Analyzis of Capacity in Ad Hoc Network with Variable Data Rates

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***Abstract*— In this paper we present how the throughput in an ad hoc network is affected by using variable data rate. The study is based on four different systems with different routing and MAC protocols. We also study the imapct of different number of available data rates. The data rate lies between 100 kbit/s to 20 Mbit/s.**

The study shows that it is of great importance to take data rate into consideration when routing, and having traffic adaptivity to be able to make use of variable data rate in ad hoc network. The results show as much as a factor 6.5 improvement in throughput when variable data rate is used.

I. Introduction

In future military engagements, the need to quickly acquire and assimilate information at all levels of the command hierarchy is foreseen.

In crucial situations, e.g. communication on the battlefield itself, there will be a need for high performance wireless communication without the support of a pre-deployed infrastructure. In these cases a radio network should be able to be successfully deployed in unknown terrain and with a minimum need of network planning. Furthermore, the networks should utilize distributed network control to increase robustness. 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, throughput, etc.

The literature on variable data rate for ad hoc networks is limited. In [3] a rate adaptive MAC protocol called the Receiver-Based AutoRate (RBAR) protocol is presented. The protocol is based on the RTS/CTS mechanism. In [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 and the dynamic source routing (DSR) protocol.

In this work we study how the capacity, in terms of throughput, is affected by the use of variable data rates in an TDMA ad hoc network. For that purpose we use four different systems with different routing and MAC protocols. The routing protocol is a shortest path routing protocol and two different metrics are used; number-of-hops metric and one-over-data-rate metric. The MAC protocol is TDMA with and without traffic adaptivity. By studying two different types of routing protocols we can draw some conclusion of how important the routing is to make use of variable data rates. Further, the study also investigates the importance of traffic adaptivity in this type of system.

We also study how the throughput is affected when the number of data rates to choose between in the system varies. In the most dynamic system 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 strongly connected, i.e. the links exist at both directions, when the links operate at the lowest data rate (100 kbit/s) respective the highest data rate (20 Mbit/s). By this we investigate how important the dynamics of data rates is, and how big the difference between the lowest and highest data rate could be.

The paper is organized as follows. In Section II, we present the radio network model. We describe the scenario in Section III, and the performance measures in Section IV. The simulation results are presented in Section V. Finally, we give our concluding remarks in section VI.

II. Radio Network Model

A. 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 stations). To estimate the basic path-loss between the nodes, we use an uniform geometrical theory of diffraction (UTD) model by Holm [5]. To model the terrain profile we use a digital terrain database. All our calculations of L_b are carried out using the ground wave propagation library DetVag-90® [6].

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

$$\Gamma_{ij} = \frac{P\, G_T(i,j)\, G_R(i,j)}{N_R\, L_b(i,j)\, R_{ij}}, \qquad (1)$$

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 transmission path-loss between nodes v_i and v_j.

Depending on the SNR on the link, the data rate are chosen, i.e. the appropriate coding and modulation scheme (data rate)

TABLE I

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

to match the prevailing channel conditions. The data rate is always chosen as high as possibly, with the goal to give the highest 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 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 I. This information is from [7]. Since information about the lower data rates are missing, we had to do extrapolation to find these values.

B. Data Link Layer

CSMA is one of the most frequently used MAC protocols in ad hoc networks. As most contention based protocols it inherently have problems with providing QoS. Another MAC protocol that is more suitable from a QoS perspective is TDMA [8]. TDMA is 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. Thus, 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 optimize 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 reamining 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 collision on the channel, see Figure 1.

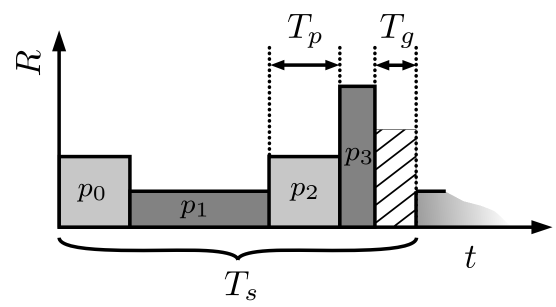

Fig. 1. Example of transmission of multiple packets in one time slot.

