Routing Hysteresis Impact on Traffic Adaptation

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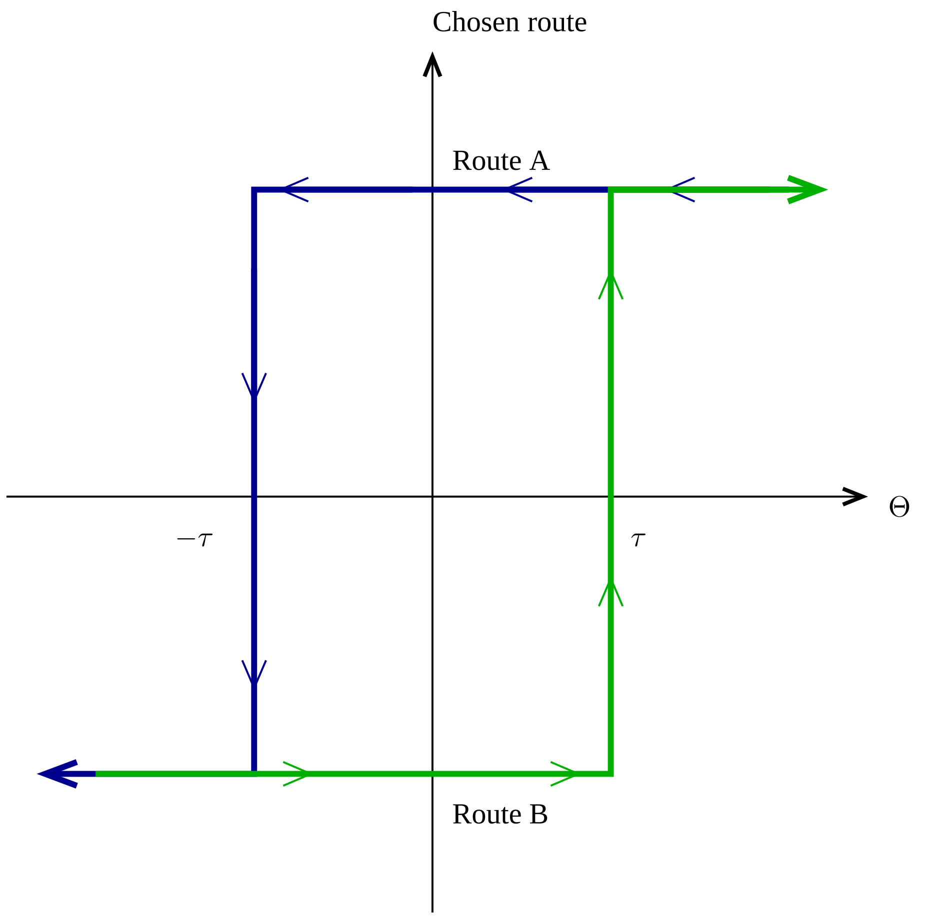

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Routing Hysteresis Impact on Traffic Adaptation

Abstract

The efficiency of multiple access (MAC) protocols is an essential issue in order to improve the capacity and service reliability of tactical mobile ad hoc networks. Traffic adaptivity in the MAC-layer is a way to increase the network throughput, i.e., bottleneck nodes in the network are assigned more channel resources than other nodes. Changes in resource requirements, due to the mobility must be communicated among the nodes in order to get a good traffic adaptivity. There is a risk that this rescheduling overhead, due to frequent route changes, will be too high to motivate the achieved throughput gain. Introducing a hysteresis threshold in the routing decision will reduce the route instability and thus also the rescheduling overhead at the expense of lower capacity on the routes. We introduce a measure of adaptation efficiency which we use to evaluate simulated networks of different sizes with fixed and variable link data rate. The networks have random mobility. We show that small threshold values improves the user throughput in these networks.

Keywords

radio, network, mobile, multi hop, ad hoc, routing, MAC, hysteresis, thresholds, overhead

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Sammanfattning
Vid taktiska operationer är kapaciteten i mobila ad hoc-nät av stor vikt. Nätets resurser måste därför utnyttjas effektivt samtidigt som kommunikationstjänster i nätet ska erbjudas med god kvalitet. För att öka kapaciteten, anpassar trafikadaptiva accessprotokoll resursallokeringen så att länkar med hög belastning kompenseras med mer kanalresurser. På grund av mobiliteten förändras rutterna i nätet, vilket medför att resursallokeringen måste anpassas till de nya trafiklaster som uppkommer. I samband med detta genereras overhead-trafik. Om rutterna ändras för ofta så kan overhead-trafiken orsakad av trafikadaptionen bli onödigt stor. Genom att införa hysteresrösklar i routingalgoritmen kan rutterna göras mer stabila till priset av rutter med lägre kapacitet. Vi tar fram ett effektivitetsmått för trafikadaptionen och beräknar detta för simulerade nät med fast och variabel datatakt på länkarna. Näten har slumpmässig mobilitet och olika storlekar. Vi visar även att små tröskelvärden i routingprotokollet möjliggör en högre nyttotrafik i de nät vi simulerat.

Nyckelord
radio, nät, mobil, flerhopp, ad hoc, routing, MAC, hysteres, trösklar, overhead

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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.

The network control can roughly be divided into two parts; *routing* and *medium access control (MAC)*. The routing protocol finds paths through the network from source to destination(s), i.e. it finds which units or radio links should be used to relay the message through the network. The MAC protocol determines when a certain unit, or a group of units, may transmit radio signals without interfering with other units communication.

In a mobile network, the available radio links 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.

1.2 Problem Overview

In some routing protocols, e.g. Ad Hoc On-Demand Distance Vector (AODV, [1]), and Dynamic Source Routing (DSR, [2]), a route is used until it breaks or until there has been no traffic to transmit on the route for a certain period of time. When a break occurs or a new route is needed, a route request - route reply process is initiated and hopefully results in a new route. This type of routing, i.e. to get routes as they are needed, is called *reactive routing*.

Another type of routing is *proactive routing* where each node in the network continously tries to maintain routes to all other nodes in the network. Example of proactive routing protocols are Fisheye State Routing (FSR, [3]), Destination-Sequenced Distance Vector (DSDV, [4]), Optimized Link State Routing (OLSR, [5]), and Topology Dissemination Based on Reverse-Path Forwarding (TBRPF, [6]).

A problem in routing is *route instability* (or route oscillation), which means that the route between a source and a destination oscillates between different "equally good" paths. This problem can occur in many networks and is especially prominent in ever-changing networks such as a mobile network. It results in constant re-routing and hence causes unnecessary routing overhead traffic.

