Performance of Ad Hoc Routing Protocols in Urban Environments

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Abstract: **Multiple wireless terminals jointly create and maintain ad hoc networks without the help of central entities. Possible applications for such networks are in urban areas to avoid additional costs for communicating over cellular networks. Whenever two nodes are not within each others proximity, they use multihop connections for data exchanges. Ad hoc routing algorithms are utilized to setup these multihop connections. Most of them have been studied with the network simulator ns-2. In contrast to the proposed scenario, simulations always utilized flat simulation environments, with all nodes within line of sight. Within this paper, we introduce the well known Walfisch-Ikegami propagation model to allow ad hoc simulations in urban areas. It allows accurate propagation predictions, but does not significantly delay computation. Following simulations in two different urban situations reveal new performance insights. Ad hoc algorithms are able to cope with this environment, but compared to simulations with flat environments the overall network performance is significantly reduced.**

Keywords: **Ad Hoc Networks, Walfisch-Ikegami, Routing, Simulation, Performance**.

1. Introduction

Ad hoc networks are self configuring wireless networks without any fixed infrastructure. Nodes are able to create connections with distant communication partners. As they ought to be small devices with limited battery lifetimes, the maximum radio transmission range is small as well. Therefore, communication partners are often not within direct radio range and connections must be setup over multiple other nodes. Sources use these nodes as relays to forward data. Nodes are free to enter and leave ad hoc networks at any place and any time. Additionally they generally do not have stationary positions, but move independent from each other through the network. Their movement patterns are generally not correlated. With this node mobility, network topologies constantly change. These changes cause frequent route breaks and force sources to reestablish or maintain connections to their distant communication partners.

Numerous ad hoc routing algorithms exist to allow networking under various conditions. They can be separated into two groups: proactive and reactive algorithms [1][2]. Proactive algorithms always maintain an overview over the network and therewith nodes are able to create instant connections to other nodes. In case of frequent topology changes, the necessary overhead to maintain the necessary link tables often exceeds the advantage of quick route creations. Frequent routing packets congest the network and delay data packets or even cause packet drops. If nodes increase the period between consecutive topology updates, connectivity information in nodes possibly contains errors. These errors lead to misguided packets and therewith cause packet losses.

Reactive routing algorithms create routes only on demand and do not try to maintain an overview over the network. This reduces the generated overhead, but requires time consuming route creations, as sources do not have any path towards their destination. Previous publications (see section 5) depict, that reactive algorithms outperform proactive ones, especially for frequently changing network topologies. The reactive algorithms AODV [3] and DSR [4] show almost equal results. Some simulations favor ADOV, some DSR.

The major drawback of these simulations is their simulation setup. Although application scenarios for ad hoc networks are mostly placed in urban areas or indoors, all previous simulations assume flat simulation areas. All nodes are within line of sight (LOS) and a correct packet reception is only determined by the distance between sender and receiver. Previous publications do not yet considered the impact of urban areas on the performance of ad hoc routing algorithms. Routing performance changes considerably, if they must cope with buildings within the simulation area. Additionally, different ground plans might favor one or the other reactive routing algorithm.

Further on, valuable routing optimizations for flat simulation areas might be destructive within urban environments. Our simulations give new insights, whether ad hoc routing algorithms are able to cope with all kinds of environments, not only flat ones.

The following paper is structured as follows: Section 2 describes existing ns-2 propagation models and section 3 introduces our new urban propagation and mobility model. A simulation evaluation and comparison of two ad hoc routing algorithms within urban environments follows in section 4 and section 5 discusses related work. The paper sums up with a conclusion in section 6.

2. Current implementations of ns-2 propagation models

The assumed propagation model has great impact on wireless network performance. A model generally depends on various parameters. Some are easy to determine within simulations, like the distance between sender and receiver or the utilized frequency. But others must be represented as random functions or constant factors, like interferences or fading effects.

To allow reasonable simulations within an acceptable amount of time, propagation models must simplify calculations and reduce the required computation to a minimum. The network simulator ns-2 knows three different propagation models to simulate wireless ad hoc networks, the free space (FS) model, the two ray ground (TRG) model and the shadowing model.

