AN ADAPTIVE MAC PROTOCOL FOR MC-CDMA ADHOC WIRELESS LAN

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***Abstract*— Multi-Carrier Code Division Multiple Access (MC-CDMA), a novel, high capacity, multicarrier modulation scheme, is developing to a key radio transmission technology for future Wireless Local Area Networks (W-LANs). However in adhoc Code Division Multiple Access (CDMA) networks near-far effects can block a receiver due to high interference. These effects occur when a receiving station is closer to an interferer than to its corresponding transmitter. Accordingly, the receiver cannot detect the intended signal out of the received one and the data transmission fails. In this work, we present an adaptive Medium Access Control (MAC) protocol for adhoc MC-CDMA based W-LANs, based on the IEEE 802.11 MAC protocol. The new protocol has the ability to overcome the near-far-problem by employing a frequency adaptation method. The key of the proposed method is an interference estimate built at each receiving Mobile Station (MS). Aided by its estimate, a MS can calculate whether the Quality of Service (QoS) expectations of the incoming link can be accomplished. If the interference is too high, the receiving MS initiates a frequency channel change and informs the corresponding transmitter over the control packets about the Id of the new channel. It is shown that this concept can deploy the high capacity characteristics of MC-CDMA in wireless environments.**

Keywords: adaptive MAC, adhoc, interference aware protocol, MC-CDMA, near-far-effects.

I. INTRODUCTION

Multi-Carrier Code Division Multiple Access (MC-CDMA) has gained recently significant attention as demands for high data rates and Quality of Service (QoS) increase. Multicarrier techniques are generally robust against multipath fading and provide high spectral efficiency and interference rejection capabilities. MC-CDMA has several additional advantages, such as spectral diversity and immunity against impulse noise [7]. All these features make it a promising candidate for future wireless high capacity Wireless Local Area Networks (W-LANs).

The use of MC-CDMA physical layer, divides the frequency channel, from the point of view of medium access control (MAC) layer, to many channels separated by different spreading sequences, which we refer to as codechannels (cchs).

Each receiver receives multiple wideband signals and uses the code assigned to a particular cch, to extract the original signal from the received one. Signals from all other cchs will appear as interference after decorrelation, thus the power of other users' signals will determine the interference level at the detector [9].

Furthermore, in asynchronous multiuser environments, such as in a distributed adhoc network, the received signal consists of all active users' information spread on all subcarriers with timing misalignment. This timing mismatch destroys the orthogonalities among different subcarriers and different users' spreading codes [7], resulting mainly in Multiple Access Interference (MAI) and Inter-Carrier Interference (ICI), which raise further the noise level at the detectors.

Should a receiving station be closer to an interferer transmitting in different cch than to its corresponding transmitter, the signal of the stronger received cch raises the noise floor at the detector for the signal of the weaker cch, thereby decreasing the probability that the weaker signal will be accepted. This is called the "near-far-problem" [9]. In this work we address this problem.

An adaptive MAC protocol is presented which can mitigate the effects of the near-far problem. Based on an interference estimate built from the Minimum Mean Square Error (MMSE) detector a Mobile Station (MS) can determine if the QoS requirements of the link can be fulfilled. For the cases when the interference at a MS becomes very high, a transition of the link to another frequency channel can take place.

The above protocol is an enhancement of the basic protocol presented in [1]. It combines the MAC protocol of the IEEE 802.11a standard [5] with a MC-CDMA Physical layer (PHY layer), exploiting the advantages of the multichannel structure of spread spectrum techniques.

The analytical approach has shown that the system can achieve higher spectral efficiency than an Orthogonal Frequency Division Multiplexing (OFDM) based system [1]. The main advantage of a MC-CDMA compared to an OFDM based system in MAC level, is mainly the longer duration of frames. Spreading the symbols by a factor of four, increases the size of frames by an equal factor, while the preamble and guard intervals (SIFS, DIFS) remain constant. This results in an indirect reduction of the overhead needed for the transmission of the data packet, thus the spectral efficiency improves. For the further reduction of overhead, a higher Spreading Factor (SF) could be applied in channels with higher capacity, where the higher transmission rate compensates for the higher delays of spreading.

The analytical results have been verified by simulation results with the Quadrature Phase Shift Keying (QPSK) ½ PHY layer mode (PHY mode) in random scenarios. The simulations have also shown the collision avoidance ability and achievement of low latency, of this approach. For higher PHY modes though, the Multiuser Detector (MUD) applied at receivers can't cope with the high interference in an adhoc network. Receivers in longer links can easily be blocked from neighbouring transmitters in shorter links and opposite, as the required Signal to Interference and Noise Ratio (SINR) values for proper reception are high. For the 64 Quadrature Amplitude Modulation (QAM) ¾ PHY mode a SNR of 22 is required for a Packet Error Rate (PER) of 3%. This makes the application of an adaptive protocol which can solve the near-far-problem inevitable.

