The Effect of the Radio Wave Propagation Model in Mobile Ad Hoc Networks

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ABSTRACT

The simulation of wireless networks has been an important tool for researchers and the industry in the last years. Especially in the field of Mobile Ad Hoc Networking, most current results have been achieved using simulators. The need for reproducible results and easy to observe environments limits the use of real world measurements for those kind of networks.

It is stated here that the radio wave propagation model has a strong impact on the results of the simulation run. This work shows the limitations of current simulation environments and describes a high accuracy propagation model based on the use of a ray-tracer. By using a parallelized preprocessing step we made this propagation model feasible for usage in network simulators. Based on two examples, the effects on characteristic performance properties in Mobile Ad Hoc Networks are shown. We found that the physical layer simulation has a great impact on routing protocol efficiency.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design; I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism—*Raytracing*

General Terms

Design, Performance

Keywords

MANET, simulation, physical layer, photon map, ray-tracing

1. INTRODUCTION

Wireless network simulation is an important part of the current research. A large number of algorithms were first implemented and evaluated using several network simulators like ns-2 [7]. Most MANET [9] routing protocols [11, 15, 3] have been developed and tested in that fashion, and only later they evolved towards real world implementations. The usage of simulators is sometimes criticized as inaccurate but nevertheless indispensable for efficient development of new protocols and networks. Especially in the case of mobile networks using dozens or hundreds of nodes, a real-life testing during the design phase of new algorithms is not feasible. Therefore the need for as accurate as possible simulators arises. In this work we will explain how to implement an accurate and efficient simulator for MANETs.

Many research groups use the network simulator ns-2 [7] for the simulation of wireless networks. It offers 802.11 and 802.15 simulation models and several Mobile Ad Hoc Network routing protocols like AODV, DSR and DSDV. Many of them made their extensions and modifications publically available so that there is a large number of protocols and applications obtainable. The presented results use an AODV implementation done by the University of Uppsala [13]. In general it can be noticed that people put a lot of trust in the results of this simulator, as numerous publications that use ns-2 show.

This work describes the radio wave propagation model of ns-2 with special emphasis on 802.11 [8] Mobile Ad Hoc Networks. It is shown how susceptible some protocols are to changes on the lower layers. Therefore, in this work we compare the performance of the AODV routing protocol with different propagation models. It is stated here that the accuracy of the radio wave propagation model has a strong impact on the simulation result in a way that questions the reliability of previous simulation results.

Our contributions are a fast and accurate radio wave model based on a raytracer, the integration of it in a network simulator and the invalidation of previous performance results for Mobile Ad Hoc Networks.

2. RELATED WORK

Radio channels are much more complicated to analyse than wired channels. Their characteristics may change rapidly and randomly. There are large differences between simple paths with line of sight (LOS) and those which have obstacles like buildings or elevations between the sender and the receiver. Most of the phenomena in radio wave propagation can be explained with reflection, diffraction and scattering. See [16] for details on the mentioned effects and propagation models.

To implement a channel model generally two cases are considered: large-scale and small-scale propagation models. Large scale propagation models account for the fact that a radio wave has to cover a growing area when the distance to the sender is increasing. Small scale models (often called *fading models*) calculate the signal strength depending on small movements (movements in the order of wave lengths) or small time frames. Due to multipath propagation of radio waves, small movements of the receiver can have large effects on the received signal strength. In the following, four fre-

