En route to a 4.Generation Medium Access Control Protocol

Ole Klein, Communication Networks, Faculty 6, RWTH Aachen University, Germany
Michael Einhaus, Communication Networks, Faculty 6, RWTH Aachen University, Germany
Alexander Federlin, Communication Networks, Faculty 6, RWTH Aachen University, Germany

Abstract

This work identifies key methods that should be taken into account when designing a MAC protocol for the fourth generation (4G) of mobile radio networks. Knowledge and experience gained from studying state-of-the-art systems are the basis for these proposals. Combining the merits of two state-of-the-art categories of MAC protocols, the Frame Descriptor Table concept [1] gives an example of how to realize the goals envisaged for 4G mobile radio networks. The concept promises to be a key element in 4G MAC protocols.

1 Introduction

At the moment mobile radio networks of third generation are being deployed. Needless to say that research on 4G is already ongoing. An important vision for this next generation radio access system is the one formulated by the ITU-R focusing on two main goals:

- Integration of existing and evolving access systems on a packet based platform to enable cooperation and interworking of these systems in the sense ”optimally connected anywhere, anytime”.
- Development of the radio access system for new mobile access and new nomadic/local area wireless access to provide access with significantly improved performance compared to today's systems.

Taking this vision as a guideline, e.g. in the project WINNER [2], a new 4G radio access system is under development. The system will provide ubiquitous access with significantly improved performance compared to today’s systems. Thus, peak data rates up to 1 Gbps in the short range assuming low mobility and up to 100 Mbps for wide area supporting medium to high or even very high mobility are predicted. This will permit usage of a wide range of services in different scenarios. The new air interface requires most importantly the implementation of a new and more efficient MAC protocol. Within this paper we outline a way forward to design a MAC protocol supporting all the needs of a 4G mobile radio network.
The remainder of this paper is organized as follows: section 2 presents the requirements for a MAC protocol of 4G. The potentials and limitations of state-of-the-art MAC protocols are studied in section 3 as basis to identify key methods to be taken into account when designing a future MAC protocol. The outcome is given in section 4. A concept implementing the results is given with the Frame Descriptor Tables (FDT) presented in section 5. A summary of the findings given in section 6 concludes the paper.

2 Requirements for a MAC protocol of 4.Generation

MAC protocols are based on Multiple Access Technologies, which enable access to the spectrum of resources for multiple users/stations. The underlying resource “radio channel” comprises the dimension space, time, code and frequency. In wireless systems the medium access control (MAC) protocol plays a decisive role especially if Quality of Service (QoS) is under consideration. The resource “radio channel” has to be assigned to all interested stations in a proper way, enabling them to meet their QoS requirements. Therefore the MAC protocol needs to possess information about the status of the channel in the sense of knowing the available resources and the requirements of the parties interested in using the resources. The way the MAC protocol controls the access to the medium significantly influences the level of QoS the whole system is able to offer. The general requirements for a MAC protocol of next generation mobile radio networks are:

- **Packet based transmission**

While voice traffic will continue to be a very important application for a 4G mobile radio network, it is assumed that the transmission of data using the available high data rates will become more important. In order to better suit the characteristics of data transfer and to ease the connection to existing data networks, 4G systems are generally assumed to be packet based.

- **Low power consumption**

Most of the time mobile devices are used while in motion or temporarily stationary (nomadic). This implies an uncertain supply of electricity. The amount

of electrical energy that can be stored in a battery is mainly limited by its size. Since mobile devices are by design as small as possible, the size of their batteries is limited as well. Hence the electrical energy available has to be made use of most sparingly. All components of such a device have to consume as little power as possible. By enabling the device to switch off its transceiver unit whenever possible, the MAC protocol can help to keep power consumption low.

- **Quality of Service**

The MAC protocol is a key element for overall system performance of wireless communication systems, especially regarding QoS. The transmission of data not only with high data rates but within rigid delay boundaries is a prerequisite for delivering high quality real time services such as video calls or streaming. Thus the support of real-time oriented classes of service will be mandatory in future radio systems. To enable QoS support in packet based systems the reservation of the medium in advance to the packet transmission is required. It is needed to be able to control the interference during the use of the channel as interference might result in degradation of the link quality in terms of the bit error rate and might even interrupt an ongoing service.

- **Multi-Hop capability**

The support of multi-hop operations increases the potential of a new mobile radio system and opens up possibilities for new use cases. Multi-hop operations can help to increase coverage while keeping costs at a minimum. This can be achieved by deploying relay stations outside the coverage area of an access point (AP). With the help of antenna gain this can expand the coverage area of the AP. Moreover the coverage area of a cell can be enlarged in a way that relays can be deployed to serve areas otherwise shadowed from the AP.
The optimization of the cell capacity and the minimization of the transmit power can be reached by deploying the relays inside the coverage area of the AP. However, the forwarding across one or even multiple stations calls for special means in the protocol stack [3,4,5].

