# MC-CDMA Based IEEE 802.11 Wireless LAN

Georgios Orfanos
*Aachen Univ. of Technology – D-52074 Aachen, Germany*
*georgios.orfanos@comnets.rwth-aachen.de*

Jörg Habetha
*Philips Research Laboratories, D-52066 Aachen, Germany*
*joerg.habetha@philips.com*

Ling Liu
*Aachen Univ. of Technology – D-52074 Aachen, Germany*
*ling.liu@comnets.rwth-aachen.de*

## Abstract

*In this paper, a modified version of the IEEE 802.11a protocol is proposed and evaluated. We combine Multi-Carrier Code Division Multiple Access (MC-CDMA), a novel, high capacity multicarrier modulation technique, with the standard Medium Access Control (MAC) protocol of the 802.11 Wireless Local Area Network (WLAN). The suggested system utilizes spread spectrum to divide the channel bandwidth in parallel codechannels, and allows for a number of mobile terminals to share the medium in a more fair and efficient way. The proposed system has been evaluated using a protocol simulator, MACNET-2, and the performance results are discussed in this paper.*

## 1. Introduction

A multicarrier system is a system where several subcarriers are used for parallel transmission of data packets. A new multicarrier mechanism is applied to a Code Division Multiple Access (*CDMA*) network. In a CDMA network each data symbol is spread over a larger bandwidth, larger than the bandwidth needed for transmission. This allows to transmit with a spectral energy that is lower than in a non spread spectrum system, a fact that allows the use of parallel transmission channels, at the same time in the same frequency band. The data transmitted in the different channels can be distinguished by the use of a different spreading code for each channel. The data stream consists of a successive sequence of symbols or chips.

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

The MAC protocol of the IEEE 802.11a is based on the CSMA/CA protocol. The time needed, to listen to the medium is called InterFrame Space (*IFS*). The collision avoidance is based on a randomly operating backoff procedure [8]. The Distributed Coordination Function (*DCF*) of the standard [2] is commonly used. As shown in Fig. 1, the Mobile Station (*MS*), which has a data packet to transmit, draws a random number between 0 and CW, which determines the duration of the backoff timer in number of timeslots.

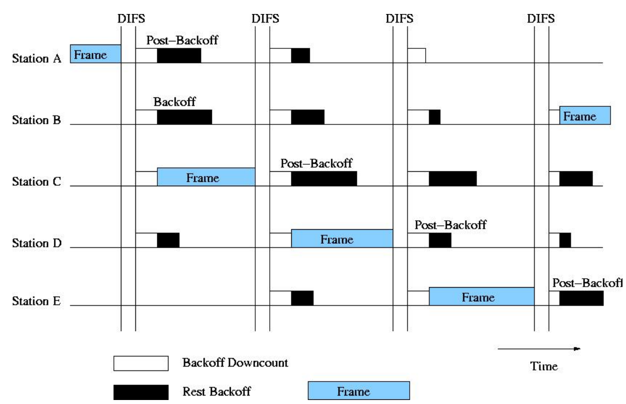


Figure 1. Distributed Coordination Function

The Contention Window (*CW*) has a minimum starting value of 15 and it doubles after a collision. Thus its value can rise up to 255 and is decremented after a successful transfer. The receiver acknowledges a successful transmission with an Acknowledgement (*ACK*) frame.

While the medium is free the MS counts down the backoff timer until it reaches zero and then after detecting the medium as free for a time of Distributed coordination function Inter-Frame Space (*DIFS*), the transmission starts. If during the countdown another MS occupies the medium all MSs in backoff interrupt their count down and defer until they detect that the medium is free for at least

DIFS. Then they continue the countdown of the backoff timer. The transmitter of the previous packet starts a new backoff procedure even if no other packet is waiting in its queue for transmission. The latter is called post-backoff.

In the following two sections a description on the modified physical layer is given, based on MC-CDMA, and the modified MAC protocol. Section 4 presents extensive simulation results and a calculation on the theoretical maximum achievable throughput. Section 5 summarizes this work with some concluding remarks.

## 2. Modification of the Physical Layer

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 SF fractions and each of them is transmitted in parallel in a different subcarrier. Since one subcarrier carries a fraction of the user's symbol, it can accept 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 Fig. 1 for a MC-CDMA system with SF=4.

