Efficient Power Control for MC-CDMA based W-LANs

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***Abstract* - Besides reducing energy consumption, efficient power control (PC) is essential for a good performance of wireless networks. This applies especially to code division multiple access (CDMA) systems, where the capacity is limited by receiver's ability to extract the intended signal from the received one. In such a network, a reliable PC function combined with a good multiuser detector (MUD) can boost its performance. In this paper we present and evaluate a new PC method based on the interference estimation by mobile stations, using the minimum mean square error (MMSE) MUD. The system for which we provide simulation results, is a modified version of the IEEE 802.11a wireless local area network (W-LAN), which uses the distributed coordination function (DCF), adapted to spread spectrum systems, with a multi-carrier code division multiple access (MC-CDMA) physical layer.**

Keywords; MC-CDMA; IEEE 802.11a/e; power control; multiuser detection

1. Introduction

In code division multiple access (CDMA) networks 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 this paper we propose a new power control algorithm for Multi-Carrier Code Division Multiple Access (MC-CDMA) based Wireless Local Area Networks (W-LANs), over the Ready To Send (RTS), Clear To Send (CTS) packets. The algorithm makes use of the Minimum Mean Square Error (MMSE) Multi-User Detector (MUD) properties in order to rapidly adjust the transmission power of the Mobile Stations (MSs). The achieved enhancement of the application of the proposed algorithm to a MC-CDMA based W-LAN is shown in the simulated results.

1.1. Related Work

A lot of research has been done in recent years, on power management for W-LANs. One way to save power is to force mobiles to enter a "sleep" modus, as suggested in [13] and [14].

Another approach for power shaving is to adaptively adjust the power for the frame transmissions. The reduced interference during network operation is another achievement of these algorithms. In [15] an algorithm was suggested, where the transmit power of data frames is adjusted with the help of an enhanced RTS/CTS handshake. In [16] the authors propose a power saving method which both adjusts the transmission power of data packets and their size. The method of [15] was further developed in [9], where the authors combined PC with link adaptation.

In this work we extend apply the PC method proposed in [15] in a MC-CDMA network. Needed information for PC is exchanged in the RTS/CTS frames. The key idea is to use the MUD at the stations' receivers to build an accurate interference estimate, instead of emission measurements during idle times. This has the privilege of a fast transmission power adjustment, according to a good metric of the interference at the receivers', which can boost the networks performance.

The application of the proposed algorithm doesn't raise the system's complexity. It uses a feature of the MUD to enhance the network's performance.

1.2. Organisation

The rest of the paper is organized as follows: at first an introduction is provided on the MC-CDMA technique, the MC-CDMA based W-LAN protocol and MMSE multiuser detector functionality. In the section II a detailed presentation of the Power Control (PC) algorithm is given. Section III contains a short description of the simulation environment, which is used for the performance evaluation of the protocol and the proposed algorithm. In section IV, simulation results are presented and discussed. Section V contains concluding remarks and future tasks.

2. The MC-CDMA Wireless LAN

2.1. MC-CDMA

MC-CDMA has gained recently significant attention and has become a promising candidate for future wireless high capacity communication networks. Multicarrier techniques are generally robust against multipath fading, provide high spectral efficiency and interference rejection capabilities. MC-CDMA has several other advantages, such as spectral diversity and immunity against frequency selective fading and impulse noise [11].

Each symbol of the data stream of one user is multiplied by each element of the same spreading code and is placed in several narrow band subcarriers. Multiple chips are not sequential, but transmitted in parallel on different subcarriers [5]. In MC-CDMA one single data symbol is spread in frequency [3]. Such a system with spreading factor (SF) four is presented in Fig. 1.

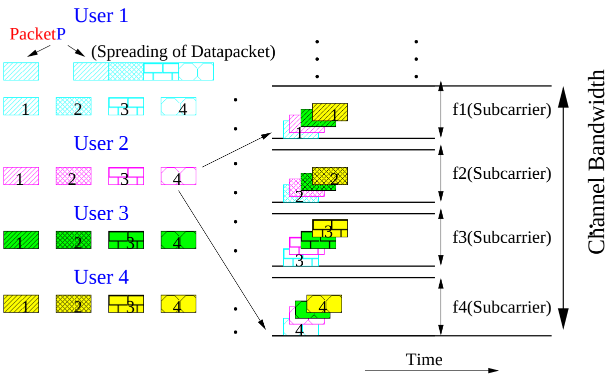

Figure 1: MC-CDMA with SF= 4

2.2. The MC-CDMA based Protocol

The protocol of the proposed system is based on the Medium Access Control (MAC) protocol of the IEEE 802.11a WLAN, with some modifications needed to support the CDMA Physical Layer (PHY layer).

