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Real-World Environment Models for Mobile Network Evaluation

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***Abstract*—Simulation environments are an important tool for the evaluation of new concepts in networking. The study of mobile ad hoc networks depends on understanding protocols from simulations, before these protocols are implemented in a real-world setting. To produce a real-world environment within which an ad hoc network can be formed among a set of nodes, there is a need for the development of realistic, generic and comprehensive mobility, and signal propagation models. In this paper, we propose the design of a mobility and signal propagation model that can be used in simulations to produce realistic network scenarios. Our model allows the placement of obstacles that restrict movement and signal propagation. Movement paths are constructed as Voronoi tessellations with the corner points of these obstacles as Voronoi sites. Our mobility model also introduces a signal propagation model that emulates properties of fading in the presence of obstacles. As a result, we have developed a complete environment in which network protocols can be studied on the basis of numerous performance metrics. Through simulation, we show that the proposed mobility model has a significant impact on network performance, especially when compared with other mobility models. In addition, we also observe that the performance of ad hoc network protocols is effected when different mobility scenarios are utilized.**

***Index Terms*—Ad hoc networks, mobility modeling.**

I. Introduction

The NATURE of mobile ad hoc networks makes simulation modeling an invaluable tool for understanding the operation of these networks. Wireless channels experience high variability in channel quality due to a variety of phenomenon, including multipath propagation, fading, atmospheric effects, and obstacles. While real-world tests are crucial for understanding the performance of mobile network protocols, simulation provides an environment with specific advantages over real-world studies. These advantages include repeatable scenarios, isolation of parameters, and exploration of a variety of metrics. Due to these benefits, simulation has become a popular tool for the development and study of ad hoc networking protocols. The vast majority of networking protocols proposed for ad hoc networks have been evaluated with some simulation tool.

Important components of ad hoc network simulators are the mobility and the signal propagation models. Once the nodes are initially placed, the mobility model dictates how the nodes move within the network. A variety of mobility models have been proposed for ad hoc networks [7], [11], [16], [18], [22], [28], and a survey of many has been conducted [8].

Though these models vary widely in their movement characteristics, what all of these models have in common is that the movement patterns they create are not necessarily comparable to true real-world movement. The models create random uncorrelated movement across unobstructed domains. In reality, people on college campuses, at conferences, and in shopping areas generally do not move in random directions in unobstructed areas. People tend to select a specific destination and follow a well-defined path to reach that destination. The selection of the path is influenced by both pathways and obstacles. For instance, on a college campus, individuals generally stay on paths that are provided for interconnecting the campus buildings. While certain individuals may stray from these paths (e.g., by cutting across lawns), the majority of people walk along the provided paths. Additionally, the destinations are typically not random, but are buildings, park benches, and other specific locations within the campus.

Previous research [8], [19] has shown that the mobility model used can significantly impact the performance of ad hoc routing protocols, including the packet delivery ratio, the control overhead, and the data packet delay. Hence, it is important to use mobility models that accurately represent the intended scenarios in which the protocol is likely to be utilized. In this way, the performance of the protocol can be more accurately predicted.

In this paper, we propose to create more realistic movement models through the incorporation of obstacles, the construction of realistic movement paths, and the determination of signal attenuation due to obstacles. The obstacles are placed within a network area to model the location of buildings within an environment, i.e., a college campus. Once the buildings are placed, we use the *Voronoi diagram* [23] of obstacle vertices to construct movement paths. Nodes are then randomly distributed across the paths. Destinations are selected from the set of obstacles, and shortest-path route computations are used to determine the path each node will use to reach its selected destination.

When introducing obstacles that affect the movement of mobile nodes in the simulation environment, it is necessary to model the properties of multipath propagation and fading properties of signals in the presence of these obstacles. Subsequently, we also propose the introduction of a noncomplex signal fading model that modifies the behavior of radio signals that propagate between a source and destination transceiver. The signal fades by a factor that depends on the relative

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positions of the two nodes and the material properties of the obstacles that lie in the path between the two nodes.

Our goal in this paper is to extend our previous work [19] and create a fully developed real-world model. To this extent, we have augmented the model with additional features including, most importantly, movement heuristics and realistic signal fading. Through an extensive set of new simulations, we believe that this extended model fully considers the major factors that affect communication in a mobile environment. Our specific contributions in this paper are the following.

- A signal propagation model that simulates fading of the radio signal as the signal propagates through obstacles that lie between a pair of nodes.
- A feature to modify the paths of the Voronoi graph to create a more realistic graph through control over the placement of doorways between the exterior and the interior of a building.
- A model for the selection of destination points on the Voronoi graph that is based on an exponential distribution.
- A configurable flash-crowd feature that helps a user simulate the confluence of a percentage of the nodes to a particular *attraction point* on the terrain.
- The evaluation of an additional set of metrics that compare the properties of the mobility models.

To evaluate our mobility model, we use two methodologies. In the first set of evaluations, we compare the network characteristics generated by our model to those of the random waypoint [7] and the random direction [28] models on the basis of mobility metrics. Second, we use the ad hoc on-demand distance vector (AODV) routing protocol [25] to compare its performance with our model to that of the random waypoint and the random direction models. Simulation results show that the use of obstacles and pathways have a significant impact on the performance of the AODV routing protocol. Network performance is also evaluated for movement variations and for variations in the signal attenuation factors.

The remainder of the paper is organized as follows. Section II details related research in the area of mobility modeling and signal propagation models and motivates the importance of creating realistic mobility and signal propagation models. Our proposed mobility model and our modeling of transmission through obstacles is described in detail in Section III. Section IV provides a description of the simulation setup. Section V presents the evaluation of our mobility model, and finally, Section VI offers some concluding remarks.

II. Background

There exists a wide variety of mobility models that have been postulated from both analytic and simulation-based studies on mobile systems. This section describes a sampling of these models. A concise categorization of mobility models has been presented previously [3].

Guerin's mobility model [15] has become the foundation for a number of mobility models. In this model, each node selects a direction θ in which to travel from the range $[0 \ldots 2\pi]$. The nodes select their speeds from a user-defined distribution of speeds, and then each node moves in its selected direction at its selected speed. After some randomly chosen period of time, each node halts and selects a new direction and speed. It then starts moving again.

A number of variations of this model have been proposed. For instance, in the random direction model, instead of moving for some period of time, each node moves until it reaches the boundary of the simulation area. It then selects a new direction in which to move. In a different variation of this model [17], [24], when a node reaches the simulation area boundary, it is reflected back into the simulation area in the direction of either $-\theta$, if it is on a vertical edge, or $(\pi - \theta)$, if it is on a horizontal edge. The velocity of the node is held constant. Like these two models, the group mobility model [18] is also based on the Geurin's model.