The rest of the paper is organized as follows: at first an introduction is provided on related work. Section III gives a description of the MC-CDMA technique and the MC-CDMA based W-LAN protocol. In section IV a detailed presentation of the frequency adaptation algorithm is given. Section V contains an extended presentation and discussion on simulation results. Section VI summarizes this work with concluding remarks.

II. Related Work

In literature, several approaches can be found where the influence of near-far-effects in a MC-CDMA system is studied and solutions are proposed. The main focus is on PHY layer and the receiver's design.

In [11] the impact of a Successive Interference Cancellation (SIC) and Parallel Interference Cancellation (PIC) detectors is discussed. The robustness of the detectors to near-far-problems is investigated, when QPSK modulation is applied. Simulations show that the SIC receiver outperforms the PIC receiver, but the performance of both degrades with the number of users. The complexity of this approach is high and the latency times of a SIC receiver in a fully loaded system could be a drawback for delay sensitive traffic.

In [10] the theoretical near-far resistance of the MMSE detector is derived. The results show that the MMSE detector can in general cope with near-far-problems, when Binary Phase Shift Keying (BPSK) modulation is applied. There is a tradeoff though, between the number of active users and the near-far ratio. The resistance becomes very poor in a fully loaded system when a near-far ratio of 20dB occurs.

In [7], [8] a partial sampling MMSE and an adaptive minimum Bit Error Rate (BER) detector were presented. With BPSK ½ and less than the maximum number of cchs active, the above solutions show a good performance. Furthermore in [12] and [13] complex receiver constellations are analysed and their performance with BPSK ½ is proven to approach the ideal maximum SINR receiver with perfect channel knowledge.

In general, the previous work focuses on PHY layer and the robust Phase Shift Keying PSK PHY modes. In [1], it is shown that the ad-hoc MAC protocol combined with the MMSE receiver doesn't face near far-problems when QPSK is used in Small Office/Home Office (SOHO) scenarios. These results comply with the investigations in [10] and [11]. The PSK PHY-modes are very robust, but cannot achieve high capacity. It is therefore necessary to design an interference aware MAC protocol, suited to MC-CDMA networks. Another approach to solve the near-far-problem with higher PHY modes from the MAC layer is not known to the authors.

III. MC-CDMA based W-LAN

A. PHY-layer

In MC-CDMA, each symbol of the output data stream of a user is multiplied by each element of the user's spreading code. The MC-CDMA chips are formed in this way and placed via Inverse FFT (IFFT) in several narrow band subcarriers. Multiple chips are transmitted in parallel on different subcarriers [3]. This method is called "frequency spreading".

Due to the Fast Fourier Transform (FFT) associated with OFDM, MC-CDMA chips are long in time duration, but narrow in bandwidth [3]. Consequently interchip interference is reduced, and synchronization is easier compared to other spread spectrum techniques.

In the proposed system a SF of 4 is chosen, thus the symbol of one user is divided into 4 fractions and each of them is transmitted in parallel in 4 different subcarriers. Since the channel utilizes 48 data subcarriers, another (48-4)/4=11 symbols of the same user can be transmitted in parallel to use the complete channel bandwidth.

From the system's point of view, one subcarrier carries a fraction of the user's symbol, and can therefore 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 4 fractions of 4 symbols that belong to 4 different users. See Fig. 1 for a MC-CDMA system with SF=4. As spreading sequences the orthogonal Walsh Hadamard codes of length 4 are used.

B. MAC-layer

The MAC protocol of the proposed system is based on the MAC protocol of the IEEE 802.11a WLAN, with modifications needed to support the MC-CDMA PHY layer. In this case the frequency channel is divided into 4 parallel codechannels (SF = 4). Each of them can be accessed from the MSs applying the Distributed Coordination Function (DCF), as described in the standard [2] [5].

A Mobile Station (MS) ready to transmit has to select a cch. For this selection two methods are possible:

- The first is to select a cch before every packet transmission. Initially this selection is done randomly. For later transmissions, the MS does not select cchs, which have already been reserved by other MSs (according to the standard the considered MS has set a Network Allocation Vector (NAV) for an occupied channel).

- The second method consists of selecting the cch with the least traffic, according to initial channel monitoring, and keeping this cch for the entire duration of the connection.

According to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) procedure, after detecting the medium idle for time DCF Interframe Space (DIFS), a MS defers for a certain time, called backoff, before transmitting its packet in order to avoid collisions. The duration of the backoff time is defined in [5]:

$$\text{Backoff Time} = \text{Random} \cdot \text{aSlotTime}$$

where Random is a uniformly distributed random integer number in interval [0, CW], and aSlotTime equals 9µs. The Contention Window (CW) has a starting value of 7, is doubled after a collision and reduced after a collision resolution.