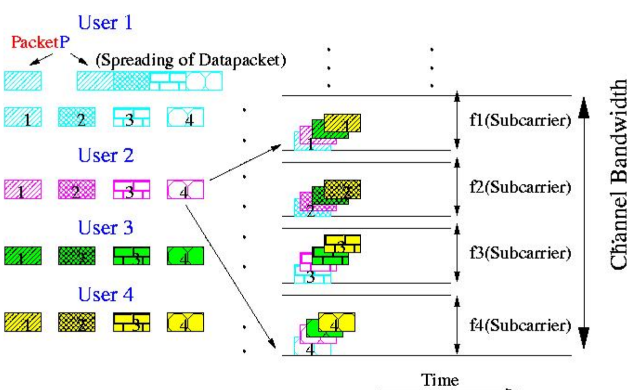


Figure 2. Principle of MC-CDMA.

As spreading sequences the orthogonal Walsh Hadamard codes of length 4 are used, leading to a maximum of 4 parallel code channels. Since the Walsh Hadamard Codes lose their orthogonality in asynchronous systems, 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.

Other parameters of the PHY layer have been chosen to be the same as in the standard 5 GHz OFDM based system. A convolutional encoder k =7 is used, and data packets are transferred using the QPSK ½ PHY mode, thus achieving a data rate of 12 Mbps. For the control packets, RTS, CTS and ACK, the standard [2] defines the use of a mandatory PHY mode, and for our simulations the QPSK ½ with 12 Mbps is used.

## 3. Modification of the MAC Protocol

The MAC protocol of the proposed system is based on the MAC protocol of the IEEE 802.11a WLAN, with the modifications needed to support the CDMA PHY Layer.

In this case the frequency channel is divided (from the use of MC-CDMA with SF = 4) into 4 parallel codechannels. Each of them can be accessed by the MS using the DCF, as described in the standard [2] [5].

A station ready to transmit has to select a codechannel. Initially this selection is done purely randomly. For later transmissions, the station does not select codechannels for which a Network Allocation Vector (*NAV*) is set.

After the station determines the medium as free for the duration of DIFS, it transmits an RTS packet to signal the intended transmission. All stations able to receive this control packet, and determining that they are not the intended receivers, set their NAV timer and defer from the medium in order not to interfere with the transmission. If the receiver of the RTS is idle and thus able to receive data, it responds with a CTS packet, after a time equal to the Short InterFrame Space (*SIFS*). Mobile stations which receive this CTS set their NAV timer as well. Then the sender can transmit its data packet after SIFS, which is acknowledged by the receiver in case of successful reception through an ACK sent with a delay of SIFS after the end of the reception as shown in Fig. 3. This is the procedure for a data transmission in every codechannel.

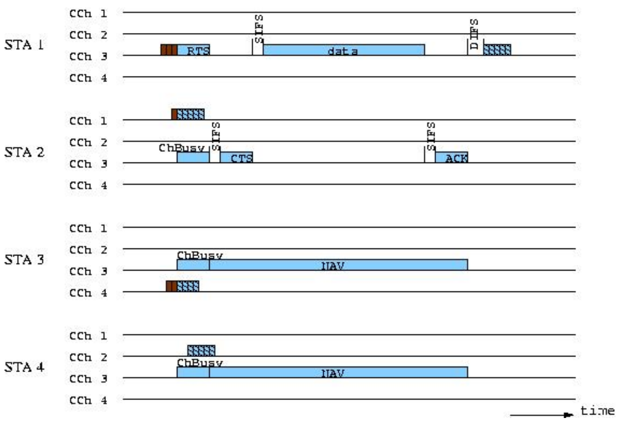


Figure 3. CSMA/CA with 4 parallel codechannels

In case two or more stations access the same codechannel on the same frequency band at the same time a collision occurs. Although the backoff mechanism provides a solution to resolve collisions, in scenarios with many stations, collisions are a limiting factor for the achieved throughput and delay. The proposed modification of the protocol has an advantage in this respect, since each frequency channel is divided into SF parallel codechannels, and only n/SF stations compete against each other in accessing this frequency channel. The collisions are therefore reduced allowing the use of a lower value for the minimum CW size.

From Fig. 3, it is obvious that each station occupies only part of the available resources. In a situation where only two stations are transmitting, each one in a different codechannel, two of the 4 codechannels remain idle. Additionally using a SF of 4 the duration for a packet transmission becomes 4 times longer, meaning a bigger delay for the next packet waiting in the queue. To overcome this problem the proposed protocol allows parallel transmissions in more than one codechannel. This means that a station with enough traffic, determining more than one codechannels as idle for a time DIFS, can use them to transmit more than one packet in parallel.

