2) one reflecting off of the wall of a neighboring building and (b2) one reflecting off of the wall of neighboring building and undergoing a ground reflection. In one vertical plane path there are potentially many ray paths that include repeated reflection off of the ground, transmission through buildings, and diffractions over buildings. In our simulator, we include three types of ray paths, direct paths (line of sight or transmissions through buildings), ground reflected paths, and paths that diffract over buildings without being transmitted through the buildings. For paths that diffract over buildings, if the transmitter or receiver is indoors, then the ray path passes through the building where the transmitter and/or receiver is, but must pass over all other buildings intersected by the vertical plane path.

A straightforward implementation of even 2-D ray-tracing is not computationally efficient. Instead, a technique that is more appropriately called beam tracing can be performed. Like ray tracing, the goal of beam tracing is to determine the paths from the transmitter to receiver. Beam tracing begins with the source broadcasting the signal in all directions (assuming an omnidirectional antenna). This transmission is not modeled as a large number of rays, but as a small number of beams. When a beam intersects a building, two beams are generated, one is reflected off of the building and one is transmitted into the building. If only a part of the beam intersects the building, the beam is split into three with one part of the beam continuing to the next wall (if it exists) and the other part of the beam generating two beams, a reflected beam and a transmitted beam. Finally, if the receiver is found to be included within the span of a beam, the ray from transmitter to receiver can be computed easily.

The beam tracing computation can be further simplified by discretizing the 2-D space into a grid (*floor-tiles*) and then determining the propagation between the center points of each square. Furthermore computed signal strength is averaged over several points inside the floor-tile. To reduce the number of grid-points, these floor-tiles are determined only along the center-lines of sidewalks, roads ,hallways and in every location a node can be inside the office locations/rooms. The walls of buildings are also divided into small tiles (*wall-tiles*). Since the beam tracing is in 2-D, these tiles are 1-dimensional segments.

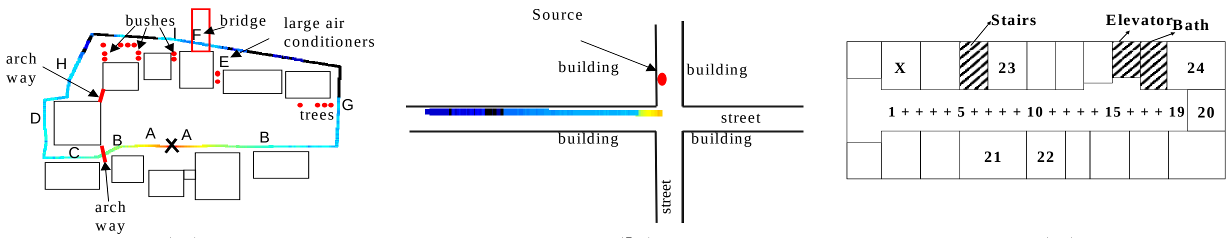
The computation is divided into two parts, preprocessing and beam tracing. During preprocessing, *ray neighbors* for each tile are found. A tile's ray neighbors are all the tiles that could be directly reached (i.e., without reflection, transmission through a wall, or diffraction) by a ray emanating from the tile. Once the ray neighbors are found, beam tracing can be performed efficiently. This process of beam tracing is carried out in a breadth first manner with each beam continued to be reflected, transmitted, and, perhaps, subdivided until either the beam exits the modeled area or until the estimated path loss of the beam surpasses a threshold. Once the ray neighbors are found, the propagation characteristics between each pair of floor-tiles, referred to as path loss matrix, can be found. From a single source, the propagation characteristics to all destinations can be found at the same time. That is, as the beam is reflected, the illumination of any floor-tile is recorded. Beam tracing is a feasible but highly computationally complex task. The complexity is both in terms of memory usage and processing time. Processing times for a 1km$\times$1km urban region is often on the order of tens of processor days. But the process is highly parallelizable and nearly scales with the number of processors used (i.e., 75 processor days takes about 5 days on 15 processors). Of course, the entire path loss matrix for each city only needs to be found only once.

