A CENTRALIZED MAC PROTOCOL WITH QOS SUPPORT FOR WIRELESS LANS

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ABSTRACT

Wireless Local Area Networks (WLANs) are widely used in homes and offices, as well as in public places, mainly as the last mile of an Internet connection, but also as an interconnection between different devices. This extensive usage of WLANs, with the need of modern applications (such as Voice over IP) for high throughput and low transmission delays, impose the necessity for efficient protocols with Quality of Service (QoS) support.

In previous work [6] the ability of Multi Carrier-Code Division Multiple Access (MC-CDMA) based Medium Access Control (MAC) protocols to achieve high efficiency has been demonstrated. This paper presents a MAC protocol, based on MC-CDMA that uses an Access Point (AP) to centrally control the network and provide QoS support. Extensive simulation results and a comparison with the standard IEEE 802.11e[3] prove the efficiency of the proposed protocol.

INTRODUCTION

In many cases, Wireless Local Area Networks (W-LANs) are interconnected over an Ethernet backbone network, connected to the Internet. For that purpose, at least one Mobile Station (MS) in each W-LAN network, the so called Access Point (AP), must participate in both wireless and wired communication. APs typically carry a large fraction of networks traffic, and should therefore be prioritized over other MSs. They can even control the networks' resources.

Although there are some drawbacks of centralized networks – the main one being the need for deployment, which inherently brings higher cost, centralized networks outperform decentralized ones. Since every MSs has to apply for resource grant at the AP, the AP has an overview of the network load situation and can consequently schedule the available resources according to the needs of MSs. Moreover, it can avoid collisions and near-far-problems. All these, in accordance with the capability to reserve resources for transmissions of certain MSs, enhance the ability of the protocol to support Quality of Service (QoS). Further, QoS is achieved with significantly reduced overhead compared to decentralized networks, since the network coordination (allowance to channel access) is done by the AP and not in a distributed manner, thus the efficiency of the protocol and the network throughput increase.

In [6], the Coded Distributed Coordination Function (C-DCF) a Multi Carrier-Code Division Multiple Access (MC-CDMA) Medium Access Control (MAC) protocol was presented. C-DCF is a decentralized MAC protocol based on the Distributed Coordination Function (DCF) of IEEE 802.11[1], adapted to the MC-CDMA Physical (PHY) layer, where the frequency channel is divided in 4 parallel subchannels (as the applied Spreading Factor (SF) is four), separated from each other by orthogonal spreading sequences, called Codechannels (cchs). A MS having data for transmission selects first a cch and applies the rules of DCF for channel access and data transmission. The analysis in [6] proved the benefits of a MC-CDMA PHY layer, such as contention reduction (due to the parallel channels separated in code domain) and effective overhead reduction (due to the larger size of data packets after spreading, while the protocol guard times remain). The protocol proposed in this work extends C-DCF with the operation in centralized mode, combining the advantages of central network organization with the ones of MC-CDMA

This paper is structured as follows: in Section II an overview of related work is given. In Section III the proposed centralized MAC protocol is introduced, followed by a capacity analysis of the new MAC protocol and a comparison with the standard IEEE 802.11e in Section IV. In Section V extensive simulation results of the proposed protocol are presented, that demonstrate its ability to achieve high throughput and QoS support. In Section VI the summary of this work is given and conclusions are drawn.

RELATED WORK

Besides DCF, the IEEE 802.11 standard [1] defines the Point Coordination Function (PCF), on top of DCF. In PCF contention free services are provided by Point Coordinators within APs. After announcing the interval used for contention free services followed by the Contention Period (CP) of defined duration, stations can transmit only if the AP solicits the transmission with a polling frame. PCF is an optional part of the specification, and it has not been deployed [9]. The reasons include its high complexity and limited throughput and QoS support.

The later standard IEEE 802.11e [3] brought many enhancements to provide QoS, such as negotiable Acknowledgment (ACK), (legacy, no ACK, no explicit ACK, and block ACK), Transmission Opportunities (TXOP) and traffic prioritization. It also brought the new coordination function – Hybrid Coordination Function (HCF), which combines the aspects of DFC and PCF. HCF uses the Enhanced Distributed Channel Access (EDCA) for a contention based channel access, and HCF-Controlled Channel Access (HCCA) for the reservation of TXOPs.

