MAC-PHY Enhancement for 802.11b WLAN Systems via Cross-layering

Luis Alonso, Ramón Ferrús, Ramón Agustí
Dept. of Signal Theory and Communications - Polytechnic University of Catalonia (UPC)
c) Jordi Girona 1-3. Campus Nord. Edifici D4. 08034.-Barcelona. Spain
Phone: 34-93-401 71 95 Fax: 34-93-401 72 00 e-mail: [luisg, ferrus, ramon]@tsc.upc.es

***Abstract*—This paper analyses the performance of a novel MAC-PHY scheme for wireless local area networks (WLAN) that makes use of distributed queues and cross-layer concepts to improve radio channel utilisation. Analytical values for the maximum throughput performance are derived as a function of different scenario parameters. The obtained results show that the proposed scheme outperforms throughput bounds achieved when using a legacy 802.11 MAC protocol. The usage of distributed queues and cross-layer information eliminates back-off periods and collisions in data packet transmissions, makes performance to be independent of the number of stations transmitting in the system and provides stability for high load conditions. Furthermore, the cross-layer concept allows MAC layer to improve its decisions by means of physical layer information knowledge.**

Keywords: IEEE 802.11, MAC, expected effective throughput, Cross-layer dialogue

I. INTRODUCTION

A great variety of Medium Access Control (MAC) schemes have been developed and studied for wireless communication systems in the last years. All these proposals pursue the objective of efficiently manage the scarce radio frequency spectrum resource.

On the other hand, when considering any wireless communication system, many upper-layer entities, such as MAC, radio link control, RRM or even routing algorithms, could benefit from some degree of awareness concerning PHY layer state. Substantial benefits in terms of throughput improvement, reduction of the network latency, energy saving, minimization of transmitted power and reduction of human exposure to radiation would be expected to follow from this cross-layer concept.

Focusing in the possibility of getting a certain throughput improvement in a WLAN environment, the system performance of the standard 802.11 MAC mechanism has been analysed. From this analysis, it is clear that the throughput is remarkably degraded due to the presence of collisions and back-off periods. Then, the elimination of such wasted intervals should produce a throughput improvement.

With this ideas in mind, a distributed MAC scheme based on distributed queues [1]-[2] and using cross-layering concepts [3]-[4] has been proposed in order to improve radio channel utilisation. The proposed scheme, called Distributed Queuing Collision Avoidance (DQCA), is a distributed always-stable high-performance protocol that behaves as a random access mechanism for low traffic load and switches smoothly and automatically to a reservation scheme when traffic load grows. The key feature of the proposed scheme is that its distributed queues and embedded cross-layer mechanisms eliminate the collisions and back-off periods in data packet transmissions. Furthermore, the cross-layer dialogue, inherently included in the system, is used to properly manage the MAC transmissions and select the most appropriate PHY level data rate.

In order to get a measure of the potential obtainable benefit of using this novel proposal, analytical results on maximum throughput are obtained in a scenario where signal-to-noise ratio (SNR) variation is modeled by a two-state discrete Markov chain.

The paper is organised as follows. Section II addresses the achieved performance in terms of throughput of a legacy 802.11 MAC protocol, showing the potential available margin for improvement. Section III is devoted to the description of the novel proposal and its performance efficiency. In Section IV we go further in detail of the cross-layer mechanism embedded in the proposal, while Section V shows the comparison of the standard and the novel proposal features. Finally, Section VI summarizes the conclusions of the paper.

II. THROUGHPUT BOUNDS FOR 802.11 MAC

A. Overview of 802.11

802.11 MAC standard is based on CSMA/CA protocol. As it is shown in Figure 1, a Virtual Transmission Time (VTT) is defined as the period to successfully transmit a packet and takes into account ACKs transmissions, contention periods where back-off mechanisms are applied, inter-frame spaces (IFS) and the possibility of multiple retransmission attempts due to collisions or erroneous reception caused by the presence of fading or noise.

