Opportunistic Scheduling using an Enhanced Channel State Information Update Scheme for WLAN Systems with DQCA

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Opportunistic Scheduling using an Enhanced Channel State Information Update Scheme for WLAN Systems with DQCA

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Abstract—Cross-layer opportunistic scheduling on DQCA-based WLAN systems yields high performance results. This paper emphasizes the need for accurate Channel State Information (CSI) and presents an enhanced mechanism that provides frequent CSI updates. The proposed idea consists in introducing special Update Frames specifically dedicated to channel state estimation. The impact of this mechanism on the performance of the system is evaluated through simulations. The paper shows that there is a trade-off between the overall system performance and the number of Update Frames that are used. The periodicity of these special frames is a parameter that needs to be carefully selected, depending on the channel time-variation characteristics.

Index Terms—Opportunistic Scheduling, cross-layer, rate-adaptive transmission, Channel State Information updates.

I. INTRODUCTION

Over the last decade the Wireless Local Area Network (WLAN) technology has become a very appealing solution to network connectivity. Its popularity is mainly due to the mobility and flexibility that it provides, along with its low-cost and easy deployment. The extensive use of WLANs has led to increased demands in terms of bit rates and Quality of Service.

Our focus is laid on the Medium Access Control (MAC) layer which has a great impact on the performance of the system, being responsible for the channel access and for the scheduling mechanism. A lot of research is being conducted on MAC optimization. Furthermore, the cross-layer concept is a very promising field of investigation [1]. Cross-layer design, unlike the traditional layer architecture, allows the exchange of information between OSI layers. This could be, for instance, the exchange of information between PHY and MAC layers.

Another example of a scheduling mechanism with cross-layer is the use of opportunistic scheduling using channel state information (CSI). Its aim is to encourage transmissions when the wireless channel condition is good and delay them when the channel condition is bad [2]. One way to do that is by giving transmission priority to users with better link conditions. A user with a better channel quality can transmit at higher rates by adapting appropriately its modulation and coding schemes, thus achieving higher throughput values. In addition, the packet transmission time will be reduced, leading to a smaller average mean delay. On the contrary, transmission under harsh channel conditions forces the use of low transmission rates and may suffer from errors. In order to implement this policy, the CSI of all users, which is a PHY layer parameter, must be made available to the MAC layer.

Our research is based on the near-optimum MAC protocol named DQCA (Distributed Queuing Collision Avoidance) which behaves as a random access mechanism under low traffic conditions and switches smoothly and automatically to a reservation scheme when traffic load grows [3], [4]. It has been shown that opportunistic scheduling policies applied on DQCA can significantly enhance the system performance [5], [6]. However, these results were obtained under the assumption that accurate and perfect CSI is available when needed. In reality, the information acquired through channel estimation does not always reflect the actual link condition at the moment when the scheduling decision is taken, due to the time variability of the wireless channel. This may lead to serious performance degradation.

This paper proposes a solution to this problem by introducing special Update Frames dedicated to channel estimation. It will be shown that this mechanism is very efficient despite the introduced overhead.

The rest of the paper is organised as follows: Section II includes an overview of the DQCA protocol, a description of the problem an explanation of the proposed solution. Section III contains the study case scenario and Section IV the simulation results. Some conclusions and future work directions are given in Section V.

II. SYSTEM MODEL

A. DQCA Protocol Description

The detailed description of the DQCA protocol is beyond the scope of this document but can be found in [4]. Only a
brief general description is presented here. A more thorough analysis of the DQCA rules is given in [3] and this reading is probably necessary in order to understand in depth the presented ideas hereafter.

