Are Ad-hoc Networks Able to Substitute Cellular Networks? A Performance Comparison of Ad-hoc Network Routing Protocols in Realistic Scenarios

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***Abstract*—There are several deployment scenarios for mobile ad-hoc networks discussed in the literature. However, the most results have been made in artificial environments. In this paper we study the performance of state of the art routing protocols for mobile multi-hop ad-hoc networks in an environment which emulates a city downtown. The studied simulation environment differs in three aspects from that of well known: i) The used mobility model emulates a city downtown with several zones and different mobility models. ii) The number of mobile nodes and the number of connections is inspired from real traces. iii) We use duplex-connections.**

***Index Terms*—Ad-hoc Network, Mobility model, Routing, AODV, DSR, ARA**

I. Introduction

A mobile ad-hoc network is created by a collection of nodes which communicate over radio. In contrast to a wireless local area network (WLAN), where at least one access point regulates the access of the nodes, an ad-hoc network does not need any such infrastructure. Additionally, it is supposed that ad-hoc networks are inherently adaptive and auto-configured. Therefore, ad-hoc networks offer immense flexibility. These properties of ad-hoc networks have increased the interest in them in recent years, also for real world scenarios.

There are several deployment scenarios for ad-hoc networks discussed in the literature. Among them are emergency scenarios, small-office-home-office (SOHO) applications, lecture and exhibition scenarios, and last but not least military scenarios [1]. While the vast research in ad-hoc networks, consisting in development and evaluation of applications and protocols, has been done by using simulation tools, there is a trend to transfer the gained experience in real world experiments. The spectrum of these projects is very wide and include car-to-car communication via an ad-hoc network [2] and high bandwidth data offering over static multi-hop radio networks [3].

However, the most experience with mobile ad-hoc networks is based on simulations with artificial environments. The typical simulation environment which is used to study mobile ad-hoc networks, which we will denote as 'standard' scenario, has the following properties. The simulation scenario is rectangular, a certain amount of mobile nodes move according to a random mobility model, which is very often the Random-Waypoint Mobility model. During the simulation time a certain number of connections are established which are typically constant bit rate (CBR) traffic. The sources and destinations of the connections are selected randomly among the nodes.

This scenario has various simplifications and hence does not produce realistic results. The simulation area on which the mobile nodes move does not have any borders and obstacles. All mobile nodes move according to the same mobility model with same parameter settings, in fact mobile users move according to a couple of mobility models, e.g. on market places and streets. The used communication traffic is typically unidirectional, however in reality the traffic is duplex-communication, i.e. both nodes of a communication pair are also sender and receiver.

To our knowledge, there are only few studies which consider a more realistic environment. Choi et al. study in [4] the performance of several ad-hoc network routing protocols in military scenarios. Their simulation scenario differs in several aspects from the 'standard' scenario. They simulate a certain military device, with low bandwidth 9.6-384Kbps. The simulation area is of the size of 12×22 km^2 on which they consider varying number of nodes from 100 to 200. The mobility model and the considered traffic are similar to that of other performance studies, and set to Random Waypoint and 512 Byte packets per second, respectively. Except the specific military device, other settings in this study are chosen arbitrarily. In the study of Hsu et al. in [5] the simulation parameters are obtained from real exercises. The mobility of the nodes are based on logs of GPS data. The data traffic is also obtained by transforming the real exercise traffic into the simulator.

In this paper, we study the deployment of mobile multi-hop ad-hoc networks for audio communications and ask the challenging question 'Are mobile multi-hop ad-hoc networks able to substitute cellular networks?'. There are many reasons which makes the study of mobile multi-hop ad-hoc networks reasonable under this question. At the one hand, some of the above mentioned scenarios require the support of audio communication beside of data communication, and at the other hand it is interesting to study the performance potential of current mobile multi-hop ad-hoc networks in the environment of mobile cellular networks, since emerging WLAN phones could be used in this environment.

