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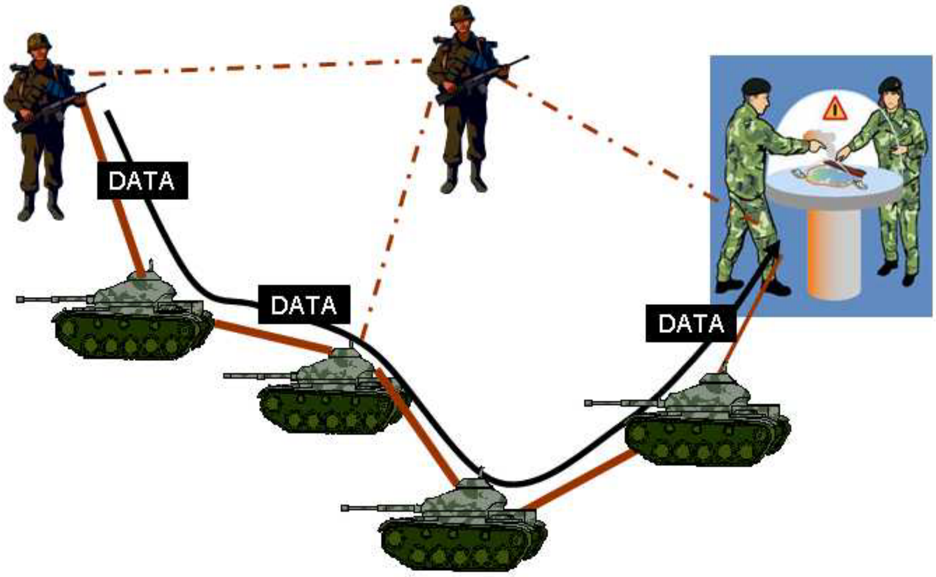

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AODV Routing in Ad Hoc Networks with Variable Data Rates

Abstract

In tactical operations, the capacity of a mobile radio network is of paramount importance. It is thus essential that the resources in the network are utilized as efficiently as possible. In a heterogeneous ad hoc network, where each link can have different possible data rates, a routing protocol should efficiently be able to take the data rate of each link into account when determining which route should be used.

Reactive routing protocols, contrary to proactive routing protocols', usually do not compare different route options. Instead the “first” found route is used. When choosing the most efficient route over links with variable data rates, comparing routes is necessary.

In this report we show that it is possible to add a metric that takes this into account to a reactive routing protocol (AODV). However, the inherent properties of AODV made optimization of the routes problematic and maximum throughput is thus not achieved. Better results may be obtained but this will add more complexity to the routing protocol and cause more routing traffic. It is thus important to consider the total cost and gain of capacity in the network when evaluating the benefit of such an algorithm modification.

Keywords
ad hoc network, variable data rate, routing, AODV

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AODV-routing i ad hoc-nät med variabel datatakt

Sammanfattning

Vid taktiska operationer är kapaciteten i det mobila radionätet av stor vikt. Nätets resurser måste därför utnyttjas på effektivast möjliga sätt. I ett heterogent ad hoc-nät är det möjligt ha olika datatakt på varje länk. Ett effektivt routingprotokoll bör därför utnyttja och ta hänsyn till datatakterna på länkarna, då rutter väljs genom nätet.

Till skillnad från proaktiva routingprotokoll väljer reaktiva routingprotokoll normalt sett inte mellan olika ruttalternativ utan den första rutt som hittas används. När den effektivaste rutten ska hittas genom ett nät med variabla datatakter på länkarna måste man dock kunna jämföra olika ruttförslag.

Vi visar i denna rapport att det är möjligt att i ett reaktivt protokoll, AODV, ändra till en mer komplex metrik för att välja en effektivare rutt. Det visade sig dock svårt att hitta de bästa rutterna i nätet p.g.a. en del egenskaper hos AODV, och resultaten är därför inte optimala. Bättre resultat skulle kunna uppnås, men detta skulle dock tillföra mer komplexitet till protokollet och även generera mer routingtrafik. Vid en bedömning av lönsamheten av en sådan förändring är det därför viktigt att se både till kostnaden och kapacitetsvinsten för hela nätet.

Nyckelord

ad hoc-nät, variabel datatakt, routing, AODV

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Contents

Chapter 1

Introduction

1.1 Background

One of the fundamental capabilities in a network based defense is the ability to quickly acquire and disseminate information from users and other information sources, e.g. a sensor network or an unmanned aerial vehicle (UAV). It is thus apparent that a robust, high capacity radio network is of paramount importance for future military operations.

To achieve tactical goals, the radio network must be able to operate without the use of pre-deployed infrastructure. Its deployment must be successful even if it takes place in unknown terrain without any previous network pre-arrangements. Furthermore, the network should be self-forming and self-maintaining. To increase robustness, the network can utilize distributed network control. To provide coverage, since military units must be able to operate even when scattered throughout rough terrain where line-of-sight communications cannot always be guaranteed, multi-hop communication can be used in the network. Such networks are often referred to as *ad hoc* networks.

In the modern defense, different types of radio equipment are used by different users. To get the best network possible, one needs to fully utilize the different types of radios, i.e. the network as a whole should not be limited by the performance of the least well-equipped radio. An example of this is if some, but not all, radio units are capable of transferring real-time videos, the network should support video transfer between these units as well as less demanding services, which all radio units can take part in. Even if the same radio equipments are used, their performance may differ due to e.g. different data rates and their mobility. A network who, like this, takes the different capabilities of the radio equipment into account is referred to as a *heterogeneous* network.

1.2 Problem Overview

A military ad hoc network must supply a wide category of services [1, 2], e.g. group calls, situation awareness data, and intranet connections. The different services can have different *Quality of Service (QoS)* demands, i.e. different demands on delay, packet loss ratio, throughput, etc. An important component in providing these services is the routing protocol, i.e. the protocol that finds and determines by which route through the network a packet should be forwarded on its way to its destination. The issue of finding a suitable routing protocol for QoS in a military ad hoc network has been examined in e.g. [3].

Since the radio units move, the radio links available and usable in the ad hoc network will change over time. If variable data rates are used, the data rate on a link can be decreased to cope with deteriorating channel condition. This means that the link can be used for a longer period of time, thus decreasing the need for re-routing. Similarly, by adapting the data rate to be lower on long-range links, users far away can be offered a limited service instead of being disconnected from the network. On the other hand, some real-time services, such as video, demands high throughput. By always using the highest possible data rate that the current channel conditions permits, the throughput in the network can be increased and users can be allowed to use more throughput demanding services. All in all, the ability to adapt the data rate offers possibilities to increase capacity in ad hoc networks.

