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Methodology Report

Editor: Jan Nilsson

Mobile Ad Hoc Networks
- A Project Summary

Command and Control Systems
P.O. Box 1165
SE-581 11 LINKÖPING
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Report title

Mobile Ad Hoc Networks - A Project Summary

Abstract

One important component in future military communications is a high performance radio network that is independent of fixed communications infrastructures. Such a network, which we call a tactical ad hoc network, must be self-forming, self-healing and be able to support different types of services even in a high mobility scenario. Upholding the service requirements is usually denoted as Quality-of-Service (QoS) guarantees. A combination of QoS and high mobility requires careful design of the network protocols. This is one of the most challenging problems today in ad hoc network research. The QoS issue involves all protocol layers. In wireless communication, where the bandwidth is scarce, some sort of QoS control and adaptation to the situation will be needed.

This report summarizes the two year long Mobile Ad Hoc Network project. The project has focused on QoS issues and on the protocol layers Medium Access Control (MAC), Routing and TCP/IP.

Keywords

Radio, network, mobile, multi hop, ad hoc, QoS, MAC, routing, TCP/IP

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En viktig komponent i försvarets framtida kommunikationsarkitektur är ett mobilt taktiskt radionät som är oberoende av fast infrastruktur. Ett sådant radionät som vi kallar mobilt ad hoc-nät måste klara olika typer av tjänster och också fungera under olika typer av taktiska förhållanden. Ett av nyckelproblemen är att under svåra taktiska förhållanden tillhandahålla kommunikation med bibehållen hög tjänstekvalitet. Frågor kring tjänstekvalitet berör alla nätverkslager. Trådlös kommunikation innebär att bandbredden är begränsad, vilket i sin tur innebär att vi behöver kunna kontrollera tjänstekvaliteten på de olika nätverkslagren och kunna adaptera protokollen efter situationen.

Denna rapport sammanfattar det tvååriga projektet mobila ad hoc-nät. Projektet har inriktats mot frågor rörande tjänstekvalitet i ad hoc-nät och på protokollagren MAC, Routing och TCP/IP.</td></tr>
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Contents

Foreword

This report summarizes the two year long Mobile Ad Hoc Network project. The content is the following: a short executive summary of the project; a description of the tactical ad hoc networks we consider; our research direction and results; and future work and co-operations. We have chosen to keep the report short which means that the results are not described in details.

More information about our work and results can be found in the project papers [1–18].

Chapter 1

Executive Summary

One important component in future military communications is a high performance radio network that is independent of a fixed communications infrastructure. Such a network, which we call a tactical ad-hoc network, must be self-forming, self-healing and be able to support different types of services even in a high mobility scenario. We assume that upholding the service requirements, i.e., Quality-of-Service (QoS) guarantees, is very important in tactical networks. A combination of QoS and high mobility require careful design of the network protocols. This is one of the most challenging problems today in ad hoc network research. The QoS issue involves all protocol layers.

In wireless communication, where the bandwidth is scarce, some sort of QoS control and adaption to the situation will be needed. To control this adaptation at the different protocol layers and determine how the layers should interact for QoS guarantees, are main areas for research. The project has focused on the layers Medium Access Control (MAC), Routing and TCP/IP. Other layers, and in particular the interaction between layers, are topics we plan to study in more detail in the future.

The MAC layer controls the channel resource and determines which node and what traffic flow should have access to the channel at any given time. Thus, the MAC layer is very important when locally dealing with QoS issues. In this project, we have focused on reservation based access and ways to efficiently utilize the channel resource. The particular assignment strategy, or access protocol,

that we have focused on is called Spatial reuse Time Division Multiple Access (STDMA). Furthermore, we have studied several methods of distributed control to enable the network to locally adapt to a rapidly changing environment.

The routing layer is responsible for setting up reliable routes that are suitable for the services supported. We do, however, want to find these routes while using a minimum of overhead traffic. Areas we have covered, what level of mobility can be handled by reactive routing protocols, how can node position information be used to reduce routing overhead, and how should a network be divided into hierarchies to simplify the routing.