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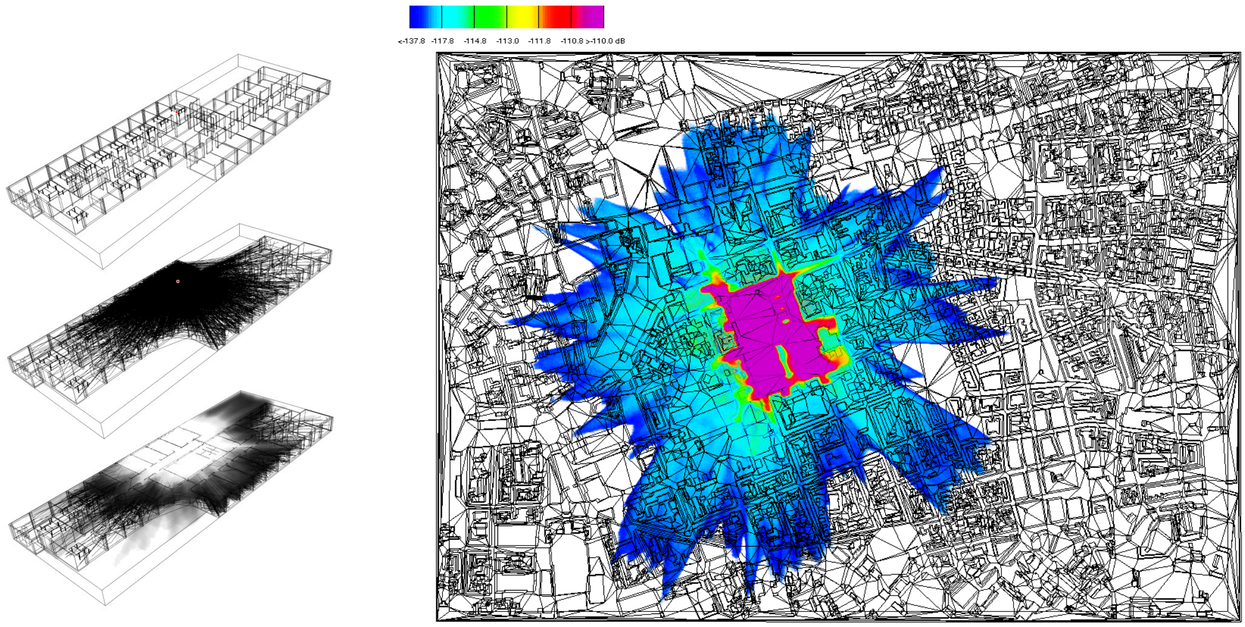


1.1: The Photon Path Map principle

1.2: Munich city center

Figure 1: 1.1 The left row of images shows the construction of the Photon Path Map. Starting with some geometry we compute the paths of the photons, beginning at the radiation source. In this image only paths that interact with boundary surfaces are given, for clarity purposes. After that a kernel density estimator is used to compute a radiance estimate for each voxel. 1.2 The volume image produced by the Munich city center scenario.

quently used models for the ns-2 network simulator are described in more detail.

- **Free Space Model:** This is a large scale model. The received power is only dependent on the transmitted power P_t, the antenna's gains (G_s and G_r) and on the distance between the sender and the receiver. It accounts mainly for the fact that a radio wave which moves away from the sender has to cover a larger area. So the received power decreases with the square of the distance.
- **Two Ray Ground Model:** The Two Ray Ground model is also a large scale model. It is assumed that the received energy is the sum of the direct line of sight path and the path including one reflection on the ground between the sender and the receiver. A limitation in ns-2 is that sender and receiver have to be on the same height.
- **Ricean and Rayleigh fading:** These two models are fading models, meaning that they describe the time-correlation of the received signal power. Fading is mostly caused by multipath propagation of the radio waves. If there are multiple indirect paths between the sender and the receiver, Rayleigh fading occurs. If there is one dominant (line of sight) path and multiple indirect signals, Ricean fading occurs.
- **Shadowing:** The shadowing model of ns-2 realizes the log-normal shadowing model. It is assumed that the average received signal power decreases logarithmically with distance. A gaussian random variable is added to this path loss to account for environmental influences at the sender and the receiver.

A common restriction of the presented models is the fact that they do not allow to specify obstacles in the environment. One model is used for the entire simulation time as well as for the simulation area, so that spatial and temporal variations cannot be modeled.

The quality of wireless network simulations has been questioned before. In [14] the credibility of simulation studies in general is criticized. It is stated there that this is mainly due to inaccurate explanations of the used simulation setup. Especially using pseudo random number generators and the type of the simulation (steady state or terminating simulation) are often not reported. Commonly used axioms for wireless network simulations are described and evaluated in [12] on the basis of real-world measurements. As a conclusion they give some recommendations. One is to use more realistic radio wave propagation models. Nevertheless the authors propose shadowing as the propagation model, stating that detailed radio and environmental modeling is difficult and out of the scope of their paper.

Quite a few ray-tracing approaches have already been proposed for wave propagation simulations [2], [17], [18], [19]. In the work of [2] it is doubtful if the algorithm scales well with larger scenes and huge target grid resolutions. The algorithm developed in [17] is effective, but the accuracy of the ray-tracing step depends on the selected grid resolution. The two publications by [18] and [19] do not have this problem, but the algorithm has to be augmented for indoor and outdoor scenarios. It is also a hybrid approach, using empirical methods to model the propagation and as such has other limitations. While they achieve very fast simulations for 2D indoor and 2.5D outdoor simulations, their performance at least for real 3D indoor scenarios degrades. In these cases our ray-tracing approach performs similarly, while it works on both indoor and outdoor scenes equally well.

