This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2007 proceedings.

A MAC Protocol for MIMO Based IEEE 802.11 Wireless Local Area Networks

Jelena Mirkovic, *Member, IEEE*,
Georgios Orfanos, *Member, IEEE*, Hans-Jürgen Reumerman, and Dee Denteneer

***Abstract*— An increasing number of wireless devices and services imposes higher demands for wireless networks' capacity. Likewise, contemporary bandwidth requirements of each user in the network rise significantly, being a mixture of traffic types such as Web surfing, File Transfer Protocol (FTP), video, video-teleconference, and voice.**

Multiple Input – Multiple Output (MIMO) techniques are recognized as methods that can meet these requirements, since they significantly increase the capacity of wireless networks, without additional bandwidth or transmission power. With a MIMO physical layer (PHY), the transmission channel gets a layered structure. Consequently, support from higher layers with a cross-layer approach [6] that provides efficient management of the channel's spatial layers, can significantly increase the network's performance on both link and system level.

In this paper a high capacity Medium Access Control (MAC) protocol for MIMO support is presented. The proposed protocol is based on IEEE 802.11 standard [3], and provides a flexible and scalable support for multiple antenna terminals, backwards compatible with legacy stations.

***Index Terms*—MAC Protocol, MIMO, Spatial Diversity, Spatial Multiplexing**

I. Introduction

An ever-increasing number of wideband applications imposes high demands for the wireless medium. MIMO is globally seen as a solution able to meet these needs, as it significantly increases the capacity of the system, without additional bandwidth and transmission power. Different MIMO schemes (Space Time Spreading (STS), Space Time Coding (STC) and beamforming (BF)) are included in new standards such as CDMA2000 [4] and IEEE 802.11n [7].

Embedding MIMO technology into existing standards might require significant changes to the protocol. Therefore, with widely deployed legacy networks, interoperability of the MIMO enabled stations with the legacy stations is an important issue. This paper presents an efficient way of integrating MIMO into IEEE 802.11 Wireless Local area Networks (WLANs). It supports fast link adaptation, a scalable number of antennas and is interoperable with legacy stations. If generalized, the method is not limited to IEEE 802.11 networks. The proposed MIMO aware MAC protocol is evaluated on MC-CDMA based 802.11 WLANs [5] and its performance is compared to the equivalent Single Input – Single Output (SISO) system.

The paper is organized as follows: in Section II, a description of IEEE 802.11 Distributed Coordination Function (DCF) is given, and in Section III a description of the applied MIMO schemes. In Section IV, MIMO DCF (M-DCF) with the necessary modifications for MIMO support in the MAC layer is presented. In Section V we give a performance evaluation of the protocol on MC-CDMA based IEEE 802.11 WLAN [5], using both theoretical analysis and simulation. In Section VI, conclusions are drawn and an outlook to future work is provided.

II. Description Of The IEEE 802.11 MAC Protocol

The basis of DCF of the IEEE 802.11a MAC protocol is Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), with a random backoff procedure. A station with a data packet to transmit draws a random number between 0 and Contention Window (CW), which determines the duration of the backoff timer in timeslots. The CW has a minimum starting value of 15, doubles after a collision, can rise up to 1023, and is set back to its minimum value after a successful transfer, indicated by an Acknowledgement (ACK) frame.

After detecting the medium free for a time interval equal to Distributed Coordination Function Inter-Frame Space (DIFS) (34 μsec), the mobile station counts down the backoff timer until it reaches zero and initiates then its transmission. If during the countdown another mobile station occupies the medium, all mobile stations in backoff interrupt their count down and defer until they detect the medium free for at least DIFS.

The standard includes an optional Request-to-Send (RTS) – Clear-to-Send (CTS) handshake prior to the transmission to alleviate the hidden node problem [3] and reserve the medium for the data transmission. A station with a data packet, after finishing the backoff procedure, first transmits an RTS frame. The stations which receive the RTS packet and are not its intended receivers set their Network Allocation Vector (NAV)

Manuscript received October 2, 2006. J. Mirkovic is with the Chair of Communication Networks, Faculty 6, RWTH Aachen Univeristy, Kopernikusstr. 16, 52074 Aachen, Germany (phone: +49 (0)241 80 27919; fax: +49 (0) 241 80 22242; e-mail: jem@comnets.rwth-aachen.de).

