A simulation study of routing performance in realistic urban scenarios for MANETs ⋆

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Abstract. We study through simulation the performance of two MANET routing algorithms in a realistic urban environment. The two algorithms, AODV and AntHocNet, are representative of two different approaches and design methodologies. AODV is a a reference state-of-the-art algorithm following a purely reactive approach. AntHocNet is based on swarm intelligence and integrates proactive and reactive mechanisms. Our objective is to investigate the usefulness of the different approaches they adopt when confronted with the peculiarities of urban environments and the requirements of real-world applications. At this aim we define a detailed and realistic simulation setup. We model node mobility by limiting node movements to the streets and open spaces of the town, use a ray-tracing approach to model the propagation of radio waves, and investigate different kinds of realistic traffic patterns resulting from SMS messaging, VoIP communications, interaction between a control node and a fleet of vehicles, and existence of a fixed infrastructure mesh.

1 Introduction

In the past few years, the study of *mobile ad hoc networks (MANETs)* has attracted a lot of research interest, mainly from the networking community, but also from the swarm intelligence community. A significant part of the research efforts have focused on routing, which is particularly challenging in MANETs due to the extremely dynamic nature of these networks, and requires algorithms that work in a fully distributed way, are able to self-organize, and to show a robust and adaptive behavior. As a result, a number of MANET routing protocols have been designed so far (see [1–3] for overviews). However, due to the high cost and technological difficulty of setting up real MANET testbeds, most of research is carried out in simulation. These simulation studies are usually based on highly simplified scenarios, where nodes move randomly in a large open area, and rely on idealized models of physical phenomena such as radio propagation and interference. In recent years, however, experiences with real world testbeds (e.g., [4]) have lead to an increasing awareness that results from such simple simulations do not reflect well the difficulties and the performance that can be expected in reality. There is therefore now a lot of interest in the study of simulation scenarios that reflect the more complex situations that can be found in reality (see e.g. [5]). Urban scenarios are hereby of primary interest, since mesh ad hoc networks in densely populated areas can be seen both as an alternative or a complement to GSM networks, and are actually already being deployed in some major cities, such as Philadelphia and Taipei.

In this paper, we investigate the distinctive properties of urban scenarios in terms of radio propagation, mobility patterns, and data patterns, and we study how they affect the effectiveness of different core mechanisms commonly used in routing algorithms. At this aim, we consider two well-known algorithms, *AntHocNet* [6, 7] and *Ad-hoc On-demand Distance Vector routing (AODV)* [8], which have different characteristics and are representative of two

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different approaches to routing. AODV, developed in the network community, is a state-of-the-art algorithm that adopts a purely reactive strategy: it sets up a route on-demand at the start of a communication session, and uses it till it breaks, after which a new route setup is initiated. AntHocNet is a swarm intelligence algorithm designed by the authors after a specific self-organizing behavior of ant colonies, the shortest paths discovery, and the principles of the related framework of *ant colony optimization (ACO)* [9, 10]. AntHocNet is based on the integration of a reactive and a proactive approach to set-up, maintain, improve paths.

We evaluate both algorithms under different scenarios in an urban environment derived from the street organization of the Swiss town of Lugano. We model urban mobility by limiting the movements of the nodes to streets and open areas in the town, and adjusting their speed to the typical speed of people in a urban environment, be it pedestrians, cyclists or cars. We model the physical propagation of radio waves through the streets of the town using a ray-tracing approach, which accounts for interactions between radio waves and buildings, such as reflection and diffraction [11]. We also did an effort to account for different possible usages of the network, modeling different kinds of entertainment and commercial applications, such as interactive short messaging service (SMS), voice-over-IP (VoIP) traffic, and the case of a single node concentrating most of the traffic, to model a main server or a control center communicating with a fleet of goods delivery vehicles. The aim of this work is to point out pro and cons of the considered approaches, both originally developed to mainly address open space situations, when dealing with the challenges of realistic urban scenarios.