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.

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 RTS packet (Fig. 2).

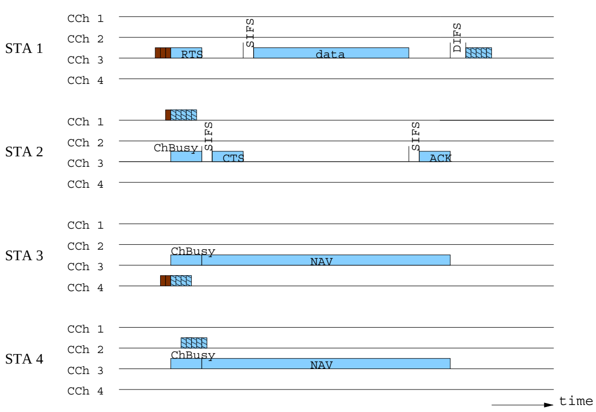

Figure 2: CSMA/CA with four codechannels

All stations that receive this control packet, and are not the intended receivers, set their 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 CTS packet, after a time called Short Inter-Frame Space (SIFS). In case the receiver is busy the RTS transmission is repeated after a new backoff. 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 Acknowledgement (ACK) also a SIFS time after the end of the data frame. The above standard Distributed Coordination Function (DCF) procedure is followed in every codechannel for each data transmission.

2.3. The MMSE Multiuser Detector.

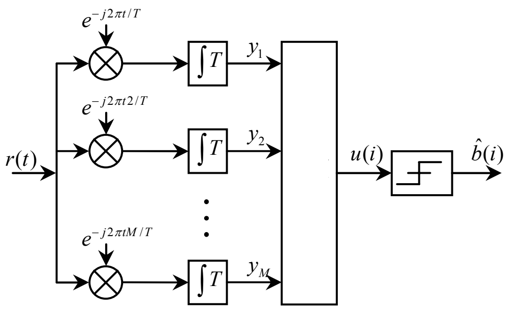

Figure 3 : MUD diagram

In an asynchronous multi-access MC-CDMA system like the one presented in [1], the received signal consists of all active users' information. This timing mismatch destroys the orthogonality of different users' spreading codes leading to multiple access interference (MAI) [5]. For this reason in [1] a linear MUD is applied at the receiver's side based on the MMSE criterion. A MMSE receiver combines both good performance and simplicity of implementation.

As seen in the diagram of the MUD in Fig.3, in a linear multiuser detector the demodulator outputs y_m are multiplied with a decision variable w_m which is used for optimizing the decision of the detector on the transmitted symbol and mitigate the effects of the channel. In case of the MMSE MUD, the optimum weight matrix for a given set of delays τ_K and fading parameters β_{km} is selected to minimize the mean square error of the detector:

$$MSE(\tau,\beta) = E\left\{\left(\mathbf{w}^H y - b_k\right)^2\right\} \quad (1)$$

where b_k is the the k-th user's symbol.

3. Power Control

3.1. Estimation of the Interference Situation in each Station

In order to achieve an optimum PC, mobile stations should be able to estimate the interference they sense upon receiving a frame. One possible way to achieve this, is to estimate the expected interference according to the mean interference during the reception of previously receives frames, P_{MeanIF}. The value of P_{MeanIF} is calculated in each MS separately, as given in (2).

$$P_{MeanIF} = \begin{cases} P_{LastIF} & , P_{MeanIF} = 0 \\ 0,75 P_{MeanIF} + 0.25 P_{LastIF} & , \; else \end{cases} \quad (2)$$

The interference during the last received frame, is weighetd with 25% since this is the most actual value.

