Multihop MAC Protocol for MC-CDMA based WLANs

Georgios Orfanos[1], Hans-Jürgen Reumerman[2], Jelena Mirkovic[1], Aurelien Kwuimo[1]

[1]RWTH Aachen University, Chair of Communication Networks, Aachen, Germany
{orf|jem|kwu}@comnets.rwth-aachen.de

[2]Philips Research Laboratories, Aachen, Germany
hans-j.reumerman@philips.com

***Abstract* - Besides reducing interference, multihop transmissions are essential for coverage extension and interconnection of different subnetworks. In rich scattering environments, especially in home and office environments, the coverage of Wireless Local Area Networks (WLAN)s is considerably decreased. One of the ways to provide continuous coverage is deploying multihop networks. In this paper, multihop functionality extension for the Multi-Carrier Code Division Multiple Access (MC-CDMA) based Distributed Coordination Function (DCF) [1] is presented. The proposed Medium Access Control (MAC) protocol deals efficiently with the problem of packet forwarding without raising the system's complexity, while exploiting the multi channel structure of the MC-CDMA based system. It must be noted that the proposed solutions are not limited to MC-CDMA networks but can be easily adapted by other systems with multi channel structure, where multiple channel separation is not necessarily done in code domain.**

Keywords; MC-CDMA; WLAN; multihop; Smart Backoff; multiple channels; IEEE 802.11a, e.

1. Introduction

A multihop connection consists of consecutive links, which enable the data transfer between two Mobile Stations (MS)s that cannot establish a direct radio link, and its realization requires the support of the network. A relay function is required, providing the functionality of forwarding MSs, for relaying of data packets to the next node of a multihop connection. Such relay functions can be implemented either in the first, second or third layer of the ISO /OSI reference model.

For the IEEE 802.11 MAC protocol, several relay functions for the MAC sublayer have been proposed. Based on the legacy MAC rules, in [7], a data-driven cut-through MAC is proposed, for efficient forwarding. In [8] a receiver initiated protocol, namely RObust Ack-Driven Media Access Protocol (ROADMAP), is proposed which avoid the problem of traffic prediction and reduces the overhead for multihop transmissions. Further reduction of overhead, is achieved with the Multiple Access with ReduCed Handshake (MARCH) protocol presented in [9], where implicit Acknowledgements (ACK)s are considered.

The main focus of the above protocols is multihop support for single channel networks, operating on basis of the IEEE 802.11 Wireless Local Area Network (WLAN). The focus of this paper is the extension of the Medium Access Control (MAC) layer functionality to support packet relaying, in modified Distributed Coordination Function (DCF) [1] proposed for Multi-Carrier Code Division Multiple Access (MC-CDMA) based WLANs. For this reason, a simple relaying operation is taken into consideration and further optimized for the support of the MC-CDMA Physical layer (PHY layer). Throughout this work, multihop connections of up to 3 hops are considered, where the same Physical Layer mode (PHY mode) is used for all data transmissions within a multihop transmission. It is assumed that necessary information from layer three (routing) is known and provided to the MAC sublayer from network layer, and that all MSs are equipped with one transmitter only.

The rest of the paper is organized as follows: Section 2 gives a description of the MC-CDMA technique and the MC-CDMA based WLAN protocol. In Section 3, a detailed presentation of the multihop MAC protocol is given. Section 4 contains an extended presentation and discussion on simulation results. Section 5 summarizes this work with concluding remarks.

2. MC-CDMA based WLAN

In this Section, an overview of the main protocol for MC-CDMA based DCF is given.

2.1. MC-CDMA

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 [4]. This method is called "frequency spreading".

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 and has 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]. Consequently interchip interference is reduced, and synchronization is easier compared to other spread spectrum techniques.

In the proposed system 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 in 4 different subcarriers. Since the channel utilizes 48 data subcarriers, a total of 48/4=12 symbols of the same user can be transmitted in parallel to use the complete channel bandwidth.

