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The Ad Hoc On-Demand Distance Vector Protocol: An Analytical Model of the Route Acquisition Process

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Abstract. Ad hoc networking research suffers from the lack of meaningful and realistic models to describe the route acquisition process of ad hoc routing protocols. There is a strong need for such models to be able to perform realistic calculations supporting important yet difficult tasks, such as performance estimation and protocol scalability analysis. Based on existing work for ideal source routing we formulate and validate an analytical model to match the route acquisition process executed by the Ad Hoe On-Demand Distance Vector (AODV) protocol. This allows us to predict the probability density function of estimated route lengths, a powerful metric for characterization of the network behavior. We further extend our study to include multiple refinements to the basic AODV protocol. The instantiation and validation of the model is completed by means of an experimental analysis.

1 Introduction

The promise of self-organizing operation of mobile and wireless nodes gives rise to several interesting research challenges, of which routing is a very prominent one. A number of experimental protocols have been designed (see, for example, [1] and [2]; Royer presents a fairly comprehensive taxonomy of ad hoc routing in [3]). The main directions of research in this area include performance optimization. Recently, quality of service, security, and scalability issues have also drawn attention. Despite the fact that extensive work is being performed in this area, large-scale ad hoc networks are not currently available for civilian applications.

One key concept of ad hoc routing protocols is the adaptability to constraints induced by mobility and the nature of the wireless medium. Nearly all existing protocols include various performance optimizations, thus complicating the proper analysis of overall network efficiency. There are many simulation-based studies which investigate special but restricted scenarios. To allow for easy generalization of results and further study of scalability related metrics, analytical models describing the detailed behavior of ad hoc routing protocols are of great importance. Only few such models exist, however.

We believe that the availability of precise models is very important for further analysis and optimization of existing and future protocols. Our investigation provides:

1. An analytical model of the route acquisition process used in various ad hoc routing protocols. We include the modeling of transmission errors and exemplify our findings using the AODV [1] protocol.
2. The extension of our model to incorporate various protocol optimizations of AODV. We include *expanding ring search* and *reply by intermediate* [1].
3. The experimental validation of these models.

Our results enable the precise prediction of the route length distribution inside the network which characterizes the overall network behavior. We regard this knowledge as crucial for the study of scalability issues which hinder the further evolution of ad hoc networks to reach a critical mass of wide deployment.

Outline

The next section reviews related work in the area investigated. Sect. 3 introduces the modeling of the ad hoc routing process. We start with an idealized analytical model of ad hoc routing, which we subsequently adapt to fit our prerequisites. Sect. 4 details the modeling of transmission errors. Modeling the AODV protocol is detailed in Sect. 5 while the features *expanding ring search* and *reply by intermediate* are added to the model in Sect. 6 and Sect. 7. The model equations are instantiated and validated by means of simulation. We finish by drawing conclusions and by pointing to possible future work.

2 Related Work

A large number of performance comparisons of various ad hoc routing protocols exist, the work of Das et al. [4] is an early example. These studies are of great importance for verifying exact protocol behavior in well-defined environments. However, they are likely to be imprecise due to the large set of predictor and response variables which need to be considered [5] and cannot deliver qualitative metrics to describe overall network behavior and protocol scalability.

The limitations of simulation studies clearly mandates analytical models which can provide more general results. Early work related to the capacity of multi-hop packet radio networks was performed by Kleinroek et al. (see [6], [7] and [8]). The results account for the link layer performance under various circumstances and are based on a sound analytical approach. They focus on the spatial capacity [6] as well as the optimal transmission ranges for randomly distributed packet radio terminals ([7] and [8]). Recently, the work of Kleinrock et al. was enhanced by Gupta and Kumar in [9], a cornerstone of analytical capacity and performance estimation for large-scale ad hoc networks.