If variable data rates are to be used in the network, the routing protocol should take this into account when choosing what route should be used between each source - destination pair. The classic approach of minimum hop routing, i.e. to choose the route with the fewest hops between the source and the destination, is not sufficient anymore. This is due to the fact that few hops usually implies that each hop is long and long hops typically results in lower data rates since the signal-to-noise ratio (SNR) tends to be lower on long links.

1.3 Previous Work

The literature on variable data rate for ad hoc networks is sparse. A study of the capacity gains possible if variable data rates are utilized can however be found in [4]. Here the network capacity with and without variable data rates is compared. Furthermore, this comparison is done for two different routing metrics, including minimum hop and the data rate sensitive metric used in this report.

In the Yuen, Lee and Andersen work, [5], the routing layer uses the channel conditions estimated at the receiver for optimal route selection. The modifications in this study are made on the IEEE 802.11 protocols and the dynamic source routing (DSR) protocol.

In [6] a Multi-Rate aware Sub layer (MAS), located between the network layer and the MAC layer is suggested for use with IEEE 802.11b and DSR. The main idea here is to use the information available regarding neighbors within two hops to, when appropriate, change the next hop into a hop with higher data rate. The result is a higher throughput, where the gain of MAS grows with the packet size.

A more theoretical approach is taken in [7] where a Medium Time Metric (MTM), is presented as an alternative to the minimum hop metric and evaluated for Destination-Sequenced Distance-Vector routing algorithm (DSDV) [8] and IEEE 802.11b. No extra layer is added with this approach and the MTM of a link is proportional to the time necessary to transmit a packet on the link.

In [9] it is shown that when evaluating the efficiency of a routing protocol, it is crucial to weigh the throughput gains against the generated routing traffic. During the evaluation, factors such as the traffic load and the number of active routes must be taken into account, e.g. the extra routing traffic generated by an algorithm modification may be negligible if the traffic load is high enough.

1.4 Contributions

The Ad Hoc On-Demand Distance Vector (AODV) routing protocol [10] is a well known reactive routing protocol. It is designed to use the a minimum hop metric, where the “first” found route is used. This approach is however not always optimal in a heterogeneous ad hoc network where e.g. each link can have several possible data rates and we want to discern routes based on other premises. A small routing packet may be transmitted fast over a slow link but thereby consuming more of the networks resources than if it would had used multihop over links with higher capacity.

In this report, we study some modifications of AODV for using a more general metric. We also test these modification, using a data rate sensitive metric which takes the data rate of each link in the route into account when determining which routes should be used. Furthermore, we evaluate the used metric and how efficiently AODV can utilize multiple data rates by studying how efficient the chosen routes are with and without the use of multiple data rates and comparing it with the routing traffic overhead.

1.5 Outline

In Chapter 2 we give a brief introduction to AODV and a data rate sensitive metric. We also describe the modifications necessary in AODV to use the data rate sensitive metric and the problems that may occur. Chapter 2 also introduces the used performance measures and Chapter 3 describes the used radio network model. The simulations set-up and the results are presented in Chapter 4. Our conclusions from the results are discussed in Chapter 5 and our ideas concerning future work are presented in Chapter 6.

Chapter 2

The AODV Routing Protocol

2.1 A Short Description of AODV

The Ad Hoc On-Demand Distance Vector (AODV) routing protocol [10, 11] is an on-demand algorithm, i.e. a route is not created until it is needed. The protocol is, as the name implies, designed for mobile ad hoc networks. It is loop-free, scalable to large networks and distributed. Furthermore, AODV uses sequence numbers to avoid old routes and the propagation of old information.

When a node has data to send to another node and it does not already have a route to that node, the source node broadcasts a route request (RREQ). The RREQ packet contains the address and sequence number for both the source and the destination node. Nodes that receive the RREQ update their information regarding the source and notes that they have received a RREQ for the destination in question. The nodes also set up backwards pointers towards the source node as a preparation for the transmission of a route reply (RREP) back to the source.

A RREP is transmitted either by the destination node when it has received a RREQ or by an intermediate node, if it has a valid route to the destination. A route is here considered valid if it has a destination sequence number that is at least as large as the one in the RREQ. A node that receives a RREQ and does not return a RREP either re-broadcasts the RREQ or, if it already has processed a packet with the same RREQ, discards the RREQ.

While the RREP is unicasted to the source node, the intermediate nodes set up forward pointers towards the destination. This means that once the RREP reaches the source, the route is ready to use. Sometimes the source node receives additional RREP packets. If these packets contain newer information regarding the destination, i.e. has a higher destination sequence number, or if it contains a route with fewer hops, the source may change its route.

A forwarding node should maintain accurate information of its connectivity to its next hop neighbors. This can be done by the periodic broadcasting of Hello messages or, if possible, from information gathered by the MAC layer.

A route is maintained as long as it is needed, i.e. as long as packets are transmitted on it. If no packet is transmitted for a certain period of time, the links time out and are deleted from the routing table. If a link in an active route fails, e.g. due to the motion of the nodes, a route error (RERR) packet is transmitted to the source but not the destination. If the source is reached by a RERR message and still have traffic for the destination in question, it can initiate a new route search. A RERR message can also initiate a local repair, see [10] for more information.

2.2 Metrics

Most routing protocols for mobile ad-hoc networks tries to find routes with as few hops as possible [8, 12], i.e. uses a minimum hop metric. In networks where the “cost” of using a route equals the number of hops in this manner, it often results in a tendency to use the route upon which the route request traveled fastest through the network. This phenomenon is most pronounced for reactive routing protocols such as AODV [10].

In a heterogeneous network, there are often other factors than the number of hops that determine how good a route is, e.g. the data rates of the included links, the traffic load or the power consumption. A more complex metric must therefore be used, since the minimum hop metric is unable to distinguish between routes with different data rates and hence it can not be used to maximize the network throughput [4] and to fully take advantage of the available network capacity.