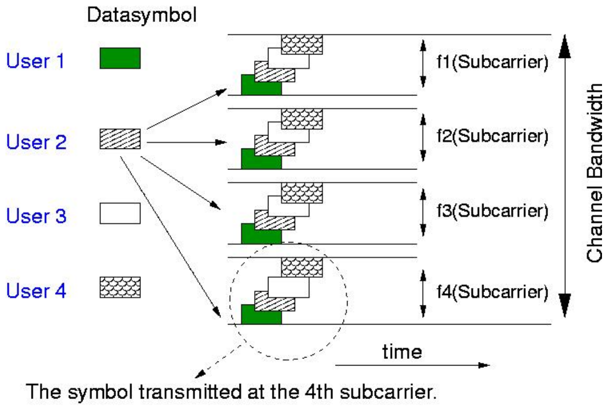

Figure 1. The MC-CDMA spreading mechanism with spreading factor 4.

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).

2.2. PHY layer of MC-CDMA based DCF

In the MC-CDMA based DCF, orthogonal Walsh Hadamard spreading codes of length 4 are used, obtained from the rows of the 4th order Hadamard matrix:

$$\mathbf{H}_4 = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}$$

Unlike Universal Mobile Telecommunications System (UMTS), where each transmitter uses a unique spreading sequence, in the proposed system with four available sequences, this is not feasible. Therefore, we introduce the concept of a Codechannel (cch). A cch is a spreading sequence, which is not explicitly assigned to a MS, but shared among a number of MSs. Each MS considers each spreading sequence as a subchannel of the frequency channel. Consequently, the frequency channel is divided (logically) by the four spreading sequences in four subchannels, the cchs.

For channel coding, the K=7 convolutional encoder is used and at receiver's side besides the convolutional decoder the Minimum Mean Square Error (MMSE) MultiUser Detector (MUD) is applied. The rest of the PHY parameters have similar values to the ones proposed in IEEE 802.11a [5]. An overview of the PHY layer performance of the MC-CDMA based WLAN can be obtained from [6].

2.3. MC-CDMA based DCF

The MC-CDMA based DCF is a development of the IEEE 802.11a WLAN MAC protocol, 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 by the MSs applying the DCF, as described in the standard [2] [5].

A MS ready to transmit has to select a cch. 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).

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]:

Backoff Time = Random · 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.

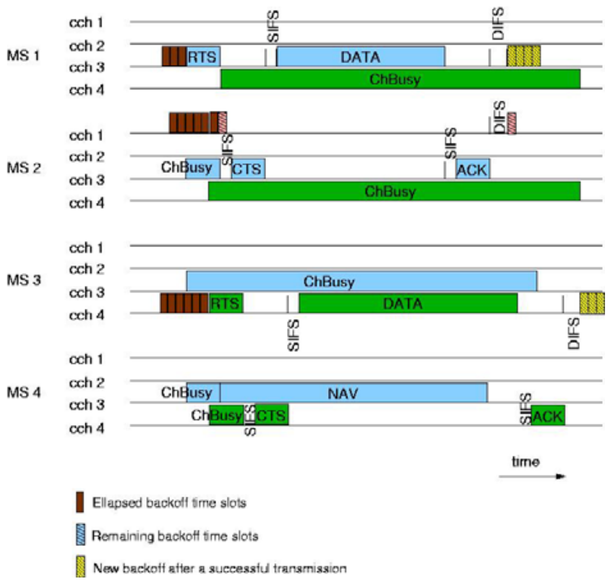

Figure 2. The multichannel approach for the IEEE 802.11 MAC.

If the countdown of the MS's backoff timer, carried out in steps of aSlotTime (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. 2.

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. Compared with the standard IEEE 802.11 WLAN [5], in the MC-CDMA system each MS utilizes separate NAV states for each cch.

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 ACK frame, sent from the receiver with a delay SIFS after reception's end. Should two or more MSs 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, the number of simultaneous transmissions can be increased until the Signal to Interference and Noise Ratio (SINR) at the receiver 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 [3], using the RTS and CTS frames.