Since a proactive routing protocol typically maintains a much greater number of routes than a reactive one, the effects of route instability will be much greater in a proactive protocol. However, a military network must also fulfill certain demands on e.g. delay, loss rate, capacity, priority handling, and connectivity. This means that the used protocols must be able to give some guarantees on the *Quality of Service (QoS)*. Due to their on-demand nature, few reactive routing protocols can give such guarantees. We will thus focus our efforts on proactive routing protocols in this report. The demand for QoS also affects the choice of MAC protocol. To be able to give QoS guarantees, *scheduled* MAC protocols such as Frequency Division Multiple Access (FDMA) or Time Division Multiple Access (TDMA) are to be preferred. One drawback of scheduled MAC protocols is that they do not have automatic *traffic adaptation*. A traffic adaptive MAC protocol is made to perceive changes in the network and to use this information to re-allocate the channel resources to reduce the effects of bottle-necks, minimize queues and avoid congestion. Hence, in a network with varying traffic and limited resources, traffic adaptation is a desired property. Traffic adaptation has thus been added to some scheduled MAC protocols, e.g. in Spatial Reuse Time Division Multiple Access (STDMA, [7]). A traffic adaptive MAC protocol is unfortunately more susceptible to the effects of routing instability than a protocol with no adaptation. The constant route changes brought on by routing instability also changes the traffic in the network. This causes a need for constant changes in the allocation of channel resources and hence an extra overhead due to the traffic generated from the MAC protocol. In this report we try to increase the route stability, and thus reduce this MAC adaptivity overhead, by introducing *routing hysteresis*. This means that a new route must improve the old one by at least a threshold value before the new route is used. As route cost, both shortest path routing (i.e. the best route is the one with the fewest hops) and variable data rate routing (i.e. the best route is the one with the highest capacity) have been used. Furthermore, the effects of different sized thresholds on route cost, route length, and the resulting traffic changes in the network are investigated. We will here focus on scheduled, traffic adaptive MAC protocols since we want QoS and are interested in cross-layer issues involving routing and MAC protocols and the information used by these protocols.

1.3 Previous Work

In [8], it is shown that the introduction of Intelligent Route Control (IRC) systems can increase the risk of routing and traffic oscillations in a network. The paper further proposes to solve the problem by estimating the available bandwidth and introducing a random component in the route switching decision or time scale.

Routing instability can also result from the use of traffic adaptive routing protocol with congestion control since the traffic adaptation and the congestion control might try to cancel each other out. This issue is addressed in [9] where a solution for traffic adaptive routing protocols with the so-called “min-max” property is suggested. It however, excludes algorithms that use link weights.

In [10], the instability effect of “greedy” route selection (i.e. always choosing the route with the most available bandwidth) on overlay network routing is restrained. The proposed solutions are; randomization of route selection, using a routing hysteresis threshold (improvement in available bandwidth), and an increase in the time between re-routing considerations. Randomization yields a significant decrease in loss-rate. The appropriate values for the hysteresis thresholds can be very dependent of the system parameters and it is suggested that these should be determined dynamically.

1.4 Contribution

We suggest a method using routing hysteresis to reduce the overhead generated by traffic adaptive MAC protocols. The method works for link weight routing algorithms as well as other types of algorithms for both networks with a fixed data rate and when variable data rates are used. Furthermore it is easily implemented, it reduces the number of re-routings, the routing overhead, the need for traffic adaptation, and the MAC overhead. If appropriate thresholds are chosen, it results in improved behaviour in two of the OSI stacks layers as well as links the routing and MAC protocols closer together.

1.5 Outline

In Chapter 2 we give a more detailed description of the routing instability problem, its effect on routing and MAC overhead, and the used thresholds. We also describe the modifications necessary to use thresholds in a routing protocol. Chapter 3 describes the simulation set-up, and our results. Our conclusions are discussed in Chapter 4 and our ideas concerning future work are presented in Chapter 5.

Chapter 2

Hysteresis

***Hysteresis** is a property of systems (usually physical systems) that do not instantly follow the forces applied to them, but react slowly, or do not return completely to their original state: that is, systems whose states depend on their immediate history [11].*

Most proactive routing protocols, changes a route as soon as there is a better (according to some metric) route available. Some reactive routing protocols may even change route if there is an equally good but newer route (i.e. a route with a newer sequence number).

These types of routing protocols are prone to route instability, since the routes change frequently when something changes in the network. There are situations where this is a desired behaviour, and it results in a network that is very responsive to changes. However, there are also many situations where the behaviour is unadvantageous since it also renders the network susceptible to instability. If a source-destination pair has two or more routes with equal or near equal costs, the route of choice may start to alternate between these routes, depending on which route at the moment has the lowest cost or the newest sequence-number. The network then experiences route oscillations. This result in an unnecessarily large amount of re-routing and, if a traffic adaptive MAC protocol is used, large amounts of re-scheduling of the network resources for very little gain in route quality.

To decrease the route instability, we propose the use of a threshold when determining if the route should be changed or not. When determining if one route is better than another one, there are many metrics that the routing protocol can use. Has the new route fewer hops? More available bandwidth? Higher data rates? Lower delay? Better signal-to-noise-ratio? Or is it simply newer? Here we choose to focus on two metrics; shortest path routing, and routing with a data rate metric. Shortest path routing is the most commonly used metric. The use of thresholds can however be applied to routing with any other link (or node) weight metric.

2.1 Shortest Path Routing

Shortest path routing (or minimum hop routing) is the classic routing method; from all paths that can be found between source and destination, the path containing the fewest number of hops (i.e. message relays) is chosen. This route is believed to be the best path possible. In a fixed data rate network, this metric usually results in good routes. A few examples of shortest path routing algorithms are DSDV, AODV, and FSR.

The cost of using a route created by shortest path routing is equal to the number of hops in the route, i.e.

$$C_k = \sum_{\forall l_{i\,j} \in U_k} 1 \tag{2.1}$$

where $l_{i\,j}$ denotes the link between nodes i and j, and U_k is defined as the set of links used in route k. See Section 2.3 and Figure 2.1 for an example.

2.2 Variable Data Rate Routing

In a network where variable data rates are used, it is not only the number of hops in a route that determines how good the route is. If shortest path routing is used in a network with variable data rates, it will still find the path containing the fewest hops. This means that no regard will be taken to the data rates on the links in the path and hence the routing method can not utilize the advantages of variable data rates. To be able to maximize the path and network throughput, a data rate routing metric must be used. We here use a metric based on the data rates of the links included in the route [12]. The cost, C_k, of using such a route

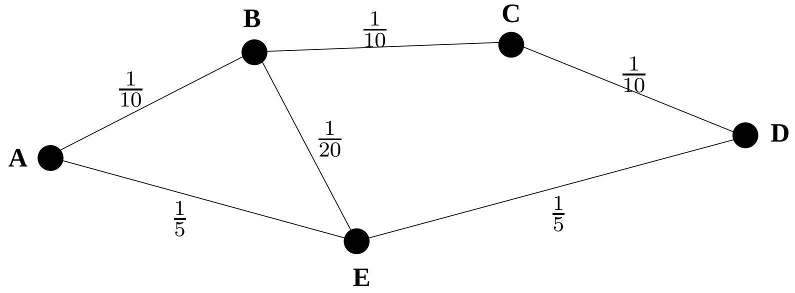

Figure 2.1: Example of a network with multiple data rates.

can then be expressed as

$$C_k = \sum_{\forall l_{i\,j} \in U_k} \frac{1}{R_{i\,j}} \tag{2.2}$$

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 resources is used and that the throughput can be high. It can also be noted that, for a network with a fixed data rate, if this metric is normalized by the lowest possible data rate R_0, it is identical to the minimum hop metric.

2.3 Example of Route Costs

To illustrate, let us study an example of route costs for a network with variable data rates. We can see how the resulting routes differ, depending on the used metric.

Node A wants to transmit a packet to node D. As can bee seen in Figure 2.1, there are 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 shortest path routing is used, the cost C_k of using these routes is 3, 2, 3, and 4 respectively. Since C_2 is the smallest, route U_2 will be chosen.

However, the links in the network have different data rates. 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.