To achieve compatibility with the overall communication architecture for the ad hoc networks, the TCP/IP protocol suite has to be supported, even if special solutions can be sought at the lower layers. For this reason, a part of the project has been directed towards learning more about this protocol suite. Furthermore, the transport protocol TCP, and also some modifications of it, have been tested and assessed for use in ad hoc networks.

Chapter 2

Description of tactical mobile ad-hoc networks

An ad hoc network is a collection of wireless mobile nodes that dynamically form a temporary network without the need for any pre-existing network infrastructure or centralized administration. Due to the limited transmission range of wireless network interfaces, multiple network "hops" may be needed for one node to exchange data across the network with another. An ad hoc network is both self-forming and self-healing and it can be deployed with minimal or no need of network pre-planning.

We have put emphasize on mobility, since this is a very important property of tactical networks in future network centric warfare. The network has to cope with platforms moving at great speed, while still upholding connectivity. This contrasts with many of the commercial ad hoc network applications, where mobile means that a node can be moved to a new location, e.g., a Bluetooth network connecting equipments in a home environment or a WaveLan network used in a conference room. For these commercial networks, it is usually of less importance to uphold connectivity during movement to a new location.

A tactical network may be partitioned or fragmented into parts due to e.g., movements or terrain obstacles. It is therefore necessary that parts of the network can function autonomously, this requires a distributed network control. A tactical network could embrace everything from a small group of soldiers to several battalions. The terrain of operations can also vary considerably. The tactical unit we mainly have had in mind is a Swedish mechanized battalion. Two possible scenarios for the deployment of such a battalion are described in [19].

The network should be flexible to different types of command and control structures. Foreseeing future service requirements is difficult. We have, however, chosen some services that seem important to include in the network evaluations: situation awareness data, group calls, background traffic (e.g. e-mails), sensor data fusion, weaponry controlled by data from remote platforms, and extremely urgent alarm messages. The services can be divided into different QoS classes [20]. For example, the group call may consist of speech for which low delay and low delay variations are important QoS parameters. For the mechanized battalion we have so far focused on situation awareness data, group calls and background traffic, see [21].

Furthermore, we would like to stress that we assume that QoS guarantees is a very important property of tactical ad hoc networks, though the price tag on QoS guarantees may be high. It is therefore doubtful that the commercial sector will, at least to the same extent, prioritize QoS guarantees in their wireless ad hoc networks.

Chapter 3

The research direction

The main research direction has been towards QoS oriented issues for ad hoc networks and distributed network control. The future heterogeneous network architecture will consist of many different types of networks and, though the project has dealt with ad hoc networks, the overall architecture thus puts constraints on all other networks in order to allow for seamless communication. For the ad hoc networks to be compatible with this architecture, the TCP/IP suite has to be supported, even if special solutions can be sought at lower layers. Thus, one of the topics in the project has been to investigate how standard IP protocols would perform in ad hoc networks. Other focal points of our research have been routing and MAC. These topics and our results are described in more details below.

To be able to evaluate complex network architectures, we have also built up a new simulation environment based on OPNET. Let us point out that in this project, the building of competence in how to use the new environment has been the main output. The actual benefits from this work are long-term.

More information about our work and results can be found in the project papers [1–18].

3.1 Mechanisms for QoS

Military end users are usually not interested in networking details, the important thing is that the used application is delivered with sufficient quality (QoS). The QoS issue is complex and can be dealt with in many different ways. Furthermore, it involves all networking layers, from application to the physical layer. One method to obtain QoS used in many wired networks, is over-provisioning the bandwidth and "hoping for the best" using standard network protocols. In wireless communication, where the bandwidth is scarce, some sort of QoS control and adaption to the situation is necessary.

At the upper layers, context aware services, or adaptive services, could be applied. Thereafter the traffic management protocols becomes important. In order to avoid overloading, some sort of network admission control has to be implemented. Furthermore, preempting lower priority connections may be needed when traffic with very high priority, e.g., Nuclear Biological or Chemical alert, is present. The network need to be responsive to the mode of operation.

