SWEDISH DEFENCE
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FOI-R- -0928- -SE
September 2003
ISSN 1650-1942
Technical Report

Linda Farman, Ulf Sterner, and
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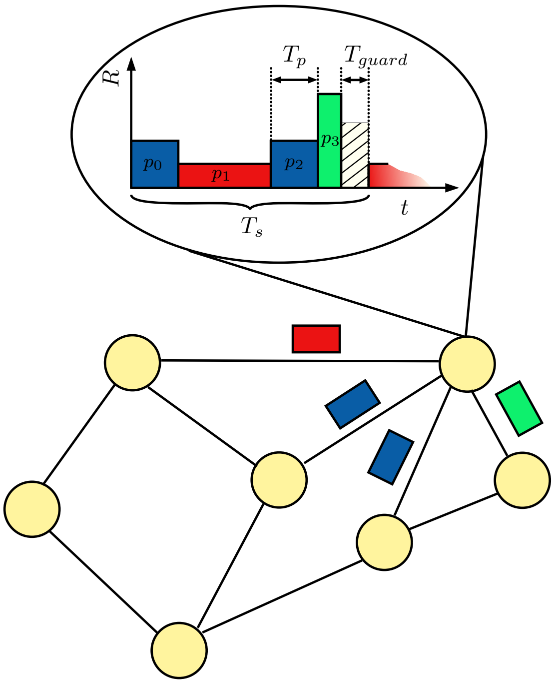

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Issuing organization

FOI- Swedish Defence Research Agency
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P.O. Box 1165
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Report number, ISRN

FOI-R- -0928- -SE

Report type

Technical Report

Research area code

4. C4ISR

Month year

September 2003

Project No.

E7035

Customers code

5. Contracted Research

Sub area code

41. C4I

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Sponsoring Agency

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Report title

Analysis of Capacity in Ad Hoc Networks with Variable Data Rates

Abstract

We investigate how to use variable data rate in ad hoc TDMA networks and the possible gain in throughput. The use of variable data rate enables the network to adapt to changes in the environment, which is crucial for the ability to guarantee QoS in a mobile network.
We study the impact that the routing metric and traffic adaptivity have on the networks ability to utilise variable data rate. Furthermore, we study how the number of data rates to chose from improve the throughput. We also investigate the relative gain in throughput for a system with variable data rate compared to a system with fixed data rate.
The study shows that it is of paramount importance to take data rate into consideration when routing, especially when variable data rate is used to add long range low data rate links. We also note that traffic adaptivity plays an important role for the utilisation of variable data rate at the network level. Furthermore, the gain of having a great dynamic in data rates, i.e. having many data rates to chose from, is not obvious. The results also show a substantial improvement in throughput when variable data rate is used.

Keywords

ad hoc network, variable data rate

Further bibliographic information

Language English

ISSN 1650-1942

Pages 32 p.

Price acc. to pricelist

Utgivare

Totalförsvarest Forskningsinstitut-FOI
Ledningssystem
Box 1165
581 11 LINKÖPING

Rapportnummer, ISRN FOI-R- -0928- -SE	**Klassificering** Teknisk rapport
Forskningsområde 4. Spaning och ledning	
Månad, år September 2003	**Projektnummer** E7035
Verksamhetsgren 5. Uppdragsfinansierad verksamhet	
Delområde 41. Ledning med samband och telekom och IT-system	

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Uppdragsgivare/kundbeteckning

Försvarsmakten

Teknisk och/eller vetenskapligt ansvarig

Jan Nilsson

Rapportens titel

Analysis of Capacity in Ad Hoc Networks with Variable Data Rates

Sammanfattning

Vi studerar hur variabel datatakt ska utnyttjas i ad hoc-nät med TDMA samt möjliga vinster i genomströmning. Genom att använda variabel datatakt kan nätet anpassa sig till förändringar i omgivningen, vilket är avgörande för att kunna garantera tjänstekvalitet (QoS) i ett mobilt nät.

Vi undersöker hur val av routingmetrik och trafikutjämning påverkar nätets förmåga att utnyttja variabel datatakt. Vidare studerar vi hur antalet tillgängliga datatakter förbättrar genomströmningen. Vi undersöker även den relativa vinsten i genomströmning för ett system med variabel datatakt jämfört med ett system med fix datatakt.