In [5] an approach using ray-tracing technology is described. The authors include a propagation model into the ns-2 which uses ray-tracing to calculate the mean signal strength at the receiver. They include the ray-tracing algorithm into the ns-2 and repeat the ray-tracing step every 0.05s. The runtime of the simulator increases up to 100 times than without the ray-tracing step. The results of this computation cannot be saved for repeated simulations of the same scenario. We show how a preprocessing run allows the reuse of the ray-tracing results and thus makes the simulation efficient. We will also show how the propagation model increases the reliability of the presented simulation results and how it can even invalidate previous interpretations of performance comparisons.

3. RAYTRACED RADIO WAVE PROPAGATION MODEL

In this section we will introduce the underlying ray-tracing model for the simulation. The algorithm used is inherently capable of simulating 3D scenes and works with indoor and outdoor scenarios without modification. It can be thought of as a variant of other ray-launching algorithms or as a derivation of the light-tracing techniques known from computer graphics [6].

We will only sketch the algorithm, since its inner workings are not important here. Details will be published in a later work to show the complete algorithm.

3.1 Implementation

Our implementation is derived from the Photon Map which was introduced by [10]. The Photon Map is a data structure which describes the radiance on a surface. Radiance is a radiometric quantity, defined as the energetic flux per area.

Each sample in the photon map consists of a point, an associated energy and a direction (impulse) of a photon. By using density estimation techniques on these samples and knowledge of the surface materials one can compute the reflected radiance from the map. The reflected radiance describes the energy leaving the surface, that is the energy being received by a viewer.

We extend the idea of the Photon Map from a data structure containing the energy at boundary surfaces to a structure containing information about the energy density in a volume. Therefore we do not only store points, but whole photon path segments in the map. By applying a kernel density estimator we can tell for each 3D point in the scene the pathloss for a given signal. Furthermore the path structure allows for evaluation of delay spread and impulse response time information, although this has not yet been implemented.

In our specific implementation of the Photon Path Map we utilize a standard raytracer, which is capable of reading in user-specified scenes. These scenes consist of objects, e.g. buildings, for which surface properties can be specified. These properties determine the amount of radiation reflected or transmitted by the material. Also any number of radiation sources can be specified by giving their position, wavelength in meter and energy in Watt.

The raytracer will then perform a discrete, random sampling of the energy emitted from the radiation sources. This is done by shooting photons from the emitter and tracing their paths through the scene. On their way through the scene the photons may interact with the objects. They can be reflected, refracted, diffracted or absorbed by the obstacles that they encounter. These interaction paths are stored and later rendered into the volumetric image to give a density estimate of the energy in the volume. So actually instead of storing point samples like in the original Photon Map approach by [10], we store complete paths, i.e. sequences of line segments. This allows us to evaluate the radiance at any point in space, as seen in figure 1.1.

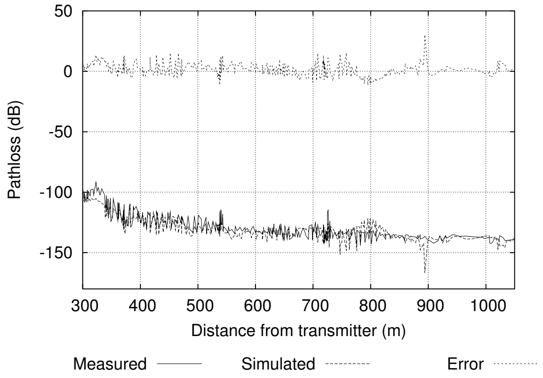


Figure 2: Simulation results for the Munich city center dataset. The lower two curves show the measured and simulated pathloss in dB and the plot at the top shows the error made in the simulation.

Also the resulting radiance volume image can be reused as long as the emitter is static. So for moving receivers the propagation simulation has to be computed only once. We use this property of the Photon Path Map to heavily accelerate the running time of the ns-2 over previous approaches using a raytracer [5]. We only need to precompute the scene for a subset of possible sender positions and do an interpolated lookup, as we will explain later. The preprocessing step can be done in a distributed manner. In our implementation we use a cluster of 49 dual core Opteron nodes, each of them being able to compute one or more possible base positions of the transmitter. So the result is an array of three-dimensional radiance images that describe the energy distribution in the scene for one given transmitter position.