One of the most widely used mobility models is the random waypoint model. In this model, each node selects a random point in the simulation area as its destination, and a speed v from an input range $[v_{\min}, v_{\max}]$. The node then moves to its destination at its chosen speed. When the node reaches its destination, it rests for some amount of time. At the end of this period, it selects a new destination and speed and resumes movement. The properties of the random waypoint model have been extensively studied [4], [5], [27], [28]. One of the interesting results of these studies addresses the node spatial distribution of the random waypoint model. It is shown that, due to the characteristics of the model, the concentration of nodes follows a cyclic pattern during the lifetime of the network. The nodes tend to congregate in the center of the simulation area, resulting in nonuniform network density.

Another model, the boundless simulation area mobility model [16], removes the limitation of a "border" to the simulation are by allowing nodes to *wrap around* to the other side of the simulation area when they encounter a border. The effect of this change is to create a simulation area modeled as a torus, rather than a rectangular surface.

While each of the aforementioned mobility models generates random mobility and can be used to simulate ad hoc networking protocols, none of these models attempts to model the behavior of nodes in a realistic environment. The models assume open, unobstructed areas in which the nodes are free to move according to the constraints of the mobility model. Efforts to model real-world movement are represented by the Manhattan and the freeway mobility models [1], which simulate the movement of ad hoc nodes on streets and freeways, respectively. Mobile nodes are only allowed to move on horizontal and vertical pathways. Similarly, in the restricted random waypoint mobility model [6], nodes move within a certain geographic location, for instance a town, for a majority of the time. However, nodes may occasionally move from one town to another over a freeway. These papers suggest mobility models that do not depend on totally random movement, but instead involve certain real-movement characteristics.

The notion of constrained movement paths and obstructed signals due to natural and man-made obstacles has not been considered by any of the mobility models mentioned above. In real-world scenarios, it is rare that groups of people are located in completely unobstructed areas; there are typically buildings, vegetation, benches, cars, and other objects that obstruct one's path. Additionally, it is unlikely to be the case that people follow random trajectories. On campuses, people tend to follow provided pathways, in cities people follow sidewalks, in buildings people are confined to hallways, etc. While occasionally individuals may stray from the provided pathways, the majority of movement typically occurs along these paths. The obstacle mobility (OM) model that we develop in this paper provides a mechanism for modeling movement in a variety of real-world environments, where ad hoc network deployment is expected. A sampling of these include cities, campuses, highways, conferences, and battlefields. What most of these environments have in common is the presence of obstacles that block node movement. In this paper, we target scenarios that include the presence of buildings. These scenarios include college and business campuses, cities, and highways.

In addition to movement, it is important to model diffraction, reflection, scattering, multipath propagation, and attenuation that radio signals undergo due to the presence of building material, doors, windows, and other objects that lie in their path. To understand how a protocol will perform in an obstructed environment, it is necessary to create a combination of realistic mobility and signal propagation models that accurately model these environments. Methods to approximate the attenuation experienced due to the presence of a dielectric materials have been proposed [9], [10], [14], [20], [26]. These methods describe detailed approaches to evaluate the behavior of an electromagnetic wave that is incident upon the surface of a building. They also provide empirical results for penetration losses. Additionally, radio signal fading models have been suggested in books that address concepts of the electromagnetic wave theory [20], [26]. These books discuss sophisticated methods that closely approximate the attenuation experienced by a radio wave in the presence of materials of varying electrical, magnetic and environmental properties. Hence, it is important to create a lossy environment that models the real world so that protocols can be evaluated and further developed. The performance of protocols strongly relies on the estimation of loss-prone channels of communication between ad hoc nodes. Radio waves display an erratic behavior due to the following:

1) other waves in the range of the device that interfere with each other;
2) the nature of the ground surface;
3) reflection, deflection, diffraction, and scattering of a radio wave incident on a material object;
4) mobility of the transceiving devices.

Thus, we observe that connectivity between a pair of nodes cannot be assessed by merely assuming free-space losses of the signal power and signal interference effects of signals. Instead, it also depends on various obstacles that lie in the space through which radio signals propagate. In this paper, we consider empirical results [10], [14] and build a propagation model that can be used with existing network simulators [2], [13], since current versions of network simulators need to be updated so that they support these requirements. The results in these papers were obtained through an extensive set of real-world experiments. The most accurate way of obtaining the propagation loss of a radio wave by using a ad hoc network simulator is via computationally intensive ray-tracing methods. In order to account for the scalability constraints of network simulators, we decided to tradeoff the accuracy of signal fading/loss calculations to instead using a noncomplex method of modifying the signal strengths based on the aforementioned empirical results.

The following sections describe in detail the proposed mobility and signal propagation model and its effects on the movement and transmission ranges of the nodes within model.

III. Obstacle Mobility (OM) Model

Our *obstacle mobility (OM) model* has been designed to model the movement of mobile nodes in terrains that resemble real-world topographies. The objects model buildings and other structures that provide a barrier to both the movement of the mobile nodes, as well as the wireless transmission of these nodes. Our model consists of multiple components. The first component involves modeling a terrain in which a user can define the positions, shapes and sizes of these objects. Our model can handle arbitrary shapes and positions for the objects, allowing us to model many real-world terrains. The second component of our mobility model is a movement graph, which is a set of pathways along which the mobile nodes move. We use the Voronoi diagram [12] of the obstacle corners as our movement graph; this is a planar graph whose edges are line segments that are equidistant from two obstacle corners. While it may not be the case that pathways are always equidistant between building cites (i.e., in a city, sidewalks would typically line one or both sides of the street), the calculation of these pathways creates predetermined movement paths for the nodes to follow; it prevents the random movement. Thus, the Voronoi diagram captures the intuition that pathways tend to lie "halfway in between" adjacent buildings. Through the use of doorways on the sides of the building, we also allow movement through the buildings. The third component of the model is the route selection. We use the *shortest-path* routing policy to move the nodes between two locations in the movement graph. That is, each node moves to its destination by following the shortest path in the Voronoi diagram, where the cost of each path segment is its Euclidean length. Finally, the fourth component is the signal propagation model. This model computes the approximate signal attenuation experienced by the radio wave.

The following sections describe in detail the construction and placement of obstacles, the Voronoi diagram computation, and the movement and signal propagation models.

A. Obstacle Construction

In our model, arbitrarily complex polygonal shapes can be used to specify the obstacles (buildings). Each polygonal shape is specified as an ordered sequence of its vertices (corners), where each vertex is defined by its coordinates. Nonlinear shapes such as circles can be approximated by polygons, with the quality of approximation improving with the number of vertices in the polygon. The shape and the placement of the obstacles has an effect on the node connectivity and mobility. Each side of the object (building) has one or more doorways through which the nodes can enter or leave the building.