The underlying channel model in ns-2 is quite simple. The simulator calculates the receiving power P_r for every transmission between two nodes with the chosen propagation model. The channel model distinguishes primarily between three cases. In case P_r is greater than the receiving threshold RX_{Thresh}, the transmission has enough power to allow proper reception at the receiver side. Other simultaneous transmissions with reasonable transmission powers may certainly interfere with this transmission and make a correct reception impossible. If P_r is below RX_{Thresh} but greater than the carrier sense threshold CS_{Thresh}, the receiving node must drop the packet. However, the receiving power of this transmission is still strong enough to interfere with other simultaneous transmissions. Consequently, these interfered packets are also invalid and nodes must drop them as well. Transmissions with receiving powers P_r smaller than CS_{Thresh} do not even obstruct other simultaneous transmissions at the same node. As ns-2 forwards all transmissions to all nodes, it is the most probable case. It is only necessary to improve simulation performance and to simplify packet processing during simulation.

2.1 Free space model

The free space model is the simplest model. It only assumes the direct path between transmitter t and receiver r. The receiving power P_r depends on the transmitted power P_t, the gain of the receiver and transmitter antenna (G_t, G_r) the wavelengthλ, the distance d between both nodes and a system loss coefficient L. All parameters, but the distance d, are system wide constant parameters. During a simulation run, the receiving power P_r only changes with the distance between sender and receiver. As both receiving parameters RX_{Thresh} and CS_{Thresh} are also constant throughout simulations, receiving nodes must be inside a perfect disc. Otherwise, they are unable to collect packets properly.

$$P_{r,FS} = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{\left(4\pi \cdot d\right)^2 \cdot L} \tag{1}$$

2.2 Two ray ground model

The TRG model is an improved version of the FS model. It considers the direct ray between sender and receiver, but also the ground reflection. As with the FS model, both nodes are assumed to be in LOS. The heights of both antennas over the ground are depicted with h_t and h_r and are constant during simulations. Up to the crossover distance $d_{Thresh} = 4\pi \cdot h_t \cdot h_r / \lambda$, the TRG model is equal to the FS model. Beyond this distance, the ground reflection destructively interferes with the direct ray and further reduces the field strength. The receiving signal strength is then inverse proportional to d^4. Just like the FS model, TRG contains only the distance between sender and receiver as variable parameter.

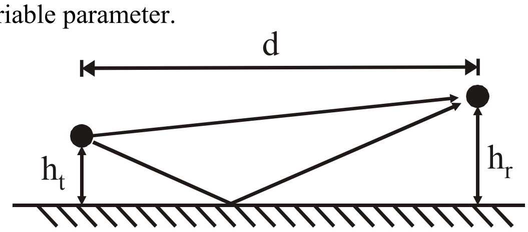

Figure 1: Two ray ground propagation model with its direct ray and the reflection.

$$P_{r,TR} = \begin{cases} P_{r,FS} & d < d_{Thresh} \\ \dfrac{P_t \cdot G_t \cdot G_r \cdot h_t^2 \cdot h_r^2}{d^4 \cdot L} & d \geq d_{Thresh} \end{cases} \tag{2}$$

2.3 Shadowing model

For both previous models, the sender-receiver distance is the only variable parameter during simulations. This forms a circular coverage around a sending node and a sharp range limit. Beyond this range, no further reception is possible. To introduce random events, the *shadowing model* utilizes a random variable X. The shadowing model requires a reference distance d_0 to calculate the average received FS signal strength $P_{r,FS}(d_0)$. The path loss exponent β in (3) depends on the simulated environment and is constant throughout simulations. Values vary between two (free space) and six (indoor, non-line-of-sight). X is normal distributed with an average of zero and a standard deviation σ (called shadow deviation). Again it is non-variable and reasonable values vary between three (factory, LOS) and twelve (outside of buildings). Values for β and σ were empirically determined.

$$\begin{aligned} P_{r,SH} &= P_{r,FS}(d_0)\left(\frac{d}{d_0}\right)^{-\beta} \cdot 10^X \\ X(x)&: \{x \in [-\infty, \infty] \,|\, P(x) = N(0, \sigma^2)\} \end{aligned} \tag{3}$$

Therewith the shadowing model introduces some kind of unpredictability for data transmissions. Correct receptions are guaranteed for close proximities and impossible over long distances, whereas correct receptions are unpredictable for medium distances. Nevertheless, the correct reception area still forms a disc when considering many transmissions.