3.2 Experimental Results

To show the validity of our chosen approach, we have used the ray-tracer on a large scale outdoor model, namely the Munich city center dataset [4], which was originally sampled by Mannesmann Mobilfunk GmbH, Germany. This dataset also includes real measurement data, against which our simulation can be tested. The tests were performed on a 2.2 GHz PC with 2 GByte of RAM. The scene contains approximately 80.000 triangles, generated from the original vector data set. An approximate 4 million photons have been generated in the simulation, leading to a volume image of size 512x512x16 as shown in figure 1.2. A graph of the simulation, the real measured values and the error made can be seen in figure 2. Our experimental results are summed up in the following table, as compared to [18]:

Method	Accuracy	Time	Abs. mean error	Standard deviation
Photon Path	~5 m	9m 20s	4.54 dB	5.82 dB
Dom. Path	10 m	~36s	3.75 dB	6.41 dB

The Dominant Path Prediction Model (DPP) which is described in [18] seems to be much faster, but uses a much lower target resolution of only 10m. Thus our approach has a relative performance loss here of about a factor of two to four.

For indoor scenarios the runtime of our algorithm is between 10 to 40 seconds, depending on the complexity, while the DPP takes only one or two seconds. The error our approach makes is on a similar scale as the one made by the DPP algorithm, where the standard deviation of both approaches lies around 5 dB for all simulations. Multi-story buildings and other geometry are no problem for our algorithm and especially here it is as fast as the other approach, if not better. This shows that our algorithm is very general and works well with real 3D scenarios, while the DPP is mostly optimized for 2D or 2.5D settings.

In general it can be said that the simulation is better, the more geometric detail is included in the scene. But even with coarse models, the simulation performed well in all our tests. We will use this approach in the propagation model of the ns-2.

The material properties of our models have been taken from measurements on the spot and also guesses that showed good correlation to the real measured pathloss values. After all, not every material aspect of the scene can usually be determined, as there are so many of them. But on the other hand many of them are not important for the simulation. For the transmitters, arbitrary configurations can be specified by the user. Different antenna configurations can be programmed, that exhibit different photon emission characteristics. The user can also specify the wavelength of the sender and its power.

4. SIMULATOR INTEGRATION

To be able to use the results generated by the ray-tracer, some modifications to the ns-2 wireless components have to be implemented. To better understand the needed changes, a short overview of the current implementation is given here.

If a node wants to transmit a packet, this packet will be handed down the network stack and will finally arrive at the wireless channel object. The wireless channel in turn identifies all *affected nodes* by searching all nodes which are within the interfering range of the sending node. The interfering range is determined by the propagation model. It is the maximum distance at which an unobstructed signal could disturb another transmission. It is dependant on the transmission power of the sender and the carrier sense threshold of the receiver. If a signal with power below the carrier sense threshold is received by a node, this signal is ignored.

In the next step, the propagation model is used to calculate the signal power received by each node in the interfering range. For this calculation, the propagation model is given information about the current position of the nodes, the sending power, and some antenna characteristics like height and gain.

Because of performance issues it is not possible to run the ray-tracer for every transmission. Instead, the ray-tracer is started from a set of points P_{start} within the simulation area. The selection of these points is done during the design of the simulation setup. As a result we have a set of precomputed propagation simulations which can be interpolated. A new signal strength between a transmitter t and a receiver r is calculated by selecting the k nearest start points regarding the transmitter position pos_t. This can efficiently be done by using a kd-tree [1]. In these k associated maps, the field strength s_i for the receiver position pos_r is looked up. The field strength s_{t-r} between the sender and the destination is then calculated by doing a nearest neighbor weighted interpolation.

$$s_{t-r} = \frac{\sum_{i=0}^{k-1} \frac{s_i}{\|pos_i - pos_t\|^p}}{\sum_{i=0}^{k-1} \frac{1}{\|pos_i - pos_t\|^p}}$$

where p is a weighting factor. This formula is chosen because it gives more emphasis to closer points which represent a better approximation of the field strength. The lookup in the tree and the calculation of the mentioned formula of course take some time. Table 1 shows the average time needed to run the simulations for the indoor scenario, which will be presented later.

Table 1: Runtime of the ns-2 simulator.