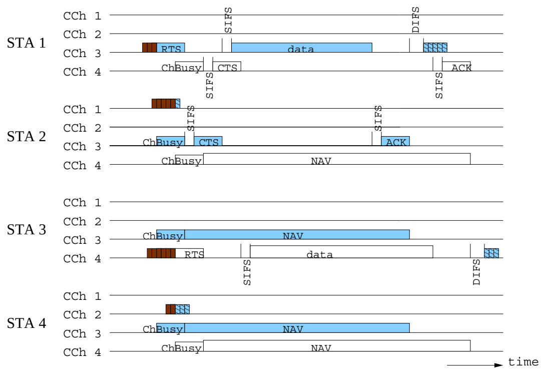

Figure 1. The multichannel approach for the IEEE 802.11 MAC

If the countdown of the MS backoff timer, carried out in steps of 9µs, is not interrupted by another transmission, the MS can initiate data transfer by transmitting a Ready To Send (RTS) packet in the selected codechannel, as depicted in Fig. 1. All MSs, which receive the RTS frame, and are not the intended receivers, interrupt their backoff down counts and set their NAV. The NAV denotes the time a MS must defer from the medium in order not to interfere with an ongoing transmission.

The intended receiver, if idle i.e. able to receive data, responds to the RTS frame with a Clear To Send (CTS) frame, after a time Short InterFrame Space (SIFS). The SIFS time is mainly the transceiver turnaround time, as each MS is assumed to be equipped with one transceiver. We assume that MSs are equipped with four correlators and thus can monitor all four cchs in idle state. Similar to the RTS frame, MSs which receive this CTS set their NAV timer as well.

The sender can now transmit its data packet after SIFS. The packet is acknowledged in case of successful reception by an Acknowledgement (ACK) frame, sent from the receiver with a delay SIFS after reception's end. Should two or more stations access the same cch, on the same frequency channel, at the same time, a collision occurs. A retransmission attempt is started with a new RTS frame after backoff. The above procedure is followed in every codechannel for each data transmission.

In CDMA networks one can say that the number of simultaneous transmissions can be increased until the SINR at the receivers decreases to a limit that sets them unable to correctly receive and detect the incoming packets. Therefore power control plays a major role for the system's capacity. In the proposed system power control is applied by means of an efficient algorithm proposed in [14], using the RTS, CTS frames as suggested in [6]. An RTS for a new data packet is sent with the same transmission power used in the previous transmission to that receiver. In case of an RTS collision the retransmission of the frame is done with doubled transmission power, etc.

IV. Frequency Adaptation Method

The proposed adaptation method of the MAC protocol to overcome the near-far-problem is based on frequency switching. The receiver forms an interference estimate with the help of MUD and calculates the maximum possible SINR (max SINR). If this max SINR doesn't satisfy the QoS expectation for the link, the receiver MS proposes a change of the frequency channel to the transmitter MS. With a special CTS frame it guides the transmitter to another channel, where the interference situation is better for the data transfer. Additionally, the previous channel is no longer used by both MSs and the other MSs remaining on that channel can improve their performance.

A. *Forming an interference estimate*

The received signal in an asynchronous MC-CDMA system can be described by [4], [7]:

$$r(t) = \sum_{k=1}^{K} \sqrt{a_k} b_k \sum_{m=1}^{M} c_{km} h_{km} e^{j2\pi(t-\tau_k)m/T} p(t-\tau_k) + \eta(t) \quad (1)$$

where K is the maximum number of active users, a_k the transmission power of the k-th user's symbol b_k , c_{km} the m-th element of the k-th spreading code, M the number of subcarriers, $p(t)$ a rectangular pulse over [0,T], τ_k the delay of the k-th user's signal and $\eta(t)$ denotes the additive white Gaussian noise. The Rayleigh fading process for the m-th subcarrier and k-th user is represented as:

$$h_{km} = \beta_{km} e^{j\varphi km} \quad (2)$$

with β_{km} a Rayleigh distributed and φ_{km} a uniform over $[0,2\pi)$ distributed variable.

In this case the SINR for user 1, at the detector, is given by the following expression [4], [8]:

$$SINR = \frac{\left|\sqrt{a_1}\mathbf{w}^H p_{K+1}\right|^2}{\mathbf{w}^H \Gamma \mathbf{w} + \left|\mathbf{w}^H \mathbf{P}_{K+1} \mathbf{A}_{\mathbf{K+1}}\right|^2} \quad (3)$$

where the matrices $\boldsymbol{P}$ and $\boldsymbol{p}$ are obtained from the decorrelator outputs as derived in [8] $\boldsymbol{w}$ is the weight vector of the MUD and $\mathbf{\Gamma}$ the covariance matrix of the Gaussian noise vector.

It is obvious from Eq. (3) and the analysis in [4] that a MS, which uses four correlators is able to calculate an estimate of the SINR according to Eq. (4). After estimating the SINR, the MS can estimate the mean interference during the packet reception for a known reception power.

