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TÍTOL: Application of the DQCA protocol to the optimization of wireless communications systems in cellular environments

AUTOR: Alex Cateura Díaz

DIRECTOR: Luis Alonso Zárate
DIRECTOR EXTERN: Christos Verikoukis

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Author: Alex Cateura Díaz

Director: Luis Alonso Zárate
External director: Christos Verikoukis

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Overview

This final career thesis (Master thesis) is a contribution on the enhancement of wireless communications, specifically WLAN multi-cell systems based on the IEEE 802.11 standard. The objectives were to propose and study different Cross-Layer AP selection mechanisms that include single, dual and multiple metric based criteria using PHY-MAC interactions. These mechanisms are designed in order to improve system efficiency through the increase of the utilization of the available transmission resources. The key idea of these mechanisms is to make use of certain PHY and MAC parameters, other than the traditional RSSI measurements, in order to optimize the association to the best AP, specially focusing on the innovative use of MAC level state metrics. In this regard, of special interest is the inclusion of MAC level AP traffic load estimations within these association decisions.

All the proposals are based on the use of a high-performance MAC protocol called DQCA (*Distributed Queueing Collision Avoidance*), which is specially fitted to include the proposed techniques. Computer simulations have been carried out to evaluate and quantify the benefits of the proposed mechanisms and techniques in representative scenarios. Moreover, a completely new handoff procedure has been designed for the DQCA muti-cell operation. This handoff process allows implementing each of the proposed AP selection mechanisms.

Furthermore, the interaction between a Cross-Layer scheduling technique at the MAC level and two proposed AP selection mechanisms has also been studied. The performance of these techniques has also been assessed by means of computer simulations.

The analysis of the obtained results show that the proposed mechanisms perform differently under the considered scenarios. However, the main conclusion that can be drawn is that AP selection mechanisms that are based on joint multiple metrics considerations (SNR, AP load, delay, etc.) perform significantly better than those that use only single or dual metric based mechanisms.

After the study, we can conclude that the proposed techniques and mechanisms provide significant efficiency enhancements for DQCA-based WLAN multi-cell systems so that all of them may be taken into account in future wireless networks.

Desde aquí, quisiera agradecer todo el apoyo prestado por parte de los directores de este Proyecto de Fin de Carrera, Luis Alonso Zárate y Christos Verikoukis, que con su orientación e inestimable ayuda han hecho posible este trabajo.

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INTRODUCTION

Widespread deployment of IEEE 802.11 wireless LAN is currently progressing. The family of IEEE 802.11 wireless LANs are pervading diverse places such as hotels and airports as well as offices and home in recent years because hey can provide a great deal of flexibility and high bandwidth. In consequence, they actually provide convenient and important ways to access the Internet.

With the spread of wireless LANs, multiple Access Points (APs) will be much more likely to be available there for the nodes. Since nodes share the communication resource provided by APs, multiple APs are required to serve many nodes and to improve the transmission capacity in the wireless LAN. In fact, IEEE 802.11 wireless LAN can extend the communication range through the use of multiple APs. Consequently, the following significant issue can arise in those cases: how to select an appropriate AP among available APs. In the existing architecture and commercial 802.11 devices, the received signal strength is usually used to select an AP. However, such AP selection strategy causes the concentration of nodes to specific APs: many nodes may associate with only a few APs because their signal strengths measured by the nodes are strong; while only a few nodes may associate with the remaining APs. This results in imbalanced traffic load on APs in the wireless LAN, thereby degrading the fairness in nodes' throughput and harming an efficient use of the wireless LAN resources. Indeed, many studies have shown the traffic characteristics and user behavior in the wireless LAN and they report that traffic load is often distributed quite unevenly among APs. In this sense, studies have focused on proposing novel AP selection mechanisms which are not solely based on received signal measurements but also take into account AP traffic loads.

On the other hand, the 'Distributed Queuing Collision Avoidance' (DQCA) MAC protocol has been proved to significantly outperform the 802.11 MAC [9]. It is a distributed MAC scheme based on distributed queues that eliminates back-off periods and collisions in data packet transmissions and it is stable for whichever the traffic conditions are. Due to its clear benefits with respect to 802.11 MAC [1], this has been the MAC protocol used in this work. Nevertheless, to the moment DQCA has been studied and analyzed under single cell WLAN infrastructure scenarios. Thus, this work has focused on adapting DQCA to multi-cell scenarios where nodes move around associating and reassociating with several APs. Moreover, DQCA inherently provides control information that can be effectively used in order to implement smarter AP affiliation decisions based on MAC metrics and accurate traffic load estimations. In this regard, new AP selection mechanisms have been proposed for the DQCA multi-cell operation.

Furthermore, recent studies ([16]-[17]) have shown that wireless communications systems as WLANs can be optimized when some information exchange among layers of the protocol stack is considered. This concept is known as Cross-Layer optimization. Several Cross-Layer mechanisms have been proposed in the literature for WLAN systems. More importantly, DQCA allows easily implementing Cross-Layer techniques as proposed in [21]. In this sense, the use of MAC level measurements in the AP selection procedure can be considered a Cross-Layer mechanism. Moreover, the interaction of a Cross-Layer scheduling that manages and modifies the MAC level behavior using PHY level measurements can be also considered to further improve the system performance. This Cross-Layer scheduling design has been included in the system together with some of the proposed AP selection mechanisms and its overall performance has also been studied.

The basic methodology employed for evaluating the designed DQCA handoff process and the proposed mechanisms has been based on the use of link level computer simulations. In this sense, a DQCA multi-cell simulator has been developed using the object-oriented language C++. All the proposed techniques and mechanisms have been implemented in the simulator and its benefits and drawbacks have been subsequently analyzed.

CHAPTER 1. INTRODUCTION, MOTIVATION AND OBJECTIVES

1.1. Introduction to Wireless Local Area Networks

A Wireless Local Area Network (WLAN) is wireless network in which several devices (typically laptops or personal computers but increasingly PDAs, printers, servers, etc.) communicate with each other without the need of wires. WLAN utilizes spread-spectrum technology based on radio waves to enable communication between devices in a limited geographical area. The major advantage of this technology is that it gives users the mobility to move around within a considerably broad coverage area while offering high access data rates.

The first standard for WLANs was created by the IEEE (Institute of Electrical and Electronics Engineers) in 1997 and it primarily takes shape in the various versions of the 802.11 standard. This standard solely addresses the specifications of the PHY and MAC layers of the stack [1]. Since its appearance, several international organizations have developed great activity in the WLAN standarization process and a wide range of standards have been issued. In the United States the bulk of the work has been carried out by the IEEE and the 802.11 series of standards (b, g, a, e, h, n, etc.) whereas in Europe it has been the European Telecommunications Standards Institute (ETSI) with its activities on the HIPERLAN/2 standard. Table 1.1 shows the characteristics and capabilities of the main WLAN standards.

Table 1.1. Main characteristics of the the most extended WLAN standards.

WLAN Standard	IEEE 802.11b	IEEE 802.11a	IEEE 802.11g	HIPERLAN/2
Organization	IEEE (USA)	IEEE (USA)	IEEE (USA)	ETSI (Europe)
Year of publication	1999	2002	2003	2000
Frequency Band	2.4 GHz ISM	5 GHz	2.4 GHz ISM	5 GHz
Max. Bit Rate	11 Mbps	54 Mbps	54 Mbps	54 Mbps
Air Interface	DSSS	OFDM	OFDM	OFDM

IEEE 802.11b leads the global market and its evolution 802.11g is already achieving high shares. Even though HIPERLAN/2 solves some 802.11g drawbacks related to lack of robustness to interference and QoS (quality of service), it has most likely lost its chance to make its room into the market.

Along with 802.11g, 802.11b is the adopted standard by most vendors. At this point it is worth mentioning that we will focus our attention on the IEEE 802.11b standard even though most of the concepts and notions described here are still valid for 802.11a and 802.11g. As seen on Table 1.1, 802.11b operates in the 2.4 GHz ISM band. It has 14 channels that are distributed over the range from 2.402 GHz to 2.483 GHz, each channel being 22 MHz wide. Of these channels, channels 1, 6 and 11 are commonly considered as non-overlapping. So, in a well configured wireless network, all or most of the Access Points (APs) will operate on channel 1, 6 and 11. Also, to avoid co-channel interference, two adjacent APs should never be on the same channel.

1.2. Introduction to Access Point Selection Mechanisms

IEEE 802.11 has become the de facto protocol for wireless access in urban areas capitalizing on the large deployment of 802.11 Access Points. Within such dense deployments, users usually move around the area selecting the APs to connect to so that a wireless client has a variety of choice in its association with the wired infrastructure. A *handoff* occurs when a mobile station moves beyond the radio range of one AP, and enters another one's range (at the MAC layer). The state of the art mechanism, implemented in most 802.11 wireless adaptors, relies on measurements of received signal strength (RSSI): The client simply associates with that AP that is heard at the highest signal strength.

The reason driving such a decision stems from the fact that wireless adaptors employ the so called rate adaptation, tuning their transmission rate in response to the quality of the wireless link they experience to their AP. If the link quality is poor, then the client needs to employ more robust modulation and coding schemes, thus reducing its effective transmission rate. Affiliating with an AP featuring a high signal strength implies that the client can communicate with the AP at higher transmission rates. Such an affiliation algorithm has received significant criticism due to its ignorance of AP load. Sole consideration of link quality in the AP affiliation process can lead to the overload of APs with high client concentration, while other APs remain unused due to their slightly longer distance from the majority of the clients. As a consequence, new algorithms were proposed that incorporate AP load in the selection process [8][15]. Some of these algorithms rely on passive measurements collected from Beacon frames, while a recent approach advocates the use of active measurements for the identification of the "best" AP [6].

It is worth mentioning that handoff and affiliation decisions do not strictly belong to neither the PHY nor the MAC 802.11 layers as specified in the legacy standard definition. Thus, 802.11 clients have a certain freedom of decision regarding AP affiliation decisions. On the other hand, the currently implemented affiliation mechanisms do not guarantee seamless handoffs. Without seamless, efficient and fast handoff procedures, communications cut offs may occur and nowadays real-time and highly session-oriented applications such as voice and video would undergo serious degradation. Hence, considering the state of the art in terms of handoff and mobility in the context of wireless local area networks, it seems appropiate and suitable to focus efforts on this research area. In this regard, this current work suggests novel proposals that not only take into account PHY parameters within the handoff processes but also considers MAC parameters.

1.3. Introduction to MAC protocols

It is often necessary in the communications systems that several users share a transmission medium. In order to manage the use of this common resource, certain management strategies or access protocols must be set up.

The *Medium Access Control protocol* or simply *MAC protocol*, is the mechanism that determines which user has access to the transmission medium at a given time. In short, MAC protocols are the mechanisms in charge of organizing the access to the medium in order to avoid collisions. In case that collisions occur the MAC protocol determines what users should do.

In IEEE 802.11, regardless of the physical layer used, all wireless clients use the same radiofrequency channel to transmit on. This means the standard needs to define a way in which clients know when they can transmit and when they can't. This is handled using several multiple access mechanisms or MAC protocols. The most basic of these is the Carrier Sense Multiple Access with Carrier Avoidance (CSMA/CA) mechanism. This mechanism is defined as part of the Distributed Coordination Function (DCF) of the IEEE 802.11b standard. The DCF is the mandatory method by which clients work together and difer access to the medium so that the all users can use the same wireless channel.

An optional MAC protocol that is part of the IEEE 802.11 standard is the Point Coordination Function (PCF). This function allows time critical or delay sensitive packets to be given priority over regular data transmissions. The PCF uses a polling procedure to setup a contention free period which takes priority over the DCF procedure. During the PCF established contention free period, a single host poles clients and allows them to transmit. In this way delay sensitive packets such as voice or video can be given priority over other data. Further descriptions on the 802.11 MAC may be looked up in Annex 1.

On the other hand, the Distributed Queueing Collision Avoidance (DQCA) is a distributed high-performance MAC protocol designed for WLAN environments that offers an enhanced performance compared to the 802.11 MAC protocol [9][10]. It is a reservation scheme that eliminates back-off periods and collisions in data packet transmissions. In addition, it inherently provides useful information that can be taken into account by the AP selection mechanisms. For these reasons, in this project, DQCA has been applied over the 802.11b standard physical layer. A brief description of DQCA is given in chapter 2 and a more detailed description can be found in Annex 1.

1.4. Introduction to Cross-Layer design

The research discipline of wireless communications is one of the areas that is recently undergoing major progress and developments. Layering is the dominating design methodology of wireless communications protocol stacks. They have the traditional Open System Interconnection (OSI) layer-based architecture where layer-independency is the main layer principle. Even though this consideration simplifies protocols' design, it seems to be suboptimal for wireless communication systems. This is due to the fact that the wireless medium is available to multiple users that intent to get access and transmit their information. In addition, wireless systems introduce high error rate, burst errors distribution and time varying link capacity.

The efficiency, in terms of QoS, of such systems can be optimised when considering some vertical information exchange between layers of the protocol stack. This general concept is known as Cross-Layer optimization [16][17]. Therefore, several physical layer parameters should become available to higher layers and, based on this information, higher layer protocols can adapt their behaviour in order to improve network performance. The Cross-layer concept is more evident at the interface between the Physical and the Data Link Control (MAC) layers. In this case, MAC protocols, radio link control, Radio Resource Management algorithms and routing algorithms can benefit from some degree of awareness of the time varying characteristics of the radio channel.

On the other hand, several Medium Access Control (MAC) schemes have been proposed for WLANs´ Data Link Layer. All these protocols manage the radio resources and try to provide certain Quality of Service (QoS) level to mobile users by avoiding or at least reducing collisions.

The efficiency, in terms of QoS, of such systems can be optimised when considering some vertical information exchange between layers of the protocol stack. This general concept is known as Cross-Layer optimization [16]-[17]. Therefore, several physical layer parameters should become available to higher layers and, based on this information, higher protocol layers can adapt their behaviour in order to improve network performance.

The interest in using cross-layer design issues in mobile communication systems has been growing recently. Regarding to 802.11-based WLAN systems, some Cross-Layer mechanisms have been proposed in the literature. For example, in [2] the authors propose video streaming over 802.11 using a cross-layer approach, considering the Point Coordination Function. They propose an adaptive cross-layer mechanism for enhancing the efficiency of scalable video transmission by performing tradeoffs between throughput, reliability and delay depending on the channel conditions and application requirement. The authors in [14] propose an enhancement in 802.11 MAC without any change in its current MAC protocol structure. The proposed algorithm is based on the received signal strength measured from the received frames. The proposed algorithm selects which rate to use for each particular frame transmission.

Generally, the Cross-layer concept is more evident at the interface between the Physical and the Data Link Control (MAC) layers. In this case, MAC protocols, radio link control, Radio Resource Management (RRM) algorithms and routing algorithms can benefit from some degree of awareness of the time varying characteristics of the radio channel. In this sense, several authors have studied the benefits of Cross-Layer designs when these are applied to RRM algorithms such as handoff processes ([3]-[4]). Authors in [5] describe the need for the definition of a cross-layer metric based on which affiliation decisions should be driven. This metric makes use of physical layer parameters along with others MAC-related such as AP load and delay.

In view of the growing interest that the Cross-Layer optimization has arised, AP selection mechanisms based on Cross-Layer designs have been proposed and studied in this work. In this sense, several AP selection mechanims have been proposed that make use of different parameters related to different OSI layers. Specifically, PHY and MAC layer parameters are jointly taken into account in some of the novel mechanisms that are described and analyzed further on. Moreover, the interaction between these novel selection mechanisms and a scheduling technique based on a Cross-Layer design has been studied.

1.5. Motivation and Objectives

Once described the context of the project, at this point we are set to describe its motivation and specific objectives.

The nature of the transmitted information through the communications networks has undergone an incessant evolution in the recent years. The amount of information transmitted in packet mode is growing day by day. Even voice flows are being packetized and transmitted by means of the VoIP (voice over IP) protocol and becoming discontinuous data flows. Thus, it seems especially interesting to focus our researching efforts on strategies that take into account this transmission mode.

On the other hand, the various versions of the most extended standard for WLANs (IEEE 802.11) issued in the last years have mainly consisted in modifications of the physical layer in order to achieve higher transmission rates. Hence, the legacy 802.11 MAC protocol has been hardly changed. Moreover, the 802.11 standard specifications do not specify the criteria or parameters that must be considered in order to select an AP. As a result, proprietary selection mechanisms are being deployed by WLAN equipment vendors. The state of the art mechanism behind such a decision typically relies on received signal strength, associating clients to that AP in their neighborhood that features the strongest signal. However, recent studies ([5], [6], [7], and [8]) prove that more intelligent algorithms allow to achieve more efficient decisions resulting in a better system performance.

Considering this framework, this final career thesis aims to accomplish different objectives which are also linked together. Firstly, the work has been focused on the proposal and study of different Cross-Layer AP selection mechanisms that include single, dual and multiple metric based criteria using PHY-MAC interactions. These mechanisms are designed in order to improve system efficiency through the increase of the utilization of the available transmission resources. The key idea of these mechanisms is to make use of certain PHY and MAC parameters, other than the traditional RSSI measurements, in order to optimize the association to the best AP, specially focusing on the innovative use of MAC level state metrics. In this regard, of special interest is the inclusion of MAC level AP traffic load estimations within these association decisions.

Second, efforts have been put on designing an efficient handoff algorithm for the DQCA protocol. It consists of establishing certain procedures in order to perform the AP discovery, selection and association procedures as nodes move freely around a multi-AP scenario.

As a consequence of this objectives and the need of evaluating the proposed enhancements, a complete computer simulator of highly configurable WLAN multi-cell scenarios will be implemented. The MAC protocol used will be the aforementioned DQCA protocol. In this sense, the infrastructure mode defined in the 802.11 standard will be implemented. Moreover, the simulator should allow implementing the designed DQCA handoff process. Hence, these computer simulations will allow implementing and evaluating the proposed enhancements under significant conditions and scenarios.

Finally, the interaction between a Cross-Layer scheduling technique at the MAC level and two proposed AP selection mechanisms has also been studied. The performance of these techniques has also been assessed by means of computer simulations.

In short, the thesis goals are schematically outlined next:

- Proposal of different novel AP selection mechanisms for WLAN infrastructure networks. First, traditional mechanisms (RSSI-based) will be taken into account. Next, smarter selection mechanisms will be proposed, such as those based on joint PHY and MAC measurements, as traffic load information.

- Design of an efficient DQCA basic handoff process.

- Study and evaluation of the benefits of the proposed novel AP selection mechanisms through the evaluation of their performance under significant scenarios.

- Study of the interaction of the proposed AP selection mechanisms with further Cross-Layer scheduling MAC algorithms.

- Obtaining relevant conclusions for the feasibility of all the proposed mechanisms in future WLAN systems.

- Implementation of a link-level computer simulator. This simulator is in fact a required tool to achieve all the previously mentioned objectives. It should allow implementing and evaluating all the proposed techniques and enhancements under highly configurable cellular WLAN systems.