The value of the mean interference, during the reception of one frame, can be calculated by the MSs from the estimate of the mean SINR of that frame. Latter can be calculated with the help of the MUD:

The received signal can be described from the following equation:

$$r(t)=\sum_{k=1}^{K}\sqrt{a_k}\,b_k\sum_{m=1}^{M}c_{km}h_{km}e^{j2\pi(t-\tau_k)m/T}\,p(t-\tau_k)+\eta(t) \quad (3)$$

where K is the maximum number of active users, a_k the transmission power of the k-th user's symbol b_k , M the number of subcarriers, $p(t)$ a rectangular pulse over [0,T], τ_k the delay of the k-th user 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:

$$h_{km}=\beta_{km}e^{j\phi km} \quad (4)$$

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

In this case the SINR can be given from the following expression [11],[12]:

$$SINR=\frac{\left|\sqrt{a_1}\,\mathbf{w}^H p_{K+1}\right|^2}{\mathbf{w}^H\Gamma\mathbf{w}+\left|\mathbf{w}^H\mathbf{P}_{K+1}\mathbf{A}_{\mathbf{K+1}}\right|^2} \quad (5)$$

where the matrices ***P*** and ***p*** are obtained from (3) as derived in the appendix and ***w*** is the weight vector of the MUD.

It is obvious from eq. (5) and the analysis in the appendix, that a station which uses four correlators is able to calculate an estimate of the SINR according to eq. (5). After estimating the SINR, the MS can estimate the mean interference during the packet reception for a known reception power.

In order to make the exchange of the interference status between MSs possible, which is needed for PC, RTS and CTS frames had to be extended with two more fields, *TxPow* and *IfPow*, as depicted in Fig. 4 and Fig. 5. In the field *TxPow* the transmit power of the current frame is encoded and *IfPow* carries information about the last estimate of mean interference for this station at the channel on which the data transfer takes place. The length of each field consists of one byte.

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

MAC Header

Figure 4: Extended RTS frame

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

MAC Header

Figure 5: Extended CTS frame

3.2. Power Control Algorithm

As mentioned above the PC algorithm is based on the RTS-CTS-Data-ACK packet transfer cycle. Let station 1 (S1) denote transmitter and station 2 (S2) the corresponding receiver. Further variables needed for the algorithm are defined in Table I. All values are given in dBm.

Table I: Power Control Parameters

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 transnission of RTS
P_{IF}^{S2}	Mean interferance estimate of S1 before the transnission of CTS
P_{RX}^{RTS}	Rx-Power of the RTS frame in S2
P_{RX}^{CTS}	Rx-Power of the CTS frame in S1

Additionally each MS uses a fixed threshold *minSINR* (set in dB), giving the minimum needed value of SINR, for the reception of the packets. The value of this threshold is chosen, depending on the used PHY layer mode (PHY mode), for the Packet Error Rate (PER) to be 1%.

Figure 6 provides an overview of the PC algorithm. Station S1 transmits an RTS frame, using the extended frame format of Fig. 4. In the frame the current values of P_{TX}^{S1} and P_{IF}^{S1} are set. Station 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:

$$L = P_{TX}^{S1}-P_{RX}^{RTS} \quad (6)$$

Afterwards, S2 calculates the minimum needed receive power for S1 under consideration of the actual mean interference estimate P_{IF}^{S1} and the set threshold *minSINR*:

$$\min P_{RX}^{S1}=\min SINR+P_{IF}^{S1} \quad (7)$$

From (6) and (7) the minimum needed Tx-Power for S2 can be calculated:

$$P_{TX}^{S2}=\min P_{RX}^{S1}+L \quad (8)$$

This Tx-Power is saved in S2 and used for coming transmissions to S1.

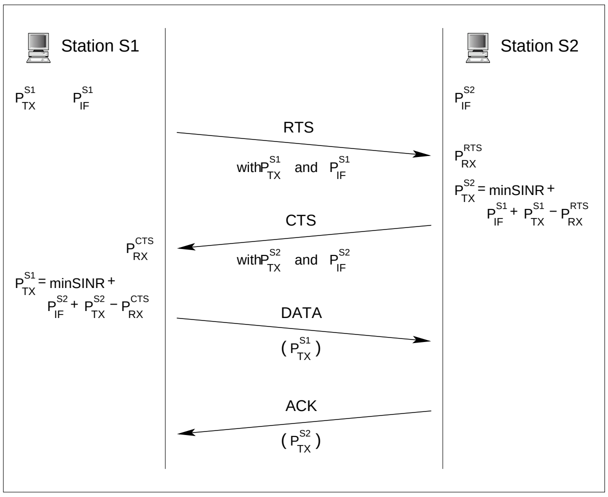

Figure 6: Power control algorithm

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:

$$L = P_{TX}^{S2} - P_{RX}^{CTS} \quad (9)$$

and the minimum needed Rx-Power for S2:

$$\min P_{RX}^{S2} = \min SINR + P_{IF}^{S2} \quad (10)$$

From (9), (10), the Tx-Power for S1 can be calculated:

$$P_{TX}^{S2} = \min P_{RX}^{S1} + L \quad (11)$$

The calculated Tx-Power is saved in S1 and used for oncoming transmissions to S2.