2.4. Smart Backoff

Instead of selecting a cch randomly, a MS can apply Smart Backoff for prioritized medium access.

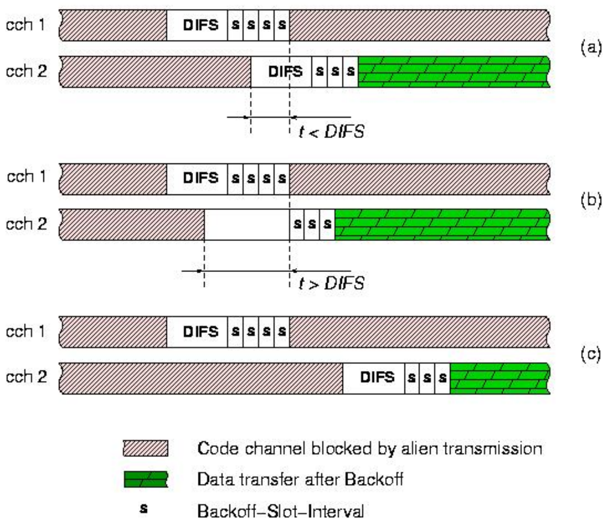

Figure 3. Smart Backoff.

The Smart-Backoff procedure, shown in Fig. 3, allows a MS to iterate between cchs during backoff thus directly reduces the delay of a data transfer. For this purpose, MSs applying Smart Backoff monitor all cchs during backoff and mark the moment a cch gets idle. If the backoff down count is interrupted one of the three cases shown in Fig. 3 occurs:

1. Another cch seems idle. The MS has to monitor the cch for at least a DIFS interval to determine whether it is really idle and then it can continue the down count of backoff timer in this cch.
2. Another cch is determined idle and the MS can directly continue its backoff timer down count in this cch.
3. No cch is idle. The MS must wait.

Should two or more cchs be idle when the backoff down count is finished, the MS will choose one of them, preferably the one that is idle for the longer period, for its transmission. Alternatively, the MS can transmit two or more packets in parallel, if after Smart Backoff procedure the correspondent amount of cchs is idle.

3. Multihop MAC Protocol

The progress of a multihop connection spanning over 3 hops is shown in Fig. 4 (solid lines). MS 1 is the initiating node, transmitting data packets over MS 2 and MS 3 to the final destination MS 4. In this case, every forwarding MS is responsible for the correct transmission in the next hop, as with its own data. Signalization of the route is done, using the four address fields in MAC overhead as follows:

- Address 1: Contains the source address of the multihop connection (MS 1).
- Address 2: Contains the next hop (MS 2).
- Address 3: Contains the address of the final receiver. (MS 4).
- Address 4: Contains the address of the second forwarding mobile station (MS 3).

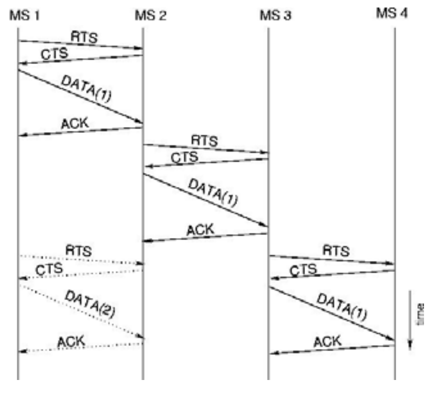

Figure 4. 2-hop multihop transmission.

MS 2 signals the correct reception of a data packet, with an ACK, and prepares the transmission to MS 3 starting a new backoff. A new backoff is started in MS 1 too, and a new the transmission between MS 1 and MS 2 would delay the transmission between MS 2 and MS 3. In order to prioritize packet relaying at MS 2, a multihop guard interval is introduced for MS 1 (Fig. 5). MS 1, being the initiator of the multihop connection MS 1 to MS 4, has to provide time for forwarding station MS 2 to forward the data packet to MS 3. For this reason MS 1 abstains for an interval, equal to the transmission window duration of the certain data packet. After the above guard interval expires, MS 1 can initiate a transmission according to the carrier sensing rules. Depending on the scenario topology, MS 1 can transmit in parallel to MS 3 (dotted lines), using another cch, which increases overall performance of the multihop connection and reduces the delay.