G. Orfanos was with Chair of Communication Networks, Faculty 6, RWTH Aachen Univeristy, Kopernikusstr. 16, 52074 Aachen, Germany, where he obtained his PhD. (e-mail: orf@comnets.rwth-aachen.de)

H.-J. Reumerman is with Philips Research Laboratories, Aachen, Germany. (e-mail: hans-j.reumerman@philips.com)

D. Denteneer is with Philips Research Laboratories, Eindhoven, Netherlands. (e-mail: dee.denteneer@philips.com)

1525-3511/07/$25.00 ©2007 IEEE

timers and defer from the medium in order not to interfere with the transmission. If the intended receiver of the RTS is idle and thus able to receive data, it responds with a CTS packet, after SIFS. Mobile stations which receive the CTS set their NAV timer as well, and the sender of the RTS can transmit its data packet after SIFS. The data packet is acknowledged by the receiver in case of a successful reception.

III. SPATIAL MULTIPLEXING, SPATIAL DIVERSITY, AND SELECTION DIVERSITY CONCLUSION

A coarse classification recognizes two types of MIMO techniques based on the propagation channel properties, i.e. on the structure of the spatial correlation matrix at the receiver's antenna array. In case of high correlation of the received signal different beamforming algorithms are applied, while in case of low correlation of the received signal - diversity (DIV) and multiplexing (MUX) approaches give better performance [8].

In MUX schemes presented in Fig. 1, multiple streams are transmitted simultaneously, each using one dedicated antenna. This increases the throughput with a factor equal to the number of streams being transmitted.

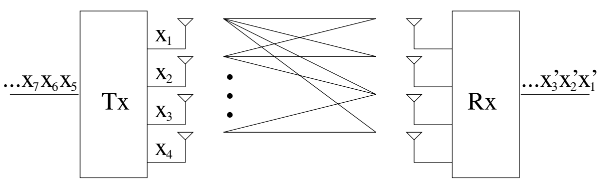

Fig. 1 Schematic representation of spatial multiplexing – MUX.

In DIV schemes from Fig. 2, multiple antennas are used in a different way: for the basic DIV scheme the transmitter uses only one antenna. The receiver with multiple antennas receives multiple copies of the transmitted signal so that using an appropriate signal processing algorithm achieves significantly higher SNR. This value is referred to as post-processing per-stream SNR. In this paper, we assume that the receiver is applying the zero-forcing (ZF) algorithm. For fixed PHY mode, DIV schemes do not increase the throughput, but the reliability of the transmission.

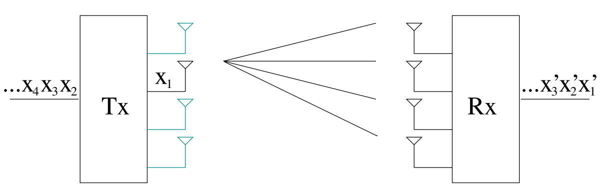

Fig. 2 Schematic representation of spatial diversity – DIV.

In the schemes combining MUX and DIV, more transmit antennas are active, but the receiver, as in all DIV schemes, still has more antennas than the number of streams. Multiplexing is present, but the receiver gets more information about the transmitted signal than in the pure MUX case.

In case that the post-processing SNR for a stream from a certain antenna is not higher than a predefined threshold, it is better not to activate transmission from this antenna, but instead to use more transmit power for the antennas whose channel is in better condition. This leads to selection diversity (SDIV). Based on the post-processing per-stream SNR values, the best antenna, or a subset of the best antennas, is identified to be used for the transmission and this information is fed back to the transmitter [1], [2]. Selection diversity with a lower multiplexing factor may lead to higher throughput than pure multiplexing schemes (with a higher multiplexing factor), because of the adaptive transmit power distribution among the antennas.

In all the described schemes, MIMO channel is divided into a set of independent Single Input – Single Output (SISO) channels, where each of them is used to transmit a single stream, which can be received with the respective post-processing SNR. Channel state information (CSI) is assumed at the receiver side only.

Fig. 3 presents the number of correctly received data bits normalized to symbol duration for the following MIMO schemes: SISO 1×1, DIV 1×2, SDIV 2×2, MUX 2×2, MUX 3×4, and MUX 4×4. The first number in a scheme name represents the number of transmit, and the second one stands for number of receive antennas. Performance comparison is done for adaptive coding and modulation over the PHY modes defined in IEEE 802.11a standard [3], and is presented in Fig. 3.