After receiving the data packet, S2 transmits the ACK with the Tx-Power calculated before.

It is though possible that S2 cannot receive correct either the RTS or the data packet (no CTS or ACK arrives in S1) due to high interference. In this case, S1 repeats the transmission with double Tx-Power:

$$P_{TX}^{S1} = P_{TX}^{S1} + 3dBm \quad (12)$$

The successful reception of a frame follows an update of P_{MeanIF}.

4. Simulation Environment

the performance analysis of wireless communication systems, 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). An overview of the simulation environment is given in Fig. 7.

The above described algorithm, together with the modified protocol [1], are formally specified in SDL which is able to bind C++ functions from the user interface, in form of Abstract Data Types (ADT). The simulation control section manages the initialization, control and the event driven scheduler of the simulator. It is also responsible, for the assignment of the user specified values to the system parameters, and the periodic update of the output files. The load generators are implemented with the help of SPEETCL and offer load defined by type, packet length and mean interarrival time, which can be set for each station individually.

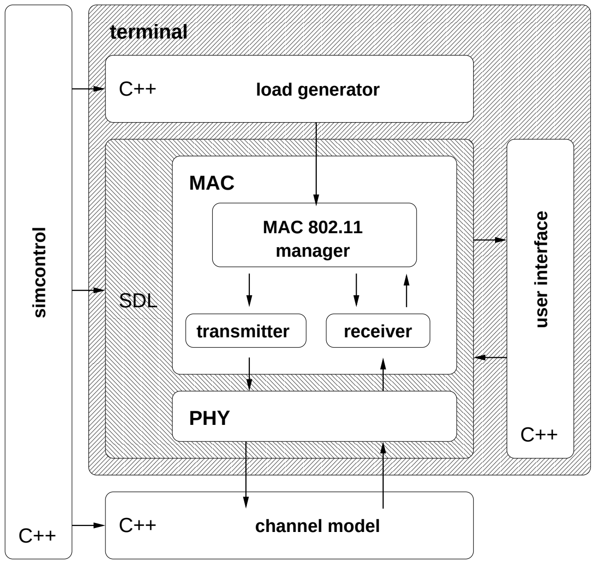

Figure 7:The simulation environment

Coding and mapping of the information bits in modulated symbols take place in PHY layer. In addition MC-CDMA spreading is performed, then coded Orthogonal Frequency Division Multiplex (OFDM) symbols are built and the cyclic prefix of 0,8 us is added. Adequate functions for the reverse operations exist at the receiver’s part. The channel is used to connect different MS entities providing different models. For the presented simulations a pathloss coefficient of 3.5, and Rayleigh fading according to the BRAN channel A parameters [10] are used. These models provide measures of the received power and the interferences at the receivers which are used to calculate the SINR and further the PER.

Finally, the SDL code is translated to C++ code with the use of the SDL2SPPETCL tool, which has been developed together with SPEETCL in the Chair of Communication Networks.

5. Simulation results and evaluation

he performance evaluation of the proposed system, we use event-driven simulations to measure the throughput that is practically achievable. For the evaluation of delay measurements, the Least Relative Error (LRE) algorithm [7] is used with maximum relative error of 2%. Further parameters of the simulation setup are given in Table II.

Fig. 8 shows the simulated scenario consisting of 9 terminals establishing 5 links in a 10mx10m area, addressing Small Office-Home Office (SOHO) scenarios. Simulations are performed using the QPSK ½ PHY mode for both data and control packets. Connections from station 1 (S1) to S2 and S1 to S9 take place in codechannel (cch) 1, the connection from S3 to S4 in cch 2, connection from S5 to S6 in cch 3 and connection from S7 to S8 takes place in cch 4. The *minSNR* value is set to 12 dB. For this PHY-mode and the used packet length a value of 9.5 dBm is sufficient for the PER to be zero. The 2.5 dB margin is added in order to mitigate the effects of short term fading.