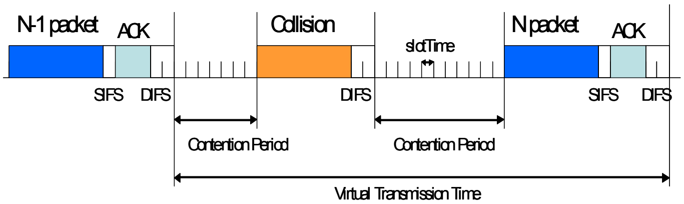

Figure 1. Transmission scheme for a data packet with CSMA/CA

Note that contention periods and possible presence of collisions are wasted intervals that limit the maximum achievable throughput. For further description on the 802.11 MAC operation refer to [5].

This research was supported by CYCIT project TI2001-2222

B. Throughput bounds for 802.11 standard

In order to evaluate the potential available margin for throughput improvement in 802.11 systems, analytical bounds for its achievable throughput have been calculated. The reference scenario is defined by a set of parameters taken from the 802.11b extension of the standard. In particular, parameters concerning physical layer are provided in Table 1 while Table 2 contains the length of the frames defined within the MAC layer.

Table 1. PHY level dependent parameter values.

t_s (aSlotTime)	20µs
SIFS	10µs
DIFS(=SIFS+2·t_s)	50µs
t_p	1µs
***W*min**	31
***W*max**	1023
Physical Header	96µs

Table 2. Frame formats in MAC Layer

MAC Header+FCS	30+4 bytes
Payload	0-2312 bytes
ACK	14 bytes
RTS (Request To Send)	20 bytes
CTS (Clear To Send)	14 bytes

Using the values from Table 1 and Table 2 the throughput of the system can be numerically evaluated in percentage of useful radio channel occupancy [6]. Figure 2 shows the variation of the system throughput versus the number of mobile stations when considering a constant packet length of 2312 bytes and 11 Mbps transmission rate. Two cases have been considered: with RTS/CTS and without RTS/CTS (RTS/CTS mechanism is included in 802.11 to reduce the number of packet collisions in front of what is called the hidden terminal problem). As it is observed from the Figure 2, the maximum achievable throughput is not higher than 77%. This maximum bound is obtained when only 2 stations compete for the channel and RTS/CTS is not used. But without using RTS/CTS, if the number of stations increases, throughput suffers a considerable reduction due to the effect of contention and collision. On the other hand, when RTS/CTS is applied, 802.11 MAC is capable of maintaining a throughput around 73% when the number of stations increases but throughput also suffers an important degradation when having few stations in the system due to the overhead of the RTS/CTS mechanism.

It is worth to note that in case of beeing able to eliminate contention periods and collisions within 802.11 MAC operation, the maximum theoretical throughput obtained would be increased up to 85% for any number of stations when not using RTS/CTS. This value has been calculated from expressions in [6] by assuming that no time is wasted in contention and collisions in a VTT period. So, in case of considering 20 stations, improvement due to congestion elimination could be as high as 20% in useful channel occupancy. The DQCA scheme described in the following will exploit this fact.

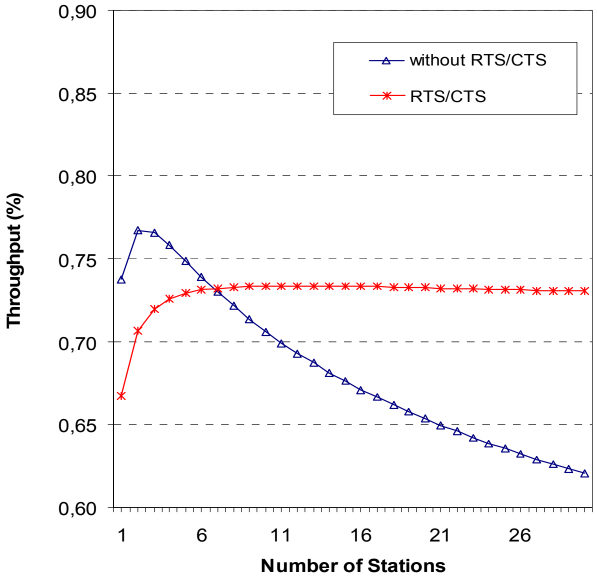

Figure 2. 802.11b performance (Constant packet length of 2312 bytes)