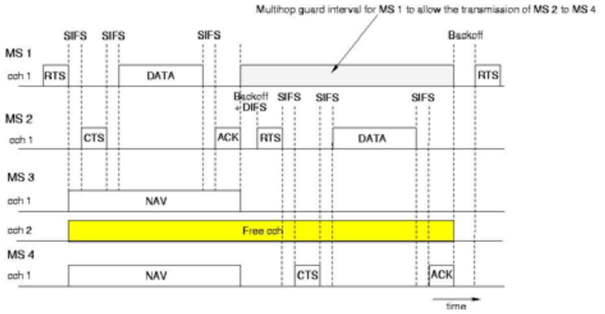

Figure 5. The standard NAV problem.

In order to improve performance, Smart Backoff can be used at transmitting MSs, which enables parallel transmissions. Especially in the case of forwarding MSs serving two multihop connections, like the star topology in Fig. 6. Parallel transmissions at MS 3 are essential for achieving lower delays. In such topologies though, Smart or Parallel Backoff might increase the number of collisions.

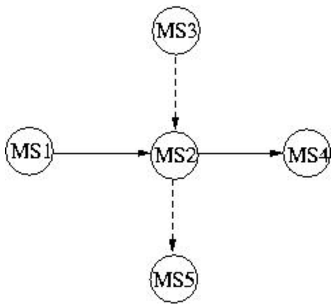

Figure 6. The star scenario.

In Fig. 6 two multihop transmission take place over the common forwarding MS 2: one connection from MS 1 to MS 4 and another from MS 3 to MS 5. MS 3 sets, according to the modified DCF, its NAV timer for the corresponding cch 1 upon receiving the RTS frame from MS 1 (Fig. 5), or the corresponding CTS from MS 2. Smart Backoff would lead MS 3 to another idle cch (cch 2 in Fig. 5), where it can proceed with backoff count down. A transmission from MS 3 would interfere in this case with the ongoing data transfer from MS 1 to MS 2. To overcome this problem, an extend NAV is proposed, the NAV per cch and MS. According to the new NAV, each MS receiving a RTS and/or CTS, sets its NAV timer for the denoted duration of transmission, on the channel in which the control frame was received, and marks additionally the involved MS(s) as occupied. This precaution prohibits collisions in multihop scenarios, while it enables Smart Backoff deployment in multichannel networks..

4. Simulation Results

A representative multihop scenario is shown in Fig. 7. Besides a bottleneck station (MS 7), the scenario comprises four multihop connections of 1 to 3 hops. All transmitting MSs are capable of Smart Backoff and parallel transmissions in two cchs are allowed for MS 7, facing highest traffic. The applied values for further simulation parameters are given in Table I.

End-to-end connections are named as follows: connection between MS 2 and MS 4 is referred to as con. 1, between MS 5 to MS 9 as con. 2, between MS 6 and MS 10 as con. 3 and between MS 11 and MS 12 as con. 4.

Table I: Simulation Parameters

Parameter	Value
Max. TxPower	17dBm
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

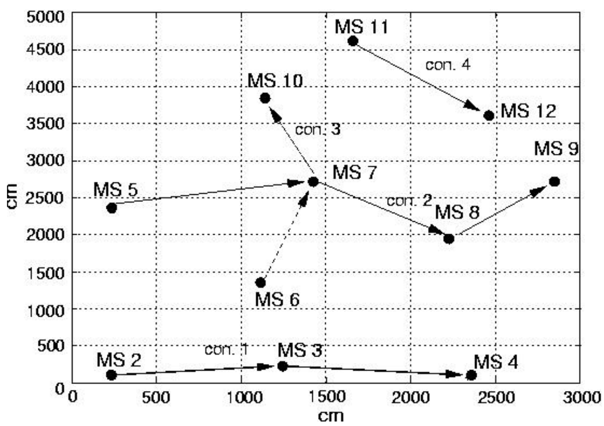

Figure 7. The simulated scenario for multihop transmissions.