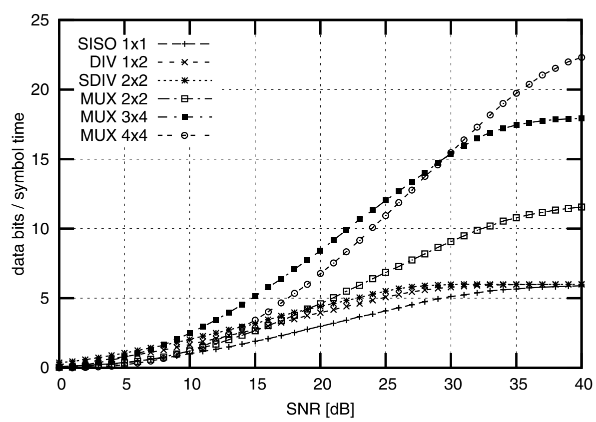

Fig. 3 Link level performance for different MIMO schemes with adaptive coding and modulation.

MUX 3×4 gives the best performance in the area of low and moderate SNR. The maximum throughput that can be reached in the SISO system for SNR higher than 35 dB (6 data bits per symbol time) is reached with MUX 3×4 at 16 dB. For high SNR values, over 30 dB, MUX 4×4 gives better performance; the reason for this is that MUX 3×4 goes into the saturation with 18 data bits per symbol duration, while the throughput for MUX 4×4 continues to grow with SNR up to 24 data bits per symbol duration. The lack of diversity in multiplexing schemes is compensated by multiple spatial streams. Further details about the link level model can be found in [9].

IV. PROTOCOL EXTENSIONS FOR MIMO SUPPORT – M-DCF

A. Extending control frames: M-RTS, M-CTS, and M-ACK

Prior to the transmission, in the association procedure, stations share among each other their hardware capabilities. *Without changing the standard IEEE 802.11 MAC transmission time diagram [3]*, we propose an extended form of RTS and CTS control frames (see Fig. 4 and Fig. 5) for negotiation about the active antenna elements. Besides reserving the channel for the pending data transmission, the extended control frames – MIMO-RTS (M-RTS) and MIMO-CTS (M-CTS) are used for channel estimation and selection of the MIMO scheme, based on the stations' hardware capabilities, Quality of Service (QoS) demands of the connection, radio propagation conditions, etc.

2 bytes	2 bytes	6 bytes	6 bytes	**1 byte**	4 bytes
Frame Control	Duration	Receiver Address	Transmitter Address	**Proposed Antenna Bitmap (PAB)**	Frame Check Sequence

Fig. 4 M-RTS frame structure

2 bytes	2 bytes	6 bytes	**1 byte**	4 bytes
Frame Control	Duration	Receiver Address	**Confirmed Antenna Bitmap (CAB)**	Frame Check Sequence

Fig. 5 M-CTS frame structure

Both M-RTS and M-CTS are based on the structure described in the standard [3]. In order to support multiple antennas, both have a new field. In M-RTS this field is called Proposed Antenna Bitmap (PAB) and encodes the chosen subset of available antennas proposed for the pending data transmission. The receiver of the frame, based on the estimated post-processing SNR values for each antenna, confirms which antennas should be active in Confirmed Antenna Bitmap (CAB) of M-CTS.

Extended standard ACK frame [3] – MIMO-ACK (M-ACK) contains an one byte long bitmap (Fig. 6). This field is called Acknowledged Packet Bitmap (APB) and contains an acknowledgement – either positive or negative, over all spatial streams. It should be noted that this is still immediate packet acknowledgement, although there are multiple packets being transmitted at a time. The length of these bitmaps determines the number of antennas supported – it is a system design parameter. We propose the length of one byte, supporting in this way up to eight antennas.

2 bytes	2 bytes	6 bytes	**1 byte**	4 bytes
Frame Control	Duration	Receiver Address	**Acknowledged Packet Bitmap (APB)**	Frame Check Sequence

Fig. 6 M-ACK frame structure

All the control frames are transmitted using a diversity scheme, to ensure correct reception and to support all mobile stations, independently on their hardware capabilities (also legacy mobile stations with only one antenna). The actual scheme choice is a system design issue: random or adaptive antenna selection, transmit or receive diversity or both, etc. In this paper we assume receive diversity, with random transmit antenna selection.