B. Modifications of the frames

In order to make the exchange of the interference status between MSs possible, which is needed for the frequency adaptation algorithm, RTS and CTS frames have been extended by two more fields, *TxPow* and *IfPow*, as depicted in Fig. 2 and Fig. 3 respectively. In the field *TxPow* the transmit power of the current frame is encoded and *IfPow* carries information about the last estimate of mean interference at this MS, of the channel on which the data transfer takes place. The length of both fields is one byte each.

Octets:	2	2	6	6	1	1	4
	Frame Control	Duration	RA	TA	TxPow	IfPow	FCS

MAC Header

Figure 2. Extended RTS frame

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	Frame Control	Duration	RA	TxPow	IfPow	FCS

MAC Header

Figure 3. Extended CTS frame

C. The new frequency adaptation algorithm

The frequency adaptation algorithm is based on the RTS-CTS-Data-Ack transmission cycle. Let MS 1 (S1) denote the transmitter and MS 2 (S2) the corresponding receiver. Further variables needed for the algorithm are defined in Table I.

TABLE I. PARAMETERS FOR THE ADAPTATION ALGORITHM

Parameter	Value
P_{TX}^{S1}	Tx-Power of station S1
P_{TX}^{S2}	Tx-Power of station S2
P_{IF}^{S1}	Mean interferance estimate of S1 before the transmission of RTS
P_{IF}^{S2}	Mean interferance estimate of S1 before the transmission of CTS
P_{RX}^{RTS}	Rx-Power of the RTS frame in S2
P_{RX}^{CTS}	Rx-Power of the CTS frame in S1
$\max P_{TX}$	Maximum transmission power
$newFreqId$	Id of the new frequency channel

MS S1 transmits an RTS frame, using the extended frame format, Fig. 2. There the current values of P_{TX}^{S1} and P_{IF}^{S1} are set. MS S2 receives the RTS frame with power P_{RX}^{RTS} and decodes the values of P_{TX}^{S1} and P_{IF}^{S1}. S2 can now calculate the pathloss L between S1 and S2 as:

$$L = P_{TX}^{S1} - P_{RX}^{RTS} \quad (4)$$

Afterwards, S2 calculates the maximum possible SINR for packet reception under consideration of its actual mean interference estimate P_{IF}^{S2}, the pathloss L and the maximum allowed transmission power $\max P_{TX}$:

$$\max SINR = \max P_{TX} - L - P_{IF}^{S2} \quad (5)$$

MS S2 can now decide whether the packet transfer can take place under the current interference situation at S2 (P_{IF}^{S2}).

Two cases are possible:

a) $\max SINR \geq \min SINR$.

The data transfer can take place in the current frequency channel. S2 sends an extended CTS frame, as shown in Fig. 3, with the actual values of P_{TX}^{S2} and P_{IF}^{S2}.

Should the CTS frame be received correctly, S1 will transmit the actual data packet according to the protocol. In case of erroneous reception, the RTS retransmit timer of the MAC protocol of S1 will reach zero and S1 will start a retransmission attempt with a new RTS packet after having increased the CW by a factor of two.

b) $\max SINR < \min SINR$

where $\min SINR$ denotes a set threshold needed, according to the used PHY-mode, for the reception of the data packet with PER of, say less than 3%. In this case S2 changes the frequency channel with a certain probability, which in this work is set to 50%. The selection of the new frequency channel is done randomly out of the set of the system's channels.

The probabilistic change of the frequency channel is needed in order to prohibit unnecessary frequency changes and collisions owing to the near-far-problem in the new frequency channel. In scenarios with heavy load, it can occur that more than one receiver are blocked by other transmissions or are even blocking each other. If a link is diverted to another frequency channel, the interference situation is changed at once, and it might be then possible there for all other receivers to communicate with much less near-far-problems. If this is not the case other MSs will have to change the frequency channel, too.

The extended CTS frame is send to S1 using $\max P_{TX}$ and the robust BPSK ½ PHY-mode to ensure the correct reception. The fields P_{TX}^{S2} and P_{IF}^{S2} are filled with the current values of S2.

The Duration field is used in the IEEE 802.11 standard [5] to denote the duration of the data transfer after the end of the CTS frame, in microseconds. In case of a frequency change, S2 can use the Duration field to denote a frequency change and to encode there the new frequency channel id. This does not create inconsistencies to the receiver of the frame, since the small values in Duration field are not used by the standard [5].