Table II: 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
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

In Fig. 9 the carried system load vs. the offered load is given for the cases of both activated and deactivated power control. The offered load is a percentage of the channel capacity, which is for QPSK ½ 12Mbit/s. The system's performance with PC is almost 100% better than without. In this case the maximum achieved throughput is 9.8 Mbit/s, which corresponds to 96% of the theoretical maximum [1]. The throughput loss when PC is deactivated is a result of the near-far-effect. This effect occurs when an interferer is closer to a receiving station than it's corresponding transmitter. Accordingly the receiver cannot detect the intended signal out of the received one and the data transmission fails.

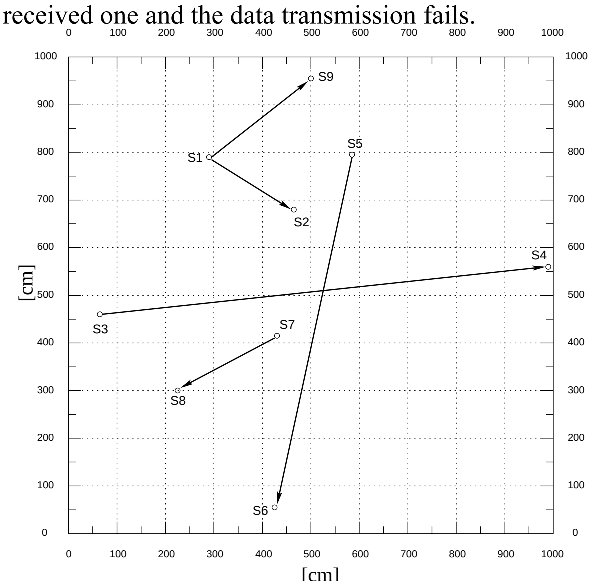

Figure 8: SOHO simulation scenario

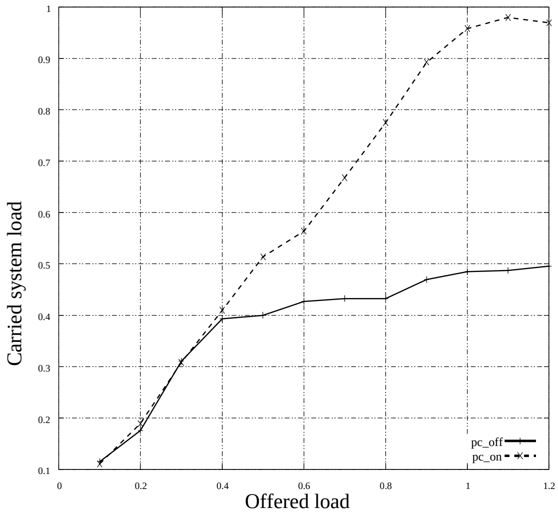

Figure 9: System throughput

This effect as well as the contribution of PC to its solution can be better depicted from the next figures. Fig. 10 gives the carried load per codechannel without PC. All stations use the maximum transmit power of 50mWatt (17dBm). In this case, the long distanced transmissions, S3 → S4 and S5 → S6, suffer from high interference. Even with the robust PHY-mode of QPSK ½ no data packet can be carried from these connections. At the same time, short distance connections run without problems and as can be seen from the diagram, the corresponding codechannels (cch1 and cch4) achieve almost the maximum throughput (each a quarter of the channel throughput).

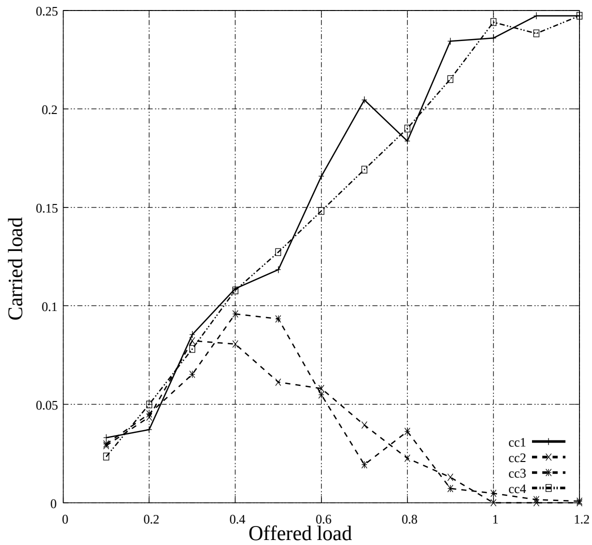

Figure 10: Throughput per codechannel without power control

Fig. 11 presents the carried load per codechannel with the offered load for the case that PC is activated. The output powers of the transmitting stations are now adjusted by the PC algorithm to the following:

S1 -32.0dBm
S3 -25.3 dBm
S5 -27.4 dBm
S7 -33.4 dBm

It can be seen from Fig.11 that after these power arrangements no connection is blocked and the system achieves in every codechannel high throughput.