There is, however, little work which takes an analytical approach for describing the realistic characteristics of ad hoc routing protocols. This is especially true if we take protocol optimizations into consideration. The work of Kail, Németh, et al. [10] estimates the possible capacity of ad hoc networks—using a model of the idealized source routing process. In contrast, Santiváñez et al. [11] developed a general performance comparison metric on an abstract level. Their results account for various principles of protocols. In particular, they studied the complexity of the individual schemes with respect to the induced overhead. Although the work studies the protocol complexity, the cbaracteristic network behavior is not explained furtber.

Our approach is to obtain deeper insights in the overall network behavior for dedicated protocols—with a higher abstraction level than currently available through simulation. The envisioned model should be realistic enough to describe detailed protocol behavior from the networks perspective. This allows for further application of the model to investigate the influence of problems, such as, node misbehavior on the overall network operation. The route acquisition process constitutes the essential behavior of ad hoc routing protocols. In particular, we have chosen the distribution of route lengths as the metric for our study. Loosely related work in the area of fixed networks which uses the same metric does, however, exist. In [12] Zegura et al. introduce the metrics "length-distribution" and "hop-length-distribution" to compare graph-based models for Internet topology. This metric yields a powerful prediction tool to visualize the overall network characteristics, the interpretation in ad hoc networks being significantly different from within fixed networks. In the following, we describe our model.

3 Modeling of Ideal Source Routing

Basic properties of packet radio networks, which serve as foundation for our work, are provided by Kleinrock and Sylvester [7]. Based on these, our model describes the distribution of route lengths within the network. This metric is used to describe the network behavior. Recently, a model for ideal source routing was studied by Kail, Németh, et al. [10]. The derived equations are not entirely correct, however. In parallel to our work, the excellent work of Miller [13] derived the distribution of link distances in a wireless network. Ref. [13] provides more general results for the link-distance distribution than we do but omits the modeling and validation of realistic protocol behavior. We use the following set of assumptions:

- The investigated area, A, is a normalized square of side length 1.
- The x and y coordinates of the nodes are independently and identically uniformly distributed in the interval $[0,1]$.
- The nodes, N, share a uniform transmission range, r, which is considerably smaller than the side length of the square. The system consists of n nodes.
- The nodes are not in motion.

To describe networks of arbitrary connectivity, property, and size, we make the length parameters dimensionless. Fig. 1 shows the dimensionless network used during modeling. Performing an ex-post analysis of the geometrical node distribution, we find the area, A_0, one node eovers related to the entire area of investigation, A, to be

$$A_0 = \frac{A}{n} . \tag{1}$$

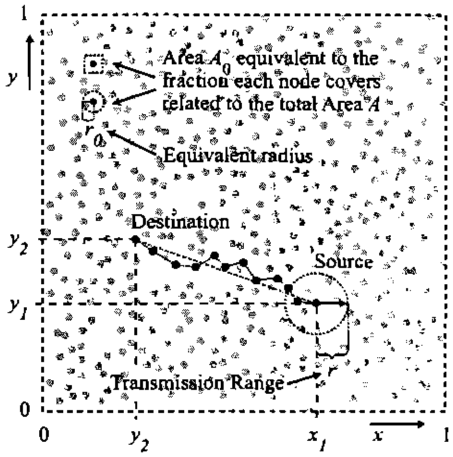

Fig. 1. Normalized sample network. The highlighted nodes, areas, and distances represent the most important properties of the network.

The radius, r_0, of a circle and side length, b_0, of a square equivalent to A_0 are

$$r_0 = \sqrt{\frac{A}{n\pi}} \text{ and } b_0 = \sqrt{\frac{A}{n}} \text{ respectively (see Fig. 1).} \tag{2}$$

The average degree, M, of the network (expected number of nodes in a transmission radius at any point) can easily be obtained by

$$M = \frac{\pi r^2}{A_0} = \left(\frac{r}{r_0}\right)^2 . \tag{3}$$

It is intuitive that the average number of receiving nodes equals $M - 1$. Knowing of M allows one to predict how many nodes will be influenced, on average, if one node transmits a signal. We are particularly interested in route lengths. Starting with idealized source routing, a first approximation of the shortest path between two nodes follows the direct line between these, assuming a very large or infinite number of nodes (see Fig. 2 for the corresponding visualization). Thus, the estimated length of hops, h, between two nodes is a function of the geometric distance, d.