The rest of this paper is organized as follows. First, we explain the simulation setup. We show the urban scenario, explain how mobility and radio propagation was simulated, and describe the different types of traffic patterns that we simulate. Next, we provide a short description of the two routing algorithms. Then, we provide a set of simulation results, and draw some conclusions about the usefulness of the two different approaches for MANETs in an urban environment.

2 The simulation setup

For the simulations presented in this paper, we made use of the QualNet [12] discrete event simulator, to which we have made some adaptations in order to get a realistic simulation of urban conditions. QualNet provides faithful implementations of the different network protocols. At the physical and datalink layer, we used the IEEE 802.11b algorithm, running in distributed coordination function mode, and sending 2Mbps at 2.4GHz. At the network layer, we used the routing algorithms described in Section 3. Finally UDP is used at the transport layer, as it is commonly known that TCP has difficulties to work properly in MANETs [13]. In the following of this section, we first describe the town scenario and the associated node mobility. Next, we explain how we modeled urban radio propagation. Then, we discuss the data traffic patterns we used.

2.1 The urban scenario and node mobility

Lugano is a relatively small old town presenting an irregular street topology common to most European cities. We focused on an area of $1561 \times 997 m^2$, which covers most of downtown Lugano. The street structure is shown in Figure 1. The cityscape is basically composed of streets (the white lanes) and buildings (the gray polygons). In the image, the dark segment is the train rail that goes through the train station, while the bottom part shows a part of the lake. Streets define the open spaces where nodes are free to move. Buildings are inaccessible to the nodes and basically play the role of obstacles that put constraints on node movements and shield and reflect signal propagation. Node movements were generated according to an

Fig. 1. The Swiss town of Lugano used as urban model for our simulation studies.

adaptation of the popular random waypoint mobility model (RWP) [14]. Under this model, nodes iteratively choose a random destination and speed, move in a straight line to the chosen destination at the chosen speed, and then pause for a certain time. In our urban version of RWP, destinations are only chosen from among the open spaces in the town, and nodes do not move along a straight line to their destination, but instead follow the shortest path through the streets of the town.

In all our simulations, we have chosen node speeds that correspond to realistic inner city movements. In most simulations, we chose the MANET nodes to be pedestrians, with a maximum speed of 3 m/s. Only in the experiments with increased mobility, we allow nodes to go up to 15 m/s, which is a reasonably maximum speed for cars in an urban environment. The pause time of our RWP is always 30 sec. Finally, in all experiments, we keep 20% of the nodes static, to represent immobile network users in the town or mesh infrastructure devices.

2.2 Radio propagation

Wireless communication in an urban environment is strongly conditioned by the way radio waves interact with the objects they encounter. The most basic effect is that waves produced at street level are blocked by buildings, so that connectivity in urban wireless networks is restricted compared to open space scenarios. Many urban simulation studies for MANETs only account for this effect, using open space propagation models along the line of sight (LoS) and blocking any non-LoS communication (see e.g. [15]). Others use different heuristic approximations, reducing signal strength for each encountered building (e.g., [5]). In the current study, we use a more detailed approach, which incorporates also other propagation effects. The most important of these effects is reflection off buildings: as radio rays bounce off building walls, they can travel around corners into side streets. Also, reflection allows a signal to travel further along the LoS through a street than it would in open space, since multiple reflected rays are tunneled in the same direction. This means that crude approximation models that do not account for reflection are too restrictive. Another important effect is diffraction, which allows rays to bend around corners to a certain extent. This further improves connectivity to side streets. Other effects include scattering, which is the reflection off small objects and uneven surfaces, and signal variations over time due to changes in the environment, such as the passing of vehicles or people. Both of these last effects are hard to model correctly and greatly increase the computational complexity (see [16]), and were therefore not taken into account.

The modeling of radio propagation was done in preprocessing using the WinProp tool [17], which is a commercial software package to calculate ray propagation in urban environments. We started from a two-dimensional map of the center of Lugano, and assumed each building on the map to be of a height sufficient to block radio communication going over it (a height of

5 meters already makes diffraction over the building impossible [16]). Then, we took sample positions every 5 meters along the streets of the town, resulting in 6070 different positions. We placed a transmitter sending with 10mW at 2.4GHz in each of these positions, and calculated the resulting received signal strength in each of the other positions using WinProp. Subsequently, we adapted the radio propagation module of QualNet. The precalculated signal strength values are read into memory. During the simulation, the signal strength between a transmitter a and a receiver b is approximated by the precalculated signal strength between a transmitter in the sample point closest to a and a receiver in the point closest to b. This results in a maximal error of 2.5 meters on each side.

