A Modified IEEE 802.11 MAC Protocol for MC-CDMA

Georgios Orfanos
Aachen University of Technology
Kopernikusstrasse 16
52074 Aachen, Germany
+49-241-8027919
orf@comnets.rwth-aachen.de

Jörg Habetha
Philips Research Laboratories
Weisshausstrasse 2
52066 Aachen, Germany
+49-241-6003560
Joerg.Habetha@Philips.com

Ling Liu
Aachen University of Technology
Kopernikusstrasse 16
52074 Aachen, Germany
+49-241-8027919
lli@comnets.rwth-aachen.de

ABSTRACT
In this paper, we introduce a modified version of the IEEE 802.11a protocol and evaluate its performance. The new protocol is a combination of the standard Medium Access Control (MAC) protocol of 802.11 and the Multi-Carrier Code Division Multiple Access (MC-CDMA) scheme, a novel, high capacity multicarrier modulation technique. The system can achieve higher throughput and shorter delays, owing to the division of the spectrum in a number of parallel codechannels.

Categories and Subject Descriptors
D.3.3 [**Computer-Communication Networks**]: Network Architecture and Designs – *distributed networks, packet-switching networks, wireless communication.*

General Terms
Algorithms, Performance, Design.

Keywords
MC-CDMA, IEEE 802.11, MAC, WLAN

1. INTRODUCTION
In a multicarrier system, several subcarriers are used for the parallel transmission of data. MC-CDMA, combines multicarrier modulation techniques with Code Division Multiple Access (CDMA). Typically, in a CDMA network each data symbol is spread over a larger bandwidth, larger than the bandwidth needed for transmission, thus achieving a lower spectral density than non-spread-spectrum systems.

In conventional Direct-Sequence CDMA (DS-CDMA), each user symbol is transmitted in the form of many sequential chips, each of which is of short duration, thus having a wide bandwidth.

PE-WASUN'04, October 7, 2004, Venezia, Italy.

In contrast to this, due to the Fast Fourier Transform (FFT) associated with Orthogonal Frequency Division Multiplexing (OFDM), MC-CDMA chips are long in time duration, but narrow in bandwidth [4]. Each symbol of the data stream of one user is multiplied by each element of the same spreading code and is thus placed in several narrow band subcarriers. Multiple chips are not sequential, but transmitted in parallel on different subcarriers [4].

In IEEE 802.11 the MAC protocol is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), where the collision avoidance is based on a randomly operating backoff procedure. Each Mobile Station (MS), which has a packet to transmit, defers from the medium for a backoff time equal to the product of the slot time with a random number between 0 and CW, before it can access the medium. This protocol is called the Distributed Coordination Function (DCF) of the standard [2], which is the basis for our proposed system.

In the following two sections our modifications of the physical and MAC layer are described. Section 4 includes a calculation of the maximum throughput and section 5 simulation results. Section 6 summarizes this work.

2. PHY LAYER MODIFICATIONS
The proposed system uses MC-CDMA in the physical layer (PHY layer), a modulation technique where one single data symbol is spread in frequency [1]. The 20 MHz channel is split into 52 subcarriers with 48 data and 4 pilot subcarriers, like in the IEEE 802.11a OFDM physical layer [2].

A Spreading Factor (SF) of 4 is chosen, thus the symbol of one user is divided into 4 fractions and each of them is transmitted in parallel on 4 different subcarriers. One subcarrier carries a fraction of the user's symbol, and can thus carry additional load, coming from symbols of other users. At the end the symbol that is transmitted in one subcarrier consists of the sum of n fractions on n symbols that belong to n users, with $n \leq SF$. See Figure 1 for a MC-CDMA system with SF=4.

Orthogonal Walsh Hadamard codes of length 4 are used as spreading sequences, leading to a maximum of 4 parallel code channels. Since the orthogonality of the Walsh Hadamard Codes is distorted in asynchronous environments, the use of a multi-user detector is inevitable. The adaptive Minimum Mean

Square Error (MMSE) multi-user detector performs well for asynchronous MC-CDMA systems in indoor Rayleigh fading channels [3], leading to a good separation of signals encoded with different spreading sequences and therefore is employed at the receivers of the proposed system.