Studien visar att det är av stor vikt att ta hänsyn till datatakten vid routing. Den visar även att trafikadaptivitet är viktig för att kunna utnyttja variabel datatakt. Vinsten med att ha en stor dynamik i datatakter är dock inte uppenbar. Resultaten visar även en betydande ökning av genomströmningen när variabel datatakt används.

Nyckelord

ad hoc-nätverk, variabel datatakt

Övriga bibliografiska uppgifter	**Språk** Engelska
ISSN 1650-1942	**Antal sidor:** 32 s.
Distribution enligt missiv	**Pris: Enligt prislista**

Contents

Chapter 1

Introduction

1.1 Background

One of the fundamental abilities in a network based defence is the ability to quickly acquire and disseminate information from information sources, such as sensor networks and unmanned aerial vehicles (UAV). It is apparent that a robust, high capacity radio network is of paramount importance to future military operations.

Such a network is able to be successfully deployed in unknown terrain with a minimum need of network planning and must therefore function without support of a pre-deployed infrastructure. Furthermore, the network should be self-forming and self-maintaining. To increase robustness the network should utilise distributed network control. Military units must be able to operate scattered in rough terrain where line-of-sight communications cannot always be guaranteed. To provide coverage the network must therefore support multihop functionality. Such networks are often referred to as ad hoc networks.

A military ad hoc network must also support a wide category of services [1, 2], e.g., group calls, situation awareness data, and fire control data. The different services will all have different quality of service (QoS) demands, i.e. different demands on delay, packet loss ratio, and throughput for example.

1.2 Problem Overview

To guarantee QoS, it is important that the network has the ability to quickly adapt to changes in the environment. Quick adaptation is best achieved on the lower layers, since the adaption is local, i.e., information only has to be exchanged between two nodes.

Since the radio units move, the radio links that can be used in an ad hoc network will change over time. When using variable data rate, the data rate on the link can be decreased to cope with the current channel condition and the link can then be preserved. Additionally, by adapting the data rate for long-range links, their users can be offered limited service, instead of being disconnect from the network.

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 increases. This will allow users to use more throughput demanding services. All in all, the ability to adapt the data rate looks like a promising technique to increase capacity in ad hoc networks.

1.3 Previous Work

The literature on variable data rate for ad hoc networks is very sparse. In the Holland, Vaidya and Bahl work, [3], a rate adaptive MAC protocol called the receiver-based autorate (RBAR) protocol for wireless local area networks is presented. The RBAR is implemented inside IEEE 802.11, and the rate adaption is performed during the RTS/CTS set up phase.

In the Yuen, Lee and Andersen work, [4], 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 [5]. The rate adaption is based on the RTS/CTS packets, similar to [3].

1.4 Contributions

In this work, we study how capacity, in terms of throughput, is affected by the use of variable data rate in a TDMA ad hoc network. To that end, we use four different systems with different routing and MAC protocols. The routing protocol is a minimum cost routing protocol and two different metrics are used: number-of-hops metric and inverse-data-rate metric. The MAC protocol is of TDMA sort, with and without traffic adaptivity. By studying two different types of routing protocols, we draw conclusions of how important the routing is to make use of variable data rates. Further, the study also investigates the importance of traffic adaptivity in these types of systems.

We also study how the throughput is affected when the number of data rates to choose between varies in the system. In the most dynamic system studied, the data rate can be chosen from six discrete levels between 100 kbit/s and 20 Mbit/s. This is studied for two types of network topologies where the power is chosen such that the network is connected, i.e., all nodes can reach all other nodes through multihop, when the links operate at the lowest data rate (100 kbit/s) and the highest data rate (20 Mbit/s) respectively. By this, we investigate how important the dynamics of data rates is, and how big the difference between the lowest and highest data rate should be.

1.5 Outline

The report is organised as follows. In Chapter 2, we present the radio network model. We describe the scenario in Chapter 3, and the performance measures in Chapter 4. The simulation results are presented in Chapter 5. Finally, we give our concluding remarks and presents some topics for future research in Chapter 6.