Number of nodes	Runtime (s) TwoRayGround	Runtime (s) PhotonPropagation	Factor
10	13.6	16.5	1.2
20	34.3	61.9	1.8
30	59.3	91.1	1.5
40	69.1	119.2	1.7
50	90.2	147.5	1.6

The changed propagation model also requires some other modifications when using the simulator. One is that the movement of the nodes is restricted by the obstacles. Nodes cannot move through an obstacle. For this, a movement generator has been developed which obeys to this restriction. The generator offers the possibility to define regions in which the nodes move and obstacles which prevent nodes from moving through it. For every region, a specific mobility model can be selected. The obstacles are set up with two values: the transparency and the reflection parameter needed by the ray-tracer.

To study the impact that the radio wave propagation model has on the performance of higher layer protocols, simulations were run, which only differ in the radio wave propagation model. Since Mobile Ad Hoc Networks have high requirements towards the simulation tool used, section 5 presents two scenarios with Mobile Ad Hoc Networks.

5. SIMULATION RESULTS

To evaluate the impact of the radio wave propagation model on the performance of a Mobile Ad Hoc Network the throughput and delay of multiple constant bit rate (CBR) streams is taken as an indicator. Measurements conducted by several researchers show that most simulators give too good values for these metrics. So any prediction derived from this simulation that concerns real networks is based on false assumptions.

In this work, two scenarios are simulated in detail. They represent very different working environments. One is an indoor scenario with low mobility and high node density. The second one is an outdoor scenario simulating pedestrian walking through a city. This scenario is characterized by a very low node density and a very hostile environment for radio waves: a few larger places, but mostly relatively narrow streets.

In the following two subsections the simulation setup and the results are shown. Both scenarios share some similarities: Network traffic is created by starting CBR connections between randomly selected nodes. The simulation duration is 15 minutes. All nodes are equipped with IEEE 802.11 network interfaces. The interface configuration is similar to the Cisco Systems access point *Aironet 1240 AG*. A receiving threshold of 1.58489×10^{-9}W (-88dBm) and a sending rate of 11Mbps is selected. The carrier sense threshold is set to 1.58489×10^{-11}W (-108dBm). All nodes send with a transmitter power of 0.1W (the maximum allowed power). Under FreeSpace assumptions these values yield a transmission range of approximately 133.6m and a sensing range of about 422.8m.

5.1 Indoor scenario

The indoor scenario is conducted on a simulation area whose layout is taken from the computer science building of RWTH Aachen

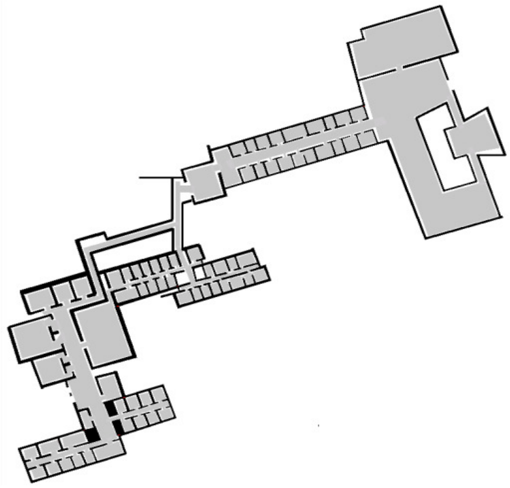


Figure 3: Indoor layout: The Computer Science building of the RWTH Aachen University.

University. For this building a 3D architectural map and some measurements of the radio signal strength exist. Figure 5.1 shows the model, which is on an area of $205m \times 209m$.

The movement for the nodes is created using a modified version of the random waypoint model. Nodes moving inside the offices have a very low mobility. Their pause time is equally distributed between 30 and 50 seconds. The movement speed is distributed uniformly between zero and two m/s. On the hallways, the node speed is uniformly distributed between one and two m/s and the nodes never pause. They may move from an office to the hallway, where they randomly select an exit to move to. The parameters for the ray-tracer were selected in a way that the resulting signal strengths are close to the measured ones.

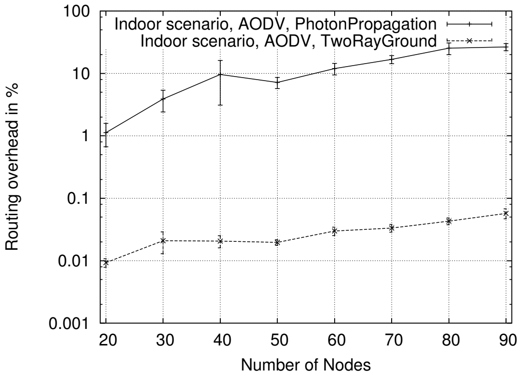


Figure 4: Average routing overhead for the indoor scenario.