If the data rate metric defined above is used, we get the following route costs;

$$C_1 = \sum_{\forall l_{i\,j}:U_1} \frac{1}{R_{i\,j}} = \frac{1}{10} + \frac{1}{10} + \frac{1}{10} = \frac{6}{20}$$

$$C_2 = \sum_{\forall l_{i\,j}:U_2} \frac{1}{R_{i\,j}} = \frac{1}{5} + \frac{1}{5} = \frac{8}{20}$$

$$C_3 = \sum_{\forall l_{i\,j}:U_3} \frac{1}{R_{i\,j}} = \frac{1}{10} + \frac{1}{20} + \frac{1}{5} = \frac{7}{20}$$

$$C_4 = \sum_{\forall l_{i\,j}:U_4} \frac{1}{R_{i\,j}} = \frac{1}{5} + \frac{1}{20} + \frac{1}{10} + \frac{1}{10} = \frac{9}{20}$$

Route U_1 will then be chosen instead of route U_2.

2.4 Routing Hysteresis Thresholds

Introducing hysteresis thresholds in shortest path routing is pretty straight forward: if the new route is Θ hops or more shorter than the old route, change route, otherwise keep the old one. The value of Θ is always an integer.

The introduction of thresholds is equally easy for the data rate metric. If the new route is Θ or more cheaper, change to the new route. The choice of threshold values are however not as obvious as when using the minimum hop metric.

In Figure 2.2, we can see an example of how hysteresis thresholds work. There are two routes available between the source and destination nodes; route A and route B. The threshold, according to some cost metric, is chosen to be τ. If route A is in use, it will stay in use until route B is τ better. Once route B is in use, it will stay in use until route A is again at least τ better. This means that we have a “safety zone” of 2τ that hopefully will absorb route instability in the network.

To introduce routing thresholds for any other cost metric can be done in the same manner as for shortest path routing and data rate routing. How to choose the appropriate threshold value is another matter, according to [10], the choice of a threshold for available bandwidth is very dependent of the system parameters.

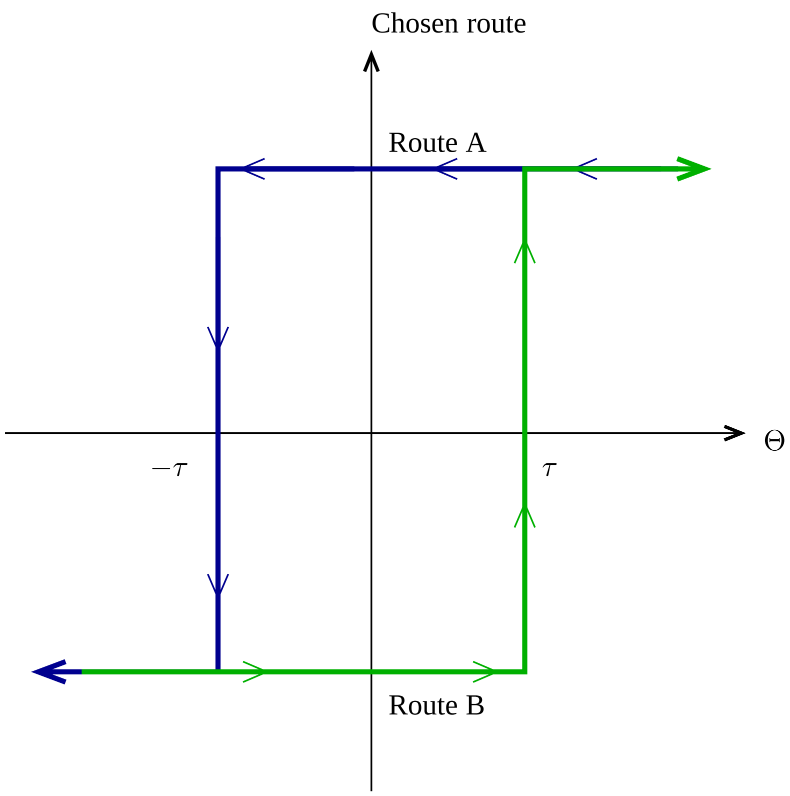

Figure 2.2: An example of routing hysteresis where $\Theta = C_{RouteB} - C_{RouteA}$ and C_k is the route cost of route k.

2.5 Scheduled MAC protocols

As mentioned in Section 1.2, we here focus on scheduled MAC protocols since we want to be able to give some QoS guarantees in our network. The most common scheduled MAC protocols are versions of FDMA and TDMA. In FDMA, the available frequency band is divided into "frequency slots". The slots is then allocated to the nodes (*node assignment*) or links (*link assignment*) in the network. Transmission can occur in several frequency slots at the same time, thus giving multiple access. In TDMA, the slots are in the time domain instead. The time slots together form a *frame* of a certain length. This frame is then repeated, meaning that a slot allocated to a certain node / link will periodically be available for transmissions from the node / link.

In its simplest form, the MAC protocol allocates a slot (time or frequency) to each node if it is a node assignment protocol or each link if it is a link assignment protocol. This type of allocation is however very rigid. *Spatial reuse*, i.e. the possibility to reuse a slot if the nodes or links are so far apart that they can not cause disturbances or collisions, is not possible for this type of allocation. This means that the wait for a transmission slot will be unnecessarily long and that the network throughput is hampered, never reaching its full potential. Furthermore, this type of allocation does not allow for such features as traffic adaptation where one wants to give more resources to heavily loaded parts of the network.

To get good QoS in our network, we need traffic adaptation and preferably also spatial reuse. In a network with varying data rates on the links, the transmission time of a packet on a link with high data rate will be shorter than the transmission time of a packet on a link with lower data rate. If an equal amount of channel resources, e.g. a slot per link, are allocated in such a network there is a large risk of congestion on links with low data rates and (partially) empty slots on links with high data rate. Hence the need for traffic adaptation increases when variable data rates are available.

There are scheduled MAC protocols where both traffic adaptation and spatial reuse is possible, an example of such a protocol is STDMA [7]. In Figure 2.3 an example of how STDMA works is shown.

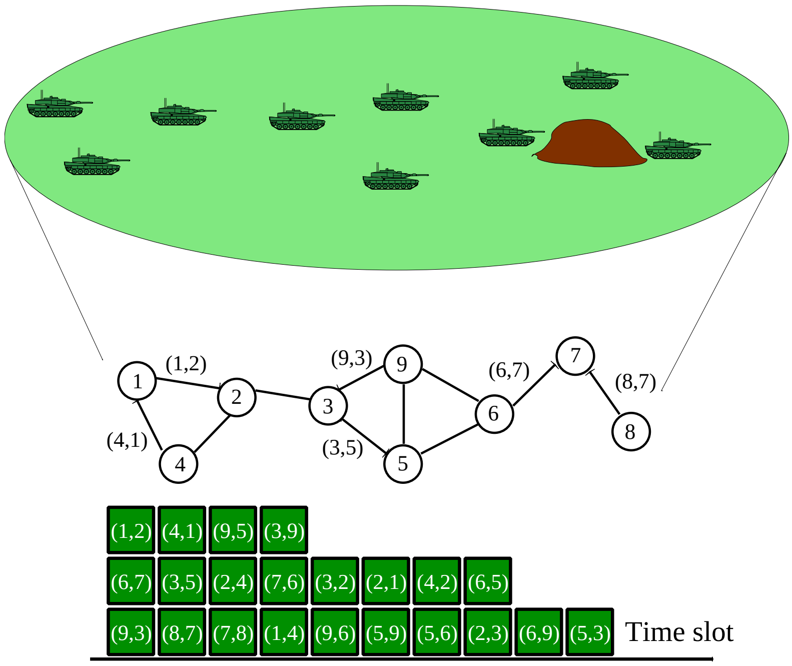

Figure 2.3: Example of STDMA with link assignment (from [7]).