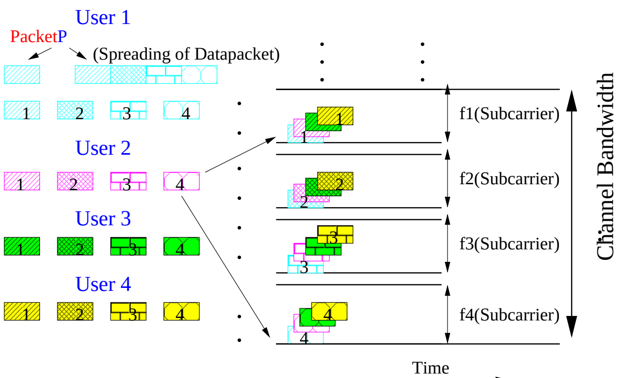

Figure 1. Principle of MC-CDMA

Other parameters of the PHY layer have been chosen like in the IEEE 802.11a 5 GHz OFDM based system.

3. MODIFIED MAC PROTOCOL

The MAC protocol of the proposed system is based on the MAC protocol of the IEEE 802.11a WLAN, with some additions to make efficient use of the CDMA PHY Layer.

In this case the frequency channel is divided into 4 parallel codechannels. MSs can access the codechannels using the DCF [2].

A station ready to transmit has to select a codechannel. For this selection two methods are possible. The first is to select a codechannel before every packet transmission. Initially this selection is done randomly. For later transmissions, the station does not select codechannels, which have already been reserved by other stations (according to the standard the considered station has set a "Network Allocation Vector (NAV)" for an occupied channel). The second method consists of selecting the codechannel with the least traffic and keeping this codechannel for the entire duration of the connection.

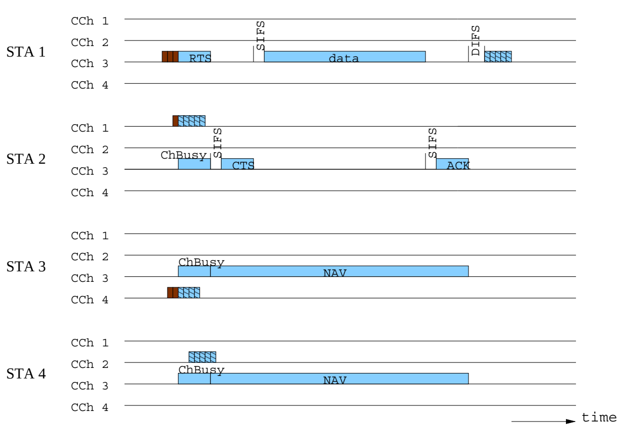

Figure 2. CSMA/CA with four codechannels

Before accessing the medium a station should detect the medium as idle for a duration called "Distributed Inter-Frame Space (DIFS)", and signals the intended data transfer by transmitting a Ready To Send (*RTS*) packet (Figure 2). All stations that receive this control packet, and are not the intended receivers, set their Network Allocation Vector (*NAV*) timer, interrupt their backoff down counts, and defer from the medium in order not to interfere with the transmission. If the receiver of the RTS is idle i.e. able to receive data, it responds with a Clear To Send (*CTS*) packet, after a time called "Short Inter-Frame Space (*SIFS*)". Mobile stations which receive this CTS set their NAV timer as well. The sender can now transmit its data packet after SIFS. The receiver acknowledges a successful reception by an ACK also a SIFS time after the end of the DATA frame. The above standard DCF procedure is followed in every codechannel for each data transmission.

A collision occurs in case two or more stations access the same codechannel on the same frequency band at the same time. The proposed modification of the protocol has an advantage in this respect, since each frequency channel is divided into SF parallel codechannels, in which only n/SF stations compete against each other in accessing the channel. The collision probability is therefore reduced, allowing the use of a lower value for the minimum size of the contention window CW (see above).

The MC-CDMA system has more but "smaller" codechannels than the original 802.11a system has frequency channels. The smaller channel capacity can be a major drawback for the system especially in scenarios with only a few active transmissions when one of them may have more load than the attached codechannel can carry. To overcome this problem we allow stations to transmit in multiple code operation. This means that a station, which has sufficient traffic, can use several codechannels to transmit more than one packet in parallel.