After the transmission of the CTS frame, S2 changes to the new frequency channel and resets all its transmission relevant parameters:

$$P_{TX}^{S2} = startP_{TX} \qquad (6)$$

$$P_{IF}^{S2} = P_{NOISE} = -93dBm \qquad (7)$$

S1 receives the CTS frame with Rx-Power P_{RX}^{CTS} and decodes from the frame the values of P_{TX}^{S2} and P_{IF}^{S2}. Accordingly, S1 calculates the pathloss between S1 and S2

$$L = P_{TX}^{S2} - P_{RX}^{CTS} \qquad (8)$$

and the minimum achievable SINR under the current interference situation

$$\max SINR = \max P_{TX} - L - P_{IF}^{S2} \qquad (9)$$

S1 compares the values of $\max SINR$ and $\min SINR$ to decide about a frequency change. This operation is not really necessary since the information about the frequency change is also available from the Duration field of the extended CTS frame by S2, but it provides an additional control mechanism for the algorithm. S1 changes to the new frequency channel and resets its relevant parameters:

$$P_{TX}^{S1} = startP_{TX} \qquad (10)$$

$$P_{IF}^{S1} = P_{NOISE} = -93dBm \qquad (11)$$

S1 initiates a new transmission with a RTS packet in the new frequency channel after monitoring the channel for at least a period of five DIFS intervals in order to gain a picture of the interference situation in the new frequency channel.

V. SIMULATION RESULTS

For the performance evaluation of the proposed system, we use event-driven simulation to measure the throughput that is practically achievable in a given scenario. The parameters of the simulation setup are given in Table II.

Fig. 4 shows the simulated scenario consisting of 11 terminals operating 6 links in a 10mx10m area, addressing an SOHO scenario. Simulation is performed using the QPSK ½ PHY-mode (12 Mbit/sec)for control packets and the 64QAM ¾ PHY-mode (54 Mbit/sec) for data packets. The scenario presents the worst case operation with one large distance link competing to several short links, which leads to near-far-problems. Parallel transmission of a MS in more than on cch is not allowed in order to focus on the effects of the proposed new frequency channel adaptation method.

We assume that the oscillator offsets are small and do not cause any degradation to the system.

TABLE II. SIMULATION PARAMETERS

Parameter	Value
Max. TxPower	17dBm
start TxPower	6dBm
Spreading Factor	4
Cwmin	7 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	54Mbps
TxRate Control	12 Mbps
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
PDU Length	1024 Byte
Frequency Change Probability	50%
minSNR	24 dB
Number of Frequency Channels	2

The link from MS1 to MS2 (con1) takes place in cch 0, the link between MS3 and MS4 (con2) is placed in cch 1 together with the links of MS9 to both MS10 and MS11 (con5). MS5 communicates with MS6 (con3) in cch 2 and MS7 uses cch 3 for transmissions to MS8 (con4). The cchs where the MS initiate their transmissions are chosen randomly under the condition, that different links of the same transmitter are placed in the same cch.

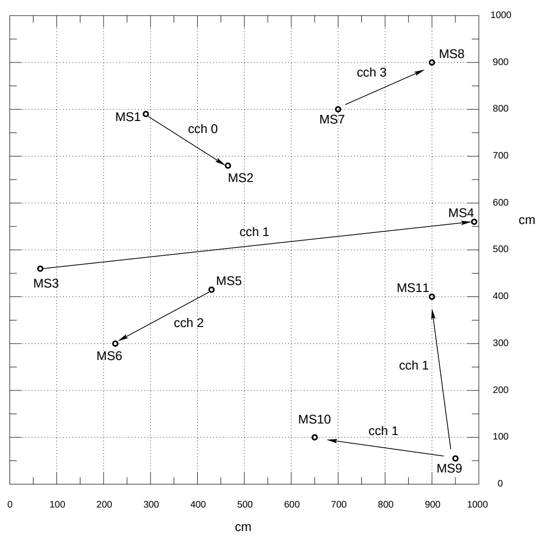

Figure 4. The simulation scenario

The minSNR value is set to 24 dB. For the user data PHY-mode considered and the packet length used, a value of 22 dB is sufficient for a PER of 3% [4]. The 2 dB margin is added in order to mitigate the effects of short term fading. Data packets are 1024 Bytes long and they are generated by Poisson load generators with variable mean interarrival time.

In Fig. 5 the carried traffic vs. the offered system load is given for both cases, of activated and deactivated frequency adaptation. When frequency channel adaptation is switched off, the saturation network throughput averages to 26.5 Mbit/sec. According to the analysis given in [1], the maximum achievable throughput of the system when data packets use the 64QAM ¾ PHY-mode and control packets use QPSK ½ is 31.58 Mbits/sec, for the given packet length. The 16% loss results from the near-far-problem.