A station can obtain a TXOP in two ways: if it receives a Quality of Service-Contention Free-Poll (QoS-CF-Poll) during the CP or CFP, or using EDCA during the CP [10]. Although IEEE 802.11e can support QoS, the protocol has high complexity and its efficiency is limited to about 60% of the channel's capacity (see Section 0).

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DESCRIPTION OF THE CENTRALIZED MAC PROTOCOL

The proposed protocol takes the intervals between two consecutive beacon frames – superframes, as the basic structure element of the centrally controlled MAC. In the presence of an AP, the network operation within a superframe is divided in two phases: CP and CFP. During CP, all the stations follow the rules of C-DCF [6], and during CFP the AP has central control over the network. Allocation of available resources is done in both, time and code domain, according to the information contained in the beacon that is broadcasted by the AP to all cchs. An example is given in Fig. 1, where CP in cch 2 and cch 4 takes 60% of the superframe duration and cch 1 and cch 3 are operating in CFP only.

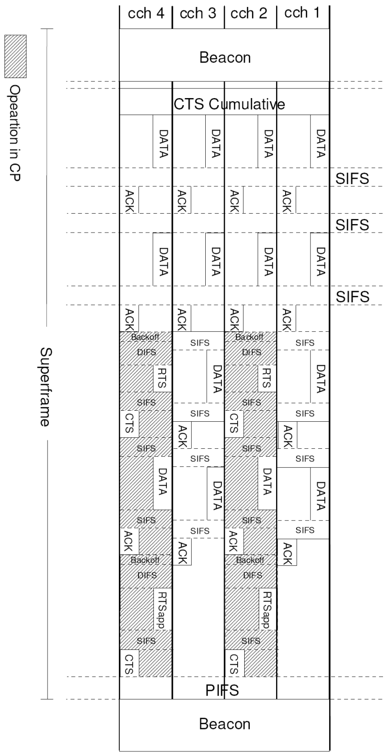

Fig. 1 Data transmission in CP and CFP.

The AP transmits the first beacon immediately after its initialization, and signals the network's operation characteristics. Besides the information contained in the IEEE 802.11a beacon, the AP specifies for each cch the duration of the following CFP (Fig. 1), that depends on the network traffic and can be adjusted by the AP in each superframe. Such a cch-specific division of CFP and CP durations adds flexibility compared to an allocation for the whole channel. MSs, initiating a new connection may use the CP for their first transmission, thus reducing delay until they are granted resources for CFP in response to their request. MSs with low load or with best effort traffic class may operate in CP continuously. The total duration of CFP per cch depends on the network traffic and can be adjusted by the AP in each superframe.

MSs may request resources for transmission during CFP, by sending a Ready-To-Send-application (RTSapp) frame (Fig. 3) to the AP during CP according to the C-DCF access rules.

Octets:	8	2	2	0–32	1–8	6	6	4	256
	Timestamp	Beacon Interval	Capability Information	SSID	Supported Rates	MC–CDMA Parameter Set	CF Parameter Set	IBSS Parameter Set	TIM

Fig. 2 Beacon frame format.

Octets:	2	2	6	6	4	2	2	1
	Frame Control	Duration	Receiver Address	Transmitter Address	FCS	TxPower	IfPower	Application Type

Fig. 3 RTSapp frame format.

Octets:	2	2	N.6		4	2	2
	Frame Control	Duration	Receiver	Addresses	FCS	TxPower	IfPower

Fig. 4 CTScum frame format.

The RTSapp frame contains either the amount of data to be transmitted or a request for transmission according to a traffic class. A traffic class specifies a transmission rate [8] or maximum tolerable delay [3], which guide the AP to appropriately schedule transmissions for this MS.

After a guard interval of one slot, a beacon transmission is followed by the transmission of the Clear-To-Send-cumulative (CTScum) frame (Fig. 4). Same as the beacon frame, CTScum is transmitted in parallel via all cchs, and contains information for the forthcoming transmissions during CFP in each cch, the so called access grants. An access grant contains the addresses of the transmitters in the order of transmission within a superframe and may be different for each cch. An extra byte in CTScum signals the periodic repetition of the cch allocation within a superframe, valid until the end of the superframe and the period duration, in order to reduce overhead.