CHAPTER 2. WIRELESS LOCAL AREA NETWORKS

2.1. IEEE 802.11 Overview

Like all IEEE 802 standards, the 802.11 standards focus on the lower two levels of the ISO model, the physical layer and data link layer. Any LAN application, network operating system, or protocol, will run on an 802.11-compliant WLAN as easily as they run over Ethernet. The basic architecture features, and services of 802.11b are defined by the original 802.11 standard. The 802.11b specification affects only the physical layer, adding higher data rates and more robust connectivity.

2.1.1 Operating modes

802.11 defines two pieces of equipment, a wireless *station*, which is usually a PC equipped with a wireless network interface card (NIC), and an *access point* (AP), which acts as a bridge between the wireless and wired networks. The access point acts as the base station for the wireless network, aggregating access for multiple wireless stations onto the wired network.

The 802.11 standard defines two modes: *infrastructure* mode and *ad hoc* mode. In infrastructure mode (Figure 2), the wireless network consists of at least one access point connected to the wired network infrastructure and a set of wireless end stations. Since most corporate WLANs require access to the wired LAN for services (file servers, printers, Internet links) they will operate in infrastructure mode. Ad hoc mode is simply a set of 802.11 wireless stations that communicate directly with one another without using an access point or any connection to a wired network (Figure 3). This mode is useful for quickly and easily setting up a wireless network anywhere that a wireless infrastructure does not exist or is not required for services, such as a hotel room, convention center, or airport.

2.1.2 802.11b Physical Layer

The three physical layers originally defined in 802.11 included two spread spectrum radio techniques and an infrared specification. The radio-based standards operate within the 2.4 GHz ISM band. As such, 802.11-based products do not require user licensing or special training. Spread spectrum techniques, in addition to satisfying regulatory requirements, increase reliability, boost throughput, and allow many unrelated products to share the spectrum without explicit cooperation and with minimal interference.

The original 802.11 standard defines data rates of 1 Mbps and 2 Mbps via radio waves using frequency hopping spread spectrum (FHSS) or direct sequence spread spectrum (DSSS). Using the frequency hopping technique, the 2.4 GHz band is divided into 75 1 MHz subchannels. The sender and receiver agree on a hopping pattern, and data is sent over a sequence of the subchannels. In contrast, the direct sequence technique divides the 2.4 GHz band into 14 22 MHz channels. Adjacent channels overlap one another partially, with three of the 14 being practically non-overlapping. Data is sent across one of these 22 MHz channels without hopping to other channels.

The channels that are available for use in a particular country differ according to the regulations of that country. In the United States, for example, FCC regulations only allow channels 1 through 11 to be used. In Europe channels 1 to 13 are licensed for 802.11b operation but only allow lower transmitted power (20 dBm) to reduce the interference with other users and systems present in the band.

The key contribution of the 802.11b addition to the wireless LAN standard was to standardize the physical layer support of two new speeds, 5.5 Mbps and 11 Mbps. To accomplish this, DSSS was selected as the sole physical layer technique for the standard. To increase the data rate in the 802.11b standard, advanced coding techniques are employed.

To support very noisy environments as well as extended range, 802.11b WLANs uses *dynamic rate adaptation*, allowing data rates to be automatically adjusted to compensate for the changing nature of the radio channel. Ideally, users connect at the full 11 Mbps rate. However, when devices move beyond the optimal range for 11 Mbps operation, or if substantial interference is present, 802.11b devices will transmit at lower speeds, falling back to 5.5, 2, and 1 Mbps. Likewise, if the device moves back within the range of a higher speed transmission, the connection will automatically speed up again. Rate shifting is a physical layer mechanism transparent to the user and the upper layers of the protocol stack.

2.1.3 802.11 Data Link Layer

The data link layer within 802.11 consists of two sublayers: Logical Link Control (LLC) and Media Access Control (MAC). 802.11 uses the same 802.2 LLC and 48-bit addressing as other 802 LANs, allowing for very simple bridging from wireless to IEEE wired networks, but the MAC is unique to WLANs. The 802.11 MAC protocol is very similar in concept to 802.3, in that it is designed to support multiple users on a shared medium by having the sender sense the medium before accessing it. 802.11 uses a slightly modified protocol known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) or the Distributed Coordination Function (DCF). Further information on the MAC protocol specified in the 802.11 standard can be found in Annex 1.

2.1.4 Association and Cellular Architectures

The 802.11 MAC layer is responsible for how a client associates with an access point. When an 802.11 client enters the range of one or more APs, it chooses an access point to associate with, usually based on signal strength and observed packet error rates. Once accepted by the access point, the client tunes to the radio channel to which the access point is set. Periodically it surveys all 802.11 channels in order to assess whether a different access point would provide it with better performance characteristics. If it determines that this is the case, it reassociates with the new access point, tuning to the radio channel to which that access point is set.

Reassociation usually occurs because the wireless station has physically moved away from the original access point, causing the signal to weaken. This process of dynamically associating and reassociating with APs allows network managers to set up WLANs with very broad coverage by creating a series of overlapping 802.11b cells throughout a building or across a campus. To be successful, the network manager ideally will employ "channel reuse", taking care to set up each access point on an 802.11 channel that does not overlap with a channel used by a neighboring access point. As noted above, while there are 14 partially overlapping channels specified in 802.11 DSSS, there are only three channels that can be considered non-overlapping, and these are the best to use for multi-cell coverage. If two APs are in range of one another and are set to the same or partially overlapping channels, they may cause some interference for one another, thus lowering the total available bandwidth in the area of overlap.

2.2. DQCA Overview

The Distributed Queuing Collision Avoidance (DQCA) is a distributed high-performance medium access protocol designed for WLAN environments that offers an enhanced performance compared to the DCF MAC protocol implemented in the 802.11 standard [9]. Due to space constraints, the purpose of this section is to highlight the basic features of DQCA which are essential for the understanding of the proposed selection mechanisms and other enhancements. A detailed explanation of DQCA, along with the protocol operating rules can be found in [9], [10] and Annex 2 in this work. In a few words, the main characteristic of DQCA is that behaves as a random access mechanism under low traffic conditions and switches smoothly and automatically to a reservation scheme when traffic load grows.

Consider an infrastructure network in which *N* nodes share a wireless channel in order to communicate with an Access Point (AP). The time axis is divided into DQCA frames which consist of three fields (see Figure 2.1). The first is the access field, also referred to as Contention Window (CW). The CW is divided into *m* control minislots, during which the nodes may request access to the channel by sending an Access-Request Signal (ARS) to the AP. The second field is the data slot, devoted to the transmission of data packets in the uplink[1]. Only one node can be transmitting at a given data slot. At the third field the AP broadcasts a Feedback Packet (FBP) with some required information. The feedback information plays an important role in DQCA. Essentially, it acknowledges the previously transmitted data packet and broadcasts information on the minislots state. During every minislot three events may occur: no attempt of transmission (idle), successful transmission by one node (success) or transmission attempt by more than one node (collision). At every DQCA frame the AP detects the states of all slots (*m* control slots and one data slot) and incorporates this state information into the FBP. A SIFS (Short Inter Frame Space) interval is added for processing purposes.

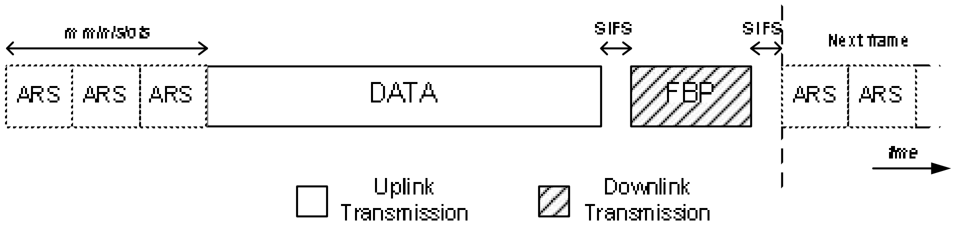


Figure 2.1 DQCA frame structure

The protocol uses two distributed queues: the Collision Resolution Queue (CRQ) and the Data Transmission Queue (DTQ). A node with a new message to transmit randomly chooses one of the *m* minislots and sends an ARS. This signal is simply a burst of energy which does not contain any information. Thus, ARS duration can be significantly reduced so that overhead is minimized. When two or more nodes transmit an ARS in the same minislot, a collision occurs. The nodes are aware of the collision by means of the FBP packet. The involved nodes enter the CRQ and in the next frame the collision resolution algorithm is applied: the nodes at the head of the CRQ resend an ARS in a randomly selected access minislot within the next frame. If they collide again, they reenter the CRQ and the process is repeated until they succeed in their request. In order to prevent instability, nodes are blocked from sending new ARS while the CRQ is not empty. The nodes that have successfully sent an access request enter the DTQ and wait their turn to transmit their message. Collision resolution and data transmission processes work in parallel.

A key feature of DQCA is that the two queues are distributed. This means that at any time, each node is aware of the state of the queues and its position in both of them, if it has any. The information concerning the queues is not directly transmitted by the AP, but instead it is derived at each node through the processing of the FBP broadcasted by the AP, and the execution of a predefined set of rules at the end of each DQCA frame. This is very important since the position of each node in the queues define its action at the next frame: a node in the head of the CRQ is enabled to transmit an ARS in the next frame

[1] Without losing generality, the transmission of data packets in the downlink has not been taken into account throughout this work. Nevertheless, the data slot could also be devoted to downlink packets transmissions.

in order to attempt to resolve its collision, while the node in the head of the DTQ is enabled to transmit a data packet in the next frame. For this operation, only four integer counters are kept at each node: TQ, RQ, pTQ and pRQ. TQ and RQ represent the number of nodes in the DTQ and in the CRQ respectively, and therefore have the same value for all nodes. pTQ and pRQ point to the position of each node in the respective queue. pTQ should have different values for each node, while nodes collided in the same minislot will have the same pRQ value. We remark here 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.

This work is focused on the use of DQCA as it outperforms 802.11 MAC and it can easily allow implementing smart scheduling and handoff techniques based on Cross-Layer design.

CHAPTER 3. FRAMEWORK

3.1. Introduction

This chapter is devoted to describing in detail the main elements of the communications system that sets up the framework of this thesis wherein several AP selection mechanisms will be tested. The detailed description of the proposed mechanisms is presented in CHAPTER 4.

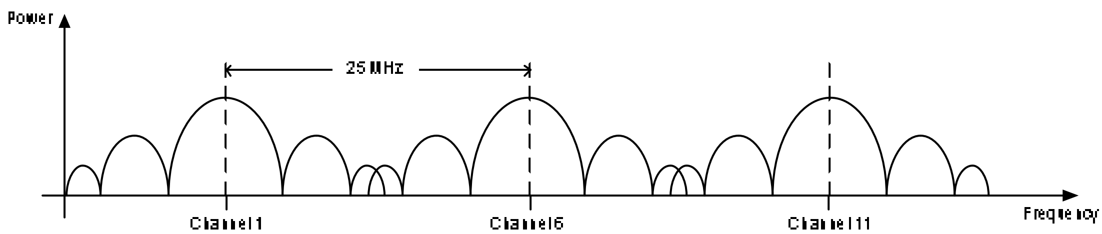
This chapter is divided up into two sections. In the first one, which corresponds to section 3.2, the scenario to be studied is described. Some details on the hypothesis and assumptions for simulation purposes are also included.

On the other hand, section 3.3 is devoted to the definition of the performance parameters that will be taken into account when assessing the benefits of the proposed selection mechanisms. These results are presented in CHAPTER 6.

3.2. Study case scenario

3.2.1 802.11b Infrastructure WLAN System

The scenario under study is an 802.11b WLAN system set up as infrastructure mode with three APs operating at the so-called "non-overlapping" channels, i.e., channels 1, 6, and 11 (see Figure 3.1). These channels correspond to a center frequency of 2.412, 2.437 and 2.462 GHz, respectively.



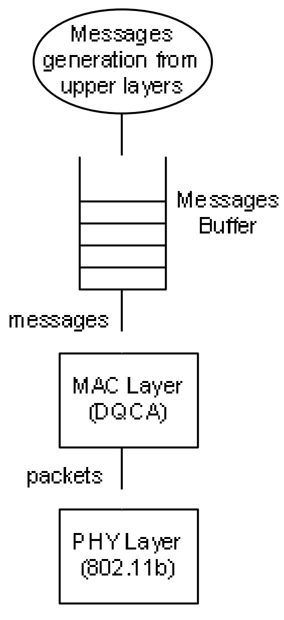
constant value, the higher the channel losses, the lower the received power and SNR measured by the AP, so that a lower bit rate must be set in order to maintain the bit error rate (BER) level. Therefore, nodes transmit their data packets using 1, 2, 5.5 or 11 Mbps depending on the channel losses. Furthermore, as specified by the 802.11b standard, control traffic is transmitted at the minimum bit rate, regardless of the channel losses, in order to guarantee an error-free reception of this system critical information.

Eventually, Table 3.1 summarizes the main PHY parameters specified in the 802.11b standard and adopted in this project framework.

Table 3.1 Main parameters of the 802.11b PHY layer.

Frequency range (channels 1, 6 and 11)	2.412, 2.437, 2.462 GHz
Spread spectrum technique	DSSS
Transmission power	20 dBm
Available data transmission rates	1, 2, 5.5, 11 Mbps
Control plane transmission rate	1 Mbps

On the other hand, nodes have been modeled has mobile devices that generate information messages according to a certain traffic pattern. The used traffic models are further on described in section 3.2.7. These information messages are queued up into memory buffers with a maximum capacity of 200 messages and a variable bit length. Messages' length is not necessary equal to the data packet length transmitted in each DQCA frame (MAC frame) which is a fixed constant value. In case that a node generates a message whose length is larger than what can be transmitted in a single DQCA frame, the node will fragment the message into several packets and transmit them using more than one DQCA frame.
Figure 3.2 depicts the nodes model that has been used.



3.2.2 DQCA parameters

Next, we detail the values of several DQCA parameters that have been implemented in the computer simulations.

The duration of the ARS packet is 2 µs. FBP packets transmitted from the AP to nodes include 6 bytes which contain enough information in order to allow nodes to execute the protocol rules. Apart from this, the FBP packet includes other control information such as an ACK. Therefore, the total length of the FBP packet is set to 13 bytes which include:

- 2 bytes devoted to the *Frame Control* field.
- 1 byte for the ACK.
- 6 bytes for feedback information needed for DQCA operation.
- 4 bytes for the *Frame Checksum Sequence* (error control).

At this point, it worth pointing out that the FBP includes the values of the TQ and RQ variables (number of nodes in DTQ and CRQ, respectively). This values are included in the FBP with the aim of allowing mobile nodes to capture the MAC state (DQCA counters) from a certain AP in order to apply the corresponding DQCA rules. Alternatively, this information allows nodes to recover from errors and possible loss of DQCA counters. As discussed later, this inherent control information may result very useful and profitable for the implementation of advanced AP selection mechanisms.

With respect to the data slot, its duration is variable as it depends on the transmission rate used by the transmitting node. However, the packet size L_d that can be transmitted within each data slot is fixed to a certain quantity of bits or bytes.

It is worth mentioning here that this FBP length should be incremented when implementing certain AP selection mechanisms and/or handoff services so that extra information can be included.

All the selected values for the parameters related with the DQCA protocol are shown in Table 3.2. Other parameters such as the physical and MAC headers are also included in the table. The values of these values have been extracted from the 802.11 standard.

Table 3.2 Selected values for DQCA, PHY and MAC parameters.

Number of control minislots (*m*)	3
ARS duration	2 µs
SIFS interval	10 µs
Propagation delay	1 µs
PHY Header duration	96 µs
MAC Header length	34 bytes
FBP length	13 bytes
MAC data packet length (L_d)	2312 bytes
Data slot duration	*Variable depending on transmission rate*

Note that, as shown in Table 3.2, data packet length is a fixed value which has been set to 2312 bytes. However, the data slot has no fixed duration as it depends on the bit rate used by the transmitting node. Therefore, it has a variable duration.

3.2.3 Scenario Layout

The considered layout consists of a 2-D circular scenario with a radius of 175 m, that is, a plain terrain is considered henceforth. As shown in Figure 3.3, three APs are positioned so that an equal distribution of coverage from each AP is guaranteed within the circular scenario and besides non-coverage areas are prevented. Distance between APs has been set to 300 m.

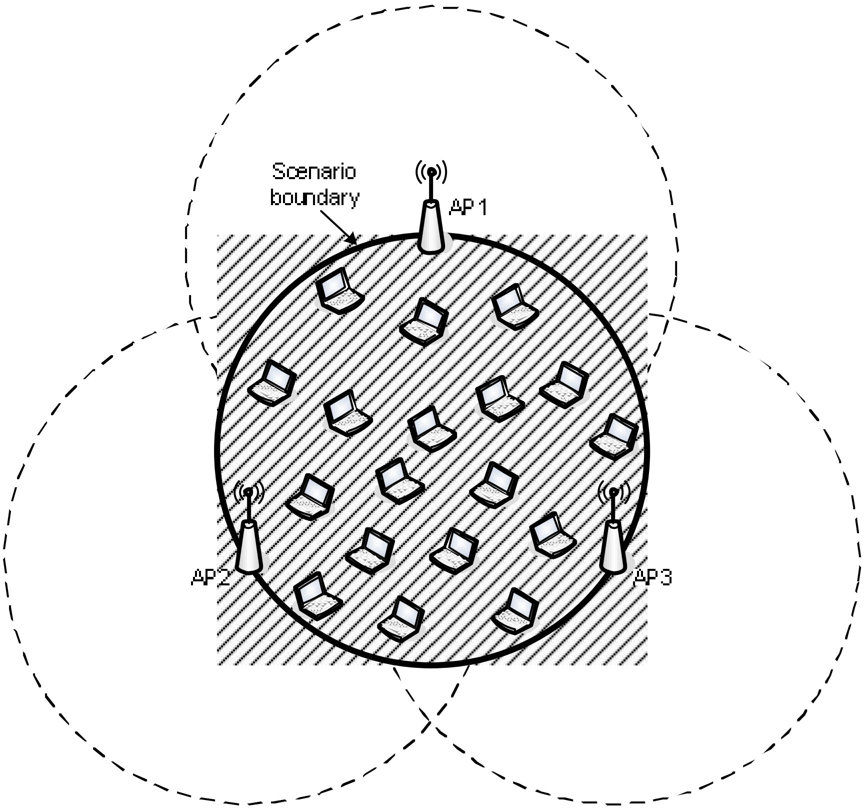


Figure 3.3 Circular scenario configuration and APs positioning

In Figure 3.3, the dashed lines delimit the coverage areas of the three APs. These areas represent the maximum achievable range beyond which signal-to-noise ratio (SNR) is degraded below certain threshold so that no communication can be maintained. Using the channel model introduced later in section 3.2.6, the maximum coverage distance from each AP is equal to 199 m. That is, beyond 199 m from the current AP, the SNR falls below 2 dB and the communications can not be maintained even with the lowest rate.

The solid line represents the physical scenario boundaries within which nodes (in Figure 3.3 nodes are depicted as laptops) move freely following the mobility model described in 3.2.5.

