DCF/DSDMA: Enhanced DCF with SDMA Downlink Transmissions for WLANs

Ruizhi Liao, Boris Bellalta, Cristina Cano and Miquel Oliver
NeTS Research Group
Department of Information and Communication Technologies
Universitat Pompeu Fabra
Roc Boronat 138, 08018, Barcelona, Spain
{*ruizhi.liao, boris.bellalta, cristina.cano, miquel.oliver*}*@upf.edu*

***Abstract*—Multi-user MIMO is a promising technology to enhance the performance of WLANs. However, the MAC protocol of the IEEE 802.11 standard (the DCF MAC protocol) is not able to solve the new coordination and synchronization issues that are needed to enable multiple simultaneous transmissions. This paper presents an enhanced MAC protocol for Downlink SDMA in WLANs where only the Access Point is equipped with multiple antennas. Compared to the traditional WLANs, results show that the proposed protocol is able to exploit the benefit of multiple antennas at the Access Point, providing significant performance gains in terms of throughput and delay as well as the most suitable number of active users that a WLAN can support.**

***Index Terms*—MU-MIMO, MAC, SDMA, downlink, WLANs**

I. INTRODUCTION

In the last decade, IEEE 802.11 Wireless Local Area Networks (WLANs) have been widely deployed due to their merits, for example, low cost and simplicity. However, the throughput of a WLAN is, sometimes, less than half of the Physical layer (PHY) raw data rate because of the collisions, inter-frame spaces and protocol overheads [1][2], which can not be mitigated by increasing the transmission rate only.

Multiple-Input Multiple-Output technology (MIMO), in both Single-User MIMO (SU-MIMO) and Multiple-User MIMO (MU-MIMO) configurations, provides a new direction to improve the performance of WLANs by exploiting the spatial dimension that becomes available due to the presence of multiple antennas. SU-MIMO is able to provide a significant improvement when most of the traffic load is directed to only a few number of multiple-antenna Mobile Nodes (MNs) by using the multiple spatial streams in point-to-point communications. The IEEE 802.11n-2009 [3], which is a recent amendment to the IEEE 802.11-2007 [4], is able to improve the system throughput compared to the two previous standards (the 802.11a and 802.11g) by introducing SU-MIMO. For instance, the use of four spatial streams, together with a channel width of 40 MHz, achieves a significant improvement in the maximum raw data rate, which is increased from 54 Mbit/s to 600 Mbit/s. On the other hand, MU-MIMO is able to enhance the system performance in scenarios with a high number of active MNs, and among where the traffic is uniformly distributed. Additionally, MU-MIMO only requires multiple-antennas at the AP. In the downlink, the AP can transmit multiple frames to different MNs simultaneously, increasing the system throughput and reducing the AP bottleneck effect; In the uplink, MNs can communicate with the AP at the same time to reduce collisions.

In this paper, both SU-MIMO and MU-MIMO are used to refer to the PHY layer techniques, which allow to take benefits of the spatial dimension of the channel. In comparison, Space Division Multiple Access (SDMA) is used to refer to a channel access scheme that uses the MIMO techniques to multiplex different frames (data streams) over that space dimension. There are two challenges that need to be tackled before SDMA is applied to WLANs: firstly, in the downlink, the AP needs the Channel State Information (CSI) feedback from MNs for the frame/destination selection and precoding scheme, which can be solved by acquiring the CSI embedded in the Clear-to-Send (CTS) message or by directly estimating it at the AP from the frames received; secondly, in the uplink, MNs need to be coordinated and synchronized, which are much more complicated as MNs access the channel in a distributed and asynchronous way, thus requiring more signalling and message exchanges [2]. Additionally, the traffic characteristics from Internet, where the downlink traffic is usually much higher than the uplink, make less urgent to exploit the benefits of SDMA in the uplink. Therefore, in this paper, a SDMA-enhanced MAC protocol focusing only on the downlink transmission is proposed. In the uplink, MNs will operate as the conventional Distributed Coordination Function (DCF) mechanism, although with some modified parameters such as the EIFS and the Collision Timer.

The rest of the paper is organized as follows: Section II gives a brief review of the related work, then in Section III the scenario and system parameters of the simulation are introduced. After that, Section IV presents the proposed SDMA MAC protocol while Section V evaluates the performance of the proposed approach. Finally, Section VI concludes the paper.

II. Related Work

The MU-MIMO technology has became an important research topic due to its potentials to improve the performance for the next generation wireless systems without utilizing additional frequency bandwidth or transmitting power. As a result, extensive research efforts have been seen in different areas such as signal processing [5], [6], coding/precoding schemes [7], [8], queueing theory [13], [14], and, the one in which we are interested, medium access control for WLANs [1], [2], [9], [10], [11], [12].