Related to the services is the source coding. Adaptive, and efficient source coding for wireless networks should e.g., have the ability to deliver graceful degradation. An example of this is a video transfer: as long as the connection is good, it has high resolution, but when the connection degrades, only the most important parts in the video picture are transmitted in high resolution. Graceful degradation can to some extent be provided by clever source and channel coding independently of each other but many cases, like the video example, requires interaction between non adjacent network layers since the service need to know the quality of the connection.

As mentioned earlier seamless communication means that the TCP/IP protocol suite needs to be supported. The IP QoS protocols, and how well they perform over wireless links, will therefore also determine how our heterogeneous network handles QoS. There are existing QoS IP protocols, e.g., Differentiated Services and Integrated Services, and some others that are under considerations. Furthermore, the connection control protocols, like TCP, may need to be modified to better allow for QoS.

QoS aware routing can have a great impact on the overall performance. Large heterogeneous networks will have a hierarchical structure. The global routing is handled by the standard IP routing protocols. However, for a particular tactical ad hoc network, subnetwork or network domain, it may be clever to apply other and more local routing protocols. That is, we will have routing at different levels and it is important to set up a "good" overall route between the end users. Good means that we should set up a route that take the QoS requirements into account.

To let the MAC layer be aware of QoS parameters is a promising approach in order to more locally be able to control the crucial traffic flows. The MAC layer controls the channel resource and determines which node and which traffic flow that should have access to the channel at a given time.

Clearly, also at the lower levels, a lot can be done to improve the performance. Here, we control the quality of particular links. By selection of frequency band, adaptive modulation, smart antennas, power control and multiuser detection we have the ability to adapt the links to the service requirements. Furthermore, we can control the overall network connectivity.

In conclusion, let us point out that for QoS guarantees the ability to adapt quickly to a new situation is crucial. The fastest response can be obtained at the lowest layers. For example consider a connection over many links and a high priority service requiring a low delay. When a link, or channel, deteriorates, start by decreasing the data rate by adaptive modulation. If the interference in neighboring nodes can be mitigated, we could also increase the transmit power. Next, when this doesn't help any more, go up to the MAC layer and assign more channel resource, e.g., by more traffic slots, to that connection. Thereafter, go up to the routing layer and find a new route and so on. A main problem and research area is how to control this adaption at the different layers and how the layers should interact. Still, according to the general networking principle, we do not want to much interaction between layers since this will make the overall network control extremely complicated.

3.2 The TCP/IP protocol suite

A protocol suite is a combination of different protocols in various layers, and the most widely used is the TCP/IP suite [22]. It is used as the standard suite over Internet and is an open system; the code of the protocol suite is available

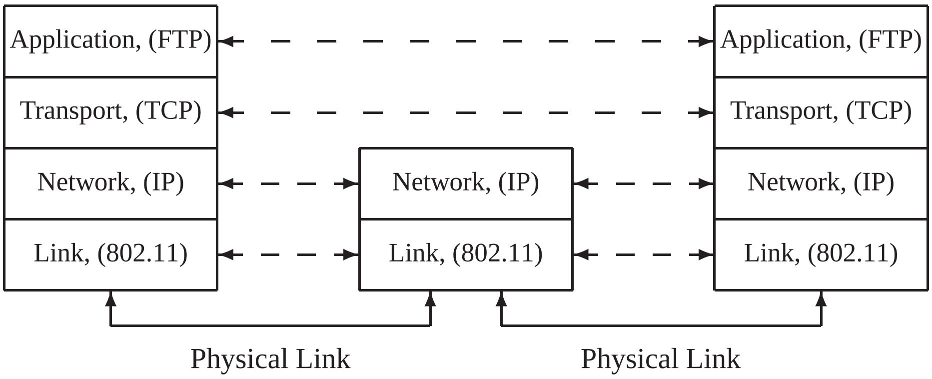

Figure 3.1: The TCP/IP protocol suite in the client, router and server with protocol examples in parentheses.

for implementations. The TCP/IP-suite is divided into four layers, as shown in Figure 3.1.

