Technical University Berlin

Telecommunication Networks Group

Medium Access Issues for QoS Support, Power Control and Multiple Frequency Channels in Distributed Multi-Hopping Wireless Networks

—

A Literature Survey

Emma Carlson, Holger Karl and Adam Wolisz
carlson,karl,wolisz@tkn.tu-berlin.de

Berlin, January 2004

TKN Technical Report TKN-04-010

TKN Technical Reports Series

Editor: Prof. Dr.-Ing. Adam Wolisz

Abstract

Multi-hopping, or relaying is an option for enhancing the performance of a wireless network. One aim of this report is to investigate the different possible configurations of such a network. We describe how relaying, routing and medium access control can be conducted. We suggest a system model to be used with distributed medium access and describe the problems with this model, mainly concurrent transmissions, exposed terminals and QoS support.

Further, we describe possible enhancements that can be introduced for our system model. We identify usage of multiple frequency channels, power control and reservation mechanisms as the main mechanisms that could enhance our distributed multi-hop wireless network.

The main focus of this report is a study of existing work where the problems described above have been approached with special emphasis on work that uses the three above described main mechanisms; power control, multiple frequency channels and reservation mechanism.

Contents

Chapter 1

Introduction

Relaying, or multi-hopping, is a potential option to increase capacity, extend coverage and improve energy efficiency in wireless networks. It can be conducted in networks with varying degrees of infrastructure such as pure base-station based networks, fixed relaying stations, or pure ad-hoc networks. Also, relaying can and has to be controlled in the sense of both routing and medium access, either in a distributed or centralized fashion.

This report discuss advantages and disadvantages with the different relaying possibilities and approaches and focuses then on a specific system model for a relaying network. We believe that a decentralized structure of the MAC layer is an appropriate approach due to flexibility and robustness. However, for this approach there are some unsolved issues with the efficiency of the multi-hop communication and with support of Quality-of-Service sensitive applications over such a multi-hop transmission path.

Further, this report discusses improvements that can be made to the decentralized system. In summary, we see three main areas where improvements can be made, namely distributed reservations for QoS-sensitive traffic, power control over multi-hop paths and multi-channel MAC protocols for multi-hop paths. For these three approaches, we survey and investigate previous work in these areas.

The report is organized as follows: In Section 2, we discuss the different possible system concepts for relaying. We suggest a system to use in Section 3 and an example for this system in Section 3.3. We then discuss previous work in Section 4 and draw conclusions in Section 5.

Chapter 2

Possible system concepts for a multi-hop system

This section describes the possible system configurations of a multi-hopping system. Section 2.1 describes how the relaying can be performed. After that comes the different ways of how to perform routing in Section 2.2, followed by the possible MAC set-ups in Section 2.3. Section 2.4 summarizes the different concepts.

2.1 Relaying

2.1.1 What is relayed?

Relaying can be done on the basis of either an electro-magnetic impulse (repeated analogously) or a digital entity (store and forward).

- Electro-magnetic impulse. The intermediate node forwards the packet directly on the physical layer. It amplifies the incoming signal with hardly any delay. There is no requirement for decoding or any other processing. A downside with this method is that the errors are also amplified.
- Digital entities. The intermediate node receives, decodes, and possibly alters the packet before forwarding. The packet goes up in the protocol stack to find the next node. This means that the intermediate node decodes symbols, bits and packets before retransmitting them. Analog errors can be compensated. This is a more complex solution, processing in intermediate nodes is needed. An advantage is that decisions for this packet can be taken in intermediate nodes.

Which method to use is dependent on the attenuation of the wireless channel. The store and forwarding method introduce a maximum system throughput limit that depends on the attenuation [59]. The analog relaying can for small attenuation provide unbounded transport capacity for a certain fixed power but it is not feasible in a network with high attenuation. This means that the path loss coefficient is between 0 and 3/2 [59]. However, according to the simplest propagation model, i.e. free space propagation [63] where no obstacles introduces reflections and fading the path loss coefficient is 2. For other models where fading is present, the attenuation is even bigger. This implies that store-and-forward method almost always is used in wireless networks.

2.1.2 Who relays?

Relaying can be done by fixed relay nodes or the users themselves. Using fixed nodes makes it possible to have some sort of cell-planning. It is possible to put up more relay nodes where the traffic is heavier. It is also possible to increase the coverage of the network by putting a relay station in side streets, etc. A problem with this is that it is hard to know where to put the relay station, since the users are mobile and move around in an unpredictable manner. Research in this area has been done by, e.g., RWTH Aachen, where they call their relaying stations *mediastations* [2].The fixed stations can also be interconnected by wires, which means that these nodes do not need to use the already limited air interface.

Relaying by the participants has advantages compared to fixed relaying stations as it is hard to know where they should be set-up since users are mobile. Relaying done by participants is done where it is needed, since it is needed where the users are. This is a simple approach. No extra processing is needed, nodes forward data using the link layer. Disadvantages with this solution are that the stations need to relay using the radio interface and that they need to use battery power for transmissions other than their own. Terminals in a wireless network often are small, portable and battery limited. There is also a probability that there are no relaying stations present. This is a problem for the coverage extension aspect, but less so for the capacity increasing aspect. If there is no relaying node, then the system is most probably not heavily loaded, which means the capacity extension is not needed.

2.1.3 Relaying in which domain?

Relaying can be performed using three different multiplexing techniques: Time-, Frequency- or Code- Division Multiplex (TDM, FDM, CDM).

- TDM: The multiple packet transmissions that are required for relaying are serialized in time. As an intermediate node receives a packet destined for another at a certain time slot, it forwards it in a following slot. This is the simplest solution and it is supported by current technology, i.e. IEEE 802.11.

  It is possible to give priority for applications with QoS demands, by scheduling traffic and letting high priority packets be transmitted first.

- FDM: Forwarding is done using different frequency channels. One configuration example is to use one channel for forwarding and one for own transmissions. There are several benefits with this concept. However, frequencies are a scarce resource. It is important to organize the frequencies for the best re-usage and utilization. This could be done in many ways and is the biggest issue for implementation. Also, using more frequencies cost more.

- CDM: Forwarding is done by means of using several codes for transmission. There are various combinations of how these codes could be assigned and how forwarding is conceivable. Possible ways are: code per terminal, per originator, or per flow. A disadvantage of this mechanism is that intermediate nodes must have knowledge about codes not used for their own transmissions. Other issues are how to handle power control and how to distribute codes in best way to avoid interference.

2.2 Routing

Routing in wireless multi-hop networks is difficult since there are problems that do not exist in a wired network, like fading, shadowing and mobility. These problems can ruin a path that under normal radio circumstances would be good. Nodes enter, exit and move around in an unpredictable manner, which puts demands on the routing protocol. An intermediate node can leave and it is up to the routing protocol to find a new path for communication. The routing protocol has to be dynamic and follow the fast changes of the network. It must find the best way at the moment for a transmission.

A lot of research for routing protocols in wireless multi-hop ad hoc networks is done by IETF mobile ad-hoc network working group [13]. They basically look at two different sorts of protocols, reactive and proactive. With reactive protocols, a node looks up a route when it has something to transmit. With proactive protocols, the routes are determined before transmission and a node knows about the routes in the network before it has anything to transmit. Nodes update their routing tables according to the changes as they happen. When a node notices a change, it sends out a route update message to the other nodes in the network, which updates their routing tables. With reactive protocols the routes are changed only when a transmission is not successful or after a time-out. When using proactive protocols, nodes update their routing tables more often, even when they have nothing to send. It is not important for all nodes to know about all changes in the network anything to transmit. Reactive might have more delay since nodes might have to find a new route for the transmission.

Orthogonal to the proactive or reactive routing protocol, there are another classification. The first is to have centralized routing, which means that a base station or access point handles all routing decisions. This implies that the base station needs to have information about the radio conditions in the network in order to take a routing decision. If this information can be supplied, the approach of centralized routing is simple. The base station needs to inform the users about the routing. For this, signalling is needed. This signalling uses bandwidth from the radio interface, hence is not very attractive in a network where load is heavy. There is also a question of how often information should be requested by the base station in order to keep routes up to date.