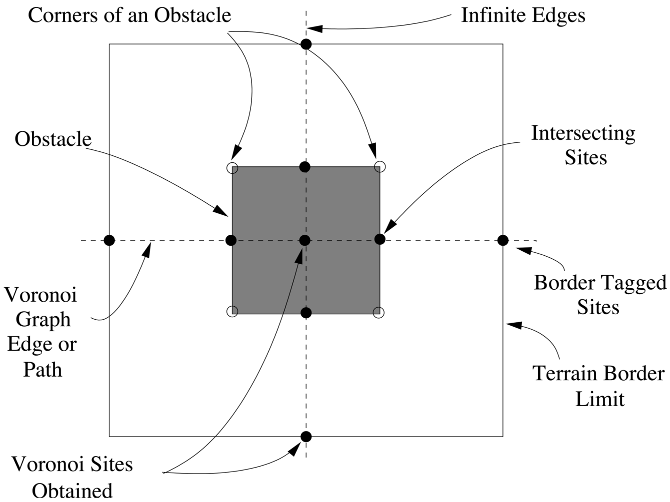

Fig. 1. Simple Voronoi diagram.

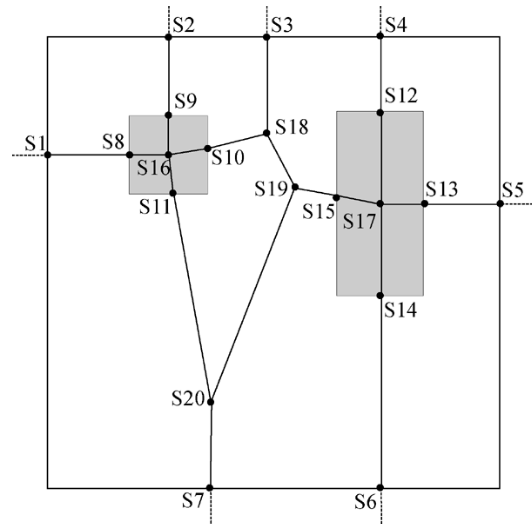

Fig. 2. Example terrain with labeled sites.

B. Voronoi Tessellation and Pathways

We now discuss how to generate the pathways between the obstacles. There can be no single model that is the best for all terrains, but an appealing "geometry-based" approach is to let the *obstacles determine the pathways*. Voronoi-diagram-based pathways generalize the intuitive notion that the pathways typically run in the middle of the two *adjacent* buildings. Before we discuss our pathways, we briefly describe this classical notion of Voronoi diagrams from computational geometry.

Consider a set of n points $P = \{p_1, p_2, \ldots, p_n\}$ in the two-dimensional plane. For ease of reference, we call each of these points a *location point*. The *Voronoi diagram* of P is a partition of the plane into convex polygonal cells, one cell per location point, so that every point in a cell is closer to its location point than to any other location point. Thus, a Voronoi cell of a location point p_i can be thought of as p_i's *region of influence*. The boundary edges of the cells are straight line segments, and each segment is *equidistant* from its two closest location points. The Voronoi diagram of n location points has $O(n)$ vertices and edges, and it can be computed in worst case time $O(nlogn)$ [23].

The topological structure of a Voronoi diagram is an embedded planar graph with straight line edges, as seen in Fig. 1. We will call this the *Voronoi graph* of P. Some of the edges of the diagram are semi-infinite[1] and, thus, it is convenient to assume that the diagram is drawn on the surface of a sphere. In our case, we assume that the simulation is limited to a large square region of the plane, and so the Voronoi diagram is clipped inside the square. Thus, if our terrain has only *point-size* obstacles $P = \{p_1, p_2, \ldots, p_n\}$, then the Voronoi graph will represent a natural set of pathways; that is, the path segments lie at equal distance from the two closest obstacles (location points).

We now describe how we build the Voronoi graph and pathways for our polygonal obstacles, and how we connect the pathways to buildings. We use the *corners* of all the obstacles in our terrain as the set of location points. Thus, the example in Fig. 2 has eight location points, which are the corners of the two rectangular obstacles. The reader may note that the shown Voronoi diagram has eight cells (regions). The vertices of the Voronoi graph, together with some additional vertices (defined next), act as the vertices of our pathways. First, we clip the Voronoi graph to lie entirely within the simulation region. The points of intersections between this outer boundary of the simulation region and the Voronoi graph also become the vertices in our pathways. Finally, the points of intersection between the Voronoi graph and the obstacle boundaries act as *doorways*.

[1]A semi-infinite edge is defined to be an edge that is unbounded on one end.

Fig. 2 illustrates the computed Voronoi diagram for a network containing two objects. The set of sites is

$$\mathcal{S} = \{s_1, s_2, \ldots, s_n\} \cup \{s_{b1}, s_{b2}, \ldots, s_{bm}\} \cup \{s_{i1}, s_{i2}, \ldots, s_{ik}\}$$

where s_1 to s_n are the n intersecting sites (e.g., s_8 through s_{15} in Fig. 2), s_{b1} to s_{bm} are the m border sites (e.g., s_1 through s_7), and s_{i1} to s_{ik} are the k sites generated by the Voronoi computation (e.g., s_{16} to s_{20}).

Given the set of sites S, the resulting set of edges generated by the Voronoi computation are

$$E = \{e_1, e_2, \ldots, e_l\}$$

where e_i is an edge in the Voronoi diagram D.

In this model, the user is free to modify the Voronoi diagram after it has been computed. It could be the case that, as result of the Voronoi computations, there are multiple pathways leading from the inside of an object to the outside, through different doorways on the same side of the object. To create more realistic structures, the user can limit the number of doorways on each side of an object to, say, one. Subsequently, the edges of the Voronoi diagram are modified such that the pathways that connect a point interior to an object to an external point pass through a single point (the doorway) on that side of that object.

C. Semi-Definitive Node Movement

In the proposed mobility model, nodes move along paths that are defined by the edges of the Voronoi diagram between the set of objects. These edges represent pathways that would typically be present connecting buildings on a business or college

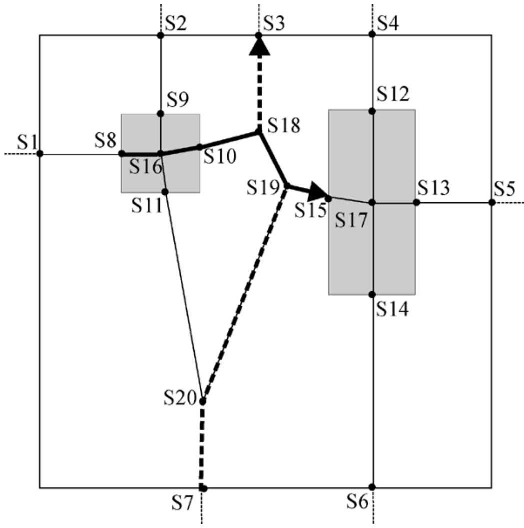

Fig. 3. Example of movement.

campus. Fig. 3 represents examples of paths that may be selected in the given network. Once the location of a node and its intended destination is determined, the path it will take to the destination is selected from the paths defined by the Voronoi diagram. The Voronoi diagram is predefined and establishes a path from each site to every other site. It is possible for the path between a pair of sites to traverse intermediate sites, as indicated by the example in Fig. 3.