The unpredictability is also the great disadvantage of this model. The signal strength variations are not direction-dependent and possible errors can occur during every transmission. It varies significantly between consecutive transmissions and even differs for the reception of the same transmission at different receiver. This might force ad hoc routing algorithms to establish new routes, even if packet losses are one-time events and following packets would be received successfully.

As shown, the receiver signal strength of all currently implemented propagation models for the ns-2 do only depend on the distance between sender and receiver as variable parameter. All other parameters are constant throughout simulations.

3. The city propagation model

With those simplified models, reasonable simulations of ad hoc algorithms in urban areas are not possible. Within cities, radio transmissions are heavily direction dependent and they do not solely depend on sender-receiver distances but also on the position of obstacles.
Numerous propagation models exist to forecast signal strength distributions in urban areas, but most require complex calculations. This leads to long simulation runs and therefore they prove oneself inappropriate for simulations with the ns-2 program suite.

3.1 Urban propagation model

Unlike others, the Walfisch-Ikegami model (WIM) [5] requires only few calculations to achieve sufficient accuracy for signal strength distributions in urban areas. The European Co-Operation in the field of Scientific and Technical research (COST) developed the model and the International Telecommunication Union (ITU) accepted it as propagation model for cellular networks. The COST 231 project [6] enhanced it for predictions in urban cells with small to medium radio transmission ranges. It shows small deviations compared to real-world measurements. Although COST originally developed WIM to forecast signal strengths in urban cellular networks, this model is also reasonable to predict field strengths in ad hoc network simulations.
The WIM model distinguishes only between two cases, LOS and non-LOS (NLOS) with buildings between sender and receiver. It assumes NLOS propagations only over roofs with diffractions at the first and the last building (see Figure 2 for details). Consequently, the decay decrease only with increasing distances between sender and receiver and not with the number of buildings in between. WIM requires several parameters in order to calculate accurate predictions. As COST developed the model for cellular networks, two parameters are outside of their approved range when used with ad hoc networks.

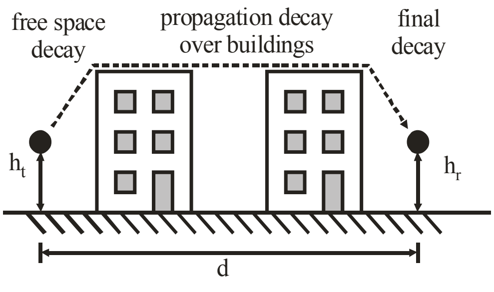

Figure 2: Over roof propagation of the Walfisch-Ikegami model.

The first parameter is the transmission frequency *f*. It should be below 2GHz, but the WLAN 802.11b standard defines its radio frequency with 2.4GHz. The second invalid parameter defines the heights of the sender. WIM requires a sender position h_t at least 4m above the ground, but a regular ad hoc node has probably a heights of 1.5m. As both differences are small and we do not need highly accurate predictions, the WIM model is still appropriate. All other parameters are within the required ranges. Node distances *d* must be smaller than 5000m and the receiver heights h_r in the range of 1...3m. Our ns-2 *cityprop* extension reads ground plans of an unlimited number of buildings from an input file. As WIM utilize only the average building heights, certain heights are not necessary, the input files provides only a single height for all buildings.
As Figure 2 shows, the overall decay value between two points is the sum of a free space, an over roof and a final decay value. Due to page restrictions, we do not show exact WIM model formulas, all details are in [5].
The WIM model unfortunately calculates only accurate decays for positions outside of buildings. In order to allow simulations with nodes inside of buildings, we added some additional computational methods. For decay calculations between positions inside buildings and locations outside, the program assumes LOS but adds additional 15dB to this result. This value ensures that transmissions span longer distances outside of buildings than to nodes inside. We assume LOS for senders and receivers within the same building.
Even with low computational requirements, WIM still lengthens simulation runs. It would be necessary to compute the field strength of all sender-receiver pairs for every transmission. To reduce this computational effort, we divide the simulation area into grid elements. Within each tile, the decay value is constant and defined by the value of its center. With the knowledge of the exact positions of buildings, the calculation of the decay value table is separable from the following simulation run.
The *cityprop* extension calculates the decay value between every two grid elements. With N_x the number of tiles in x-direction and N_y in y-direction, the number of necessary decay computations is $C=N_x \cdot N_y (N_x \cdot N_y+1)/2$. With $N_x=N_y=N$, the computational effort raise with $O(N^4)$. To allow fast calculations of decay tables, to minimize the size of output files and to save memory during ns-2 simulation runs, *N* must be as small as possible. On the other hand, to ensure reasonable decay calculations, *N* should not be too small. We run multiple simulations with 5m, 10m, and 20m edge lengths to determine a reasonable grid element size. The number of tiles per axis N_x and N_y is set according to the size of the simulation field and the tile edge lengths.
Packet loss and routing overhead of various ad hoc routing algorithms differ only by 2% for varying element sizes and therefore we omit to show these results. Although these little influence on performance, we refuse to use edge lengths of 20m. It occasionally causes NLOS conditions for clear LOS situations. As the decay value of a tile is determined by its center, fractions of tiles are outside of buildings but have decay values as they would be inside or vice versa. This falsification obviously increases with increasing edge lengths. As we do not have real world measurements, we tried to set the grid element size as small as possible to reduce the inaccuracy. For large simulations with a simulation field of 500x500m^2, 5m edge length is already too small. The size of the decay output file exceeds the 2GB limit of Linux. As tradeoff, we set the edge length of all elements in all simulations constantly to 10m. The decay value output file is still utilizable and the introduced error is negligible, when 10m tiles divide even greater simulation areas.