C. 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.

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 quoitient between Λ_{ij} and the data rate, R_{ij}, for all outgoing links from the node.

$$c_i = \sum_{\forall j : R_{ij} > 0} \frac{\Lambda_{ij}}{R_{ij}} \tag{2}$$

To get perfect traffic adaptivity node i should be assigned $c_i / \sum_j c_j$ 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

$$\hat{t}_i = \frac{c_i}{\min_j(c_j)} \, . \tag{3}$$

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.

D. Routing

We use minimum cost routing with two different cost metrics, the minimum cost routing problem is here solved with Dijkstras algorithm [9]. In the first case, the cost for all links are equal to one. This creates a routing table that minimizes the number of hops needed to deliver a packet to its destination node. In the other case, a metric where the cost for using a link is one over the data rate ($1/R$) on the link is used. This creates a routing table that minimizes the channel utilization needed to transport a packet to its destination node.

TABLE II
THE FOUR SYSTEMS IN FORM OF COMBINATIONS OF ROUTING PROTOCOL AND MAC PROTOCOL.

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

E. Traffic model

We assume unicast traffic, i.e. a packet has a single source and single destination. Unicast traffic can be modeled 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.

Furtermore 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.

III. SCENARIO

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

We use two different power levels in the network. One is the 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, and the maximum frame length to $T_{f,max} = 92\,T_s$ 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 square area of $1\,\text{km}^2$. The link model of Section II-A 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 II. 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.

IV. PERFORMANCE MEASURES

To evaluate the performance gain, we get from variable data rate, we use two performance measures; namely 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. 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, [8].

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

$$\mu_{ij} = \frac{t_{ij}}{T_f}\mathcal{P}_s\,, \tag{4}$$

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

$$\rho_{ij} = \frac{\dfrac{\Lambda_{ij}}{R_{ij}}}{\displaystyle\sum_{\forall j: R_{ij}>0} \frac{\Lambda_{ij}}{R_{ij}}}\,, \tag{5}$$

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

$$t_{ij} = t_i \rho_{ij} \left(\frac{R_{ij}}{R_{min}}\right)\,, \tag{6}$$

where t_i is the number of slots node i have in a frame and

$$R_{min} = \min_{(i,j): R_{ij}>0} R_{ij}\,. \tag{7}$$

To calculate the traffic load, λ_{ij}, on link (i,j) we note that the network is strongly 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

$$\lambda_{ij} = \frac{\lambda}{N(N-1)}\Lambda_{ij}\,, \tag{8}$$

where N is the number of nodes.

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

$$\lambda^* = \min_{(i,j)} \left(t_{ij} \frac{\mathcal{P}_s}{T_f} \cdot \frac{N(N-1)}{\Lambda_{ij}} \right) \tag{9}$$

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

V. RESULTS

Figure 2 shows the throughput vs. the delay using 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, $E[\lambda^*]$.

If we compare system $S_{1,1}$ and $S_{2,1}$ we can observe that the delay D for $\lambda \simeq 0$, increases when we introduce the

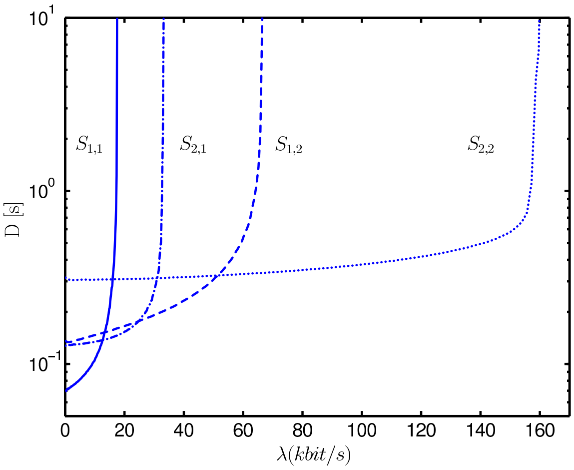

Fig. 2. The throughput-delay characteristic of a sample network for the four systems when modultion group $M_{1,6}$ and P_{low} is used.

TABLE III

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

$1/R$ routing. This is a consequence of that $1/R$ routing gives longer routes measured in hops, and that the delay for low throughputs is strongly dependent on the number of hops in the routes.

Furthermore, if we compare system $S_{1,1}$ and $S_{1,2}$ for $\lambda \simeq 0$ we see that the use of a traffic adaptive algorithm that optimize the protocol for maximum throughput might be negative for the average delay.

In Figure 2 we can also compare the maximum throughput for the four systems. We can then 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 gets a larger part of the networks resources.