The Voronoi graph consists of undirected edges, where the weight of an edge is the length of that edge. Intuitively, a mobile user would tend to select the shortest path to its destination. Using this model, we can obtain the shortest path between a node's current location and its destination by running a shortest-path computation, such as Dijkstra's algorithm. Once computed, the path to the destination site is maintained for each node. When the node reaches its destination, the process is repeated using the node's new location.

The random component of the movement is achieved through the initial placement of nodes at the sites within the network and the selection of destination sites. Further, the speed at which nodes travel to their destinations, as well as the pause times once they reach their destinations, are randomly chosen from a distribution input by the user. Hence, different seed values can be used to create variations in the initial distribution of nodes, the selection of destinations, and the speed of movement.

D. Mobility Variations

As previously described, node movement along the pathways can be as simple as random destination selection and subsequent movement to the chosen location. However, variations to this mobility pattern can be introduced to model movement scenarios that are both more realistic and more interesting, from a research standpoint. The following are mobility variations we have implemented in the obstacle model.

Exponentially distributed destination selection: In our earlier model [19], we indicated that a node selects a destination randomly and then moves to that point by computing the shortest path. This selection method follows a uniform distribution, i.e., the probability with which a node selects a destination is independent of its distance to the destination. A node may, hence, oscillate between opposite ends of the topography. In real-world movement, however, a person is more likely to select a destination that is close to his/her current location. The person is less likely to select a more distant destination, although it is still possible with a small probability. To model this movement, we suggest the use of a *weighted exponential distribution* selection of the destination, as shown in (1).

If a point m is the xth farthest point from the current location of the node, then the probability with which it is chosen can be given by

$$f(x) = ae^{-ax} \tag{1}$$

where a is a constant that can be selected to modify the distribution.[2] Thus, we see that the probability distribution function (PDF) of this expression makes the selection of a destination exponentially dependent on its distance from the current position of the node.

Attraction point movement: In addition to the exponentially distributed destination selection method, we also assume that in a real-world scenario multiple nodes may move toward a certain place of interest at the same time or within a specific interval of time. For instance, on a college campus, students and faculty members move toward the cafeterias during the lunch hour. Alternatively, special events on a campus are also likely to draw crowds of people. We call these places of interest *attraction points*. We add the support of attraction points to our mobility model so that a randomly chosen subset of nodes move toward a specific location at a specified time.

E. Signal Propagation Model

One of the primary limitations of the performance of wireless networks is the significant attenuation and interference experienced by the radio signal as it propagates from the sending node to the receiving node. In a setting with obstacles, the signal may reach the receiver via nonline-of-sight propagation mechanisms, such as reflection, diffraction, and scattering. This effect of *multipath propagation* results in a drop in the signal-to-noise ratio (SNR) of the received signal. The free-space fading models are not generally suited to calculate the attenuation undergone by the signal being received. Additionally, the fluctuations of the signal levels are lognormally distributed about a mean value and the changes in the signal levels are insignificant over short periods of time, leading to a phenomena called *long-term fading*. In our simulations, we use either the *two-ray path loss model* that accommodates the reflections of the signals off the surface of the ground, in addition to the direct path signals from the source transceiver to the destination transceiver; or the *Friis' free space equation* [26] which considers only a single path of propagation. The choice of these models depends on the value of the crossover distance d_c,[3] where d_c is the distance such that

[2] It is essential that a site on the graph is chosen at every instance of destination selection since $\int_0^\infty f(x)dx = \int_0^\infty ae^{-ax}dx = 1$. Here, we can assume that the number of points from which a selection is to be made is a large number.

[3] $d_c = (4\pi h_t h_r/\lambda)$, where h_t and h_r are the antenna heights of the transmitter and the receiver, respectively, and λ is the wavelength of the radio signal.

TABLE I
POWER ATTENUATION VALUES

	Home	Office
Single Wall	6 - 20 dB	6 - 20 db
Double Wall	40 - 50 dB	50 - 60 db

when $d = d_c$, the received power predicted by the two-ray ground model equals to that predicted by the Friis equation and:

- when $d < d_c$, we use the Friis' equation since the power attenuated is inversely proportional to d^4.
- when $d > d_c$, we use the two-ray path loss model since the power attenuated is inversely proportional to d^2.

In our previous work [19], we assumed that walls of building were thick enough to block any transmission that passes through them. In that case, two nodes located on opposite sides of one or more walls would not be able to communicate with each other. In the real world, however, a radio signal transmitted between a pair of nodes undergoes fading, attenuation, scattering, diffraction, reflection, multipath propagation, etc. In this paper, we use empirical results to simulate these effects. Hence, there is a possibility that two nodes that are obstructed by a wall or any other natural obstacle may still be able to communicate, but the signals that are received have a lower power level than if they had not passed through the obstacle.

Before a simulation begins, a user can specify the penetration characteristics of a building wall. There are two extreme cases for this specification. In the case of a perfect conductor, a radio wave that is incident on the material is completely attenuated (i.e., attenuation $A_t \to \infty$). On the other hand, an obstacle can be specified such that it obstructs only movement, and not the propagation of radio signals, e.g., a river. In this case, the radio wave does not fade due to the obstacle (i.e., $A_t = 0$). Hence, $0 \leq A_t \leq \infty$.

Some attenuation results are shown in Table I. The table shows the power attenuated when a radio wave penetrates through a single or double wall, in a home or an office building. For implementation purposes, we reduce the effective signal strength received at the receiver by a random value chosen from the range as specified in Table I for every obstacle in the straight-line path from a sender to the receiver.

IV. SIMULATIONS

The primary objective of our simulations is to understand the impact of obstacles in a simulation environment. To this end, we evaluate two aspects of the obstacle mobility model. First, we determine the characteristics of the network topology created by this model. Due to the presence of obstacles and defined pathways, characteristics, such as the average node density, are likely to differ when compared with other mobility models. Second, we determine the impact of our mobility model on the performance of an ad hoc routing protocol.

Specifically, to understand the network topology characteristics created by our mobility model, we evaluate the following metrics.

- **Node Density**: The average number of neighbors per node.
- **Path Length**: The number of hops from a source to a destination.
- **Average Link Duration (LD)**: The duration for which a link is available between two pairs of nodes.