B. M-DCF description

The following points give an overview of the additional MAC protocol functionality during a transmission cycle, in a MIMO environment omitting the ones regarding CSMA/CA:

- The transmitter sends an M-RTS frame, setting 1s in PAB field for the available antennas for the next transmission.
- The receiver responds with an M-CTS frame, setting 1s in CAB field for the antennas accepted for transmission.
- After reception of the M-CTS frame, the transmitter transmits (one or more) packets based on the receiver's instructions about the antennas to be used.
- After the reception, the receiver checks the received packets, and creates and M-ACK frame, setting 1s in APB for each correctly received packet.
- When the transmitter receives the M-ACK frame, it removes the packets from the queue and can initiate another transmission. If the M-ACK frame is lost, the transmitter will initiate a retransmission after a timeout.

This scheme supports up to 8 antennas, at the receiver and the transmitter side, providing flexible support and dynamic change over different MIMO schemes (multiplexing, transmit and receive diversity, selection diversity) using M-RTS and M-CTS frames. Moreover selecting antennas for the next transmission can also be signaled or negotiated by piggybacking in data and ACK frames.

In IEEE 802.11n, MUX and Space Time Block Codes (STBC), including Antenna Selection (AS) and beamforming [7] are supported. AS in IEEE 802.11n can be used when the number of antennas is greater than the number of transmit/receive chains, mapping of the signals at the RF chains onto a set of antenna elements [7]. The proposed scheme gives a possibility to adaptively choose between different multiplexing and diversity schemes, switching on or off the transmitter antenna elements, based on the previously estimated channel matrix. The number of spatial streams is also a parameter to be changed in the link adaptation procedure, since under some conditions having less spatial streams cam be beneficial (Fig. 3). It should also be noted that the channel estimation is included into the procedure of obtaining the medium, providing fast channel estimation in spatial domain.

V. M-DCF PERFORMANCE EVALUATION

The protocol performance evaluation is done for MC-CDMA based 802.11a wireless LANs. We first give a brief description of the system, calculate the theoretical maximum values for the throughput, and in the last part of the section present the simulation results. Simulations are done for the SISO and several MIMO schemes, analyzing and comparing throughput and delay under different load levels.

A. MC-CDMA Based 802.11a WLANs

In case of the MC-CDMA PHY, a frequency channel is divided into a number of parallel codechannels (cch) equal to the applied spreading factor (SF). Each of the cchs can be accessed by the mobile station using DCF, as described in the standard [3]. In this work the SF has the value of 4.

In case two or more stations access the same cch on the same frequency band at the same time a collision might occur. Although the backoff mechanism is a collision avoidance protocol, in scenarios with many stations, they are likely to happen. Thus collisions are a limiting factor for the achieved throughput and delay. The MC-CDMA based system has an advantage in this respect, since each frequency channel is divided into SF parallel cchs, and only n/SF stations compete against each other in accessing one cch. The number of collisions is therefore reduced allowing the use of a lower value for CWmin [5].

Power Control plays an important role in all CDMA networks. It is done over the RTS and CTS packets [10], using interference estimates from the Minimum Mean Square Error (MMSE) Multi-User Detector (MUD) that are updated each time a packet is received. In case of a collision, a repeated RTS is sent with the same transmission power as 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 reception, can calculate the path loss. According to the path loss and the interference status at the receiver, the receiver might ask the transmitter to correct its transmission power by encoding it in the CTS packet, in order to reach the target Signal to Noise Ratio (SNR) for this connection [11].

B. *Maximum Average Throughput Calculation*

Compared to the SISO case, all control frames are only one byte longer, while the same interval required for transmission of one data frame in the SISO case, will be used in the MIMO system for the transmission of multiple packets. The throughput depends on the applied PHY mode, and even more on the applied MIMO scheme, that defines the number of spatial streams used. The calculations are done for the 64 QAM ¾ PHY mode. The system parameters, based on IEEE 802.11a standard [3] are given in Table I.

The PHY mode used for transmitting control frames is QPSK ½. When mapped to OFDM symbols on IEEE 802.11a channel, the new fields in control frames produce no additional overhead.