Beam tracing can be performed indoors as well as outdoors. Since building interiors have a large number of walls, beam tracing inside all the buildings within a large region of a city exceeds today's computational abilities. Fortunately, it has been found that a realistic estimate of indoor propagation can be performed without using beam tracing. Specifically, the *attenuation factor* (AF) model has been shown to provide realistic path loss estimates, with the error found to be within 4dB [23]. The AF model assumes that communication indoors takes a straight line path (i.e., no reflections off of interior walls). Furthermore, transmissions through each interior wall and transmissions through each floor result in attenuation. While the amount of attenuation depends on the building, a value of 4dB per wall (for an office building) has been shown to work well [23] (also see Section 4.2). Attenuation for the signal propagating through floors can be modeled as 25dB+($number\_floors\_travelled \times 5$)dB. In summary, outdoors, rays make reflections off of buildings, diffractions over and around buildings, and transmissions into buildings. Once inside a building, the ray will continue in the same direction, experiencing further attenuation for any interior wall or floor that it passes through. When a ray strikes an exterior wall from the inside, it is both reflected back inside and transmitted outside in the same way as rays hitting the exterior wall from the outside.

4.1 Impact of reflections, diffraction, and transmissions

It is of interest to determine how many reflections, diffractions, and transmissions must be modeled before the quality of the model is affected. In order to investigate the impact of the different factors, we consider propagation in Paddington, London. Figure 3 shows the average of several experiments. In each experiment, the source was placed along a major street. The center column of Figure 3 shows the number of locations where the signal strength was found to be sufficiently strong for communication. In this case, each location is on a sidewalk and with 1 meter between locations. The right-hand column shows the computation time in seconds. Each row corresponds to an experiment with different number of iterations, where each iteration includes a reflection, transmission, or diffraction. From the Figure 3 we find that the coverage with only LOS is reduced by factor of 4.5 from the coverage achieved with all iterations. It is also clear that modeling diffraction is critical; for a particular number of iterations, neglecting diffraction results in a 30%-50% reduction in coverage. While not shown here, a similar experiment showed the impact of ground reflections to be minimal. The reason for this is that the canceling out effect of the ground reflection (i.e., the signal strength decays like $1/d^4$ as oppose to $1/d^2$[23]) does not occur until the distance is around 200 meters[3]. However, rays that propagate $\geq$ 200 meters also make several reflections, hence increasing the attenuation. This reduces the canceling effect.

[3]The actual distance depends on the frequency and height of the antenna. In the case of 2.4GHz and 1.5 meters heights, the distance is 200 meters.



(a) (b) (c)

Figure 2. Maps of the locations where the validation experiments were conducted. The indices (a), (b) and (c) depict the campus map, an intersection at philadelphia, and the interior floor plan of a building.

Experiment	Coverage	Time
Line of sight	937	56
1 iter	2623	59
1 iter no diffraction	1960	56
2 iter	3927	61.5
2 iter no diffraction	2616	57
3 iter	4243	67
3 iter no diffraction	2862	58
4 iter	4265	85
4 iter no diffraction	3065	63
All iter	4265	122

Figure 3.

4.2 Validation

The goal of the propagation model is not to predict the signal strength, but to merely have the signal strength behave in a realistic fashion. However, it is useful to understand the accuracy of the propagation model. Three validation experiments were performed, two outside and one inside. In all cases, an 802.11b access point and the Berkeley Varitronics Yellowjacket wireless receiver [2] were placed on 1.5 meter tripods. The access point was placed at a fixed location and wireless receiver was moved after making 600 measurements (1 minute). Figure 2 (a) shows a part of the campus and Figure 2 (b) shows a street intersection in Philadelphia. In Figure 2 (a), the buildings were 14 meters high while in Figure 2 (b) the buildings were at least 40 meters high. In both cases, the X-mark denotes the location of the transmitter while the receiver is moved along the indicated path. Figure 4 (a) shows the observed and modeled path loss corresponding to the path starting from the transmission point and moving along the path in the counter-clockwise direction. Figure 4 (b) shows the modeled and observed path loss starting at the transmitter, moving to the right and then turning at the corner.