The average link duration describes the connectivity of the nodes in the network. Bai *et al.* [1] suggest that this metric allows us to study the effect of the mobility pattern, which in turn affects the connectivity graph of nodes and the performance of the protocols. For comparison, the above metrics are also evaluated for the random waypoint model and the random direction model.

To determine the impact of the obstacles and pathways on the performance of routing, we utilize the AODV protocol for route discovery and path setup. In these simulations, we also compare the results with the performance of AODV using the random waypoint model and the random direction model. When using the random waypoint model or the random direction model, there are no obstacles in the simulation area. The metrics we evaluate in these simulations are the following.

- **Data Packet Reception**: The number of data packets received at their intended destinations.
- **Control Packet Overhead**: The number of network-layer control packet transmissions.
- **End-to-End Delay**: The end-to-end transmission time for data packets. This value includes delays due to route discovery.

The network scenario we utilize to evaluate the obstacle-oriented mobility model is shown in Fig. 4. This model was created based on the locations of buildings on the campus of the University of California at Santa Barbara. The model is a representation of the buildings on a selected area of the campus. We model an actual portion of the campus in order to create a realistic simulation terrain. The complexity of the geometric shapes of the buildings has been reduced by approximating the structures as units of rectangles, as described in Section III-A. The Voronoi paths are then generated based on this model.[4] At the beginning of simulations runs, the nodes are randomly placed at the sites composing the Voronoi graph.

In addition to these tests, we also evaluate the aforementioned metrics for the obstacle model along with the mobility variations. These variations include the exponentially distributed destination selection heuristic and the attraction point movement, as described earlier in Section III-D. Finally, we have also evaluated the effect of varying the penetration factor of building walls on the network performance.

The following sections give further details about the simulation parameters, as well as the obtained results.

A. Simulation Environment

All of the simulations were run using the NS-2 network simulator [13] with the CMU wireless ad hoc networking extensions. The simulation area is 1000 m $\times$ 1000 m, and the maximum node transmission range is 250 m. However, in the presence of obstructions, the actual transmission range of each individual node is likely to be limited. At the medium access

[4]Interestingly, the Voronoi diagram generated by this model closely approximates the actual paths that exist around these buildings.

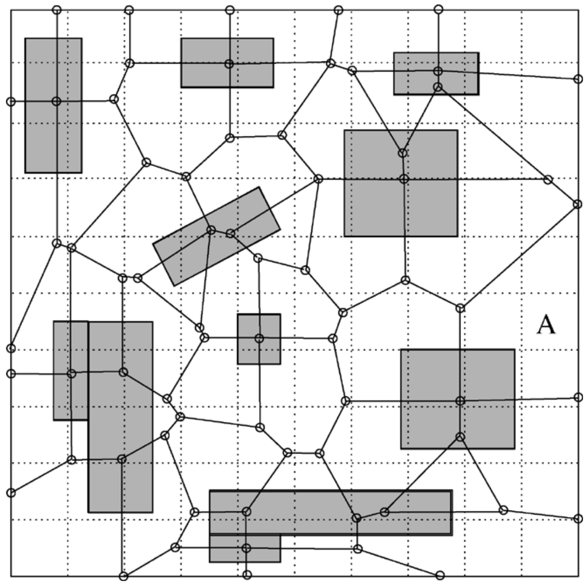

Fig. 4. Simulated terrain.

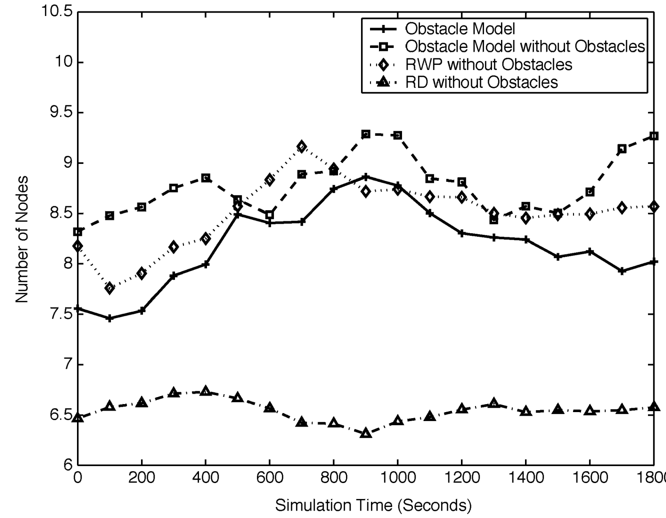

Fig. 5. Node density.

control (MAC) layer, the IEEE 802.11 distributed coordination function (DCF) protocol is used, and the bandwidth is 2 Mb/s. We assume that the nodes are on the same horizontal plane. Because we are modeling a campus environment, the mobility of the nodes, unless otherwise stated, is randomly selected between 0 and 5 m/s to represent walking speeds. The pause time in our simulations is randomly selected between 10 and 300 s. Each data point is an average of ten simulation runs with the nodes distributed in different initial positions.

To evaluate the characteristics of the network topologies created by the three mobility models, we randomly distribute the nodes at the beginning of the simulation. The number of neighbors per node is calculated for this initial distribution, as well as periodically throughout the simulation as the nodes move. To compute the average path length, nodes periodically discover routes to specified destinations throughout the simulation. The average discovered path length is plotted versus simulation time. We also calculate the average length of each link that exists between a pair of nodes during the simulations. This metric is evaluated by varying the number of nodes in the network from 20 to 100.

For these scenarios, we study the impact of both the predefined movement pathways and the inclusion of obstacles. To perform experiments using only the predefined pathways, we utilize the obstacles to compute the pathways, and then remove them when computing neighbors and path lengths. When the obstacles are included, they are utilized to obstruct transmissions, as well as for the pathway calculations. In both cases, the objects are in the locations illustrated in Fig. 4.

The second set of simulations compares the performance of the AODV routing protocol using the random waypoint model, the random direction model and our obstacle mobility model. After the initial distribution of the nodes, the nodes move for 60 s so that they are distributed throughout the simulation area. Ten data sessions are then started. The data packet size is 512 bytes and the sending rate is 4 packets/s. The maximum number of packets that can be sent per data session is set to 6000. Hence, an aggregate of 60 000 packets can be received by the ten destinations chosen. In these simulations, all nodes are assigned the same speed between 0 and 10 m/s, so that the effect of mobility can be determined. Movement continues throughout the simulations for a period of 1800 s.

In a third set of simulations, we vary the penetration factor of building walls by a specified percentage value. This implies that every obstacle wall attenuates the power of the incident radio wave by a percentage of its original power level. In these simulations, the attenuation experienced by a radio wave is varied from 0% to 100%, where 0% attenuation indicates no blocking at all, while 100% attenuation indicates complete blocking of the signal. Although this method of controlling the attenuation level is an unrealistic situation, we utilize it to evaluate the impact of the signal fading model.