In downlink SDMA WLANs, the channel access, scheduling and CSI acquisition are the three most important issues that need to be addressed in the design of the MAC protocol. A DCF scheme with the necessary modifications for the MIMO support is presented in [15]. Request-to-Send/Clear-to-Send (RTS/CTS) frames are modified to exchange the antenna selection information. Similar works could be found in [1], [10]. In [12], a multiuser downlink transmission scheme is presented without RTS-CTS exchanges, but how to synchronize before the transmission is not specified. In [2], the authors propose a dual-mode CTS responding mechanism to achieve the channel estimation and nodes synchronization in the uplink. Moreover, an analytical model is designed to adapt the system parameters to the channel condition and network load. In [11], the authors discuss four MAC schemes for multiuser downlink transmissions in IEEE 802.11 infrastructure-based WLANs: the first is the MU-Basic scheme that is used as a reference for others; the second is the MU-Deterministic scheme that ensures collision-free CTS transmissions; the third is the MU-Probabilistic scheme that divides the contention window into slots and nodes randomly choose a slot for the CTS transmission, which leads to the existence of collisions; the fourth is the MU-Threshold Selective scheme that is similar to the third one. The difference is that a SNIR threshold is introduced to allow only those nodes who have good channel conditions to take part in the contention phase. The authors present a MIMO-aware MAC scheme in [16] to schedule simultaneous transmissions in a single collision domain, which is achieved by adjusting antenna weights to listen or ignore a particular transmission. An overview of the packet scheduling algorithms for single and multiple antenna wireless systems is given in [17], which advocates the need for a cross-layer consideration in the design of scheduling algorithms. In [7] a two-stage CSI feedback scheme is designed, which includes a first stage dedicated to the scheduling and a second one for the precoding to maximize the sum rate under a fixed feedback constraint. In [18], MNs obtain the CSI via the explicit downlink training, and the uplink feedback is used to provide the base station with the CSI from the MNs.

III. Scenario

A single-hop IEEE 802.11 WLAN consisting of one Access Point (AP) and M MNs is considered. The AP has an array of N antennas, while each MN has a single antenna, which is a reasonable assumption considering MNs' power consumption and cost. A specific scenario for an AP with $N = 4$ antennas is shown in Figure 1.

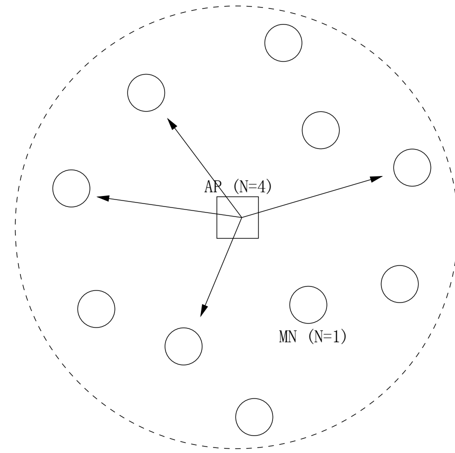


Fig. 1. The considered WLAN scenario with $N = 4$ antennas at the AP and single-antenna MNs

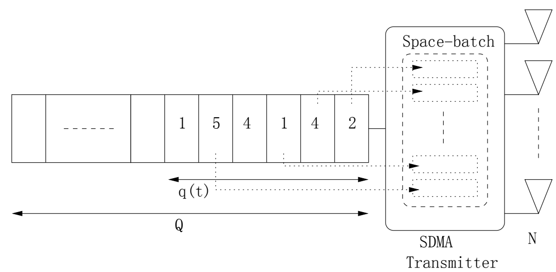


Fig. 2. The SDMA transmission queue and the Scheduler

The channel is assumed frame-flat, with the independent fading from frame to frame. Without loss of generality, it is assumed that the instantaneous channel matrix is always ideally conditioned (i.e. the channel realizations are orthogonal), and hence, the beamforming at the AP is able to completely suppress the multi-user interference without any power penalty. Moreover, a single transmission rate is considered. It is assumed that all MNs always can receive error-free frames at that rate. These assumptions lead to N independent downlink channels, which could allow up to N simultaneous transmissions from the AP to the MNs. In the uplink, as no enhancement is considered in this paper, only one MN is allowed to access the channel each time.