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 [5]:

$$\Delta T = DIFS + tRTS + SIFS + tCTS + SIFS + tDATA + SIFS + tACK + 7.5 \times aSlotTime$$

For the 64 QAM ¾ PHY mode, we calculate the following values for the transmission interval:

TABLE I SYSTEM PARAMETERS

PARAMETER	VALUE
Max. TxPower	17dBm
Spreading Factor	4
CWmin	15 slots
CWmax	255 slots
Number of Subcarriers	48 Data + 4 Pilot
Channel Bandwidth	20 MHz
Carrier Frequency	5.25 GHz
Noise Level	-93dBm
Path loss Factor	3.5
TxRate Data	54 Mb/s
TxRate Control	12 Mb/s
Data Packet Length	1024 Byte
Symbol Interval	4 µs = 3.2 µs + 0.8 µs
Guard Interval	0.8 µs
Preamble	16 µs
SIFS	16 µs
DIFS	34 µs
aSlotTime	9 µs

$$\Delta T_{SISO}^{64QAM\,3/4} = \Delta T_{MIMO}^{64QAM\,3/4} = 1037{,}5\mu s$$

The throughput values for the SISO case and for one spatial stream in the MIMO case are:

$$Throughput_{SISO}^{64QAM\,3/4} = \frac{Throughput_{MIMO}^{64QAM\,3/4}}{\#\text{ of streams}} = \frac{4 \times 1024 \times 8}{1037{,}5\mu s} = 31{,}58 Mb/s$$

For more details on the calculation see [5].

The maximum throughput *for the whole link* is multiplied with the number of admitted spatial streams, which depends on the applied MIMO scheme. E.g. when using two spatial streams with the 64 QAM ¾ PHY, the link throughput will be 63,16 Mb/s, 94,74 Mb/s for three spatial streams, etc.

C. *Simulation Results*

In the focus of this work are Small Office – Home Office (SOHO) scenarios. A representative random scenario with six connections is presented in Fig. 7. Two stations at most are transmitting on one cch. The traffic sources deliver Poisson load of variable intensity, and the data packet size is 1024 byte.

The simulations are done for the SISO system – a reference case, and for two example MIMO schemes: 2×4 and 3×4, using selection diversity. The analyzed parameters are the achieved throughput and queue delay per connection. The offered load and throughput are normalized to the maximum theoretical throughput on MAC layer per cch using 64 QAM ¾ PHY, which is 7,9 Mb/s. Other relevant parameters are given in Table I.

In Fig. 8, the achieved throughput per connection in the SISO case is presented. Connections 5 and 6 are the only connections on the cch 2 and 3 respectively. Therefore, in the saturation they reach over 90% of the theoretical cch capacity. More can not be achieved due to multiple access interference (MAI) and transmission errors. As for connection pairs 1 and 2, and 3 and 4, they share cchs 0 and 1 respectively. Each connection achieves the throughput approximately half of the cch capacity. Connections 1 and 3 have somewhat better performance then 2 and 4, because of slightly better average SNR due to the lower pathloss. For all the connections, the achieved throughput grows with the offered load until their saturation point.

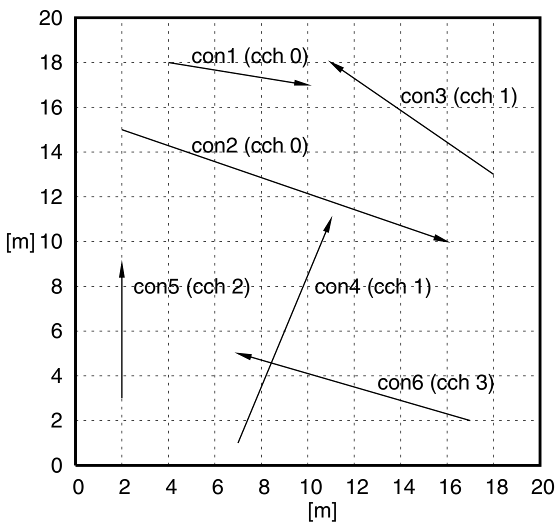

Fig. 7 Simulation scenario.

In the MIMO 2×4 and 3×4 cases, presented in Fig. 9 and Fig. 10, the shape of the curves is similar, but the saturation point is reached, as expected, for the double and triple normalized offered throughput as in the SISO case. For the same transmission power and bandwidth, using multiple spatial streams and multiple receive antennas, the throughput increases with the factor equal to the number of spatial streams.