2.3 Traffic patterns

In order to account for different possible uses of the network by the users' community, we consider two different scenarios for traffic load and distribution. In the first scenario, the network is used as a normal telephone network. All nodes are seen as equal peers and the two end-nodes of a traffic session are selected at random among all nodes. Data traffic is exchanged in bi-directional way by 20 sessions, to model interactive communications. Data rate is varied, from 1 packet every 30 seconds, representing an interactive SMS conversation, up to 25 packets/s, which is sufficient to support good quality VoIP applications. The packet size if set to 160 bytes which is the paylod used by the G.711 PCM voice codec and can also represent a typical size on an SMS. In order to represent silent periods in the interactive communication, only 40% of all scheduled packets are sent (this corresponds to the typical proportion of send time in VoIP traffic).

In the second scenario, we envisage a commercial use of the network. A control center (e.g., a depot of a delivery company) is engaged in continual bi-directional data communications with a fleet of 10 vehicles to allow, for example, the exchange of information about local traffic or of new plans for pick-up and delivery. In this case, data packets are generated according to a negative exponential distribution for both payload and inter-arrival time with, respectively, average values of 256 bytes and 0.5 sec. This star-like traffic distribution is integrated by the presence of additional 10 CBR traffic sessions (2 packets/s, payload of 64 bytes) active between the other nodes, that play the role of a lightweight background load.

3 The routing algorithms

In our performance study for urban environments we consider the ant-based algorithm AntHocNet and AODV, a reference state-of-the-art algorithm developed in the network community. Both algorithms have been presented in a number of papers, therefore, here we just provide a short description of their characteristics.

AODV [8] follows a reactive approach to routing, which means that nodes only gather routing information for destinations that they are actively communicating with. Nodes that start a data session with a destination that they have no information about, launch a route discovery process that, if successful, set up a single path to route session data. During the session, the only action taken by the routing algorithm is to periodically send out beacon messages, which allows nodes along the path to control whether each link is still alive. When a link failure is detected, either intermediate nodes try to locally rebuild the route or the source starts a new route discovery process.

AntHocNet [6, 7] combines the typical path sampling behavior of ACO algorithms with a pheromone bootstrapping mechanism analogous to that used in Bellman-Ford algorithms to adaptively learn pheromone tables playing the role of routing tables. AntHocNet can be described as a hybrid algorithm, which means that it combines both reactive and proactive elements. It is reactive since it gathers routing information at the start of a new session via the generation of path discovery agents called reactive ants, it uses periodic broadcast of messages to detect link failures, and it reacts to route failures with the generation of ants for local repair or with a new route discovery otherwise. In addition to this, and differently from AODV, while a route is being used AntHocNet also performs proactive actions to improve and extend the available routing information.

The proactive route improvement is based on a combination of two mechanisms. The first of these is a pheromone diffusion process: in the messages that nodes periodically send out, they include pheromone information about the paths that they have available. Receiving nodes use this information to update their own pheromone tables, and in turn they send out in their pheromone messages the updated information. However, since the diffused pheromone information propagates slowly the resulting routing paths are potentially unreliable (e.g., they can contain loops). Therefore, this information is kept separate from the routing information that was originally obtained via the reactive ant setup. The second mechanism involved in proactive route improvement is precisely aimed at checking the reliability of the diffused routing information. Each source periodically sends out so-called proactive ants to discover new or better paths to the destination. These ant agents make use of all the routing information at the nodes, including the diffused one, to follow the best paths that seems to be available. When a proactive ant reaches the destination, it can confirm the reliability of the routing information it has followed, and establishes a new route.