III. THROUGHPUT BOUNDS FOR DQCA NOVEL MAC PROPOSAL

In this section we will describe a novel MAC proposal able to work over 802.11x PHY layer and derive the value of the performance bound that can be achieved using it in a wireless communications system. This novel proposal is called Distributed Queuing Collision Avoidance (DQCA). The main objective is to evaluate the benefits that could be obtained from this novel mechanism.

A. DQCA Description

DQCA is based on a MAC scheme presented in [1] for a CDMA environment. The idea is to apply the same mechanism as if only one code is available (one frequency channel). It is a distributed always-stable high-performance protocol that behaves as a random access mechanism for low traffic load and switches smoothly and automatically to a reservation scheme when traffic load grows, so as the better of both mechanisms could be retained.

The proposed mechanism has the following main features:

- It eliminates back-off periods and collisions in data packet transmissions.
- Its performance is independent of the number of stations transmitting in the system.
- It is stable for whichever the traffic conditions are.
- It inherently includes a cross-layer mechanism that allows to properly manage packet data transmissions.

This MAC protocol is based on two distributed queues. They are the Data Transmission Queue (DTQ), devoted to the data packet transmission scheduling, and the Collision Resolution Queue (CRQ), devoted to the collision resolution algorithm.

These two queues are simply represented by four integer numbers. Each node has to maintain and update this numbers each frame based on a simple feedback information broadcasted by the Access Point through a special CTS packet (see below). These four numbers are denoted by TQ, RQ, pTQ and pRQ. TQ is the number of messages waiting for transmission in the DTQ. RQ is the number of collisions waiting for resolution in the CRQ. pTQ is the node position within the DTQ. pRQ is the node position within the CRQ.

We remark that TQ and RQ values have to be always the same for all nodes (i.e. they represent distributed queues) while pTQ and pRQ may differ from node to node as they denote the positions within the queues of each node.

Moreover, some short time interval is reserved for access attempts in each frame, which are represented with a special RTS packet (see below). The basic idea of the MAC protocol is to concentrate user accesses and collisions in this reserved control interval while the rest of the frame is devoted to collision-free data transmission.

A node that has just arrived to the system and has data to transmit must check the state of both the distributed queues in order to decide whether it is enabled to attempt a system access request or a data transmission. Users will be forbidden from attempting accesses if there are collisions pending to be resolved. This is a key feature of the protocol as avoids unstable situations. If the user is enabled to access, it will randomly select one of the control slots defined inside the control sub-frame and transmit an access request at this moment.

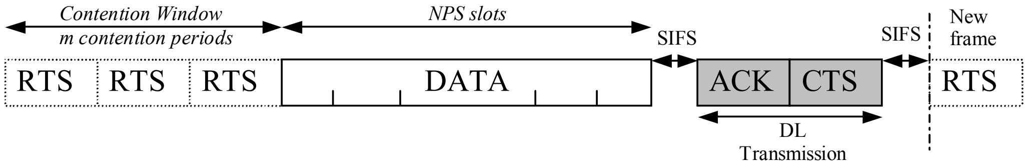

Figure 3. Frame structure of DQCA

After an access request transmission, two situations are possible:

1. No other node has transmitted an access request at the same moment. In this case the access request will be successful and the accessing node will enter the DTQ getting a valid value for its pTQ (pTQ>0). In this queue it will wait for its turn to transmit a data packet and it will be inhibited from sending new access requests. That is, when its pTQ gets the value 1 then it will transmit a data packet in the next frame.
2. One or more other nodes have transmitted access requests at the same time. In this case the access request will collide and the node will enter the CRQ, getting a valid value for its pRQ (pRQ>0). In the CRQ it will wait for its turn to transmit a new access request in order resolve the collision. That is, when its pRQ gets the value 1 then it will transmit an access request in the next frame.