The other solution is to have routing distributed. This means that all nodes take their own routing decision. One big advantage with this solution is that nodes can use information from other layers on the spot and they can utilize the information to make better routing decisions.

How to determine which type of routing to use depends on the network, where it is put up, what kind of traffic is to be supported etc. Examples are for transmission of real-time packets, where it is important not to have delays and for heavily loaded system, where it is important with as little overhead as possible.

It requires thorough analysis before such a decision can be made. Nevertheless, the vast body of exclusive research work justifies the assumption that acceptable routing protocols are available.

2.3 Medium access control

Medium Access Control (MAC) coordinates access for users in a multi-user system. The control mechanisms are design in order to avoid collisions and achieve fairness among users.

2.3.1 Centralized control

In a centralized MAC scheme, one central node controls all transmissions in the system. One example is cellular networks where the base station assign time slots (2G) or codes (3G) to users. The base station coordinates transmissions. When it is up and running, it is a very reliable and simple approach. All users know exactly when to transmit, for how long and which resources (frequencies, codes, time slots) to use. It is possible to bound time delay for users already connected.

As described in Section 1, one of the major advantages of a multi-hopping system is coverage extension. This is difficult when having a centralized MAC! Information about medium access is broadcasted from the base station or access point. When a node that only reaches the base station when hopping via another enters the system and wants to transmit, it cannot hear this broadcast frame from the base station. The information has to be relayed via the intermediate node. This is a problem since the relaying node does not know when it can forward. It is difficult to distribute information about the medium access via medium access. Research on this subject is performed at, e.g., Siemens and RWTH Aachen [1].

Another issue is that the base station needs to forward information to the nodes. This is done in allocated signalling links that use the already scarce medium. These allocated signalling links cannot be used for data transmissions.

An advantage of centralized control is the possibility for the base station to inform users about the power levels, modulation rates, codes, frequencies etc. to use.

2.3.2 Distributed control

A distributed access control means that all nodes try to access the medium on their own. This is a very simple approach, the system is self-organizing, there is no need for infrastructure or complex set-up. It is self going and “there”.

The most common mechanism is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). This is a technique where users, before a transmission, listen to the medium to hear whether it is idle. It then performs a random back-off procedure which avoids collisions. An example of a well-used CSMA/CA system today is the IEEE standard 802.11.

One existing problem is the hidden terminal problem. A hidden node cannot hear the transmission from the transmitting node, hence considers the medium idle but is located such that it can interfere with the receiver; collisions and packet losses occur. To solve this, a four-way handshake mechanism is implemented in IEEE 802.11 DCF. This includes *Request To Send* (RTS) and *Clear To Send* (CTS) messages that are transmitted before the data packet. These messages where first implemented in the MACA protocol [23]. The transmitter sends the RTS to the intended receiver. If everything is ok, the receiver returns a CTS to the transmitter. These messages include information about how long the transmission of data will be. Nodes that overhear this message can then avoid transmissions for this period of time and no collisions of data packets occur. The RTS and CTS are small [3], so if a collision with two RTS messages occur, it is not as bad as with a data packet collision. If the lengths of data packets are large, this mechanism is very useful. For small packet transmissions, it introduces unnecessary overhead. These messages are therefore optional. Hidden terminal problems have been approached in among others, [26, 37, 27, 9]. These papers describe the throughput degradation that occur when hidden terminals are present in the system. They also state that the network is unstable when hidden terminals are present. The authors investigate the IEEE 802.11 Distributed Coordination Function (DCF) [3] and show that including the RTS/CTS handshake mechanism efficiently decreases the hidden terminal effect. However, for some scenarios [26], this is not the case and there is no obvious solution for the hidden terminal problem. In reference [9], the authors show the importance of correct collision avoidance in random access protocols used in multi-hop networks.

As all users in a distributed wireless ad hoc network contend for access, there are no guarantees as to when a user can transmit and for how long. Each packet contends on equal terms in the whole system. For the end-user this means that there are uncertainties as to when a packet is received; the packet delays can be large and varying. In a multi-hopping system this contention is made at each hop; the end-to-end delay can be even more varying and it is difficult to bound the end-to-end time delay of a packet. For some applications that demand a low and stable delay, it is hard to guarantee an end-user reception that has good quality; there is no Quality of Service (QoS) support [60, 51, 11]. Examples of applications that would suffer are video-streaming (multimedia services) and normal voice (phone calls), i.e. real-time applications. There are two methods of approaching this problem: Give real-time applications priority at each node or reserve some bandwidth for these applications. We discuss existing solutions and problems with these solutions in Section 4.1.

Another issue is that the nodes have difficulties to adapt their power, increase rate or perform hand-over. These are all decisions they must base on their own locally collected information such as previous transmissions. It is unlikely to start a transmission at, for example, the correct power limit at once. However, users in such a network can help each other with these issues, and tell each other about the link quality. An example is in IEEE 802.11 standard where the RTS/CTS exchange could be used to inform the nodes which power limit to use for data transmissions. These messages should be transmitted with as high power as possible in order to inform as many nodes as possible that there will be a data transmission. But at the same time these messages cannot be transmitted with so high power that it disturbs an ongoing transmission that it is not aware of elsewhere in the system. It is of interest to fully exploit the capabilities of a multi-hopping system with power adaptations in order to increase the number of simultaneous transmissions or increase the transmission-rate by changing the modulation. This power adaptation problem is not yet solved and it is a promising issue for future work. Mechanisms that exist and research done are explained further in Section 4.2.1.

Most distributed wireless MACs are in some form or another TDMA based since users contend for access based in time. There is an option to additionally use more frequency channels to access, so called multi-channel MACs. This is also a promising issue for future work. Already existing work in this area is described in Section 4.2.2.

Other problems are: 1)Mobility. Stations join and leave the network in an unpredicted manner. This complicates maintenance and protection of the schemes for QoS support, power control and multiple frequency usage as they are distributed. An example here is when a transmission is ongoing with low transmission power and a node with higher transmit power move in on the transmission area and cannot overhear the power controlled transmission; collisions occur. 2) Devices are battery-limited devices requires simplicity on the MAC scheme. 3) Exposed terminals, see Figure 2.1. An exposed terminal is one that could send without disturbing another transmission, but avoids doing so because it avoids another transmission, often due to an overheard an RTS. This can mean that the full capacity of the system is not

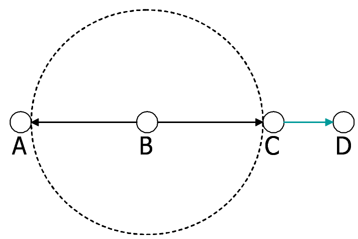

Figure 2.1: Exposed terminal problem. B transmits to A. C avoids transmission to D although it could transmit without interfering with data reception at A.

used.

These three problems are not in detail discussed in this report where we mainly focus on the QoS support, power control and multiple frequency usage.

2.4 Summary of system concepts

Centralized:

- Infrastructure: Complex set-up with base stations.
- Routing: To have a centralized routing scheme the base stations must have information about all links in the system. This information must be transfered to the base station, which demands signalling links.
- MAC: A centralized MAC scheme can provide bounded time delay and a guaranteed bandwidth per user, hence supporting applications with QoS demands (real-time, multimedia). This is done by having fixed time slots that are distributed among the users. For this, time-synchronization is needed. A centralized system can offer radio resource mechanisms, that is, the base stations tell users which transmit power, transmission rate, frequency, code etc. to use. An example of such a network is GSM. A problem is that the access information cannot be heard by nodes that only have coverage when

using an intermediate node to reach the base station. Broadcast messages sent out from a base station with information regarding medium access must be forwarded by intermediate nodes.

Distributed:

- Infrastructure: Distributed systems offer a fast set-up. They are even self-organizing, on the spot. It is a perfect system to use for temporary set-ups, such as outdoor concerts or exhibition halls. However, users are mostly mobile with small portable terminals, which introduce demands of simplicity and efficiency in MAC and routing schemes.

- Routing: With a distributed system is it possible to conduct routing with local information at the node itself. There is no need for allocated signalling links as with the centralized approach. The decision can be taken in cooperation between different layers, i.e. network, Link and MAC.