Figures 4 (a) and 4 (b) show that the results from the model and measurements match well both qualitatively and quantitatively (within 5dB in most areas). To gain more insight into propagation modeling we examine the propagation prediction quality at different locations, especially the location where the prediction quality is lower. In the area marked C, there is an unmodeled archway that is depicted in Figure 2 (a) between B and C. Similarly at location F, there is a bridge as depicted with the indicated rectangle. Ignoring these objects impacts the accuracy of the propagation prediction. In the locations marked E and G, there are several moderate sized unmodeled objects (large air conditioners at E and trees at G) that partially blocked the signal. Sometimes such small objects are called scatterers. We see that scatters can slightly decrease the received signal strength. On the other hand, in the areas where there is purely line-of-sight (marked As), line-of-sight with reflections (marked Bs) and reflections with diffraction (marked D), there is very good agreement between the model and the observations.

Figure 4 (b) also shows a good fit. Again, the influence of scatters can be observed. In this case the scatterers includes things such as mailboxes, parked cars, and irregularity of the walls (e.g., doors that are set back from the wall). Nonetheless, the model and observations are within a few dB.

Finally, Figure 2 (c) shows the layout of a building interior. The Figure 4 (c) compares the modeled and observed signal strength for the points indicated in Figure 2 (c). Again, we see that there is reasonable good agreement between the model and the observations.

5 Modeling Node Mobility

Realistic mobility differs from the popular random way-point [12] in two ways. First, nodes are restricted to sidewalks, buildings, or roads, and second, the posi-

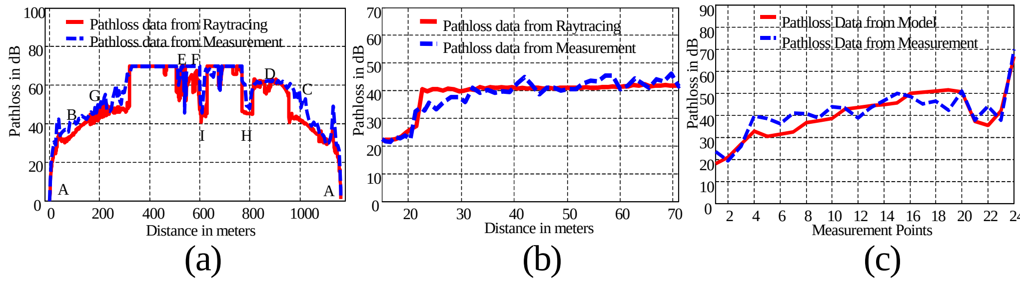


Figure 4. This figure compares the results of the measurements with the results obtained from the propagation model. The indices (a), (b) and (c) depict the comparison results for the campus map, an intersection in Philadelphia and interior of a building resepctively as shown in the Figure 2

tions of nodes are correlated, specifically, nodes often move in groups (i.e., node arrivals are bursty). Such groups of nodes are called platoons and are well known to have an impact on the capacity of roads and sidewalks [28]. Platoons of vehicles and pedestrians can arise from traffic lights and from faster nodes catching-up, but not passing the slower nodes. In the case of pedestrians, the second cause is increased by nodes that are in groups by choice. Such groups move slower than solitary nodes and limit the ability of faster nodes to pass, thus expanding the size of the group.

In this section realistic mobility modeling that accounts for these characteristics is discussed. While these models appeal to common sense, nearly all models are based on the data and experiences of urban planning and traffic engineering research communities. When available, the model parameters are derived from observations found in the literature.

5.1 Node dynamics and interactions

5.1.1 Inter-node distance-speed relationship

When a node with a higher desired speed catches up with a slower moving node, it will either follow or pass. To understand the dynamics of catching up, it is necessary to understand the distance-speed relationship. The impact of this relationship is that nodes can and will be tightly packed (i.e. high density) if their speed is low (congestion), but if the speed is higher, then the nodes must be further apart (low density). Since the density of nodes plays an important role in MANET performance, the distance-speed relationship must be understood and realistically modeled. For vehicles, the distance-speed relationship, which we denote as $D(S)$, is closely related to the "two-second rule" that specifies that a following vehicle should not be closer than two seconds behind the vehicle it follows. While $D(S)$ is not exactly linear, it is often modeled as linear, specifically, $D(S) = \alpha + \beta S$ where S is the current speed. In [26], (α, β) were found to be $(1.78, 10.0)$ and $(1.45, 7.8)$