The routing protocol uses neighboring nodes to transmit the packets from source to destination. The progress a packet makes in each step can be modeled as follows: Nodes are assumed to be connected directly if they are in range, r, of each other. The median distance, r_1, between two nodes which can reach each other is

$$r_1 = \frac{r}{\sqrt{2}} \text{ (see Appendix A for the derivation of } r_1\text{).} \tag{4}$$

If d is sufficiently large compared to r, we can approximate the average progress per routing step as r_1. As a result, the distance between source and destination is

$$d = h(d) r_1 . \tag{5}$$

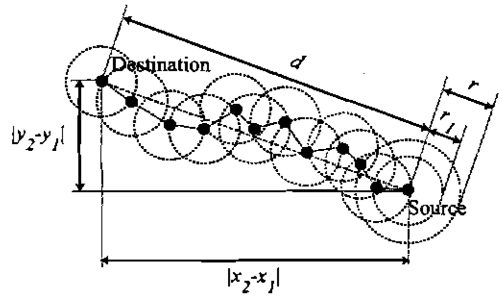

Fig. 2. Geometrical measures within the example network. The distance d between source and destination can be expressed using the hopcount h=11 and the radius r_1.

The geometric distance between two nodes on a plane is also given by the Euclidean distance between their positions. So for Node1 (x_1, y_1) and Node2 (x_1, y_2) the distance is

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{6}$$

We replace the explicit positions in Equation (6) using their distribution and obtain the probability density function $p(d)$ likewise in [13] to be

$$p(d) = \begin{cases} 2d(d^2 - 4d + \pi) & d \le 1 \\ 8d\sqrt{d^2 - 1} - 2d^3 - 4d + 4d\left(\arcsin\left(\frac{1}{d}\right) - \arccos\left(\frac{1}{d}\right)\right) & 1 < d \le \sqrt{2} \end{cases} \tag{7}$$

This serves as central equation for the remainder of this paper. It describes the statistical relation between the distance of two nodes inside the unit square and the corresponding probability of being connected. The distribution $P(d)$, which will be used to calculate the model predictions, can now be obtained by integration of the probability density function $p(d)$:

$$P(d) = \begin{cases} \frac{1}{2}d^4 - \frac{8}{3}d^3 + \pi & d \le 1 \\ 4\sqrt{d^2 - 1} + \frac{8}{3}\sqrt{(d^2-1)^3} - \frac{1}{2}d^4 + 2d^2 + \frac{1}{3} & \\ +2d^2\left(\arcsin\left(\frac{1}{d}\right) - \arccos\left(\frac{1}{d}\right)\right) & 1 < d \le \sqrt{2} \end{cases} \tag{8}$$

$$pm_{error}(d) = \begin{cases} (1 - q)^{h(d)} 2d(d^2 - 4d + \pi) & d \le 1 \\ (1 - q)^{h(d)}(8d\sqrt{d^2 - 1} - 2d^3 - 4d) & \\ + (1 - q)^{h(d)} 4d\left(\arcsin\left(\frac{1}{d}\right) - \arccos\left(\frac{1}{d}\right)\right) & 1 < d \le \sqrt{2} \end{cases} \tag{9}$$

4 Modeling of Transmission Errors

The basic model assumes that there are no transmission errors on the lower layers (idealized physical and link layer without losses). A wireless medium is, in reality, often shared competitively. To describe this behavior analytically, we relax the error condition by introducing the success probability for each packet transmitted. Our model takes a global approach instead of a local one and sets all success probabilities to be equal (note that under some circumstances the probability may be near zero, as we show later).