The fourth set of simulations compares the effect of the movement variations on the network performance. In the obstacle model used in the previous set of simulations, destinations are selected randomly. In this set of simulations, destinations are either selected according to an weighted exponential destination selection method or based on an attraction point, as described in Section III-D. For the attraction point movement, we specify an $\mathrm{AP\text{-}Begin}$ and an $\mathrm{AP\text{-}End}$ time. Every node that needs to select its next destination at a time that falls between $\mathrm{AP\text{-}Begin}$ and $\mathrm{AP\text{-}End}$,[5] selects that destination to be a specified attraction point (AP). After the node reaches the AP, it pauses for a period of time, and then again selects a random destination.

V. RESULTS

Network Topology: The average number of neighbors per node throughout the simulations is shown in Fig. 5. The number of neighbors per node for the random waypoint model and the random direction model matches those previously demonstrated for 50 nodes with 250 m transmission ranges in a 1000 m × 1000 m area [21]. Using the obstacle model with the obstacles, the average number of neighbors per node is lower than in

[5]It is necessary that $\mathrm{AP\text{-}Begin}$ and $\mathrm{AP\text{-}End}$ be selected such that, $0 \leq \mathrm{AP\text{-}Begin} < \mathrm{AP\text{-}End} \leq \mathrm{Simulation\text{-}End\text{-}Time}$.

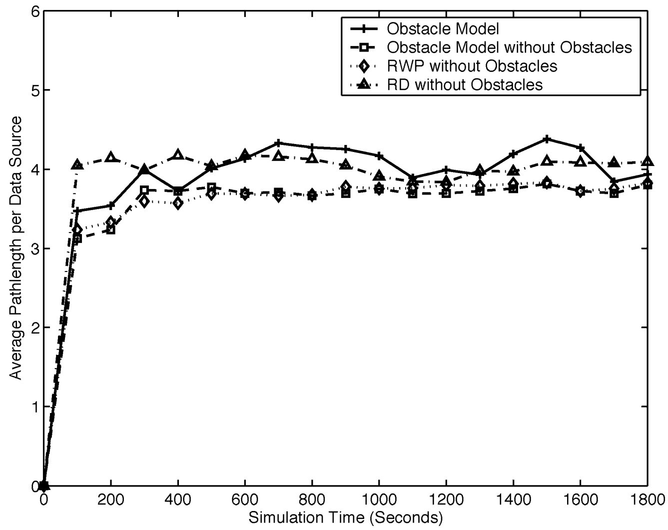

Fig. 6. Path length versus time.

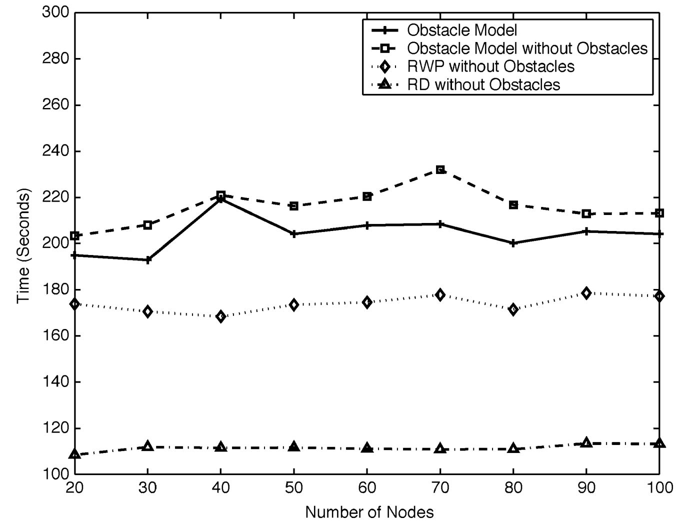

Fig. 7. Average link duration.

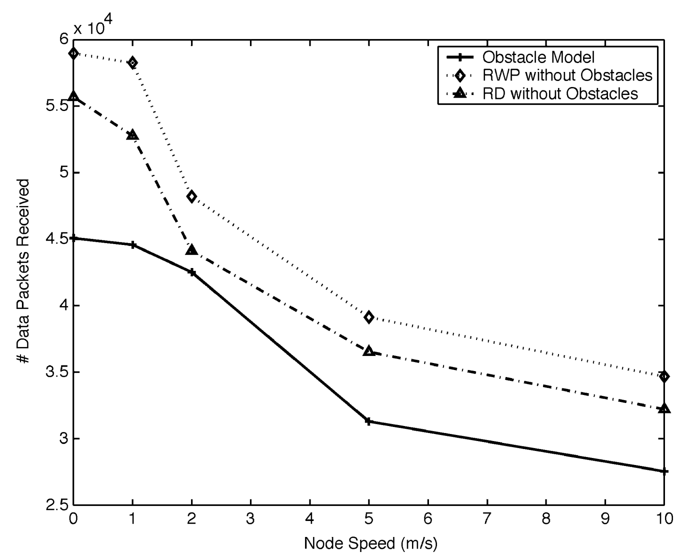

Fig. 8. Data packet reception.

the random models.[6] This can be explained by the fact that nodes that are across obstacles are obstructed by walls of the obstacles that attenuate the signal strength of the packets. Thus, the effective communication range between a pair of nodes is reduced. Hence, in many circumstances, a node's neighbors are not all nodes within the omnidirectional transmission range of the node; the transmission range is typically limited to some subset of this area. The number of neighbors is, therefore, decreased.

For the mobility model with pathways but not obstacles, the nodes maintain their 360° omnidirectional transmission ranges. In this scenario, the number of neighbors per node is about 10% greater than in the obstacle mobility model. This is due to the limitation of where the nodes may travel. Because the nodes can only traverse the defined pathways, the area of the network that can be occupied by a node is reduced. The network area can be divided into a grid as shown in Fig. 4. In the random models, each grid box has an equal probability of containing one or more nodes. However, the obstacle model limits the number of grid boxes that can contain mobile nodes to those containing pathways. For instance, a mobile node will never be located in the grid box labeled "A" in Fig. 4 because there is no pathway contained in this area. Hence, by limiting the movement of the nodes to the predefined pathways, the effective area of the network in which nodes can be located is reduced. This leads to higher clustering of nodes and, hence, a higher node density as indicated in Fig. 5.

Fig. 6 illustrates the average path length over time in each of the networks. The routes are initially discovered when the data sessions start. This occurs after 60 s of simulation time. The lengths of the paths are then tracked throughout the simulations. Path lengths may change due to link breaks and subsequent rediscovery of routes. The figure shows that path lengths are roughly the same for the random waypoint model and the obstacle model without obstacles. The obstacle model shows a slightly lower path length due to the presence of obstacles. This increase is directly dependent on the topology of the network. For instance, if a completely obstructing obstacle was placed horizontally across 90% of the network width, the path length from one side of the obstacle to the other would be increased significantly.