In CDMA networks one can say that the number of simultaneous transmissions can be increased until the Signal to Interference and Noise Ratio (*SINR*) at the receivers decreases to a limit that makes them unable to correctly receive and detect the intended packet. Therefore power control plays a major role for the system capacity. In the proposed system power control is done by means of the RTS, CTS [6]. An RTS is sent with the same transmission power than used in the previous transmission to that receiver incremented by 2 dBm. The transmission power is encoded in the RTS packet so that the receiver, upon receiving, can calculate the path loss. The receiver might ask the transmitter to change its transmission power by encoding such information in the CTS packet.

4. THEORETICAL ANALYSIS AND COMPARISON WITH 802.11a

Considering a complete transmission cycle, as shown in Figure 3, a comparison between the maximum achievable throughput of the MC-CDMA and the OFDM based system can be carried out. The time needed for a complete packet transfer (Δt) in

802.11, ignoring collisions and considering the average backoff interval, can be calculated as:

$$\Delta t = DIFS + tRTS + SIFS + tCTS + SIFS + tDATA + SIFS + tACK + 3{,}5 * aSlotTime$$

Considering the number of bits per OFDM symbol and assuming a payload of 1024 bytes, the number of symbols, that is required for the transmission of one frame with the OFDM as well as with the MC-CDMA system with SF = 4, can be calculated.

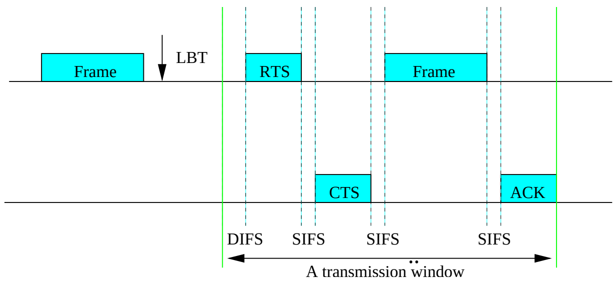

Figure 3. A complete transmission window

Considering the standardized values for DIFS (34 µs), SIFS (16 µs), aSlotTime (9 µs) and the length of one symbol (4 µs), and that at the beginning of each frame a preamble and a signal field [2] are added, we find the complete packet transfer time for both systems:

$$\Delta tOFDM = 393{,}5 \ \mu s$$

$$\rightarrow ThroughputOFDM = 1024 * 8 / 393{,}5 \ \mu s = 20{,}82 \ Mpbs$$

$$\Delta tMC\text{-}CDMA = 1037{,}5 \ \mu s$$

$$\rightarrow ThroughputMC\text{-}CDMA = 4*1024*8/1037{,}5 \ \mu s = 31{,}58 \ Mpbs$$

Thus the MC-CDMA system can theoretically achieve a spectral efficiency which is 51,68% higher than that of OFDM with the highest, 64 QAM ¾, PHY mode.

For the QPSK ½ PHY mode, we calculate the following throughput:

$$\Delta tOFDM = 915{,}5 \ \mu s$$

$$\rightarrow ThroughputOFDM = 1024 * 8 / 915{,}5 \ \mu s = 8{,}95 \ Mpbs$$

$$\Delta tMC\text{-}CDMA = 3253{,}5 \ \mu s$$

$$\rightarrow ThroughputMC\text{-}CDMA = 4*1024*8/3253{,}5 \ \mu s = 10{,}07 \ Mpbs$$

According to the above results, for QPSK ½, the spectral efficiency of MC-CDMA is 12,51 % higher than that of OFDM.

5. SIMULATIVE PERFORMANCE EVALUATION

For the performance analysis the event-driven simulation tool MACNET 2 has been developed, based on C++, the Specification and Description Language (*SDL*), the translation tool SDL2SPEETCL and the SDL Performance Evaluation Tool Class Library (*SPPETCL*).