2.6 Traffic adaptive MAC overhead

Traffic adaptivity in the MAC-layer is a way to increase the network throughput, i.e., bottleneck nodes in the network are assigned more channel resources than other nodes, see for example [13]. Changes in resource requirements, on the other hand, must be communicated among the nodes, at least within a local neighbourhood, in order to get good traffic adaptivity. For example, in STDMA and TDMA protocols, the traffic adaptation can be implemented by re-allocating one time slot at a time when changes occur. The re-allocation is continued until the traffic adaptation once again is considered good. This means that a re-routing that concerns many links tends to result in a large number of re-allocations and, for each re-allocation, the MAC protocol sends (small) overhead packets to inform of the changes made.

There is a risk that this rescheduling overhead, due to frequent route changes, will be too high to motivate the achieved throughput gain. Introducing a hysteresis threshold in the routing decision (when to use a better route), will reduce the number of route changes and thus also the rescheduling overhead. This may be a way to accomplish a cross-layer improvement without passing additional information between the MAC and the routing layer. Therefore, we derive an approximate tradeoff between the end-to-end user throughput and the rescheduling overhead, for varying routing thresholds in networks with fixed or variable link data rate.

Let γ be the total amount of available channel resources in the network. Furthermore, let γ_u denote the amount of resources consumed by the transmission and relaying of user traffic along the routes. The remaining resource consumption due to administrative traffic from the MAC and routing protocols, can in turn be divided into γ_{rs}, from the MAC rescheduling due to traffic adaptation, and a non-rescheduling part γ_0. The total resource consumption can at most be equal to γ, so we have the inequality

$$\gamma \geq \gamma_u + \gamma_{rs} + \gamma_0. \tag{2.3}$$

We are interested in the relation between the MAC rescheduling overhead, γ_{rs} and the total end-to-end traffic load λ_u.

Now consider the traffic along the routes. Packets enter the network at *source nodes*, are relayed along a route and leaves the network at *destination nodes*. For simplicity, we assume that all 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. We also assume that the average traffic load is the same on each route. With these assumptions, in order to avoid bottleneck nodes, a traffic adaptive scheme tries to allocate a proportionally larger amount of channel resources to links that are part of many routes, and to links with a low data rate. Since all routes in the network have the same traffic load, all routes through a link should be given the same amount of resources. Let φ_{ij} be the amount of channel resources allocated for a traffic load of 1 bit/s on one route trough the directed link l_{ij}. In order to compensate for the varying data rates, we want φ_{ij} to be proportional to $1/R_{ij}$, where R_{ij} is the data rate on the link. Let Λ_{ij} denote the number of routes that traverses the link l_{ij}. We define the resource requirement r_{ij} on each link as

$$r_{ij} = \begin{cases} 0, & \Lambda_{ij} = 0 \\ \frac{\Lambda_{ij}}{R_{ij}}, & \Lambda_{ij} > 0 \end{cases} \tag{2.4}$$

and say that we have perfect traffic adaptation when the amount of channel resources $\Lambda_{ij}\varphi_{ij}$ allocated to link l_{ij} is proportional to r_{ij}. Note that with perfect traffic adaptation, the total amount of resources allocated to the links in a route, is proportional to the variable data rate routing metric (2.2).

Now focusing on node-based MAC scheduling, we similarly define the node resource requirement, r_i, for node i as the sum of the resource requirements for all outgoing links from the node,

$$r_i = \sum_j r_{ij} \tag{2.5}$$

Define the maximum end-to-end user throughput $\lambda_u^\star$ as the maximum user traffic load λ_u that can be achieved with non-increasing queues in the network. Let the values of γ , γ_u, γ_{rs} and γ_0 in (2.3) corresponding to $\lambda_u^\star$ be $\gamma^\star$, $\gamma_u^\star$, $\gamma_{rs}^\star$ and $\gamma_0^\star$. Assuming that the traffic adaptation is perfect, we do not have any bottleneck nodes and all channel resources are utilized, so we have equality in (2.3). Furthermore, when the resource consumption equals the allocated resources on each link, the total user resource consumption $\gamma_u^\star$ is

$$\gamma_u^\star = \lambda_u^\star \varphi \,, \tag{2.6}$$

where φ is the sum of the resources φ_{ij} allocated for route transmissions on each link l_{ij} in the route, averaged over all routes in the network. Inserting (2.6) in (2.3) we get the maximum user throughput $\lambda_u^\star$ as

$$\lambda_u^\star = \frac{\gamma^\star - \gamma_0^\star - \gamma_{rs}^\star}{\varphi}. \tag{2.7}$$

We note that, with respect to traffic adaptation, we have an upper bound $\overline{\lambda_u^\star}$ on the maximum user throughput if we imagine a perfect traffic adaptation with negligible overhead $\gamma_{rs}^\star$ and a routing algorithm that finds routes that require a minimum amount φ_{min} of allocated channel resources:

$$\overline{\lambda_u^\star} = \frac{\gamma^\star - \gamma_0^\star}{\varphi_{min}}. \tag{2.8}$$

According to this, we define the adaptation efficiency, η, as the quotient between $\lambda_u^\star$ and $\overline{\lambda_u^\star}$,

$$\eta = \frac{\lambda_u^\star}{\overline{\lambda_u^\star}} = \frac{\varphi_{min}}{\varphi}\left(1 - \frac{\gamma_{rs}^\star}{\gamma^\star - \gamma_0^\star}\right). \tag{2.9}$$

Since φ is proportional to the variable data rate routing metric (2.2) and thus also proportional to the route length (2.1) in the case when we have a fixed data rate on the links, the adaptation efficiency can also be written as

$$\eta = \frac{C_{min}}{C}\left(1 - \frac{\gamma_{rs}^\star}{\gamma^\star - \gamma_0^\star}\right), \tag{2.10}$$

where C is the average route cost in the network . Observe that the route cost C in (2.10) is not at all related to the actual routing metric used by the routing algorithm. It is derived from the resource consumption along the routes. Since $\gamma_{rs}^\star$ at most can be equal to $\gamma^\star - \gamma_0^\star$ (resulting in zero user troughput, see (2.7)), the quotient $\frac{\gamma_{rs}^\star}{\gamma^\star - \gamma_0^\star}$ can be seen as the relative adaptation overhead of the MAC algorithm.

Each time that the traffic on a link changes, either due to a rerouting or due to varying data rates on the links in the route, we will in each affected node i have a new resource requirement r_i' that differ from the old requirement r_i. We define the node resource discrepancy δ_i in node i as

$$\delta_i = \left|r_i - r_i'\right|, \tag{2.11}$$

and we have the total resource discrepancy Δ in the network, due to a change in traffic load, by summing over all nodes:

$$\Delta = \sum_{i \in \mathcal{N}} \delta_i. \tag{2.12}$$

We now consider a traffic adaptive MAC protocol, which makes incremental updates of the channel allocation until perfect traffic adaptivity is achieved. We assume that a small fixed amount of channel resources is negotiated in each update, and that each update consumes approximately the same amount of channel resources in the network. Then the amount of channel resources consumed by the administrative adaptation to each traffic change is proportional to Δ,

$$\gamma_{rs} = \kappa\Delta \ . \tag{2.13}$$

Combining (2.10) and (2.13), the traffic adaptation efficiency can be written as

$$\eta = \frac{C_{min}}{C}\left(1 - \frac{\kappa}{\gamma^{\star} - \gamma_0^{\star}}\Delta\right) , \tag{2.14}$$

where the total amount of available channel resources $\gamma^{\star}$ and resource consumption $\gamma_0^{\star}$ due to non-rescheduling traffic not depend on Δ. Note also that C and Δ only depends on topology and routing variations.