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The focus of our study in this paper is on the performance of routing algorithms for mobile multi-hop ad-hoc networks in an environment which emulates a city downtown. It is obvious that the 'standard' scenario does not fit. Therefore, we use a more complicated scenario which is generated with CosMos[6]. The simulation world consists of several zones, which emulate entities of a city, e.g. a market place, a street, and have mutual interactions. Furthermore, we deploy duplex-connections to emulate audio connections. The design of the simulation area, i.e. the city downtown and the number of mobile nodes, as well as the communication traffic, i.e. the number of connections, is inspired from real cellular network traces.

The remainder of this paper is as follows. In Section II we discuss available realistic traces. Subsequently in Section III we introduce briefly the communication and scenario generator CosMos. In Section IV we describe the emulated city downtown in detail. In Section V we present some results and discuss the performance of modern ad-hoc routing algorithms. The paper closes with some conclusions in Section VI.

II. Input for Simulations

In this section we discuss data which can be used as sources for more realistic simulations of ad-hoc networks. The notion 'more realistic' means in the context of this paper, the used mobility patterns for the nodes and the characteristics of the communication traffic.

A. SUMATRA

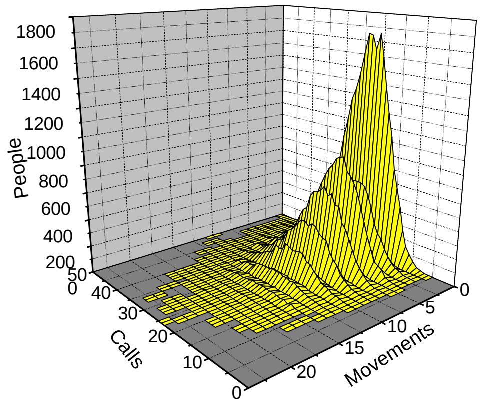
The Stanford University Mobile Activity Traces (SUMATRA) [7] is a trace generator developed at the Stanford University. The main advantage of SUMATRA is according to the publishers, that it is validated against real data.

The Stanford University has published four traces which model connection oriented traffic. Two of them are based on simple rectangle layout (SULAWESI, S.U. Local Area Wireless Environment Signaling Information) and the other two are based on the San Francisco Bay Area (BALI, Bay Area Location Information). The traces are downloadable from [7].

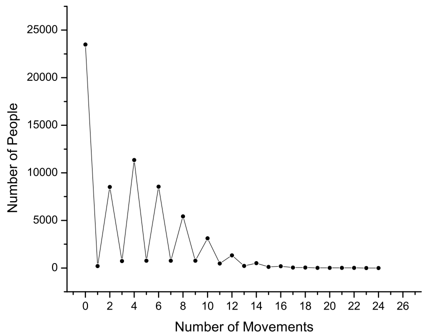
The aim of publishing these four traces was to give the wireless research community a common benchmark. Since the traces contain calling as well as mobility information of mobile users; results of experiments made with these traces are comparable and hence give researchers a better way to compare their results.

The traces contain the following information for a call and move event:

- Call: ID's of the caller and called mobile user, the zone ID's in which they are being, the time when the connection is started, and finally the duration of the call.
- Move: ID of the mobile user, the current zone ID, the zone ID in which the user moves into as next, and the time of the movement.



(a) Histrogram Movement and Calls



(b) Movements

Fig. 1. Characteristics of the BALI trace

Unfortunately, the SUMATRA traces have some disadvantages and thus it is difficult to use them for ad-hoc network simulations. The major problem is that it is not specified how a user travels from one zone to another. The velocity of the user is unknown, there is only a global velocity of 15 mph defined. Therefore, you cannot figure out how long a travel lasts, which positions the user visits, and when it finally reaches the final position.

Despite this deficits, it is worth to consider it. As next we discuss the analysis of the BALI trace, since the others were out of our interest. The mobility and call characteristic of the BALI trace is depicted in Figure 1. The graph in Figure 1(a) shows a histogram of the number of people with a certain number of movements and calls. The graph has some interesting properties. The calls show a typical Gauss distribution and the movements show an Exponential distribution, i.e. there are many people with little movements and few people with many movements. Furthermore, there are some clustering regarding the number of movement, 7 respectively. This is more clearly depicted in Figure 1(b). The number of people with odd movements are negligible. The vast majority of the people perform an even number of movements. The reason for this could be that the most people in the San Francisco Bay Area are commuters which do the same number of movements from home to work and back.