The proactive route improvement allows to adapt available routing information to continual changes. This way, better paths can be used, and multiple paths can be made available both to increase throughput and to serve as backup in case of a link failure. The cost of the process is the creation of larger pheromone messages, and the periodic transmission of proactive ants for path probing.

4 Results and discussion

In this section, we first show some general properties of our urban setup. Then we discuss the results of a number of tests we have carried out. In particular, we investigate the performance of AODV and AntHocNet in scenarios with varying traffic loads and distribution, node density, and node speed. All reported data points represent averages over 10 different runs of 500 simulated seconds each.

4.1 General network properties

We study how the structural properties of the network are affected by the fact that we work in an urban environment, in order to form a basis for the understanding of the routing performance results presented further on. The data shown here were obtained by running simulations with an increasing number of nodes in both the urban scenario and an open space scenario of the same dimensions. In Table 1, we report results for the average number of neighbors, the connectivity (i.e., the fraction of node pairs between which a path exists), the average length of the shortest path between each pair of nodes, and the average link duration. The average number of neighbors is a lot lower in the urban scenario than in the open space scenario, and, while both grow linearly with the number of nodes, the increase is steeper for the open scenario. This means that in the urban case, there is typically less interference among nodes, but also less good connectivity. The latter is confirmed when we investigate connectivity: while the open space scenario is always fully connected, the urban scenario has limited connectivity when there are few nodes in the network. It is interesting to note that the connectivity in urban conditions seems to saturate at a value that is lower than

Table 1. Graph properties of MANETs with increasing number of nodes in the urban versus open space environment

	Average # of neighbors		Fraction of connected pairs		Average path length	
# Nodes	*Open space*	*Urban*	*Open space*	*Urban*	*Open space*	*Urban*
100	20	5.6	1	0.77	2.65	5.1
150	30	7.9	1	0.87	2.60	5.0
200	39	11.0	1	0.97	2.55	4.7
250	50	13.5	1	0.98	2.50	4.5
300	61	17.5	1	0.98	2.45	4.3
350	68	19.5	1	0.98	2.50	4.3
400	77	22.5	1	0.99	2.45	4.2

100%. So even with 400 nodes, where the number of neighbors is higher than in the open scenario with 100 nodes, some nodes manage to stay out of reach because of the irregular structure of the town. The average path length is also very much affected by the environment: paths are about double as long in the urban scenario. The node density has some influence on path lengths in the urban scenario, but less in the open space since there even 100 nodes are enough to provide almost straight line paths. Finally, we also measured the average link duration (not shown in the table). Independent of the node density, we recorded an average duration of about 65 sec in open space, and 43 sec in the urban scenario. When increasing the maximum speed to 10 m/s, we got 56 sec in open space, and 28 sec in the urban scenario. This means that the change rate of the network is higher in the urban environment.

4.2 Traffic load and distribution

We tested the routing performance in the urban scenario considering different traffic loads and distributions. In a first set of experiments, we consider an urban scenario with 300 nodes and 10 randomly chosen parallel bi-directional sessions. We change their data send rate from 0.033 packets/s (1 packet every 30 seconds, corresponding to interactive SMS exchanges) up to 25 packets/s (corresponding to good quality VoIP communications). Figure 2 shows the results for delivery ratio and average delay. At the lowest data rate, both algorithms show low delivery and high delay. This is because both of them need to set up a route between source and destination prior to communication. When data packets are sent sporadically, previously constructed routes can hardly ever be reused, and a new route setup is needed almost every time. This is reflected in the overhead results, not shown here, calculated in terms of number of control packets forwarded per received data packet. AntHocNet scores bad for this measure at the lowest data rate due to its continuous efforts to improve the created route. As data rates increase, subsequent packets can profit from previous route setups. In AntHocNet, where routes are proactively maintained and therefore remain valid for longer, this effect is visible at lower rates than for AODV, and it is reflected both in the performance and in the overhead, that becomes comparable between the two algorithms starting from the rate of 1 packet/s. For the highest rate, both algorithms have a decrease in performance, because the high load of data packets starts to interfere with the control packets. For AntHocNet, this effects is stronger because the algorithms uses more and larger control packets. Both algorithms provide a delivery ratio that is insufficient for VoIP application.