Chapter 3

Simulation and Results

3.1 Simulations

In order to estimate the effects of routing hysteresis on MAC traffic adaptation for a mobile network, we do not need to simulate a traffic adaptation algorithm. Calculating η from (2.14) we only use the minimum routing cost C_{min}, according to (2.1) or (2.2), for the network and the values of C, and Δ for different routing thresholds. We use the time average of these values from our simulations. Adaptation algorithms are characterized by their relative adaptation overhead $\frac{\kappa}{\gamma^{\star}-\gamma_0^{\star}}\Delta$, without routing hysteresis. By choosing the value of the constant $\frac{\kappa}{\gamma^{\star}-\gamma_0^{\star}}$, we can then calculate the adaptation efficiency for different adaptation For the simulations, we generate networks from scenarios, where we have 8, 16, 32 or 64 nodes moving randomly in an area of 4x4 km. The terrain in the area is modeled by a digital terrain database. The nodes move independently of each other at a constant velocity of 20 m/s. The nodes randomly change direction at certain intervals. When a node reaches the area border, it turns and proceeds in a new direction. The scenario is running during 3500 seconds.

We evaluate routing hysteresis for shortest path routing and for variable data rate routing. In both cases, we use a routing algorithm that always finds routes with minimum cost. They are, however, both non-optimal in the sense that they may change to a new route with the same (minimal) cost as the old route instead of keeping the old ones. For the shortest path routing, we assume that the radio system used in the network has a fixed link data rate, R_0. For the simulations with variable data rate routing, we also use six additional higher data rate levels on the links: $2R_0, 4R_0, 8R_0, 16R_0, 32R_0$ and $64R_0$. The data rate levels are computed from the basic path-loss between the nodes, due to the terrain variations. The basic path-loss is estimated using the wave propagation library DetVag-90® [14], with a Uniform geometrical Theory of Diffraction (UTD) model by Holm [15]. Due to the mobility, the amount of node pairs that have single- or multi-hop connections vary. We say that two nodes are connected if it is possible to find a route between them. On average, 95% of all pairs of nodes were connected in the generated networks. We simulate with a low uniform traffic load and estimate Δ from the traffic on the links. We also compute the route costs in each time step.

3.2 Results

Fixed link data rates

In figure 3.1, we show the average route cost, which is equal to the average route length for networks with fixed link data rate. Note that the threshold value 1 is trivial in the sense that for this threshold, we never change to a new route with the same cost as long as the old route is usable. Naturally, this property could be expected of a good routing algorithm. This trivial threshold value does not increase the route lengths. For higher threshold values, the route lengths increase quite fast to about 30% longer routes. For very high threshold values, the average route length do not change, because for these thresholds we only change to a new route if the old one breaks. So for sufficiently high thresholds, the routes are identical for different values of the thresholds. We also note that the maximum average route length decreases with increasing network sizes.

The rescheduling overhead for fixed link data rate and shortest path routing, relative the non-threshold case, is plotted in figure 3.2. It seems to be independent of the network size. We see that we have the largest reduction in overhead for small threshold values.

In the figures 3.3, 3.4, 3.5, and 3.5 we show the traffic adaptation efficiency, η, for network sizes 8, 16, 32 and 64. We have one figure for each network size. In each figure we have a number of curves for different values of the relative adaptation overhead $\frac{\kappa}{\gamma^\star - \gamma_0^\star}\Delta$, without routing hysteresis. There is no big difference between the different network sizes. A general remark from the

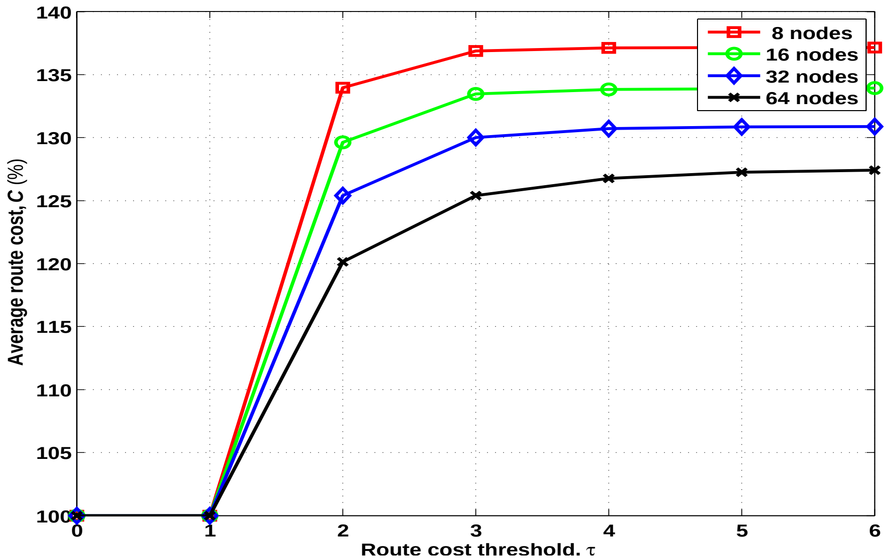

Figure 3.1: The average route cost, C, for networks with fixed data rates and shortest path routing. The route cost is given in percent of the average route cost C_{min} for the networks with no routing hysteresis.

networks with fixed data rate and shortest path routing is that for traffic adaptation algorithms with low rescheduling overhead, there is no gain in using larger thresholds values than the trivial 1-hop threshold. For algorithms with a very high overhead, 2-hop thresholds gives better adaptation efficiency.

Variable link data rates

In the discussion of these results we use relative routing thresholds,

$$\frac{\tau}{1/R_0} = \tau R_0,$$

where τ is the route cost threshold and $1/R_0$ is the maximum route cost on one link. In figure 3.7, we see the average route cost for the simulated networks. There is a higher increase in route costs, around twice the route costs with no routing thresholds, for the variable link data rate case. Since we have quite large

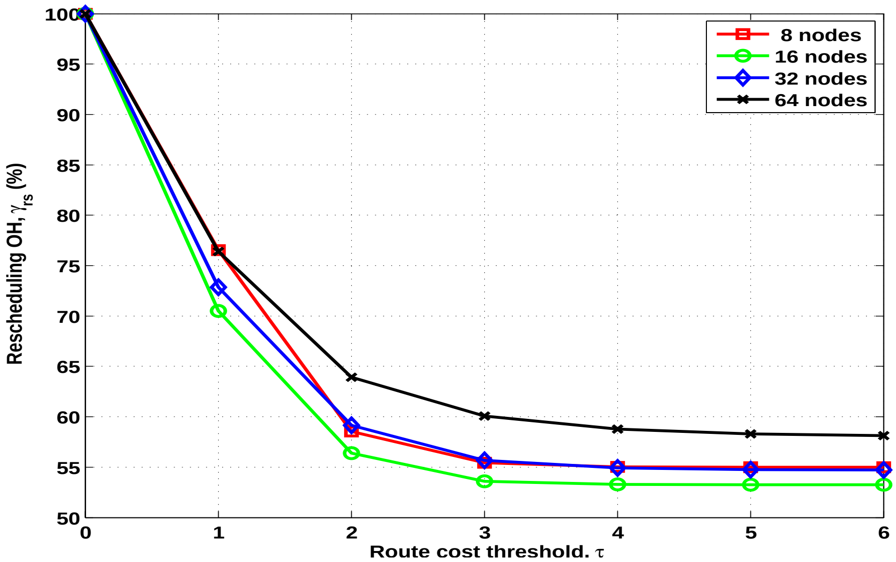

Figure 3.2: The MAC rescheduling overhead, γ_{rs}, for networks with fixed data rates and shortest path routing. The overhead is given in percent of γ_s for the networks with no routing hysteresis.

variations in the link data rate levels, it can explain the higher dynamic in the route costs compared to the fixed data rate case.