The number of nodes in a scenario is varied between ten and ninety. The maximum number of CBR connections is set to ten, the offered load per connection is 32 kByte/s. Each simulation run has been repeated 500 times with different movement and traffic patterns over the course of a simulated time of 3600 seconds. All graphs show the average values and the 99% confidence interval.

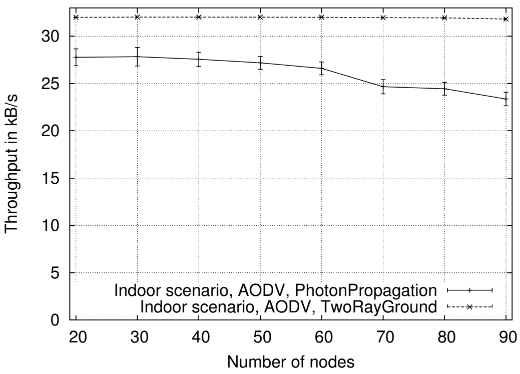


Figure 5: Throughput Comparison of different physical layer models.

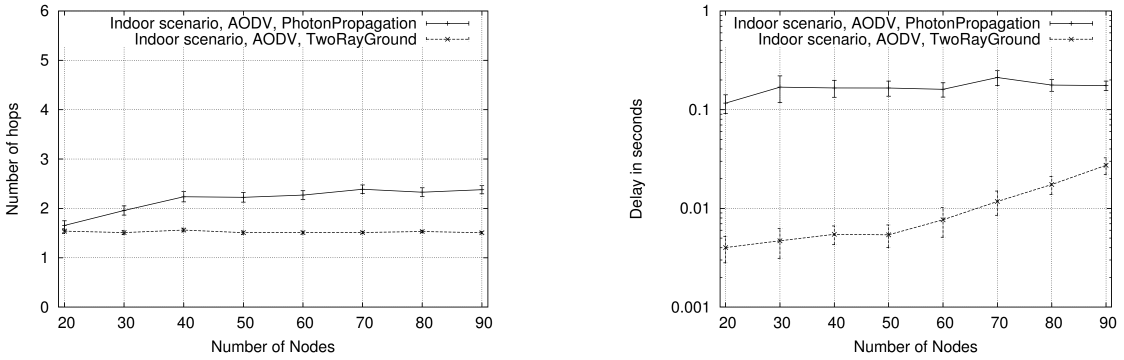
Figure 5 shows the throughput of CBR streams between randomly chosen sender and receiver pairs. The maximum offered load of each connection is 32 kBytes. With the TwoRayGround radio wave propagation model the nodes are able to achieve almost perfect throughput values. The 99%-confidence interval is only about one percent of the average value. When using PhotonPropagation model the throughput varies much more. This is due to the fact that the line of sight might be obstructed, which is not modeled in TwoRayGround.

The decreased throughput can also be attributed to the increased hopcount in the PhotonPropagation model, as shown in figure 6.1. Since this setup is more accurate, it correctly models the fact that in reality direct connections between two nodes are rather seldom in indoor scenarios. Up to now it was common use to simulate indoor scenarios by either decreasing the transmitter power or increasing the receive threshold. This way the transmission range was decreased to a value seen reasonable by the designer. In contrast our approach does not alter these settings but instead creates an accurate model of the network.

Figure 6.2 shows the average delay in milliseconds. Delay is defined as the time between the sending of the packet and the receiving of the packet. If the PhotonPropagation model is used, the delays increase drastically, which can be explained by the increased hop count and the higher number of route failures, as shown by the higher routing overhead (see figure 4). This is especially interesting, because the delay values grow larger than 200ms. As a rule of thumb, if 90 percent of the packets have less than 200ms delay, then good VoIP telephony is possible. This result confirms the observation that in Mobile Ad Hoc Networks IP telephony is hardly possible.