To further reduce the overhead, address compression is applied in centralized mode. MSs, upon association with the AP, get a unique one byte long address that is used as an identifier and is enough to support 255 MSs in a network controlled by one AP. Together with the network identifier it provides a unique address to each MS. Further, the number of MAC addresses in a data frame can be reduced to three (from 4 in [1]), namely the source, destination and subnetwork address, as long as no multihop is permitted.

The CTScum frame finalizes the broadcast transmission phase and CFP follows. According to the access grants, MSs start direct link transmissions in the assigned cchs in the order specified by the CTScum frame. The correct reception of a data frame is acknowledged with an ACK frame, transmitted after time Short InterFrame Space (SIFS). An ACK might be followed by SIFS, if fragmentation is permitted before the next data frame follows, in order to allow consecutive transmissions of data frames from the same MS.

As shown in Fig. 1, CFP ends after 40% of superframe duration in cchs 2 and 4, and CP operation follows. According to the Target Beacon Transmission Time (TBTT) announced in the last beacon frame, the AP sends the beacon, after having sensed the channel for free for duration PCF InterFrame Space (PIFS). In order to avoid collisions with beacon, resource grants for CFP consider the TBTT, and MSs operating in CP, which received the previous beacon, must end all transmissions when TBTT approaches [9]. Channel monitoring for duration PIFS, by the AP, prior to beacon retransmission is still necessary, to ensure collision avoidance between the beacon and transmissions in CP from MSs with large clock drifts.

CAPACITY ANALYSIS AND COMPARISON WITH IEEE 802.11E

In this section, the maximum achievable throughput during CFP in C-DCF and IEEE 802.11e are calculated.

Within a superframe that does not contain CP, the following frames are transmitted in each cch:

$$\text{Superframe} = \text{Beacon} + \text{aSlotTime} + \text{CTScum} + \text{Np}(\text{SIFS} + \text{DATA} + \text{SIFS} + \text{ACK}) + \text{PIFS} \quad (1)$$

Np denotes the number of data frames transmitted in one superframe per cch (It is assumed that the observed interval is completely covered by data frames.) The duration of a superframe can be then calculated, according to the values of the parameters aSlotTime, SIFS and PIFS which according to standard [2] are 9 μsec, 16 μsec and 25 μsec respectvely.

The MAC frames for data and ACK are specified in the standard [1], whilst the extended beacon and CTScum frame were described in Section III. Mapping of MAC frames to PHY layer frames follows the same rules as specified in the standard [2]. For the analysis, the worst case is considered: subsequent data frames originate from different transmitters, thus no block acknowledgement is possible. Assuming:

- that all control frames are transmitted with QPSK 1/2 and data frames with the 64QAM 3/4 PHY modes,
- MAC Protocol Data Units (PDUs) are 1024 Byte long,
- the frame formats of Figs. 2-4 for beacon, RTSapp and CTScum,
- the frame formats of the standard IEEE 802.11a [2] for the other frames, and
- the 20 MHz channel of standard IEEE 802.11a [2],

the superframe duration can be calculated:

$$\Delta T_{SF} = 338 + 4\ \mathrm{ceil}[(94 + 8\mathrm{Np})/48] + 776\mathrm{Np}\ [\mu\mathrm{sec}] \quad (2)$$

In case of IEEE 802.11e [3], assuming that the observed interval is completely covered by data frames originating from different transmitters (same as for centralized C-DCF), that transmission requests are already known to HC and they are enough to cover the whole superframe duration the following frame transmissions take place within a superframe completely occupied by Controlled Access Phase (CAP)s from the Hybrid Coordinator (HC) [3]:

$$\text{Superframe802.11e} = \text{Beacon} + \text{Np11e}(\text{PIFS} + \text{QoS-CF-Poll} + \text{SIFS} + \text{DATA} + \text{SIFS} + \text{ACK}) + \text{PIFS} \quad (3)$$

where Np11e denotes the number of CAPs in the superframe.