The effect of the mobility characteristics on the link duration between pairs of nodes is shown in Fig. 7. It can be observed from this figure that the link duration decreases in the presence of obstacles. This behavior can be attributed to more frequent link breaks due to obstacles. Shorter link lifetimes will most likely lead to lower data packet delivery and more route repairs.

Routing Performance: The total number of data packets received by their destinations is shown in Fig. 8. The number of data packets received using the obstacle model is lower than that using the random models. This is due to the lower probability of routes existing between sources that are not in the line-of-sight of each other. There is a possibility that a pair of nodes may not be able to talk to each other, even if they are geographically within the transmission range of each other. As shown in Table II, the number of failed route discoveries with the obstacle mobility model is slightly higher than with the random movement. In our model, once the route discovery is deemed a failure,

[6]Here, the term "random models" refer to the random waypoint model and the random direction model.

TABLE II
NUMBER OF FAILED CONNECTIONS

Mobility Model	Initial Failed Conn.	Total Failed Conn.
Random Waypoint	0.31	2.73
Random Direction	0.61	2.93
Obstacle	0.94	3.06

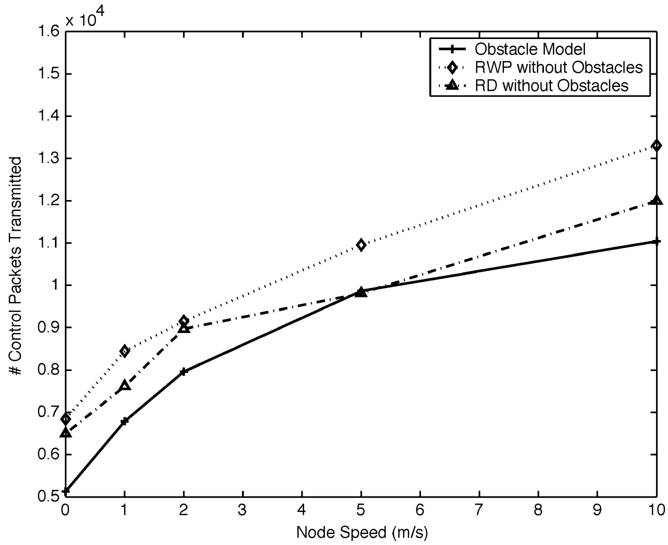

Fig. 9. Control packet overhead.

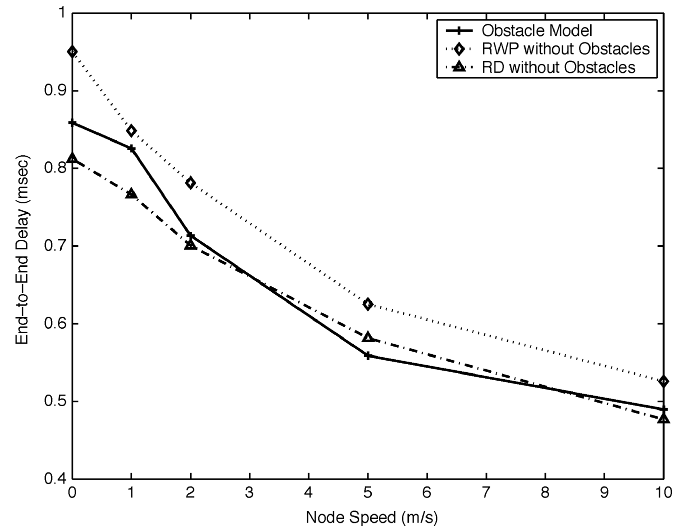

Fig. 10. End-to-end latency.

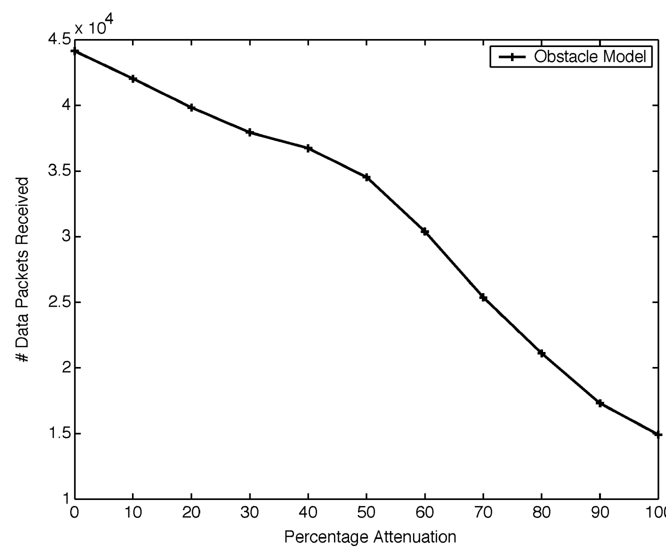

Fig. 11. Data packet reception versus signal attenuation percentage.

the data session between the source and destination is aborted; the route discovery is not reattempted later in the simulation. Based on these results, we hypothesize that, to improve data delivery, the source node should be allowed to periodically reattempt unsuccessful route discoveries throughout the simulation. That way, if a route later becomes available due to the movement of nodes, data packet delivery could resume. The investigation of this mechanism is an area of future work.

The control overhead is shown in Fig. 9. The graph shows that the number of control packets transmitted by the obstacle model is lower than in the random models. This result is directly correlated with the connectivity between nodes. In the obstacle model, routes may break more frequently due to signal fading caused by obstacle walls. Because data sessions are aborted if they cannot be repaired, fewer sessions are maintained throughout the simulation, resulting in less overhead.

Fig. 10 shows the end-to-end data packet delivery delay. This measurement includes the route acquisition latency for discovering routes. The figure shows that the data delivery delay for the obstacle model is lower than in the random models. Because there is a small decrease in the data sessions that are completed, there is less data traffic in the network overall. Hence, data packets experience less contention for transmission and are able to be delivered more quickly to their destinations.

To isolate the effect of the signal blocking property of the obstacle, we evaluate the performance of AODV for different percentages of allowed penetration. Fig. 11 shows that there is a significant decrease in the number of data packets received, as the attenuation experienced by the radio waves increases. With 0% attenuation, the number of link breaks solely due to obstacles is zero. Hence, there is no packet loss due to obstacles. As the attenuation factor increases to a *completely blocked* scenario, the number of packets received decreases. The 100% attenuation factor model is the same as the model we presented earlier [19] and, thus, the results correlate with our earlier study.