In a proactive routing protocol, it is relatively easy to change to another type of metric since the routes are continuously upheld and hence large quantities of routing information is available. Reactive routing protocols, on the contrary, are usually not comparing different route options, instead the “first” found route is used. This is however not the same as the most efficient route. A small routing packet may be transmitted quite fast over a slow link but thereby consuming more of the networks resources than if it would had used multihop over links with higher capacity. For a reactive protocol, it is quite difficult to change metric since we do not use and uphold as much information regarding the network topology.

One method to adjust the minimum hop metric in AODV, suggested in [13], is to delay a route search packet proportionally to the cost of using the traversed link. This will however only work if the delays are much greater than any delays caused by the multiple access protocol, e.g. due to the frame length. The resulting delays can thus be large.

Another method to solve this problem is to allow a node to pass on several route requests, or to allow the destination to send several route replies, if the new route is better according to the chosen metric. Since we are interested in heterogeneous networks where we e.g. have different data rates for different links, we here use a data rate sensitive metric but this metric is interchangeable with any other type of metric, including minimum hop.

We thus define a metric based on the data rates of the links included in the route. If $l_{i\,j}$ denotes the link between nodes i and j, we can define U as the set of links used in a route. The “cost”, $C_{i\,j}$, of using this route can then be expressed as

$$C_{i\,j} = \sum_{\forall l_{i\,j} \in U} \frac{1}{R_{i\,j}} \tag{2.1}$$

where $R_{i\,j}$ is the data rate used on link $l_{i\,j}$.

When choosing between several possible routes, the best route (according to this metric) is found when the cost is as small as possible. A minimized metric means that a minimum of network capacity is used and that the throughput is as high as possible.

An example of this can be seen in Figure 2.1 where node A wants to transmit a packet to node D. Here the longer links, i.e. the links $l_{A\,E}$ and $l_{E\,D}$, have a data rate of 5 Mb/s. The link $l_{B\,E}$ has a data rate of 20 Mb/s and the other links can maintain a data rate of 10 Mb/s. We have four possible routes; $U_1 = \{A, B, C, D\}$, $U_2 = \{A, E, D\}$, $U_3 = \{A, B, E, D\}$, and $U_4 = \{A, E, B, C, D\}$. If the minimum hop metric was used, the cost of using these routes would be 3, 2, 3, and 4 respectively. Route U_2 would hence be chosen. If

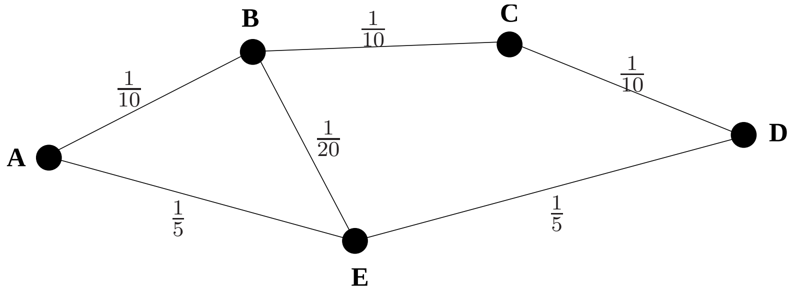

Figure 2.1: Example of a network with multiple data rates.

the metric defined above is used, we get

$$C_{ABCD} = \sum_{\forall l_{ij}:U_1} \frac{1}{R_{ij}} = \frac{1}{10} + \frac{1}{10} + \frac{1}{10} = \frac{6}{20}$$

$$C_{AED} = \sum_{\forall l_{ij}:U_2} \frac{1}{R_{ij}} = \frac{1}{5} + \frac{1}{5} = \frac{8}{20}$$

$$C_{ABED} = \sum_{\forall l_{ij}:U_3} \frac{1}{R_{ij}} = \frac{1}{10} + \frac{1}{20} + \frac{1}{5} = \frac{7}{20}$$

$$C_{AEBCD} = \sum_{\forall l_{ij}:U_4} \frac{1}{R_{ij}} = \frac{1}{5} + \frac{1}{20} + \frac{1}{10} + \frac{1}{10} = \frac{9}{20}$$

and hence route U_1 would be chosen.

2.3 Modifications of AODV

As mentioned in Section 2.1, AODV starts sending packets on the route contained in the first arrived RREP. If another RREP arrives, containing a route with a higher destination sequence number, i.e. newer information, or a route with fewer hops, the source may change its route. However, when multiple data rates are used in the network, the feasible data rate and thus the network capacity necessary to deliver a certain amount of data, will differ between different routes. This fact is not taken into account by AODV when determining which route should be used.

When AODV uses the “first” found route, this might not be the most efficient route. Even though this is the fastest route for a route request, it is not necessary the fastest route to send data traffic on, and it is not always the best route when maximizing the total network capacity. We hence modify AODV to use the metric presented in Section 2.2 instead of the minimum hop metric when determining if an additional RREP contains a better route.

Furthermore, we allow intermediate nodes to forward additional RREQ if the new RREQ packet contains a route that is better than the routes of previously transmitted RREQ. The total number of RREQ that can be forwarded by a node for a certain route search is however limited to N_{RREQ}. The value of N_{RREQ} is determined by the simulation set-up. In accordance to this, intermediate nodes may transmit multiple route replies. The destination may also transmit more than one RREP. The maximum number of RREPs a destination may transmit is N_{RREP}, each RREP must however contain a route that is an improvement. If this approach generates to many RREQ or RREP messages being transmitted in the network, it is possible to impose a limitation by only allowing a new RREQ or RREP if the new route has a cost that is at least Δ lower than the old ones.

It is also possible that a destination node will receive more RREQ than it is allowed to reply to. This means that in some cases the destination may be forced to ignore RREQ packets with better routes if they reach the destination too late.

2.4 An Example of AODV

We will here give an example of how a route is created with and without the modifications on AODV presented in Section 2.3. We use the network in Figure 2.1 where node A wants to transmit traffic to node D.

Node A initiates the route search by broadcasting a RREQ packet, see $event\,1$ in Table 2.1. The RREQ received by and re-broadcasted by node B and E, see $event\,2$. Some of the RREQ packets in this round will be discarded by its receptor, these packets are marked with gray in the table. These packets are discarded due to that the receiving node already has got a RREQ packet for this route search (original AODV) or because they contain a route that is not sufficiently better than the route in already forwarded RREQ packets (modified AODV).