Chapter 2

Radio Network Model

2.1 Link model

An essential part of modelling 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 an uniform geometrical theory of diffraction (UTD) model by Holm [6]. 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® [7].

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

$$\Gamma_{ij} = \frac{P\, G_T(i,j)\, G_R(i,j)}{N_R\, L_b(i,j)\, R_{ij}}, \tag{2.1}$$

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.

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 channel conditions. The data rate is always chosen as high as possible, with the goal to give the highest throughput. This means that when the SNR on the link

Table 2.1: The required SNR value for different data rates, with a block size of 256 bits at a packet error probability of 10^{-4}.

Level	E_b/N_0 (dB)	Data rate (Mbit/s)
1	0.03	0.1
2	0.05	0.5
3	0.3	1.0
4	1.5	5.0
5	3.3	10.0
6	7.5	20.0

is low the data rate will be low and vice versa.

In this work we have used six different data rate levels, starting with 100 kbit/s as Level 1 and ending with 20 Mbit/s as Level 6. The SNR and data rates used in our model correspond to an information block size, $\mathcal{P}_s$, of 256 bits at a packet error probability of 10^{-4}, and bandwidth of 10 MHz, see Table 2.1. This information is from [8]. Since information about the lower data rates are missing, we had to extrapolate.

2.2 Data Link Layer

CSMA is one of the most frequently used MAC protocols in ad hoc networks. Like most contention-based protocols, it inherently has problems with providing QoS guarantees. Another MAC protocol that is more suitable from a QoS perspective is TDMA, an example described in [9]. TDMA is a static collision-free protocol where the channel sharing is done in the time domain, i.e., 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. In our study, the protocol is node-oriented. Since each node has a fixed resource allocation, it is possible to make delay bound guarantees for bounded network loads.

We investigate TDMA without and with traffic adaptivity, i.e., either the nodes are allocated only one time slot each, or each node is allocated time slots corresponding to the traffic load that the node is exposed to.

Since the links in the network have different data rates, the transmission time of the packets will differ between the links. This means that the transmission time of a packet, T_p, on a link with high data rate will be shorter than the transmission time of packet on a link with lower data rate. Depending on the data rate on the links, the node can transmit different number of packets in each time slot. To optimise the use of each time slot, as many packets as possible are sent in each time slot. The first packet, p_0, sent in the time slot is the first packet waiting in the transmission queue at the node. The queue is then searched to find the first packet that fits within the remaining time of the time slot. This is continued until the time slot is full. In the end of each time slot, a guard time, T_g, is inserted to avoid collisions on the channel, see Figure 2.1.

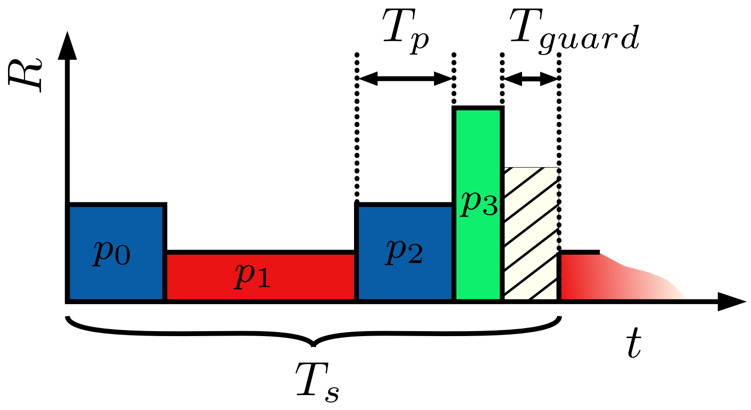

Figure 2.1: Example of transmission of multiple packets in one time slot.

2.3 Traffic adaptivity

To increase the maximum network throughput, we use traffic adaptivity in the MAC-layer, i.e., bottleneck nodes in the network are assigned more time slots than other nodes, see for example [10].