- **Spectral efficiency**

An overall goal of all radio systems is the achievement of high spectral efficiency. Spectral efficiency measures the ability of a wireless system to deliver information within a given amount of radio spectrum and is directly related to system capacity. This is a very general requirement which is influenced by a lot of parameters.
The transmission of user data is of course the only task of a radio system. In order to accomplish this task, the system has to transmit data which is not user data. This signaling data is necessary to organize the transmission of user data and is needed and added by every layer of a protocol stack. Since the resources necessary for the transmission of signaling data cannot be used to transmit user data, it decreases spectral efficiency. From this arises the necessity to keep the amount of signaling data at a minimum.
Thus the time to set up a connection should be small in relation to the duration the connection is being used; otherwise the overhead might be unacceptably high.

3 Potentials and Limitations of State-of-the-Art MAC protocols

After the presentation of the requirements for a 4G MAC protocol in the previous section, this section will assess state-of-the-art MAC protocols regarding their potentials and limitations. The protocols are presented in a categorized way.
In general there are many different ways to categorize MAC protocols. As the reservation of the medium in advance to transmission is one fundamental characteristic of a future MAC protocol to be able to fulfill the before mentioned requirements we choose a categorization based on the way the protocol reserves the medium. The three resulting categories are:

- **Packet oriented reservation**
- **Frame based reservation**
- **Reservation of Time Division Multiple Access (TDMA) channels**

The main difference between protocols belonging to different categories is the duration of the interval for which the medium is reserved.
All of the ways to accomplish the reservation of the medium have advantages and disadvantages. For this reason very few of the MAC Protocols used in state-of-the-art wireless systems fit exactly in one of these categories. Most protocols used today employ different strategies depending on the task that needs to be accomplished at the respective stage of a connection. The reason for this is to exploit the merits of each of the different strategies for different phases of connection setup and transmission each of which have different requirements. In the following examples for each of the categories will be given. Considering the protocols presented there, the advantages and disadvantages will be outlined.

3.1 Packet oriented reservation

The first type of MAC protocols perform reservation for a single packet. There is not necessarily a repeating structure as in the other types of protocols. The legacy IEEE 802.11 protocol [7] is an example for this in that it either reserves the medium by spontaneously transmitting, or applies a reservation

using an RTS/CTS handshake to reserve the medium in advance to user data transmission.
The main advantage of this architecture is that its implementation is relatively simple. No resource management or centrally or de-centrally organized resource planning is necessary. There are several disadvantages to this relatively simple solution. One major drawback of this approach is its poor scalability. The more mobile stations are present in a network, the higher the probability of collision gets [8]. A consequence is that under high network load resulting from many competing stations, the data rate per station and the total network throughput is reduced dramatically for any data rate [9].
Another drawback of a random access based medium reservation on packet basis is that QoS cannot be supported. In order to support QoS a MAC protocol must be able to guarantee the transmission of a certain packet within a maximum delay time. This is not possible, in general, if a station has to contend for each packet transmission, since there is no guarantee that a station will win a contention within a given time duration.
Legacy IEEE 802.11 shows that it is possible to realize a MAC protocol based on a packet based reservation scheme which is ad-hoc capable and able to work with decentralized or semi centralized control.
The problem of hidden stations is partly solved when applying the RTS/CTS cycle.

3.2 Frame based reservation

Protocols belonging to the second category reserve the medium on a per frame basis. Different parts of a frame are reserved for a number of packet transmissions to and from, typically, different mobile stations in the range of the AP. This reservation usually has to be performed for every single frame. This category of protocols includes the following standard systems:

1. HiperLAN/2 [10]
2. IEEE 802.11e for QoS supporting WLAN [11]
3. IEEE 802.15.3 for Ultra Wide band communication on OFDM basis [12]
4. IEEE 802.16a (HiperMAN) WMAN for Point-to-Multipoint communication to connect fixed of mobile stations to the base station [13].

The amount of overhead spent per frame is reduced compared to a reservation per packet. Accordingly, compared to legacy 802.11 systems, this type of protocols achieves a much higher throughput as shown in [9]. Owing to their ability to differentiate service classes by scheduling, these protocols are able to guarantee a maximum delay for real-time services.

To be able to support QoS, a frame structure was added to IEEE 802.11. The resulting IEEE 802.11e system shows a much improved performance compared to the legacy version 802.11.