The first RREQ packet to reach the destination contains the route $U_2 = \{A, E, D\}$ and both versions of AODV will thus generate a route reply with

event	Original AODV			Modified AODV		
	packet	*nodes*	*cost*	*packet*	*nodes*	*cost*
1	RREQ	A → B	$C_{AB} = \frac{1}{10}$	RREQ	A → B	$C_{AB} = \frac{1}{10}$
		A → E	$C_{AE} = \frac{1}{5}$		A → E	$C_{AE} = \frac{1}{5}$
2	RREQ	B → A	$C_{ABA} = \frac{1}{5}$	RREQ	B → A	$C_{ABA} = \frac{1}{5}$
		B → C	$C_{ABC} = \frac{1}{5}$		B → C	$C_{ABC} = \frac{1}{5}$
		B → E	$C_{ABE} = \frac{3}{20}$		B → E	$C_{ABE} = \frac{3}{20}$
		E → A	$C_{AEA} = \frac{2}{5}$		E → A	$C_{AEA} = \frac{2}{5}$
		E → B	$C_{AEB} = \frac{1}{4}$		E → B	$C_{AEB} = \frac{1}{4}$
		E → D	$C_{AED} = \frac{2}{5}$		E → D	$C_{AED} = \frac{2}{5}$
3	RREQ	C → B	$C_{ABCB} = \frac{3}{10}$	RREQ	C → B	$C_{ABCB} = \frac{3}{10}$
		C → D	$C_{ABCD} = \frac{3}{10}$		C → D	$C_{ABCD} = \frac{3}{10}$
	RREP	D → E	$C_{AED} = \frac{2}{5}$	RREP	D → E	$C_{AED} = \frac{2}{5}$
				RREQ	E → A	$C_{ABEA} = \frac{7}{20}$
				RREQ	E → D	$C_{ABED} = \frac{7}{20}$
4				RREP	D → E	$C_{ABED} = \frac{7}{20}$
				RREP	D → C	$C_{ABCD} = \frac{3}{10}$
	RREP	E → A	$C_{AED} = \frac{2}{5}$	RREP	E → A	$C_{AED} = \frac{2}{5}$
5	DATA		$C_{AED} = \frac{2}{5}$	DATA		$C_{AED} = \frac{2}{5}$
				RREP	C → B	$C_{ABCD} = \frac{3}{10}$
				RREP	E → B	$C_{ABED} = \frac{7}{20}$
6	DATA		$C_{AED} = \frac{2}{5}$	DATA		$C_{AED} = \frac{2}{5}$
				RREP	B → A	$C_{ABED} = \frac{7}{20}$
				RREP	B → A	$C_{ABCD} = \frac{3}{10}$
7	DATA		$C_{AED} = \frac{2}{5}$	DATA		$C_{ABED} = \frac{7}{20}$
8	DATA		$C_{AED} = \frac{2}{5}$	DATA		$C_{ABCD} = \frac{3}{10}$

Table 2.1: The routing traffic transmitted to set up a route from node A to node D in Figure 2.1. The left and right halves of the table are before and after our modifications of AODV, respectively. The gray packets are discarded by their receiver. It must here be noted that the “events” does not form a time-line.

this route, see $event\,3$. If the RREQ containing $U_3 = \{A, B, E, D\}$ arrives first when using the modified version of AODV, it will result in a new RREP since the new route according to the metric in Section 2.2 is better than route U_2. A third RREP will then be generated upon the arrival of the RREQ containing route $U_1 = \{A, B, C, D\}$ since this route is even better. See $event\,4$ in Table 2.1. If the arrival order of the RREQ's were reversed, only a RREP for route U_1 will be transmitted.

The first RREP reaches the source node in $event\,4$ and both versions of AODV will start using this route in $event\,5$. Since this route happens to be the minimum hop route, the original version of AODV will stick to this route until a new route search is initiated by node A or until something changes in the network. The arrival of additional RREP packets will thus not have any effect in the original version of the algorithm. If we use the modified version of AODV instead, we will change route once or twice, depending on which RREP arrives first. We here assume that the RREP for U_3 arrives first, see $event\,6-8$. This means that the used route changes first to $U_3 = \{A, B, E, D\}$ and then to $U_1 = \{A, B, C, D\}$, i.e. we get the route that maximize the network throughput.

2.5 Problems

There are some problems using AODV in a network with variable data rates, we will here discuss some of them.

The best route from node B to node D in Figure 2.2 is, according to our data rate sensitive metric, through node C. However, if for example node A initiates a route search for node E or a Hello message is transmitted from node B, we will lose the existing route through C and get a worse route directly from B to D. This is because node D receives new information and, in accordance to the AODV protocol, acts upon it without checking the cost of using the new route. A solution to this problem might be to add a further modification to AODV that forces the protocol to check the cost of using a new link or new route before switching to it. Since we here assume link information from the MAC layer instead of Hello messages, this specific problem does not affect the result in this report.

Another example is shown in Figure 2.3, where node A searches for a route to node B. The route request from node A propagates through the network and

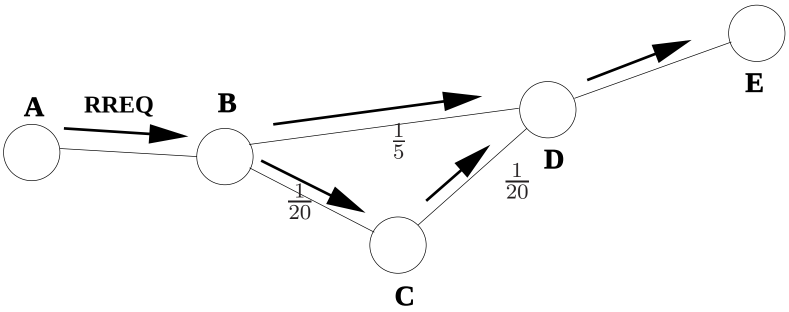

Figure 2.2: Example of a problem when node D receives new information and therefore changes its optimal route to node B through node C, to a less optimal direct route.

when node B receives the first RREQ it sends a RREP back on the shortest way to A. This however means that the rest of the nodes in the network change their shortest path to A according to from where they received the RREQ, even though the new way might be longer. For example, node C would here use the route through node D to get to node A, even though this route is much longer than the route through B. The reason for this is that the RREQ always is sent out with a new sequence number and thereby treated as newer information. This problem is not unique for networks with variable data rates.