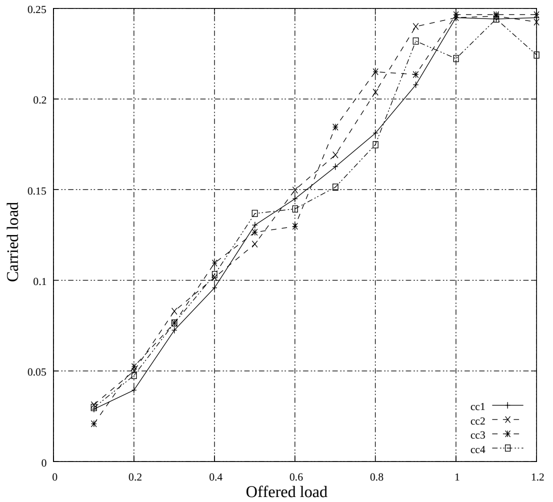

Figure 1. Throughput per codechannel with power control

In Fig. 12 the mean (over all successfully received packets) waiting and service time is shown with the offered load. When PC is activated the service time is almost constant whereas the waiting time increases with the load as expected. Turning PC off, the service time is not affected and remains constant since no collisions occur. It must be noticed that when the offered load increases to 0.4 or more, this service time refers to 3 of the 5 connections. The packet transfer for the others has been blocked due to the near-far effects.

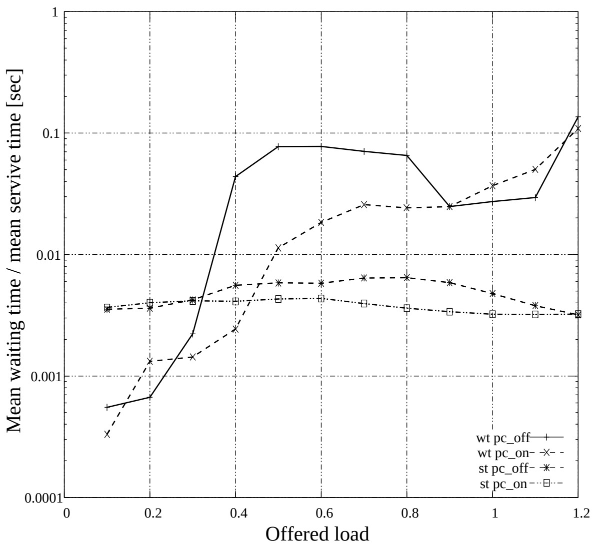

Figure 11: Delay measurements

The graph for the mean waiting time without PC is very interesting for the system's analysis. The waiting time delay increases rapidly for offered load between 0.2 and 0.5, as the two long distanced connections have a decreasing chance to transmit a packet. Successful transmissions for these connections occur after some retries with a higher Contention Window (CW), when the other two connections are not active due to small load. This leads to high queue delays. The fall of the waiting time curve for 0.9 offered load is due to the blocked long distanced connections, which from now on do not contribute to the waiting time measurements, as no more frames are successfully transmitted by them.

6. Conclusion

In this work we presented a new PC method based on the interference estimation by mobile stations, using the MMSE MUD. The algorithm is implemented in the MACNET2 protocol simulator and its performance is tested on a modified version of the IEEE 802.11 [1], based on MC-CDMA. The efficiency of the proposed method is proven by means of simulation results. The given algorithm, can be applied to any other system using MMSE MUD detectors.

Our future work focuses on further development of the MC-CDMA system, expansion to multihop communication, and 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 Quality of Service (QoS) support in modern multimedia home environments.