To allow the comparison of the optimal path and the chosen path between any two nodes as additional metric, the network simulator requires the optimal path information as input. As the shortest path between nodes depends on the network topology and its connectivity, it also depends on the calculated decay values. This would require the decay table as input parameter for the node movement generation. In order to simplify this handling, we combined the decay value calculations and the movement generation into one program and into a single output file. Therewith ns-2 jointly reads the decay value table and the node movement information before it starts the simulation.

3.2 Urban node mobility model

The random waypoint mobility (RWP) model [7] commonly generates the node movements in ad hoc network simulations. These movement patterns work well for flat simulation areas, but show unrealistic behaviors in urban environments.

RWP controlled nodes does not interfere with their surrounding environment. They enter and leave buildings at any place and do not try to go around them. In order to allow more realistic node movements, we introduce the *city motion* (CM) mobility model. It is based on the RWP model but considers the position of buildings.

Just as RWP controlled nodes, CM nodes randomly choose destinations inside the simulation area and start moving towards them. In case they reach a building on their way to the destination, they choose with an 80% probability a new destination and stay outside of the building. For the remaining 20% probability, they do not change their direction and move straight into the building. Nodes inside of buildings behave comparable. When engaging walls, they choose with 80% probability new destinations and stay inside, otherwise they leave the building. To keep the computational complexity as low as possible, CM controlled nodes may enter or leave buildings at any point. The chosen probability distribution between both cases allows nodes to stay mostly on their particular side of wall.

4. Results

As shown in section 5, AODV and DSR mostly perform better than other ad hoc routing algorithms. Therefore, we focus only on these algorithms and test how they cope with urban environments. We define two different building plans. The *Manhattan* scenario should adapt large cities with regular ground plans. All buildings have rectangular shapes and equal sizes and neighboring buildings have the same distance from each other. The *Italy* scenario has less buildings but each building has more corners and no right angles. It is more similar to European city centers with an irregular ground plan. As already described, the simulation area is limited, because the size of grid elements should be small, while the number of elements must not exceed a certain threshold value. The tile size is constant for all simulations and has an edge length of 10m. For simulations with 30 and 50 nodes, we use a 350x350m^2 simulation area, for simulations with 100 nodes both edges of the simulation field have a length of 500m. The main mobility model is the CM model. Although RWP shows unrealistic movement patterns in urban areas, we still run simulations with this model to allow comparisons with results from [8][9]. The maximum node velocity is either 1m/s or 10m/s. This allows a conclusion concerning the ability of an algorithm to cope with high and low mobility profiles. Nodes do not pause between consecutive movements. The literature shows, that algorithms have most problems to cope with these parameters and performance differences are most obvious. To minimize effects during the initial startup phase, and in accordance with previous work, the simulation period is set to 900s.

Again following previous publications, we use the existing WLAN 802.11b [10] implementation of ns-2 2.1b9a [11] version with a maximum throughput of 11MBit/s. Data packets are unacknowledged and sources do not retransmit lost packets. Data packet flows have a constant bit rate (CBR), each packet has a payload of 64 Bytes, and each source generates 4 packets/s. 50% of all simulated nodes act as traffic sources. Therefore, larger simulations with more nodes must cope with greater network loads and longer average paths.