Furthermore, an ALOHA-like data access transmission is allowed when the DTQ is empty. This feature allows the presence of collisions in data transmissions, but it also improves the delay performance for light traffic conditions.

Figure 4 shows the frame structure of the novel MAC proposal. The successful transmission of a data packet involves one whole frame. The frame duration includes 5 time intervals, that are:

- A Contention Window, with fixed length, divided into *m* contention periods wherein special simplified RTS packets are sent as access requests.
- A Data Transmission interval, where data packets are sent from stations. The duration of this period is defined as NPS slots, and could be variable.
- A SIFS interval.
- A Down-link (DL) Transmission interval, where ACK and CTS information is broadcasted by the Access Point. ACK information is the normal acknowledgement information referring to data transmission, while CTS information refers to the detection state of the previous *m* contention periods of the Contention Window. This state is, for each period, one of three possibilities: empty, success or collision. This PHY information is used at MAC level in order to schedule transmissions (cross-layer concept).
- Another SIFS interval before the beginning of the next frame.

For the rest of the details on the MAC protocol operation refer to [1] and [2].

B. Throughput bounds for DQCA

As derived from [1]-[2], DQCA is able to achieve a maximum stable relative channel usage up to the channel capacity, taking into account the reduction of capacity due to time intervals devoted to transmit control information.

Therefore, we can evaluate the relative throughput from the average transmission time of a data packet (T_m) and the total duration of a frame (T_v) as:

$$\rho = \frac{T_m}{T_v}$$

The duration of a frame can be expressed as:

$$T_v = T_s + T_{access} + T_{feedback}$$

where T_s is the time the channel is busy for a successful transmission, T_{access} is the duration of the Contention Window and $T_{feedback}$ is the time devoted to DL control information transmission.

The value for T_s can be calculated as:

$$T_s\text{=Physical\_Header+MAC\_Header+}T_m\text{+}t_p$$

where Physical_Header represents the synchronisation period (PHY level), MAC_header is the time needed to transmit the MAC header bytes and t_p is the channel propagation delay.

The value for T_{access} is:

$$T_{access}=m\cdot\text{RTS}$$

where RTS stands for the period of time needed to transmit the access request represented by special RTS packets (see above). It is not necessary to take into account the propagation delay as the data transmission is allowed to start without waiting for access request processing. Finally, $T_{feedback}$ can be evaluated as:

$$T_{feedback}=2*\text{SIFS+DL+}t_p$$

where DL stands for the duration of the down-link transmission (ACK+CTS information).

In this conditions, the resulting throughput value ρ is:

$$\rho=\frac{T_m}{T_s+T_{access}+T_{feedback}}= \qquad (1)$$

$$=\frac{T_m}{(3+m)Phy\_H+MAC\_H+T_m+2t_p+m\cdot RTS+2\cdot SIFS+DL}$$

Note that throughput values could be improved reducing the size of control intervals (denominator of (1)), in particular RTS access request packets could be minimized as the PHY level only needs to detect three different states (empty, success, collision) [2]. CTS feedback information could be also reduced to only 6 bytes, which contain information enough for the nodes to execute the MAC protocol algorithm. Summarizing, the values for all the parameters are the ones shown in Table 1 and Table 2, except for:

- Duration of RTS access requests transmissions is reduced to only 2 µs as no data information is needed to be carried.
- DL information uses only 13 bytes in total, with the following field details:
  - 2 bytes for Frame Control field
  - 1 byte for ACK information
  - 6 bytes for feedback information needed for DQCA operation
  - 4 bytes for FCS field (error control)

Table 3 shows the throughput values obtained with these considerations, when substituting in expression (1) the corresponding parameter values, and for m=3.