One of the corner stones in AODV is the need for having updated sequence numbers. In a mobile scenario this can result in non-optimal routes. If we get a message with a new sequence number, the information in this message is used indiscriminately by AODV and results in the route being changed regardless if the cost compared with the cost of the old route. The use of sequence numbers helps avoiding stale routes and routing over nodes that have moved but also means that we can get a route with e.g. more hops, lower data rates or less stable links. The propagation of bad routes throughout the network may be avoided if only the destination node is allowed to replay to RREQ messages, this however do not solve the whole problem. Another method to avoid bad routes is to force the source node to wait for a RERR message, or for a certain period of time when no traffic has been exchanged with the neighbor in question, before it re-routes. This method also diminish the behavior described in the example in Figure 2.2.

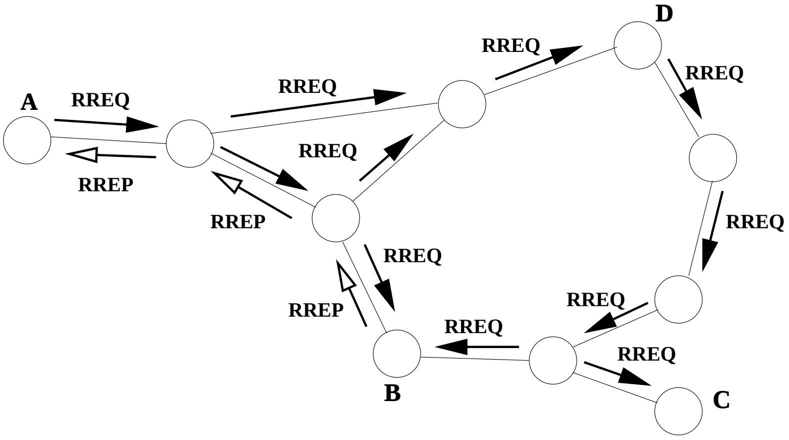

Figure 2.3: Example of a problem when the nodes upon receiving a RREQ with a higher sequence number changes their routes even though the result is less optimal routes.

Reactive routing protocols like AODV also suffer when the network is flooded with traffic, e.g. at start-up time or if there is much traffic between the majority of the nodes in the network. If any other metric than minimum hop (or rather fastest answer) is used, there will be large amounts of overhead traffic. A proactive protocol has a higher basic overhead, see e.g. [14], but the overhead does not increase significantly if the traffic is increased or if the metric is changed.

If we use variable data rates in a mobile network, the received signal-to-noise ratio will vary over time due to changes in network topology. This will continuously change the data rates of the used links. It is thus essential that the routing protocol also can handle these variations and enable re-routing when necessary.

Chapter 3

Radio Network Model

3.1 Link model

An essential part of modeling an on-ground or near-ground radio network is the electromagnetic propagation characteristics due to the terrain variation. A common approach is to use the basic path-loss, L_b, between two nodes (radio units). To estimate the basic path-loss between the nodes, we use a uniform geometrical theory of diffraction (UTD) model by Holm [15]. To model the terrain profile, we use a digital terrain database. All our calculations of the basic path-loss are carried out using the wave propagation library DetVag-90$^{\circledR}$ [16].

For any two nodes (v_i, v_j), where v_i is the transmitting node and $v_j \neq v_i$, we define the signal-to-noise ratio (SNR), here defined as E_b/N_0, in node v_j, Γ_{ij}, as follows

$$\Gamma_{ij} = \frac{P\, G_T(i,j)\, G_R(i,j)}{N_R\, L_b(i,j)\, R_{ij}}, \tag{3.1}$$

where P denotes the power of the transmitting node v_i (equal for all nodes), $G_T(i,j)$ the antenna gain of node v_i in the direction of node v_j, $G_R(i,j)$ the antenna gain of v_j in the direction of v_i, N_R is the receiver noise power, R_{ij} is the data rate, and $L_b(i,j)$ is the basic path-loss between nodes v_i and v_j.

We further assume isotropic antennas, that is

$$G_T(i,j) = G_R(i,j) = 1\ .$$

Depending on the SNR on the link, the data rate is chosen, i.e. the appropriate coding and modulation scheme (data rate) is chosen, to match the current

Table 3.1: In theory, these are the required SNR values for different data rates, with a block size of 256 bits at a packet error probability of 10^{-4}. In, reality, additional factors may require higher SNR.

Level	E_b/N_0 (dB)	Data rate (Mbit/s)
1	-0.05	0.256
2	0.05	0.512
3	0.23	1.024
4	0.55	2.048
5	1.23	4.096
6	2.68	8.192
7	5.96	16.384

channel conditions. The data rate is always chosen to be as high as possible, since the goal to achieve maximum throughput. This means that when the SNR on the link is low, the data rate will be low and vice versa.

In this work we have used seven different data rate levels, starting with 256 kbit/s as Level 1 and ending with 16.384 Mbit/s as Level 7. The SNR and data rates used in our model correspond to an information block size of 256 bits at a packet error probability of 10^{-4}, and bandwidth of 10 MHz, see Table 3.1. This information is from [17]. Since information about the lower data rates are missing, we had to extrapolate.

3.2 Data Link Layer

CSMA is one of the most frequently used Medium Access (MAC) protocols for ad hoc networks. Like most contention-based protocols, it has inherent problems with providing QoS guarantees. Another MAC protocol that is more suitable from a QoS perspective is TDMA, [18]. TDMA is a static collision-free, protocol where the channel sharing is done in the time domain. This means that the time is divided into time slots, with duration T_s, and each node is assigned one or several time slots where it is allowed to use the channel. Here, the protocol is node-oriented.

However, TDMA performs poorly in situations where the traffic intensity varies between nodes. Therefore we use a traffic adaptive version of TDMA, where each node is allocated time slots corresponding to the traffic load the node is exposed to.

Further improvements are possible by using Spatial reuse TDMA [19]. The amount of gain from using a spatial reuse TDMA algorithm is mainly related to network size and connectivity. However, since the spatial reuse will not have any major effects on the routing algorithms performance we will not use it.

Since this study is focused on the performance of the routing protocol and not on the performance of the MAC protocol, we use at rather optimal method to decide which node may use a certain slot. According to this method, we determine at each time slot, which node has the oldest queued packet. This node is then allowed to use the time slot. If any kind of priority queues is used to differentiate between different traffic types, we assign the slot to the node with the oldest packet of the traffic type who has highest priority. For simplicity, the slot assignment in our simulation is centralized, there are however ways to distribute the slot assignment, see [20].