The application layer handles the services we want to use, e-mail, file transfer, web browsing etc. The transport protocol is situated between the application layer and the network layer and is responsible for the end-to-end flow of data between the applications of two hosts. The most commonly used protocols are TCP (Transmission Control Protocol) and UDP (User Datagram Protocol). IP (Internet Protocol) is used at the network layer and handles routing. The link layer takes care of the interface between the hardware and the network interface, and one wireless link layer protocol is IEEE 802.11.

We have been studying the transport protocol TCP that is designed for the wired Internet. It provides reliability by retransmitting lost packets and using flow control to avoid congestion, and is widely used. It would be preferable to use TCP in ad hoc networks since some of the applications need a reliable connection, which TCP provides. UDP on the other hand does not retransmit lost packets nor use flow control.

In wireless networks, packet losses occur more frequently due to the uncertainty of the physical link. The problem is that TCP treats the losses as congestion, which may lead to an unnecessary low throughput. Mobile ad hoc networks are multihop wireless networks of mobile nodes, where topology changes often occur and may lead to packet losses and delays, which TCP misinterprets as congestion and therefore decreases the data rate.

In this project we have been studying the effects TCP have on ad hoc networks to see if it is possible to modify TCP to recognize the differences between link failure and congestion to improve the capacity of the connection [17]. A simple modification of TCP was made and simulated, and showed that an improvement of performance is possible. More research should be done to make a modification of TCP that would further improve the throughput.

Another important area to study is QoS in tactical IP networks, which we have done in another project concerning seamless communications. There have been some QoS protocols developed mainly for wired communications, and we have investigated their usability in tactical ad hoc networks [23]. We describe the three most stable QoS protocols in IP networks at the moment, *Integrated Services*, *Differentiated Services* and *Multiprotocol Label Switching*. When using them in tactical ad hoc networks we can anticipate problems, and they need to be redesigned to fulfill our demands.

3.3 Routing

In a mobile ad hoc network, it may be necessary for one mobile node to enlist the aid of other nodes in forwarding a packet to its destination, due to the limited range of each mobile node's wireless transmission. In order to facilitate communication within the network, a routing protocol is used to discover and maintaining routes between nodes. The primary goal of the routing protocol in an ad hoc network is to construct and maintain robust and efficient routes between a pair of nodes using a minimum of overhead.

A numerous of ad hoc network routing protocols have been developed for mobile ad hoc during the recent years. These protocols can generally be divided in to two categories; *proactive* and *reactive* protocols.

Proactive routing protocols attempt to maintain consistent and up-to-date information from each node to every other node in the network. The proactive protocols may be divided in to two groups; *link state* algorithms and *distance vector* algorithms. In *link state* algorithms, all nodes require to know the complete network topology. To handle mobility, link establishment or link breakage, all neighbors periodically sends out the status of the links to its neighbors (i.e., the list of its neighbors) to all the other nodes in the network. Upon receipt of an update at a node, the topology of the network, as viewed by the node, is updated. Shortest path algorithms can then be used to compute a path from the node in question to any other node in the network. The main disadvantage of link state algorithms is the high amount of routing overhead traffic when the mobility is high, every link change is reported to every node in the network. In *distance vector* algorithms, each node maintains a table with an entry for every destination node in the network, which specifies the distance (often number of hops) and the next-hop-neighbor to get to the destination. The tables are updated by periodic exchange of routing tables with the neighbors. One of the disadvantages of distance vector algorithms is poor scalability, due to the periodic exchange of messages and the message size is proportional to the number of destinations.

In *reactive* routing protocols, routes are created only when desired by the source node. When a node requires a route to a destination, it initiates a route discovery process within the network. Once a route has been established, it is maintained by a route maintenance procedure until either the destination becomes inaccessible or until the route is no longer desired. The motivation behind the reactive protocols is the routing overhead (typically measured in terms of the number of routing packet transmitted, as opposed to data packets) is typically lower than for the proactive protocols, since only the actively used routes are maintained. However, the routing overhead traffic in reactive protocols approaches to that of the proactive ones if a moderate to large number of routes need to be actively maintained. This is because of the route discovery process uses a flooding technique, where the source floods the entire network with a route request packet in search of a route to the destination. Flooding takes up a substantial amount of network bandwidth, which is a limited resource in wireless networks. Efficient control of frequent network-wide flooding is thus important for the efficient performance of reactive protocols.