To compare these two ad hoc routing algorithms, we chose three different metrics:

- The *packet loss* metric is the ratio between data packets dropped while traversing the network and originally send data packets. The loss ratio only considers CBR data packets and no signaling packets.
- The *routing overhead* metric depicts the ratio between signaling bytes and the total number of send bytes. All route request and route reply packets count as routing overhead. Information send over multiple hops count multiple times and this metric considers source routing information in DSR data packets as overhead.
- The *path optimality* metric describes the quotient between optimal path lengths and true number of hops required to reach destinations. Larger values (close to one) indicate frequently used optimal paths.

4.1 Italy scenario

The first simulations run with the Italy scenario and Figure 3 shows the corresponding results. The overall packet loss for simulations with 50 nodes is below the loss of simulations with only 30 nodes. We traced back the increased packet loss with 30 nodes simulations to an insufficient coverage of the 350x350m^2 area. As in previous work (see section 5), DSR performs better than AODV for limited network sizes and low node mobility. It is obvious, that the packet loss raise with increasing maximum node velocities, but it is unexpected, that the CM model has packet loss rates well below the values for the RWP model. Using the Italy ground plan, this behavior is independent from the network size, the utilized routing algorithm, and the maximum node velocity. A more detailed analysis showed packet losses mostly occur when nodes move inside of buildings, because this dramatically alters the propagation decay between sender and receiver. As the CM prevents frequent movements into buildings, it performs better than the RWP model. For larger networks (100 nodes) and with fast moving nodes, AODV has a much better performance than DSR. With up to 80%, DSR has an unacceptable packet loss rate, whereas AODV can keep it well below 40%. For small network sizes, the routing overhead is for both algorithms and any mobility pattern around 55%. For greater networks, the overhead raise to more than 80%. Comparable to the packet loss metric, the DSR overhead is below the AODV overhead for small networks and low mobility cases, whereas it is above AODV for large networks and high mobility patterns. Interestingly, the path optimality metric of DSR is always better than that of AODV, even if the routing overhead and the packet loss are worse.

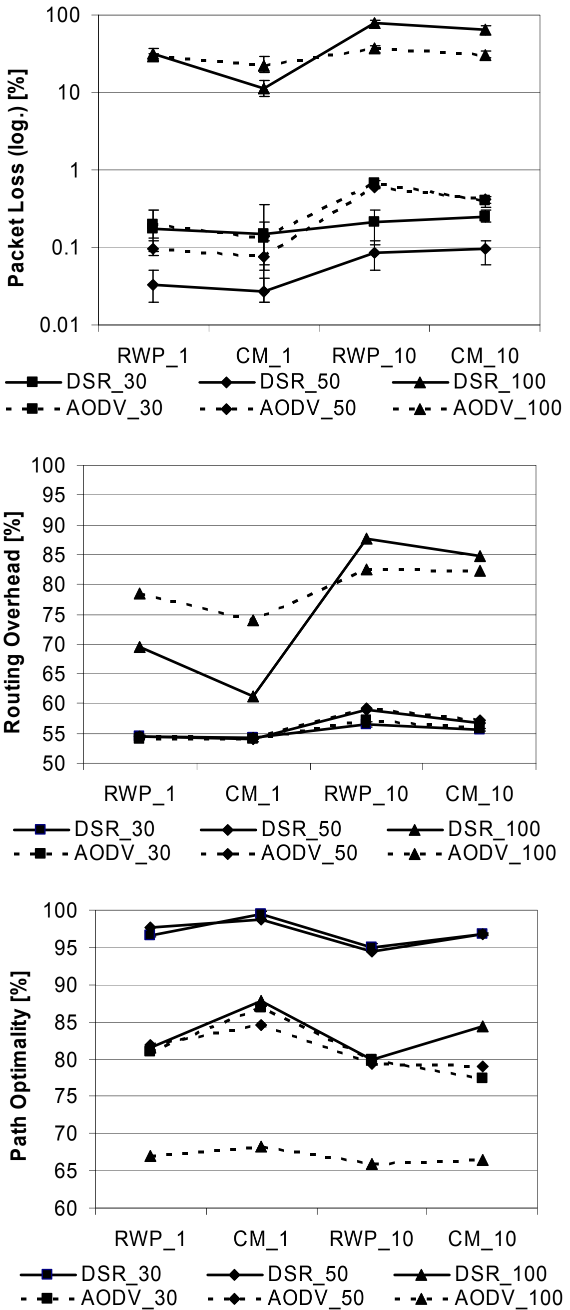

Figure 3: Packet loss, routing overhead and path optimality for the Italy scenario.