A pathloss coefficient of 3.5, and Rayleigh fading according to the BRAN channel A parameters are used. A major role in the simulative performance evaluation of the proposed protocol plays the calculation of the SINR. In CDMA, although orthogonal codes are applied for the spreading procedure to mitigate Multi User Interference (*MUI)*, a receiver is subject to interference from MSs transmitting in other codechannels, because transmissions are not synchronous. This is an effect of the loss of orthogonality of the orthogonal codes in asynchronous scenarios. To partly mitigate this interference flow from other codechannels and boost the performance of the proposed system, we employ the MMSE multi-user detector [3].

In order to measure the achievable throughput of the proposed system, we simulate an elementary scenario, as shown in Figure 4. A station with sufficient load transmits in parallel to 4 stations in its vicinity. The simulation is performed both with the QPSK ½ and the 64 QAM ¾ PHY modes, for all links. For these simulations a CWmin size of 7 is used to allow a direct comparison with the theoretical results. The load generators offer Poisson load, with payload size of 1024 bytes.

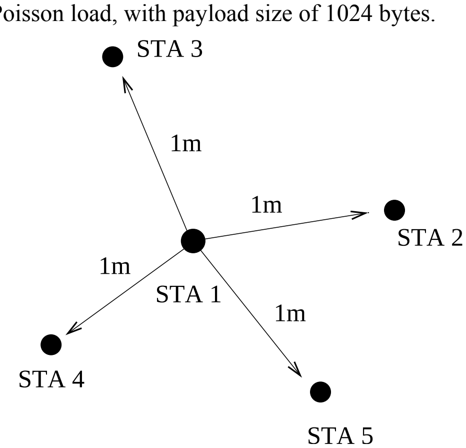

Figure 4. Parallel transmissions scenario

The system throughput and mean delays achieved are presented in Table 1, for both PHY modes. Results show that the system throughput is close to the theoretical maximum calculated above.

Table1. Results for the elementary scenario

DATA PHY mode	12 Mbps	54 Mbps
delivered packets	1264/s	3891/s
throughput	10,027 Mbps	31,559 Mbps
channel idle time	6,5%	15,1%
mean tx delay	2,88 ms	0,892 ms
mean queue delay	195 ms	286 ms

Moving to a more realistic scenario, we test the proposed modifications on the scenario shown in Fig. 6. It consists of 9 terminals establishing 5 links in a 10mx10m area, thus addressing Small Office-Home Office (*SOHO*) scenarios. The load generators offer Poisson load with mean interarrival time scaled with the offered load parameter. The value of CWmin is set to 3 to test the system for higher efficiency. This is possible because transmissions are spread across more channels and collisions are therefore less probable. All links use the QPSK ½ PHY mode.

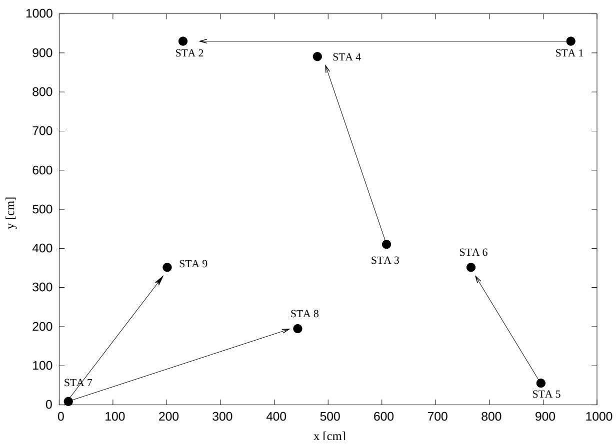

Figure 5. SOHO random scenario

The selection of the codechannels has been done randomly for all links and does not change throughout the lifetime of the connections. Before the first transmission of a data packet in each link, the transmitter sends the RTS packet in all 4 codechannels, in order to inform the receiver about the codechannel to be used. In case the receiver is able to measure interference at idle times, it may guide the transmitter to another more adequate channel.

Figure 6 shows the simulated system throughput vs. the number of active stations using packets with a length of 1024 byte, and Figure 7 shows the measured delays.