Acknowledgement

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Appendix

The received signal at the n-th subcarrier can be expressed as :

$$y_n = \frac{1}{T}\int_{T}^{(i+1)T} r(t)e^{-j2\pi nt/T}\,dt \quad (13)$$

The demodulator outputs y_n are multiplied with a decision variable w_n :

$$\hat{b}_k = \mathbf{w}^H \mathbf{y} \quad (14)$$

The optimum weight matrix $\mathbf{w}_{Mx1}$ can be calculated from eq. (1). Eq. (13) can be expressed as:

$$y_n = \sum_{k=1}^{K} \sqrt{a_k}\,\left[p_{nk} b_k(i) + \overline{p}_{nk} b_k(i-1)\right] + \zeta_n \quad (15)$$

where:

$$p_{nk} = \frac{1}{T}\sum_{m=1}^{M} c_{km} h_{km} e^{-j2\pi n\tau_k/T} \int_{\tau_k}^{T} e^{j2\pi(m-n)t/T}\,dt \quad (16)$$

$$\overline{p}_{nk} = \frac{1}{T}\sum_{m=1}^{M} c_{km} h_{km} e^{-j2\pi n\tau_k/T} \int_{0}^{\tau_k} e^{j2\pi(m-n)t/T}\,dt \quad (17)$$

$$\zeta_n = \frac{1}{T}\int_{0}^{T} \eta(t) e^{-2\pi nt/T}\,dt \quad (18)$$

By analyzing eq. (16) a simpler form can be derived:

$$p_{nk} = \frac{1}{T}\sum_{m=1}^{M} \frac{c_{km}\beta_{km}(T-\tau_k)}{T}\left\{\cos\left[\left(\frac{2\pi n\tau_k}{T}\right)-\phi_{km}\right] - j\sin\left[\left(\frac{2\pi n\tau_k}{T}\right)-\phi_{km}\right]\right\} \quad (19)$$

which can be also applied to (17). Eq. (15) can now be expressed with matrix notation:

$$\mathbf{y(i)} = \mathbf{PAb(i)} + \zeta\mathbf{(i)} \quad (20)$$

with:

$$\mathbf{y(i)} = [y_1, ... y_k]^T$$

$$\mathbf{A} = diag[\sqrt{a_1}, ..., \sqrt{a_k}, \sqrt{a_1}, ..., \sqrt{a_k}] \quad (21)$$

$$\mathbf{b(i)} = [b_1(i-1), ..., b_k(i-1), b_1(i), ..., b_k(i)]$$

$$\mathbf{P} = \begin{bmatrix} \bar{p}_{11} & \cdots & \bar{p}_{1K} & p_{11} & \cdots & p_{1K} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \bar{p}_{M1} & \cdots & \bar{p}_{MK} & p_{M1} & \cdots & p_{MK} \end{bmatrix} \quad (22)$$

$$\zeta\mathbf{(i)} = [\zeta_1, ..., \zeta_M]^T \quad (23)$$

where ζ denotes a white Gaussian noise Vector with covariance matrix $\mathbf{\Gamma}_{MxM} = \sigma_n^2 \mathbf{I}$.

For (5), $\mathbf{P}_{K+1}$ is formed from $\mathbf{P}$ when omitting the K+1 column, $\mathbf{p}_{K+1}$ is the K+1 column of $\mathbf{P}$ and $\mathbf{A}_{K+1}$ is formed from $\mathbf{A}$ when omitting the K+1 column.

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List of Abbreviations

ACK	Acknowledgement
ADT	Abstract Data Type
cch	Codechannel
CDMA	Code Division Multiple Access
CTS	ClearToSend
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	DCF InterFrame Space
IEEE	Institute of Electrical and Electronics Engineers
LRE	Limited Relative Error
MAC	Medium Access Control
MAI	Multiple Access Interference
Mbps	Megabits per second.
MC –CDMA	Multi-Carrier Code Division Multiple Access
MHz	MegaHertz
MMSE	Minimum Mean Square Error
MS	Mobile Station
MUD	MultiUser Detector
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency Division Multiplexing
PC	Power Control
PER	Packet Error Rate
PHY layer	Physical layer
PHY mode	Physical Layer mode
QoS	Quality of Service
RTS	RequestToSend
SDL	Specification and Description Language
SIFS	Short InterFrame Space
SF	Spreading Factor
SINR	Signal to Interference and Noise Ratio
SOHO	Small Office Home Office
SPEETCL	SDL Perfomance Evaluation Tool Class Library
WLAN	Wireless Local Area Network