Information about where units of interest are located, is very important in military operations. Clearly, whenever such information is available it can be used to simplify the routing in multi-hop ad hoc networks. In the papers [1–3], we investigate the routing overhead caused by the route search procedure in reactive routing protocols. The idea is to reduce the route search to a limited region with the aid of location information. Different search regions, applied both in a static and an adaptive way, are investigated. In particularly, the aim of our investigation is to see how the terrain effects the efficiency of location information aided routing. The simulations show that there is a lot to gain by using location information, if this is available and reliable, in order to limit the route search. In the tested networks we reduced the route search overhead with up to 70%, compared to flooding.

Another way of reducing the routing overhead in the route search procedure is to introduce hierarchies, the nodes are divided into clusters. The flooding in the route search can now be performed on the cluster level instead of on the node level. In the papers [4, 5], we analyze when a clustered architecture is efficient in an ad hoc network from the routing point of view. We observe which parameters of the system that are crucial in selecting either clustered or non-clustered architecture. For the analysis, the total amount of data bits required to be transmitted through the whole network is used as the measure of network efficiency, when a data message is delivered from a source to destination station according to a simple reactive routing protocol with flooding as a route search method. We have tested many different networks with various clustering formations and suggest a criterion to determine whether to use a clustered architecture or not.

In a situation where the radio-units (nodes) are moving fast through the terrain, the topology will change rapidly. An interesting question, in such a network, is whether or not routing should be performed simply by flooding the data packets. In the paper [13], we address this problem by comparing flooding and a reactive routing protocol. The simulation results show for what situations, expressed in topology change rate, traffic intensity, and network connectivity, the reactive protocol is preferable to flooding, in terms of the average total amount of traffic generated. However, for reactive routing, the fraction of data packets injected into the network that reaches their destination decreases with an increasing topology change rate, while it remains constant for flooding. Whether to use reactive routing or flooding in a certain situation thus becomes a trade-off between the cost, in terms of generated traffic, of sending one data packet and the fraction of data packets that reaches their destination.

3.4 Medium Access Control

One of the most important design issues for ad hoc networks is Medium Access Control (MAC), i.e. how to avoid or resolve conflicts due to simultaneously transmitting radio units. The MAC protocol is situated at the link layer in the TCP/IP suite. Many different methods for solving the MAC problem exists, but we can divide these methods into two different categories, conflict-free and contention-based protocols.

Conflict-free MAC ensures that whenever a transmission occurs it is successful, at least it will not fail because of other nodes in the network. Conflict-free transmissions can be achieved by assigning the channel to the users statically or dynamically, according to their needs. In a contention-based protocol on the other hand, a transmission is not guaranteed to be successful. Instead when conflicts occur they will be resolved by some means. This resolution can be done in different ways. However, in ad hoc networks (and radio networks in general) it is usually difficult for the nodes to know exactly how many and which nodes that created the conflict. Which means that rather simple probabilistic methods must be used.

Traditionally, MAC protocols for ad hoc networks are based on these probalistic contention-based access methods, due to their simplicity compared with conflict-free scheduling. The user has no specific reservation of a channel and only tries to contend for or reserve the channel when it has packets to transmit. This has clear advantages when the traffic is unpredictable. More specifically, the most frequently used protocols are based on carrier sense multiple access (CSMA), i.e. each user monitors the channel to see if it is used, and only if it is not will the user transmit. If there is a collision despite this the user will wait a random time and then try to retransmit the packet.

However, it is the transmitter that listens to see if the channel is used while conflicts occurs in the receiver. This can lead to the so-called hidden terminal problem. A way around this is to first transmit a short request-to-send (RTS) and then only send the message if a clear-to-send (CTS) is received. This is the general principle of the IEEE 802.11 standard, which at present is the most investigated MAC protocol.