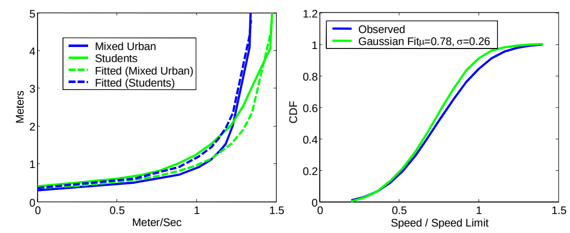


Figure 5. Left: Distance-Speed Relationship for Pedestrians. The mixed urban pedestrian data is adapted from [19] and the student observations are adapted from [16]. Right: CDF of the ratio of observed speeds to speed limit and the CDF of a fitted Gaussian distribution.

in dry conditions and $(0.415, 8.3)$ and $(0.230, 6.0)$ in wet conditions.

The distance-speed relationship for pedestrians is studied in [19] and [16]. Figure 5 shows the distance-speed relationship derived from these observations[4]. We approximate this relationship with $D(S) = S^* \times D_{\min} / (1.08 \times S^* - S)$ where $D_{\min}$ is the minimum distance between people without touching and S^* is the desired speed of the pedestrian. $D_{\min}$ was found to be at least 0.35m [22].

It has been found that pedestrian desired speeds are approximately Gaussian with mean 1.34 m/s and standard deviation 0.26 [27]. For vehicles, the ratio of the vehicle's speed to the speed limit presented in [6] can be modeled as Gaussian with mean 0.78 and standard deviation 0.26 (Figure 5).

5.2 Lane changing

While traffic lights are an important cause of platooning, lane changing also plays an important role [22]. A node will certainly not pass if there is no room

[4] The plot shown is based on area-speed relationships with the assumption of 0.75 meter of lateral space between people as found by Oeding [18].

(e.g., if the other lanes are full). Even if there is room, both pedestrian and vehicle nodes might not pass out of choice and select to slow down and follow the node ahead [29]. Such decisions lead to platooning.

Lane changes are grouped into two categories, discretionary and mandatory. The latter category results when the node's current lane ends or is blocked by a fixed obstruction, or the route to the destination requires changing lanes (e.g., to exit or make a turn). For MANET simulation, the dynamics of mandatory lane changes can be ignored since the exact moment when the node does change lanes will not have a significant impact of the distribution of nodes and will only have a minor impact on position (and hence a minor impact on signal propagation to and form the node). In [1], the probability of changing lanes was modeled as $1/\left(1+\exp\left(A+B\times\left(V_{*}-V^{*}\right)\right)\right)$ where V_{*} is the speed that the node would achieve if it remains in the current lane and V^{*} is the speed that would be achieved if the node changes lanes.

According to the findings of [1], if a node catches up to another node and there is room, it will change lanes 50% of the time when the speed difference is $V_{*}-V^{*}$ is zero. Furthermore, when the speed difference reaches one standard deviation of the nodes speed distribution and there is room, the node will change lanes 66% of the time. To mimic this behavior at the slower speeds of urban vehicles and pedestrians, we set $A_{Vehicle}=-0.225$, $B_{Vehicle}=0.1$, $A_{Pedestrian}=-0.225$, and $B_{Pedestrian}=1.7$.

5.3 Trip generation and arrival rates

5.3.1 Pedestrian trips

The rate at which nodes enter and leave buildings has been well studied with extensive data provided in [22]. It has been found that for office buildings, occupants make an average of 2.3 to 4.7 in or out trips per twelve-hour day. This amounts to a mean time between entering and exiting the building between 2.3 and 5.3 hours. In the case of restaurants, supermarkets, department stores and residences, the average time to remain in the building is 3.75, 0.6, 1.25, 5.2 hours respectively. However, in most cases, the duration is not uniform. During the lunch hours, office occupants' time to next departure is between 2 and 6 times less than the mean (i.e., between 0.38 and 2.65 hours)[5]. During non-lunch hours and during the non-rush hours, the mean duration in the building drops to values between the average and double the average duration in the building. While the duration a node remains in a building before exiting depends on the time of day, the building, and the establishment, durations range from around 25 minutes to 6 hours. Since lunchtime is rather nonstationary, afternoon rates might be preferable, which ranges from 1.25 hours for department stores to 5 hours for offices. We denote the mean time between trips that leave the building as m.