B. *Real traces*

The best input for simulations would be the ones derived from real traces of cellular networks. Unfortunately, it is very difficult for the research community to obtain those data.

A major German mobile cellular network provider has made traces for the region Aachen, Germany, available to us. Unfortunately, we are not permitted to publish the data. What we can report here is that we were able to analyze the data at the same way like we analyzed the SUMATRA data. Our analysis gave us an orientation for the number of zones and their service ranges, the number of active mobile users, and the number of calls.

III. CosMos

The goal of CosMos is to aid the researcher design more realistic simulation scenarios for wireless and mobile ad-hoc networks. CosMos integrates several mobility models, which can be combined within a scenario, e.g. a city could be modeled in the way that some mobile nodes behave according to Random-Waypoint and others to Manhattan or Freeway model.

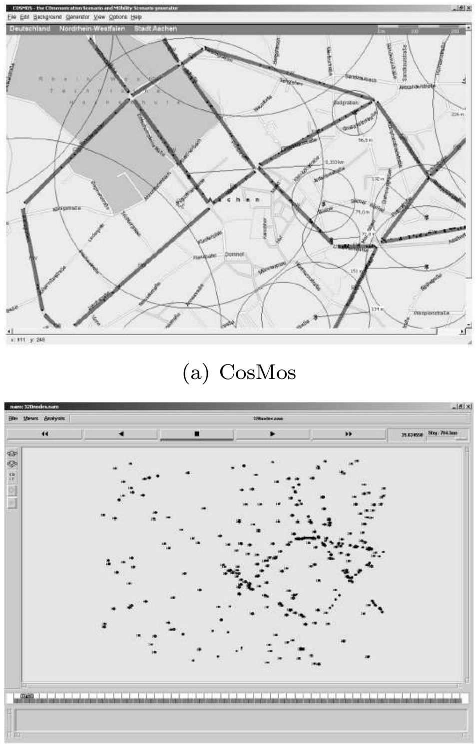
In CosMos the simulation world consists of at least one zone. Each zone has some general properties and depending on the selected mobility model some additional ones. Among zones a neighborhood relationship is defined, which is set explicitly by the user. The simulation world of CosMos builds a directed and weighted graph with zones as nodes and the neighborhood relationship as weighted and directed edges. The weight of a directed edge is denoted as 'exit probability' and gives the rate with which mobile nodes leave the zone. The combination of several zones with different characteristics allows the design of more realistic simulation scenarios. For more information about CosMos see [6].

IV. Scenario

We selected the downtown of Aachen, Germany, as the target location. All simulation parameters like velocity, the number of mobile nodes, the sizes and the number of zones, and the number of connections are chosen carefully to set up the simulation as adequately as possible.

A. *Simulation area*

We selected Aachen for two reasons. Firstly, we are acquainted with the city and therefore can estimate the distribution of the people. Secondly, a major German mobile company has made real data traces for this region available to us, which we could analyze and get a better idea about the communication characteristics. Our knowledge about the local conditions flew into the design of the simulation scenario. Figure 2 a) depicts the simulation scenario with a screenshot of CosMos and in Figure 2 b) a screenshot of `nam` is depicted. By loading the map of Aachen as background image into CosMos we were able to set up the zones adequately.



(a) CosMos

(b) nam

Fig. 2. Scenario: The downtown of Aachen, Germany

B. *Simulation method and simulation duration*

Our first intention was to simulate a whole day. The simulation of a whole day consisting of 24 hours equal to 86400 s was not possible due to the simulation restrictions of ns-2 and the used Linux-Cluster. Nevertheless to get an idea of the performance over a whole day, we have chosen the following way. For each hour of the day we simulate only 15 minutes, i.e. 900 s.

C. *Communication model*

A typical telephone connection is modeled as a bi-directional connection, which consists of two uni-directional connections, thus both nodes act as source and destination. The connection duration is exponentially distributed with mean 300 s. The total generated data rate for a connection is 64 kbps.