The duration of PIFS, and the frame structures of Beacon and QoS-CF-Poll are described in [3]. Consequently the duration of the IEEE 802.11e superframe can be calculated according to the frame formats and rules of the standard IEEE 802.11e [3], for the use of the same PHY modes and MAC PDU length as in centrally controlled C-DCF:

$$\Delta T_{SF11e} = 285 + \mathrm{Np11e}313\ [\mu\mathrm{sec}] \quad (4)$$

For different values of ΔT_{SF}, Np, ΔT_{SF11e} and Np11e, the achievable throughput for both centralized C-DCF and IEEE 802.11e, according to Eq. (2) and (4) respectively, is presented in TABLE I. The results show the high efficiency achieved by C-DCF, which is up to 60% higher than the efficiency of IEEE 802.11e.

TABLE I CFP THROUGHPUT VS. SUPERFRAME LENGTH FOR 1024 BYTE LONG DATA PACKETS.

Superframe length	**C-DCF Max. theoretical throughput on 4 cchs**	**IEEE 802.11e**
20 msec	40.96 Mbit/sec	25.39 Mbit/sec
40 msec	40.96 Mbit/sec	25.80 Mbit/sec
100 msec	41.61 Mbit/sec	26.05 Mbit/sec

Equation (2) is valid only when operating the whole superframe in CFP. The throughput for the proposed centrally controlled C-CDF, a mixed operation of CFP and CP which gives more flexibility to the network, depends on both, the superframe duration and the percentage duration of CP and CFP. The maximum throughput during CP has been calculated in [6] to 31.58 Mbit /sec for 1KByte long data PDUs without considering beacon transmissions. With periodic beacon transmissions every 100msec (superframe duration), the maximum throughput during CP reduces to 31.46 Mbit/sec. Consequently, for the example given in Fig. 1, with 60% CP on two out of four cchs, 100msec superframe duration and 1 KByte long data PDUs, the total maximum throughput is 38.6 Mbit/sec.

PERFORMANCE EVALUATION

In this section, performance evaluation results of the proposed centrally controlled MAC protocol are presented. For this purpose, an event driven simulator is used [12], developed in C++ and Specification and Description Language (SDL) at the Chair of Communication Networks.

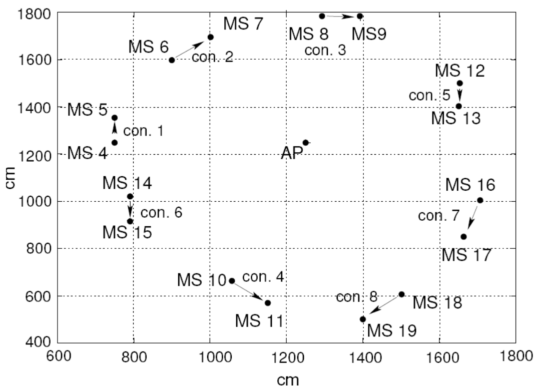

Fig. 5 Simulated scenario with AP controlling channel access.

The simulated example scenario consists of an AP with round robin scheduler and 16 MSs around it, establishing 8 direct link connections (Fig. 5). CP operation covers 60% of the 100msec superframe duration in cchs 2 and 4, as depicted in Fig. 1. Control frames are transmitted with QPSK1/2, and data frames with 64 QAM3/4. Poisson traffic load generators are applied at each transmitting MS. Other relevant simulation parameters are given in TABLE II. The channel model and transmit power control algorithm applied are described in [10] and [12] respectively.

TABLE II SIMULATION PARAMETERS

Parameter	Value
Max. TxPower	17dBm
Spreading Factor	4
CWmin	7 slots
CWmax	1023 slots
Channel Bandwidth	20 MHz, 52 subcarriers (802.11a)
Noise Level	-93dBm
Path loss Factor	3.5
Preamble	16 µs
Max. Propagation Delay	0,15 µs
PDU Length	1024 Byte

The focus of the analysis is on MSs which are either transmitting in CFP only, or on MSs with mixed transmissions in CFP and CP. For transmissions during CP only, network characteristics are the ones of the decentralized protocol [6]. In the following analysis, two different transmission sets are differentiated, according to the mode that is used by the transmitting MSs:

- In set A: MSs are of same priority and transmit during both CFP and CP.
- In set B: Prioritized MSs transmit exclusively in CFP, whilst other MSs transmit in both CFP and CP. Prioritized MSs are: MS 10, MS 12, MS 14 and MS 16, and the respective connections are con. 4, con. 5, con. 6 and con. 7.