Table 3. Maximum throughput bounds in percentage (packet length 2312 bytes)

	PHY level data rate	Throughput bound (%)
802.11b	1 Mbps	97.84 %
802.11b	2 Mbps	97.67 %
802.11b	5,5 Mbps	97.10 %
802.11b	11 Mbps	96.21 %

These values have been obtained with the maximum allowed packet size for 802.11, that is, 2312 bytes. This size has been kept constant for any number of nodes in the system.

It can be observed that all the values outperform even the maximum theoretical ideal throughput bounds for 802.11b operation.

IV. CROSS-LAYER DIALOGUE

DQCA protocol inherently includes a cross-layer dialogue as PHY layer state information from the receiver node is passed to the transmitter node MAC layer in order to manage the transmission queue. Furthermore, the transmission of access requests can be used to accurately estimate the channel state. DQCA exchanges in each frame a downlink packet which includes information about the PHY state of the Contention Window. Indeed, together with the access request detection state, the CTS packet is able to include the appropriate selection of the PHY transmission mode in order to maximize the net absolute throughput. This selection is performed based on the channel state detected in the RTS transmission.

Furthermore, the state information from the PHY level can be useful in order to properly schedule the transmissions of the DTQ (see section III.A).

Using DQCA, channel conditions estimated upon RTS reception, and notified to the transmitter through the CTS packet, should be correlated with the observed conditions when the transmission of a data packet is carried out by the mobile terminal. The degree of time-correlation of the fast fading process in the radio channel could be estimated by means of the maximum Doppler frequency deviation f_d. For example, in the case of usual speeds in an indoor system of 1m/s, the Doppler frequency is f_d=8Hz at 2.4GHz and the channel correlation (coherence time) is higher than 50% for a 500ms elapsed time. The longest packet to be transmitted lasts 20 ms at 1Mbps while the mean packet delay due to the protocol operation is about 280 ms for a traffic load close to the maximum system capacity [2], therefore, the PHY scheme is feasible for a WLAN environment.

V. THROUGHPUT COMPARISON

In order to validate the proposed approach, a scenario with N always-active stations has been selected. The SNR model for the wireless channel variation is a two-state discrete Markov chain [7]. With this model, the channel can be in two possible states, *good* and *bad*, and within each state, a uniform random variable determines the SNR value for the transmissions. Table 4 shows the model settings used.

Table 4. Channel model settings

Channel State	**Probability**	**SNR (uniform)**
Good	0.80	[10-20] dB
Bad	0.20	[0-10] dB

Consequently, a set of SNR thresholds should be defined in order to select the appropriate data rate for PHY transmissions. These thresholds have been selected based on the results presented in [8] and are shown in Table 5.

Table 5. Data rate thresholds

Rate	1 Mbps	2 Mbps	5.5 Mbps	11 Mbps
SNR	<4 dB	4-7.5 dB	7.5-11 dB	>11 dB

An ideal SNR detection and perfect rate selection scheme is supposed to exist for the 802.11 MAC operation (ideal link adaptation).

Figure 4 shows the comparison between the obtained throughput using the two different techniques of the 802.11b MAC and the proposed scheme (DQCA) versus the packet length and for N=2 and N=20 stations. The presented results assume the transmitter buffers always have packets to send (saturation).