D. *Mobility model and node distribution*

The design of the simulation area is according to the downtown of Aachen, Germany, which is depicted in Figure 2. There are 34 zones at all; 27 zones represent streets and 7 zones represent places. The nodes on the places move according to the random point mobility model with velocities uniformly chosen from the interval of [1 : 10] m/s and the mobile nodes on the streets move according to the freeway model with 1 lane in each direction and velocities uniformly chosen from the interval [1 : 20] m/s.

The number of nodes and the number of connections from the SULAWESI traces as well as from the real cel-

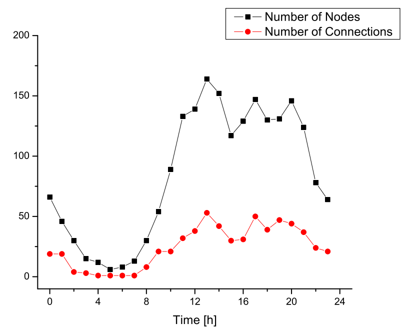


Fig. 3. Number of nodes and connections

lular network traces are too high to be used with ns-2. Therefore, we had to transform the number of nodes and connections, so that they became useful with the network simulator. Figure 3 depicts the number of nodes and connections as functions of the day hour, which we have used for our simulations.

E. Other simulation settings

The mobile nodes are equipped with typical IEEE 802.11 interface with RTS/CTS extension, a data rate of 2 Mbps or 11 Mbps, and 250 m of range. The radio propagation model is two-ray ground reflection model. The simulation area is of the size of 1190 m $\times$ 874 m. For each hour of the day we have performed 10 simulation runs and use the arithmetic average and the 95% confidence intervals.

V. Results

In this section we discuss some simulation results made with ns-2. The simulation scenario was created with CosMos. Our intention is to study the performance of current routing algorithms for mobile ad-hoc networks under conditions of mobile cellular telephone networks.

We compare three routing algorithms DSR [8], AODV [9], and ARA [10], [11].

A. Simulation results with 2 Mbps

Figure 4(a) depicts the delivery ratio for all three routing algorithms and the 95% confidence interval. From midnight to 7 o'clock the delivery ratio of all three routing algorithms fluctuate very much, which is also obvious by the large confidence intervals.

The number of nodes and connections increases from 8 o'clock up to 13 o'clock, at which they reach their maximum. With increasing number of mobile nodes and connections the delivery rate for each routing algorithm stabilizes, which is also underpinned by small confidence intervals. Unfortunately, the high number of connections have a negative impact on the delivery rate, since it falls down below 30% in all three cases.

It is interesting to see that this type of traffic has a strong impact on the performance. It looks like that due to the bi-directional connections, the number of collisions on the media is increased, which in turn affects the routing algorithms hence they run their routing error mechanisms more often.

The other metrics delay, jitter, and the overhead behave complementary to the delivery ratio, since they increase with decreasing delivery ratio. Notice that the graphs of delay in Figure 4(b), the jitter in Figure 4(c), and the routing overhead in Figure 4(d) are logarithmic in the y-axis.

However, we can make a similar observation in these graphs. With increasing number of nodes and connections they get also stabilized. Unfortunately, the delay is too high. We have put the threshold of 200 ms into the graph of delay, see Figure 4(b). Nearly in all cases the delay for all three routing algorithms is too high, hence telephone communication would not be possible.

B. Simulation results with 11 Mbps

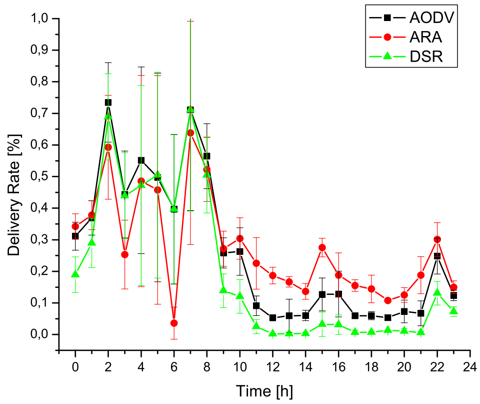
To study the effect of available bandwidth on our scenario we have performed the same simulations again; this time with higher data rate, namely 11 Mbps. All other settings are same. The results are shown in Figure 5. Although the results for both cases look similar, there are some subtle differences. The delivery ratio in Figure 5(a) shows better results at all. Additionally, the difference between the routing algorithms are higher. Similar observations are valid for the delay, jitter, and overhead. For example, in the case with 2 Mbps there are only 3 data points below the 200 ms threshold; in the case with 11 Mbps this is doubled.