- MAC: A wireless distributed MAC scheme is typically CSMA/CA based, that is, users listen for an idle medium and then perform a collision avoidance back-off. This type of network is simple and well-established. There is no need for central organization. A disadvantage is that it is not possible to bound time delay, which is important for support of QoS-demanding applications.

Based on the discussed advantages and disadvantages in this section, we make assumptions and a system proposal for the wireless multi-hopping network in Section 3.

Chapter 3

System assumptions

This section describes assumptions that are made for the wireless networks. The basic assumptions are described in Section 3.1, followed by our system proposal in Section 3.2 and an example of this in Section 3.3.

3.1 Overall assumptions

The overall assumptions made in this network are regarding the infrastructure and traffic.

- Base stations exist, it is not a pure ad hoc network. The base stations have the task to forward packets from the wireless network to, for instance the Internet, another WLAN, a cellular network or POTS. The base station functions as a normal user, it has to contend for access as every one else. There is no priority given to the links closer to the base station.
- Base stations are the only type of infrastructure. The basic assumption of the cell is that the relaying is performed by the mobile users.
- Traffic is mostly between cells; intra-cell traffic is small. All communication is therefore to the base station which forwards message out of the cell to another network or cell.
- Both real-time and non-real-time traffic exists.
- Terminals are mobile, base stations are not.

3.2 Our system proposal

The main proposal is to use a multi-hopping distributed system. As seen in previous sections, this type of system is simple, cheap and useful and can be interconnected with other network types. As it comes to these, the well-known IEEE 802.11 Distributed Coordination Function (DCF) standard is proven to work well. It is already existing and running, which makes it easy to compare with. Therefore, our suggestion is to use it as basis for multi-hopping. When introducing multi-hopping into this standard, it is important to design it to meet requirements in Section 3.1. The requirement of base stations is already met, since IEEE

802.11 can use access points in its distributed solution. As described in Section 2.3.2, there are open issues with the distributed medium access; these are also our goal to investigate and find solutions for. Existing work that strives to solve these issues are described in Chapter 4.

Routing is not crucial to this investigation. As described in Section 2.2 there are different ways of handling routing, but it is not of interest since the problems described above exists, no matter what routing is implemented. We use a popular and well investigated ad hoc routing scheme of good performance, e.g., Ad hoc On-demand Distance Vector (AODV) Routing [14].

3.3 Example

An example of a system where a IEEE 802.11 WLAN typically will be used is in a mixed system, where the WLAN is set-up in a hot-spot area, interconnected with a another network. Here is a distributed multi-hopping ad hoc IEEE 802.11 WLAN network connected to another fixed centralized network (UMTS, POTS, GSM, etc). A phone-call is coming in to user C in the WLAN cell from user A in the fixed network. The call is forwarded from the access point via user B to end-user C. Meanwhile, node D wants to transmit to node G and node E wants to transmit to node F. What happens here is that user C experiences jitter. The reason for

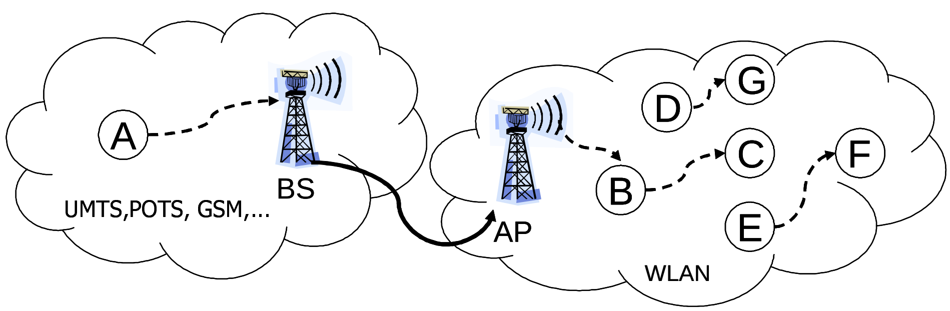

Figure 3.1: Example: Phone call coming in to hot-spot WLAN

this bad quality is in the WLAN part of the call. The centralized system can bound the time delay since it has a known bandwidth per user, i.e. time slots /codes per user. Unexpected delays in this part are rare. The problem in the WLAN part occurs due to the distributed medium access scheme. All stations share the medium, they all contend for access. There are no guarantees as to when a user can transmit its packet. There is no duration knowledge either. The user cannot bound the time delay for its transmission. One packet can experience different delays at different parts of its route. One node might be able to directly forward it, another might have a long queue where the same packet is stuck for a long time. The problem of supporting QoS-based applications in such a network is in the MAC layer. It is therefore of interest to investigate how these application types can be supported and previous work in the area of ad hoc multi-hopping distributed WLAN with QoS support.

Chapter 4

Analysis of existing MAC solutions and identification of open problems

This section describes previous work concerning open issues with distributed multi-hop wireless MAC. First we discuss schemes handling QoS support in Section 4.1 and then we look at power control and multiple frequency channel usage in Section 4.2. We conclude this chapter with a summary of what is left unanswered in Section 4.3.

4.1 QoS support

4.1.1 Standardization of QoS mechanisms for distributed MAC

IEEE work-force 802.11E is working on a new QoS supporting 802.11 standard, namely IEEE 802.11e [56]. This standard introduces two new MAC coordination functions, Enhanced Distributed Coordination Function (EDCF) and Hybrid Coordination Function (HCF). As in IEEE 802.11, IEEE 802.11e can also operate under two different phases within superframes, i.e. a Contention Period (CP) and Contention Free Period (CFP). The EDCF is used in the CP only and HCF is used in both phases. The EDCF is the basis for the HCF. EDCF differentiates between different traffic types by giving them different priorities. This is done by alternating either the Contention Window (CW) size of IEEE 802.11, which is used to determine the random back-off time, or the IFS time; shorter IFS gives higher priority. Instead of DIFS that is used before RTS transmission in IEEE 802.11, Arbitrary Inter Frame Space (AIFS) is used. The AIFS value is determined individually for each priority class that is wanted, that is, for each different traffic type that should be differentiated with priority. The minimum value of AIFS is DIFS. It is also possible to change both the CW size and the IFS in different combinations.

HCF extends the EDCF access rules. This is the centralized part of the IEEE 802.11e standard where a Hybrid Coordinator (HC) polls stations for transmissions. HCF is meant for traffic that needs time-delay bounds. It requires that all stations in the area of the HC follows its decisions of transmission order. It is a centralized scheme.

In [34, 10], IEEE 802.11e is investigated. The result of the two investigations are that the 802.11e standard will be an efficient mean for QoS support in WLANs, although there are some issues. The standard is based on giving priority to certain traffic types; when a packet arrives to a node it handles the packet according to a certain priority dependent on other traffic going through the node. It is therefore hard to actually guarantee an end-to-end delay as the traffic can be such that a real-time flow has a low priority.

4.1.2 Distributed MAC with real-time support–Reservation mechanisms

In this section, existing reserving mechanisms are described.

MACA/PR

In [32],Gerla and Lin describe a periodical packet reservation technique, Multiple Access Collision Avoidance with Piggyback Reservations (MACA/PR). This is an asynchronous network solution based on the MAC technique deployed in the IEEE 802.11 standard. They examine the tradeoffs between time synchronization and performance in various traffic and mobility environments.

MACA/PR is based on CSMA/CA and is equipped with a bandwidth reservation technique and a QoS routing protocol at the network layer (IP). The QoS routing algorithm is not further described here but can be read about in [32]. MACA/PR sets up a real-time connection over a single hop at the time.

The medium access scheme for data packets is the same as for distributed IEEE 802.11. For real-time packets, the medium access scheme works as follows:

All nodes have Reservation Tables (RT) to see when and who is transmitting. The first packet in a stream reserves a transmission window for following packets with a certain periodicity. All stations that hear the transmission of a packet or an ACK enter information in their RT. Before transmitting the first packet, the RTS/CTS exchange of MACA[23], also used in IEEE 802.11 standard [3] is performed. The packets that follow are directly transmitted without the RTS/CTS exchange. To transmit a datagram or the first packet of the real-time stream, the transmitter checks its RT. It looks for a free slot to use for its transmission. When finding one, it starts to listen to the channel, to hear if it is idle or not. When sensing it idle, it transmits its RTS to the receiver. The receiver answers with a CTS, which, when reaching the source transmitter, completes the reservation phase. The transmitter will from now on use the same slot for its transmissions until it has no more to send. Whenever a new node enters the network, it listens to the channel for a long time to hear all ongoing transmissions. To make completely sure that the new node will not interfere with an ongoing, reserved real-time transmission, an exchange of RTs in the systems is made. Packets are not retransmitted after collision. Packets and acknowledgements carry real-time scheduling information in the header.