If we compare the throughput for system $S_{1,2}$ and system $S_{1,1}$ in Table III we can see that we can 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 3 shows the quoitient between the throughput for modulation group $M_{1,1}$ to $M_{1,6}$, and the first modulation group $M_{1,1}$ (100 kbit/s), for respectively system. 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 graph 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 great. The resason why the quoitient 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 additonal 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. Though, the reason why there is a small improvement is probably because there is some local redistribution at the nodes resources when adding higher data rates, see Equation (5).

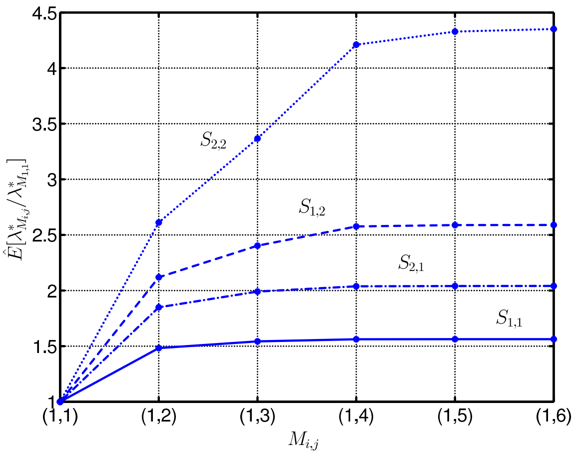

Fig. 3. Releative performance gain for the four systems when we increase the number of available data rates. Power level P_{low} is used.

TABLE IV

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

System $S_{1,2}$ has a higher quoitient than $S_{1,1}$, due to the traffic adaptivity. The factor between one respectively two data rates for this system is almost a factor 2, see Table IV.

System $S_{2,1}$ results is due to that the routing will chose links with higer data rates, but since the system has no traffic adaptivity nodes with the 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 between the different amount of data rates is much greater. The improvement of going from one data rate to four data rates is alomst a factor 4.7. The reason to the significant increase from adding the first data rates is partly due to that the routing chose the links with higher data rates and partly due to the traffic adaptivity which adjust the resources. However, having five or six data rates, $M_{1,5}$ and $M_{1,6}$, compared to four, $M_{1,4}$, give no notable increase in throughput. The reason why the quoitient does not increase for the last data rates is probably due to that the traffic adaptivity cannot handle this high differnce in data rate in a propor way. But also due to that the number of links that have the channel

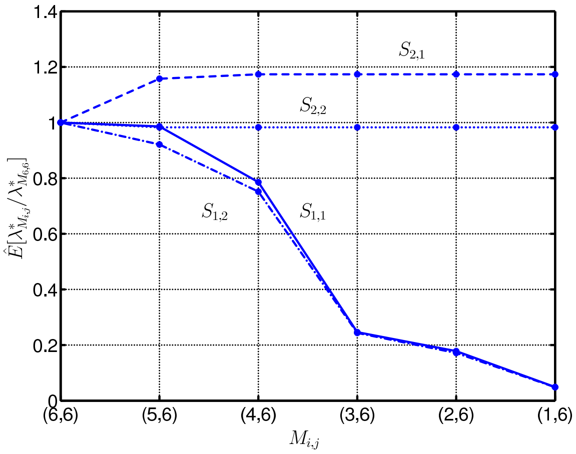

Fig. 4. Releative performance gain for the four systems when we increase the number of available data rates, by adding lower data rates when P_{high} is used.

TABLE V
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

condition necessary to fulfill the SNR are limited.

Figure 4 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 servere performance degradation for systems that uses minimum hop routing ($S_{1,1}$ and $S_{1,2}$). Since minimum hop routing does not take the data rate into account it will start to use these low data rate links and in that way create bottlenecks in the network.

System $S_{2,1}$, with $1/R$ routing and no traffic adaptivity, is able to take advantage of these additional low data rate links in a fruitful manner. Since this routing strategy prefer higher data rates links, the low data rate links will usually be used only if the throughput is increased.

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 $M_{5,6}$.

VI. Conclusions

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

The gain of having a great dynamic in data rates, i.e. having many data rates to chose in between, is not obvious. The results show that for the studied scenario it could be enough to be able to vary the data rate with a factor 50. Adding additionally data rates to chose between will not in this case increase the throughput notable. The dynamic in data rates will have a cost, which increases with additional data rates. It is therefore important to find a balance between the gain in throughput and the cost for dynamicity.

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