Consider an infrastructure system of \( N \) users that communicate with an Access Point (AP). Time is divided in frames and each frame has three main parts, as shown in Figure 1. The first is the Contention Window (CW) which is subdivided into \( m \) control slots. Each user that wishes to ask for channel access randomly selects a control slot and sends an Access Request Sequence (ARS). A collision resolution algorithm resolves any collisions that occur when more than one ARS are sent in the same control slot. The CW is followed by the data slot during which the currently transmitting user sends its data at a bit rate \( R \). Every data message is fragmented into packets of fixed length \( L \) and only one packet can be sent within a frame. Subsequently, the transmission of a large message occupies a number of consecutive DQCA frames. At the third and last part of the frame the AP broadcasts a Feedback Packet (FBP) that contains the necessary feedback for the implementation of the DQCA protocol. In particular, it contains the ternary–state information for each control slot (success – collision – idle) and an acknowledgment for the transmitted data packet in this frame. Additional information may be included in this packet if the PHY layer supports multi-rate transmission. In this case, the AP calculates the Signal-to-Noise Ratio (SNR) upon the reception of an ARS, estimates the maximum available rate of the corresponding user and includes it in the FBP.

The order in which transmissions take place is determined by a distributed queue denoted as Data Transmission Queue (DTQ). Each user keeps track of two integer counters, \( pTQ \) and \( TQ \), required for the protocol operation. \( pTQ \) has a unique value for each user and represents its position in the DTQ. \( TQ \) counts the number of users waiting in the DTQ and hence has the same value for all users. Each user updates these counters at the end of every frame, after processing the feedback information of the FBP.

The ARS is a burst of energy that does not contain any explicit information, but is sufficiently long so that it can be detected by the AP and can be used for the link estimation and the access detection. Consequently, when an ARS is received at the AP, the AP does not know the identity of the user who actually sent it. However, it is able to detect whether the reception has been correct and it can measure the SNR of the link. The users that have sent an ARS learn whether their petition has been successful or not through the information included in the FBP. In the former case they enter the DTQ and they are also assigned the available rate that corresponds to their estimated channel condition; otherwise the collision resolution algorithm is applied.

In [3], [4] the discipline of the DTQ is FIFO (First-In-First-Out) and the user in the first position of the queue is granted permission to transmit. When opportunistic scheduling is applied (as in [5], [6]), the discipline of the DTQ is altered and a virtual priority function (VPF) is used to determine the transmission order of the users. The selection of the VPF can vary depending on the desired performance metric (for example maximum throughput or fairness). In this paper we consider that the VPF depends only on the available transmission rate which means that the queue is rearranged by placing the users with higher data rates at the highest positions. Thus, at any given time the user with the highest rate (i.e. the best channel condition) transmits so as to provide maximum throughput. The use of PHY layer information (the available rate \( R \), selected upon the SNR of the link) in the Data Link Control (DLC) layer scheduling decisions is the result of the cross-layer dialogue between the PHY and the DLC layers.

### B. Problem Statement

The time-varying nature of the wireless channel is usually characterized by its coherence time \( T_C \). This is the time duration over which the time-domain signal may be considered correlated, i.e. the time over which the channel does not experiment a significant variation [7]. In [5] and [6] the \( T_C \) has been assumed large enough to ensure that the channel remains static throughout the average waiting time of the users in the DTQ. This assumption is crucial to the design of the system because it ensures that the channel estimation performed upon the entrance of a user in the DTQ (after a successful ARS) is still accurate when the user reaches the head of the DTQ and starts the data transmission.

In general, however, the channel condition of the users is likely to change while they are waiting in the DTQ. Two things happen due to the lack of this information. First, the scheduling is not optimum as it is based on outdated information. Second, the users are only aware of the rate that was assigned to them by the AP but ignore any changes of their link condition. Consequently, transmissions occur at higher or lower rates than the optimum, and this fact affects the performance of the system.

This can be clearly seen in Figure 2, where the system throughput was calculated for various packet sizes and for a \( T_C \) of 100ms. The solid lines correspond to the case in which the available CSI always reflects the channel condition at the moment of data transmissions. This is denoted by the ideal case. The dashed lines represent the case in which the available CSI is inaccurate. By the term inaccurate, it is not meant that the channel state detection was erroneous but that the acquired CSI has been outdated due to the elapse of the coherence time. In this case we assume the following:

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**Figure 1** – The standard DQCA frame structure

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• When a user transmits at a higher rate than the optimum one, the packet is considered lost (received with errors). In the next DQCA frame the user selects the immediately lower rate from a predefined set of rates and retransmits the packet. This procedure is repeated until a valid rate is found and the packet is received correctly.
• When a user transmits at a lower rate than the optimum one, it maintains this rate until the completion of the transmission (no rate update is performed).