In another set of experiments, we test the performance for the star-like configuration, described in Section 2.3, involving a control center bidirectionally exchanging data with a fleet of 10 vehicles, a light traffic load in background, and a total of 350 nodes. The challenge of this scenario mainly consists in the presence of a traffic concentration point and in the need to concurrently maintain a number of routes to and from it. In this case, in Figure 3 we show that, differently from the previous case, the network can deliver a satisfactory service, and the performance gets better and better with the increasing of the fraction of nodes that

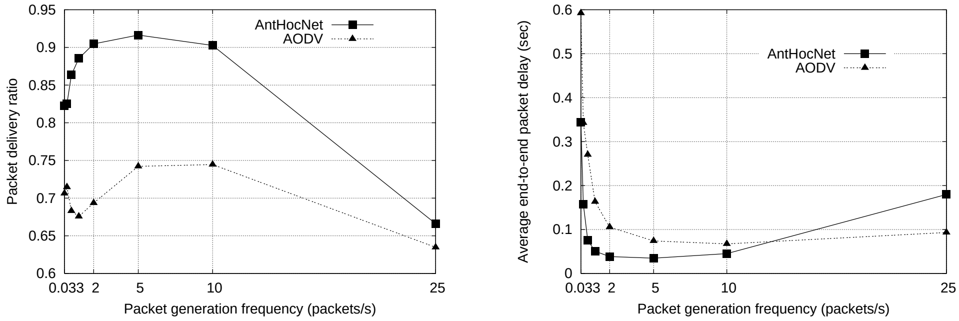

Fig. 2. Delivery and delay with increasing data send rate.

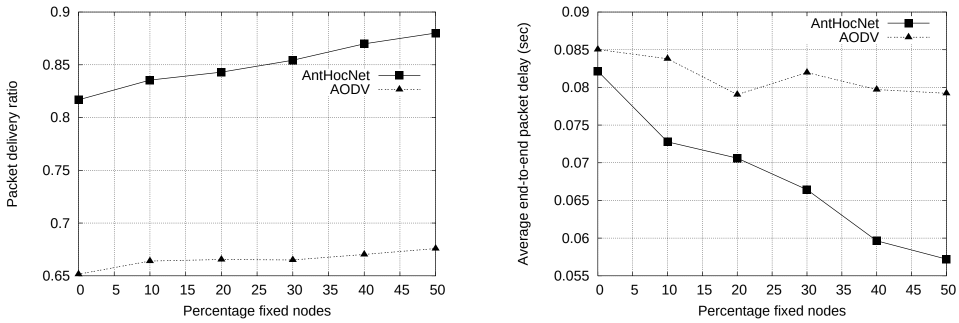

Fig. 3. Delivery and delay for scaling the fraction of fixed nodes in the scenario with a traffic concentration node.

are not mobile. These fixed nodes can model either stationary people or the existence of an infrastructure mesh. AntHocNet can exploit this fact much better than AODV. In fact, from one hand, its proactive component its a clear advantage over AODV's purely reactive behavior in order to support the continual process of maintaining and improving the routes to and from the same concentration point. On the other hand, the presence of stationary nodes greatly increases the robustness of the proactive mechanisms.

In general, we can see that AntHocNet outperforms AODV both in terms of delivery ratio and delay for most of the scenarios. Thanks to the proactive mechanism, more routing information is available in the network. In other tests (not described here due to space constraints), we have found that this leads to a lower need for route setups and to more success in local route repair attempts. This advantage can lead to less overhead in terms of number of packets despite the use of extra control packets to support the proactive function. However, in situations of high node density, or high data load, the larger beacon messages start to interfere with each other or with data packets. In urban scenarios, AntHocNet has the advantage that the local density experienced by each node (the number of neighbors) is relatively low, and grows slowly, as shown in 4.1. In previous work, we have noticed that also in open space, AntHocNet outperforms AODV more clearly in sparser scenarios with longer paths and less good connectivity [6].