Frames that arrive to the AP follow the Poisson process with a rate λ. The traffic load of the downlink is ten times higher than that of the uplink, which is reasonable because most of the downlink traffic is a response (i.e. an online video) to the requests (i.e. a http request) from MNs.

Through using the spatial multiplexing provided by the MIMO technology, the AP assembles those frames queued at the MAC layer into a Space-batch (a group of frames transmitted simultaneously) according to the destination address, as illustrated in Figure 2, where Q is the buffer size and $q(t)$ the instantaneous queue occupation. The AP selects sequentially all frames that satisfy the condition of being

TABLE I
SYSTEM PARAMETERS

Parameters	Values
AP Bandwidth per MN	200 Kbps
MN Bandwidth	20 Kbps
Data Rate	11 Mbps
Phy/Basic Rate	1 Mbps
Queue Length	20 Frames
Frame Length	4000, 8000 bits
Preamble Length	40 bits
MAC Header/RTS/CTS/ACK Length	160 bits
Slot Time	20 μs
SIFS	10 μs
DIFS	50 μs
CWmin	32
CWmax	1024
Retry Limit	5
AP Antennas	1, 2, 4

directed to different destinations. Note that, the first frame waiting in the queue is always selected, and then, up to N frames. Frames in transmission are not dequeued until they are completely transmitted.

The data rate is fixed at 11 Mbps, while the physical and basic rates are fixed at 1 Mbps. The relevant parameters considered are listed in Table I.

IV. DCF/DSDMA: ENHANCED DCF WITH SDMA DOWNLINK TRANSMISSIONS

IEEE 802.11 DCF [4] relies on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and the optional RTS/CTS mechanism to share the medium between wireless nodes. The proposed protocol, which is called enhanced DCF with SDMA Downlink transmissions (DCF/DSDMA) extends the DCF mechanism, with the RTS/CTS option enabled, to support multiple simultaneous downlink transmissions. The RTS/CTS mechanism is adopted for two reasons. Firstly, the RTS/CTS mechanism allows the AP to estimate the CSI via the preamble of the replied CTSs from the MNs. The channel information will be used for the precoding scheme at the AP to cancel the multiuser interference. Secondly, the DCF/DSDMA needs to extend the standard RTS to the Multi-User RTS (MU-RTS) frame, as illustrated in Figure 3, as the AP has to specify all receiving addresses of the next Space-batch[1].

For a MU-RTS frame, the type and sub-type fields of the frame are 10 (that denotes a control frame) and 1001 (MU-RTS identifier, one of the non-assigned combinations in the standard [4]), these values allow the receiver to identify the reception of a MU-RTS and process it accordingly.

The DCF/DSDMA conducts some minor changes compared to the conventional MAC protocol operations, as illustrated in Figures 4(a), 4(b), 5(a) and 5(b). The description of the

[1]Note that if a single frame is included in the Space-batch, the MU-RTS is equivalent to a standard RTS.

2 bytes	2 bytes	n * 6 bytes	6 bytes	4 bytes
Frame Control	Duration	n * Receiver Addresses	Transmitter Address	Frame Check Sequence

Fig. 3. MU-RTS Frame Structure

protocol is divided into two parts: successful transmissions and recovering from collisions. Note that, initially in all figures the channel is assumed busy (B), and the random Back-Off time is denoted as BO.