In contrast to legacy IEEE 802.11 systems, which are capable of working either with decentralized or semi centralized control, the frame based reservation protocols operate under central control by the local AP. Ad-hoc capabilities as well as dynamic channel allocation are not easily incorporated into this kind of protocol. It has been shown, however, that multi-hop operation and ad-hoc networking can be provided without loosing the property to be able to guarantee QoS, e.g., by means of the HiperLAN/2 Home Environment Extension [14].

3.3 Reservation of TDMA channels

With the third kind of protocols the reservation of the medium is done for the whole time a connection exists between two communication partners. I.e. at the setup of the connection, part of each frame is reserved, establishing a TDMA channel for the duration of the connection. These reservations may be altered if the need arises. This category of MAC protocols is represented by standards like GSM/GPRS [6] or DECT [6][15].
With GPRS the establishment of a TDMA channel is under central control of the base, with DECT the mobile station may suggest a frequency channel and TDMA channel where to establish a connection under non-central control. Another completely decentrally controlled approach is represented by the W-CHAMB network [17].
Like the frame based reservation scheme, this way of reserving the medium allows for support of QoS as well. Particularly with regard to multi-hop operations it shows very good performance [17].

4 Key Methods for a 4G MAC protocol

By comparing the characteristics of the state-of the-art protocols with the requirements introduced in section 2, in this section we figure out key methods to be taken into account when designing a 4G MAC protocol. Moreover we will explain the impact on the different categories of MAC protocols, when considering a technology evolution based increase of the transmission rate of wireless media and a respective reduction of packet lengths of a given application:

As described packet oriented reservation has unfavorable characteristics concerning overhead and QoS support. Due to backoff times that have to be observed as well as possible collisions during

transmission, the overhead for this kind of reservation scheme is high. Due to the inherent randomness of the medium access, QoS cannot be supported. The performance under multi-hop operation is known to be badly [16]. Protocols based on this reservation scheme will suffer more from a higher link bit rate than protocols from both other protocol categories. Overhead percentage will be maximum for this kind of protocols.

Reservation on a per frame basis causes much lower overhead. The reason is that the reservation of the medium is performed for a number of packet transmissions at the same time. MAC protocols on top of enhanced link layers with improved link bit rate will benefit from this way of sharing part of the reservation overhead. Since there is also some individual overhead per packet, the total overhead will grow, but much less than with packet oriented reservation based protocols.
This kind of resource reservation offers great flexibility and enables fast adaptation of scheduled resources to changing demand. QoS can be supported with this kind of system. Power consumption is low compared to other reservation schemes. The mobile device only has to switch on its transceiver unit for receiving the broadcast and when receiving or transmitting data. The rest of the frame it may remain switched off.

Establishing TDMA channels per connection needs little signaling with rising load. Signaling is necessary only for the establishment of connections. The ratio of signaling to user data is especially favorable for connections that, once established, are used for a long time. This can be exploited e.g. in multi-hop operations. Here, connections multiplexing the traffic of several other terminals can be established. This way of resource allocation is especially well suited to predict the future use of a channel in terms of interference produced in a system. One user reserves the channel for a long duration. This makes it easier to take into account the interference for other potential users. Protocols establishing TDMA channels under higher link bit rate will much less be affected by a non-favourable relation of connection setup time and connection duration, since reservation overhead for connection establishment is per connection, not per packet and all the packets transmitted in multiplex are not causing any overhead at all. Further, to keep the reservation overhead for connection establishment low, under a low to medium load a connection could be kept, even if partially unused, until the radio resource occupied is requested by some other station, which is called hang-on duration[6].

The advantages of the two last mentioned schemes, low overhead with long lasting connections as well as flexibility and low overhead with fast changing connections, can be combined using the Frame Descriptor Table (FDT) concept presented in the following section.

5 Frame Descriptor Table Concept

5.1 Basic Concept

FDTs are a means of establishing TDMA channels on a per-connection basis using MAC protocols natively performing reservation on a per-frame basis. As explained in the previous section, this will have a positive effect especially in multi-hop operations.