Gerla and Lin first compare their scheme with a totally asynchronous network, where not unexpectedly MACA/PR performs very well. Then the scheme is compared with a totally synchronized TDM network, where MACA/PR is outperformed. However, the conclusion is that MACA/PR is a good, cost effective compromise between the two above mentioned single-hop networks. As stated, the reservation is made on IP level. This makes it hard to guarantee anything for the MAC layer. If a collision occurs and a retransmission of anon-real-time packet has to be done on the MAC layer, a reserved IP level real-time transmission can start anyway, causing yet a collision. The reservation is done on a single-hop basis. A packet is not guaranteed all the way. If a node cannot take any more reservations and the IP layer QoS routing protocol of another node decides to hop via this anyway, a problem occurs. The packet cannot be transmitted. There is a need to have a end-to-end aspect in the MAC layer.

D-PRMA

In [20], the authors investigate support for real time services when having synchronization between terminals in ad hoc networks. This is done with the Global Positioning System (GPS). They suggest a new MAC algorithm called Distributed Packet Reservation Multiple Access, D-PRMA. With this algorithm the problem of real time services in ad-hoc networks can be solved. The authors state that due to a growing market and cost decreasing development of GPS, slotted-channel-based MAC schemes become available and most interesting for mobile ad hoc networks.

They introduce a time devided air interface with frames and time slots. These time slots are then divided in smaller time slots, so called mini slots. To gain access to the whole slot, a station has to win the contention in the first mini slot. It can then use the rest of the time slot for its transmission. The same time slot is also reserved for this node's transmission and can be used in all following frames. This is only true for transmissions that consist of real-time packets. A transmitter with data can only transmit in the time slot where it won the access contention. If the first mini slot does not lead to a winner, the contention continues in the next mini slot. If a station wins contention in one of the following mini slots, it can only start its transmission in the next frame. The contention is performed in the same way as the IEEE 802.11 standard [3] with RTS and CTS messages.

It is possible to add priority for real-time packets over data packets by letting real-time stations start their contention in the first mini slots with a probability of 1 and for data with a probability smaller than 1. This means that real-time stations start their access procedure earlier on average and therefore have priority.

The investigation shows that in a one-hop environment where all stations can here each other, D-PRMA is much more suitable for voice applications than IEEE 802.11 DCF. For data, IEEE 802.11 is better.

Blackburst

Blackburst, described in [50, 49], a technique by Sobrinho and Krishnakumar, minimizes and bounds delay of real time traffic. For data traffic, the access procedure is the same as in IEEE 802.11 DCF. The access procedure for real-time data is based on the CSMA/CA procedure, but modified. A station that wants to transmit starts its access procedure by first jamming the channel with a energy burst, so called Blackburst. The length of the jamming burst is determined by the time that the station has waited for its transmission. After transmission of the Blackburst, the station listens to the medium to see if some other station is sending a longer Blackburst. This implies that this station has waited longer and therefore that it transmits first. Whenever a packet is transmitted, the node schedules the transmission for the next packet. This is done using a time interval that is predefined and the same for all nodes and all packets. All nodes are therefore scheduling their packets with the same time intervals. If there is only real-time traffic in the system, it behaves as a pure TDM system.

The investigation in [50, 49] shows that the transmission of Blackburst before transmitting is an effective way of allocating the network periodically. However, it produces a lot of unnecessary overhead. In [50], a method for increasing the efficiency and decreasing overhead of the Blackburst algorithm is described. The stations form a chain and when transmitting they include in a packet header an invitation for transmission to the next node of the chain. The order of the chain is determined after the order they contend for real-time data transmission. Stations only transmit a Blackburst for their first packet. This method is good as long as no station ends its session and leaves the chain. This results in a split of the chain, a hole, and reduces the efficiency. In this hole, a data transfer can occur, which leads to a stretch of the chain and an increase of packet drops due to an increase of the real-time packet delay.

The authors have investigated the behavior of the Blackburst mechanism under the assumption that all stations hear each other, that is, without hidden terminals. An open issue is therefore how the transmission of Blackbursts introduces collisions when stations cannot hear each other.

The reservation is made on a per packet basis. A node allocates the medium for the next packet only when it is transmitting one. There is therefore no knowledge of the next hops of the path before transmission. No considerations are taken to that the next hops might be allocated for another transmission, or by any other reason not available to accept the packet. Also, the station only listens to other node's Blackbursts when it has a packet to send. They do not know how the system is used. Also, the Blackburst cause overhead.

DBRP, DBASE

Papers [45, 46] describe MAC protocols Distributed Bandwidth Reservation Protocol (DBRP) and Distributed Bandwidth Allocation/Sharing/Extension Protocol (DBASE), that use broadcast messages, so called Reservation Frames (RF), to allocate resources. Each station keeps a reservation table with information about ongoing reserved transmissions. A voice station that wants to transmit first listens to the channel during a predefined time period. This time period is determined after the maximum tolerance delay of real-time packets. If none, there is no active voice station, and the station gets the responsibility to broadcast periodic RF. However, before starting the RF broadcast, the station must perform a back off procedure and send an RTS, in the same manner as in IEEE 802.11. Upon receiving a CTS from the intended receiver, it broadcasts the RF and directly afterwards its voice packet. For the next cycles no RTS/CTS exchanges are performed. For the other case, when a new station hears a RF, the station finds out that there are active real time stations in the network. It must then wait and listen until the periodic cycle is over (until next RF) in order not to disturb any ongoing reserved transmissions. It also listens to hear if there is an empty slot. If so, it starts an access procedure after the RF with back off and RTS/CTS. The RTS that is sent asks the Reservation Table of the intended receiver if it has resources to reserve for the intended transmission. If so, the CTS finishes the reserving phase and the transmission can begin. If a station, when it is supposed to transmit, is quiet for longer than a certain time period, the system considers this time slot as vacant and others can use it for transmissions.

Data is transmitted via IEEE 802.11 DCF.

This scheme does not only give the real-time transmissions the opportunity to reserve resources for future transmissions. It reserves on a hop-per-hop basis, no considerations are taken for the whole path. It also uses a shorter IFS, according to IEEE 802.11 standard, when contending to give priority to real-time packets.

Another problem with this mechanism in a multi-hop environment is how to handle broadcast. When should a station forward the packet and when should it not? What rules to convey in order to avoid forwarding loops? Another issue is that the periodic broadcast channel gives overhead.

DRRP

In [17], the authors describe the Distributed Reservation Request Protocol (DRRP). This protocol uses the basic mechanism of IEEE 802.11e but further enhances the performance for QoS-demanding traffic with a reservation of future resources (IEEE 802.11e standardized transmission opportunity (TXOP)). The authors piggy-backs the request for a periodic reservation on a data packet as it is transmitted. They include information as to when the next instance is and then how it repeats periodically. Further, the reservation request includes a priority. This priority is used when two transmissions ask to reserve the same time slot. The one with the highest priority wins. It is possible to cancel a request with a NULL message that deletes the reservation.

Surrounding nodes retrieves information regarding the transmission from the overheard data packet. They also include information in acknowledgements for some nodes that cannot overhear the transmitted data packet.

This protocol do not reserve end-to-end and the question regarding if a node cannot accept the transmission remains as no set-up phase exists. The authors do state what happens if two requested time slots overlap, but not how the node that must defer handles the transmission of the QoS-demanding data afterwards. This protocol has advantages as it has included several different priority classes.