Let Λ_{ij} denote the number of routes that traverses link (i, j). We then define the capacity requirement, c_i, for node i as the sum of the quotient between Λ_{ij} and the data rate, R_{ij}, for all outgoing links from the node,

$$c_i = \sum_{\forall j : R_{ij} > 0} \frac{\Lambda_{ij}}{R_{ij}}. \tag{2.2}$$

One strategy for traffic adaptivity is to assign node i $c_i/\sum_j c_j$ time slots, where the sum is over all nodes in the network. This, however, is a number less than one, and since we have a TDMA system each node must be assigned at least one time slot otherwise that node would be excluded from the network. The optimal solution is to find the smallest integer q such that qc_i is an integer for all c_i, but this solution may lead to unrealistically long frame lengths. In order to keep the frame length short, we calculate the slot requirement, $\hat{t}_i$, for node i as

$$\hat{t}_i = \frac{c_i}{\min\limits_j(c_j)} \,. \tag{2.3}$$

This will not be an integer so it cannot be used directly as a slot allocation, instead we will use it as a measure in the slot allocation algorithm.

If we let t_i be the number of slots currently assigned to node i, then the slot allocation algorithm works as follows. First each node are allocated one time slot each. Then the node, for which the quotient $(\hat{t}_i - t_i)/\hat{t}_i$ is largest, is assigned one extra time slot. The last step is repeated until $(\hat{t}_i - t_i) < 0.5, \forall i$ or there are no more time slots to distribute, given a constraint on the maximum allowed frame length.

2.4 Routing

We use minimum cost routing with two different cost metrics. The minimum cost routing problem is here solved with Dijkstra's algorithm described in [11]. In the first case, the cost for all links are equal to one. This creates a routing table that minimises the number of hops needed to deliver a packet to its destination node. In the second case, we use a metric where the cost for using a link is inversely proportional to the data rate $(1/R_{ij})$ on the link. This creates a routing table that minimises the channel utilisation needed to transport a packet to its destination node.

2.5 Traffic model

We assume unicast traffic, i.e., a packet has a single source and single destination. Unicast traffic can be modelled as a stream of packets where each packet enters the network at a source node v_i according to a probability function $p_s(i)$, and leaves the network at a destination node v_j. The choice of destination node for a packet can be modelled by a conditional probability, i.e., given that the source node is v_i the probability that the destination node is v_j is $p_d(j|i)$.

We use a traffic model where packets of equal size, $\mathcal{P}_s$, arrive to the network according to a Poisson process, with arrival rate $\lambda/\mathcal{P}_s$. That is, on average λ bits per second arrive to the network.

Furthermore, we assume that the traffic is uniformly distributed over the nodes, i.e., each node is equally probable as source node and each node except the source node is equally probable as destination node. Hence, $p_s(i) = 1/N$ and $p_d(j) = 1/(N-1)$, where N is the number of nodes in the network.

Chapter 3

Scenario

The networks in the study consist of 20 nodes and are connected, i.e., all nodes can reach all other nodes through multi-hop.

We use two different power levels in the network. One is the minimum power required for a network to be connected when the lowest data rate is used, denoted P_{low}, and the other one is for the highest data rate, denoted P_{high}. We furthermore set the duration of a guard time to $T_g = 10^{-4}$ s, the duration of a time slot to $T_s = 2.7 \cdot 10^{-3}$ s, this ensures that at least one packet can be transmitted at the lowest data rate within one time slot. To guarantee each node at least four time slots per second we chose the maximum frame length to $T_{f,max} = 92\,T_s$.

The type of terrain we use is a mainly flat terrain, but with slightly hilly parts. The nodes are randomly distributed and scattered over an area of 1 by 1 km. The link model of Section 2.1 is used to determine possible links. The locations of the nodes in the terrain will determine which pairs of nodes that can establish a link, since the distance and the terrain between the nodes affect the elementary path loss.

We vary three different parameters for the simulations. The routing can either be minimum hop or $1/R$ routing, with or without traffic adaptivity, see Table 3.1. We also change which modulation levels that are available. We let $M_{i,j}$ denote a modulation group where modulation level i to modulation level j are available.

Table 3.1: The four systems in form of combinations of routing protocol and MAC protocol.

	No traffic adaption	Traffic adaption
Minimum hop	$S_{1,1}$	$S_{1,2}$
$1/R$	$S_{2,1}$	$S_{2,2}$

Chapter 4

Performance Measures

To evaluate the performance gain we get from variable data rate, we use two performance measures; the network delay, D [s], and the maximum network throughput, λ^* [bits/s]. We define the network delay as the expected value of the average end-to-end packet delay over all routes, and we use simulations to estimate this for one example network. We define λ^* as the largest input traffic arrival rate for which the network delay is finite, and for this measure we can derive an analytic approximation, [9].