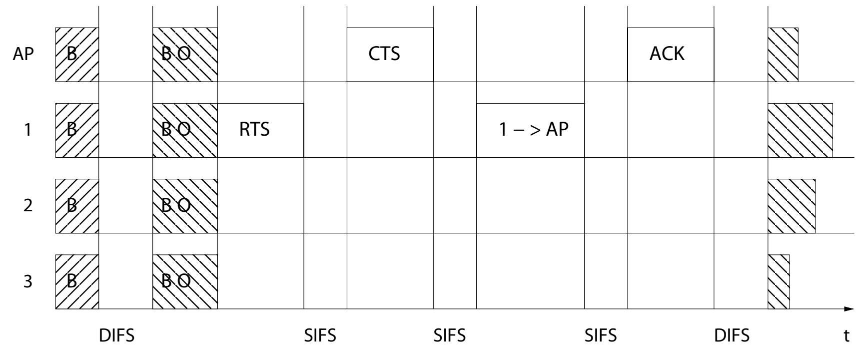
A. DCF/DSDMA: Successful Transmissions

First of all, any node, including the AP, which has frames to send operates like the conventional IEEE 802.11 DCF with the RTS/CTS mechanism: when the medium has been idle for a DCF Inter Frame Space (DIFS) time, after a random backoff time it starts to send an RTS or an MU-RTS based on the number of antenna and the frames in the queue, as previously depicted in Figure 2. If an RTS is sent out, the DCF/DSDMA operates exactly the same as the conventional one, as shown in Figure 4(a). If a MU-RTS is sent out, as illustrated in Figure 4(b), the MNs listed in the receiving field will send a CTS back sequentially (following the same order of their addresses included in the MU-RTS) to confirm that they are ready to receive a frame from the AP. Those MNs who are not included in the MU-RTS will set their Network Allocation Vector (NAV) to defer their transmission activities. The NAV is equal to the duration of the whole transmission in order to reserve the medium. On receiving all the CTS messages (if not all, the AP is going to send frames in parallel only to those who successfully replied with a CTS). Lastly, after the transmission of all frames is completed and a Short Inter Frame Space (SIFS) time, MNs start to send back their respective Acknowledgement (ACK) sequentially in the same order of the CTS.

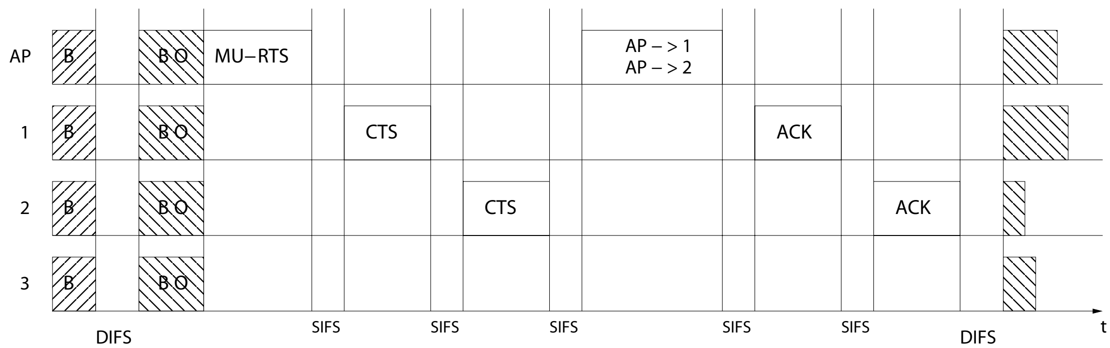
B. DCF/DSDMA: Recovering from collisions

If two (or more) nodes unluckily pick the same BO from their respective Contention Window (CW), which is a MU-RTS and a RTS or two RTS are sent out at the same time, a collision will happen, as illustrated in Figures 5(a) and 5(b), where the dashed lines denote that the frames should be there if the transmission was successful.

In standard DCF, on sending the RTS, the AP and MNs will set a timer equal to Equation (1) to receive the expected CTS, where CTS_{tx} denotes the transmission duration of a CTS. If the CTS is not received before the Collision timer expires, the sending nodes assume that collisions or errors have happened during the transmission, and they can start to compete for the channel again (to retry the transmission of the on-going frame if the maximum retry limit has not been reached, or to transmit the next frame in the queue, if any). For the non-transmitting nodes, none of the RTS can be received correctly, so after the collision time, which is the RTS transmission time, the receiving nodes wait for an Extended Inter frame space (EIFS)



(a) Successful transmission of a MN



(b) Successful transmisssion of the AP

Fig. 4. DCF/DSDMA Successful Transmissions

time, shown in Equation 2, and then they can start competing for the channel again.

$$CTS_{timer} = SIFS + CTS_{tx} \quad (1)$$

$$EIFS = SIFS + CTS_{tx} + DIFS \quad (2)$$

The above mentioned procedure has to be modified due to a longer duration of the MU-RTS and the longer period for receiving the expected CTSs. Otherwise, some issues such as unfairness between the AP and MNs (i.e. the MNs initiate the channel access procedure before the AP) and hidden-terminal problems could appear. In order to prevent these issues, the CTS timer of all nodes has to be set to the new MU_CTS_{timer} (as shown in Equation 3) and the EIFS value to the new MU_EIFS (Equation 4) value. Both parameters have to consider the worst case to make sure that all nodes start competing for the channel at the same time.