In both cases DSR shows the poorest performance for all measured parameters. AODV and ARA compete with each other. From midnight to 8 o'clock the performance of AODV is better and from 9 o'clock to 23 o'clock ARA has the better performance. This observation is valid for all measured parameters, and for the 2 Mbps case as well as for the 11 Mps case. In fact, it looks like that ARA profits at most. The difference in delivery ratio between AODV and ARA is higher and at the same time the difference in delay is smaller. The reason for that could lie in the multi-path facility of ARA.

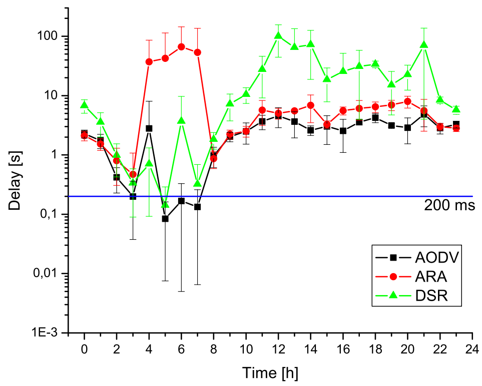
C. Summary of results

In summarizing the shown results we come to the conclusion that mobile ad-hoc networks, as they are presented here, are not able to offer the same service as mobile cellular phone networks. The results are astonishing in several aspects. To work out the differences lets compare the studied simulation environment with 'standard' simulation scenarios:

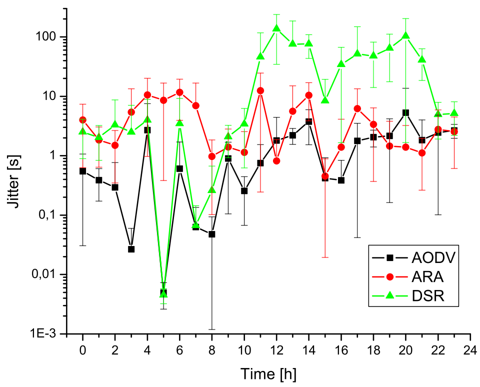
- Simulation area: In 'standard' simulations the simulation area is plain and mobile nodes can move freely on it according to the used mobility model which is very often the Random Waypoint Mobility model. In our case the nodes are restricted to the zones.
- Heterogenous movement: In 'standard' simulations all nodes move according to one mobility model and a mobile node keeps its mobility model for the whole



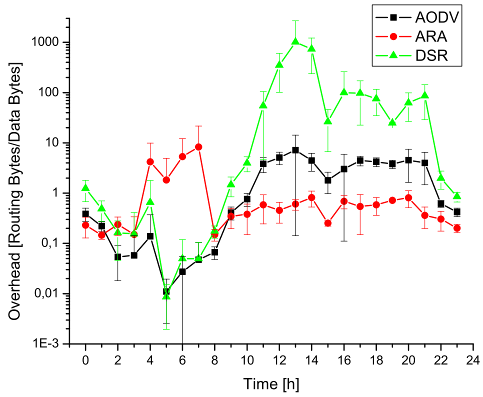
(a) Delivery Rate



(b) Delay



(c) Jitter



(d) Overhead

Fig. 4. Results with IEEE 802.11 with 2Mbps

simulation time. In our case there are several mobility models, i.e. some of the nodes move according Random Point, i.e. on places, and others according to the Freeway model, i.e. on streets. Additionally a mobile node changes its mobility model, when it moves to a zone with different mobility model.

- Connection: In 'standard' simulations the used communication connections are constant bit rate traffic. The sender and receiver of a connection is selected randomly. In our case both nodes are sender as well as receiver. Furthermore, both nodes start at the same time with the communication. This results in a higher amount of packets on same pathes.