Compared to the TRG model, the usage of WIM as propagation model does greatly reduce the maximum transmissions range and therefore requires higher node densities than before. In contrast to flat simulation areas, it also worsens the overall network performance, because it requires more frequent route reestablishments. Interestingly enough it does not alter the performance relationship between DSR and AODV, compared to the existing results (see section 5).

Only the confidence intervals for packet loss results have reasonable values, and Figure 3 and Figure 4 depict them. The confidence intervals for the routing overhead and the path optimality results are small and negligible. We omit to show them in the figures for representational reasons. The division of the y-axis for the packet loss is logarithmic in both figures.

4.2 Manhattan scenario

The Manhattan ground plan as second scenario has much more buildings within the simulation area. This forces both routing algorithms to generate more frequent route requests in order to compensate shorter path lifetimes compared to the Italy scenario. Therefore, both algorithms have significantly increased packet losses (Figure 4) for small network sizes. This is independent from the utilized mobility patterns. As within the Italy scenario, the CM model causes less packet losses than the RWP model. For larger simulations (100 nodes), AODV again outperforms DSR. We do not have a detailed explanation yet, why the CM model causes more packet losses for the high mobility case. Especially AODV generates much more losses when node movements follow the CM rather than the RWP model.

For the Manhattan scenario, it seems that the possibility to stay outside of buildings also increases the chance for nodes to disappear behind nearby corners. Nodes which move unaltered through buildings might keep an existing connection alive longer than nodes interfering with their environment.

This hypothesis is enforced by the fact that the AODV routing overhead raises for high mobility simulations with CM compared to those with RWP. As the average route lifetime with CM is below the average of RWP more route requests traverse the network, congest it, and increase the overhead. For smaller network sizes, the routing overhead proportion between CM and RWP follows the original relationship. Routes stay longer alive, when nodes move more seldom inside of buildings. The possibility that these nodes disappear behind corners is much smaller, as they move much slower.

The fact that for small network sizes (30 nodes) the packet loss decreases while the mobility of nodes increase is another important point to mention. This only happens in networks with insufficient numbers of nodes to cover complete simulation areas. Nodes frequently form two independent networks. Network separations occur with slowly and fast moving nodes, but separations last longer for low mobility patterns. With steady moving nodes, more packets get lost if source and destinations are separated. With faster moving nodes, such conditions generally do not last as long and increases the possibility that at least some packets arrive at their.

As with the Italy scenario, DSR outperforms AODV with regard to the path optimality metric, while the difference between both algorithms is less significant. For AODV with 100 fast moving nodes, the path optimality metric decrease as fast as its belonging packet loss and routing overhead increases.