For a single hop and a given loss probability, q, the success probability is $1-q$. If we assume a multihop route consisting of h hops, the success probability is $(1-q)^h$. Our base model assumes a success probability of 1, thus we need to introduce $(1-q)^{h(d)}$ respectively $(q)^h$ as a correction term which describes the success probability as a function of $h(d)$, as given in Equation (9).

We are now able to obtain the probability density functions for both; the successfully established routes and, the routes hindered to be established, respectively. We are interested in a direct comparison of the number of routes between the error-free case and the case with errors, in order to predict the routing performance. Thus we give a probability measure, which accounts for the routes remaining unaffected by the error condition (see Equation (9)).

5 Modeling of AODV

We now refine the route length model to include realistic protocols. As a consequence, the routes discovered will differ from the ideal routes. If we take the AODV protocol [1] as an example, we obtain non-optimal routes, due to the loop-freedom criterion.[1] Hence, the forward routing graph which is spanned according to the propagation of the *RREQ* is sub-optimal in the case of AODV. The route length increases due to this effect.

For large networks this elongation of routes may be described by a factor θ. This factor acts multiplicatively on the geometrical distance d. All routes discovered can be described using $d' = \theta d$. Since routes may not be any shorter than the optimal distance, $\theta \geq 1$ for all protocols. θ depends on the routing protocol variant used. The curve resulting from Equation (9) will appear contracted in the y-axis by the factor θ, and stretched in the x-axis by the factor θ. Equipped with this refined model, we are now able to directly compare the analytical results with simulation results, using θ as correction term for the protocol chosen. We thus obtain $h(d) = d'/r_1 = d\theta/r_1 = d(\theta/r_1) = d/r'_1$ where $r'_1 = r_1/\theta$.

5.1 Experimental Validation of the Basic Model

To allow for experimental validation, we extended the Qualnet® network simulator to comply with a recent AODV draft. Tab. 2 provides an overview of the parameter set for

1. A node which received a route request (RREQ) on a longer but faster way forwards this non-optimal request.

all simulations used for experimental validation within this paper. We use IEEE 802.11b in ad hoc mode as lower layer protocol [14].

The model assumptions for the basic model have been validated using Test1. Since we are mainly interested in investigating the distribution of route lengths, we generated a series of single packets. The rationale behind this configuration is to trigger route discoveries without loading the network unnecessarily. Using the AODV protocol as a predictor variable, the simulations validate the hypothesis of the route length distribution. Moreover, we obtain a first estimate for θ. The possible *reply by intermediate* (see next Section) was avoided by setting the pause time between the individual route requests to 10 seconds. AODV invalidates the cached reverse paths within this period. We measured the length and number of valid routes as response variable. The results are given in Fig. 3. The mean values were obtained in 20 simulation runs with different seeds. Unless stated otherwise, we also calculated and present the estimated standard deviation and the two-sided 95% confidence interval of all the data obtained experimentally.

We use the least-squares method to obtain the fitting parameter, θ, of the curve described by Equation (9) for the measured data. Routes longer than $h = 22$ hops for AODV are not used in the fitting. These routes can be considered unstable and only account for less than 5% of all routes acquired. The application of Equation (9) produces Fig. 3. We obtain a good fit above $h = 5$ hops, while for small h, the measured values are too high. This can be explained by the average transmission range. Our initial assumption was that the number of hops, h, multiplied by the average distance between nodes, r_1, equals the estimated distance. For routes longer than 5 hops this holds. For neighboring nodes, however, the destination will answer directly even if outside the circle of radius r_1. This special behavior can be observed for routes up to approximately 5 hops. In theory one would need to model the average range r_1 as function of h. For the case $h > 5$, we expect $r_1(h) \approx r_1$; for the case $h = 1$, $r_1(h) = \sqrt{2}r_1 = r$. For the sake of simplicity, we omit the modeling of this special behavior in the remainder of this paper. The fitting parameter, θ, as well as q, both obtained using the simulation, are as follows: Test1: $\theta = 1.2$, $1 - q = 0.99$.