3.2.4 Transmission Assumptions

Several hypotheses have been assumed concerning transmissions and other PHY layer characteristics. These hypotheses and some approximations have been adopted with the aim of simplifying the working scenario provided that they do not distorts the obtained results focusing on the PHY and MAC level performance. They are summarized next:

- **Link adaptation and bit error rate (BER)**: An ideal SNR detection and perfect rate selection scheme is supposed to exist for the MAC operation (ideal link adaptation). Thus, BER is supposed to be zero for both the uplink and downlink. That is, all the transmitted bits through the radio channel using the selected transmission rate are correctly received.

- **Power control**: As specified in the 802.11b standard, the system does not implement power control strategies and so transmission power is constant regardless of the channel losses.

- **Channel coding**: The system does not implement any explicit channel coding scheme so that it is assumed that all the transmitted bits are effective bits from the user plane. Obviuoulsy, for an error free transmission assumption, some fraction of the effective throughput should be deducted when a coding scheme is considered.

3.2.5 Mobility model

For the sake of simplicity, it has been considered that all nodes move with a speed vector of which its modulus is kept constant and its direction is changed every certain time with a given probability within a certain angle range. This model is based in the one that can be found in [11].

Specifically, it has been established that every 2 µs and with probability 0.2, nodes change its direction within a range of ±45º. In any case, initial directions of the nodes are computed by means of a uniformly distributed variable between 0 and 2p radians.

On the other hand, regarding the speed modulus it has been considered that all nodes move at a constant speed of 10 m/s. At this point it is worth pointing out that this speed value is too high and cannot be considered realistic in the context of indoor environments. Nevertheless, without losing generality, this value has been adopted in order to generate sufficient number of handoffs during a reasonable simulation time. If nodes' speed is set too low, impracticably long simulation times have to elapse in order to accurately assess the performance of the proposed enhancements and mechanisms.

Furthermore, the initial position of the nodes in the system is uniformly distributed within the scenario boundaries and cells. Besides, when nodes move beyond the scenario limits its direction of movement is rotated in order to make them come back to the scenario.

3.2.6 Channel model

Most radio propagation models are based on a combination of analytical and empirical methods. The empirical approach is based on fitting curves or analytical expressions that recreate a set of measured data. This has the advantage of implicitly taking into account all propagation factors, both known and unknown, through actual field measurements. However, the validity of an empirical model at transmission frequencies or environments other than those used to derive the model can only be established by additional measured data in the new environment at the required transmission frequency.

Over time, some classical propagation models have emerged, which are now used to predict large-scale coverage for wireless communications systems design. One of these is the path loss models. By using path loss models to estimate the received signal level as a function of distance, it becomes possible to predict the SNR for a wireless communication system.

Both theoretical and measurement-based propagation models indicate that average received signal power decreases logarithmically with distance, whether in outdoor or indoor radio channels. Such models have been used extensively in the literature. The average large-scale path loss for an arbitrary transmitter-receiver separation is expressed as a function of distance by using a path exponent, *n*:

$$\overline{L}(dB) = L(d_0) + 10n\log\left(\frac{d}{d_0}\right) \quad \textbf{(3.1)}$$

where *n* is the path loss exponent which indicates the rate at which the path loss increases with distance, d_0 is the close-in reference distance which is determined from measurements close to the transmitter, and *d* is the transmitter-receiver separation distance. The bar in equation (3.1) denotes the ensemble average of all possible path loss values for a given value of *d*. The value of *n* depends on the specific propagation environment. For example, in free space, *n* is equal to 2, and when obstructions are present, *n* will have a larger value.

In our case, for the path loss model we have selected the dual-slope breakpoint model presented in [12] combined with a log-normal shadowing variation that takes into account the effects of the surrounding environment [13]. Specifically, a breakpoint model is characterized by a breakpoint distance that separates the different properties of propagation in the near region and the far region as relative to the transmitter. Typically, in the near region below the breakpoint distance it uses the free space loss distance exponent (?=2) and beyond the breakpoint distance it assumes a more hostile loss and considers a larger distance exponent. Specifically, [12] proposes a model for indoor radio propagation at 2.4 GHz that uses a breakpoint distance equal to 5 m and a distance exponent of ?=3.5 beyond that distance. Equation (3.2) shows the expression of the average loss at 2.4 GHz expressed in *dB* using this model.

$$\overline{L}(2.4\text{ GHz}) = \begin{cases} 40 + 20\log(d),\ (\text{dB}) & d \le 5m \\ 54 + 10g\log(\frac{d}{5}),\ (\text{dB}) & d > 5m \end{cases} \quad \textbf{(3.2)}$$

Nevertheless, the path loss model expressed in equations (3.1) and (3.2) does not consider the fact that the surrounding environmental clutter may be vastly different at two different locations having the same transmitter-receiver separation. This leads to measured signals which are vastly different than the average value predicted in equation (3.2). Measurements have shown that at any value of *d*, the path loss $\overline{L}(d)$ at a particular location is random and log-normally distributed (normal in dB) about the mean distance dependent value [13]. That is

$$L(d)[dB] = \overline{L}(d) + X_s \quad \textbf{(3.3)}$$

where X_s is a zero-mean gaussian distributed random variable (in dB) with standard deviation *s* (also in dB).

The log-normal distribution describes the random *shadowing* effects which occur over a large number of measurement locations which have the same transmitter-receiver separation, but have different levels of clutter on the propagation path. This phenomenon is referred to as *log-normal shadowing*.

In our working scenario we have assumed a zero-mean log-normal shadowing with a standard deviation *s* =5 dB [13]. Also, we have considered in the simulations that each new value of this log-normal attenuation is computed whenever a moving node travels 5 m. That is, at a speed of 10 m/s, shadowing attenuation varies every 0.5 s (slow fading).

Finally, a set of SNR thresholds should be defined in order to select the appropriate 802.11b data rate for PHY transmissions. These thresholds have been selected based on the results presented in [14] and are shown in Table 5.

Table 3.3 SNR thresholds for 802.11b data rate selection

Data Rate	1 Mbps	2 Mbps	5.5 Mbps	11 Mbps
SNR	2 – 4 dB	4 – 7.5 dB	7.5 – 11	>11 dB

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

3.2.7 Traffic model

All nodes are considered to generate data traffic with a Poisson-like behavior.

This kind of traffic includes all the services and connections with no requirements in terms of Quality of Service (QoS). Therefore, these transmissions are often called *best-effort*.

Data traffic generation is modeled as Poisson arrivals with variable message sizes that follow an exponential distribution. Their average size is $10 \cdot L_d$, with L_d being the number of bytes transmitted in each frame (defined as data packet length in Table 3.2). Thus, at the beginning of each DQCA frame, nodes have a given probability p_0 of generating a message in that frame. The change of the value of p_0 allows varying the total offered load while keeping constant the number of nodes in the system. The chosen parameters for this type of traffic model are shown in Table 3.4.

Table 3.4 Selected paramaters for the data traffic generation

Type of service	Generic data traffic (*best-effort*)
Traffic generation model	Poisson
Data packet length (L_d)	2312 bytes
Messages length distribution	Exponential
Mean message length	$10 \cdot L_d$

3.3. Performance metrics definition

In this section, we define the performance metrics that will later be used to evaluate the performance of the proposed enhancements and mechanisms. These comprises of common metrics associated with networks that provide useful information about its efficiency and performance. In CHAPTER 6, where results are put forward and analysed, these metrics are referred to according to the definitions presented in what follows.

3.3.1 Total offered load

We define the *total offered load* as the bit rate (in bits per second) at which the traffic that belongs to the nodes in the system is generated and offered to the network for delivery. Specifically, the total offered load is computed as the ratio of the total number of bits generated by all the nodes in the system and the total simulation time.

Equation (3.4) shows this ratio, where *N* is the number of nodes present in the system.

$$\text{Total offered load(bps)} = \frac{total\_number\_generated\_bits}{simulation\_time} = \frac{\sum_{i=1}^{i=N} generated\_bits_i}{simulation\_time} \quad \textbf{(3.4)}$$

Using this expression *total offered load* is computed in units of *Mbps*.

3.3.2 Total throughput

Total throughput is defined as the bit rate at which the traffic that belongs to the present nodes in the system is delivered by the network. In particular, in the computer simulations total throughput is calculated as the ratio of the total correctly received bits by all the APs present in the system and the total simulation time. Thus, as well as the total offered load, throughput is expressed in bits per second.

Equation (3.5) shows the expression of the total throughput according to which it is computed.

$$\text{Total throughput(bps)} = \frac{\sum_{AP=1}^{AP=M} total\_number\_received\_bits_{AP}}{simulation\_time} = \frac{\sum_{i=1}^{i=N} sent\_bits_i}{simulation\_time} \quad \textbf{(3.5)}$$

where *M* is the number of APs in the system and *N* is the number of nodes present in the system. Using this expression *total throughput* is computed in units of *Mbps*.

3.3.3 Mean messages delay

Message delay for a single message is defined as the elapsed time from the generation of a data message at any node, up to its complete delivery at the corresponding AP. Therefore, the mean messages delay is defined as the mean value of the messages delays undergone by all the sent messages throughput the simulation time.

Mean messages delay can be analytically defined as expressed in equation (3.6).

$$\text{Mean messages delay(s)} = \frac{\sum_{i=1}^{i=N} messages\_delay_i}{\sum_{i=1}^{i=N} sent\_messages_i} \quad \textbf{(3.6)}$$

where *N* is the number of nodes present in the system.

CHAPTER 4. DQCA HANDOFF PROCESS

4.1. Introduction

Each cell of the system (see 3.2.3) is serviced by an Access Point (AP), which is located in the center of each cell. Each node is attached to one AP at any time. Each AP implements an independent DQCA protocol engine in order to schedule packet transmissions.

When a node leaves the range of its serving AP, responsibility for the node has to be handed over to the system in order to allocate the node within another cell which may probably be the one into which the node is moving. This is referred to as the handoff process. This process is necessary due to power diminution of radio channels as distance increases. As a node moves away from the serving AP the signal strength diminishes: the signal quality deteriorates whereas bit error rate increases. At the same time the signal strength of adjacent cells increases as a node approaches the serving cell's border. To prevent excessive signal degradation and loss of Quality of Service (QoS) the system has to transfer control of the node to a new AP. The handoff process is the most frequently requested function of a cellular network and the most time-critical one since it may ensure the continuity of a connection.

DQCA is a MAC protocol that itself does not define a handoff process as it was initially proposed in [9] wherein the described rules specify how nodes access the channel and send access requests to a single isolated AP. However, it did not deal with the handoff procedure or AP selection mechanisms that must be carried out in cellular environments where several APs are present. Traditionally, handoffs have been performed in mobile communications networks when nodes move beyond the coverage are of a certain AP, and enter another AP's coverage area. In this case, the decision relies upon measurements of received signal strength indicators (RSSI) so that the node reassociates with that another AP that is received at higher signal strength. However, DQCA inherently offers system information that can be used in order to implement smarter selection mechanisms. Moreover, DQCA enables to easily extend this system information so that several advanced AP selection mechanisms can be supported.

The purpose of this section is twofold. On one hand, in section 4.2 we first describe the handoff process that has been designed for DQCA cellular environments such has the one we are dealing with. Later in section 4.5 we give a detailed description of the proposed AP selection mechanisms.

4.2. Logical functions in a handoff process

In wireless communications systems, the handoff function or process refers to the mechanism performed in order to transfer the physical layer connectivity from one AP to another with respect to a certain station in consideration. Thus the handoff is a physical layer function involving at least three participating entities, namely the station, a prior-AP and a posterior-AP. The AP to which the station had physical layer connectivity prior to the handoff is the prior-AP, while the AP to which the station gets connectivity after the handoff is the posterior-AP.

Generally, the implementation of a handoff process requires three basic functions to be supported by the system: (I) Link Status Monitoring, (II) Discovery and (III) Reauthentication as described below. The definition of the DQCA handoff process will be discussed later based on these two phases or steps.

1. Link Status Monitoring: Attributing to mobility, the received signal strength and the signal-to-noise ratio of the signal from a node's current AP might degrade. Before the quality of a connection worsens too much or even the node looses connectivity, it is necessary to initiate a discovery process to obtain information on other available resources that may provide higher permance. Thus, it is necessary to keep track of the status of wireless links from APs to nodes in order to decide whether it is or not necessary to initiate a scanning or discovery process. Generally, link status Monitoring functions may be based on several individual parameters, such as received signal strength, SNR, bit error rate, or a combination of them. Moreover, link status Monitoring may be carried out by means of several techniques but the most common is based on the transmission of beacon frames from APs that are received by nodes and used to get information on the link status. Eventually, this function may include decision criteria with respect to 'when' it is necessary to initiate a discovery process.

1. Discovery: This function is performed by nodes when they need to reassociate with other APs. At this point, nodes need to find potential APs to associate with. This is accomplished by a MAC layer function: scan. Usually, during a scan nodes listen for beacon messages (sent out by APs), on assigned channels. Thus nodes can create a list of APs prioritized by a determined metric such as the received signal strength. There are two kinds of scanning methods defined in the standard: active and passive. As the names suggest, in the active mode, apart from listening to beacon messages (which is passive), the station sends additional probe broadcast packets on each channel and receives responses from APs. Thus the station actively probes for the APs. The passive scanning mode implies that the station just listens to the beacon messages transmitted from the APs on the selected channel.

2. Reassociation: The station attempts to reauthenticate and reassociate to an AP according to the priority list. The reauthentication process typically involves a message exchange performing an authentication and a reassociation to the posterior-AP. The reauthentication phase involves the transfer of credentials and other state information from the old-AP.

Figure 4.1 shows the sequence of messages typically observed during a handoff process implementing the active scanning mode within the 802.11 standard. The handoff process starts with the first probe request message and ends with a reassociation response message from an AP. Further details on the 802.11 handoff process can be found in Annex 1.

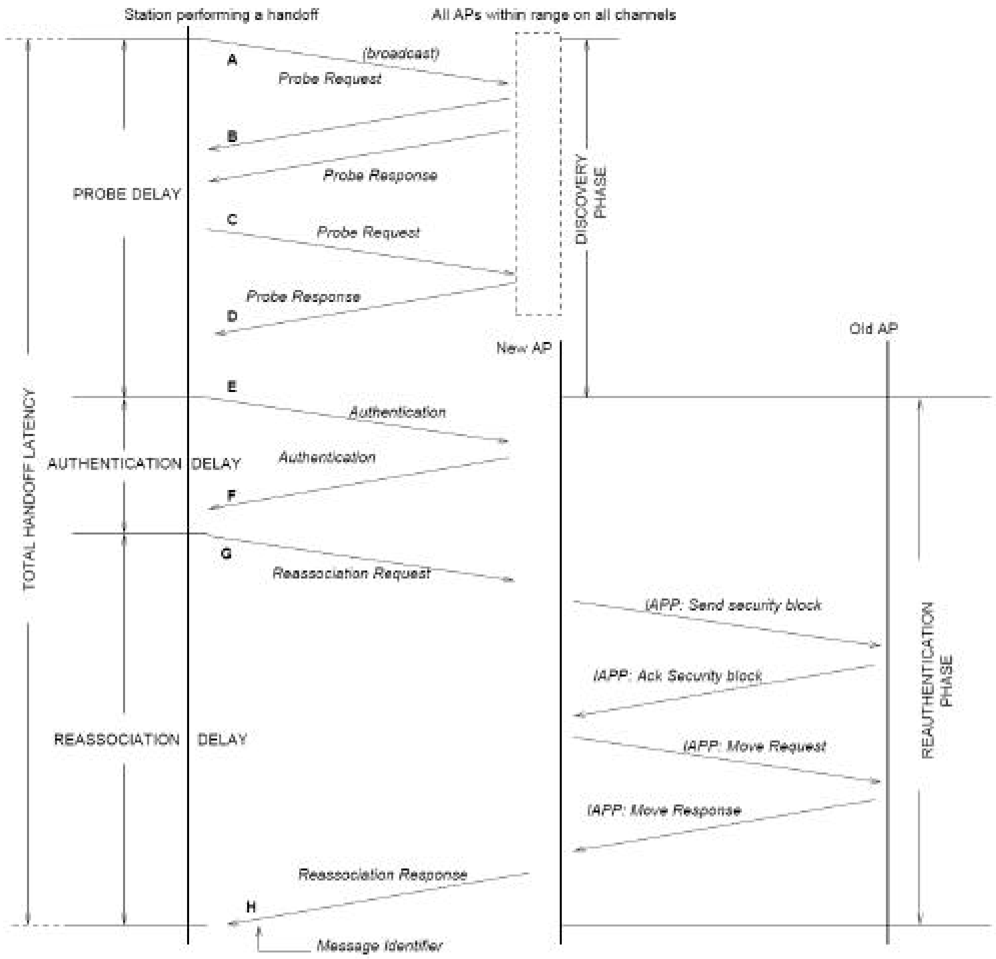


Figure 4.1 The IEEE 802.11 handoff procedure (followed by most cards)

4.3. Definition of the DQCA handoff process

Taking into account the previously described functions that make up any generic handoff process, we need to specify the specific procedure that a node in the system has to carry out in each case for the study case scenario. Next, this functions are discussed and detailed for the multi-cellular DQCA-based system.

4.3.1 Definition of the Link Status Monitoring function

As previously introduced, the Link Status Monitoring function (referred hereafter to as the LSM function) provides a mechanism for nodes to keep track of the quality of their wireless links to APs. Moreover, this function includes a criterion in order to decide whether a node needs to initiate a scanning process.

In order to design the LSM function, it is somewhat useful to notice that DQCA itself provides means of implementing it with no need of relevant changes. DQCA includes a downlink broadcast transmission from APs at the end of each frame which is devoted to the FBP packet transmission. As every node in the system will be receiving these FBPs from their current APs, this packet can be used to obtain information on the link status on a frame-by-frame basis. This information may be the received signal strength or an SNR estimate. Specifically, it has been implemented that nodes obtain an SNR measurement upon each FBP reception.

Note that using the FBP only provides a way for extracting downlink status (from AP to node) information though it is assumed that it can also be used for estimating the uplink status (from nodes to AP).

Hence, using the LSM function any node in the system is capable of monitoring the link status on a frame-by-frame basis by means of the FBP packet provided within the DQCA frame structure (see Figure 2.1).

On the other hand, it is necessary to establish a criterion in order to decide when it is required for a node to utilize the Discovery function based on the information continuously gathered by the LSM function. As aforementioned, this function obtains SNR measurements in order to evaluate the link status and decide. Thus, some criterion must be established in order to consider that a node requires initiating a discovery process. In this respect a parameter called *SNR_Scan_Threshold* has been defined. The idea is that each node continually compares the SNR measurements obtained by the LSM function with the value of this parameter. When an SNR measurement is detected to be lower than the value specified with the *SNR_Scan_Threshold* the node initiates a scanning process. In order to decide the specific value of this parameter some issues have to be considered:

- The *SNR_Scan_Threshold* should be high enough to allow a node initiate the discovery phase prior to letting the link status degrade too much or even lose connectivity with the current AP. If the node initiates the discovery phase far enough beforehand, other susceptible APs that could provide better service performance.