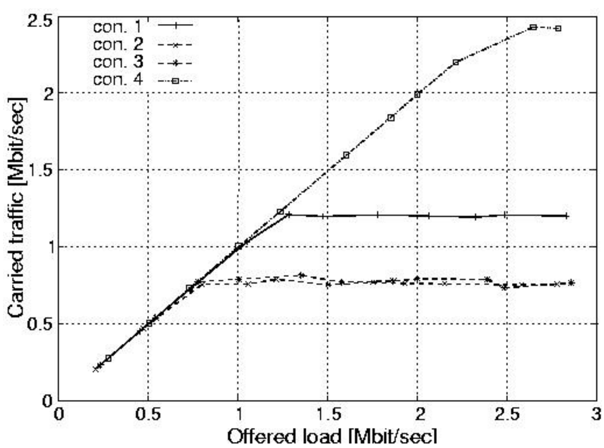

Figure 8. Carried end-to-end traffic per multihop connection vs. offered load.

Figure 8 presents the carried traffic per connection with the offered load. The one hop con. 1, reaches in saturation the maximum cch MAC level capacity for the applied PHY mode, namely 2.4 Mbit/sec. Similary, the 2 hop con. 4 reaches an end-to-end carried traffic of 1.2 Mbit/sec, that corresponds to half the cch capacity. The achieved maximum carried traffic for con. 2 and con. 3 averages to 0.8 Mbit/sec/ for each connection and is limited from the common forwarding station (MS 7), that competes for channel access, prior to every transmission, with one of the two transmitters MS 5 and MS 6.

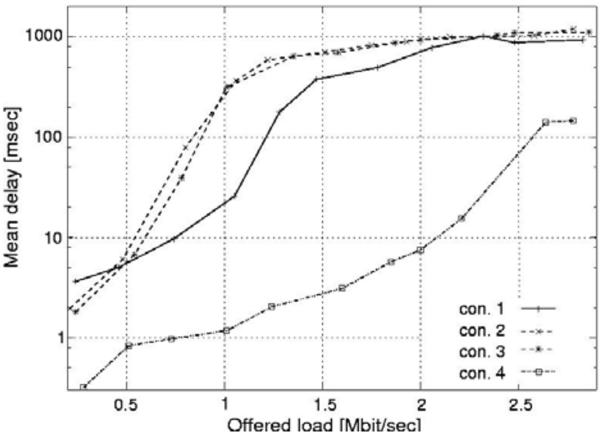

Figure 9. Mean end-to-end queueing delay per multihop connection vs. offered load.

In Fig. 9, mean end-to-end queueing delay per connection is presented. The end-to-end queueing delay comprises the queueing delay at all queues for a specific data packet. Results comply with the above throughput analysis: Multihop connections with more hops carry lower traffic and face high end-to-end queueing delay. The direct con. 4 achieves the lowest end-to-end queueing delay (as a direct link), while con. 3 and con. 2 suffer from high end-to-end queueing delay, rapidly raising with offered load. The mean end-to-end queueing delay at saturation load (which is different for every connection), is for all multihop connections approximately the same.

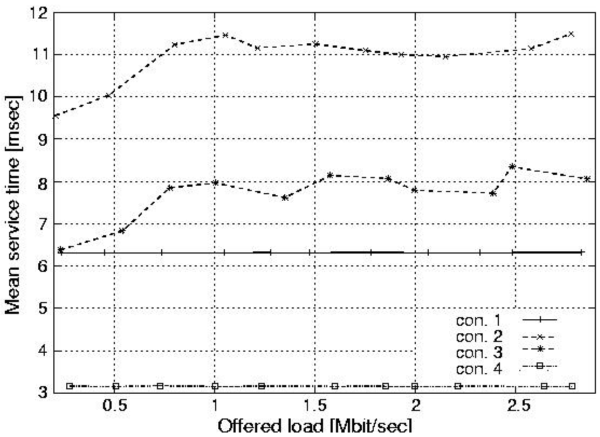

Figure 10. Mean end-to-end service time per multihop connection vs. offered load.