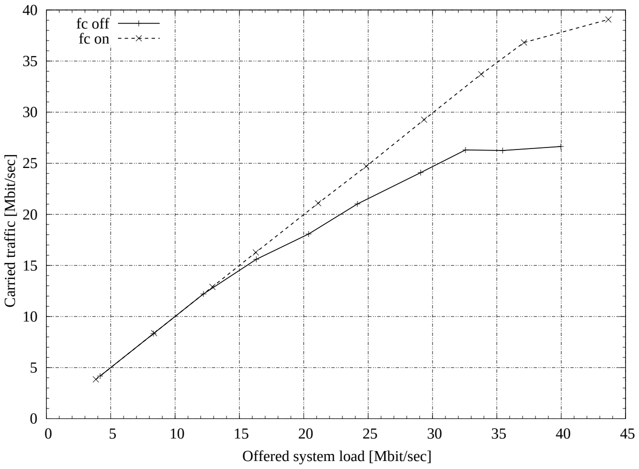

Figure 5. System throughput with and without frequency adaptation vs. offered system load.

As the offered load rises, the link from MS3 to MS4 is blocked by the other four links and the interference at MS4 prohibits the correct reception of the data packets. This is illustrated in Fig. 6, which presents the carried traffic per link vs. the offered load per link, when the frequency adaptation algorithm is disabled. Additionally, the attempts of MS3 to initiate a transmission by sending RTS frames with the maximum allowed transmission power block the packets of the nearby connections from MS1 to MS2, and MS5 to MS6. This effect lessens with time as the RTS frames of MS3 are unsuccessful in their correct reception by MS4, and must be then retransmitted with a CW that grows fast. (After short time the RTS frames of MS3 become rare and the remaining links operate without disturbances).

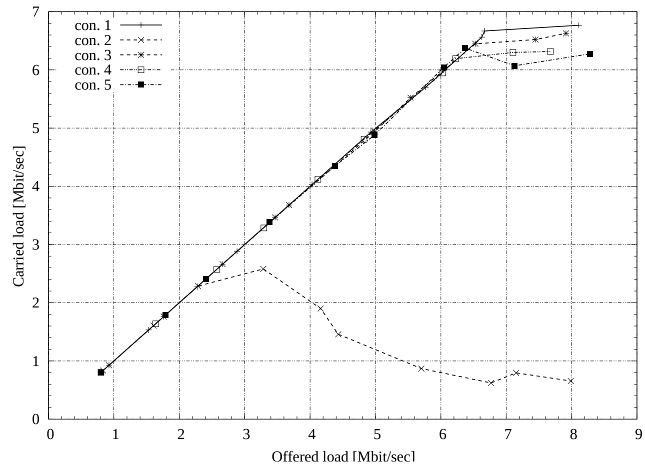

Figure 6. Throughput per link without frequency adaptation vs. offered load per link.

With frequency adaptation enabled, the link between MS3 and MS4 is diverted to the second frequency channel, thus all connections operate in an efficient manner. Since the above link is moved to another frequency channel, the network utilizes now four out of four cchs in the first channel and one in the second. The maximum achievable throughput per cch is a quarter of the frequency channel throughput [1], namely 7.895 Mbit/sec. In a system where 5 cchs are used, the theoretical maximum throughput is 31.58+7.895=39.475 Mbit/sec. As can be seen in Fig. 5 the carried system throughput in the simulation reaches 39 Mbit/sec.

Figure 7 also shows the carried traffic per link over the offered load per link but for the case of enabled frequency adaptation. The comparison between Fig. 6 and Fig. 7 illustrates the benefits of the proposed algorithm. In the absence of con2 from the first frequency channel, where the other links are operated, con2 operated at another frequency channel as well as the other links can linearly increase their throughput up to the maximum of 7.895 Mbit/sec/cch. This is an effect of MC-CDMA which divides the frequency channel in for parallel cchs. Since con2 is diverted in an other frequency channel the remaining 4 links are established one in each of the 4 cchs thus not competing with each other. The outcome is that each connection can fully utilise the resources in one cch.

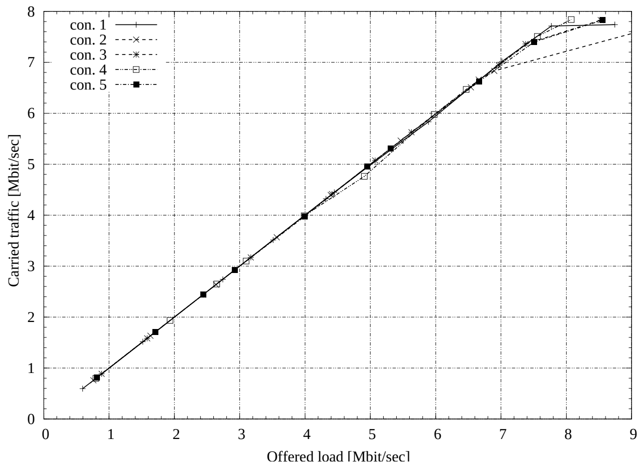

Figure 7. Throughput per link with frequency adaptation vs. offered load per link.