We calculate the maximum throughput for a set of 1024 independent networks using the derived approximation, and denote the numerical average value of the maximum throughput with $\hat{E}[\lambda^*]$. To illustrate the difference in average throughput between different systems we also calculate $\lambda^*_{S_\alpha}/\lambda^*_{S_\beta}$.

4.1 Approximation of λ^*

The maximum number bits/s that can be transmitted by link (i,j) is

$$\mu_{ij} = \frac{t_{ij}}{T_f}\mathcal{P}_s\,, \tag{4.1}$$

where t_{ij} is the number of time slots that is allocated to link (i,j) in a frame of length T_f, and $\mathcal{P}_s$ is the packet size in bits. Since we use a node oriented protocol, we need an expression for the fraction of time, denoted ρ_{ij}, that node

i uses link (i,j) when it transmits in a time slot. We approximate ρ_{ij} by

$$\rho_{ij} \approx \frac{\dfrac{\Lambda_{ij}}{R_{ij}}}{\displaystyle\sum_{\forall j: R_{ij}>0} \frac{\Lambda_{ij}}{R_{ij}}}, \tag{4.2}$$

where Λ_{ij} is the number of routes that traverses link (i,j) and R_{ij} is the data rate on the link. We can then estimate t_{ij} as

$$t_{ij} \approx t_i \rho_{ij} \left(\frac{R_{ij}}{R_{min}} \right), \tag{4.3}$$

where t_i is the number of slots node i have in a frame, and R_{min} is the lowest data rate that the system can use.

To calculate the traffic load, λ_{ij}, on link (i,j) we note that the network is connected and therefore there are a total of $N(N-1)$ point-to-point connections in the network. Since there are Λ_{ij} routes that traverses link (i,j) and we have uniform traffic, we can write λ_{ij} as

$$\lambda_{ij} = \frac{\lambda}{N(N-1)} \Lambda_{ij}, \tag{4.4}$$

where N is the number of nodes.

The network is stable if $\lambda_{ij} \leq \mu_{ij}$ for all links (i,j). The maximum throughput is reached when the condition is met with equality for at least one link. The maximum throughput in packets per time slots can therefore be written as

$$\lambda^* = \min_{(i,j)} \left(t_{ij} \frac{\mathcal{P}_s}{T_f} \cdot \frac{N(N-1)}{\Lambda_{ij}} \right) \tag{4.5}$$

With Eqs.(4.2), (4.3), (4.4), and (4.5) we have an approximation of the maximum throughput.

Chapter 5

Results

Figure 5.1 shows the throughput vs. the delay for a sample network for the four different systems. The modulation group with all six data rates is used in all cases, i.e., $M_{1,6}$. The sample network is chosen to have its maximum throughput, λ^*, near the average maximum throughput, $\hat{E}[\lambda^*]$.

If we compare system $S_{1,1}$ and $S_{2,1}$ we observe that the delay D for low throughput increases when we introduce the $1/R$ routing. This effect is a consequence of $1/R$ routing, which gives longer routes measured in hops; the delay for low throughput is strongly dependent on the number of hops in the routes.

Furthermore, if we compare system $S_{1,1}$ and $S_{1,2}$ for low throughput, we see that the use of a traffic adaptive algorithm that optimises the protocol for maximum throughput might increase the average delay.

In Figure 5.1 we also compare the maximum throughput for the four systems. We see that system $S_{2,1}$ has higher throughput than system $S_{1,1}$. Thus, the introduction of $1/R$ routing reduces the traffic in the bottleneck links since high capacity links are preferred by the routing algorithm. When adding traffic adaptivity to $S_{1,1}$, the throughput also increases, since bottleneck links get a larger part of the networks resources. Furthermore, we see that the combination of $1/R$ routing and traffic adaptivity performs even better.

If we compare the throughput for system $S_{1,2}$ and system $S_{1,1}$ in Table 5.1, we see that in our examples, we gain a factor $2.7 - 3.5$ depending of the used modulation group when we introduce the traffic adaptivity. For a system that uses both traffic adaptivity and $1/R$ routing, the gain is even higher, $2.7 - 6.8$, depending on the used modulation group.