Important for the analysis of system's behavior, is the mean end-to-end service time per multihop connection, presented in Fig. 10. In these measurements, the service time over all hops is considered. For the direct link (con. 4), 3.1msec are needed in average for a complete transmission, a time which complies with the analytical calculation in [1]. Accordingly, the two hop con. 1 requires double service time, since two complete transfers are performed. In both cases, mean end-to-end service time is constant for different offered load, which reveals the collision free operation of those connections. For, con. 2 and con. 3, mean service time has the expected value of 9.3msec and 6.2msec, respectively, for low offered load only. For higher load, RTS collisions and RTS timeouts (no CTS response) for transmission attempts from MS 5 and MS 6 to the common forwarding station MS 7 raise the required service time.

In Figs. 11 and 12, the CDFs of queueing delay per hop are presented, for 0.75 and 1.25 Mbit/sec offered load per connection, respectively. In the first case (0.75 Mbit/sec/connection offered load), the offered load is chosen at the saturation point of con. 2 and con. 3, which achieve the lowest carried traffic. The highest queueing delay comprises 200msec for transmissions of MS 5. Its queueing delay distribution is similar to the one of MS 6, since both MSs are the sources of two multihop connections sharing the same first forwarding station (MS 7). Furthermore, the multihop guard interval prohibits after a successful data packet transfer the immediate transmission of next data packet, raising the delay of next packets in the queue. Additionally, some collisions occur among Ms 5 and MS 6, which increase further the delay. The second highest queueing delay is achieved by transmissions of MS 2, owing to the multihop guard interval for prioritization of forwarding station MS 3. The direct link between MS 11 and MS 12 follows, with better queueing delay performance. In this case, queueing delay is affected by the ability of Smart Backoff to detect a free cch.

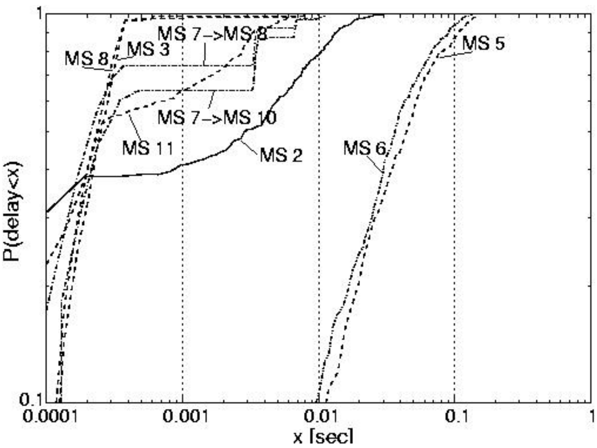

Figure 11. CDF of queueing delay per hop for 0.75 Mbit/sec offered load per connection.

Queueing delay distributions of the hop between MS 7 and MS 8, and the hop between MS 7 and MS 10, are almost equal. The 3.1msec stepwise raise of queueing delay at 63% and 73% respectively, is the evidence of contention between MS 7 and MS 5 or MS 6. In case MS 5 (or MS 6) transmits a data packet to MS 7, MS 5 (or MS 6) defers for a duration equal to the multihop guard interval. MS 7 competes then with MS 6 (or MS 5) on channel access and in 37% (27%) of the cases, MS 6 (MS 5) gains control of a cch, blocking MS 7 with its RTS. The outcome is an increased queueing delay at MS 7, equal to a transmission cycle (3.1msec). After its transmission, MS 6 (MS 5) defers according to the multihop guard interval duration, and MS 7 competes for medium access with MS 5 (MS 6). Should MS 5 (MS 6) win the competition, MS 7 sets its NAV and delays its transmission further, for another 3.1 msec. The steps on queueing delay diagrams for MS 7 (MS 7 to MS 8 and MS 7 to MS 10) give evidence to this situation, which might repeat, up to 3 times.