However, several RTS can be lost in a row which makes delay guarantees difficult. Therefore, we have made investigations of the IEEE 802.11 behavior in ad hoc networks with delay guarantees. This have been presented in [14–16]. From these works it can be seen that there is a large decrease in expected channel capacity when comparing a networks average characteristics to its firm demand characteristics. It can be concluded that when determining capacity needs in networks with contention-based MAC protocols with QoS demands, other measures than averages must be used. It is also clear that the only simple way to handle QoS traffic in networks with contention-based MAC is to use over-provisioning as is used in many wired networks.

Another possibility to give QoS guarantees is instead to use conflict-free protocols. However, although delay guarantees can be obtained once the assignment of the channel is done, the problem of doing this assignment efficiently in a mobile network is not easy. A pure static division of the channel like TDMA is usually inefficient due to different need of the nodes. Instead we have studied Spatial reuse TDMA (STDMA) which is a conflict-free protocol in which time slots are reused whenever the distance between the nodes are sufficiently geographically separated. Although STDMA has several properties that could make it useful in tactical military communication, much research and development is necessary if we want this MAC protocol to reach its full potential, especially in mobile environments.

STDMA schedules can assign transmission rights to nodes or alternatively assign transmission rights to links, i.e. transmitter/receiver pairs. These two methods have been compared to determine which one is preferable for unicast traffic. We conclude that both methods have undesirable properties in certain cases, e.g. link assignment gives a higher delay for low traffic loads but can achieve much higher throughput than node assignment. We also proposed a novel assignment strategy called Link assignment with Extended Transmission rights (LET), that have the advantages of both methods. Our results show that the proposed method can achieve the throughput of link assignment as well as the lower delay characteristics of node assignment for low traffic loads. Both of these results was partly presented in [7] and then the investigation was expanded in a scientific report [6].

These works assumed unicast traffic. However, node assignment have clear advantages for broadcast traffic, since a radio transmission can reach several recipients. Therefore, in a paper [8] we investigate how LET behaves compared to node assignment in terms of delay and throughput for broadcast traffic using simulations.

One conclusion that could be drawn from work done so far was that the performance of LET is dependent on the link schedule which it is based on. In [11], the design of the algorithms that generate the link schedules was studied and we suggested how to expand a basic link assignment algorithm in order to take better advantage of LET so as to decrease the packet delay.

We use a interference-based model to describe our networks, since this model gives a very accurate description of a radio network. However, one drawback with this model is its complexity and an alternative model is a graph-based model. The advantage of a less complex model is that much less information must be exchanged when the network changes due to mobility. In [9] we have investigated the properties of schedules generated with these models. From this we can conclude that interference-based scheduling gives considerably much more capacity than based on a graph-based scheduling. This suggests that the model we have assumed so far really is interesting for distributed algorithms.

All the work on STDMA described so far was presented in a Licentiate thesis [10].

In the last part of the work on MAC protocols [12] we have investigated and made a list of all properties that a distributed algorithm must have to work efficiently in the scenarios we are interested in. These properties has been investigated for existing distributed algorithms, but none of the them fulfill all these properties. Although, with the ideas given from these existing algorithms we can see ways to create such a algorithm. The exact description of a distributed STDMA algorithm with all the properties we want will be left for further work.

3.5 The simulation environment OPNET

One long-term objective for the radio network research group is to have the ability to evaluate heterogeneous communication networks through software simulations. One reason for this is that it is very hard to analytically analyze function and performance of communication network systems. Other reasons are for example that there are very few existing real-world systems to study, that it is very expensive to build a complete radio system and that it is also very difficult to carry out experiments of an entire communication system where for example the radio units are moving. In several former and ongoing projects simulations of different network functions have been an important method to determine the performance of different network concepts.