It is important to note that in all situations these new values have to be considered for all nodes, even in the scenario when there are only collisions between MNs, as illustrated in Figure 5(b). This is because colliding MNs can not know if they are colliding with the AP or another MN. Obviously, these required changes introduce some overheads such as waiting a longer time when the collisions are between MNs or when the collisions are between the AP and MNs but the AP is sending a Space-batch with less than N frames.

$$MU\_CTS_{timer} = N \cdot (SIFS + CTS_{tx}) \quad (3)$$

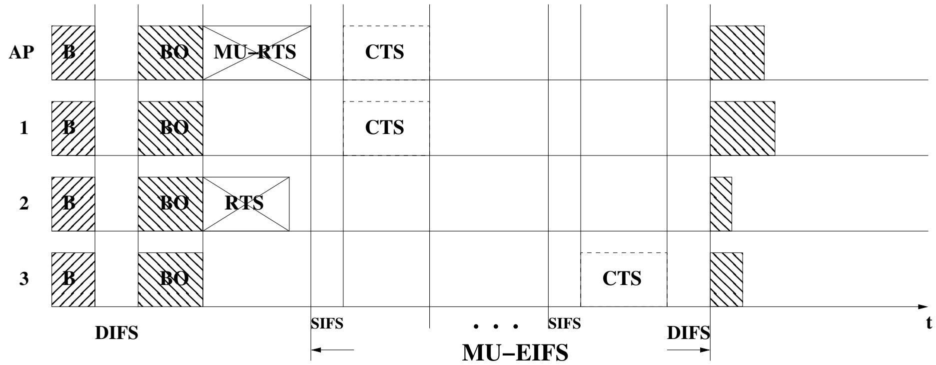
$$MU\_EIFS = N \cdot (SIFS + CTS_{tx}) + DIFS \quad (4)$$

C. Other considerations

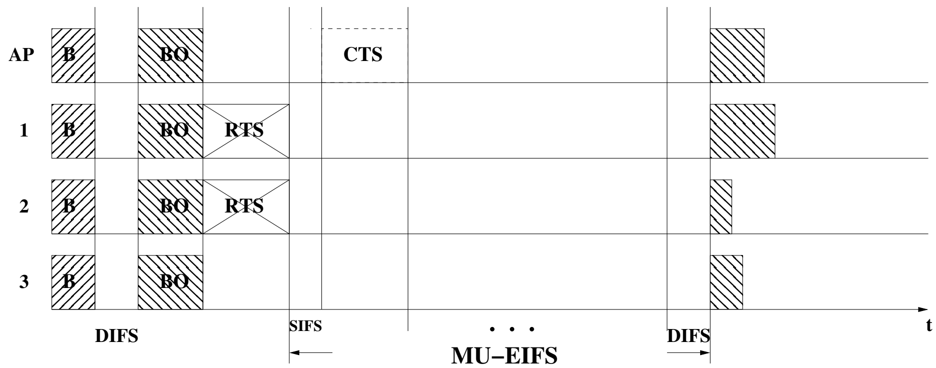
The AP will only send frames to those MNs whose channel condition meets some certain quality and with the compatible channel signatures. As illustrated in Figure 6, the channel between the AP and Node 1 does not reach the required quality, and therefore, the AP will send a frame to Node 2 only. A noticeable thing is that Node 2 has to wait for an extra $SIFS + ACK$ time before it can send its own ACK even if it is the only receiver. This is because the transmission duration and the sequence of sending CTS and ACK are decided in the MU-RTS and all nodes set their NAV timer based on that.

V. Performance Evaluation

The parameters considered to evaluate the proposed DCF/DSDMA are listed in Table I. The Component Oriented



(a) Collision between the AP and a MN



(b) Collision between two MNs

Fig. 5. DCF/DSDMA: Recovering from collisions

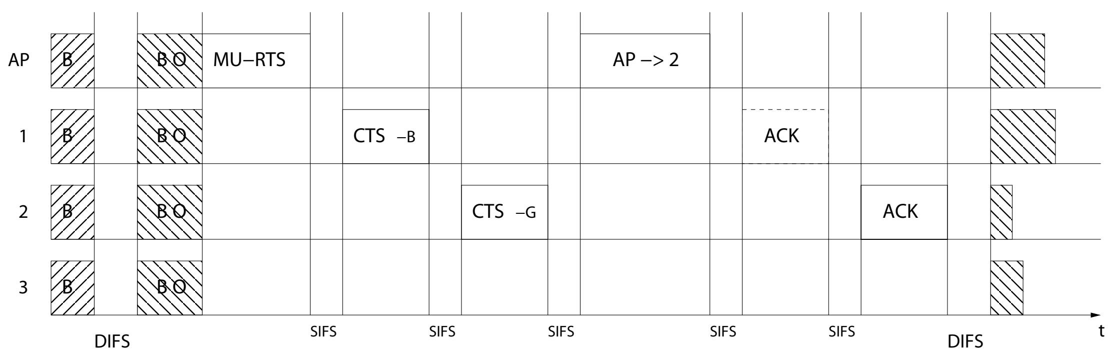


Fig. 6. Unfeasible transmission due to the channel conditions between the AP and the 1-th MN. The (-G) in the CTS means 'good' and the (-B) means 'bad'.