Best performance on queueing delay is achieved at MS 3 and MS 8, which are neither using the multihop guard intervals, as the last forwarding MSs of con. 1 and con. 2 respectively, nor are they participating in a second multihop connection. Particularly, MS 8 can transmit concurrently with MS 5 in another cch.

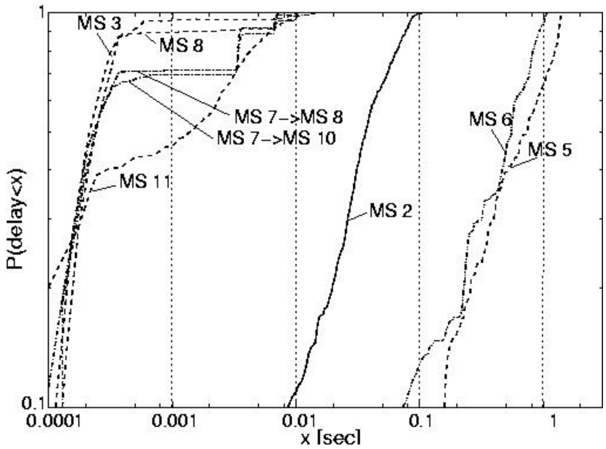

Figure 12. CDF of queueing delay per hop for 1.25 Mbit/sec offered load per connection.

In Fig. 12, the Cumulative Distribution Function (CDF)s of queueing delay per hop are presented, for the case of 1.25 Mbit/sec offered load per connection. Network operation shows the same performance characteristics as in previous case, with the difference of higher queueing delay for MS 5 and MS 6, which are now in overload. Additionally, data packets at MS 2 experience increased queueing delay, with distribution similar to the one of MS 6 in Fig. 11, as now the offered load is chosen at the saturation point of MS 2 (and not at the saturation point of MS 6, as it was the case in Fig.11).

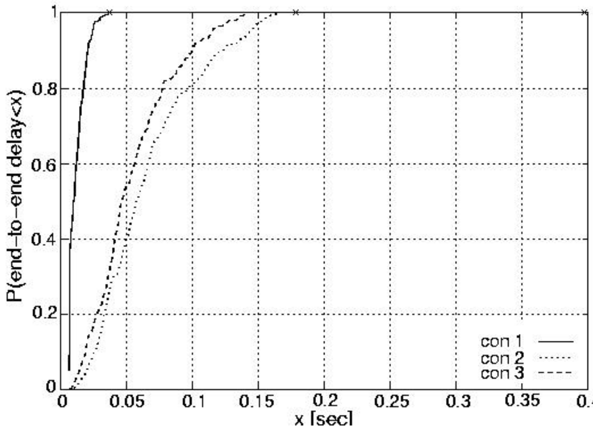

Figure 13. CDF of end-to-end delay per multihop connection for 0.75 Mbit/sec offered load per connection.

The CDF of end-to-end delay, measured as the delay between the arrival of a data packet in the network and the reception of the ACK at the last hop, is depicted in Fig. 13, for 0.75 Mbit/sec offered load per connection. For con. 2 and con. 3, the end-to-end delay has a similar distribution, due to the common forwarding station MS 7. The reason for the small difference between the two CDFs is the one more hop at con. 2. Similar results are shown in Fig. 14, presenting the end-to-end delay for 1.25 Mbit/sec offered load per connection. The network operates in saturation and the high offered load introduces high end-to-end delay for data transfer.