4.3 Node density

We study the effect of varying node density in both the two groups of scenarios for traffic distribution. Figure 4 shows results for delivery ratio and delay for three types of realistic data load: low (0.033 packets/s), medium (2 packets/s) and high (25 packets/s). The general pattern is similar for each of the data rates: delivery increases as density increases, while the

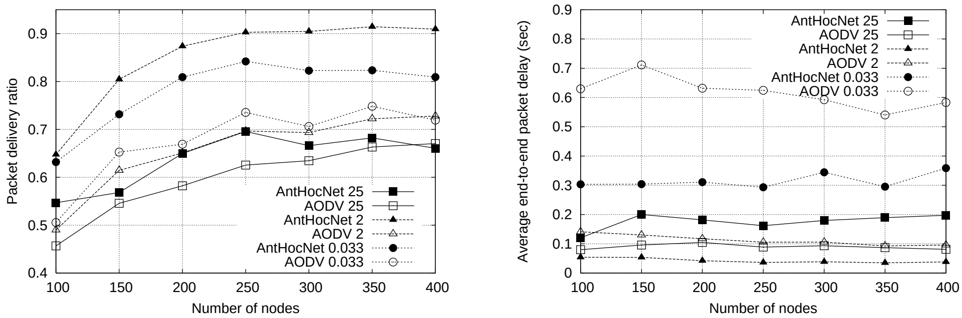

Fig. 4. Delivery and delay with increasing node density and different data send rates.

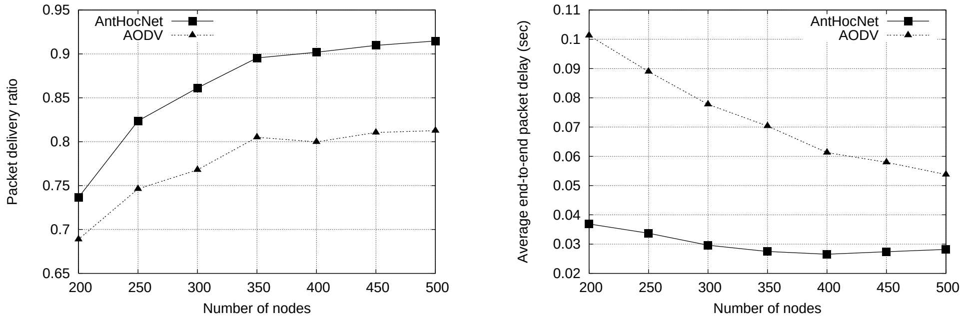

Fig. 5. Delivery and delay with increasing node density for the scenario with a traffic concentration node.

delay stays more or less constant. The graphs for delivery follow the same trend with respect to the node density as the connectivity (see Table 1), especially for the medium data rate: first increasing steeply and then stabilizing. In terms of delivery, AntHocNet always outperforms AODV, except for the highest data rate in the densest scenario, confirming that the proactive mechanism has its limits when interference gets too high. The same is seen in terms of delay, with AntHocNet outperforming AODV at all densities for the low and medium data rate, but suffering at the highest rate.

Figure 5 shows similar results for the scenario with a single node concentrating bidirectional traffic. Settings are the same as in Section 4.2. We can see that at the lower densities performance is relatively poor for both algorithms especially in terms of delivery, while, as expected, it rapidly grows with the addition of more nodes in the network. The relative trend between the two algorithms is similar to that observed in the previous case for the medium data load, with AntHocNet systematically outperforming AODV.

4.4 Node speed

We use 300 nodes, and vary the maximum node speed. We use the same low, medium and high data rates as before. Results are presented in Figure 6. As it can be expected, delivery ratio generally goes down with increased mobility. Delay on the other hand remains more or less constant. It is interesting to note that the node speed has overall relatively little impact on the performance, especially in the limited range of speeds that can be found in a realistic city scenario. The impact of node density and data traffic load seems to be much more important, even if in many MANET simulation studies, however, the speed parameter has often gotten relatively more attention. On the other hand, the results in Figure 5 show the positive impact on performance deriving from the presence of a consistent fraction of stationary nodes.