5.2 Outdoor Scenario

The outdoor scenario is based on the street map of the Aachen city, reproducing the streets and places which are pedestrian areas. The Buildings act as obstacles for the radio waves and narrow streets may act as wave guides. Buildings have high attenuation but do not completely block the signal. To generate the movement of the nodes, the Freeway model was assigned to all streets. All open spaces use the Random Waypoint model. Nodes move with speeds between one and three meters per second. The pause times are equally distributed between 20 and 50 seconds. If a movement



6.1: Number of hops

6.2: Average delay

Figure 6: Average number of hops and average delay for the indoor scenario.

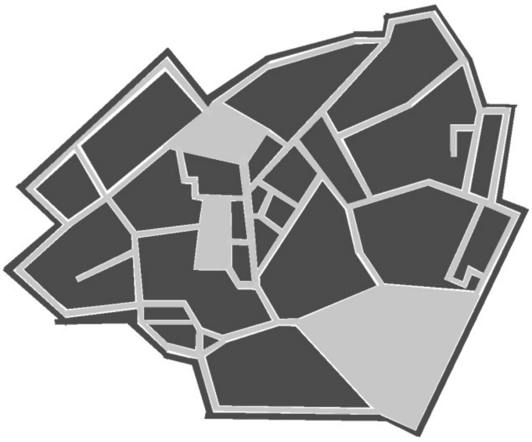


Figure 7: Layout of the movement zones for the outdoor scenario.

zone has more than one neighbor, then it is equally likely for every movement zone to become the next selected zone. Nodes are only moving on the streets, they cannot enter buildings. The layout is shown in figure 7. The light-grey zones are movement zones and the dark-grey zones model the buildings.

Figure 8.1 shows the throughput in kilobytes per second per connection, figure 8.2 shows the average delay. At first it may seem suprising, that the results with enabled photon propagation model are better than those with TwoRayGround. But the fact is that the environment is very hostile to the radio waves and as a consequence only very few connections can be build up with the photon propagation model. We have observed that many unidirectional links are established, to which the AODV algorithm is very sensitive. The established connections are those between nodes which are really close to each other.

6. CONCLUSION

This work presented a new radio wave propagation model with high accuracy and showed how this model affects the performance of Mobile Ad Hoc Networks in different scenarios.

It was demonstrated how a ray-tracer can be efficiently included into the ns-2 simulator. By these means a highly accurate propagation model could be created without sacrificing simulator performance. With these enhancements we have shown that the AODV routing algorithm performs quite different than as it performs when using a simple TwoRayGround model. We have observed an increasing hop-count and increasing delays for the indoor scenario. This result is important, because it gives another hint to the fact that simulation results for Mobile Ad Hoc Networks have to be interpreted with a lot of care. With our implementation we provide a tool that is much more reliable than previous works.

As further work, more detailed simulation scenarios will be created to shed more light on the question of which nature the bottlenecks in Mobile Ad Hoc Networks are. For example more accurate movement and communication patterns could give hints where existing protocols still have drawbacks and what has to be changed in order to overcome these problems. Especially when developing QoS-aware algorithms one can profit from a highly accurate simulator.

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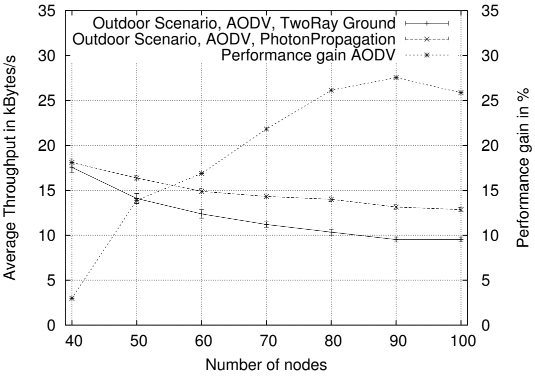
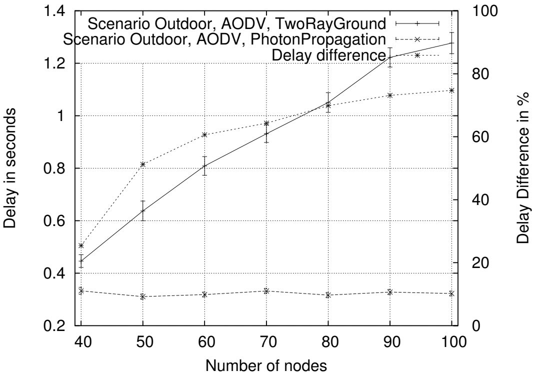


8.1: Throughput in the outdoor scenario



8.2: Delay in the outdoor scenario

Figure 8: Performance evaluation for the outdoor scenario.

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