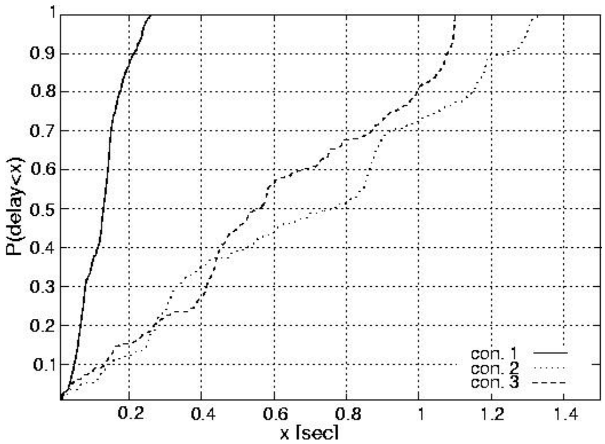

Figure 14. CDF of end-to-end delay per multihop connection for 1.25 Mbit/sec offered load per connection.

5. Conclusions

In this paper, an efficient forwarding method for the MC-CDMA based DCF is proposed. Performance evaluation results show the ability of the multihop network to achieve an overall good performance. Using Smart Backoff, forwarding MSs, which participate in more than one multihop connection can improve their performance, and achieve higher throughput. Technical solutions proposed in this chapter for the realization of relays, such as the NAV timer per MS and cch, can be adopted from other wireless systems with multi channel structure, which don't necessarily use MC-CDMA.

Future work focuses on further development of the MC-CDMA based DCF for support of Quality of Service (QoS), by resource reservations from MS.

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REFERENCES

[1] G. Orfanos, J. Habetha, L Liu, , "MC-CDMA based IEEE 802.11 wireless LAN," Proc. IEEE MASCOTS 2004, Oct. 2004.

[2] B. Walke, Mobile Radio Networks. Willey & Sons Ltd, Chichester, Sussex, U.K., 2nd Ed., 2001.

[3] G. Orfanos, J. Habetha, W. Butsch, , "Efficient Power Control for MC-CDMA based WLANs," Proc .European Wireless 2005, Apr. 2005.

[4] J. Linnartz, "Performance analysis of synchronous MC-CDMA in mobile rayleigh channel with both delay and doppler

spreads," IEEE Trans. On Vehicular Technology, vol. 50, issue 6, Nov. 2001.

[5] IEEE 802.11 WG, Draft supplement to standard for information technology 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.

[6] G. Orfanos, J. Habetha, W. Butsch, "Error Probabilities for Radio Transmissions of MC-CDMA based W-LANs," Proc. VTC Spring 2005, Mai 2005.

[7] A. Acharya, A. Misra, S. Bansal, "High-Perfrmance Architectures for IP-Based Multihop 802.11 Networks," IEEE Wireless Communications, Oct. 2003.

[8] D. Kim, C.-K. Toh, Y. Choi, "ROADMAP: A Robust ACK-driven Media Access Protocol for Mobile Ad Hoc Networks," Proc. of MILCOM 2001, Oct. 2001.

[9] C.-K. Toh, V. Vassiliou, G. Guichal, C-H Shih, "MARCH: A Medium Access Control Protocol For Multihop Wireless Ad Hoc Networks," Proc. of MILCOM 2000.

List of Abbreviations

ACK	Acknowledgement
cch	Codechannel
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CSMA/CA	Carrier Sense Multiple Access/ Collision Avoidance
CTS	ClearToSend
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	DCF InterFrame Space
DS-CDMA	Direct Sequence-CDMA
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourrier Transformation
FFT	Fast Fourrier Transformation
MAC	Medium Access Control
MARCH	Multiple Access with ReduCed Handshake
Mbit/sec	Megabits per second.
MC–CDMA	Multi-Carrier Code Division Multiple Access
MMSE	Minimum Mean Square Error
MS	Mobile Station
MUD	MultiUser Detector
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency Division Multiplexing
PHY layer	Physical layer
PHY mode	Physical Layer mode
QoS	Quality of Service
ROADMAP	RObust Ack-Driven Media Access Protocol
RTS	RequestToSend
SIFS	Short InterFrame Space
SINR	
SF	Spreading Factor
UMTS	Universal Mobile Telecommunications System
WLAN	Wireless Local Area Network