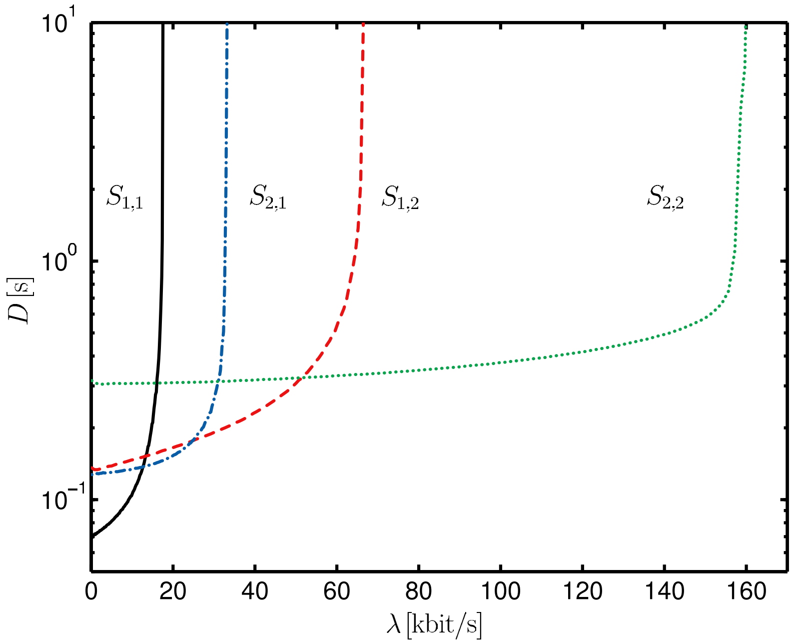

Figure 5.1: The throughput-delay characteristic of a sample network for the four systems when modulation group $M_{1,6}$ and P_{low} are used.

Table 5.1: Performance gain for P_{low}.

	$M_{1,1}$	$M_{1,2}$	$M_{1,3}$	$M_{1,4}$	$M_{1,5}$	$M_{1,6}$
$\hat{E}[\lambda^*_{S_{1,2}}/\lambda^*_{S_{1,1}}]$	2.69	3.40	3.51	3.54	3.54	3.54
$\hat{E}[\lambda^*_{S_{2,2}}/\lambda^*_{S_{1,2}}]$	1.00	1.39	1.63	1.90	1.94	1.95
$\hat{E}[\lambda^*_{S_{2,2}}/\lambda^*_{S_{1,1}}]$	2.69	4.70	5.66	6.67	6.80	6.82

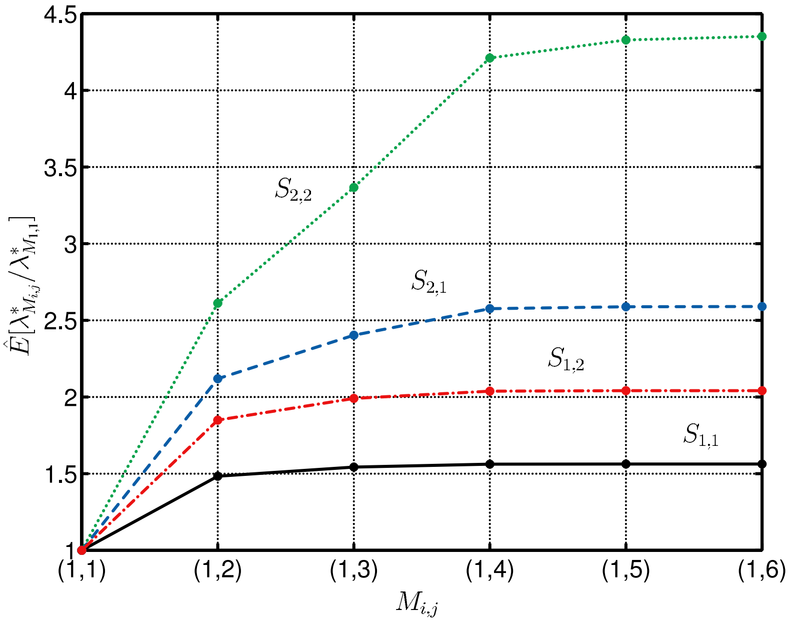

Figure 5.2: Relative throughput gain, $\hat{E}[\lambda^*_{M_{i,j}}/\lambda^*_{M_{1,1}}]$, for the four systems when we increase the number of available data rates. Power level P_{low} is used.