In Fig. 6 the carried system traffic vs. offered load is presented. The three curves correspond to the two operation modes (CP and CFP) and the total system throughput. Total system throughput rises linearly with the offered load until 28 Mbit/sec, where saturation starts for CP. Maximum values for total throughput are reached in overload, due to small scale channel re-use of the same cch during CP (during CP, the maximum throughput is 32.5 Mbit/sec which is 3.3 % higher than the analytically calculated upper bound of 31.46 Mbit/sec [6]), while for the CFP characteristic, the results comply with the analytical ones.

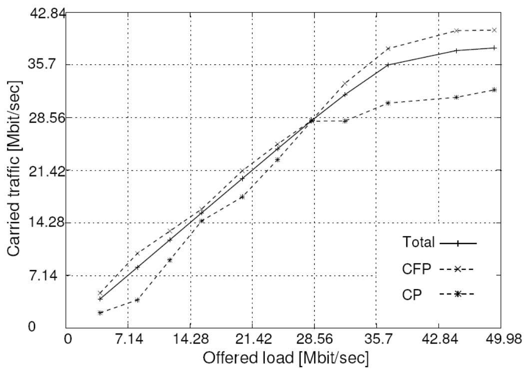

Fig. 6 Carried traffic in the network for the two operating modes and total carried traffic.

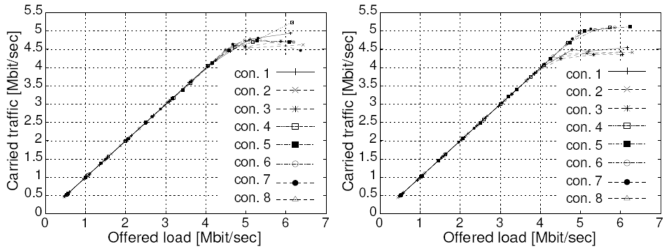

Fig. 7 Carried traffic per connection over offered load. Left for set A, right for set B.

The carried traffic for each connection is presented in Fig. 7. Same as the total carried traffic, carried traffic per connection shows linear increase with offered load up to the saturation load, which is different for each set (A or B) and operating mode (CFP or mixed). In set A, the throughput per connection is the same for all connections, as they share operation in CFP and in CP. For setup B, prioritized connections operating only in CFP, achieve the highest throughput, which is in average almost 14% more than the throughput of connections in mixed operation.

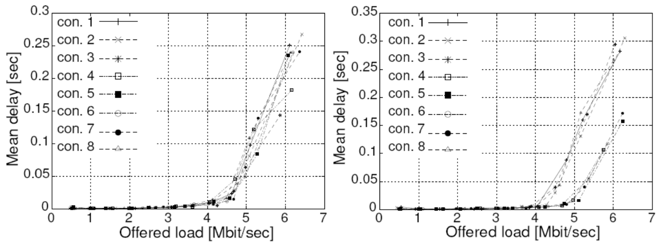

Fig. 8 Mean queueing delay over offered load. Left set A, right set B.

Similar behavior is observed for mean queuing delays, presented in Fig. 8. Queuing delay is limited for both sets to 10msec for load up to 4 Mbit/sec/transmitter, which corresponds to a network load of 32 Mbit/sec. The break point in the queuing delay curves, i.e. the point where a steep raise of queuing delay starts, depends on the applied set and operating mode. It corresponds to the amount of offered load which brings the network in saturation, according to Fig. 6. The best queuing delay performance is observed for MSs operating in CFP only, while queuing delay for mixed operation (set A, no priorities) is equal for all MSs.

Fig. 9 shows the mean service time per connection, as a function of the offered load. For CFP, service time measurement starts with the transmission of data packet and ends with the reception of the corresponding ACK, while for CP the service time includes the interval between the first transmission of an Ready-to-Send (RTS) frame (corresponding to the data packet) and the reception of the corresponding ACK. For set B, the mean service time is 0.76msec for CFP transmissions and 0.9msec for the mixed case. The absence of collisions contributes to a constant service time with offered load. In set A, all the MSs experience approximately the same mean service time, as all of them transmit in the mixed mode. A variation of service time in the order of 60µsec is observed owing to the random duration of Backoff timer and the ratio of the number of frames transmitted in CP to those transmitted in CFP.