The AP notifies the users of the upcoming Update Frame in the FBP of the immediately previous DQCA frame with a simple one-bit flag. The time between Update Frames is a parameter that depends on the channel time-varying conditions and needs to be carefully defined, as it will be shown through simulations.

C. Update Frames

The problem described in the above section is caused by the time-varying nature of the wireless channel. A possible solution would be to update the CSI by performing SNR measurements at periodic time intervals. We propose the use of special Update Frames during which all users in the DTQ transmit an ARS. Unlike within the CW of a regular DQCA frame, no collisions take place here since the users transmit in the control slot that corresponds to their DTQ position, expressed by the $p_TQ$ counter (the user in the head of the DTQ transmits in the first slot, the second user transmits in the following slot, and so on). In this occasion, the role of the ARS is not to ask for channel access but to allow the AP to perform link estimation and update the available rates of all users. In the downlink part of the frame the AP broadcasts a FBP that contains the recalculated rates. These updated and accurate values are used to reorganize the DTQ. Therefore, in the following DQCA frames the transmissions will take place using these maximum available rates for each user. The transmission of the FBP also marks the end of the Update Frame and no further notification is necessary.

The performance of the proposed technique has been evaluated in an infrastructure WLAN system where $N$ data users communicate with an AP through a shared radio channel. Without losing generality, the PHY layer follows the IEEE 802.11b specifications and four rates of 1, 2, 5.5 and 11 Mbps are supported, although any set of available data rates could be applied.

A. Channel Model

In the simulations the wireless channel has been modelled as a four-state discrete Markov chain similar to one described in [8], where each state represents one of the four available bit rates. The idea is based on the fact that although wireless channels are characterized by fast-fading, some correlation exists between the current transmission state and the immediately previous state. The Markov chain is represented by a transition matrix $P$ which expresses the probability for each user to select a certain bit rate every time the $T_C$ has elapsed. Once again without losing generality, the matrix $P$ shown below was used in the simulations.

$$P = \begin{bmatrix}
0.5 & 0.4 & 0.1 & 0 \\
0.2 & 0.5 & 0.2 & 0.1 \\
0.1 & 0.1 & 0.5 & 0.3 \\
0 & 0.2 & 0.3 & 0.5
\end{bmatrix}$$

It has also been assumed that, when the rate is properly selected there are no errors during packet transmission.

B. Traffic Model

Data traffic generation is modeled as Poisson-arrival with variable packet sizes that follow an exponential distribution. Their average size is $10L$, with $L$ being the number of bytes transmitted in each frame. The data service does not accept any loss of packets and can tolerate reasonably large delays. A simple Stop&Wait ARQ has been considered.
C. System Parameters

A system with 20 users which generate variable data traffic load has been considered. The parameters concerning the PHY layer were taken from the IEEE 802.11b extension of the standard. The MAC layer parameters are summarized in Table 1. All control packets (ARS, FBP) are sent at the minimum rate of 1 Mbps in order to ensure reliable transmission and backwards compatibility. The FBP contains a vector with all the rates \( R \) of the users in the DTQ. Since there are four possible rate values, \( R \) can be simply represented by 2 bits. Therefore, an overhead of \( 2 \times TQ \) bits, rounded up to an integer number of bytes, is added.