- However, a too high value for *SNR_Scan_Threshold* may result in nodes initiating a scanning process too frequently. As a result, system efficiency would be decreased as nodes spend too much time seeking other available resources instead of transmitting their information messages.

With these ideas in mind, a value of ***SNR_Scan_Threshold* = 4 dB** has been selected and implemented for the system evaluation. According to the relation between data rates and SNR thresholds presented in Table 3.3, an SNR value of 4 dB corresponds to the threshold below which a node transmits its packets using the minimum available data rate, 1 Mbps. Hence, when a node detects (by means of the LSM function) that an FBP packet from the node's current AP is received with an SNR lower than 4 dB, the node initiates the Discovery function.

Note that, according to the given definition of the LSM function it is still left to specify the criterion according to which the scanning nodes decide to reassociate with an AP. In this sense, several criteria using different performance parameters may be used. Section 4.5 is devoted to the proposal and description of several AP selection mechanisms based on different parameters.

4.3.2 Definition of the Discovery function

The Discovery function is initiated once a node has determined that it is necessary to scan for other available APs in the system. To do so, a certain procedure has to be defined for the nodes to scan other available frequency channels and gather information on other available APs and its performance.

Thus, when a node has initiated the scanning process it must obtain information on the available frequency channels and their corresponding APs. The DQCA MAC protocol provides a simple way to obtain this information as it transmits beacon frames. The obtaining of this information is carried out by the previously described LSM function.

One of the main constraints that have to be taken into account when designing the handoff process is the fact that, using DQCA, nodes keep some state information (positions in the queues, queues size, etc.) by means of the feedback information transmitted in the FBP packet. That is, although being in the Discovery phase, any node must receive the FBPs from the AP it is currently connected to. This is necessary as a node may decide to remain connected to the current AP after the discovery phase.

Keeping these ideas in mind, we establish the next procedure that a node has to implement when using the Discovery function:

1. Once a node has determined that it must initiate the scanning process, at the beginning of the next frame it has to tune its transceiver to the next available frequency channel and during a certain period of time (*MAX_SCAN_TIME*) it has to wait for the reception of the FBP from the corresponding AP. If the node receives the FBP it will measure and store a certain selection metric (such as the SNR). Immediately afterwards the node must tune its radio transceiver again to the frequency channel of the AP that it is currently associated. If the node does not receive the

FBP from the scanned AP it may be due to two possible reasons: (I) The scanning node is not within the radio range of the scanned AP and so it does not 'listens' that AP transmissions or (II) the scanned node has not received the FBP during the scanning period, that is, the FBP transmission from the scanned AP has not coincided in time with a scanning period of the node. In the latter case, the node considers that the AP is not available and so it will not consider it as a candidate AP to associate with.

2. After the scanning period of duration of *MAX_SCAN_TIME* seconds, the node must reconnect to its current AP in order to receive the FBP packet and maintain the MAC status with the current AP. After receiving and decoding the FBP from this AP the node must tune its radio transceiver to the next frequency channel in the list of available channels and will perform the same procedure described in point 1. The available channels in system are scanned consecutively. That is, if the WLAN system is configured to operate on channels 1, 6 and 11 and a given node is currently associated with the AP operating on channel 6, it will start scanning for FBPs on channel 11. Then, after reconnecting to channel 6, it will continue scanning on channel 11 and so on.

3. Once all the available channels in the system have been scanned, the node will select the AP to associate with. This decision will be based on the value of the metrics computed during the scanning periods. The AP with the greatest metric will be the selected one. Next, the node will tune its transceiver to the selected AP and, in case that the selected AP is different than the one the node was connected to, the node will then reset its queue pointers (TQ = RQ = pTQ = pRQ = 0) and wait for receiving a first FBP from the new AP in order to obtain control and state information (it will adjust the queue pointers according to the information and values received in the FBP). From this moment on, the node will consider itself reassociated with the new AP and will apply the DQCA nodes as usually. In case that any FBP from any AP have not been received the node will remain associated with the current AP.

Note that it is assumed that nodes know the possible PHY frequency channel set used in the system.

The value of the parameter *MAX_SCAN_TIME* is critical as it sets the duration of the scanning period that a node spends at each frequency channel. To determine the duration of this period we must take into account some issues:

- The scanning period must last long enough so that a node could receive and demodulate a complete FBP packet from the scanned AP.

- The period must be short enough as a node has to reconnect to the original channel (the channel at which it is currently connected) once the scanning period has elapsed.

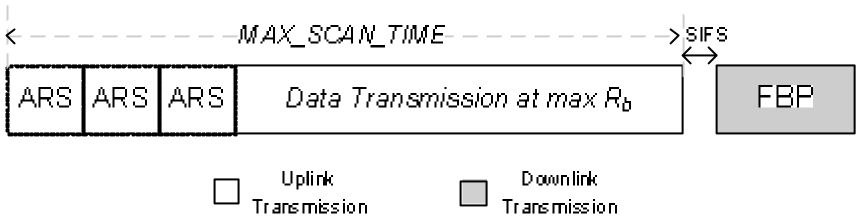
That is:

FBP_duration ≤ MAX_SCAN_TIME ≤ (DQCA_frame_duration - FBP_duration)

Let us recall that due to the rate adaptive feature of 802.11 systems, the duration of the DQCA frames is not constant as the duration of the data slot is variable. That is, within the data slot a fixed amount of bytes are transmitted (L_p) using one of the four 802.11b available data rates so that its duration depends on the link quality of each transmitting node. Therefore, a node in the Discovery phase does not know how long the next DQCA frame will last and so it does not know for how long it can be scanning another frequency channel. In this respect, a conservative decision has been adopted:

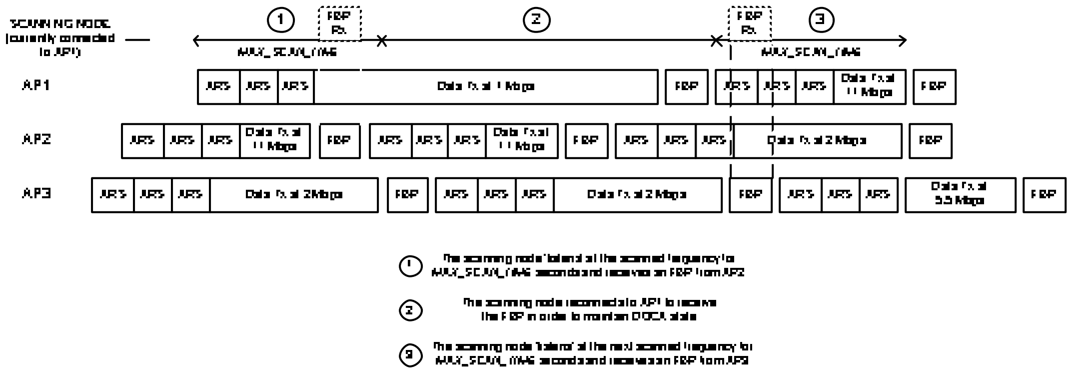
- The value of *MAX_SCAN_TIME* is set to the longest possible period while assuring that the node reconnects in time in order to receive the FBP from the AP to which the node is currently associated.

It means that *MAX_SCAN_TIME* has been set so that the node is able to receive the FBP regardless of the duration of the current data slot. Essentially, *MAX_SCAN_TIME* has been set equal to the duration of the control minislots plus the minimum data slot duration, that is, when a node transmits its packet using the highest available data rate. Figure 4.2 shows the *MAX_SCAN_TIME* duration with respect to the DQCA frame duration.



Note that in the computation of *MAX_SCAN_TIME* the FBP packet duration is subtracted due to the fact that the scanning node needs to receive and demodulate the complete FBP packet so that it is not necessary to keep scanning during the last *FBP_duration* seconds. In other words, in case that a node detects the transmission of an FBP packet during the last *FBP_duration* seconds it will not have enough time to decode the complete FBP before the scanning period elapses so it is not necessary to keep scanning.

Next, Figure 4.3 shows an example of operation of the Discovery function where a node initiates the scanning process according to what specified with respect to the scanning periods duration.



into account with respect to the Discovery function. This particular situations are summarized next.

After a node has determined to initiate a scanning process and then initiates the Discovery function it may be within on of these situations:

SITUATION A. The node has no data message in its buffer pending transmission and so it is not present neither in the DTQ nor in the CRQ (pTQ=0, pRQ=0).

SITUATION B. The node has one or more data messages in the buffer pending transmission but has not yet sent the corresponding access request for the first message. Thus, it is not present neither in the DTQ nor in the CRQ (pTQ=0, pRQ=0).

SITUATION C. The node is present in the DTQ and so with one or more data messages in the buffer but not currently transmitting a message (pTQ>1, pRQ=0).

SITUATION D. The node is transmitting a message, that is, the node is currently within the phase of using a certain number of DQCA frames to transmit a message. Therefore, the node occupies the first position in the DTQ (pTQ=1, pRQ=0).

SITUATION E. The node occupies a position in the RTQ with one or more data messages in the buffer and so pending to resolve a previously collided access request (pTQ=0, pRQ>0).

The simplest case is a node in situation A. In this case the node can easily initiate the scanning process with no complication. A node in situation B is in the same situation but having pending messages in the buffer. Likewise, the node can start scanning in the next frame with no complication for the whole system.

Situations C and D are different but they can be solved in the same manner. In the former situation the node is occupying a position within the DTQ when it determines that it is necessary to perform a scanning action. Note that the proposed Discovery function does not allow for a node to transmit a data packet as during the data slot where data transmissions are allowed the node will be scanning at other frequency channels. In situation D the node is already transmitting packets using the data slot of several contiguous DQCA frames when it determines to use the Discovery function. Before proposing a solution to these situations it is worth pointing out a certain feature of DQCA. As described in [9] and [10], the FBP includes the so-called ‘final message bit’ that is enabled by the AP when a transmitted packet within a DQCA frame corresponds to the last packet of the message. This information is required for the nodes in each cell since when a node is transmitting the final packet of a message it means that this node will next leave the DTQ and therefore the queue pointers must be updated (pTQ, TQ, etc.). Of course, nodes must also include a ‘final message bit' in their data packet transmissions in order to indicate the AP the transmission of the final packet of each message.

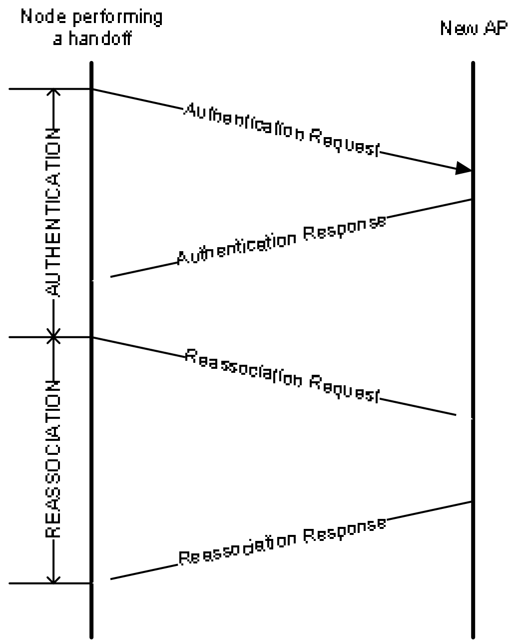
Regarding situations C and D, the 'final message bit' can be employed in order to solve them. In case that a scanning node in situation C reaches the first position in the DTQ it will not even transmit the first packet and so after a certain time the AP will detect an empty data slot. Then, the AP can enable the 'final message bit' in the next FBP an so the rest of nodes present in DTQ will advance one position in that queue. Note that using this mechanism the only resulting shortcoming is an empty data slot and a corresponding loss of efficiency. However this loss of efficiency can be significantly reduced if the time interval that the AP requires to determine a data slot to be empty is minimized. In this sense, the parameter '*EMPTY_SLOT_THRESHOLD*' has been defined. Whenever an AP detects no data transmission during a data slot for a period of time equal or greater than *EMPTY_SLOT_THRESHOLD* seconds the AP will consider that an empty data slot event has occurred and will enable the 'final message bit' in the next FBP.

Similarly, this mechanism can also be applied to solve situation D wherein the node is transmitting a message and then it decides to start scanning. In this case, when the node initiates the scanning process it will abort the data transmission to start 'listening' at other frequencies and when that occurs an empty data slot event will happen. Then again, the AP will detect the situation and enable the 'final message bit' in the next FBP. The scanning node will then reset its pTQ value (pTQ=0) and so consider itself to have left the DTQ. It is worth pointing out that in that case the node will have not finished the message transmission and it will have to send new access request whether to a new AP if after the scanning process it reassociates with a different AP, or to the current AP in case that the node determines to keep associated with it.

With respect to the last possible case, situation E occurs when the node is pending to resolve a previous access request collision and it starts scanning. Therefore, the node is only occupying a position within the CRQ. Under normal conditions the node would send an access request (ARS) in order to solve the collision but since it will be scanning other APs that will not be feasible. Thus, in this case the node will not participate in the collision resolution and simply will reset its pRQ value (pRQ=0). If, after the scanning process, the node determines to keep being associated with the current AP, it will have to resend a new ARS in order to gain access when the MAC rules allow it to do so.

4.3.3 Definition of the Reassociation function

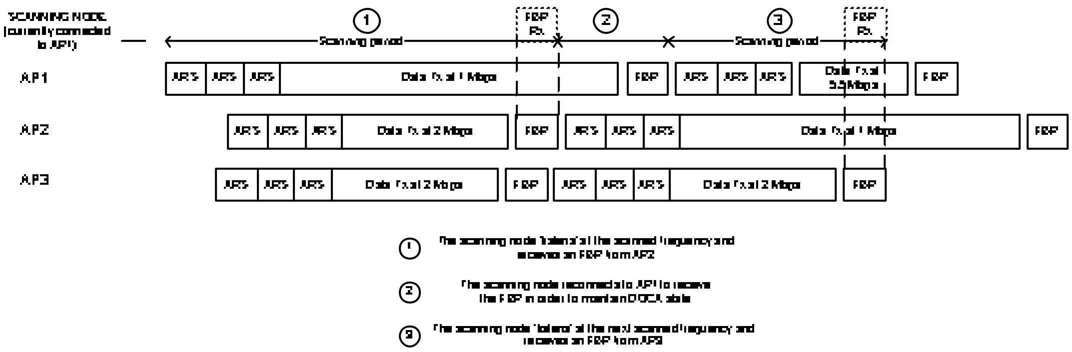
The Reassociation function consists of a message exchange devoted to authorizing and reassociating a node with a certain AP. In this sense, the 802.11 standard defines two procedures: the authentication process and the reassociation process (see Figure 4.1). Once the node has found an AP, and decided to join it, it will go through the Authentication Process, which is the exchange of information between the AP and the node, where each side proves the knowledge of a given password. When the node is authenticated, then it will start the Association Process, which is the exchange of information about the nodes and AP capabilities. Only after the association process is completed, a node is capable of transmitting and receiving data frames again.



current channel and receive the FBP. This is due to the fact that, in principle, scanning nodes are not aware of the duration of the DQCA during which they scan on other frequency channels for beacon frames (FBPs).

As previously introduced, an ‘Advanced Scanning Technique’ (referred hereafter to as ‘AST’) has been proposed in order to overcome this limitation. The aim of this technique is to allow nodes to be aware of the DQCA frame’s duration. This would allow the scanning nodes to profit the whole data slot duration regardless of its duration. To do so, nodes need to know the transmission rate that the transmitting node will use in the data slot. Recall that the amount of information transmitted within the data slot is fixed (L_p bytes) so that nodes only need to be aware of the used transmission rate.

To this end, each AP estimates the available transmission rates of the nodes in DTQ. This estimation is based on the measured RSSI of the successfully received ARS (transmitted by nodes as access requests). According to these estimates, at any given time the APs are aware of the transmission rates that nodes in the DTQ will use. Specifically, the duration of each DQCA frame solely depends on the data rate of nodes occupying the first position within the DTQ. Therefore, if APs would include the value of this data rate in the FBP, scanning nodes could receive this value, process it and derive the amount of time they can spend scanning on other channels. This process is shown in the example of Figure 4.5.



The performance of the Advanced Scanning Technique is studied later in section 4.4.

4.5. Proposal and definition of AP selection mechanisms

4.5.1. Introduction

So far, the DQCA handoff process has been defined. Nevertheless, the aforementioned 'Link Status Monitoring' function has not been completely defined since it may include the decision criteria according to which the nodes select the appropriate AP to associate with. In this sense, several AP selection mechanisms are proposed hereafter and their performance is evaluated. These proposals are based on the use of the DQCA MAC protocol in a WLAN multi-cell scenario.

Within such scenarios, a node has a variety of possibilities to select its association with a certain AP. The state of the art mechanism, although not standardized it is implemented in most 802.11 wireless adaptors, and relies on measurements of received signal strength (RSSI): The client associates with that AP that is heard at the highest signal strength. The reason driving such a decision stems from the fact that wireless adaptors employ rate adaptation, tuning their transmission rate in response to the quality of the wireless link they experience to their AP. If the link quality is poor, then the client needs to employ more robust modulation and coding schemes, thus reducing its effective transmission rate. Affiliating with an AP featuring a high signal strength implies that the client can communicate with the AP at higher transmission rates. Such an affiliation algorithm has received significant criticism due to its ignorance of AP load. Sole consideration of link quality in the AP affiliation process can lead to the overload of APs with high client concentration, while other APs remain unused due to their slightly longer distance from the majority of the clients. As a consequence, new algorithms were proposed that incorporate AP load in the selection process [8][15]. Some of these algorithms rely on passive measurements collected from Beacon frames, while a recent approach advocates the use of active measurements for the identification of the "best" AP [6].

This section is split into two subsections. On one hand, in subsection 4.5.2 fundamental metrics that may drive the AP selection process are identified. After, on subsection 4.5.3, the proposed AP selection mechanisms are described in detail based on the previously identified parameters.

4.5.2. AP selection decisions

Regardless of the MAC protocol in use, the following metrics have been identified as critical factors in the determination of the most appropriate AP to connect to:

a) **Received Signal Strength Indicator (RSSI)**: This is the typically used parameter regarding user affiliation decisions. The quality of the link between the AP and the new client, which determines the client's instantaneous transmission rate. The higher the received signal strength, the higher the transmission rate a node may use while keeping a proper bit error rate (BER).

b) **Signal-to-noise ratio (SNR)**: Likewise RSSI, it is a critical factor regarding the potential transmission rate a node may use when connected to the AP. It is a more accurate predictor as the selected transmission rate ultimately relies upon the proportion relationship between the received signal level and the noise level.

c) **Traffic Load**: The traffic load an AP experiences is directly related on the quality of service a node undergoes. Overloading conditions at the MAC layer may directly lead to increasing collisions so that congestion may occur resulting into bad quality of service (higher transmission delays, lower throughput, etc.).

d) **Expected Queueing Delay (EQD)**: EQD aims to capture the average amount of time a scanning node needs to spend until it is allowed to actually transmit information messages. Note that this factor not only depends on the traffic load the AP is experiencing but also on the transmission rates the present nodes in the cell are able to use. That is, if the already present nodes transmit using higher data rates, the amount of time a newly arrived node will wait will be lesser. Finally, it is worth pointing out that these data rates ultimately depend on the RSSIs or SNRs of the already present nodes.