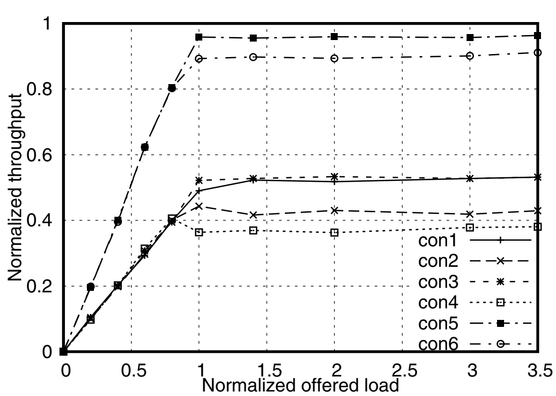

Fig. 8 Achieved throughput vs. offered load, SISO

As for the delay characteristic, first we analyze the delay in the SISO case, presented in Fig. 11. The delay has acceptable values until the offered load approaches the cch's capacity. Afterwards, the delay grows continuously. For the calculation of delay no timeouts are considered.

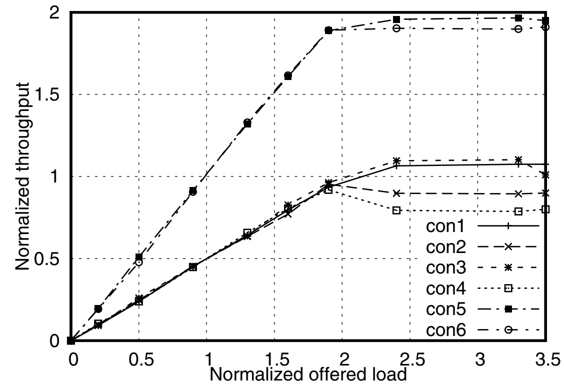

Fig. 9 Achieved throughput vs. offered load, MIMO 2 × 4

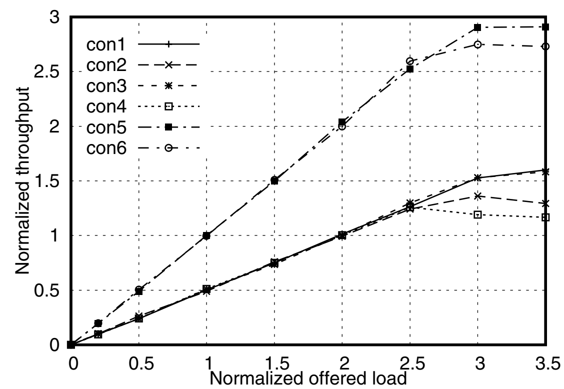

Fig. 10 Achieved throughput vs. offered load, MIMO 3 × 4

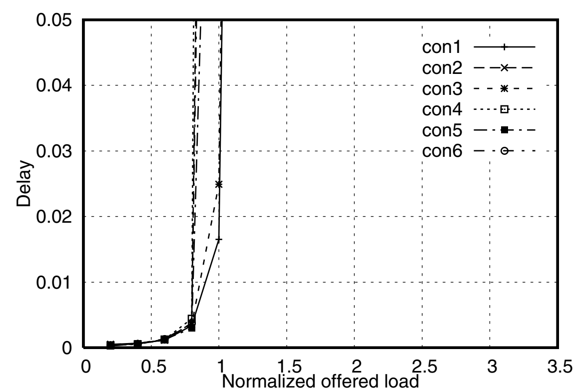

Fig. 11 Delay vs. offered load, SISO

Fig. 12 and Fig. 13 give the delay characteristics for the 2×4 and 3×4 MIMO schemes. Since the MIMO channel (in the examined cases) has two/three times higher capacity, the basic version of the protocol tries to utilize it completely. What suffers is the delay characteristic under low load. Packets which are generated have to wait for another one/two packets to arrive in the queue in order to be transmitted. As the load grows, the characteristic improves, until the saturation point. For higher offered load, the delay grows infinitely, like in the SISO case.

A conclusion can be made that using this method, the more spatial streams are applied – the throughput grows, but at the same time, the delay characteristic under low load gets worse.

It should be also noted that under low load the increased capacity of the channel practically does not bring any benefit at all for the stations with low load, since the high channel capacity is actually not needed. This imposes the need of enhancing the method to provide better service for these stations too.