Figure 5.2 shows the quotient between the throughput for modulation group $M_{1,1}$ to $M_{1,6}$, and the first modulation group $M_{1,1}$ (100 kbit/s). We start with modulation group $M_{1,1}$, which means that the network is fully connected at the lowest data rate, P_{low}. Higher data rates are then added gradually to the system, but the same network topology is retained.

For systems $S_{1,1}$, $S_{1,2}$, and $S_{2,1}$ we can see a clear improvement when adding one additional data rate to the first one, but the improvements from additional data rates are not so pronounced. The reason why the quotient for $S_{1,1}$ increases when the second data rate is added is probably because a bottleneck link gets a higher data rate. However, when additional higher data rates are added, the links that did not get higher data rates when $M_{1,2}$ was introduced, will certainly not get higher data rate when $M_{1,3}$ is introduced. These links will therefore probably become bottleneck links. The small improvement is probably the result of some local redistribution at the nodes resources when adding

Table 5.2: Maximal network throughput for the studied systems with different available data rates when P_{low} is used.

	$M_{1,1}$	$M_{1,2}$	$M_{1,3}$	$M_{1,4}$	$M_{1,5}$	$M_{1,6}$
$\hat{E}[\lambda^*_{S_{1,1}}]$ kbit/s	12.4	18.9	19.8	20.1	20.1	20.1
$\hat{E}[\lambda^*_{S_{1,2}}]$ kbit/s	31.8	60.4	65.5	67.3	67.4	67.5
$\hat{E}[\lambda^*_{S_{2,1}}]$ kbit/s	12.4	27.6	31.6	34.2	34.4	34.4
$\hat{E}[\lambda^*_{S_{2,2}}]$ kbit/s	31.8	86.7	114.5	148.2	153.1	154.1

higher data rates, see Equation (5).

System $S_{1,2}$ has a higher quotient than $S_{1,1}$, due to the traffic adaptivity. The factor between using one compared to two data rates for this system is 2, see Table 5.2.

The increase in performance for system $S_{2,1}$ is due to that the routing will chose links with higher data rates. However, since the system has no traffic adaptivity nodes with low data rate links will soon be the bottlenecks in the system.

Finally, for system $S_{2,2}$, traffic adaptivity and $1/R$ routing, the improvement from different number of available data rates is much greater. The improvement of going from one data rate to four data rates is almost a factor 4.3. The reason for the significant increase from adding the first data rates is partly due to the use of links with higher data rates and partly due to the traffic adaptivity, which adjusts the resources. However, having five or six data rates, $M_{1,5}$ and $M_{1,6}$, compared to four, $M_{1,4}$, gives no notable increase in throughput. The reason why the quotient does not increase for the last data rates is probably that the traffic adaptivity cannot handle this high difference in data rate in a proper way. Also, the number of links that have the channel condition necessary to meet the SNR requirements are limited.

Figure 5.3 also shows the relative performance gain from increasing the number of available data rates. Here, we use power level P_{high}, i.e., the network is fully connected at the highest data rate, $M_{6,6}$.

As lower data rates are added, the network topology will change and new shorter routes, over low data rate links, will emerge. As we see, this causes severe performance degradation for systems that use minimum hop routing ($S_{1,1}$ and $S_{1,2}$). Since minimum hop routing does not take the data rate into account,