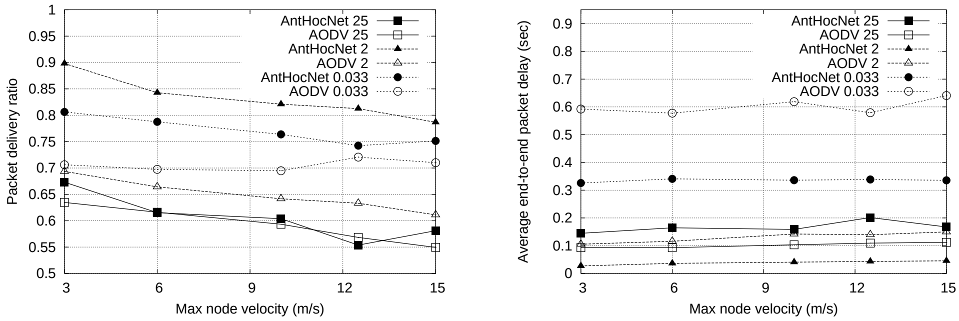

Fig. 6. Delivery and delay with increasing node speed and different data send rates.

5 Related work

There exists a lot of work comparing different MANET algorithms (e.g., see [18, 19]), but almost all of it was carried out in open space scenarios with random mobility and idealized signal propagation models. Only recently has there been an increasing interest in using more realistic setups. In [20], the authors propose a scenario with randomly placed building blocks and a simple heuristic propagation model in which only LoS communication is allowed, and evaluate how this influences the performance of AODV compared to open space scenarios. Similarly, the authors of [15] investigate the behavior of the DSR routing protocol in a grid shaped town scenario with only LoS radio propagation. In [5], a similar grid town pattern is used with a different heuristic radio propagation model (here, radio signals are weakened with a fixed amount for every corner they take) to investigate the feasibility of a commercial MANET application.

The use of town maps and realistic ray propagation has been proposed in a few recent publications. In [21], the performance of AODV is evaluated for different traffic types in a London area, pointing out the need for high node density. The authors of [22] make a detailed simulation of the Munich city center, and evaluate how the performance of AODV in this scenario compares to that in open space simulations. Our work is to our knowledge the first that compares different routing strategies in such a detailed simulation of an urban environment.

6 Conclusions

In this paper, we reported the results of extensive simulation studies investigating the performance of two routing algorithms in a realistic urban environment. The algorithms, AODV and AntHocNet, differ in their design approach. AODV is a reference state-of-the-art algorithm that uses a purely reactive strategy, while AntHocNet is based on the Ant Colony Optimization framework and combines a reactive approach to route setup with a proactive mechanism to improve and extend existing routing information. The aim of the study was to investigate the advantages of either approach in relationships to the peculiar characteristics of urban environments and to concrete application models for real-world MANETS. As a setting for our urban environment, we chose the Swiss town of Lugano. We created urban node mobility by limiting movements to the streets and open spaces of the town, used ray tracing techniques to model the propagation of radio waves in the urban environment, and applied different types of traffic loads and distributions to reflect different kinds of utilization of the network for entertainment or commercial purposes such as exchange of SMS, VoIP communications, interaction from a control node and a fleet of vehicles, and exploitation of the presence of a fixed infrastructure mesh. Up to our knowledge, the level of detail and concreteness of our study has been hardly achieved in previous MANET simulation studies.

We first investigated general properties of the network graph in the urban environment compared to equivalent settings in an open space scenario. We found that in the urban scenario, the local density experienced by each node is lower, and that it grows slowly with increasing number of nodes in the network. Moreover, connectivity in the network is worse, average path lengths are longer, and link durations shorter. Next, we compared both routing algorithms in a number of tests in which we varied the traffic load and its distribution, the node density, and the node speed. We found that AntHocNet profits from the lower local density in urban settings to let its proactive mechanism work efficiently. However, at high rates, it suffers from interference. At very low rates, both algorithms have difficulties due to their specific approach. We observed that the hybrid design of AntHocNet can very effectively exploit the presence of a fixed mesh infrastructure and is well suited to deal with the presence of traffic concentration nodes. We found that node density has a strong impact on the delivery ratio, while the node speed seemed to have relatively lower impact.

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