As we can see in figure 3.8, the rescheduling overhead decreases for small threshold values and then increases for higher threshold values. The main reason for the increase is that even if we keep to an old route, the data rates on its links will vary. This requires traffic adaptations. Due to the high dynamics in the data rate levels, it becomes very expensive (in terms of rescheduling overhead) to keep a route until one of its links disappears. Since the resource requirements for a link l_{ij} is proportional to $1/R_{ij}$, variations between high link data rate levels does not affect the rescheduling as much as variations between the low rate levels. For the smaller networks (8 and 16 nodes), the overhead even reaches a maximum level that is significantly higher than in the case with no routing thresholds. This is not the case for the two larger networks.

Figure 3.9, 3.10 and 3.11, and 3.11 show the traffic adaptation efficiency, η, for network sizes 8, 16, 32 and 64. As for the case with fixed data rate, we have in each figure a number of curves for different values of the relative adaptation overhead $\frac{\kappa}{\gamma^\star - \gamma_0^\star}\Delta$, without routing hysteresis. Also in this case, with variable link data rates, we see that relatively small threshold values give the best adaptation efficiency. Here, however, the efficiency improvement is larger for the larger networks. We can also note that introducing small routing thresholds improves the adaptation efficiency for MAC algorithms with a low relative rescheduling overhead. We can see an improvement from 10% rescheduling overhead for the networks with 32 and 64 nodes.

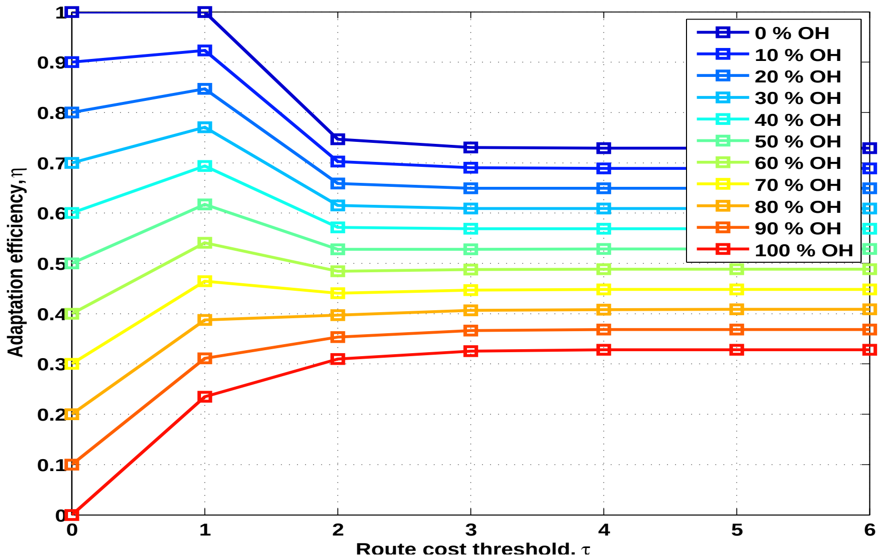

Figure 3.3: The traffic adaptation efficiency, η, for the network of size 8 with fixed data rates and shortest path routing.

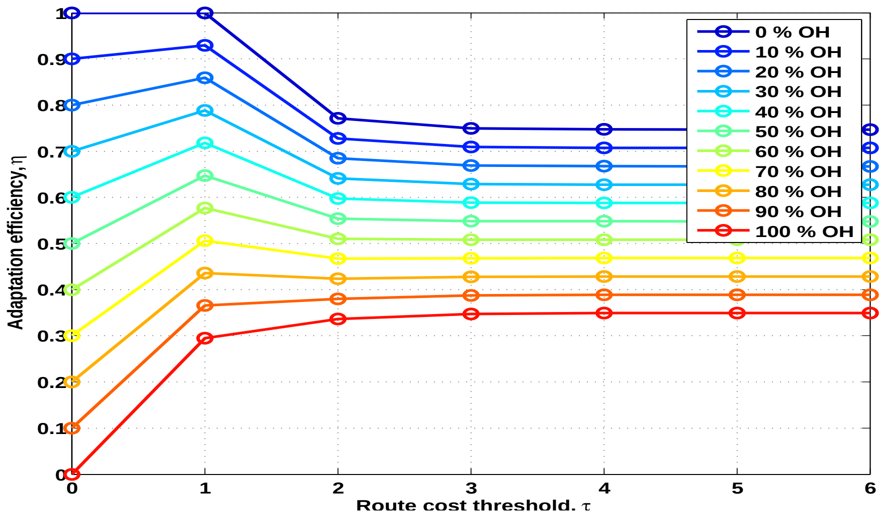

Figure 3.4: The traffic adaptation efficiency, η, for the network of size 16 with fixed data rates and shortest path routing.

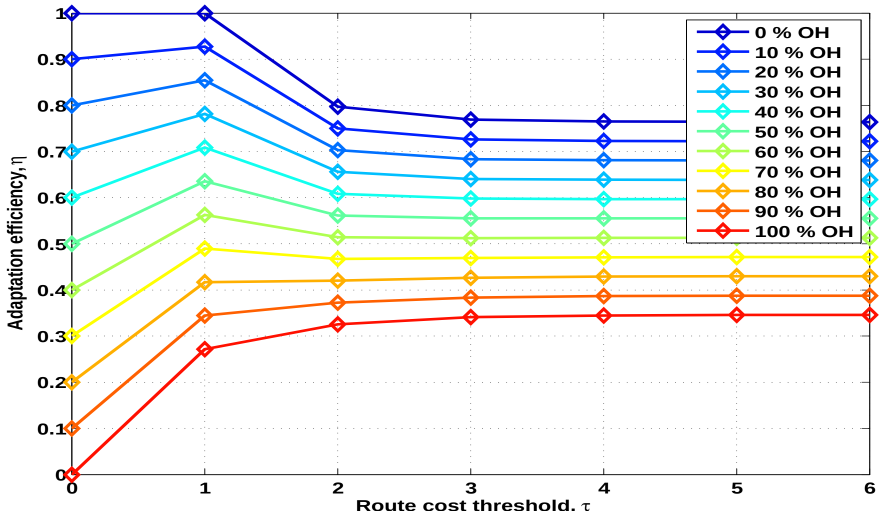

Figure 3.5: The traffic adaptation efficiency, η, for the network of size 32 with fixed data rates and shortest path routing.