### Table 1 – System Parameters

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>3</td>
<td>Number of control slots</td>
</tr>
<tr>
<td>ARS</td>
<td>10µs</td>
<td>Access Request Sequence</td>
</tr>
<tr>
<td>L</td>
<td>{570, 1000, 2312} bytes</td>
<td>Size of data packets</td>
</tr>
<tr>
<td>R</td>
<td>{1, 2, 5.5, 11} Mbps</td>
<td>Data transmission rate</td>
</tr>
<tr>
<td>MAC</td>
<td>34 bytes</td>
<td>MAC Layer Overhead</td>
</tr>
<tr>
<td>FBP</td>
<td>13 bytes</td>
<td>DQCA Feedback information</td>
</tr>
<tr>
<td>CPL_overhead</td>
<td>( \frac{2 \times TQ}{8} ) bits</td>
<td>Overhead for Cross Layer Opportunistic scheduling</td>
</tr>
</tbody>
</table>

### IV. SIMULATION RESULTS

The impact of the Update Frames on the system performance has been evaluated through simulations. Results on throughput and mean packet transmission delay have been obtained and analyzed. Throughput is defined as the total number of the correctly received bits per second. Mean packet delay is the average waiting time of the data packets from their generation until their correct reception by the AP.

The parameter Data to Update ratio (DU ratio) indicates the frequency of the Update Frames. It expresses the number of standard frames (Figure 1) that are sent between two consecutive Update Frames. For example, a DU ratio of 10 means that an Update Frame is sent every 10 regular frames. Larger DU ratio values correspond to less often updates while smaller values indicate higher update rates.

Figure 4 shows the maximum throughput values achieved for various DU Ratios, for three data packet sizes \( L \) and for \( T_c \) equal to 100ms and 150ms. As shown, the throughput increases with the use of Update Frames. This is obvious since a comparison with Figure 2 reveals that without Update Frames the throughput does not exceed 2.5Mbps (approximately) for a \( T_c \) of 100ms. However, for very often updates on the channel state the throughput is low due to excessive overhead, as every Update Frame is in fact control information. As the DU ratio is increased an optimum region is reached where the throughput is maximized. This optimum region depends on the \( T_c \) and the packet size \( L \). For larger values of \( L \) (\( L=2312 \) bytes) this region is narrower and throughput decreases more steeply as the update packets become less often. For smaller packets (\( L=512 \) bytes) throughput decreases very smoothly even when the DU ratio is large. Finally, the performance is worst for smaller coherence times since the channel changes more rapidly.

![Figure 4 – Maximum Throughput for various Data to Update Ratios](image1)

Figure 5 illustrates the average time interval between two consecutive Update Frames. This time depends on the time duration of the standard frames, which is a function of the data packet size \( L \) and the transmission rate \( R \). For example, for a DU ratio of 26, the time interval for \( L=1000 \) bytes is approximately 43ms and for \( L=2312 \) bytes it is around 100ms (which is also the \( T_c \)). This means that while a DU ratio of 26 may be convenient for packets of 1000 bytes, the same update frequency is not sufficient for packets of 2312 bytes as the average transmission time is higher, and more frequent channel updates are necessary.

![Figure 5 – Average time interval between consecutive Update Frames](image2)
smaller (more often updates) and one bigger (less often updates) than the optimum. The selected DU ratio values were taken from the results of Figure 4. The results are also compared with the system performance when there are no updates (out-of-date CSI) and with the ideal case where perfect CSI is known (without any additional overhead).

The gain from the use of the proposed scheme is remarkable, since even the worst-case improvement for infrequent updates is 69.25% in the maximum achievable throughput. With an optimal selection of DU ratio, the throughput can be increased up to 132.45%.

It can also be observed that between more often and less often updates, the first option is preferable. Although the system performance is significantly enhanced, the ideal case cannot be reached. This is due to the overhead added with the incorporation of the Update Frames and is the price that has to be paid in order to have accurate CSI.

Through simulations it has been shown that when the data packet size is big, there is a need for more frequent Update Frame transmission. Often updates are also required for smaller coherence times that correspond to rapid changing channels.

An interesting topic for future study would be to study the system performance for users with different or variable Tc. The protocol could be further optimized by dynamically adjusting the Data to Update Ratio based on performance metrics.

**REFERENCES**