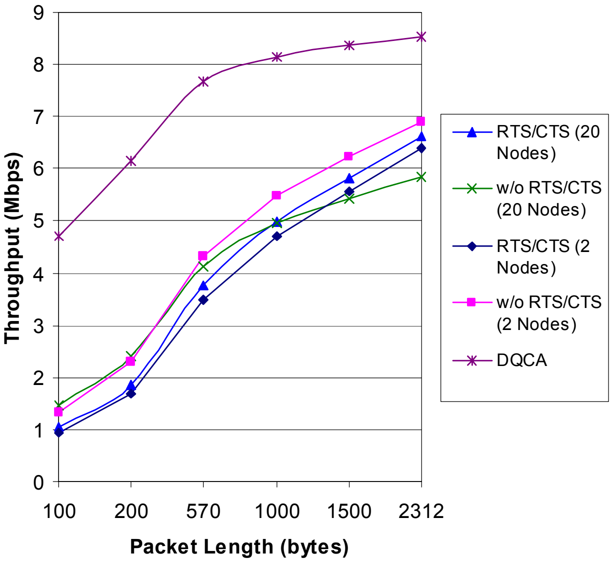

Figure 4. Achievable estimated throughput improvement

As it was expected from previous analysis in section II, throughput values for 802.11 MAC mechanism depends on the number of stations. Results shown in the figure for this access scheme indicates that for N=2 stations, independently of the packet length, the maximum throughput is obtained without using RTS/CTS. However, when the number of stations is N=20, the usage of RTS/CTS allows the throughput to be increased when packets are longer than 1000 bytes. Focusing now in the DQCA scheme, we can observe that results obtained improve significantly the system capacity over 802.11 MAC. Furthermore, it is worth to note that DQCA is able to maintain throughput values for any number of nodes N in the system. In fact, under this scheme, throughput value will keep always constant, and only the packet delay will be increased when the traffic load exceeds the PHY level capacity. Observe that with DQCA the length of the data packets can be variable, and, like in the 802.11b standard, the system efficiency is improved when packets grow in bit size.

VI. CONCLUSIONS

A novel MAC proposal, named DQCA, for WLAN systems has been presented and its performance has been analysed for a representative system scenario.

Using DQCA represents a throughput improvement for this situation, when compared to the legacy 802.11 MAC protocol. This benefit is obtained by means of a distributed queuing MAC protocol and an inherently embedded cross-layer mechanism which eliminate collisions and back-off periods in data packet transmissions.

Under the studied scenario, a minimum of a 25% throughput improvement in terms of effective data rate can be obtained over conventional 802.11b using the novel MAC-PHY scheme.

REFERENCES

[1] L. Alonso, R. Agusti, O. Sallent, "A near-optimum MAC protocol based on the distributed queueing random access protocol (DQRAP) for a CDMA mobile communication system", IEEE Journal on Selected Areas in Communications, Vol. 18, Issue 9, pp. 1701 – 1718. September 2000.

[2] W. Xu, G. Campbell, "DQRAP – A Distributed Queueing Random Access Protocol for a Broadcast Channel", SIGCOMM '93, San Francisco, September 14, 1993. Computer Communication Review, Vol 23, No. 4, October 1993, pp. 270-278.

[3] Yue Fang, A.B. McDonald, "Cross-layer performance effects of path coupling in wireless ad hoc networks: power and throughput implications of IEEE 802.11 MAC", Performance, Computing, and Communications Conference, PCCC'2002. Page(s): 281 –290. 2002.

[4] Wing Ho Yuen, Heung-no Lee, T.D. Andersen, "A simple and effective cross layer networking system for mobile ad hoc networks", Personal, Indoor and Mobile Radio Communications, PIMRC'2002. Vol. 4, pp. 1952 –1956, 2002.

[5] IEEE 802.11, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Standard. IEEE. 1997

[6] Giuseppe Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function", JSAC vol.. 18, nº3, March 2000

[7] D. Qiao, S. Choi, K.G. Shin, "Goodput Analysis and Link Adaptation for IEEE 802.11a Wireless LANs", IEEE Transactions on Mobile Computing, Vol. 1, No. 4, pp. 278-292, October-December 2002.

[8] J. Del Prado, S. Choi, "Link Adaptation Strategy for IEEE 802.11 WLAN via Received Signal Strength Measurement", ICC'03, pp. 1108-1113, Anchorage, Alaska, may 2003.