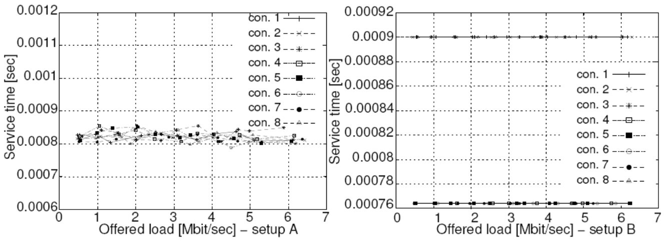

Fig. 9 Mean service time over the offered load. Left set A, right set B.

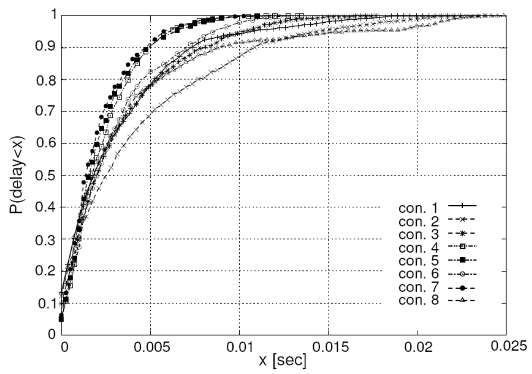

Fig. 10 CDF of queueing delay per MS with 2.8 Mbit/sec/MS Poisson distributed offered load.

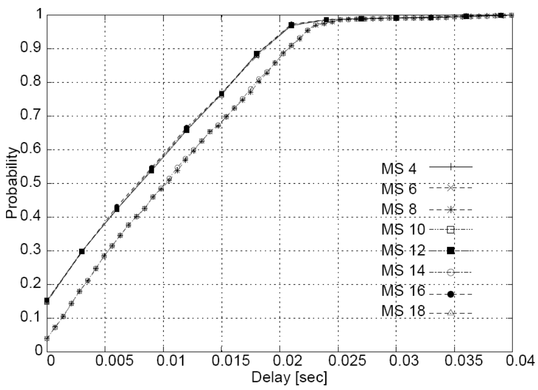

Fig. 11 CDF of queueing delay at different transmitters, each carrying an MPEG stream with data rate 280 kbit/sec. The superframe is fully occupied from CFP.

In Fig. 10, the Cumulative Distribution Function (CDF) of queuing delay is presented, for 2.8 Mbit/sec offered load per connection. The graphs refer to set B, which is more interesting for system operation, as two priorities are differentiated. Consequently, each MS faces different network conditions, depending on its priority. With probability 90% the queuing delay is limited to less than 11.5msec for all MSs, underlying the QoS support ability of the centralized mode. The maximum values of queuing delay are 18msec for CFP transmissions and 25msec for MSs is mixed operation (con. 1, con. 2, con. 3, and con. 8).

In Fig. 11 the CDF of queuing delay is given for the case of Moving Picture Experts Group (MPEG) load for all active connections. The MPEG traffic load generators deliver data packets of variable length according to MPEG-4 loaded H.263 video traces as defined in [7]. For these simulations, the network is fully operating in CFP. The queuing delay for 98% of successfully transmitted packets is less than 23 msec, proving the ability of QoS support in the proposed protocol.

CONCLUSION

This paper presented a centrally controlled MAC protocol for MC-CDMA based WLANs. Extensive simulation results show its high performance and ability to support QoS. Channel bandwidth division in 4 parallel cchs enables operation of CFP and CP in parallel on the same radio channel. Such a channel is advantageous for many reasons. Since any MS can use the signaling cchs for sending an access request for CFP at any time, access delay reduces. Moreover, unpredictable beacon delays and collisions from the operation of CP and CFP on the same channel as mentioned in [5] can be avoided, since separation between CP and CFP takes place in code domain, rather than in time domain, as in IEEE 802.11a/e. Additionally, MSs with high QoS requirements may transmit exclusively in CFP, where transmission delays can be guaranteed.

Future work focuses on the extension of the presented protocol to variable spreading factor and support for MIMO PHY layers, two elements that will further enhance the performance characteristics.

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