The objective for the software simulation work is to create a common software simulation environment for future simulation needs in different projects. In consultation with other projects, which use simulations, it was decided that the simulation environments that existed in different projects were to be replaced with one common simulation environment. Finally, the choice fell on OPNET Modeler [24]. OPNET is a simulation environment in which different types of communication networks can be evaluated concerning behavior and performance. The important reasons for choosing OPNET were for example that other organizations and companies, which are in the line with our activities, tend to use this simulation environment. The fact that OPNET is a commercial product was also important since it then exists a company that has the overall responsibility concerning debugging and development of the software. OPNET also provides a wide range of essential components for a communication network e.g. WirelessLAN, mobile telephone stations and routers.

The simulation activity that has been carried out during the project Mobile Ad Hoc Networks has been focusing on the MAC layer and the transport layer. The objective for the work concerning MAC has been to build a fundamental infrastructure for future implementations of different access protocols in OPNET [18]. One important part in this work was to enable import of link attenuation values from different scenarios to simulations in OPNET. The simulation activity concerning the transport layer was mainly about how the transport protocol TCP works in an ad hoc network. Topology changes may often occur and cause packet losses and delays, which TCP often misinterprets as congestion. A simple model of a connection with packet losses and where interrupts could take place was modeled and used.

Other projects, which have been participating in the work concerning the common simulation environment, have taken the responsibility for applications and routing.

The main result from this work within the project Mobile Ad Hoc Networks is that we, in collaboration with other projects, have been building competence concerning how effectively the new simulation environment can be used for evaluation of communication networks.

Chapter 4

Future work

We will continue to focus on QoS issues for mobile ad hoc networks. As described in Section 3.1 there are many different QoS mechanisms at different layers and a future research area is how to control this adaption at the different layers and let the layers interact. Another related topic for further investigations is the QoS IP protocols and how they perform in heterogeneous wireless ad hoc networks. Also, we plan to continue to study QoS aware routing and how large ad hoc networks should be divided into hierarchies.

The future heterogeneous networks will be heterogeneous at many different levels. For example, terrain and mobility may vary for different parts of a tactical ad hoc network and this means that these parts need to use different protocols and frequency bands. Furthermore, radio nodes within a particular sub-network may have different capabilities since it can be anticipated that future wireless systems will contain many different types of radio equipment. For example, different generations of radio platforms that have different communication capabilities. Whenever, a new radio platform, or new radio software, becomes available it should be usable within the current wireless infrastructure and stepwise enhance the overall network performance. To allow for an evolutionary upgrading process we aim at investigating what features of future radio terminals that are important to integrate in the higher network control layers and what features that can be dealt with at the lowest layers. Furthermore, it is also of interest to investigate what can be gained in terms of network performance by these features.

An important issue we plan to further study during the next year is how to utilize adaptive nodes in a radio network. Such nodes should try to control, or at least as far as possible mitigate the local interference situation and adapt its data rate to the channel and what is going to be transmitted. The adaptation can be made using smart antennas, multi-user detection, power-control, and adjusting modulation and coding to the channel conditions. Let us point out that the issue here is how to look upon an adaptive node from the network perspective. How should the adaptivity be used and interact with the MAC and Routing protocols to achieve maximal network performance and service flexibility? Also, the node adaptivity has to be modeled taking the feasibility of implementation into account.

Research co-operations

Below we only point out areas where we already have established cooperations and can foresee a continuation during the next year. Clearly, of great interests are also the new possibilities that opens up for co-operations within Europe.

Part of the research work, where we have common interests, will be done in cooperation with Wireless@KTH and participating in the Affordable Wireless Services and Infrastructure (AWSI) project. We have most interests in the "Low Cost Wireless Infrastructure" part and there in the work package called "Distributed ad hoc infrastructure"; see www.wireless.kth.se /AWSI/LCI/.

We will continue our cooperation with Wireless@KTH and Uppsala University and arrange a 3rd Scandinavian Workshop on Wireless Ad-Hoc Networks in May 2003: see www.wireless.kth.se /adhoc03/. In the area of MAC protocol optimization we have had some cooperations with Linköping University, Campus Norrköping, and hope to be able to continue this work also next year. Finally, we plan to continue our cooperation with Korea Military Academy, Seoul, and Professor Yeongyoon Choi who was a visiting researcher at our department from July 2001 to July 2002.

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