Unfortunately, there is much less data on the trips people take within buildings. Without such data we are forced to make a guess based on our own experiences. We selected to model the duration between trips as exponentially distributed with mean μ where $\mu\leq m$. Thus, the fraction of trips that lead the node outside is μ/m. Hence durations within the building are also exponentially distributed.

Groups of pedestrians play an important role in platooning [22]. Again, there is little data on the frequency of groups. However, we have made observations of over 500 pedestrians in an urban street and found the number of pedestrians within a group is well modeled with the Zipf distribution with shape parameter of 2.18, i.e., $P\left(\text{Group size}\geq g\right)=1/g^{2.18}$. We allow groups of node to congregate in an office and then proceed to a destination. While in transit, the nodes walk abreast of each other unless there are on-coming nodes or when the sidewalk can support all the nodes in the group. In such cases, some nodes will follow behind.

For outdoor trips, the duration and distance traveled has been well observed (e.g. [22]). The distribution is well modeled by an exponential distribution with means 554m, 380m, 403m, 344m, 813m, and 216m for Manhattan from office buildings, Manhattan from residences, Chicago, Seattle, London and Edmondton respectively. We see that the US cities have approximately the same mean. Thus, once a node selects to travel outside, it then selects a range of distances to travel. Buildings within that range are selected uniformly and offices within the selected building are also selected uniformly.

5.3.2 Vehicle trips

Traffic simulators such as CORSIM [7] allow vehicle trips to be generated in two ways, with origin-destination (O-D) flow matrices or with turning probabilities. With O-D matrices, the rate at which vehicles enter the simulated region at a origin O and proceed to the destination D is given by the O,D element of the O-D matrix. If only turning probabilities are used, vehicles enter into the modeled area at one of the preselected locations and proceed until the vehicle arrives at any exit location (often at the edge of the modeled area). O-D matrices yield a more accurate simulation, however, accurate O-D matrices are difficult to deter-

[5] A maximum of 2.65 hours in the building before the next trip does not agree with a mean number of 2.3 trips per day. However, the rate of 2.65 is only for the lunch hour. Nodes that do not leave during this period of high exit rate are subject to the longer duration inside the building that occurs after the lunch.

mine.

Drawbacks of turning probabilities are that vehicles might travel in long loops or meander through the city for extended periods of time. However, since turning probabilities are quite small (often they are in the range of 0.1 to 0.3 [9]) such unrealistic behavior is rare; most trips proceed through the city with only a few turns.

To model the rate at which the vehicles enter the city, we borrow urban traffic models for "upstream" lights (i.e., the traffic that exits a light upstream of the light under investigation). The upstream traffic is from two sources, vehicles that pass through the green light and go straight, and vehicles that turn on to the street. Following [14], it is sufficient to assume that the number of vehicles that enter is Poisson with mean

$$\frac{\lambda_{VehicleStartRate} \times \text{Signal Period} \times (1 - prob\_turning)}{\text{Number of Entering Roads}}$$

conditioned on that the number does not exceed the number that can pass through an intersection during a single green light. These vehicles enter at periodic moments with period equal to the traffic signal period. Furthermore, the number of turning vehicles into the road that leads to the modeled area is Poisson process, but with rate

$$\frac{\lambda_{VehicleStartRate} \times prob\_turning}{\text{Number of Entering Roads}}.$$

Hence, the total average rate that vehicles enter the city is $\lambda_{VehicleStartRate}$.

6 Conclusions

Realistic simulation techniques for mobile ad hoc networks in urban areas have been presented. 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 now. One challenge in realistic simulation is to keep the usage complexity low. The methods, models, and model parameters developed in this paper reduce the complexity of use while still maintaining realistic simulation.