INSIGNIA and ASAP

INSIGNIA [30] has in band signalling in the IP header, which allows for resource reservations. In each hop the flow reserves a bandwidth to meet a MAX or MIN level. At bottleneck hop where only MIN can be reached all the preceding nodes will change their reservation according to this bottleneck. Reservations are made on IP level and one hop at the time. Here, it is only possible to chose a reservation on two different levels and the signalling overhead is rather high. This has been the motivation for the Adaptive reServation And Pre-allocation protocol (ASAP) [61], which uses the basic functionality of INSIGNIA. This protocol offers soft state reservations and not only hard state. It is a two phase set-up of reservation, first a Soft Reservation (SR) is made. This reservation can be used by other traffic but can not be reserved by another flow. Secondly a Hard Reservation (HR) is made, no other traffic can be transmitted in these time slots. The source transmits a SR message and each host creates a flow entry in their reservation table according to what bandwidth is requested in this message if they can meet the request; the request can be any value within the range of MIN and MAX. Next node in the transmission path makes the same but updates the soft bandwidth field of the SR message if the reservation it can allow is less than previously stated amount. At the final receiver a HR message is sent with bandwidth request equal the soft bandwidth field of the latest SR. All nodes along the path fix their reservations and when the source receives the HR message it can start the transmission with the reserved bandwidth.

The SR messages are in-band signalling, inserted in the IP header as the INSIGNIA protocol. This means that the request is piggy-backed on a data packet, hence the reservation is done one hop at the time and the request, as stated above might not be realizable end-to-end. The HR messages are out-of-band signalling, that is, a separate message and is sent whenever there are changes in the network as to the available resources; they are transmitted in the opposite direction of the flow to update the reservation. This approach demands overhead.

After set-up, SRs are also periodically inserted in the IP header to collect QoS information and the source and receiver can exchange information regarding the QoS. Source can also scale down its transmission rate if the allocated resources can no longer be maintained. The authors conclude that ASAP is better than the INSIGNIA protocol. However, as the reservation is done one hop at the time, the needed bandwidth for real-time applications might not be fulfilled.

Other

Other reservation mechanisms are described in [62, 35, 29, 28, 39] but are not discussed more in detail here.

4.1.3 Distributed MAC with real-time support–Priority mechanisms

So far, the real-time supporting mechanisms described have been reservation mechanisms. Another type of method to give real-time support in distributed MACs is to give priority to real-time packets. Nodes schedule transmission of packets according to some priority tag of the packets.

Distributed Fair Scheduling (DFS) [53] uses the back-off mechanism to determine which station should transmit first. Different traffic flows have different weights. The back-off time grows with the higher weight a flow is assigned. This mechanism also tries to take fairness into consideration by including packet size when calculating the back-off time.

Another mechanism is described in [22]. Here Kanodia et al. introduce support for real-time traffic in multi-hop environments using scheduling, based on IEEE 802.11. First, they introduce Distributed Priority Scheduling. This scheme uses priority tags for packets that are piggy-backed onto the RTS and CTS messages. All nodes have a scheduling table where they keep entries for all packets they can hear. As a packet is successfully transmitted, the entry in the table is deleted. The authors then introduce a mechanism for multi-hopping support. If a packet arrives at an intermediate node late due to unexpected events, such as collisions, the intermediate node is able to alter the priority that the packet has in the node. It can increase the priority of the packet on its internal queues for transmission (forwarding). The same goes for packets that are arriving earlier than expected according to the priority tag (time delay demand). For these packets, the node can decrease the priority and transmit late packets earlier.

Scheduling (priority) mechanisms can introduce unfairness for data transmissions since real-time packets are always transmitted first. Another problem is that the scheduling is done above MAC. Although the mechanism in [22] suggests a solution for unexpected MAC events, this solution cannot guarantee a time bound. If a lot of packets are suffering from heavy delays, they all need to be transmitted earlier. This is of course not possible.

For a network with only a few applications and transmissions that need to bound delay, priority mechanisms can work in a distributed multi-hop network. However, this is rare and therefore not a suggestion for further investigations of real-time services in distributed multi-hop medium access controlled networks. Further mechanisms that schedules traffic and give priority are described in [43, 18, 44, 6] but not further described here.

4.1.4 Distributed MAC with real-time support–Other mechanisms

Some articles describe research using the DCF for data and the IEEE 802.11 centralized MAC scheme, *Point Coordination Function* (PCF), for voice [55, 64]. The outcome of [55] is that the PCF performs poorly and the number of voice conversations are limited due to the cooperation of DCF and PCF in the superframe structure of IEEE 802.11[3]. In [64], the authors divide the PCF part of the superframe into more fields, for different traffic types. Their outcome is better, but still shows the bad performance of the PCF.

Other mechanisms designed to support voice communications can be read about in [66, 54, 42, 48, 47] but are not further described here.

4.1.5 Comparison of different QoS mechanisms

Lindgren, Almquist and Schelen [33] evaluate and compare mechanisms for providing QoS. The mechanisms are: IEEE 802.11 PCF [3], IEEE 802.11e [56], DFS and Blackburst, see Section 4.1.2. The outcome is that the IEEE 802.11 PCF performs poorly. Blackburst gives the best performance for high-priority traffic. It also avoids collisions. There is a high requirement on Blackburst regarding constant access intervals between high priority traffic. If these cannot be met, IEEE 802.11e is a suitable alternative, although it suffers from a high rate of collisions and is not able to provide as good service differentiation as Blackburst. Both Blackburst and IEEE 802.11e starve low priority traffic. DFS has a major advantage here by trying to include fairness. This scheme will not starve low priority traffic, which is an issue with many QoS schemes that utilize some sort of priority mechanism.

4.2 Power control and multiple frequency channels

4.2.1 Power control in distributed MAC protocols

One typical approach to power adaptation is to transmit RTS/CTS at highest transmission power and then data with the one that is needed. One example where this is used is [12]. When an interfering node hears RTS/CTS, it sets its Network Allocate Vector (NAV), which keeps track of ongoing transmissions and how long the node must avoid transmission, according to the duration value of the message it hears. If an intermediate node is only in the carrier range, that is, it hears a message but cannot read it, it will not know about the duration of the transmission. When data is transmitted at lower power, the carrier sensing nodes cannot hear this anymore. This will lead them to regard the channel as idle, a transmission of an RTS with maximum power and a collision. Even if the possible interferer uses a power level that does not reach the receiver, it might (if it is in a geographical bad place) interfere with the transmitter's reception of the acknowledgement.

The conclusion is that power control might make it worse when it comes to collisions. This affects throughput. It has been shown that the overall throughput is lower in an IEEE 802.11 system where nodes transmit at different power levels than a system where they all use the same levels [41]. The problem is also discussed in [21], where the authors describe a possible solution. It is called Power Control MAC (PCM) and periodically increases the transmit power during a data transmission. This is to inform nodes in the carrier zone of the ongoing transmission. This works fine in order to decrease collision numbers, but affects the possibility to use the wireless medium for more simultaneous transmissions. If there is an ongoing transmission that a transmitter have no knowledge about, these periodic pulses of maximum power can cause collisions elsewhere in the network. However, the authors show with simulations that the PCM uses less power in the system without degrading the throughput compared to IEEE 802.11 DCF. A problem with this is fading. If the fading disturbs the high power pulses, others can not hear the transmission and ruin the rest of it by starting its own.

Another method of alternating the transmission power is described in [4]. Every node maintains a table for the transmit power necessary for communication with its neighbors. To get hold of this information, nodes include transmit power information in headers of all sent packets (RTS, CTS, DATA, ACK). When a node starts a transmission with an RTS, it includes the transmit power in this packet header. When the receiver gets this message and sends its CTS, it includes in the CTS information to the source about the minimal acceptable signal strength it can receive at and the receive power level of the RTS. This makes it possible for the source to alter its transmission power. As the source transmits data, it includes the same information to the receiver, so the receiver can change its transmission power for future messages to it. Nodes enter this information in their tables. They also have the possibility to change the transmit power later. After successful transmissions, the transmit power is typically lowered.

This scheme is hard to maintain. Since mobility introduces changes to the necessary transmission power, calculations and message transmissions are needed in order to use the correct transmission power. Also, the asymmetric links cause collisions. When a communication starts between two nodes that need high transmit power, it can collide with a communication that uses lower transmission power that it cannot hear.