It is important to notice that not all of these parameters are available at PHY level and so they are not readily obtainable at the 802.11b air interface. Thus, they need to be obtained from the MAC layer or a combination of MAC and PHY measurements. As previously advanced, DQCA itself provides control information that the AP selection mechanisms can take advantage of in order to obtain such metrics, so a Cross-Layer optimization design arises.

4.5.3. DQCA-based AP selection mechanisms

In this section several novel AP selection mechanisms are proposed. These are aimed at providing efficient reassociation decisions within the previously described DQCA handoff process.

Initially, two similar RSSI-based selection mechanisms are proposed. Next, a third mechanism solely based on AP's traffic load conditions is presented. Finally, two mechanisms that use cost functions are presented. These cost functions consider several parameters and attempt to jointly capture several of the aforementioned dimensions in AP selection. This section is devoted to the definition of these mechanisms whereas their performance assessment is presented in CHAPTER 6 from computer simulation results.

4.5.3.1. AP Selection Mechanism #1

The first AP selection mechanism is based on the SNR metric, that is, a scanning node selects to reassociate with the available AP whose beacon frames (FBPs) are received with the highest SNR.

The decision occurs after the DQCA scanning phase and is the point at which nodes decide whether to stay connected to the current AP or transition to a new AP. As discussed when describing the DQCA handoff process (section 4.3), nodes begin scanning when the SNR drops below the *SNR_Scan_Threshold*. Channels are subsequently scanned using the mechanisms discussed within the Discovery function.

Specifically, for this mechanism a new parameter has been defined, which is called *Delta_SNR* and defines an hysteresis mechanism. If the difference between the SNR of the old AP and a newly scanned AP with highest SNR (among the scanned APs) is greater than the *Delta_SNR*, the node will trigger a handover procedure to the new AP. *Delta_SNR* specifies the minimum SNR difference between the old AP and the new AP to begin the handover. This parameter is necessary because SNRs of wireless links are never static hence *Delta_SNR* prevents clients from 'ping ponging' between APs due to slight SNR oscillations. Specifically, in the computer simulations a value of ***Delta_SNR* = 1.5 dB** has been implemented.

During the DQCA Discovery phase, the node listens for beacon messages (FBPs sent out by APs on each DQCA frame), on assigned channels (with 802.11b PHY channels 1, 6 and 11). Thus the station can create a list of APs prioritized by the received signal strength. In case that after the Discovery phase no FBP has been received for a certain channel, the corresponding AP will not be included in the list of potential APs. Note that prior to initiating the Discovery process the node knows the SNR to the current AP and so this is the first value included in the list.

Moreover, this mechanism establishes that each scanning node listens on all the available channels before deciding which AP to reassociate with. This feature is modified in the next proposed mechanism.

4.5.3.2. AP Selection Mechanism #2

Likewise mechanism #1, the secondly proposed mechanism is based on SNR measurements. That is, scanning nodes select to reassociate with the APs that are 'listened' with the highest SNRs.

The differentiating point of this mechanism with respect to the mechanism #1 is the fact that during the Discovery phase, whenever the scanning node receives an FBP from a scanned AP with higher SNR than the current SNR (with the node's current AP), the node directly reassociates with that AP. Hence, the reassociation is carried out regardless of if the node has scanned on the available channels at that time.

Again, the hysteresis *Delta_SNR* parameter (with the same value of 1.5 dB) is employed in mechanism #2 in order to avoid oscillations and ping pong effects.

4.5.3.3. AP Selection Mechanism #3

So far, two RSSI-based AP selection mechanisms have been presented. Such kind of affiliation algorithms have received significant criticism due to its ignorance of the AP load. Sole consideration of link quality in the AP affiliation process can lead to the overload of certain APs with high node concentration, while other APs remain unused due to their slightly longer distance (and so lower RSSI) from the majority of the clients. As a consequence, new algorithms that incorporate AP load in the selection process are herein proposed.

In this respect, the AP selection mechanism #3 aims at providing means to implement solely traffic load based AP selection decisions. The amount of traffic load an AP is serving may be estimated by several means such as:

- Number of nodes currently associated with the AP
- Average collision rate (number of collisions per second)
- Queueing delay
- Number of retransmissions
- Etc.

At this point it is worth recalling that DQCA is based on the use of two different distributed queues: DTQ and CRQ. The state of the queues is maintained by the nodes in the system by means of four numbers or counters: TQ, RQ, pTQ and pRQ. Nodes keep these four values updated using the feedback information sent by the APs through the FBP packet. pTQ and pRQ are maintained using the feedback information included in the FBP regarding the state of the control minislots. However, TQ and RQ values (number of nodes in the DTQ and CRQ, respectively) are explicitly transmitted with the aim of allowing mobile nodes to capture the MAC state (DQCA counters and variables) of a certain AP in order to properly apply the corresponding DQCA rules. Alternatively, this information allows nodes to recover from errors and possible loss of DQCA counters.

More importantly, this feedback control information provides a specific mean of estimating each AP's current traffic load. Indeed, TQ corresponds to the number of nodes awaiting for transmission in the Data Transmission Queue (DTQ). Hence, TQ is a parameter that is directly proportional to the traffic load level an AP is experiencing. The greater TQ is, the more loaded the corresponding AP is.

Therefore, DQCA offers an easy to implement way to estimate AP's traffic load and mechanism #3 is based on its use. Keeping in mind the defined DQCA handoff process, in this case, node will scan for beacon frames (FBP packets) on each scanned channel and store the TQ values. Nodes will reassociate with that AP with lower TQ value, that is, the least loaded AP. SNR or RSSI measurements are not considered at all within this load-based affiliation algorithm.

It is worth mentioning the fact that the implementation of this AP selection mechanism does not introduce any extra overhead as it is based on DQCA inherent information.

4.5.3.4. AP Selection Mechanism #4

Up to this point three mechanisms based on single metrics have been proposed. Probably, none of these mechanisms considered so far are able to help make the right decisions under all circumstances. This is inherently due to the fact that a single metric cannot capture all factors that influence QoS performance. That is, sometimes it may be preferable to decide according to RSSI criteria and others it may be more appropriate to reassociate with lesser loaded APs.

With these ideas in mind, the AP selection mechanism #4 is proposed with the aim of including several of the previously stated parameters that may influence AP selection decisions. Specifically, SNR measurements and traffic load estimations, by using the TQ value, are employed in this case. In order to do so, it has been defined a cost function, *F*, which computation is given by:

$$F = \frac{SNR}{1+TQ} \qquad \textbf{(4.1)}$$

where *SNR* is the signal-to-noise ratio measured for each scanned channel and *TQ* is the number of messages present in the corresponding scanned AP's DTQ. With this expression, AP reassociation decisions are made in such a manner that considers both link status information (SNR) and traffic load conditions (TQ, number of nodes in DTQ). Note that SNR is included in the factor as a multiplicative factor: the better the link quality af an AP the higher its priority when considering to associate with. Otherwise, TQ is included as a dividing factor so that the priority of that AP to be selected is inversely proportional to the amount of traffic it is serving.

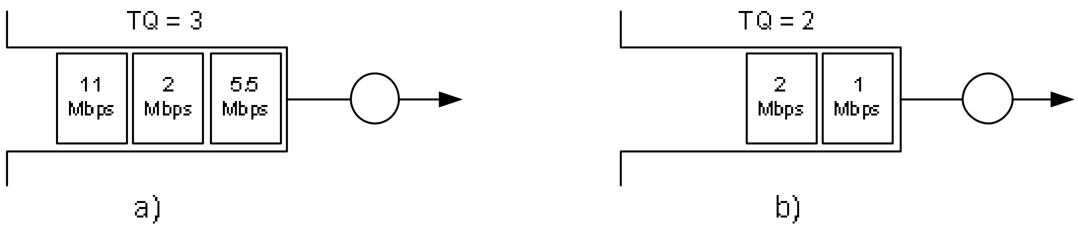
The key is to jointly prioritize APs that provide good link quality while rejecting very loaded APs. The proper selection of the cost function *F* allows weighting of the contribution of each parameter in the scanned APs prioritization.

Using mechanism #4 a scanning node computes the value of *F* for each scanned AP and reassociates with the one that presents the highest *F* value. APs whose FBPs have not been received by the scanning node are not considered in the election decision.

Again, the implementation of this mechanism does not introduce any extra overhead as it only makes use of RSSI measurements and inherent DQCA information.

4.5.3.5. AP Selection Mechanism #5

Lastly, another mechanism based on the use of a cost function has been presented. In this case, the aim is to include an additional factor not included in the previous mechanism #4: the Expected Transmission Delay (ETD). This parameter has been defined in order to reflect the fact that solely consideration of the size of the Data Transmission Queue is not enough when considering the effects of traffic concentration in certain APs. This is due to the fact that the delay that a node will experience since it reassociates to a new AP, enters the DTQ and finally initiates transmitting its message, does not only depends on the number of nodes already present in the queue but also on the transmission rates these nodes will use. This fact is explained using a simplified example in Figure 4.6.



SNRs to these AP are the same value, let's say 5.0 dB. If the node implements mechanism #3 it will connect to the AP with lower TQ value, that is, AP in case (b). Otherwise, if it implements the selection mechanism #4 it will compute the next value for the cost functions *F* in each case:

$$
\begin{aligned}
\mathrm{F}_{(a)} &= \frac{5}{1+3} = \frac{5}{4} = 1.25 \\
\mathrm{F}_{(b)} &= \frac{5}{1+2} = \frac{5}{3} = 1.67
\end{aligned}
\tag{4.2}
$$

As a result, according to mechanism #4 the node would connect to the AP in situation (b). The same selection result is obtained as with mechanism #3. Nevertheless both cases have led to the worse affiliation decision as selecting the AP in situation (b) results in a higher queueing delay. Without losing generality, we assume that messages in DTQ have a normalized mean message size of 1 and compute the period of time that take the present nodes in DTQ to leave this queue. Thus, we are computing the elapsed time that a scanning node would spend from entering the DTQ until reaching the first position:

$$
\begin{aligned}
\mathrm{D}_{(a)} &= \frac{1}{5.5} + \frac{1}{2} + \frac{1}{11} + K = 0.77 + K \\
\mathrm{D}_{(b)} &= \frac{1}{1} + \frac{1}{2} + K' = 1.5 + K'
\end{aligned}
\tag{4.3}
$$

where *K* and *K'* correspond to the total amount of time not devoted to data transmissions and thus their values are not dependant of the user's data rate.

Observing the delay computations in equation (4.3) it can be concluded that selecting the AP in situation (b) will result in a higher queueing delay for the newly arrived node. Therefore, a better decision would have been to select AP in situation (a). This is due to the fact that even though situation (a) presents a greater number of queued messages than situation (b); the required time to transmit these messages is lower than in case (b) as the nodes in case (a) are able to transmit using higher transmission rates.

Therefore, we propose to introduce some additional metric in the AP selection mechanisms in order to capture the effect of the queueing delay. This metric was previously introduced as the EQD (Expected Queueing Delay) parameter. The next computation of the EQD for a determined AP is proposed:

$$
EQD = \sum_{pTQ=1}^{TQ-1} \frac{1}{R_{b_{pTQ}}} \tag{4.4}
$$

where Rb_{pTQ} corresponds to the available transmission rate for the node occupying the *pTQ*th position within the DTQ and *TQ* is the number of messages present in the corresponding scanned AP's DTQ. Note that the proposed computation for the EQD consists of the summation of the inverses of the data transmission rates of the nodes present in DTQ. Thus, this metric inherently captures two factors: Firstly, the queue size and second the queueing transmission delay.

The proposed expression in equation (4.4) accomplishes:

- The more nodes are present in DTQ, the higher the EQD value will be.
- The higher the data transmission of the nodes in DTQ are, the lower the EQD value will be.

Once the EQD metric has been defined, the cost function *F*, for the fifth proposed mechanism can be proposed and studied. In this regard, the following requirements should be demanded for this function when computed for a certain scanned AP:

- The more the link quality, the higher *F* should be.
- The more the number of nodes in DTQ, the lower *F* should be.
- The higher the data transmission rates of the nodes in DTQ, the higher *F* should be.

Keeping in mind these behaviour features that the cost function should capture, the following expression has been proposed:

$$\mathrm{F} = \frac{\mathrm{SNR}}{1+EQD} = \frac{\mathrm{SNR}}{1+\sum_{pTQ=1}^{TQ-1}\frac{1}{R_{b_{pTQ}}}} \qquad \textbf{(4.5)}$$

where *SNR* is the signal-to-noise ratio measured for the corresponding scanned channel, *TQ* is the number of messages present in the corresponding scanned AP's DTQ and Rb_{pTQ} corresponds to the available transmission rate for the node occupying the *pTQ*th position within the DTQ. This implementation of the cost function captures the previously mentioned features.

It is worth noting that, unlike the previously presented mechanisms, this one actually requires the addition of certain extra feedback information in order to be implemented. This is due to the fact that the computation of the EQD factor requires each scanning node to be aware of the R_bs of all the users in the DTQ and so these must be transmitted within the FBP packet. The way the AP is able to deduce the available R_bs of each node in the DTQ is explained next: As all the nodes present in DTQ have previously sent a successful ARS within a control minislot, this uplink transmission can be used by the AP to measure the SNR. Using this measurement and the thresholds shown in Table 3.3 an AP is able to deduce the available R_b for each node in DTQ and include the values in the FBPs.

Since R_b can assume four values (in the study case scenario), it can be represented by 2 bits. In addition, the number of users in the DTQ is expressed by the TQ value. Hence, an overhead of (2×TQ) bits, rounded up to the closest number of bytes, must be added to every downlink FBP packet.

4.5.4. Further Cross-Layer scheduling techniques

One of the main aims that were initially specified was to study the interaction and impact that a Cross-Layer scheduling technique may have on the AP selection mechanisms. In these terms, certain preliminary descriptions are given on this kind of scehduling mechanisms and its impact on the affiliation decision mechanisms its included. Finally, two new AP selection mechanisms are proposed. These new mechanisms, #6 and #7, are the result of adapting mechanisms #4 and #5 to the inclusion of the new Cross-Layer scheduling policy.

4.5.4.1. DQCA Cross-Layer scheduling technique

Authors in [21] propose a scheduling algorithm that makes use of the DQCA MAC protocol over 802.11b legacy physical layer in order to enhance its performance. The proposed mechanism implements a Cross-Layer interaction between the PHY and MAC layers.

The 802.11b PHY layer supports multi-rate packet transmission, with higher rates being available when the wireless channel quality is good. The objective of the Cross-Layer scheduling mechanism is to achieve a more efficient utilization of the channel bandwidth by granting access to the users that can transmit at the maximum available bit rate (R_b), whereas users with lower bit rates wait until the condition of their link improves.

In the basic DQCA operation each user sends an ARS to the AP as an access request. Upon the ARS reception the AP calculates the Signal-to-Noise Ratio (SNR) of the link, deduces the maximum bit rate at which the user can transmit and includes the R_b value in the FBP packet. The AP, who knows the available bit rates of all the users in the system, rearranges the DTQ by placing users with higher transmission rates to higher positions. If no distinction can be made by means of R_b, the users are sorted by their arrival at the DTQ, that is, their pTQ value. The AP attaches to the FBP a vector with the available R_b values of all the users by order of their position in the DTQ. Therefore, every user is aware of the condition of all other users and it is in position to derive its own pTQ, that is, its position in the DTQ.

The evaluation of the benefits of the proposed technique is shown in [21]. In the particular scenario conditions analysed, a throughput improvement of up to 75% is achieved over the maximum throughput obtained with DQCA protocol without cross-layer concepts. On the other hand, a remarkable mean packet delay reduction is also achieved.

Nevertheless, authors in [21] study the novel Cross-Layer technique in a single cell WLAN scenario. The application of this technique within DQCA multi-cell WLAN scenario poses new possibilities regarding the AP selection mechanisms. The aim of this section is to study the interaction of the Cross-Layer scheduling and the DQCA handoff process. Specifically, the inclusion within the two selection mechanisms based on multiple metrics is studied, that is, mechanisms #4 and #5.

4.5.4.2. Impact of the Cross-Layer scheduling technique on AP selection mechanisms

The impact of the described Cross-Layer technique on reassociation decisions is explained next:

- The Cross-Layer technique prioritizes data transmissions with good link quality and so it gives transmission grants to those nodes in DTQ that are able to transmit data using high bit rates. It leads to an R_b-based reorganization of the DTQ.

- Both AP selection mechanism #4 and #5 take into account a traffic load metric in order to prioritize candidate APs for a scanning node to reassociate with. This traffic load metric is essentially based on the value of TQ, that is the number of nodes in DTQ.

- Using the Cross-Layer technique, when a node reassociates to a new AP it will enter de DTQ but generally it will not actually occupy the last position of this queue as its transmission priority will depend on its available R_b, estimated by the AP. Specifically, a newly arrived node will occupy the position in DTQ immediately after the nodes with higher or equal R_b and immediately before the nodes with lower available R_b.

In what respects to the overhead required in order to implement the described Cross-Layer scheduling technique, it is exactly the same amount than the added using mechanism #5 (R_b values of the nodes in DTQ). Otherwise, recall that mechanism #4 does not requires extra overhead so that in order to implement it along with the Cross-Layer technique all R_b values of the nodes in DTQ must be included in the FBP packet.

Since the described Cross-Layer technique is used, certain modifications must be applied to the AP selection decision criteria. Specifically, the cost functions that both mechanisms use in order to prioritize candidate APs must be computed differently:

a) **AP selection mechanism #4**: The cost function takes into account the TQ value of candidate scanned APs. Originally this parameter represents the number of nodes in DTQ. However, since the Cross-Layer technique is applied, this value should only take into account the number of nodes with equal or higher R_b than the scanning node's available R_b regarding the candidate AP. Thus, the cost function F is computed as shown next:

$$F = \frac{SNR}{1+TQ'}$$

where SNR is the measured signal-to-noise ratio to the scanned AP and TQ' represents the number of nodes with equal or higher R_b than the scanning node's available R_b regarding the candidate AP.

The resulting mechanism will be referred henceforth as **AP selection mechanism #6**.

b) **AP selection mechanism #5**: The function takes into account the proposed computation for the EQD metric, however, when the Cross-Layer is applied the computation of this metric should only consider the R_b values present in the DTQ that are equal or higher than the scanning node's R_b with respect to the candidate scanned AP. Thus, when Cross-Layer is applied the cost function F must be computed as:

$$F = \frac{SNR}{1+EQD} = \frac{SNR}{1+\sum_{pTQ} \frac{1}{R_{b_{pTQ}}'}}$$

where SNR is the measured signal-to-noise ratio to the scanned AP and R_{bpTQ}' represents R_b values in DTQ that are equal or higher than the scanning node's available R_b regarding the candidate AP.

The resulting mechanism will be referred henceforth as **AP selection mechanism #7**.