It is worth noting that Fig. 7, as well as all other figures referring to results with enabled frequency adaptation, present the packet throughput in stationary operation of the adaptation algorithm. As the time duration for the system to become stationary we define the duration until the last frequency change has been performed and no further channel changes occur. The network behaviour before stationarity is the same as the one when the algorithm is not applied. In stationary operation, the throughput maximises, the service times minimise, whilst the queuing delays reduce, but still depend on the duration until stationarity of the algorithm has been reached, as will be shown from the results.

Figure 8 depicts the mean queuing delay of all successfully transmitted packets per link over the offered load per link, without frequency adaptation. The queuing delay is defined as the delay between the arrival time of a packet at the MS from the load generator, until the first RTS frame transmission for this data packet. Looking at con2 which has a different behaviour than the other connections, as the load increases from 2.4 to 3.2 Mbit/sec, the queuing delay increases from 2msec to 90msec. This is due to the fact that con2 with increased load is more and more blocked by the other links, see also Fig. 6. It is therefore expected for con2, to suffer a high queuing delay. Additionally, some successful transmissions on con2 occur after some retries with a higher CW size, when the other connections are not active due to small load.

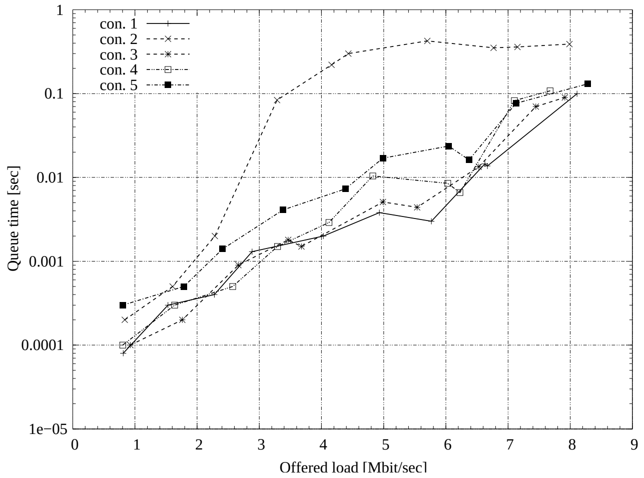

Figure 8. Mean queuing delay of successfully transmitted packets per link vs. offered load per link without frequency adaptation.

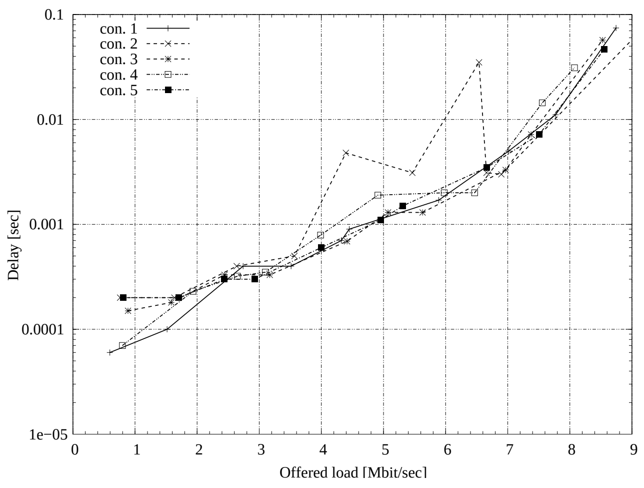

Figure 9. Mean queuing delay of successfully transmitted packets per link vs. offered load per link with frequency adaptation.

For all other links the queuing delay increases with the load as expected. Some decrease occurs for con1 and con3 at about 5.5 Mbit/sec and for con4 and con5 at about 6.5 Mbit/sec, respectively. These decreases result from con2 becoming stepwise inactive and the remaining links take advantage of both, unused resources of the blocked link and less interference in the network. These advantages are realised randomly by the two transmitters and disappear as the offered load approaches its maximum of > 7 Mbit/sec/con.

In Fig. 9, the queuing delay under frequency adaptation is presented, showing a progressive increase with the offered load. Compared to the delay without adaptation, an order of magnitude is gained for con2.

The curve for the mean queuing delay of con2 in Fig. 9 is very interesting for the system's analysis. The curve shows a progressive increase with the offered load, similar to the other curves, but two peaks occur. These peaks are related to the duration until network stationarity, when applying the adaptation algorithm, and affect mainly con2 as this is the link involved.

Figure 10 presents the duration until the steady state of the network, is reached when using the frequency adaptation algorithm. In addition the mean queuing delay of all successfully transmitted packets of con2 is shown, with the adaptation method enabled. The duration until steady state depends on the offered load and has random values, as the algorithm is probabilistic. For an offered load more than 3.5 Mbit/sec it doesn't exceed 170msec for a frequency change probability of 50%, in our simulations. For smaller loads it can take up to 350 msec, but doesn't affect the connections' queuing delay characteristics, see Fig. 9.