Simulation Toolkit (COST) [19] libraries have been used to implement and simulate the considered system.

The theoretical maximum throughput of the AP using N antennas is shown in Equation 5, where $MU\_RTS_{tx}(N)$ denotes the transmission time of the MU_RTS frame with N receiving addresses. The subscript tx means the transmission duration of the control or data frame. Note that the assumptions made for computing the theoretical maximum throughput are: 1) only the AP is transmitting and 2) the AP is saturated. For instance, considering a frame length L equal to 4000 bits, the maximum achievable throughput following the Equation 5 are $S_{max}(1) = 2.82$ Mbits/s, $S_{max}(2) = 4.24$ Mbits/s, and $S_{max}(4) = 5.66$ Mbits/s, for the AP with $N = 1$, $N = 2$ and $N = 4$ atennas respectively.

Figures 7(a) and 7(b) show the throughput of the AP and MNs. As we can see from Figure 7(a), the throughput of the AP with one antenna (AP-N=1 in the legend) increases proportionally with the number of MNs until it saturates (around 2.54 Mbits/s). Given the considered downlink /uplink traffic distribution, the AP becomes saturated mainly due to its own traffic load, although collisions with MNs can not be neglected, which is why the throughput is decreasing as the number of MNs goes higher after the saturation.

In Figure 7(a), the considerable gain is observed in the AP

$$S_{max}(N) = \frac{N \cdot L}{(DIFS + (Slot \cdot CW_{min}/2) + MU\_RTS_{tx}(N) + N \cdot (CTS_{tx} + ACK_{tx}) + FRAME_{tx} + (2 \cdot N + 1) \cdot SIFS)} \quad (5)$$

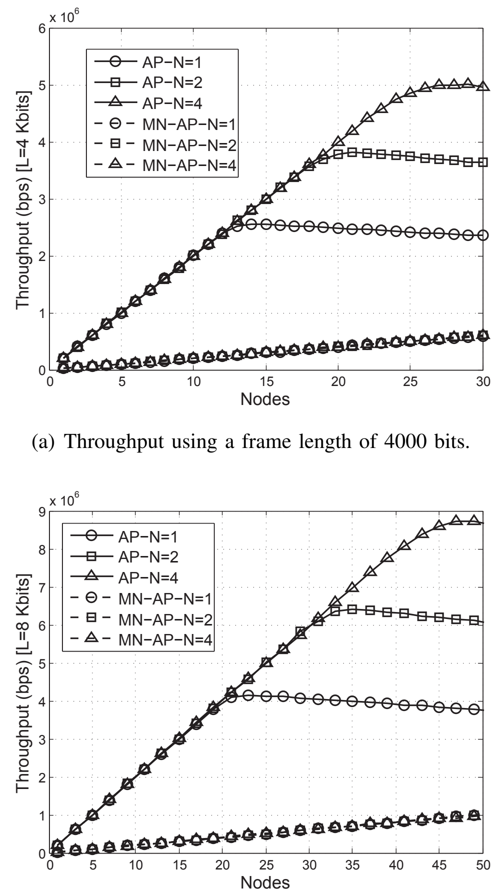
throughput, from 2.54 Mbits/s with $N = 1$ antenna to 3.81 Mbits/s with 2 antennas (AP-N=2 in the legend) and 5.00 Mbits/s with 4 antennas (AP-N=4 in the legend). A noticeable outcome is that the gain is not linear with the increase of the number of antennas, the reason of that is two-fold: 1) the higher service time for each frame due to the backoff interruptions and the higher collisions as the system gets more MNs and 2) the presence of a finite queue as shown in [14] can not take full benefits of employing more antennas at the AP. These reasons also justify the difference between the maximum throughput computed in Equation 5 increasing with N.

In Figure 7(b), significant gains are achieved if a longer frame length ($L = 8000$ bits) is used. For example, the maximum throughput of the AP with $N = 2$ antennas increases from 3.81 Mbits/s in Figure 7(a) to 6.39 Mbits/s in Figure 7(b) and the number of MNs that the wireless system can support goes from 20 to 32 nodes. The main reason is that each Space-batch now includes more bits as the frame length is longer, which makes the overhead of the control messages (i.e. $MU\_RTS_{tx}(N)$) less significant and the WLAN works more efficiently.