4.5.5. Summary of proposed AP selection mechanisms

Up to this point, several AP selection mechanism have been proposed. These mechanisms are based on the use of one or more parameters in order to carry out AP associations. Although cost functions have only been introduced for mechanisms #4, #5, #6 and #7, all the proposed mechanisms can be interpreted as based on single, dual, or multi-parameters cost functions. In this regard, Table 4.1 shows a brief summary of these proposed AP selection mechanisms.

Table 4.1 Characteristics of the proposed AP selection mechanisms

AP selection mechanism	Cost Function (*F*)	Required Extra Overhead	Commentary
#1	F=SNR	No	RSSI-based. Prior to decision all the available channels must be scanned
#2	F=SNR	No	RSSI- based. Reassociation is carry out whenever a better scanned channel is found.
#3	F=TQ	No	Solely based on traffic load estimation.
#4	$F = \frac{SNR}{1+TQ}$	No	It captures 2 metrics: SNR and traffic load.
#5	$F=\frac{SNR}{1+\sum_{pTQ=1}^{TQ-1}\frac{1}{R_{b_{pTQ}}}}$	Yes	It captures 3 metrics: SNR, traffic load and queueing delay
#6	$F = \frac{SNR}{1+TQ'}$	Yes	Adaptation of #4 mechanism for the inclusion of a Cross-Layer scheduling technique
#7	$F = \frac{SNR}{1+\sum_{pTQ}\frac{1}{R_{b_{pTQ}}}'}$	Yes	Adaptation of #4 mechanism for the inclusion of a Cross-Layer scheduling technique

CHAPTER 5. DQCA MULTI-CELL SIMULATOR

5.1. Introduction

This chapter is devoted to the description of the structure and main features of the developed computer simulator aimed to assess the performance that the proposed mechanisms and techniques.

5.2. General structure

The simulator has been written in the object-oriented C++ language. As an object-oriented language, C++ allows creating objects and classes directly related to entities in the WLAN system (nodes, AP, channels, etc.).

It takes traffic parameters and network parameters (such as number of nodes and their mobility models) as inputs and returns the simulation results in an output text file. The output can then be analysed or presented graphically. The simulator can be used for modeling topological changes such as the shape of the cells or the APs location. Additionally, it supports studies of different types of services and traffic patterns (data, voice, video, etc.).

One of the main requirements that the simulator had to fulfill was the ability of running multiple DQCA engines whose frames are not synchronized in time. To do so, it is required a time basis with high granularity; that is, each iteration in the simulator corresponds to a small simulation time. Hence, the simulator uses a time basis of 2 µs. The simulator performs a specified number of iterations so that the total simulation time corresponds to a user-adjustable value. The total simulation time must be high enough to guarantee that the steady state of the simulation is achieved and the output results are reliably obtained.

The simulator defines several classes and the corresponding methods in order to implement the different entities and roles that made up the infrastructure WLAN scenario under study: nodes, frequency channels, messages buffers, frames, messages, packets, etc. Moreover, the class '*Tx_Scheduler*' has been defined in order to schedule data transmissions and, in case of using Cross-Layer techniques, to reschedule the queues.

Next, a brief description of the main classes that are used within the simulator:

- **'DQCAmobile' class**: It is used to define the objects that represent mobile nodes in the system. It contains the required DQCA parameters such as the counters and pointers representing the distributed queues, several PHY such as the SNR and transmission power, the node identifier, as well as several statistical parameters in order to compute the previously defined performance parameters. A number of methods are included related with the application of the DQCA rules, the traffic generation and the management of the buffer of information messages. Mobility models are also implemented within.

- **'AP' class**: This class is devoted to the implementation of AP entities in the system. Each object of this class corresponds to an actual AP in the simulator. Several attributes are defined such as the AP position within the scenario, the elapsed number of DQCA frames in the AP, the duration of each of these frames, etc. It also includes various methods such as those related to keeping track of packets reception from nodes. Each AP object includes a 'TX_scheduler' object that manages the packet transmission scheduling functions.

- **'Tx_Scheduler' class**: It implements a centralized entity located in each AP that manages and controls data transmissions. It contais several vectors aimed at storing information on the nodes in the queues (SNR, id, etc.). In each frame it carries out the selection of the transmitting node according to the DQCA rules or Cross-Layer criterions in case these are implemented.

- **'DataSlot' class**: It represents the data slot within the DQCA frame. An object of this class is included in the 'AP' class definition. This class is accessed from the 'TX_scheduler' objects in order to control the state of the data slot. Nodes also access the 'DataSlot' objects in order to notify their data transmissions along with the R_b used, the node id, and the 'final message bit'.

- **'Minislot' class**: Each object of this class represents a single control minislot wherein nodes transmit ARSs as access requests. It contains information on the number of ARS transmission attempts and the identifiers of the nodes that select the minislot to transmit their ARSs.

- **'Messages_queue' class**: This class is devoted to the representing the buffer in every node where information messages are stored awaiting for transmission. The buffer represents a FIFO (First-In, First-Out) queue with a length of 200 position where in each them are stored the number of generated bits and the generation timestamp. It provides the required methods in order to schedule the queue (*push* and *pop* mechanisms) and information on the level of occupation (number of generetad messages). When the queue of messages is full, newly arrived packets are lost.

- **'RadioChannel' class:** It represents the wireless communications channels. Each 'DQCAmobile' object contains a 'RadioChannel' object aimed at mantaining and updating the radio channel state. It implements previously described dual-slope breakpoint channel model and the lognormal shadowing fading. Further information on the frequency channel is included. The class updates the SNR values as the simulation time passes and the node moves. This SNR values are consulted by nodes in order to select the proper R_b to transmit their packets.

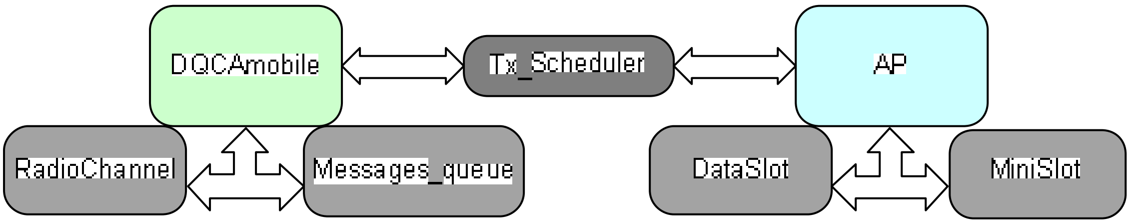


Figure 5.1 Interaction between classes and objects defined in the DQCA multi-cell simulator

Figure 5.1 shows a simplified diagram of interaction between the defined classes. The triple arrows forming a square angle represent the interaction between two classes, one of which, the lowerly located is a member class of the upper one, that is, it is a member object of the upper one. Instead, the horizontal arrows show a relation between independent objects.

The main core of the DQCA simulator is based on the use of the so-called ‘nested loop’ structure. A *nested loop* is a loop within a loop, an inner loop within the body of an outer one. How this works is that the first pass of the outer loop triggers the inner loop, which executes to completion. Then the second pass of the outer loop triggers the inner loop again. This repeats until the outer loop finishes. The employed nested-loop structure of the main program is described with the pseudo-code shown in Figure 5.2.

```
While (Elapsed_Time<Total_Simulation_Time)
{
        For each AP
        {
                For each node
                {
                        Traffic generation;
                        Move node;
                        Update SNR;
                }

                Execute DQCA rules;
                If (node is in Discovery phase)
                        Execute scanning functions;

                Update AP state;
                Update Tx_Scheduler parameters;
        }

        Elapsed_Time+= 2 µs;
}
```

CHAPTER 6. RESULTS ANALYSIS

6.1. Introduction

This chapter addresses the description of the simulations carried out using the previously described DQCA multi-cell simulator. Moreover, the performance of the DQCA handoff process is analysed under the study case scenario described in section 3.2. Likewise, the performance and enhancements of the proposed AP selection mechanisms and other mechanisms are assessed.

The chapter is organized as follows: Section 6.2 is devoted to the description of preliminary results such as losses due to the designed DQCA handoff process. Section 6.4 analyses the performance of the AST mechanism, whereas section 6.3 analyses the performance of the studied AP selection mechanisms. Finally, section 6.5 is devoted to describing the interaction and performance of some of the proposed selection mechanisms with a transmission-oriented Cross-Layer strategy.

Although explicitly explained, all the conditions under which the computer simulations have been carried out are those detailed in CHAPTER 3.

6.2. Preliminary results

6.2.1. DQCA handoff net loss

As an initial stage of the study, focus is put on obtaining a benchmark reference on the performance of the DQCA handoff process that was proposed in CHAPTER 4. To this end, a different scenario than the proposed in CHAPTER 3 has been implemented. The aim is to obtain a worst-case quantitative reference of the inherent loss that the proposed DQCA handoff process entails. The scenario presented in CHAPTER 3 is not suitable for this purpose as it presents certain cell overlapping so that losses due to handoffs are overcome by the fact that performing a handoff, a node finally transmits its message with a better link quality with a high probability. As a result, total throughput is increased with respect to the one obtained in a single cell scenario wherein handoffs do not occur. In this regard, the performance of a single DQCA cell with a single AP is compared to that of a three cell scenario. In the former situation (Figure 6.1), 20 nodes are confined in single cell, therefore handoffs will not be carried out. Otherwise, in the second scenario (Figure 6.2) the 20 nodes are randomly distributed among three cells, thus, handoffs will occur as nodes move freely. The AP selection mechanism used in this case is the previously described SNR-based #1 mechanism.

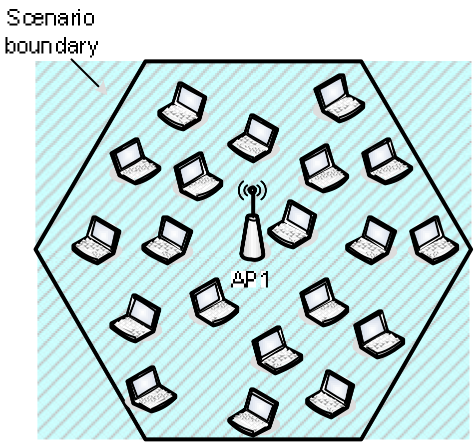


Figure 6.1 Single cell scenario where handoffs do not occur.

The scenario in Figure 6.2 consists of three hexagonal cells where handoffs occur as nodes move freely around the scenario area (see 3.2.5). It is worth mentioning that the coverage areas of the three APs in Figure 6.2 do not represent actually feasible radio coverage areas. Nevertheless, the scenario allows computing the net loss due to handoffs as no cell overlapping is present that would cause a total throughput increase.

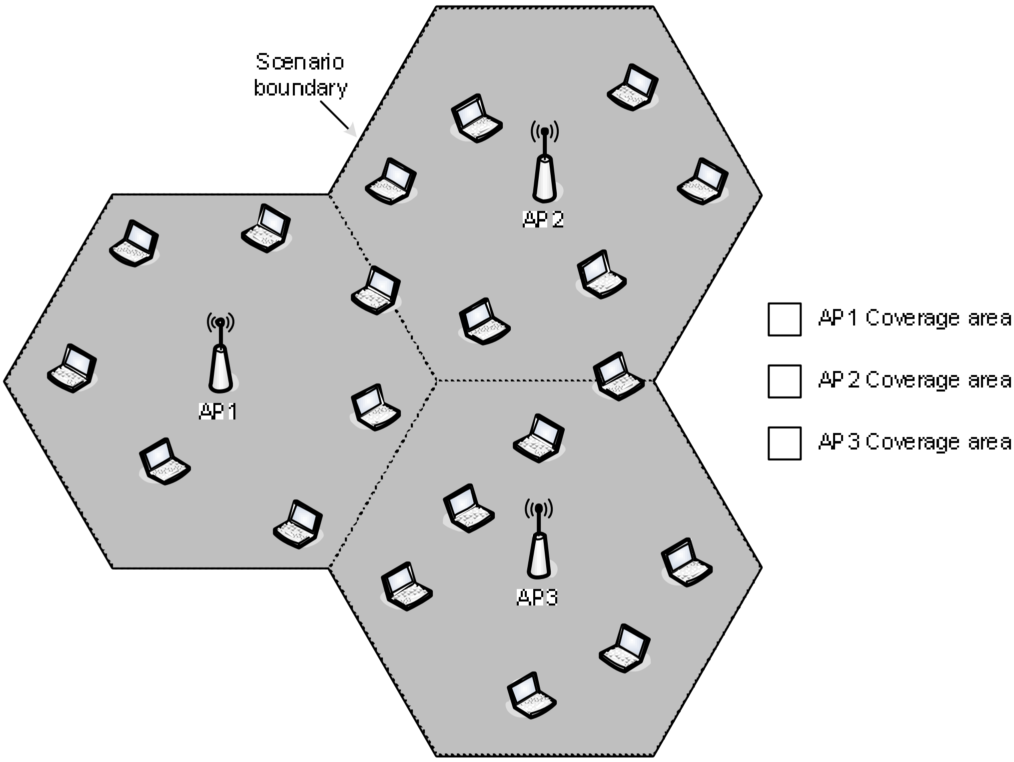


Figure 6.2 Three cell scenario without overlapping and where handoffs do occur.

Next, Figure 6.3 shows the obtained throughput performance in both scenarios.

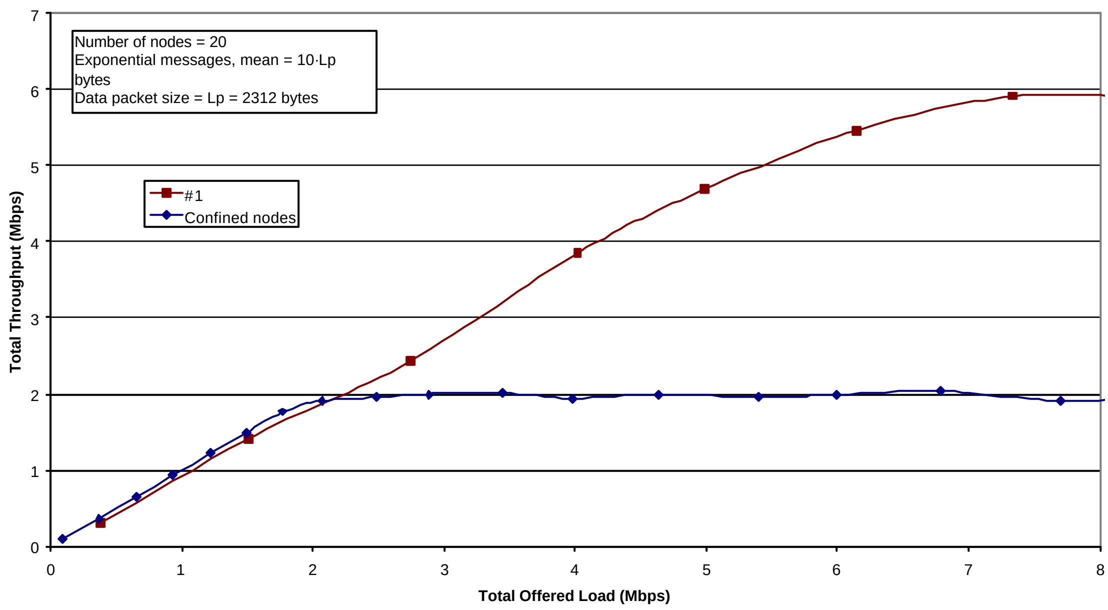


Figure 6.3 Throughput performance for the scenarios presented in Figure 6.2 (blue) and Figure 6.2 (red).

The maximum throughput that is obtained for the single cell scenario is around 2.0 Mbps whereas a value of 5.93 Mbps corresponds to the three cell case. These values allow obtaining the resulting loss due to handoffs. In an ideal case where handoff losses were zero or negligible, the total throughput obtained with N cells should be N times the one obtained with a single cell. With the obtained results (where N=3) this is not accomplished:

2.0 Mbps x 3 APs = 6 Mbps Total throughput

5.93 Mbps < 6 Mbps → **Net Handoff Loss = 1.17%**

It means that in the three cell scenario every single cell achieves a maximum throughput 1.17% lower with respect to that ideal case with a single cell and no handoffs. This 1.17% loss is solely due to handoffs occurring. Recall that according to the designed DQCA handoff process scanning nodes in certain situations cause that a certain number of DQCA frames do not include data, that is, the data slot becomes empty with the corresponding loss of efficiency. Furthermore, the authentication phase within the handoff process includes the transmission of non-payload packets (Authentication and Reassociation Requests) an it also represents a certain loss of efficiency.

This slight loss of efficiency in the DQCA handoff process also has repercussions in terms of mean delay performance. Figure 6.4 shows the messages mean delay results.

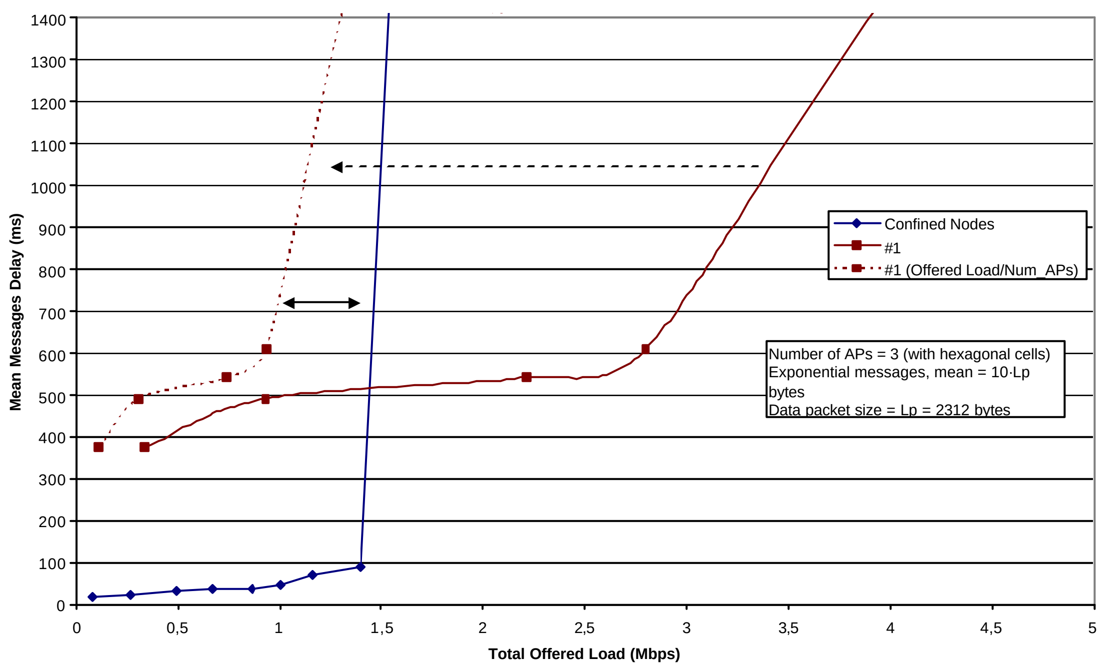


Figure 6.4 Mean delay performance for the scenarios presented in Figure 6.2 (blue) and Figure 6.2 (red).