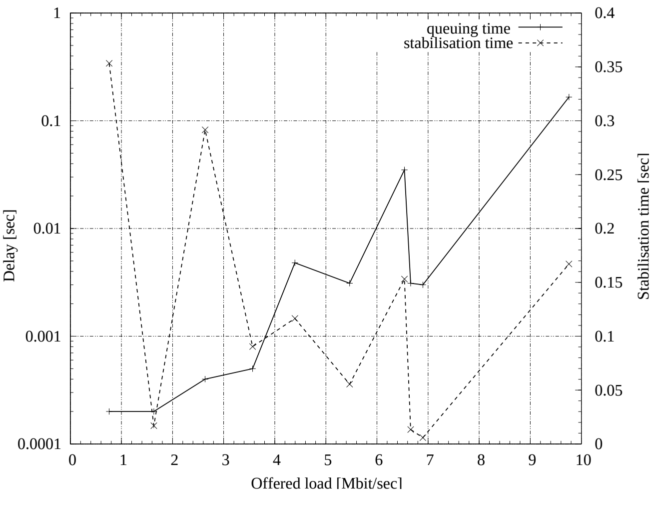

Figure 10. Duration until steady state and mean queuing delay of successfully transmitted packets, under frequency adaptation for con2.

The correlation of the two curves in Fig. 10 for medium and high offered load is obvious. For offered load up to 3.5 Mbit/sec, the duration until steady state does not affect much the mean queuing delay of con2 as the load is small and the link can easily transmit the few gathered packets in the queue after switching to the new channel. As the offered load increases the number of packets that accumulate in the queue of transmitter MS3 becomes large. After having changed the channel MS3 must transmit both the newly arriving and the buffered packets as well. This task is achievable since for medium to high loads the algorithm needs less than 170msec to stabilise. The longer the duration until steady state lasts the more packets are collected in the buffer. The MS then needs more time to process these packets increasing the queuing delays of con2.

Figure 11 presents the mean service time of successfully transmitted packets per link, with disabled adaptation algorithm. The service time is measured as the duration between the first RTS frame transmission corresponding to one data packet, and the arrival of the ACK for this packet at the transmitting MS.

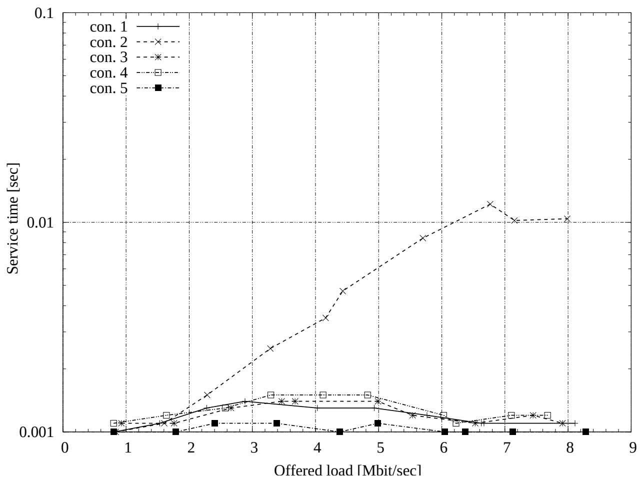

Figure 11. Mean service time of successfully transmitted packets per link vs. offered load per link without frequency adaptation.

In Fig. 11 con1, con3, con4 and con5 have almost a constant service time around 1,5 msec. For medium load some collisions occur as a result of the high interference from con2 that disappears under high load since con2 gets blocked then con2 experiences with increasing load continuous increase of its service time due to increased number of collisions. Multiple collisions of RTS frames increase a lot the CW of MS3. This, in conjunction with the high traffic of MS9 operating in the same cch, doesn't leave any chance to MS3 for transmissions. Shortly before MS3 is blocked, few packets come through, with service time of up to 180 msec for the high load cases.

In the case of enabled frequency channel adaptation, the service time for all links is constant as no collisions occur any more. While in the OFDM based W-LAN four transmitters would compete with each other for the same channel, in MC-CDMA based systems with SF=4 the competition for one cch is reduced by a factor of four. The probability of collision becomes very small. The 1 msec service time complies with the analytically calculated service time of 1.03 msec with average backoff [1].

VI. CONCLUSION

We presented and evaluated an adaptive MAC protocol for MC-CDMA adhoc W-LANs that reduces substantially collisions caused by the near-far-problems. A receiving MS calculates an interference estimate and decides whether the QoS expectation of the incoming link can be accomplished. If the interference is too high, the receiving MS initiates a frequency channel change and informs the corresponding transmitter by means of a control packet about the id of the new channel. Simulation results show the success of this approach, even in worst case scenarios, which allows the MC-CDMA network to reach the analytically calculated maximum throughput and a collision free operation.

Our future work focuses on the development of the MC-CDMA system and its expansion to multihop communication, which is very important for the QoS support in modern multimedia home environments.

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