In [40], the COMPOW MAC protocol is described. This mechanism selects a common power level for all nodes in the network to assure bi-directional links. The power level is the smallest one that can still offer the same amount of connectivity as the original one.

Other power controlling mechanisms are described in [5, 25, 24, 8] but are not further described here.

4.2.2 Multiple frequency channel MAC protocols

Usage of multiple frequency channels enhances the performance due to more simultaneous transmissions and less collisions. They can be devided in two classes, one where each user has its own channel and the other where users share a number of frequency channels. The IEEE standards 802.11a and 802.11b already have support for multiple frequencies, 12 in IEEE 802.11a, and 3 (that can be used for data totally non-overlapping) in IEEE 802.11b [3]. One possible reason for not using them today is that the users of these networks are only equipped with a half-duplex transceiver. This means that a user can only transmit or receive at one time. This can cause performance degradations in a multi-channel environment [57]. However, it is possible to use these frequencies with the restraint of frequency planning and agreement between the users on what frequency to use. A correct configuration of a multiple frequency channel system enhances the performance and the total throughput of the system, as shown in [36]. An investigation of multiple frequency channel MAC with one transceiver is described in [57]. This protocol has one channel dedicated to control messages, such as RTS/CTS, and two channels assigned for data transmissions (when applied on IEEE 802.11b). The RTS includes a suggestion about which data channel to use. The CTS includes the selected channel. Data and acknowledgements are transmitted on the data channels. With two channels for data, this protocol has 33% overhead.

In [19], the same scheme is used but with N channels for data and one channel for control. The receiver chooses the channel to use. This scheme shows a better performance, but still has the disadvantage of bottleneck situations when load is high. This is owing to the single control channel's inability to handle all set-ups. The authors compare their results with the DCF function of IEEE 802.11 and conclude that their scheme increases throughput and lowers time-delay.

Another mechanism is Hop-Reservation Multiple Access (HRMA) [65]. This is a protocol that uses frequency hopping and time synchronization. The hosts hop together according to a pattern that they have agreed upon in a synchronization phase before the hopping starts. This is done on a predetermined synchronization frequency channel that is allocated throughout the network for synchronization. At each frequency hop, there is one phase where stations are allowed to initialize a transmission with a RTS/CTS exchange. After this exchange, the communicating nodes stay on this frequency and the data packet can be transmitted. Other stations follow the hop sequence and change frequency. If the hopping pattern would repeat itself and the transmission between the two communicating nodes is not finished, the source node sends a reservation information message in the beginning of the hop; some time is allocated at each hop for exchange of these messages. This message tells all other nodes that it cannot use this frequency. The source also retransmits an RTS to block the possibility that some other nodes have not heard the reservation information messages and starts their own transmission with an RTS. As a new node enters, it must wait for a long time to discover the hopping pattern and synchronization of the network.

There is a big overhead with this scheme and RTS/CTS messages are compulsory. When the number of channels for data is small, this proposed protocol causes a lot of overhead. When the number of data channels is too large, the control channel can be a bottleneck if it cannot handle set-up on all data channels

Other mechanisms using multiple frequency channels can be read about in [16, 52, 31]

4.2.3 Power Control and multi-channel MAC protocols

Power Controlled Multiple Access Protocol (PCMA)[38] enhances the IEEE 802.11 standard's typical on-off state (transmit or, if channel busy, not transmit) into a more soft state version by bounding transmission power. It increases the number of simultaneous transmissions by allowing a node that detects the channel busy to transmit with a certain power limit, so the ongoing transmission is not interfered with.

The mechanism uses two physical channels, one for data and one for energy pulses called busy tones. Receiving nodes periodically transmit energy bursts at the busy tone channel, with the transmit power equal to the maximum interference it can receive in order not to disrupt the reception. A node that wants to start transmission determines the maximum transmit power it can use by listening to this channel.

The scheme works as follows: When a node wants to transmit it first listens to the busy tone channel over a determined period of time. During this time it determines the maximum power it can use for its transmissions in order not to interfere with any other transmission. The station then performs a back-off procedure. The node continues to listen to the busy tone channel while backing off, in order to hear if the maximum power limit changes (especially, decreasing). The station then transmits a message comparable to RTS but here called Request-Power-to-Send (RPTS). This message is sent on the data channel. It contains the transmission power level. When the receiver receives this message it calculates Signal-to-Interference ratio (SIR) and uses the transmission power and received power to determine the channel gain. The receiver transmits an Acceptable-Power-to-Send (APTS) message, which includes information to the source about the transmission power it should use, in order to meet the requirements for successful transmission at the receiver. When the source receives this APTS it checks if the demanded power is lower than the bound it got from the busy tone channel. If so, it transmits the data. The receiver starts sending busy tones at the busy tone channel when it starts receiving data. When the data transmission is finished, the receiver transmits an acknowledgement to the source. Upon receiving this, the source node returns to its idle state.

The results of the investigation shows an enhancement of the throughput performance by a factor of 2, compared with IEEE 802.11. This is at highly dense areas where all distances between nodes are small. However, there is a need for two physical frequency channels where one is only used for the busy tones. All messages are sent with the transmission power that is needed. This means that the Request and Response message are not heard by all stations that could interfere. If a transmit-receive node pair are at small distance from each other, they will use small transmit power for RPTS-APTS, hence also for the busy tones. This leads to a problem if another station starts a transmission with a transmission power that interferes with the one using lower power. Terminals today are equipped with one transceiver, which means it can only listen to one frequency at the time. If a channel is listening to detect busy tones at the busy tone channel, it can miss a RPTS or APTS message at the data channel, hence not getting information that a transmission is about to start. This can cause collisions.

Other mechanisms that uses busy tones in a multi-channel manner are described in [7, 15, 58].

4.3 What is left unanswered?

To give support for real-time services in a distributed wireless network, two different types of mechanisms can be used. The first is the priority mechanisms. By giving priority to real-time traffic, other traffic types are influenced negatively. However, some mechanisms try to look at the fairness aspect as well. Priority is given by scheduling transmissions of real-time packets before other data packets. There are plenty of different mechanisms for this scheduling. The most common one is to use some sort of tag on the packet. Priority cannot bound time delay for all network types. It depends on the traffic load and the scheduler used. It can make it better, but it is not possible to always bound it since there is no knowledge of traffic conditions later on the transmission path.

Different from priority mechanisms are the reservation mechanisms that reserve bandwidth for future packet transmissions. These mechanisms can, under normal circumstances, bound the time delay. It is possible to know at one hop when transmission starts and ends. They also have an advantage regarding the fairness as it is possible to put a limit on the reservation. It is possible to determine how much of the bandwidth that should be used only for real-time and non-real-time transmissions. However, there is no support for these mechanisms in a multi-hopping system. There are no reservations or allocations of resources done for the whole path. This means that there can be a congestion on one of the hops of the path and nodes still send packets this way. They do not know anything about future hops. This makes reception hard since packets arrive with different delays, although they belong to the same flow. What some of these mechanisms also do are reserving resources for the next packet only if there is one to transmit. A packet reserves resources for the next one in line, as it is transmitted. If this is not the case, resources are not reserved. Since a phone call can have silent periods it is hard to have the reservation in this way. When a silent period happens of a certain length in these schemes, the reserved connection is broken. This means a new access procedure, which causes unnecessary overhead. It is relevant to have a flow aspect when reserving resources.

Finally, the existing mechanisms use techniques like broadcast and synchronization that makes the network loose its simplicity. They also introduce overhead by having separate signalling channels, broadcast messages and explicit exchanges of reservation tables.

To fully exploit the multi-hop capabilities, power control or multiple channels can be used in order to allow for more concurrent transmissions, hence increase the system throughput. This is especially interesting for a system where some transmissions have allocated parts of the channel bandwidth. Power control and multiple frequency channel usage have also been widely investigated, but the multi-hop aspect is lacking.

Chapter 5

Conclusions

This literature study describes possibilities, problems and existing solutions for a distributed multi-hop wireless network. The possibilities with relying are increased coverage, capacity and energy efficiency. To fully exploit these possible enhancements, power control to minimize the power usage can be used. Existing work lack an end-to-end aspect and implements power control for each hop separate. Here, we believe interesting research can be done.