The transmission time for a packet, T_p, on a link with high data rate is shorter than the transmission time of the same packet on a link with lower data rate. Depending of the data rate on the links, a node can transmit different number of packets in each time slot. To optimize the use of each time slot, as many packets as possible are sent in each time slot. The first packet sent in the time slot, p_0, is the first packet in the node's queue with highest priority. The same queue is then searched to find the first packet that fits into the remaining part of the time slot. When the first queue is searched through the queue of the next priority in the same node is searched. This is repeated until the time slot is full. At the end of each time slot, a guard time, T_g, is inserted to avoid collisions on the channel, see Figure 3.1.

If a packets transmission time T_p is larger than the available time in a slot, a packet can be spitted into smaller packets with a minimum size of 256 bits, i.e. the block size used for coding the packets. If a packet is smaller than 256 bits, the packet will be filled with dummy data until it reaches a size of 256 bits.

3.3 Traffic model

The user traffic is modeled as sessions of point-to-point traffic. We assume that new sessions start according to a Poisson process and that they have an exponen-

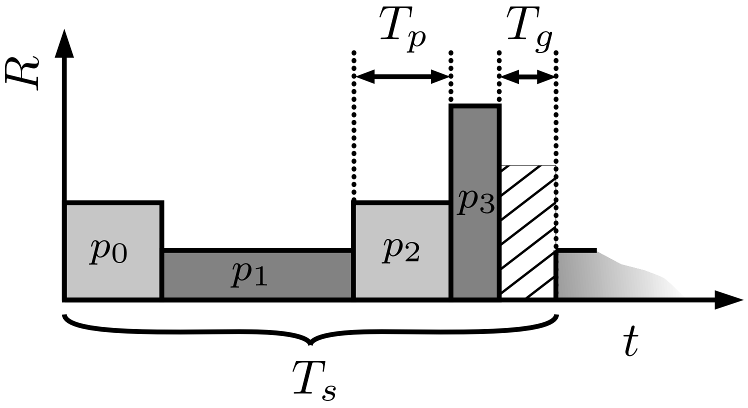

Figure 3.1: Example of transmission of multiple packets in one time slot.

tial distributed duration. Furthermore, we assume that the traffic is uniformly distributed over the nodes, i.e. each node is equally probable as the source node and each node except the source node is equally probable as the destination node. During a session, the source is assumed to transmit packets to the destination with a constant low bite rate and with constant packet size.

Chapter 4

Simulation and Results

4.1 Simulation Set-up

In our simulations, we have used stationary networks consisting of $\{8, 16, 32, 64\}$ nodes. Seven different data rates are available, from 256 kbit/s to 16.384 Mbit/s. In each network the transmission power is such that the network is fully connected, i.e. all nodes are part of the multihop network for a data rate of 256 kbit/s. The nodes in each network are randomly distributed over a real terrain area according to a rectangular distribution, and the size of the area increases with the number of nodes in the network.

The used area is Revingehed in the southern Sweden, where the terrain is mainly flat and open with some foliage.

We use the GTD model in the wave-propagation library Detvag-90 [16] to calculate the SNR between the nodes. This model takes the terrain into account and the resulting SNR is used to determine which data rates may be used on each link, see 3.1. We use TDMA with “perfect” traffic adaptation as MAC protocol, see 3.2.

We have performed simulations both for the case where only the destination node may reply to a route request, i.e. the AODV Destination Only flag is set, and for the case where intermediate nodes may generate a route reply. Furthermore, we have varied the number of route requests that a node may forward from 1 to 64 packets. The maximum number of route replies that may be generated by a node equals the number of route requests that may be forwarded.

Our simulation is 100 s long. There is no mobility in the network. During the simulation all nodes initiate and maintain routes to all other nodes in the network. The initiation order of the route searches is random, see Section 3.3. Once a route is found, we transmit the minimum amount of traffic needed to keep the route active for the rest of the simulation run. In our network, routing traffic has priority to data traffic. However, the traffic load is low and no queues are generated.

During the simulation, we log the amount of routing traffic packets. At the end of the simulation run, we compare the generated routes and the optimal routes for the network in question.

The number of networks simulated depends on the network size since the variance of a network with few nodes is higher than in a network with many nodes. For the networks with 32, 16, and 8 nodes we have simulated 128-256 different networks for each network size and number of allowed RREQ. For the network with 64 nodes however, only 9 networks were simulated due to the considerable amount of simulation time necessary for each network.

4.2 Cost of Using a Route

In this Section we look at the mean cost, according to the metric of Section 2.2, of using the routes found by AODV. We also look at the resulting mean cost of using the standard AODV protocol where the first RREQ generates the RREP. Furthermore, we compare these costs with the cost resulting from an optimal $1/R$ routing where all possible route options are compared.

In Figure 4.1 we can see the results when intermediate nodes are allowed to generate route replies. The cost is shown for different network sizes and as a function of the allowed number of forwarded RREQ. This number equals the number of RREPs a node may generate. The results are normalized by the mean cost of optimal $1/R$ routing, i.e. we desire a result as close to one as possible. The corresponding results when only the destination may generate route replies can be found in Figure 4.2.

As we can see in Figure 4.1 and Figure 4.2, we get closer to achieving optimal throughput if only the destination is allowed to reply to route requests. This is due to the fact that intermediate nodes, when they may reply, can reply and suggest non-optimal routes.