6 Modeling "Expanding Ring Search"

Expanding ring search is a protocol optimization which AODV uses to increase the protocol efficiency. Given the assumption that the communicating nodes are located nearby, the pure flooding of route requests would generate an unnecessary amount of network traffic. *Expanding ring search* is a stepwise increase of the time-to-live of routing requests (*RREQ*). The *RREQ* is first propagated with hop count 1. If no route is found, the hop count is increased to 3, then 5 and then 7. As the propagation boundary increases, the network load increases as well. The limited propagation over the short distance produces nearly optimal graphs. As soon as the *RREQ* is flooded throughout the network, contention for the medium may introduce additional errors. This hinders an optimal propagation and, as a result, the graph (spanning tree) degenerates. This needs to be considered within the model in two ways. Firstly, the propagation needs to be divided into two distinct areas. For the area covered by the *expanding ring search,* h_{ers}, we obtain θ_{ers}; for the wider area we obtain θ_f as the correction factors. Secondly, the net-

$$pm_{ers}(d) = \begin{cases} (1-q_{ers})^{h(d)} 2d(d^2 - 4d + \pi) & \mathrm{d} \le r_1 \frac{h_{ers}}{\Theta_{ers}} \\ (1-q_f)^{h(d)} 2d(d^2 - 4d + \pi) & (h_{ers}+1)\frac{r_1}{\Theta_f} \le d \le 1 \\ (1-q_f)^{h(d)}(8d\sqrt{d^2-1} - 2d^3 - 4d) & \\ + (1-q_f)^{h(d)} 4d\left(\arcsin\left(\frac{1}{d}\right) - \arccos\left(\frac{1}{d}\right)\right) & 1 < \mathrm{d} \le \sqrt{2} \end{cases} \quad (10)$$

$$\Theta(d) = \begin{cases} \Theta_{ers} & \mathrm{d} \le r_1 \frac{h_{ers}}{\Theta_{ers}} \\ \Theta_f & (h_{ers}+1)\frac{r_1}{\Theta_f} \le d \le \sqrt{2} \end{cases} \quad (11)$$

$$d' = d\Theta(d) \quad (12)$$

$$h = \frac{d\Theta(d)}{r_1} \quad (13)$$

work load is influenced. If the *expanding ring search* is successful, the overall network load is reduced and thus the error probability decreases. For hop counts larger than h_{ers}, the errors follow the model introduced in Sect. 4.

As a result, we obtain a function with 3 sections. Consequently we only investigate the case where $h_{ers}r_1 < 1$, since the transition to flooding will usually be smaller than the normalized distance $d = 1$. The corresponding model equations are Equation (10)-(13). Please note that the equations are only valid if appropriate fitting is performed.

6.1 Experimental Validation of "Expanding Ring Search"

For experimental validation, we conducted the experiment Test2 to examine the behavior of AODV with *expanding ring search* activated (see Tab. 2 for parameters). The remainder of the simulation parameters is set identical to the ones used to validate the base model (Test1). We carried out 20 replications for the experiment.

The results for Test2 are shown in Fig. 4. We see a significant increase in routes in the close vicinity. Moreover, the steps of *expanding ring search* are clearly visible for AODV. The parameters for *expanding ring search* are set to *TTL_START*=1 and *TTL_INCREMENT*=2. The upper bound for the search is *TTL_THRESHOLD*=7. The *RREQ* will thus be flooded if no route is found using TTLs of 1, 3, 5 and 7. For our model, these increments induce different network loads and thus a stepwise function for the area $h = 1$, $1 < h \le 3$, $3 < h \le 5$, $5 < h \le 7$, and $h > 7$. The end of the curve is a result of *RREQ* flooding. For the sake of simplicity, we considered only the two main segments of the curve within Equations (9) and (11). The parameters obtained for these two segments are as follows (see also Tab. 1): Test2: $\theta_{ers} = 1.04$, $\theta_f = 1.19$, $1 - q_{ers} = 0.958$, $1 - q_f = 0.98$.