Power Control is done over the RTS CTS packets [9]. An RTS is send with the same transmission power 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 it, can calculate the path loss. According to the path loss, the interference status at the receiver and the mean Signal to Noise Ratio (*SNR*) of the last received packet of this connection the receiver might ask the transmitter to correct its transmission power by encoding such information in the CTS packet.

## 4. Simulative performance evaluation

The proposed system has been implemented in the MACNET-2 simulation tool to evaluate its performance, applying the parameters of Table 1.

Table 1. Simulation Parameters

| **Parameter** | **Value** |
|---|---|
| Max. TxPower | 17dBm |
| Spreading Factor | 4 |
| CWmin | 4 slots |
| CWmax | 255 slots |
| Number of Subcarriers | 48 Data + 4 Pilot |
| Subcarrier Spacing | 0.3125 MHz |
| Channel Bandwidth | 20 MHz |
| Carrier Frequency | 5.25 GHz |
| Noise Level | -93dBm |
| Path loss Factor | 3.5 |
| TxRate Data | 12Mbps |
| TxRate Control | 12 Mbps |
| Data Packet Length | 1024 Byte |
| RTS/CTS | enabled |
| Symbol Interval | 4 µs = 3.2 µ + 0.8 µs |
| Guard Interval | 0.8 µs |
| Preamble | 16 µs |
| Max. Propagation Delay | 0,15 µs |
| Max. Error on CDF | 2% |

Considering a complete transmission cycle, as shown in Fig. 4, a comparison between the maximum theoretically achievable throughput of the MC-CDMA and the OFDM based systems can be carried out.

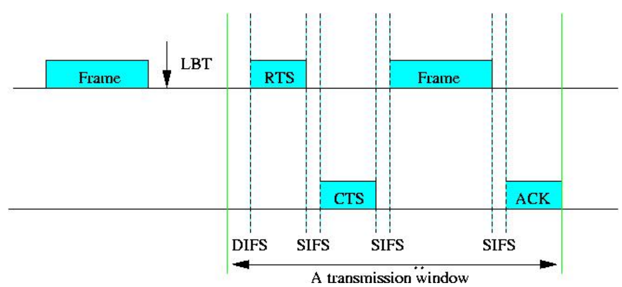


Figure 4. A complete transmission cycle

The time needed for a complete packet transfer in the IEEE 802.11 system, ignoring collisions and considering the average backoff interval, can be calculated as:

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

Table 2. Durations

| Parameter | Duration |
|---|---|
| SIFS | 16 µs |
| DIFS | 34 µs |
| aSlotTime | 9 µs |

Table 3. Information bits per OFDM symbol

| PHY mode | Information bits per symbol |
|---|---|
| QPSK ½ | 48 |
| 64 QAM ¾ | 216 |

Combining the parameters of Table 1 and 3 the number of OFDM respectably MC-CDMA (with SF= 4) symbols, required for the transmission of each frame can be calculated.

Table 4. Number of OFDM symbols per frame

| Frame Type | OFDM | MC-CDMA |
|---|---|---|
| RTS | 4 | 16 |
| CTS | 3 | 12 |
| DATA QPSK ½ | 179 | 713 |
| DATA 64 QAM ¾ | 40 | 159 |
| ACK | 3 | 12 |

Given the length of one symbol which is 4 µs for both systems, and that at the beginning of each frame a preamble and a signal field [2], are added; we find:

$$\Delta t_{OFDM} = 393{,}5\ \mu s$$
$$\rightarrow Throughput_{OFDM} = 1024 * 8 / 393{,}5\ \mu s = 20{,}82\ Mpbs$$
$$\Delta t_{MC\text{-}CDMA} = 1037{,}5\ \mu s$$
$$\rightarrow Throughput_{MC\text{-}CDMA} = 4*1024*8/1037{,}5\ \mu s = 31{,}58\ Mpbs$$

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

For the QPSK ½ respectably, we calculate the following throughput:

$$\Delta t_{OFDM} = 915{,}5\ \mu s$$
$$\rightarrow Throughput_{OFDM} = 1024 * 8 / 915{,}5\ \mu s = 8{,}95\ Mpbs$$
$$\Delta t_{MC\text{-}CDMA} = 3253{,}5\ \mu s$$
$$\rightarrow Throughput_{MC\text{-}CDMA} = 4*1024*8/3253{,}5\ \mu s = 10{,}07\ Mpbs$$

According to the above results the spectral efficiency in this case is 12,51 % higher for MC-CDMA.