Known problem with the distributed multi-hop network is the support of real-time services. This problem has been widely investigated, but as with power control approached on a single hop basis. Our description of previous work show the lack of end-to-end aspect and we consider this a promising field of research. We conclude that what seems to be the best option for allowing QoS is to reserve future resources for real-time packet transmissions. Here, resources can be allocated both in time and frequency. In order to handle reservation set-up and maintenance, multiple frequency channels can be used. Most common option here is to have different frequency channels for data and control messages. We show with this literature study that the existing solutions for reservation schemes and multiple frequency channel usage are based on a single hop transmissions. what is missing is a multi-hop perspective.

For a distributed multi-hop wireless network, what seems to be the best option is an integration of power control, multiple frequency channels and reservation scheme in order to effective transmit over a multi-hop path and minimize interference, maximize the number of simultaneous transmissions and support QoS demanding applications.

Bibliography

[1] Coverage project,university of aachen, http://www.comnets.rwth-aachen.de/ cover.

[2] Media stations project,university of aachen, http://www.comnets.rwth-aachen.de/ ftp-mul/.

[3] IEEE Standard 802.11. Wireless lan medium access control (mac) and physical layer (phy) specifications. 1999.

[4] S. Agarwal, S. Krishnamurthy, R.H. Katz, and S.K. Dao. Distributed power cotrol in ad-hoc wireless networks. In *Proc. IEEE Intl. Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, San Diego, California, USA, Oct 2001.

[5] N. Bambos and S. Kandukuri. Power controlled multiple access (pcma) in wireless communication networks. In *Proc. Joint Conf. of the IEEE Computer and Communications Societies (INFOCOM)*, Tel Aviv, Israel, Mar 2000.

[6] A. Banchs and X. Perez. Distributed weighted fair queuing in 802.11 wireless lan. In *Proc. IEEE Intl. Conf. on Communications (ICC)*, Copenhagen, Denmark, May 2002.

[7] J. Deng and Z. J. Haas. Dual busy tone multiple access (dbtma) : A new medium access control for packet radio networks. In *Proc. IEEE Intl. Conf. on Universal Personal Communications (ICUCP)*, Italy, Oct 1998.

[8] T. ElBatt and A. Ephremides. Joint scheduling and power control for wireless ad-hoc networks. In *Proc. Joint Conf. of the IEEE Computer and Communications Societies (INFOCOM)*, New York, USA, Jun 2002.

[9] J.J. Garcia-Luna-Aceves and T. Zhenyu. Collision avoidance in multi-hop ad hoc networks. In *Proc. 10th IEEE Intl. Symposium on Modeling, Analysis and Simulation of Computer and Telecommunications Systems (MASCOTS)*, Fort Worth, Texas, USA, Oct 2002.

[10] P. Garg, R. Doshi, R. Greene, M. Baker, M. Malek, and X. Cheng. Using ieee802.11e mac for qos over wireless. In *Proc. IEEE Intl. Performance, Computing and Communications Conf. (IPCCC*, Phoenix, Ariziona, USA, Apr 2003.

[11] M. Gerharz, C. de Waal, M. Frank, and P. James. A practical view on quality-of-service support in wireless ad hoc networks. In *Proc. of the IEEE Workshop on Applications and Services in Wireless Networks (ASWN)*, Bern, Switzerland, Jul 2003.

[12] J. Gomez, A.T. Campbell, and M. Naghshineh. Conserving transmission power in wireless ad hoc networks. In *Proc. IEEE Intl. Conf. on Network Protocols (ICNP)*, Riverside, California, Nov 2001.

[13] IETF MANET Working Group, March 2003. http://www.ietf.org/html.charters/manet-charters.html.

[14] IETF MANET Working Group. Rfc-ad hoc on-demand distance vector (aodv) routing, July 2003. https://www1.ietf.org/rfc/rfc3561.txt.

[15] Z. J. Haas and J. Deng. Dual busy tone multiple access (dbtma) performance evaluation. In *Proc. IEEE Vehicular Technology Conference (VTC)*, Houston, Texas, USA, May 1999.

[16] L. Handong, Z.J. Haas, and M. Sheng;. Capacity evaluation of multi-channel multi-hop ad hoc networks. In *Proc. IEEE Intl. Conf. on Personal Wireless Communications (PWC)*, New Dehli, India, Dec 2002.

[17] G.R. Hiertz, J. Habetha, P. May, E. Weiß, R. Bagul, and S. Mangold. A decentralized reservation scheme for ieee 802.11 ad hoc networks. In *Proc. IEEE Intl. Symposium on Personal Indoor and Mobile Radio Communications (PIMRC*, Bejing, P.R. China, Sep 2003.

[18] L. Jacob, R. Radhakrishna Pillai, and B. Prabhakaran. Mac protocol enhancements and a distributed scheduler for qos guarantees over the ieee 802.11 wireless lans. In *Proc. IEEE 56th Vehicular Technology Conference (VTC)*, Boston, USA, Sep 2002.

[19] N. Jain, S.R. Das, and A. Nasipuri. A multichannel csma mac protocol with receiver-based channel selection for multihop wireless networks. In *Proc. Intl. Conf. on Computer Communications and Networks (ICCCN)*, Scottsdale, Arizona, USA, Oct 2001.

[20] S. Jiang, J. Rao, D. He, X. Ling, and C. C. Ko. A simple distributed prma for manets. *IEEE Transactions on Vehicular Technology*, Mar 2002.

[21] E.-S. Jung and N. H. Vaidya. A Power Control Mac Protocol for Ad Hoc Networks. In *Proc. ACM Intl. Conf. on Mobile Computing and Networking (MOBICOM)*, Atlanta, Georgia, USA, Sep 2002.

[22] V. Kanodia, C. Li, A. Sabharwal, B. Sadeghi, and E. Knightly. Distributed multi-hop scheduling and medium access with delay and throughput constraints. In *Proc. ACM Intl. Conf. on Mobile Computing and Networking (MOBICOM)*, Rome, Italy, Jul 2001.

[23] P. Karn. Maca – a new channel access method for packet radio. In *ARRL/CRRL Amateur Radio 9th Computer Networking Conf.*

[24] V. Kawadia and P.R. Kumar. Power control and clustering in ad hoc networks. In *Proc. Joint Conf. of the IEEE Computer and Communications Societies (INFOCOM)*, San Franscisco, USA, Apr 2003.

[25] V. Kawadia, S. Narayanaswamy, R. Rozovsky, R.S. Sreenivas, and P.R. Kumar. Protocols for media access control and power control in wireless networks. In *Proc. IEEE Conf. on Decision and Control*, Orlando, USA, Dec 2001.

[26] S. Khurana, A. Kahol, S.K.S. Gupta, and P.K. Srimani. Performance evaluation of distributed co-ordination function for ieee 802.11 wireless lan protocol in presence of mobile and hidden terminals. In *Proc Intl. Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS)*, College Park, Maryland, USA, Oct 1999.

[27] S. Khurana, A. Kahol, and A. Jayasumana. Effect of hidden terminals on the performance of the ieee 802.11 mac protocol. In *Proc. of Local Computer Networks Conf. (LCN)*, Boston, Massachusetts, USA, Oct 1998.

[28] S. Koutroubinas, T. Antonakopoulos, and V. Makios. A new efficient access protocol for integrating multimedia services in the home environment. *IEEE Transactions on Consumer Electronics*, pages 481–487, Aug 1999.

[29] S. Lal and E. Sousa. Distributed resource allocation for ds-cdma based multi-media wireless lans. In *Proc. IEEE Military Communications Conference (MILCOM)*, Boston, USA, Oct 1998.

[30] S. Lee and A. Campell. INSIGNIA: In-band signalling support for qos in mobiloe ad hoc networks. In *MoMuC*, Berlin, Germany, Oct 1998.

[31] L.J. Li, Z.J. Haas, M. Sheng, and Y. Chen. Performance evaluation of modified ieee 802.11 mac for multi-channel multi-hop ad hoc network. In *Proc. Intl. Conf. on Advanced Information Networking and Applications (AINA)*, Xi'an, China, Mar 2003.

[32] C.H.R. Lin and M. Gerla. Asynchronous multimedia multihop wireless networks. In *Proc. Joint Conf. of the IEEE Computer and Communications Societies (INFOCOM)*, Kobe, Japan, Apr 1997.