Movement Variations: The effect of movement variations is shown in Figs. 12–14. It is evident that with the exponential destination selection heuristic, every node remains localized in a certain area for a majority of the simulation time. This results in a lower probability of link breaks and broken routes. Consequently, we see in Fig. 12 that the number of data packets received does not decrease with the increase in the mobility, as compared with that of the random models. On the other hand, the attraction point feature displays a small increase in the number of data packets as mobility increases, as compared with the obstacle random model. This is because there is a convergence of a majority of the nodes close to the attraction point. Hence, path lengths between sources and receivers decrease, which in turn increases the data reception. Because the impact of attraction points is likely to be affected by the amount of traffic, we also evaluate this movement model in a congested network. In this case, we increase the number of data sessions

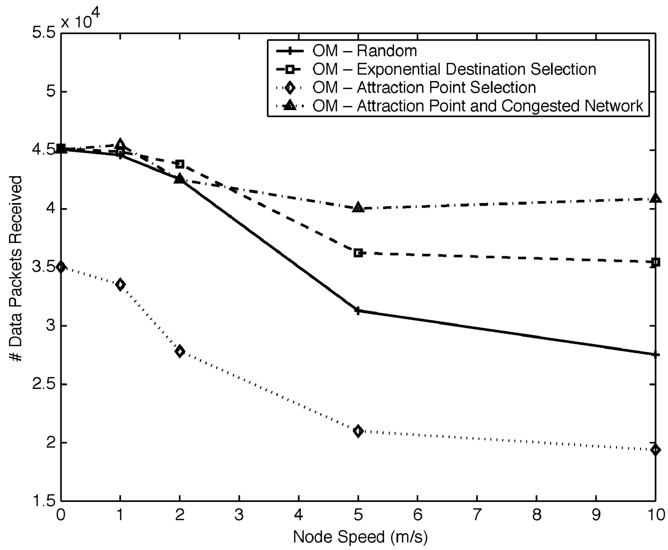

Fig. 12. Data packet reception.

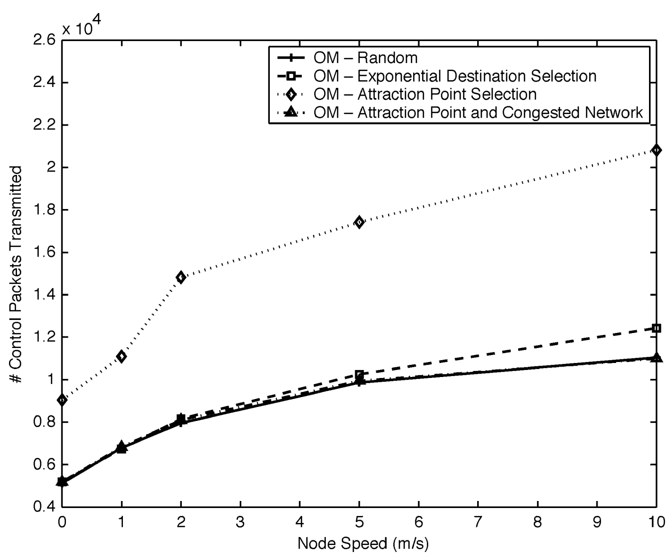

Fig. 13. Control packet overhead.

to 30. From Fig. 12, we observe that, as traffic congestion in the network increases, the number of data packets received decrease. This can be attributed to a significant increase in channel contention when a group of nodes come closer to the attraction point, resulting in a fewer packets delivered successfully.

Fig. 13 shows that the number of control packets for the exponential heuristic increases as mobility increases, but at a slower rate than the simple obstacle model. This agrees with our observation that nodes tend to remain localized, resulting in a reduction in the need to rediscover broken routes. The attraction point feature shows an increase in the control overhead due to congestion since convergence of nodes leads to an increase in the number of route changes and channel contention problems.

Fig. 14 shows the end-to-end latency for the models. The low latency value for the attraction point feature is due to shorter path lengths. However, as congestion increases, the latency of transmission of data packets between the sources and destinations increases significantly. This can also be attributed to the channel contention problems.

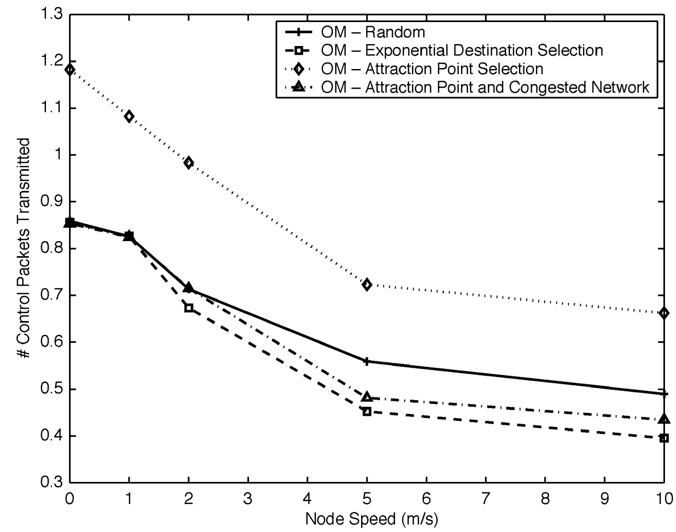

Fig. 14. End-to-end latency.

VI. Conclusion

This paper describes an obstacle mobility model that enables the inclusion of obstacles in ad hoc network simulations that are used both to define the movement pathways of the mobile nodes by Voronoi graph tesselations, and to obstruct the transmission of the nodes. The signal propagation model determines the reduction of signal power that takes place when communicating pairs of nodes must transmit through obstacles.

Our simulation results concur with a previous mobility model comparison [8] in that the mobility model significantly impacts the performance of ad hoc network routing protocols. Through the use of the AODV protocol, we have shown that the mobility model effects a variety of performance characteristics. We have shown that realistic movement patterns effects mobility metrics such as internode connectivity, node density, and the average link duration between nodes.

There are a number of ways to further extend this work. The first of these relates to the combination of movement characteristics of various mobility models presented in Section II to create a more diverse and comprehensive mobility model. For instance, multiple people may move to a destination as a group. This movement variation allows the combination of our obstacle mobility model and the group mobility model [18]. In another scenario, people may follow well-defined pathways to travel to their destination, such as a conference hall. Once they arrive at the hall, these people follow random movement. This scenario involves the combination of the obstacle mobility model to define pathway movement and the random mobility model after a node reaches its destination.

The specific values obtained in our simulations are strongly dependent on the configuration of the obstacles in the network terrain. However, the data leads to an important conclusion. The results show that a wide range of scenarios must be studied to discern the overall performance of the routing protocol.

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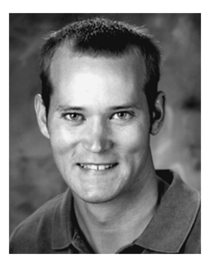

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