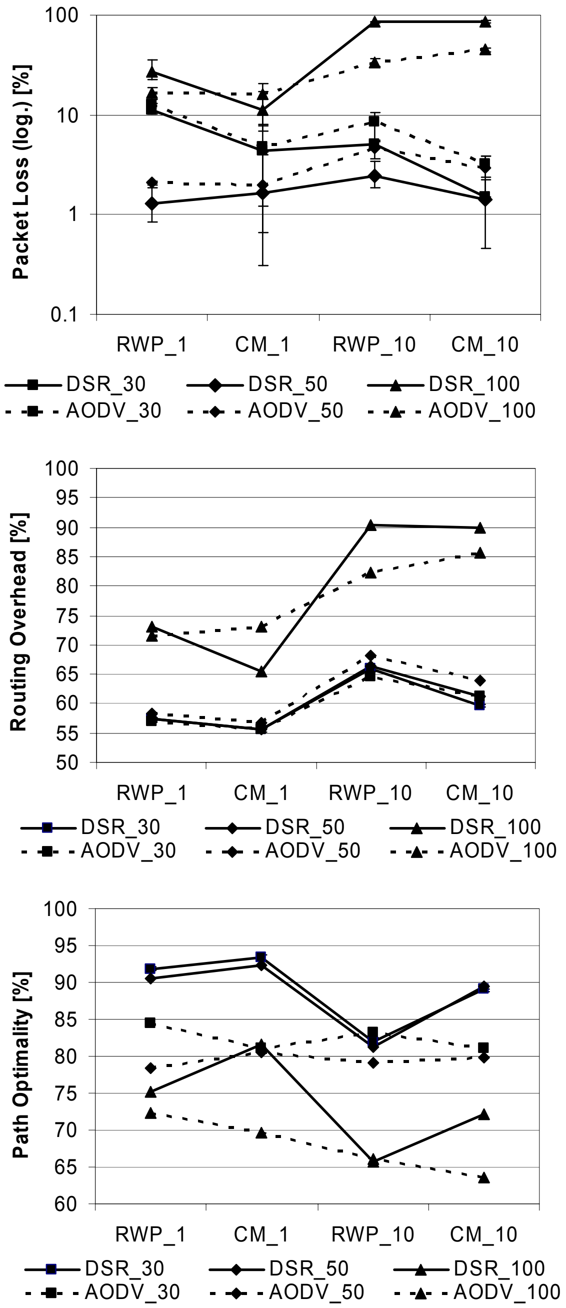

Figure 4: Packet loss, routing overhead and path optimality for the Manhattan scenario.

For the Manhattan scenario, DSR still performs better than AODV for low mobility patterns and within networks with limited numbers of nodes, while AODV is able to show its strength to cope with large networks and fast moving nodes.

Significant differences appear when comparing simulations with WIM as propagation model with results from the literature using the TRG model. While the performance relations between AODV and DSR remains unchanged, the absolute performance is much worse. Especially for simulations with 100 nodes, the packet loss is unacceptable. From this point of view, it is questionable if large networks in urban environment can exist, and nodes are able to keep their connections alive.

5. Related work

Broch et. al. [8] firstly use the ns-2 for performance measurements of ad hoc algorithms. They use the standard WLAN 802.11 as MAC layer and the TRG model as propagation model. They run simulations with 50 nodes. Their results reveal that all algorithms perform worst if they must cope with continuous node movements. DSDV and TORA always cause high packet losses and routing overheads. For networks with limited number of nodes, Broch's simulations reveal that DSR outperforms AODV in terms of packet loss and routing overhead.

Johanson et. al. [9] run similar simulations, again with TRG as propagation model. It reveals, that AODV has a reduced packet loss compared to DSR within low load scenarios, and shows equal results for high loads. AODV requires more routing packets, but DSR generates more byte overhead. An obstacle scenario shows the ability of the algorithms to cope with frequent link breaks. This very basic model only considers the LOS and the NLOS case. If obstacles are between senders and receivers correct packet receptions are impossible. The results show no new insights. AODV and DSR perform almost equal.

Das et. al. [12] also use TRG. Their simulation setup differs slightly from previous experiments, but results again show, that AODV outperforms DSR within challenging scenarios (network load, number of nodes, maximum node velocity). Whereas DSR is more suitable for less challenging conditions and for situations, in which routing overhead has to be low. To our knowledge, no further publications exist, considering the impact of propagation models on ad hoc network performance.

6. Conclusion

Within this paper, we introduced the Walfisch-Ikegami propagation model to allow ad hoc network simulations within urban areas. The literature shows that it allows sufficient accuracy while not significantly delaying the computation. In order to use a realistic simulation setup we do not use the random waypoint mobility model but introduce an improved version. With this model, nodes consider the position of buildings when moving within the simulation area. Running simulations with both extensions show large deviations to previous work. While the relation between the performance of AODV and DSR remains unchanged, the absolute performance values significantly degrade. DSR outperforms AODV in simulations with small networks and a low mobility profiles with respect to packet loss and path optimality. In contrast to that, AODV shows better performance in scenarios with more nodes and an increased terminal mobility. As expected, the ground plan has great influence on network performance. Densely positioned buildings cause more route breaks and packet losses than environments with sparsely deployed buildings.

Compared to results using flat simulation environments, AODV and DSR show significantly degraded results. The path lifetimes are very short and require frequent route reestablishments in order to allow continuous data exchange. Especially large networks with 100 nodes suffer from these route breaks and show poor results. Packet losses beyond 80% and routing overheads of almost 90% prevent any kind of reasonable node-to-node communication. Using our simulations as reference, it is very questionable, if large ad hoc networks can be maintained in urban environments.

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