As seen on Figure 6.4 the steady mean delay for the three cell case presents a value around 550 ms. This value for the single cell case is around 150 ms. This messages mean delay increase is also solely due to the handoff processes. However, the main side effect due to handoffs can be observed in terms of the maximum offered load that the system can support while keeping the messages delay bounded. Note that in the three cell case this maximum offered load is around 3.5 Mbps whereas in the single cell case it is around 1.5 Mbps. Again, in an ideal case the former 3.5 Mbps should be 3 x 1.5 Mbps = 4.5 Mbps which represents a 22% decrease. Once again, this decrease in the maximum offered load is due to the handoffs occurring.

It is worth mentioning that these reference values of the loss incurred due to handoffs are particular of the scenario under study. For instance, if the nodes velocity is increased, these values would worsen, or even get better if the velocity is reduced. Anyway, the obtained values of net handoff lossess allows assessing the designed performance. In conclusion, as this kind of losses are inherent to handoffs, these can be considered reasonably low.

6.3. Performance of the proposed AP selection mechanisms

6.3.1. Comparison between mechanisms #1 and #2

Figure 6.5 shows the throughput results obtained for the AP selection mechanisms #1 and #2. In this case, the simulation scenario consists of that presented in Figure 3.3 where overlapping between cells occurs. This will be the scenario under consideration throughout the description of results described henceforth. At this point, it is worth recalling that these two mechanisms are both based on SNR measurements in order to make AP affiliation decisions. However, they differ in what follows:

- With mechanism #1 nodes always scan on all the available channels before deciding the AP to associate with.

- With mechanism #2 nodes can reassociate with an AP whose FBP is received with and SNR higher than the SNR measured to their current AP, regardless of if they have already scanned on all the available channels.

As shown in Figure 6.5, the maximum throughput values are 14 Mbps and 13.2 Mbps for the mechanisms #1 and #2, respectively. The obtained throughput with #1 is higher than with #2 due to the fact that with #1 nodes are able to make smarter AP selection decisions since nodes scan on all the available channels and get complete information of the available nodes. As a result, #1 outperforms #2 with a 6% maximum throughput enhancement.

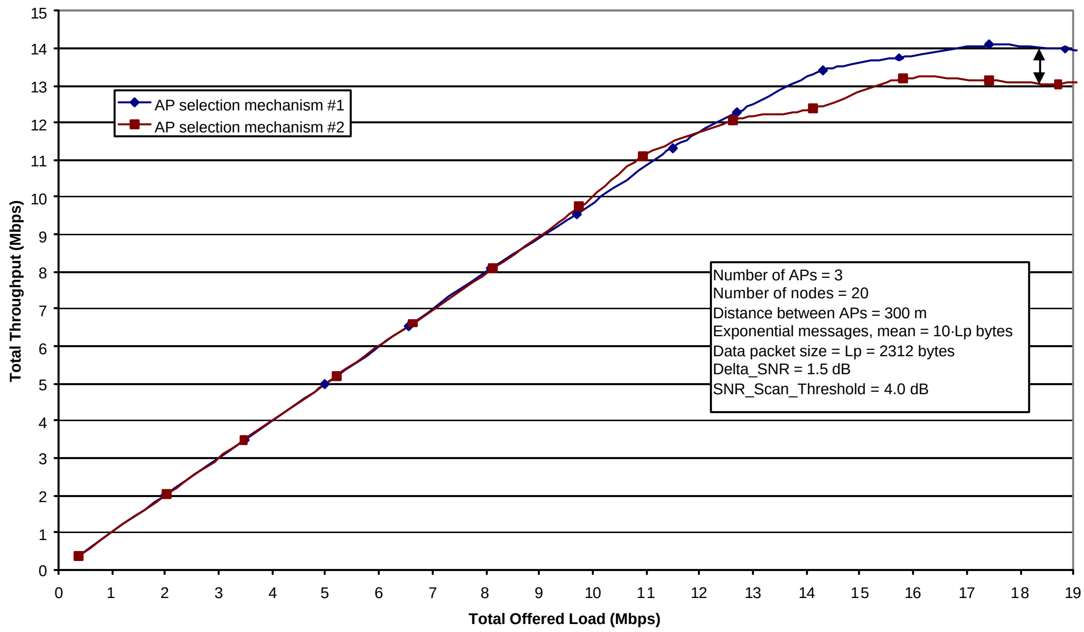


Figure 6.5 Throughput performance with mechanisms #1 and #2.

However, when nodes initiates a scanning process using mechanism #1 they spend more time scanning than when using #2 as they need to scan all the available channels prior to deciding which AP to reassociate with. This drawback is reflected in terms of messages delay. Figure 6.6 shows the messages mean delay performance obtained with these two mechanisms.

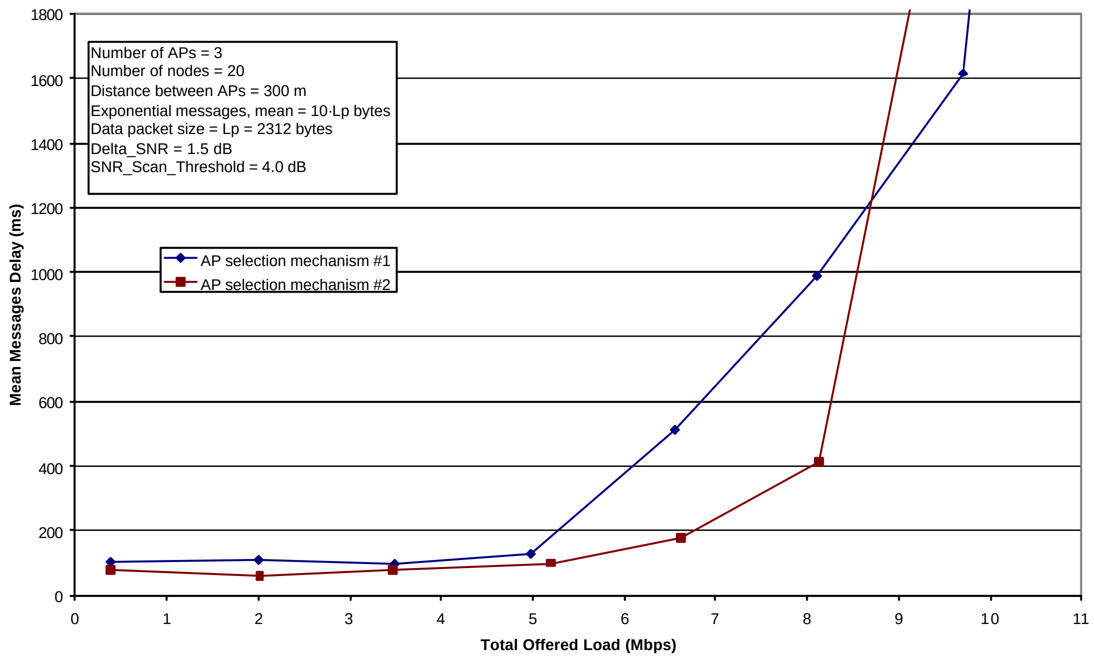


Figure 6.6 Mean messages delay performance with mechanisms #1 and #2.

Figure 6.6 shows that mechanism #2 keeps a slightly lower level of mean delay for a wide range of total offered load values. Moreover, mechanism #2 keeps the delay steady for up to an offered load of 8 Mbps whereas with #1 delay becomes unstable from around 6 Mbps. This mean delay reduction obtained with mechanism #2 with respect to #1 is due to the fact that with #2, scanning nodes employ less time during scanning phases as they do not always need to scan on all the available channels in the system.

The conclusion that is drawn from the comparison between results obtained with mechanism #1 and #2 is that there exists a tradeoff between throughput and mean delay optimization. #1 maximizes the maximum achieved throughput at the expense of slightly higher mean delay, whereas #2 minimizes the obtained messages mean delay at the expense of a not so high maximum throughput.

6.3.2. Performance analysis of AP selection mechanism #3

Mechanism #3 is the only proposed mechanism that is solely based on AP's traffic load estimation. Figure 6.7 shows the obtained results obtained in terms of throughput with respect to those obtained with the previously analysed mechanisms #1 and #2. As it can be seen, with mechanism #3 the maximum throughput that can be achieved is a value around 13.5 Mbps which is a value between the obtained throughput results with #1 and #2. Roughly, it can be said that this traffic load based mechanism outperforms #2 in terms of throughput but still it is not as optimum as #1. However, the goodness of this mechanism arises when considering the mean delay results depicted in Figure 6.8.

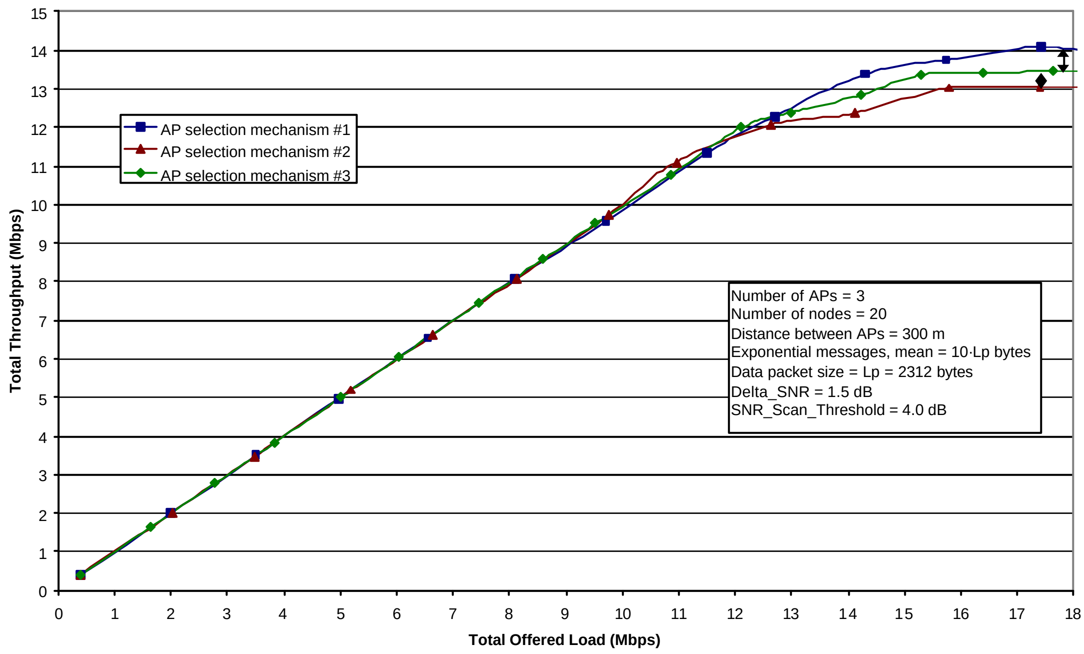


Figure 6.7 Throughput performance of mechanism #3 with respect to #1 and #2.

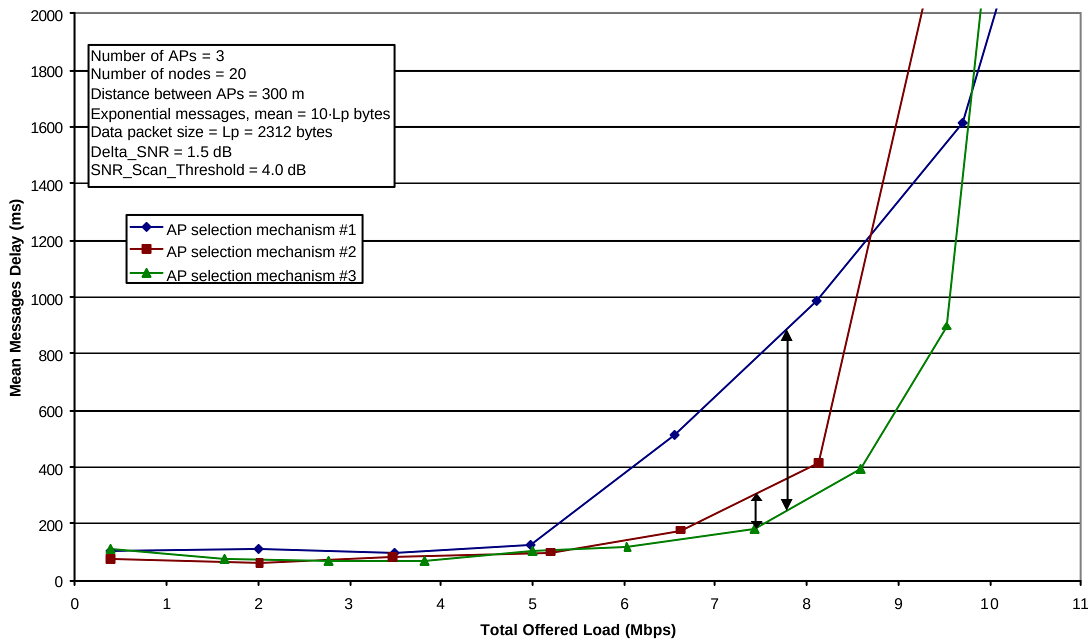


Figure 6.8 Mean messages delay performance of mechanism #3 with respect to #1 and #2.

As Figure 6.8 shows, mechanism #3 obtains lower mean delay levels than those obtained with #1 and #2. Actually, the obtained delay is approximately equal to that obtained with #1 and #2 when traffic load is low. Otherwise, #3 keeps the delay stable up to offered load levels where delay with #1 and #2 is already asymptotically increasing.

6.3.3. Performance analysis of AP selection mechanism #4

From the previous results, it can be concluded that the benefits of employing traffic load based decisions within the handoff process is, at least, equally critical and beneficial as making SNR-based decisions. Keeping this idea in mind, mechanism #4 was proposed and its performance is evaluated next.

Mechanism #4 is the firstly proposed mechanism that considers both traffic load conditions and SNR measurements to candidate APs in order to implement selection decision. Its performance in terms of throughput is shown in Figure 6.9. In this case, the combination of parameters in the affiliation decisions allows achieving a considerably high maximum throughput value of 14 Mbps. In this regard, mechanism #4 outperforms #2 and #3 and reaches the value obtained with #1.

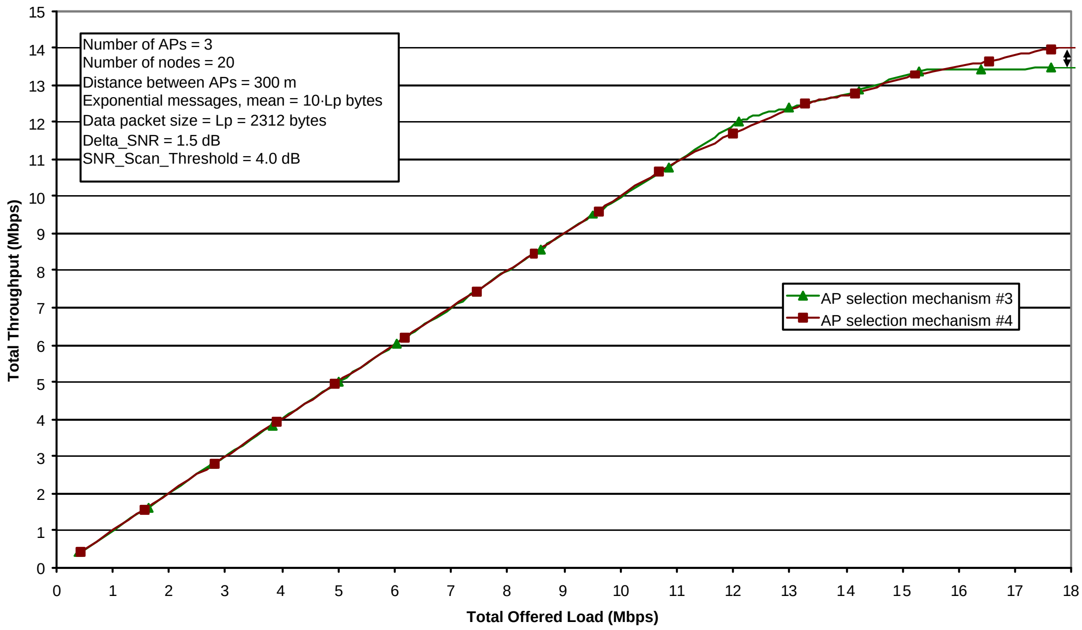


Figure 6.9 Throughput performance of mechanism #4 with respect to #1, #2 and #3.

Mean messages delay performance of the proposed mechanism #4 is shown in Figure 6.10. As it can be seen, #4 maintains mean delay levels as low as those obtained with #3 and even lower when the offered load increases beyond 9 Mbps. Consequently, from these results it can be concluded that, up to this point, the best performance both in terms of throughput and mean messages delay is achieved when implementing AP selection decisions considering several factors or metrics (i.e. with mechanism #4).

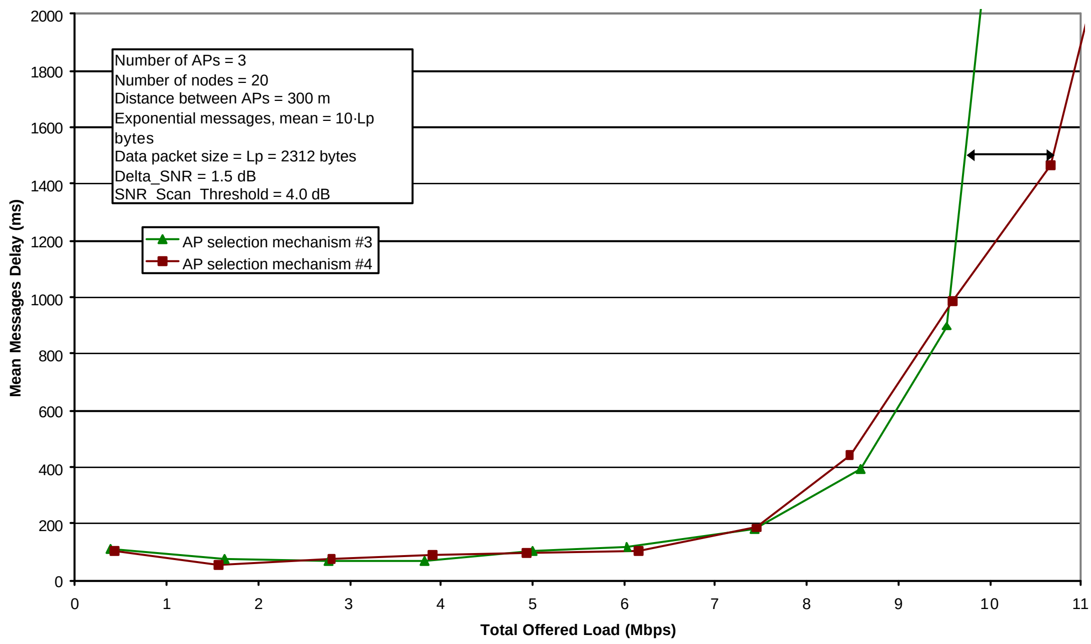


Figure 6.10 Mean messages delay performance of mechanism #4 with respect to #3.