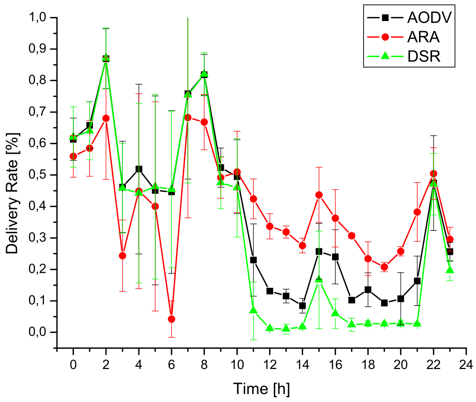
D. *Disadvantage of our approach*

The mobility model of CosMos does not consider any obstacles which are essential for cities, since they are reasons for poor radio communication. An approach like in [12] could improve it.

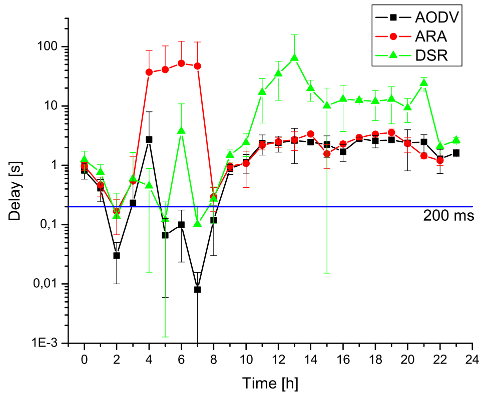
The number of mobile nodes and the number of connections were inspired by our analysis of the SUMATRA traces and the real data traces. However, there are some arbitrarily decisions in the determination of these numbers. We had to define the total number of mobile nodes for the simulation, however in the traces only the number of active nodes, which are involved in communication at that time, was given. The number of passive nodes was not given and had to be defined by us. The performance of the considered protocols are very sensitive to the relation between the number of connections and the ratio of active nodes to passive nodes. The results for the time from 0 to 8 o'clock are good examples for this discrepance. The same number of connections with more passive nodes show a much more better performance.

VI. Conclusions

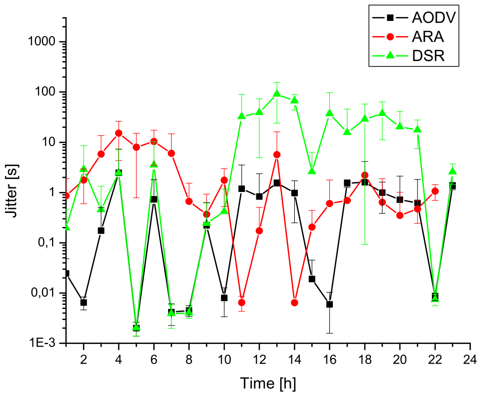
In this paper we have studied the performance of state of the art routing protocols for mobile ad-hoc networks in an environment which emulates a city downtown. Our simulation environment differs in three aspects from that of well known literature: i) The used mobility model emulates the downtown of Aachen, Germany. ii) The number of mobile nodes and the number of connections are inspired from real traces. iii) We used duplex-connections in which the both



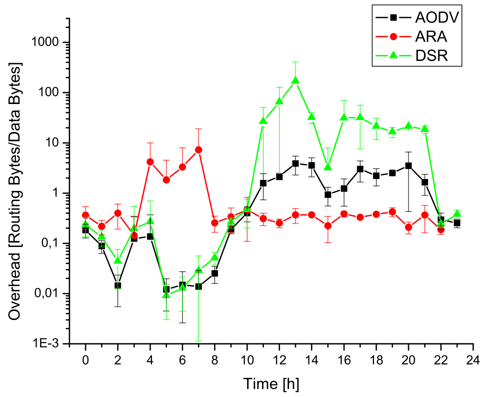
(a) Delivery Rate



(b) Delay



(c) Jitter



(d) Overhead

Fig. 5. Results with IEEE 802.11 with 11Mbps

parties of the communication are source and destination.

Our study has shown that mobile ad-hoc networks as used in our simulations with current routing algorithms are far away from being able to substitute cellular networks. The delivery rate as well as the delay of the connections are very poor, so that a typical audio communication is not possible. We conclude, that further improvement in communication medium as well as routing algorithms are required to ensure audio communication in large mobile multi-hop ad-hoc networks, as we are used from mobile cellular phone networks.

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