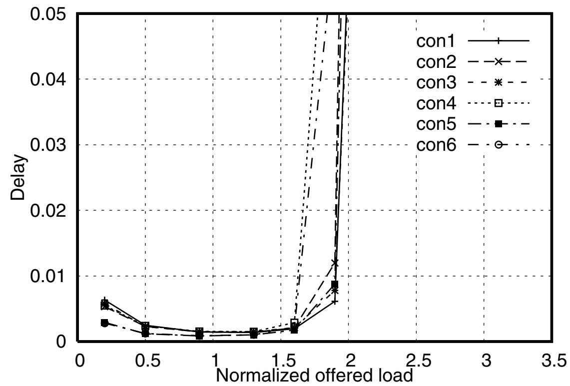

Fig. 12 Delay vs. offered load, MIMO 2 × 4

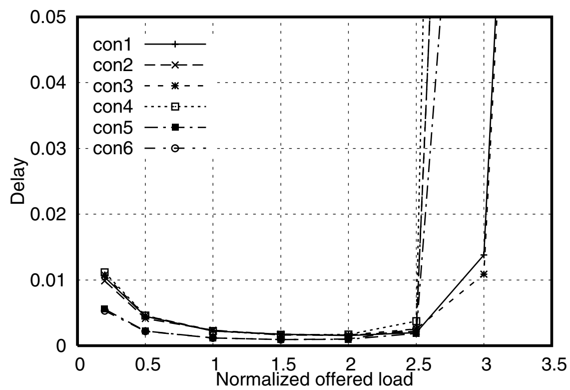

Fig. 13 Delay vs. offered load, MIMO 3 × 4

VI. Conclusion

In this paper, a high capacity MAC protocol for MIMO support is presented. The performance of the proposed protocol and its potential to increase the throughput is demonstrated on a MC-CDMA based IEEE 802.11 WLAN, by both mathematical analysis and simulations.

Using the spatial multiplexing scheme, the throughput was increased n times, where n is the number of spatial streams. Reducing the time needed for a transmission of the same amount of data compared to the SISO case, overhead is effectively decreased n times. At the same time, additional information needed for the protocol introduced no increase in overhead in our example system. (For different channel parameters though, it might introduce some insignificant raise.)

It is important to note that these schemes are scalable: the number of antennas is the main parameter of the scheme, meaning that the complexity (and price) of stations can vary from the simple terminals having one antenna only (including legacy stations), to sophisticated access points, depending on the required performance. Depending on the deployment, increased system capacity can be used to meet higher QoS requirements, increase the number of stations in the network, etc.

The performed analysis also gave an indication of a reduced performance in sense of delay characteristic under low load. The future work will focus on improving the protocol under those conditions. It will also include the development of the protocol to support MU MIMO scenarios, as well as further steps in cross-layer optimization.

Acknowledgment

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

References

[1] Andreas F. Molisch, Moe Z. Win, Yang-Seok Choi, Jack H. Winters, “Capacity of MIMO Systems With Antenna Selection,” IEEE Transactions on Wireless Communications, vol. 4, no. 4, pp. 1759-1772, July 2005.

[2] R. W. Heath, A. Paulraj, “Antenna selection for spatial multiplexing systems based on minimum error rate,” Proceedings of the IEEE International Conference on Communications, Helsinki, Finland, June 2001.

[3] 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.

[4] 3GPP2, “Physical Layer Standard for CDMA2000 Spread Spectrum Systems,” C.S0002-D, Revision D, v2.0, September 2005, available at: http://www.3gpp2.org/Public_html/specs/C.S0002-D_v2.0_051006.pdf.

[5] G. Orfanos, J. Habetha, L Liu, “MC-CDMA based IEEE 802.11 wireless LAN,” Proceedings of IEEE MASCOTS 2004, Oct. 2004.

[6] V. Srivastava, M. Motani, “Cross-layer design: a survey and the road ahead,” IEEE Communications Magazine, vol. 43, no. 12, pp. 112- 119, Dec. 2005.

[7] IEEE 802.11 WG, “Draft Amendment to Standard for Information Technology-Telecommunications and information exchange between systems- Local and Metropolitan networks- Specific requirements- Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Enhancements for Higher Throughput”, July 2006.

[8] M. Haardt, A. Alexiou, "Smart antennas and related technologies" WWRF - WG4 White Paper, May 2005.

[9] Jelena Mirkovic, Georgios Orfanos, Hans-Jürgen Reumerman, "MIMO Link Modeling for System Level Simulations", accepted to PIMRC, Helsinki, Finnland, Sept. 2006.

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

[11] G. Orfanos, J. Habetha and W. Butsch, “Efficient Power Control for MC-CDMA based W-LANs,” in Proceedings of 11th European Wireless Conference 2005, vol. 1, pp. 365–371, Nicosia, Cyprus, Apr. 2005.