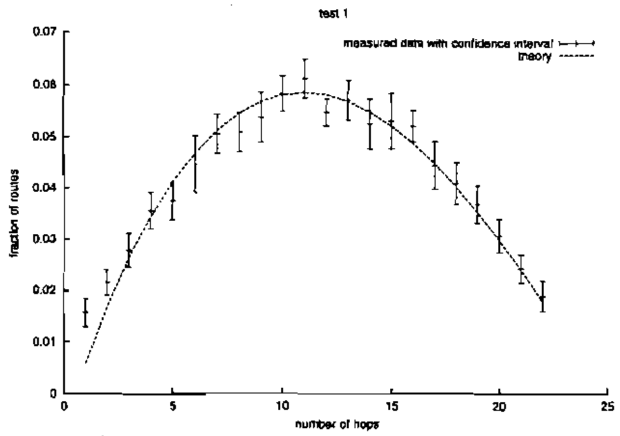

Fig. 3. Least-Squares Fit for Test1.

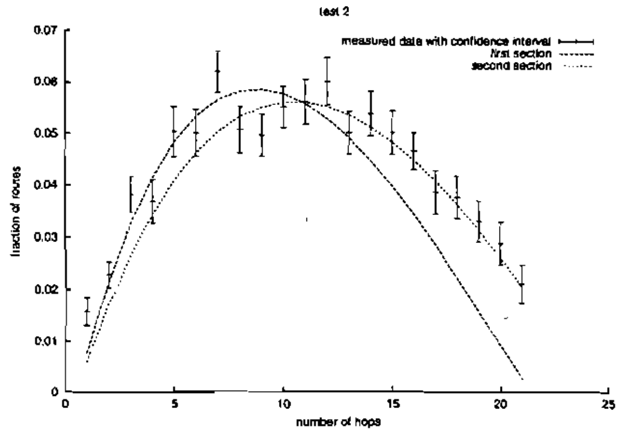

Fig. 4. Least-Squares Fit for Test2.

7 Modeling "Reply by Intermediate"

Another feature of AODV is the possibility that intermediate nodes with valid routes answer the *RREQ*. This feature firstly may shorten the duration of the routing cycle. Secondly, the probability of acquiring longer routes is heightened and thirdly, the resulting routes may be prolonged under special circumstances.

The correction term introduced in Sect. 4 needs to be adopted according to *reply by intermediate*. If we assume the length is reduced by half, we obtain $(1-q)^{h(d)/2}$ instead of $(1-q)^{h(d)}$. In general, route reductions from $h(d)$ to $\sigma h(d)$ (with $\sigma < 1$ as the correction term) can be modeled by $(1-q)^{\sigma h(d)} = ((1-q)^{\sigma})^{h(d)}$. The measurement of σ on the right side of the equation is not trivial, because we are only able to calculate the combination of σ and q from our experiments. The value of $(1-q)^{\sigma}$ may be obtained by knowing h. For an exact estimation of σ, we need to know the distance at which the replying node resides. Nevertheless, the results are suitable for our purpose. Quantitatively, we see a decreasing error probability and a subsequent increase in longer routes.

Table 1. Results of Routing Related Simulations

Test	AODV		
	Test1	Test2	Test3
θ_{ers}	n.a.	1.04	1.064
θ_f	1.2	1.19	1.19
$1 - q_{ers}$	n.a.	0.958	0.976
$1 - q_f$	0.99	0.98	0.98

7.1 Experimental Validation of "Reply by Intermediate"

The experimental validation is performed with Test3 to examine the behavior of AODV. To allow for a greater number of active routes, we increased the number of *RREQs* while the rest of the simulation parameters was kept the same as previously used. The experiments were performed using 20 replications each.

The results for Test3 are depicted in Fig. 5. We notice a better reply behavior due to the increased activity and possible replies by intermediate nodes. Moreover, the *expanding ring search* characteristics produce two sections of the curve which are clearly visible. The combination with *reply by intermediate* gives a smoother transition between the individual steps, thus supporting our approach of modeling the whole equation in two steps. The fitting of the curves is also given in Fig. 5 for Test3. The measured values and fitting parameters for the experiments are listed in Tab. 1.