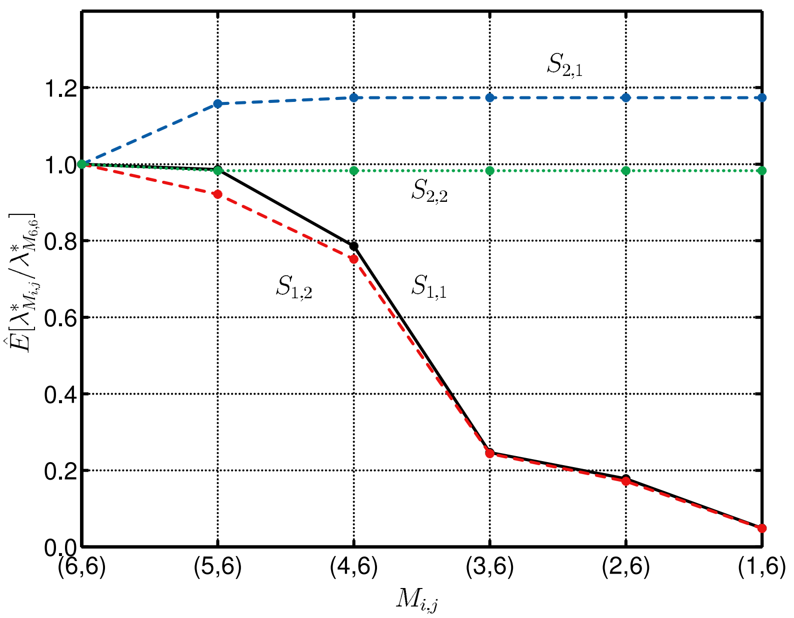

Figure 5.3: Relative throughput gain, $\hat{E}[\lambda^*_{M_{i,j}}/\lambda^*_{M_{6,6}}]$, for the four systems when we increase the number of available data rates, by adding lower data rates when P_{high} is used.

it will start to use these low data rate links and in that way create bottlenecks in the network.

$1/R$-routing optimises the channel utilisation, and therefore system $S_{2,1}$ is able to take advantage of these additional low data rate links in a fruitful manner.

However, system $S_{2,2}$ also uses $1/R$ routing and this system suffers from a slight performance degradation. This is probably due to the fact that the optimal protocol according to the traffic adaption algorithm results in a protocol length that is shorter than $T_{f,max}$ for modulation group $M_{6,6}$, while it is longer than $T_{f,max}$ for modulation group $M_{5,6}$.

Table 5.3: Maximal network throughput for the studied systems with different available data rates when P_{high} is used.

	$M_{6,6}$	$M_{5,6}$	$M_{4,6}$	$M_{3,6}$	$M_{2,6}$	$M_{1,6}$
$\hat{E}[\lambda^*_{S_{1,1}}]$ Mbit/s	2.48	2.39	1.89	0.59	0.44	0.12
$\hat{E}[\lambda^*_{S_{1,2}}]$ Mbit/s	6.68	6.11	4.99	1.63	1.16	0.34
$\hat{E}[\lambda^*_{S_{2,1}}]$ Mbit/s	2.48	2.86	2.89	2.89	2.89	2.89
$\hat{E}[\lambda^*_{S_{2,2}}]$ Mbit/s	6.68	6.51	6.51	6.51	6.51	6.51

Chapter 6

Conclusions

Our simulations show that there is a clear need for $1/R$-routing in an ad hoc network to make use of variable data rates in a proper way, especially if links with lower data rates are added to the network. Furthermore, this type of routing demands traffic adaptivity in the network.

The results show that for the studied scenario the two highest data rates do not give any noticeably gain in throughput. This is mostly due to that there are very few links in the network that have the necessary channel conditions for these higher data rates. Therefore, the gain of having a large number of data rates to chose from is not obvious. The dynamic in data rates will have a cost, which increases with additional data rates. It is therefore important to consider the trade-off between the gain in throughput and the cost for that gain.

6.1 Future Work

One drawback of TDMA-type protocols is poor utilisation of the radio channel when the nodes are geographically scattered. Spatial reuse TDMA (STDMA) [12] provides a better channel utilisation by allowing spatial reuse of time slots. Here, radio units that are sufficiently spatially separated for their transmissions not to interfere with each other can be assigned the same time slot. Therefore, it is interesting to study STDMA with variable data rate. Compared to regular TDMA, this requires modifications of the STDMA algorithm, however it has a promising potential.

Since a military ad hoc network must support a wide category of services that have different QoS demands, it would also be of great interest to study how an ad hoc network with variable data rate supports different applications. For this study traffic models for the corresponding applications have to be formulated.

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