For the performance evaluation of the proposed system, we use event-driven simulations to measure the throughput that is practically achievable. For the results concerning delays, we present the mean delays of the resulting stochastic data. .

The interference calculation plays a major role in the simulative performance evaluation. In our simulations interference is generated both from transmissions in the same as well as in other codechannels. This second kind of interference, Multiuser Interference (*MUI*), caused by loss of the Walsh-Hadamard code orthogonality due to the asynchronous transmissions, can be partly mitigated by the MMSE multi-user detector [3], applied in the stations´ receivers.

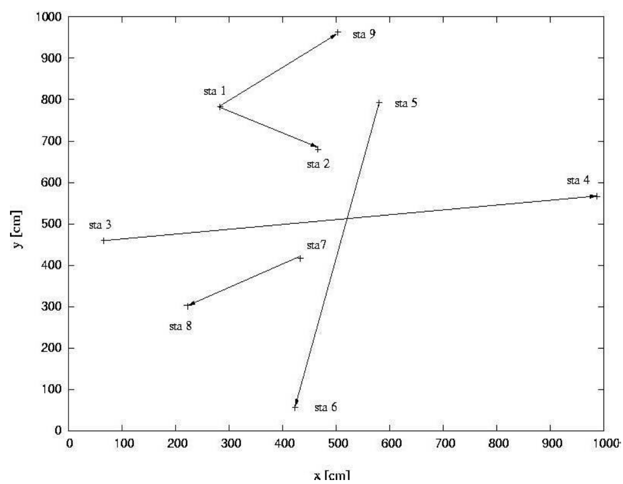


Figure 5. The simulated, random scenario

The simulated scenario, shown in Fig. 5, consists of randomly positioned MSs in an area of 10x10m, thus representing Small Office – Home Office (*SOHO*) environments. The pathloss coefficient $\gamma$ is 3.5 and the load generators are delivering Poisson traffic with variable rate and 1024 Bytes packet length. Fig. 5 shows the simulation results for the throughput achieved in a random scenario with 9 stations establishing 5 links, using the QPSK ½ mode.

The simulation results, presented in Fig. 6, show a maximum achievable throughput of 9,96 Mbps, very close to the theoretical maximum. This is an achievement of the parallel codechannels. In codechannels used by one connection there are no collisions and those who are being shared, can be used very efficiently since two connections alternate their transmissions in one codechannel.

Additionaly, as mentioned above, $CW_{min}$ is limited to four timeslots, thus maximizing the traffic. The mean idle time of the four codechannels under full load, was measured in the simulations to be 6%. From the graphs of Fig. 6, referring to the carried traffic of the single codechannels, it is obvious that they do not suffer from near far effects, due to the use of the MMSE multiuser detector.

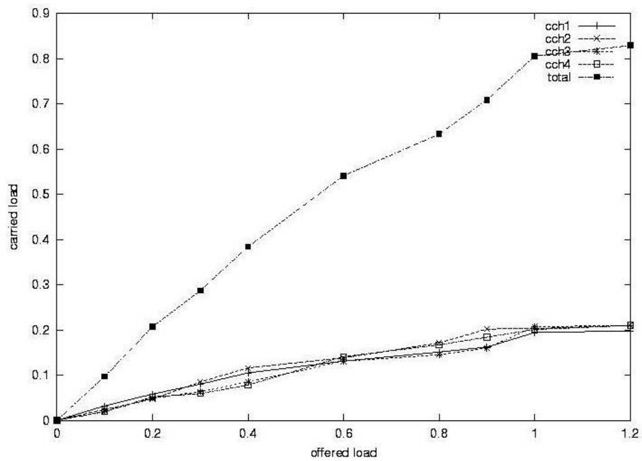


Figure 6. Carried throughput per CodeChannel (cch) and achieved system throughput vs. offered load