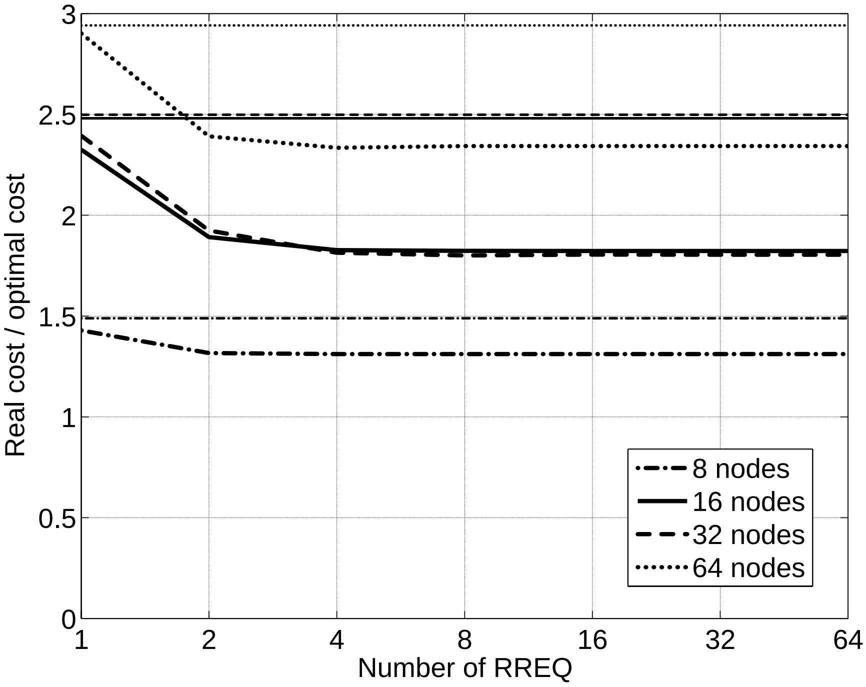

Figure 4.1: The mean cost of using a route as a function of the network size and the allowed number of RREQ (RREP) a node may forward when intermediate nodes may generate RREPs. The thick lines represent the results for AODV using $1/R$ metric. The corresponding costs of using standard AODV with minimum hop metric is shown as thin lines.

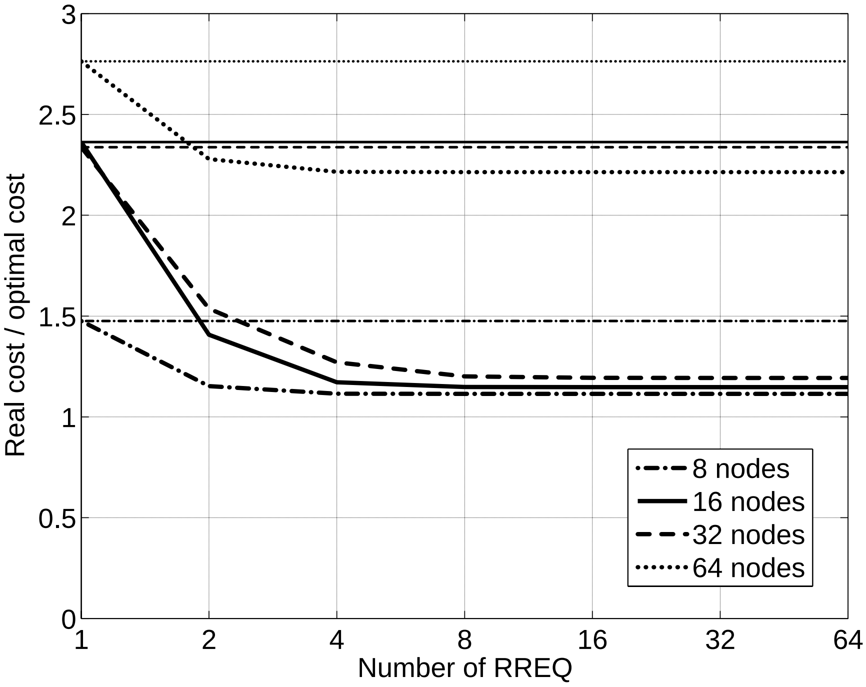

Figure 4.2: The mean cost of using a route as a function of the network size and the allowed number of RREQ (RREP) a node may forward when only the destination may generate RREPs. The thick lines represent the results for AODV using $1/R$ metric. The corresponding costs of using standard AODV with minimum hop metric is shown as thin lines.

Furthermore, Figure 4.1 and Figure 4.2 shows that the influence of allowing additional RREQ to be forwarded vary for the different network sizes. No further improvement is achieved for the network with 8 nodes when increasing the number of allowed route requests beyond four. The 16 and 32 node networks show a larger improvement when additional RREQ are forwarded because these, larger networks, have more alternative routes between each node pair. For the 16 node network, allowing the forwarding of eight RREQ is enough and for the 32 node network 16 RREQ is sufficient. The 64 node network show a smaller improvement which seems to stagnate for four allowed RREQs.

We expected results closer to optimal 1/R routing when additional route requests were allowed. However, reactive routing protocols are not designed for networks where all nodes simultaneously create and use routes to all other nodes, hence we believe that better results would have been achieved if only a couple of node pairs were active at a time. An explanation for the obtained results is that AODV utilizes gathered routing information and this may result in both that a node changes an existing route for a worse (but newer) route, and that a node omits sending a RREQ because it already knows of a (non-optimal) route to the destination. This means that if a node can reach another node in one hop, it will never send out a RREQ for that node. Nodes that are one hop away from each other but actually have an optimal route that is longer will consequently not always find the better way. The effect of these phenomena appears to depend on the network size and topology. Our 64 node networks are quite dense and additional networks should be simulated to further ensure the sufficient randomness of the networks.

4.3 Amount of Routing Traffic

In this Section we present results for the amount of routing traffic generated, both when we use the metric of Section 2.2 and when we use standard AODV. The routing traffic is here calculated as the mean number of routing packets that are transmitted when creating a route, i.e. a RREQ that traverses four hops is counted as four routing packets.

In Figure 4.3, the mean number of routing packets necessary to create a route when intermediate nodes may generate RREPs is depicted as a function of how many route requests each node may forward. The corresponding results, when only the destination may return a route reply is shown in Figure 4.4.

If we compare the results in Figure 4.3 and Figure 4.4, we can see that more routing traffic is generated by AODV when only the destination may reply to the route request. The results for the standard AODV algorithm with minimum hop routing equals the results for one allowed RREQ and, as could be expected, the use of a data rate sensitive metric and allowing additional RREQs results in a larger amount of routing traffic. For an 8 node network, there is no difference if intermediate nodes may reply and a small difference when only the destination may reply. For the 16 node network, the traffic increase is 24% and 144%, when intermediate nodes may and may not answer to a RREQ. The corresponding figures for the 32 node network is 100% and 380% respectively. This is by far the largest traffic increase. The 64 node network shows an 49% and 26% increase. One reason for this smaller increase may be that the initial routing traffic is much higher. Furthermore, the network topology in this case is denser and a node generally has many neighbors which means that much routing information may be available without actual route searches.