References

[1] K. I. Ahmed. *Modeling Drivers' Acceleration and Lane Changing Behavior*. PhD thesis, MIT, 1999.

[2] Berkeley Varitronics. http://www.bvsystems.com/.

[3] T. Camp, J. Boleng, and V. Davies. A survey of mobility models for ad hoc network research. *WCMC*, 2(5):483–502, 2002.

[4] S. Cass.

[5] J.-M. Dricot and P. D. Doncker. High-accuracy physical layer model for wireless network simulations in NS-2. In *IWWAN*, 2004.

[6] J. Du and L. Aultman-Hall. An investigation of the distribution of driving speeds using in-vehicle GPS data. In *Vermont Institute of Transportation Engineers Annual Meeting*, 2004.

[7] FHWA. *CORSIM User's Manual, Version 5.0.* ITS Research Division, FHWA, 2000.

[8] GIS. Geographic information system. http: www.gis.com.

[9] J. E. Hummer. Unconventional left-turn alternatives for urban and suburban arterials. *ITE Journal*, 68, 1998.

[10] A. Jardosh, E. M. Belding-Royer, K. C. Almeroth, and S. Suri. Towards realistic mobility models for mobile ad hoc networks. In *MobiCom*, 2003.

[11] P. Johansson, T. Larsson, N. Hedman, B. Mielczarek, and M. Degermark. Scenario-based performance analysis of routing protocols for mobile ad-hoc networks. In *MobiCom*, 1999.

[12] D. Johnson and D. Maltz. Dynamic source routing in ad hoc wireless networks. In Imielinski and Korth, editors, *Mobile Computing*, pages 153–181. kluwer academic publishers, 1996.

[13] E. C. Jordan and K. G. Balmain. *Electronmagnetic Wave and Radiating Systems.* Prentice hall, NJ, 1968.

[14] A. Kamarajugadda and B. Park. Stochastic traffic signal timing optimization. Technical Report UVACTS-15-0-44, Center for transportation studies at the university of Virginia, 2003.

[15] D. A. McNamara, C. W. Pistorius, and J. A. G. Malherbee. *Introduction to Uniform Geometrical Theory of Diffraction.* Artech House, 1990.

[16] F. P. D. Navin and R. J. Wheeler. Pedestrian flow characteristics. *traffic engineering*, pages 30–36, 1969.

[17] Network Simulator - NS-2. Wireless and mobility extensions to ns-2 http://www.monarch.cs.cmu.edu/cmu-ns.html.

[18] D. Oeding. Traffic loads and dimensions of walkways and other pedestrian circulation facilities. *Strassenbau and strassenverkehrstechnik*, 22, 1963.

[19] S. J. Older. Movement of pedestrian on footways in shopping street. *traffic engineering and control*, pages 160–163, 1968.

[20] OPNET. http://www.opnet.com.

[21] Philadelphia Mayor's Office. Government leaders teleconference - wireless: The 21stCentury techhology http://www.phila.gov/mois/press/multimedia/pdfs/ wirelessphiladelphia092004.pdf, 2004.

[22] B. Pushkarev and J. M. Zupan. *Urban Space for Pedestrians.* MIT press, 1975.

[23] T. Rappaport. *Wireless Communications - Principles and Practice.* Prentice Hall, 2002.

[24] K. Rizk. *Propagation in Microcellular and Small Cell Urban Environment.* PhD thesis, Swiss Federal Institute of Technology of Lausanne, 1997.

[25] Scalable Network Technologies. The QualNet simulator http://www.qualnet.com/.

[26] S. Shekleton. A GPS study of car following theory. In *Conference of Australian Institutes of Transport Research (CAITR)*, 2002.

[27] G. K. Still. *Crowd Dynamics.* PhD thesis, university of warwick, 2000.

[28] Transportation Research Board. *2000 Highway Capacity Manual.* National Research Council, Washington, D.C., 2000.

[29] Y. Zhang, L. E. Owen, and J. E. Clark. A multi-regime approach for microscopic traffic simulation. In *The 77th TRB Annual Meeting*, 1998.