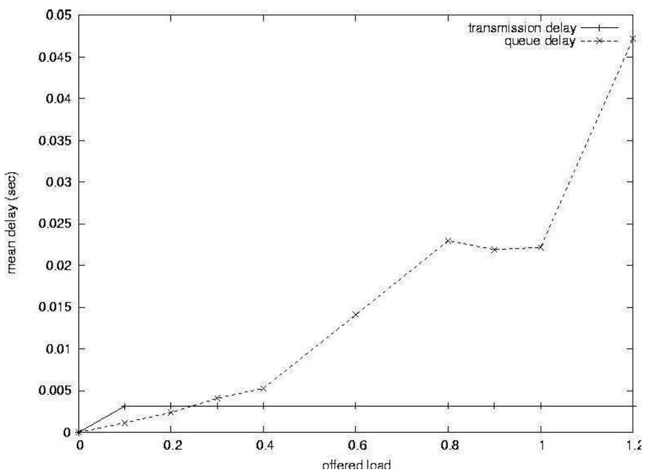


Figure 7. Mean queue and mean transmission delay vs. offered load

In Fig. 7 the simulated results for the packet delivery delays are presented. The queue delay is meassured as the time for which a packet stayed in the queue and the transmission delay expresses the time between the first transmission of a packet and the reception time of the corresponding ACK.

## 5. Summary

A modified version of the IEEE 802.11 system, based on MC-CDMA is presented and analytically compared with the standard IEEE 802.11a W-LAN [2]. The theoretical analysis and the simulation results demonstrate the ability of MC-CDMA to support Quality of Service (*QoS*) with respect to the throughput and the transmission delays. Even in high load scenarios the MC-CDMA based system manages to keep a low number of collisions and a minimum idle time for the channels.

Our future work, focuses on the further development of the MC-CDMA system, the expansion to multihop communication, and the design of an adaptive protocol to mitigate the problem of the near far effect with higher PHY modes, two parameters which are very important for the QoS support in modern multimedia home environments.

## 6. Acknowledgement

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

## 7. List of Abbreviations

| | |
|---|---|
| *ACK* | *Acknowledgement* |
| *cch* | *Codechannel* |
| *CDF* | *Complementary cumulative Distribution Function* |
| *CDMA* | *Code Division Multiple Access* |
| *CTS* | *ClearToSend* |
| *CW* | *Contention Window* |
| *DCF* | *Distributed Coordination Function* |
| *DIFS* | *DCF InterFrame Space* |
| *DS-CDMA* | *Direct-Sequence CDMA* |
| *FFT* | *Fast Fourier Transform* |
| *GHz* | *GigaHertz* |
| *IEEE* | *Institute of Electrical and Electronics Engineers* |
| *IFS* | *InterFrame Space* |
| *LRE* | *Limited Relative Error* |
| *MAC* | *Medium Access Control* |
| *Mbps* | *Megabits per second.* |
| *MC –CDMA* | *Multi-Carrier Code Division Multiple Access* |
| *MHz* | *MegaHertz* |
| *MMSE* | *Minimum Mean Square Error* |
| *MS* | *Mobile Station* |
| *MUI* | *Multiuser Interference* |
| *NAV* | *Network Allocation Vector* |
| *OFDM* | *Orthogonal Frequency Division Multiplexing* |
| *PHY layer* | *Physical layer* |
| *PHY mode* | *Physical Layer mode* |
| *QoS* | *Quality of Service* |
| *RTS* | *RequestToSend* |
| *SIFS* | *Short InterFrame Space* |
| *SF* | *Spreading Factor* |
| *SNR* | *Signal to Noise Ratio* |
| *SOHO* | *Small Office Home Office* |
| *WLAN* | *Wireless Local Area Network* |

## 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 to STANDARD FOR Telecommunications and Information Exchange Between*

*Systems – LAN/MAN Specific Requirements – Part 11: Wireless Medium Access Control (MAC) and physical layer (PHY) specifications : 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] Walke, B., *Mobile Radio Networks,* Chichester, Sussex, U.K.: *Willey & Sons Ltd.*, 2nd Ed., 2001.

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

[7] Schreiber, F., "Effective Control of Simulation Runs by a New Evaluation Algorithm for Correlated Random Sequences", in *AEÜ International Journal of Electronics and Communications,* vol. 42, no. 6, pp. 347-354, 1988.

[8] Walke, B., *Mobifunknetze und ihre Protokolle,* Stuttgart, Germany: *B.G.Teubner,* vol. 2, 2nd ed., 2000.

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