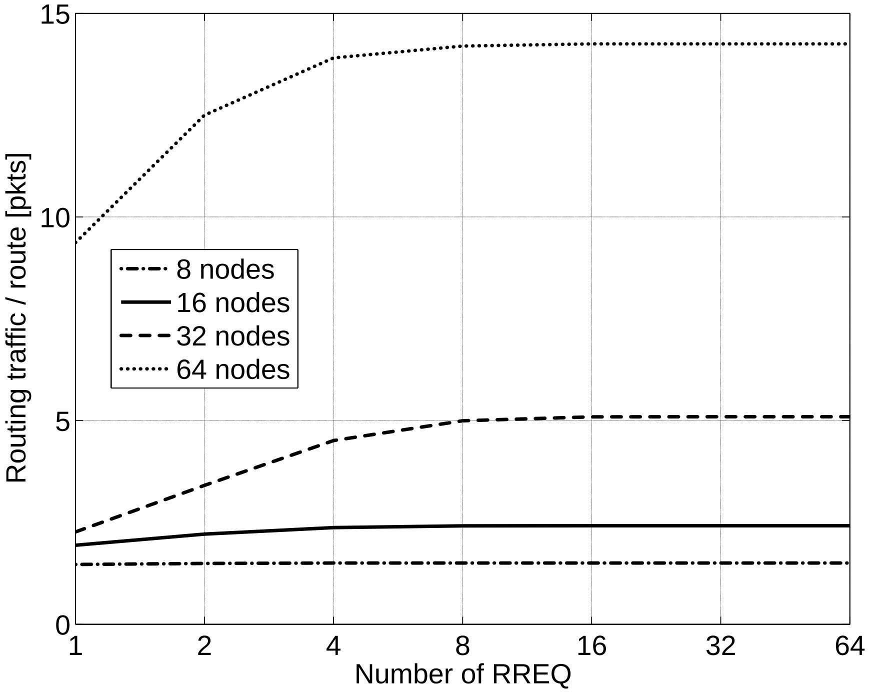

Figure 4.3: The mean number of routing packets necessary to create a route is shown here as a function of the network size and the allowed number of RREQ (RREP) that a node may forward when intermediate nodes may generate RREPs. The result for one allowed RREQ equals the traffic necessary for standard AODV.

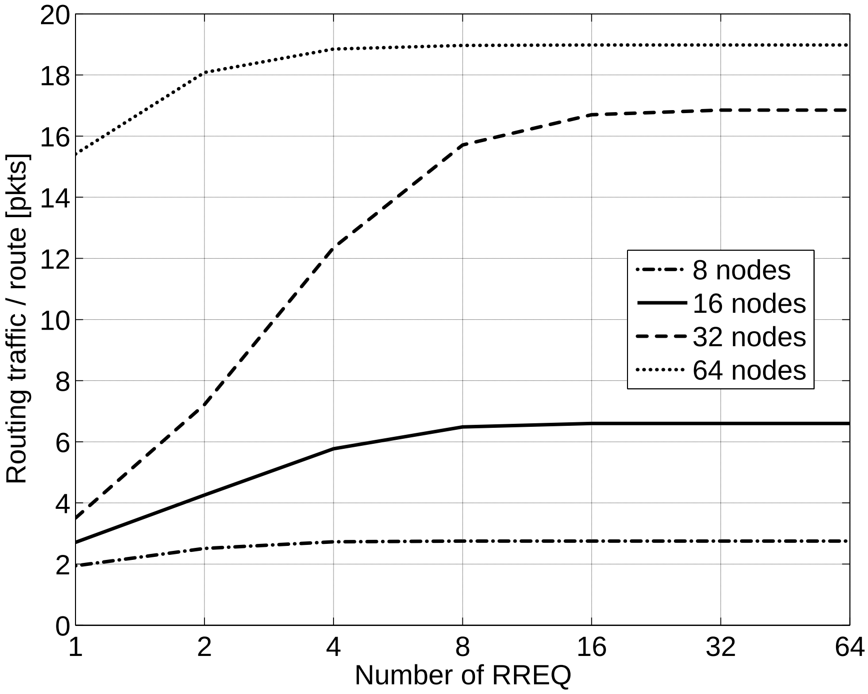

Figure 4.4: The mean number of routing packets necessary to create a route is shown here as a function of the network size and the allowed number of RREQ (RREP) a node may forward when only the destination may generate RREPs. The result for one allowed RREQ equals the traffic necessary for standard AODV.

Chapter 5

Conclusions

From our results in Section 4.2, we can conclude that the use of a data rate sensitive metric along with allowing the forwarding of additional route requests, indeed yields routes with better throughput than if standard AODV routing is used. Furthermore, we find that the routes when only the destination may generate route replies, are better than when intermediate nodes may send a reply. For each network size, it is possible to find an optimal number of forwarded route requests where additional route requests does not yield any improvement of the throughput. However, by using the modified AODV algorithm, the amount of generated routing traffic increases. This increase depends on the network size and on the number of forwarded route requests and is, understandably, larger for the case where only the destination node may generate a route reply.

Reactive routing protocols usually do not compare different route alternatives, instead the first route found is used. When choosing the most efficient route over links with variable data rates, comparing routes is necessary. As we have shown this report, it is possible to add such a metric to a reactive routing protocol. The achieved results are however not optimal. Better results may be obtained but this will add more complexity to the routing protocol as well as causing more routing traffic.

It seems like small networks can handle variable data rates better than large networks. One reason for this, see Section 2.5, is that AODV utilizes routing information gathered from other nodes and this sometimes results in non-optimal routes. The use of sequence numbers to prohibit old routes may cause additional capacity losses through changing good routes to poorer routes. Furthermore, we believe that in a network with fewer active routes, the results would probably be better.

We have in this report shown that more efficient routes, with regard to the network throughput, can be achieved in a network with variable data rates by modifying a reactive routing protocol. However, when improving the routes more routing traffic is generated. It is therefore crucial to consider the total cost, e.g. routing traffic, and the resulting capacity gain when evaluating if the algorithm modification is worth while.

Chapter 6

Future Work

Military networks are often mobile, not only should they be able to relocate but they should also work while actually moving. This means that the SNR on the links will change frequently both due to distance and to terrain obstacles. One interesting area would be to look at how a reactive routing protocol, AODV, can handle these changes, when using multiple data rates.

In a highly mobile environment, it is also of interest to evaluate if a proactive or a reactive routing protocol should be used. We intend to make this comparison, using Fisheye State Routing (FSR) [12] and AODV as representatives for the respectively categories. We would also like to determine which protocol that works best in a heterogeneous network where radio units have multiple data rates and possibly other differentiating features.

Furthermore, it would be interesting to investigate how scalable the protocols are, i.e. how much the number of nodes in the network influences the result.

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