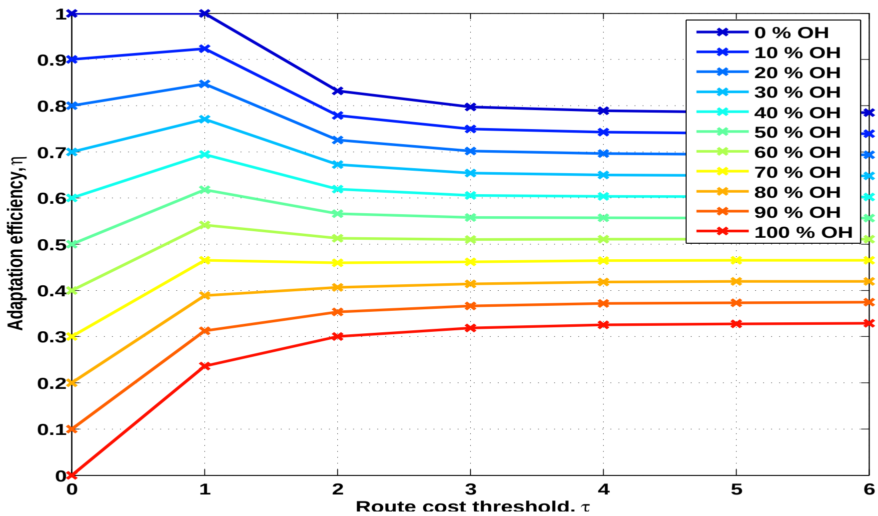

Figure 3.6: The traffic adaptation efficiency, η, for the network of size 64 with fixed data rates and shortest path routing.

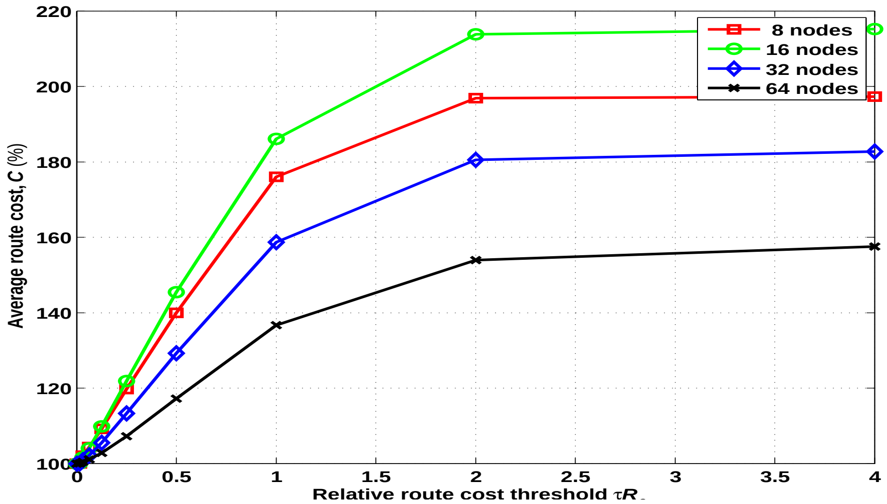

Figure 3.7: The average route cost, C, for networks with variable data rates and variable data rate routing. The route cost is given in percent of the average route cost for the networks with no routing hysteresis.

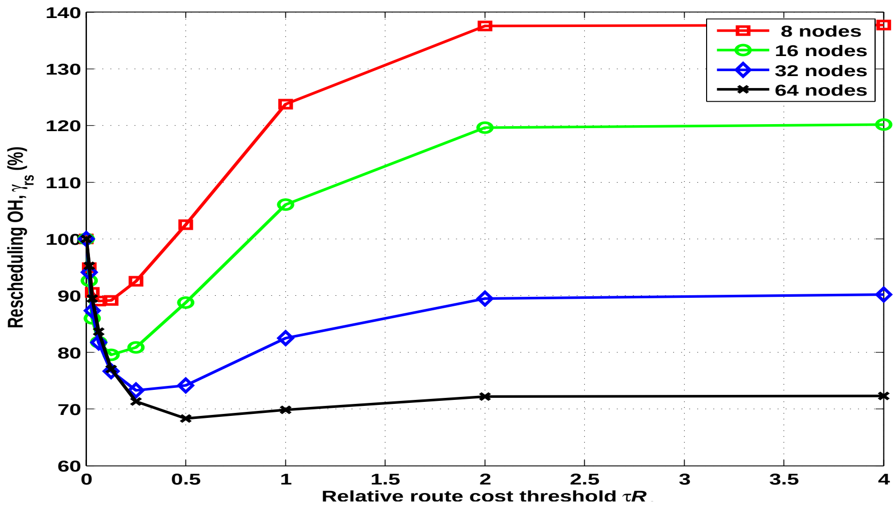

Figure 3.8: The MAC rescheduling overhead, γ_{rs}, for networks with variable data rates and variable data rate routing. The overhead is given in percent of γ_{rs} for the networks with no routing hysteresis.

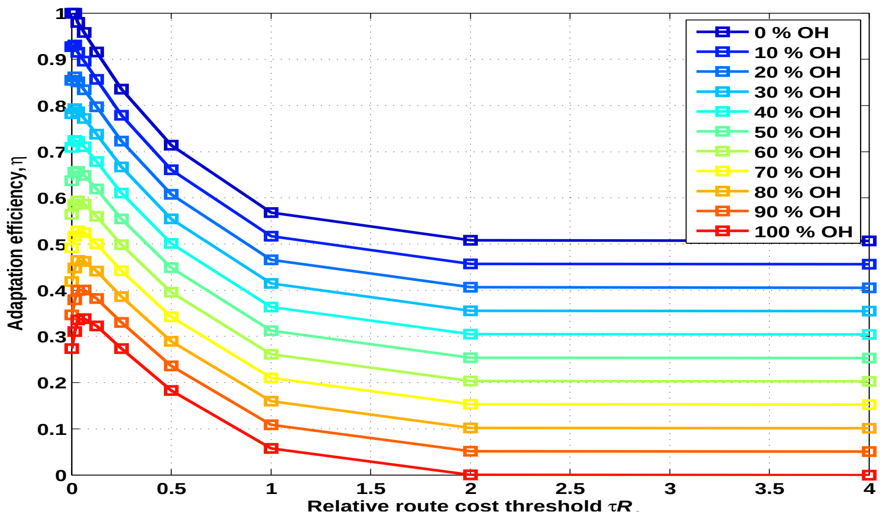

Figure 3.9: The traffic adaptation efficiency, η, for the network of size 8 with variable data rates and variable data rate routing.