Note that in the considered scenario the MNs never become saturated as the aggregate throughput of MNs (Figures 7(a) and 7(b)) increases proportionally with the number of nodes regardless the number of the antennas at the AP.

In Figures 8(a) and 8(b) the delay of the AP is shown. Obviously the average delay decreases significantly by employing multiple antennas. A noticeable aspect here is that the average delay increases significantly at a certain region before the AP becomes saturated. It is called the turmoil region in this paper. For example, the turmoil region for the AP with one antenna in Figure 8(a) is from 10 to 15 nodes and for the AP with one antenna in Figure 8(b) is from 15 to 25 nodes, which could be useful for finding out what is the most suitable number that a wireless network can support.

Finally, it is interesting to observe the average Space-batch size in Figures 9(a) and 9(b) increases as the number of MNs increases. Note that it is load-aware as the size of the Space-batch increases with the number of MNs.



(a) Throughput using a frame length of 4000 bits.

(b) Throughput using a frame length of 8000 bits.

Fig. 7. Throughput against the number of nodes with different transmitting antennas N

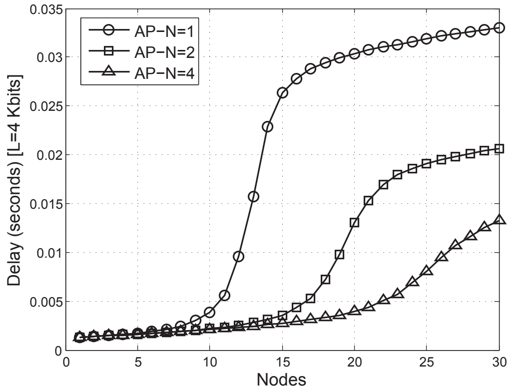
VI. Conclusions

In this work the DCF/DSDMA protocol has been presented. The results show that considerable performance gains, in terms of a higher throughput and lower delays, are achieved by employing multiple antennas at the AP. However, the results also show that the achieved gain is neither linear with the number of antennas nor the frame length due to the extra overheads of the DCF/DSDMA, the own behavior of the DCF and the presence of a finite queue length.

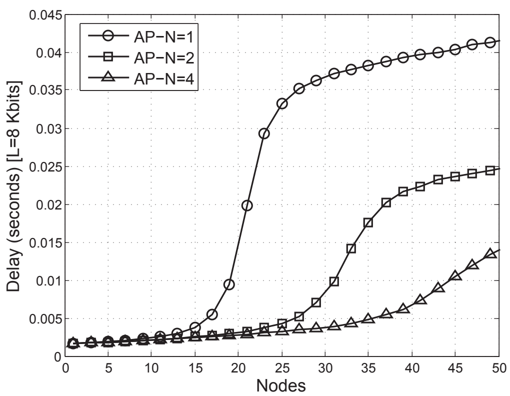
Next steps will focus on the consideration of SDMA transmissions in the uplink, the use of a realistic channel model, including the impact of the beamforming at the AP for the downlink transmissions, the post-processing for the uplink ones, as well as the presence of channel errors and different transmission rates. Another important issue to be addressed is the coexistence between legacy stations using the conventional DCF and those using the DCF/DSDMA protocol.

Acknowledgments

This work has been partially supported by the Spanish Government under projects TEC2008-0655/TEC (GEPETO, Plan Nacional I+D), CSD2008-00010 (COMONSENS, Consolider-Ingenio Program) and by the Catalan Government (SGR2009#00617).

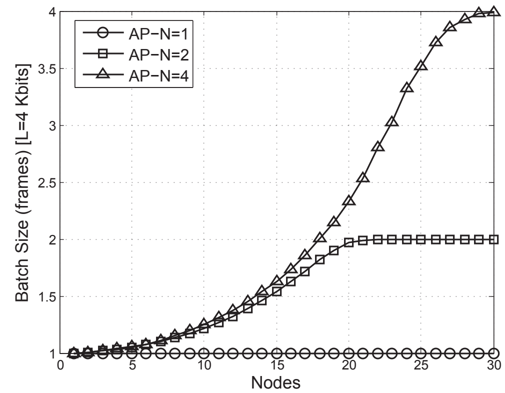


(a) Delay using a frame length of 4000 bits.

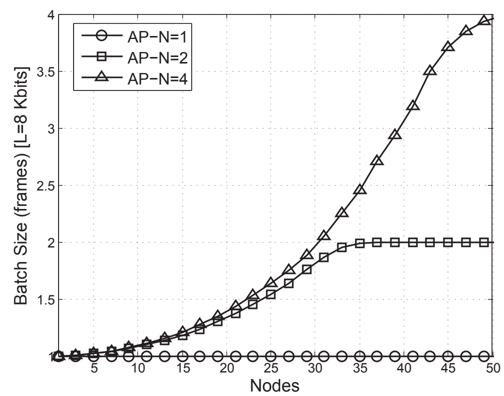


(b) Delay using a frame length of 8000 bits.