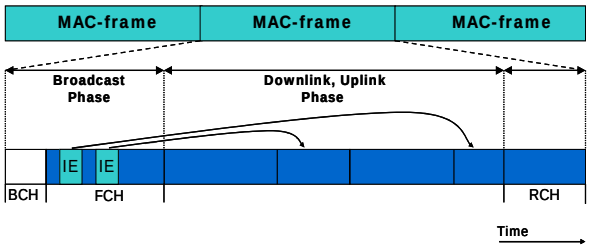

Figure 1. Basic MAC Frame structure

There are several ways to employ the concept of FDTs (see [1]). In the following the concept is explained, assuming a frame based MAC protocol (cp. Figure 1) in which the AP sends out a broadcast channel (BCH) in the beginning of each frame followed by a frame channel (FCH) describing the layout of the frame with the help of so called information elements (IE). These IEs describe the connections scheduled by the AP for the upcoming downlink phase (DL) and uplink phase (UL) in which the DL comprises transmissions from the AP to the associated stations whereas the UL comprises transmissions from the stations towards the AP. Basically this approach of allocating resources for transmissions can be found in all of the MAC protocols mentioned in Section 3.2.
Implementing the concept of FDTs first we introduce the so called “Frame Descriptor” (FD). It contains IEs which describe the frame layout, i.e. the contents of the UL and DL phase. It differs from an FCH in that it is not transmitted every frame, but only in certain intervals. Additionally each FD transmitted has a unique ID.
Maintaining an FDT, now each station is able to store a certain number of FDs indexed by their ID. With the help of the ID an FD can be referred to by the AP in one of the following frames. The stations can look up the content of the FD by consulting their FDT with the help of the ID. If there is a certain periodicity in the communication needs of a particular service (e.g. VoIP) the AP can easily adapt to these needs by referring to two or more FDs in an alternating fashion.
The main advantage of the FDTs is the resulting decrease in overhead. The description of the frame layout is coded and can be communicated to the

stations by transmitting the index in form of a simple number. The valid index for the current frame could easily be contained in, e.g. the BCH.
To be able to support highly dynamic resource requests it is reasonable to allow for the usage of the "normal" FCH in addition to the FDs. Thus the FCH can be used dynamically to inform the stations about upcoming resource allocations only valid for the current frame whereas the potentially announced FD describes "fixed" resources (TDMA channels) of the frame layout (cp. Figure 2).

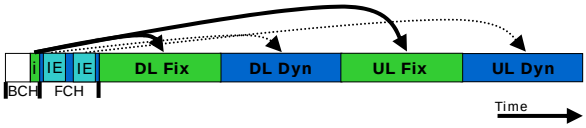

Figure 2. Description of Fixed and Dynamic Portions

The analysis and simulative assessment of the concept done in various papers [18][19][21] show the effects this concept can have on signaling overhead. The results show that with this concept a reduction of overhead and establishment of TDMA channels using a MAC protocol employing a frame based reservation is feasible and promising.

5.2 FDT in Multi-hop

As explained in the section before the concept of FDTs allows for a reduction of overhead by decreasing the amount of signaling. When examining multi-hop solutions for frame based MAC protocols it becomes obvious that this reduction will get even more important. A drawback of the multi-hop MAC protocol is the fact that control signaling is needed for each hop. This results in an increasing overhead with an increasing number of hops. With the help of the FDTs this overhead can be kept small [20]. Considering a multi-hop solution which establishes fixed or even partly fixed connections for the relaying of data, implementing the concept of FDTs in such MAC protocols is even more interesting.
In a typical multi-hop scenario there is an AP serving several stations. At least one of the stations, the relay, on his part acts as an AP for several remote stations. The traffic used by the remote stations can be multiplexed onto one single connection from the relay to the AP and vice versa. This connection has a more or less fixed resource requirement which can be almost perfectly described using an FD. Instead of describing this long standing and slowly changing connection every frame, its corresponding allocated resources can be stored in the FDT. This provides an easy means to ensure a minimum bandwidth allotted to the relay as well as saving overhead and thus enabling the allocation of more resources to the stations attached to the AP directly.
There is an additional advantage of the fixed allocation of resources on the UL connection. Usually a station has to send a resource request which has to be processed by the AP. At the earliest in the next frame resources can be allocated. This step can be omitted using this method of establishing a fixed TDMA channel.

6 Conclusions

There are a lot of requirements for a 4G MAC protocol presented in this paper. Looking at the potentials and limitations of state-of-the-art MAC protocols some of the key methods which have to be taken into account when designing the MAC protocol for next generation mobile radio networks are identified.
The concept of FDTs presented is a way to implement some of the key methods. It is a promising means to mitigate the need for resources necessary to transmit control information. The efficiency of this concept depends mainly on the scenario in which it is employed. Especially when taking multi-hop scenarios into account in which the saving in resources is adding up in each hop the concept shows its benefit, also by enabling the establishment of TDMA channels within a frame based reservation scheme in a resource conserving fashion. This makes the concept of FDTs a valuable method for achieving the high spectral efficiency necessary in 4G mobile radio systems.

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