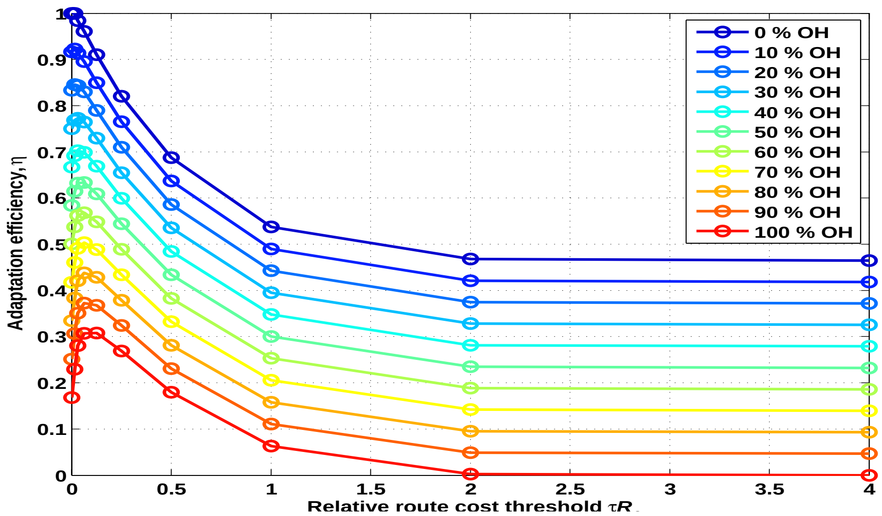

Figure 3.10: The traffic adaptation efficiency, η, for the network of size 16 with variable data rates and variable data rate routing.

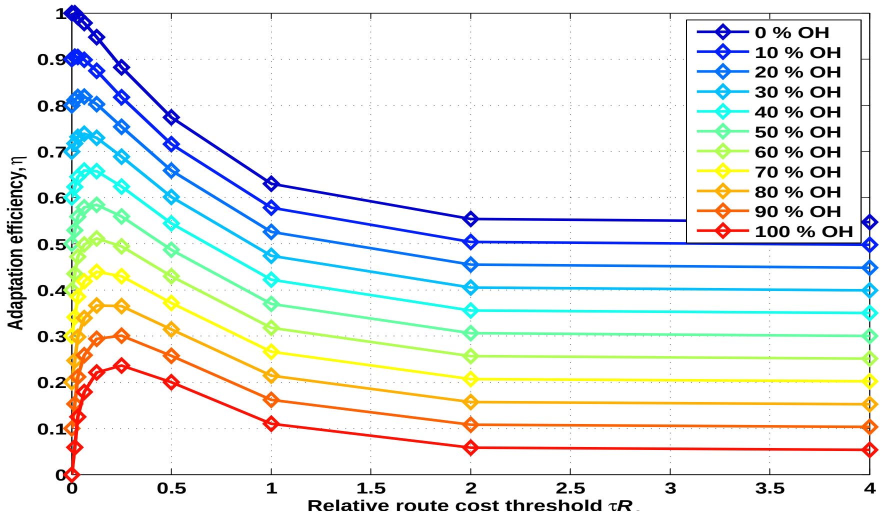

Figure 3.11: The traffic adaptation efficiency, η, for the network of size 32 with variable data rates and variable data rate routing.

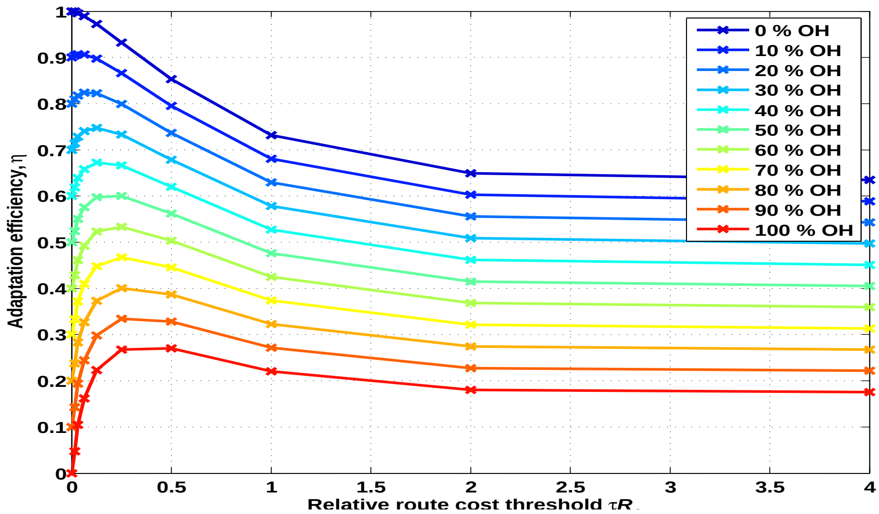

Figure 3.12: The traffic adaptation efficiency, η, for the network of size 64 with variable data rates and variable data rate routing.

Chapter 4

Conclusions

To increase the route stability in the network, we introduce routing thresholds when determining if a route should be changed or not. For small thresholds, this will decrease the need for resource allocations in a traffic adaptive medium access control (MAC) protocol, and hence the MAC rescheduling overhead. Due to the reduced MAC overhead, it is possible to obtain higher user traffic load in the network. As the thresholds grow larger, on the other hand, the routes deteriorate, and the maximum possible user traffic load decreases. Assuming a good choice of threshold values, we see that the improvements are larger for networks using variable data rates as compared to fixed link data rates. This is because also the link data rate variation will lead to changes in the resource allocation.

The rescheduling overhead decreases with larger thresholds for shorthest path routing on networks with fixed link data rates. In the case of variable data rate routing, however, the overhead starts to increase again and (for small networks) even supersedes the overhead without thresholds.

We introduce the concept of adaptation efficiency, an approximate trade-off for the user throughput, combining the effects of worsened routes and the variations in rescheduling overhead. Evaluating the adaptation efficiency for a number of simulated networks, we conclude that a small threshold improves the efficiency and a large one does not. Where to draw the line between small and large depends on the network size, fixed or variable link data rates, and the amount of rescheduling overhead in the adaptation algorithm.

In the networks with fixed link data rates and shortest path routing, the adaptation efficiency improvement is quite small. Obviously, for routing algorithms that change route even when the route cost not improves, the introduction of a threshold value is always beneficiary. In this case, the smallest meaningful threshold (one hop), result in a decreased rescheduling overhead without increasing the route costs. Only for traffic adaptive MAC with a very high level of rescheduling overhead, the adaptation efficiency is improved for thresholds larger than one,

For the evaluated networks with variable data rates and variable data rate routing, the improvement is higher, especially for the larger networks. In the larger networks, small routing thresholds is efficient for traffic adaptation algorithms with more than 10 % relative rescheduling overhead. Furthermore, the negative consequences of higher thresholds seem to be less for the larger networks.

Chapter 5

Future Work

There are a number of interesting issues left to pursue in this research area. We will here discuss a few of them.

Relative thresholds Instead of using absolute values for the hysteresis thresholds, it might be more appropriate to use relative thresholds. For example, if the new route is 10% shorter, change route (instead of, if the new route is 2 hops shorter, change route). This would make it possible for low cost routes to be more responsive than if they use the same threshold as a high cost route, while the high cost route can be kept from re-routing to make minor adjustments.

Dampening If a route "flaps", i.e. if a route alternates between existence and non-existence, it can also cause instability in the network. By adding "dampening", such a route is hindered from competing for traffic until it has existed for a certain period of time.

Link hysteresis A concept similar to dampening would be to introduce link hysteresis, hence only forming routes from links that fulfills some criteria. The time a link has existed or the signal-to-noise ratio on the link are examples of possible link hysteresis thresholds.

Connectivity In our simulations we have used a constant connectivity. It would be interesting to investigate whether the level of connectivity influences the results or not.

Delay How does the introduction of routing hysteresis thresholds affect the network delay?

Other thresholds The thresholds for route costs used in this report are by no means the only types of thresholds possible. Other possible thresholds include the time a route has existed and estimations of the route throughput or the rescheduling overhead. It is also possible to envision a system where thresholds for combinations of these characteristics are used.

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