Fig. 8. Average Delay against the number of nodes with different transmitting antennas N



(a) Average Space-batch using a frame length of 4000 bits.



(b) Average Space-batch using a frame length of 8000 bits.

Fig. 9. Average Space-batch against the number of nodes with different transmitting antennas N

REFERENCES

[1] L.X. Cai, H. Shan, W. Zhuang, X. Shen, J.W. Mark and Z. Wang. *A Distributed Multi-User MIMO MAC Protocol for Wireless Local Area Networks*. IEEE GLOBECOM, pp. 1-5, 2008.

[2] S. Zhou and Z. Niu. *Distributed medium access control with SDMA support for WLANs*. IEICE Transactions on Communications, pp. 961-970, 2010.

[3] IEEE 802.11n-2009, *Amendment 5: Enhancements for Higher Throughput*. Standard, IEEE, 2009.

[4] IEEE 802.11-2007, *IEEE 802.11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*. Standard, IEEE, 2007.

[5] L. Tong, V. Naware, and P. Venkitasubramaniam. *Signal processing in random access*. IEEE Signal Processing Magazine, pp. 29-39, 2004.

[6] Q.H. Spencer, C.B. Peel, A.L. Swindlehurst and M. Haardt. *An Introduction to the Multi-User MIMO Downlink*. IEEE Communications Magazine, pp. 60-67, 2004.

[7] R. Zakhour and D. Gesbert. *A Two-Stage Approach to Feedback Design in Multi-User MIMO Channels with Limited Channel State Information*. IEEE 18th International Symposium on PIMRC, pp. 1-5, 2007.

[8] N. Jindal. *MIMO Broadcast Channels with Finite Rate Feedback*. IEEE Transactions on Information Theory, pp. 5045-5059, 2006.

[9] P.X. Zheng, Y.J. Zhang and S.C. Liew. *Multipacket Reception in Wireless Local Area Networks*. IEEE International Conference on Communications, pp. 3670-3675, 2006.

[10] J. Mirkovic, J. Zhao and D. Denteneer. *A MAC Protocol with Multi-User MIMO Support for Ad-Hoc WLANs*. IEEE 18th International Symposium on PIMRC, pp. 1-5, 2007.

[11] E. Kartsakli, N. Zorba, L. Alonso and C. Verikoukis. *Multiuser MAC Protocols for 802.11n Wireless Networks*. IEEE International Conference on Communications, pp. 1-5, 2009.

[12] Y.J. Choi, N.H. Lee and S. Bahk. *Exploiting Multiuser MIMO in the IEEE 802.11Wireless LAN Systems*. IEEE International Conference on Communications, pp. 385-396, 2009.

[13] B. Bellalta and M. Oliver. *A space-time batch-service queueing model for multi-user MIMO communication systems*. 12th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems, pp. 357-364, 2009.

[14] R. Liao, B. Bellalta, M. Oliver and N. Garcia. *A Queueing Model for SDMA Downlink Transmissions*. Multiple Access Communications, pp. 74-78. Springer Berlin Heidelberg, 2010.

[15] J. Mirkovic, G. Orfanos, H.J. Reumerman and D. Denteneer. *A MAC Protocol for MIMO Based IEEE 802.11 Wireless Local Area Networks*. IEEE Conference on Wireless Communications and Networking, pp. 2131-2136, 2007.

[16] D.J. Dechene, K.A. Meerja, A. Shami and S. Primak. *A Novel MIMO-Aware Distributed Media Access Control Scheme for IEEE 802.11 Wireless Local Area Networks*. IEEE Conference on Local Computer Networks, pp. 125-132, 2007.

[17] C. Anton-Haro, P. Svedman, M. Bengtsson, A. Alexiou, and A. Gameiro. *Cross-Layer Scheduling for Multi-User MIMO Systems*. IEEE Communications Magazine, pp. 39-45, 2006.

[18] M. Kobayashi, G. Caire and N. Jindal. *How Much Training and Feedback are needed in MIMO Broadcast Channels?*. IEEE Communications Magazine, pp. 2663-2667, 2008.

[19] G. Chen. *Component-oriented simulation toolkit*. http://www.ita.cs.rpi.edu/sense/cost.html, 2004.