7.2 Summary of Results

We present the summary of results of our simulations in Tab. 1. The success probability of finding a valid route is larger using *expanding ring search* and *reply by intermediate* than using pure AODV. The comparison of Test2 and Test3 reveals a remarkable result. One would generally expect that the much higher network load (by factor 20) should result in lower success probabilities. Since the increased traffic on the other hand allows

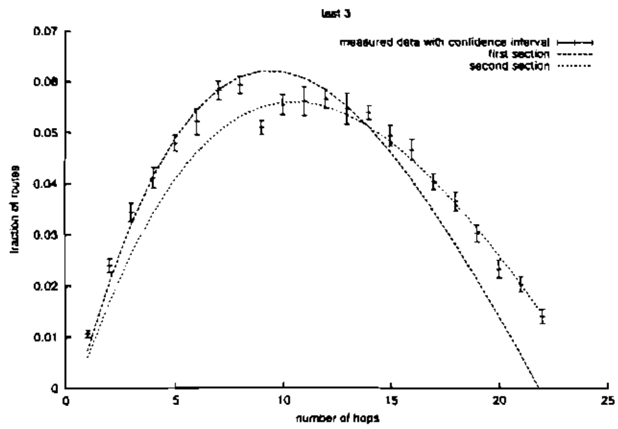

Fig. 5. Least-Squares Fit for Test3.

Table 2. Experimental Parameter Set

Test	Test1 (AODV)	Test2 (AODV)	Test3 (AODV)
Simulation area	$(3300.94m)^2$	$(3300.94m)^2$	$(3300.94m)^2$
Number of nodes	500s	500	500
Duration	5050s	5050s	1500s
Replications	20	20	20
Mobility	no	no	no
Expanding ring search	no	yes	yes
Traffic	every 10s one stream	every 10s one stream	every 500ms one stream
Packets (per flow)	1	1	1
r_0	83.287m	83.287m	83.287m
r_1	176.679m	176.679m	176.679m
M	9	9	9
Other parameters	Transmission Power = 7dBm; Propagation Model = Free Space; Transmission Range (r) = 249.862m; MAC 802.11b DCF; Max. Transmission Rate = 11 MBits/s; Local Repair = Deactivated; Hello Messages = Deactivated; Packet Size = 512Byte; UDP as Transport protocol		

for replies by intermediate nodes, the probability is nearly similar and in Test3 even above the result with low network load.

8 Conclusions

We have discussed the realistic modeling of ad hoc routing protocols. As a first step, we analytically modeled the route acquisition process. Hereby, our model predicts the route length distribution within the network. We extended the idealistic assumptions of existing models to cover transmission errors. We then modeled the behavior of the AODV protocol. To reflect more realistic protocol behavior, the AODV features *expanding ring search* and *reply by intermediate* were integrated as well.

We validated all models presented within this investigation by means of experimental analysis. Our findings are that our model gives precise predictions of the route length distribution within ad hoc networks operating with realistic protocols. Our model aids to realistically analyze routing performance within the area of ad hoc networking, thus allowing to serve for various purposes in scalability / performance estimation. As future work, we perceive the improvement of currently available routing protocols by, for example, quantifying the effect of node misbehavior with support of our model [15].

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Appendix A—Derivation of r_1

Let A_n denote the area a node covers with its radio:

$$A_n = \pi r^2 \tag{14}$$

Given a random distribution of all nodes located within this area, we calculate the area which hosts 50% of the nodes:

$$\frac{A_n}{2} = \frac{\pi r^2}{2} \tag{15}$$

The radius covering this area is:

$$r_1 = \sqrt{\frac{r^2}{2}} = \frac{r}{\sqrt{2}} \tag{16}$$

This radius r_1 describes the median distance between two neighboring nodes.