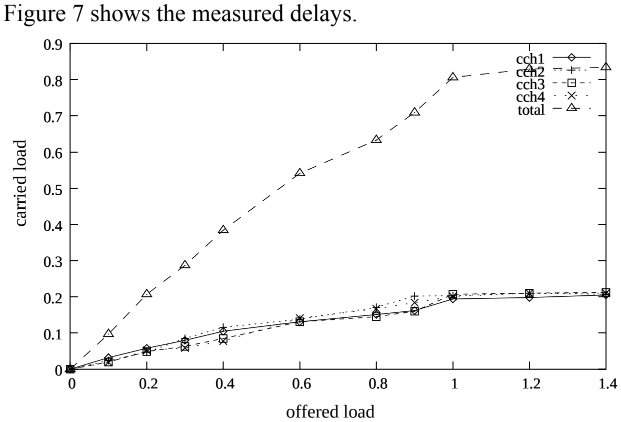

Figure 6. Throughput in SOHO scenario

The simulations show that the proposed system achieves low delays, and throughputs close to the theoretical maximum (of 10.08 Mbps for QPSK ½). Although the simulations were done with CWmin= 3, which pushes the total throughput slightly higher than in the above calculation with the standard value of 7, the transmissions don't suffer from collisions. This is an achievement of the parallel codechannels since each station has now fewer competitors for medium access.

6. SUMMARY

A modified version of the IEEE 802.11, based on MC-CDMA has been presented and analytically compared with the standard IEEE 802.11a W-LAN. The theoretical analysis given and the simulation results demonstrate the considerable improvements that have been achieved in terms of throughput and delay.

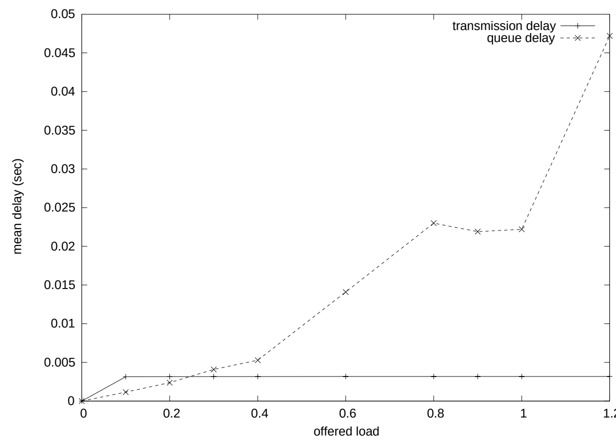

Figure 7. Packet Delay in SOHO scenario

7. ACKNOWLEDGEMENT

The authors would like to thank Prof. Dr.-Ing. B. Walke for his support and friendly advice to this work.

8. REFERENCES

[1] Hara, S. and Prasad, R., "Overview of Multicarrier CDMA", in *IEEE Comm. Magazine*, vol. 35, no. 11, Dec. 1997.

[2] IEEE 802.11 WG, *Draft Supplement: High-speed Physical Layer in the 5GHz Band*, IEEE Std. 802.11a, 1999.

[3] Yi, S. and Tsimenidis, C. and Hinton, O. and Sharif, B., "Adaptive Minimum Bit Error Rate Multi-user Detection for Asynchronous MC-CDMA Systems in Frequency Selective Rayleigh Fading Channels", in *Proc. IEEE PIMRC 2003*, Sept. 7-10, 2003.

[4] Linnartz, J., "Performance Analysis of Synchronous MC-CDMA in Mobile Rayleigh Channel with Both Delay and Doppler Spreads", in *IEEE Trans. On Vehicular Technology*, vol. 50, issue 6, Nov. 2001.

[5] Wang, Z. and Giannakis, G., "Wireless Multicarrier Communications – When Fourier Meets Shannon", in *IEEE Signal Processing Magazine*, vol. 17, no. 3, May 2000.

[6] Qiao, D., Choi, S., Jain, A. and Shin, K., "Adaptive Transmit Power Control in IEEE 802.11a Wireless LANs", in *Proc. IEEE VTC 2003-Spring*, April 2003.

[7] Wang, K., Zong, P., Bar-Ness Y., "A Reduced Complexity Partial Sampling MMSE Receiver for Asynchronous MC-CDMA Systems", in *Proc. GLOBECOM'01 IEEE*, 2001.