[33] A. Lindgren, A. Almquist, and O. Schelén. Evaluation of Quality of Service schemes for IEEE 802.11 wireless LANs. In *Proc. IEEE Conf. on Local Computer Networks (LCN)*, Tampa, Florida, USA, Nov 2001.

[34] S. Mangold, S. Choi, P. May, O. Klein, G. Hiertz, and L. Stibor. Ieee802.11e wireless lan for quality of service. In *European Wireless*, Florence, Italy, Feb 2002.

[35] M.K. Marina, G.D. Kondylis, and U.C. Kozat. Rbrp: a robust broadcast reservation protocol for mobile ad hoc networks. In *Proc. IEEE Intl. Conf. on Communications (ICC)*, Amsterdam, Netherlands, Jun 2001.

[36] S. Mengesha and H. Karl. Relay routing and scheduling for capacity improvement in cellular wlans. In *Proc. Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, Sophia-Antipolis, France, Mar 2003.

[37] W.M. Moh, D. Yao, and K. Makki. Wireless lan: Study of hidden-terminal effect and multimedia support. In *Proc. Intl. Conf. on Computer Communications and Networks (ICCCN)*, Lafayette, LA, USA, Oct 1998.

[38] J.P. Monks, V. Bharghavan, W. Mei, and W. Hwu. A power controlled multiple access protocol for wireless packet networks. In *Proc. Joint Conf. of the IEEE Computer and Communications Societies (INFOCOM)*, Anchorage, Alaska, USA, Apr 2001.

[39] A. Muir and J.J. Garcia-Luna-Aceves. Group allocation multiple access with collision detection. In *Proc. Joint Conf. of the IEEE Computer and Communications Societies (INFOCOM)*, Kobe, Japan, Apr 1997.

[40] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, and P. R. Kumar. Power control in ad hoc networks: Theory, architecture, algorithm and implementation of the compow protocol. In *European Wireless*, Florence, Italy, Feb 2002.

[41] N. Poojary, S. V. Krishnamurthy, and S. Dao. Medium access control in a network of ad hoc mobile nodes with heterogeneous power capabilities. In *Proc. IEEE Intl. Conf. on Communications (ICC)*, Amsterdam, Netherlands, Jun 2001.

[42] A.R. Prasad. Performance comparison of voice over ieee 802.11 schemes. In *Proc. IEEE Vehicular Technology Conference (VTC)*, Amsterdam, Netherlands, Sep 1999.

[43] Qiu Qiang, L. Jacob, R. Radhakrishna Pillai, and B. Prabhakaran. Mac protocol enhancements for qos guarantee and fairness over the ieee 802.11 wireless lans. In *Proc. Intl. Conf. on Computer Communications and Networks (ICCNC)*, Miami, USA, Oct 2002.

[44] D. Qiao and K.G. Shin. Achieving efficient channel utilization and weighted fairness for data communications in ieee 802.11 wlan under the dcf. In *Proc. IEEE Intl. Workshop on Quality of Service*, Miami Beach, USA, May 2002.

[45] S.-T.Sheu, T.-F. Sheu, C.-C. Wu, and J.-Y. Luo. Desing and implementation of a reservation-based mac protocol for voice/data over ieee802.11 ad hoc wireless networks. In *Proc. IEEE Intl. Conf. on Communications (ICC)*, Amsterdam, Netherlands, Jun 2001.

[46] S.-T. Sheu and T.-F. Sheu. Dbase: A distributed bandwidth allocation/sharing/extension protocol for multimedia over ieee 802.11 ad hoc wireless lans. In *Proc. Joint Conf. of the IEEE Computer and Communications Societies (INFOCOM)*, Anchorage, Alaska, USA, Apr 2001.

[47] J. L. Sobrihno and J. M. Brazio. A multiple access protocol for intergrated voice and high-speed data in wireless networks. In *Proc. IEEE Intl. Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, The Hague, Holand, Sep 1994.

[48] J. L. Sobrihno and A. S. Krishnakumar. Distributed multiple access procedures to provide voice communications over ieee 802.11 wireless networks. In *Proc. Global Telecommunications Conf. (GLOBECOM)*, London, United Kingdom, Nov 1996.

[49] J.L. Sobrinho and A.S. Krishnakumar. Real-time traffic over the ieee802.11 medium access control layer. *Bell Labs Technical Journal*, pages 172–187, 1996.

[50] J.L. Sobrinho and A.S. Krishnakumar. Quality of service in ad hoc carrier sense multiple access wireless networs. *IEEE Journal on Selected Areas in Communications*, pages 17(8):1353–1368, Aug 1999.

[51] K. Sundaresan, H.-Y. Hsieh, and R. Sivakumar. IEEE 802.11 over multi-hop wireless networks: Problems and new perspectives. *Elsevier Ad Hoc Networks*, Apr 2004.

[52] A. Tzamaloukas and J.J Garcia-Luna-Aceves. A channel-hopping protocol for ad-hoc networks. In *Proc. Intl. Conf. on Computer Communications and Networks (ICCNC)*, Las Vegas, USA, Apr 2000.

[53] N.H. Vaidya, P. Bahl, and S.Gupta. Distributed fair scheduling in wireless lan. In *Proc. Intl. Conf. on Mobile Computing and Networking (MOBICOM)*, Boston, USA, August 2000.

[54] M. Veeraraghavan, N. Cocker, and T. Moors. Support of voice services in ieee 802.11 wireless lans. In *Proc. Joint Conf. of the IEEE Computer and Communications Societies (INFOCOM)*, Anchorage, Alaska, USA, Apr 2001.

[55] M.A. Visser and M. El Zarki. Voice and data transmission over an 802.11 wireless network. In *Proc. 6th IEEE EEE Intl. Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Toronto, Canada, Sep 1995.

[56] IEEE 802.11 WG. Draft supplement to international standard for information technology telecommunications and information exchange between systems lan/man specific requrements. IEEE802.11e/2.0 Nov. 2001.

[57] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng, and J.P.-Sheu. A new multi-channel mac protocol with on-demand channel assignement for multi-hop mobile ad hoc networks. In *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Chicago, USA, Sep 2000.

[58] S.-L. Wu, Y.-C. Tseng, and J.-P. Sheu. Intelligent medium access for mobile ad hoc networks with busy tones and power control. *IEEE Journal on Selected Areas in Communications*, 2002.

[59] L.-L. Xie and P. R. Kumar. A network information theory for wireless communication: Scaling laws and optimal operation. In *Submitted to IEEE Transactions on Information Theory*, Apr 12, 2002. Revised November 9, 2003.

[60] S. Xu and T. Saadawi. Does the ieee 802.11 mac protocol work well in multihop wireless ad hoc networks? *IEEE Communications Magazine*, Jun 2001.

[61] J. Xue, P. Stuedi, and G. Alonso. ASAP: An adaptive qos protocol for mobile ad hoc networks. In *IEEE Intl. Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Beijing, China, Sep 2003.

[62] Z. Ying, A.L. Ananda, and L. Jacob. A qos enabled mac protocol for multi-hop ad hoc wireless networks. In *Proc. IEEE Intl. Conf. on Performance, Computing, and Communications (IPCCC)*, Phoenix, USA, Apr 2003.

[63] J. Zander and L. Ahlin. *Principles of Wireless Communications.* Studentlitteratur, Sweden, 1998.

[64] L. Zhao and C. Fan. A multi-cell dynamic reservation protocol for multimedia over ieee802.11 ad hoc wlan. In *Proc. 17th Intl. Conf. on Advanced Information Networking and Applications (AINA)*, Xi'an, China, Mar 2003.

[65] Y. Zhenyu and J.J. Garcia-Luna-Aceves. Hop-reservation multiple access (hrma) for ad hoc networks. In *Proc. Joint Conf. of the IEEE Computer and Communications Societies (INFOCOM)*, New York, USA, Mar 1999.

[66] E. Ziouva and T. Antonakopoulus. Voice communication over ieee 802.11 wireless lans interconnected using atm links. In *Proc. Local Computer Networks (LCN)*, Tampa, Florida, USA, Nov 2001.