6.3.4. Performance analysis of AP selection mechanism #5

The AP selection mechanism #5 is proposed based on the observed benefits that the combination of parameters in the AP selection decision allow obtaining. In this case, the combined factors include an EQD estimation as well as the measured SNR to the candidate AP and a traffic load estimation based on the number of nodes in DTQ (*TQ* value transmitted within the FBP).

The results obtained with #5 are shown in Figure 6.11 and Figure 6.12 where the results corresponding to mechanism #4 are also included.

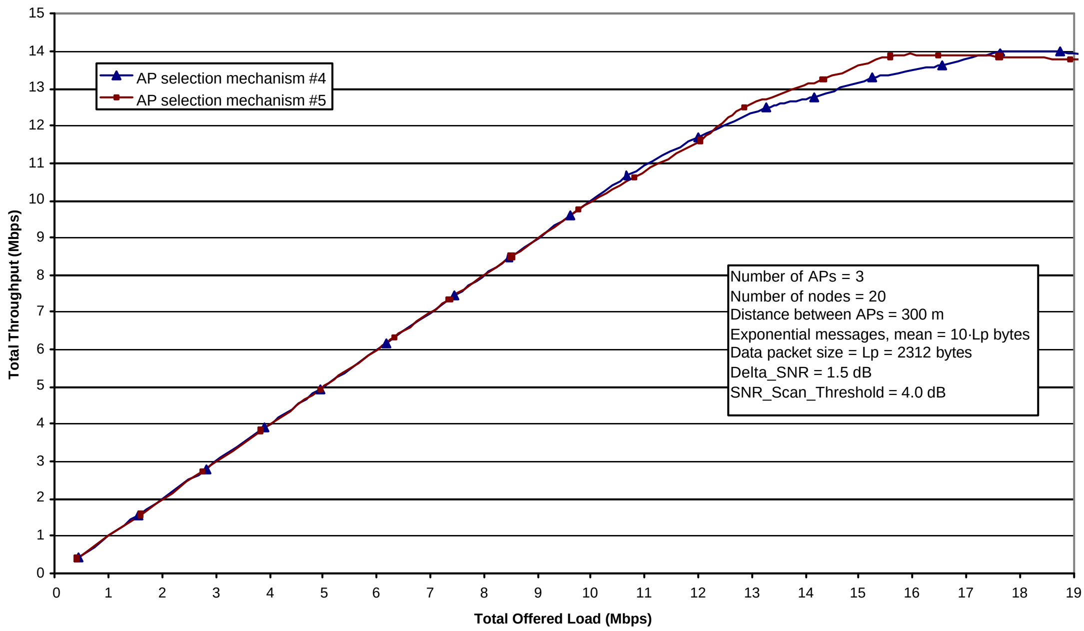


Figure 6.11 Throughput performance of mechanism #5 with respect to mechanism #4.

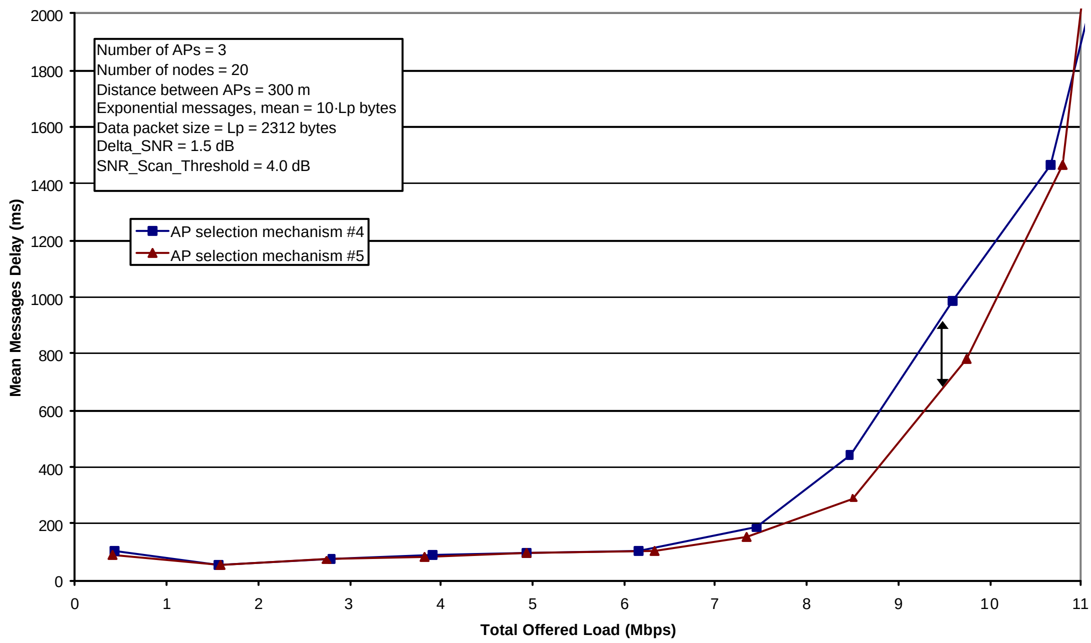


Figure 6.12 Mean messages delay performance of mechanism #5 with respect to mechanism #4.

In terms of total throughput results, it can be seen in Figure 6.11 that this last AP selection mechanism achieves a maximum throughput of 13.8 Mbps that is a slightly lower result than the highest value obtained up to the moment with #1 and #4, that is, 14 Mbps. Nevertheless, with respect to mean delay results, mechanisms #5 shows the best performance when compared with the rest of the mechanisms. This better performance in terms of delay is especially noticeable when the total offered load increases beyond the 10 Mbps level and delay enters in the non-stable zone.

Finally, taking into account the previous results for each of the proposed techniques, we can conclude that mechanism #5 is one of the best performing one. As a matter of fact, mechanisms #1 and #4 achieve a slightly higher maximum throughput but #5 presents optimal results in terms of messages mean delay along with significant results regarding throughput.

6.4. Performance of the 'Advanced Scanning Technique'

As described in section 4.4, the AST is proposed in order to perform scanning process in a more efficient manner. The aim of this technique is to allow nodes to be aware of the DQCA frame's duration. This allows scanning nodes to profit the whole data slot duration regardless of its duration. To do so, nodes need to know the transmission rate that the transmitting nodes will use in the data slot. This is accomlished with the AST mechanism by means of including the next DQCA frame's transmission rate within the feedback packet (FBP).

The performance and benefits of this scanning mechanism have been evaluated by means of computer simulations. In this sense, simulations have been carried out implementing the #4 mechanism with and without the AST. Results in terms of throughput and messages mean delay are shown in Figure 6.13 and Figure 6.14.

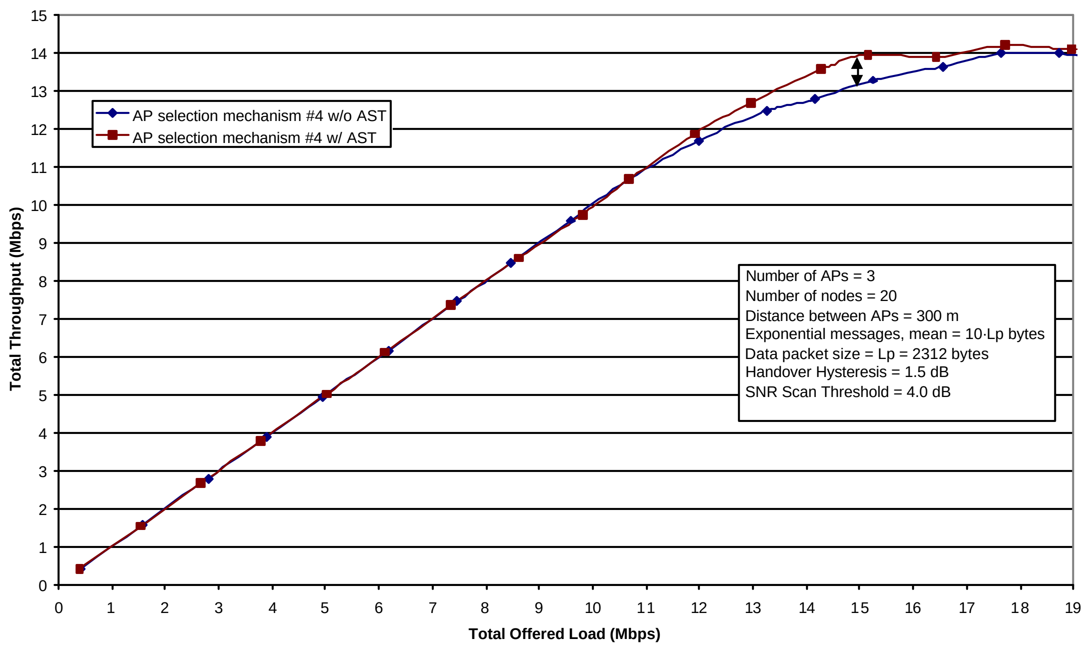


Figure 6.13 Throughput performance for the #4 mechanism with and without the AST mechanism.

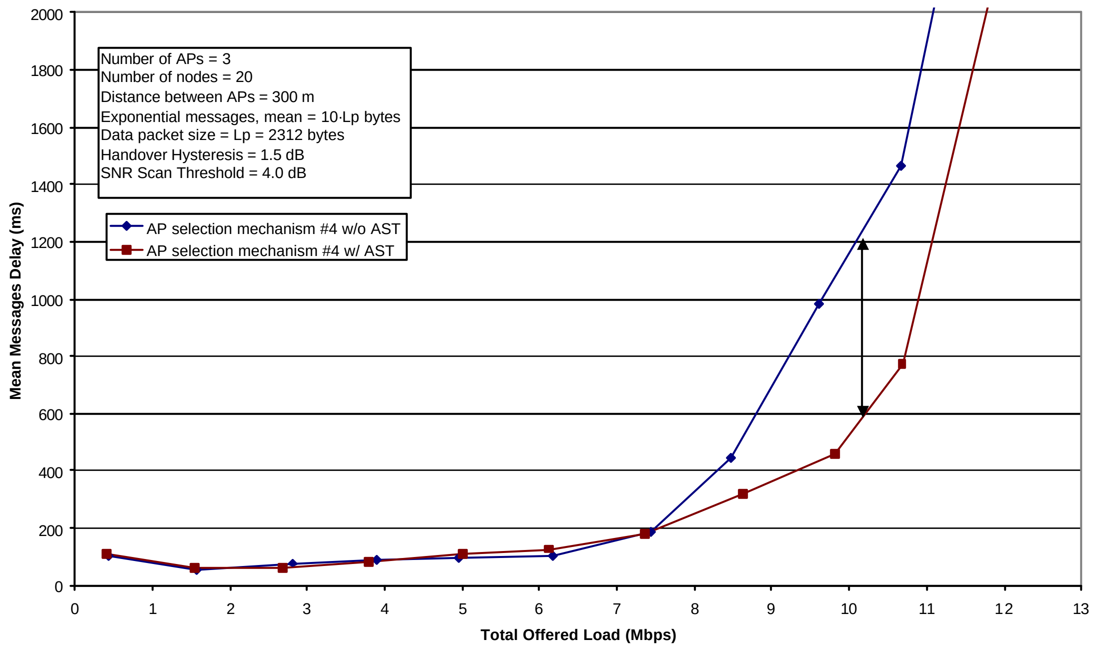


Figure 6.14 Mean messages delay performance for the #4 mechanism with and without the AST mechanism.

These figures show that the AST offers benefits both in terms of throughput and mean delay but especially in terms of the latter. Figure 6.13 shows that the maximum achievable throughput when using the AST mechanism is approximately equal to the obtained without it. However, this is a positive result in the sense that the practical implementation of the AST requires certain amount of extra overhead to be added and despite of it, the achievable throughput is almost unaffected. The reasons regarding this throughput performance are twofold: On one hand, the required extra overhead is minimum as in the worse case it is of 8 bytes; and on the other hand the AST allows node to perform more efficient handoffs and AP reassociations.

With respect to mean delay results, Figure 6.14 shows that when offered traffic load is low (below 5 Mbps) results are practically the same in both cases, with and without using the AST. Nevertheless, as offered load increases the obtained mean delay when using the AST is remarkably reduced with respect to the case when the AST is not applied.

From these noticeable benefits it can be concluded that, although it requires extra overhead control information to be implemented, the AST effectively improves the DQCA scanning process especially in terms of messages mean delay.

6.5. Performance analisys of AP selection mechanisms #6 and #7

One of the main aims that were initially specified was to study the interaction and benefits obtained from incuding a Cross-Layer scheduling technique within the AP selection mechanisms. Next, the obtained results when applying AP selection mechanisms #6 and #7 are described. Recall that these two mechanisms are based on mechanisms #4 and #5, and result of taking advantage of the Cross-Layer scheduling technique.

Next, Figure 6.15 and Figure 6.16 show the throughput and messages mean delay results obtained when the previously described Cross-Layer scheduling technique is employed (mechanisms #6 and #7) and when not (mechanisms #4 and #5).

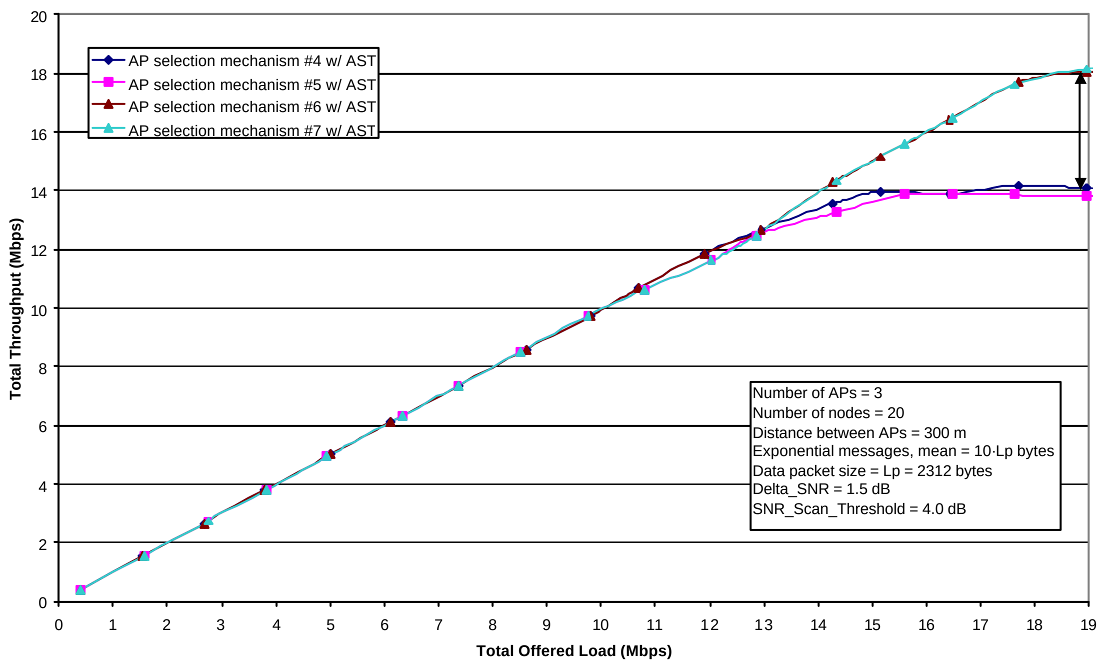


Figure 6.15 Throughput performance of the Cross-Layer scheduling applied with mechanisms #4 and #5.

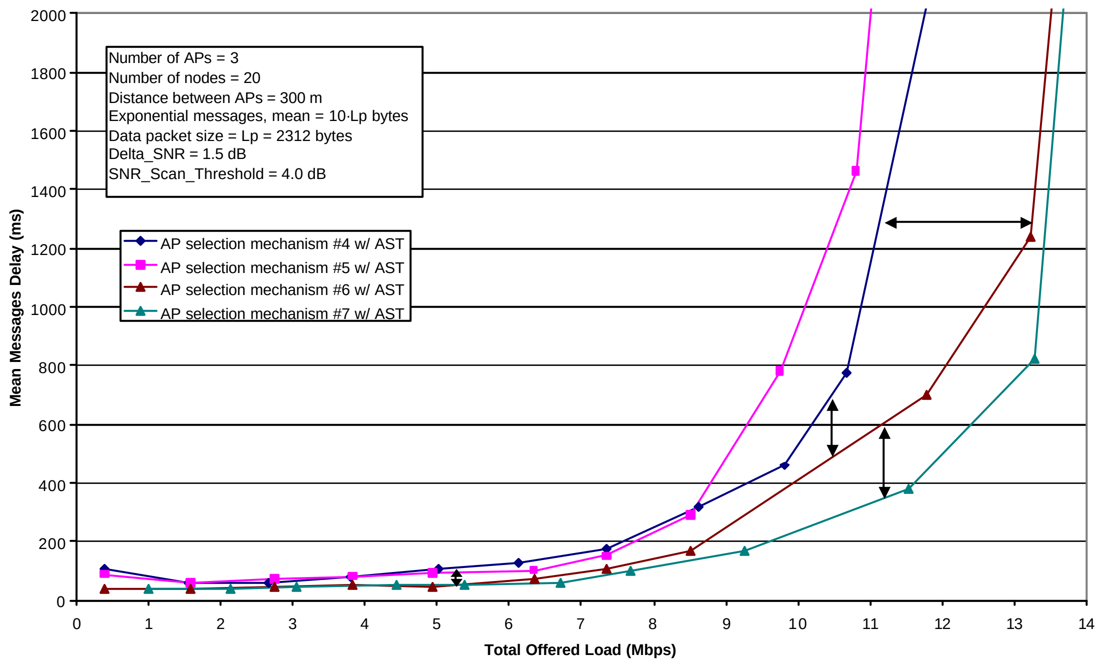


Figure 6.16 Mean Delay performance of the Cross-Layer scheduling applied with mechanisms #4 and #5.

Observing the results shown in Figure 6.15 and Figure 6.16 regarding the throughput and mean delay performance, the next remarks can be listed:

- The maximum achievable throughput is significantly increased with both mechanisms #6 and #7 with respect to #4 and #5. That is, when the Cross-Layer scheduling technique is applied throughput is noticeably increased. Specifically, an approximately 28% increase is achieved in these terms.

- Mean delay is slightly reduced for both mechanisms #6 and #7 with respect to #4 and #5, especially in the stable zone with traffic loads lower than 8 Mbps. That is, when the Cross-Layer scheduling technique is applied messages mean delay is considerably reduced in the stable zone (low offered loads).

- When using mechanisms #6 and #7, the maximum offered load below which mean delay is kept stable is significantly increased with respect to mechanisms #4 and #5.

- Mechanisms #6 and #7 achieve very similar performance results in terms of throughput. However, with respect to messages mean delay, differences between these two mechanisms are noticeable, that is, mechanism #7 mantains lower mean delay values than #6 when this Cross-Layer scheduling is employed than when it is not (mechanisms #4 and #5 are used then).

The first three remarks in the list could have been expected prior to obtaining simulation results. As shown in [21], the proposed Cross-Layer prioritization offers a remarkable enhancement of the total throughput and mean delay.

However, the last remark could not have been as easily expected. Previously, mechanisms #4 and #5 were studied and compared by using computer simulations. There was shown that these two mechanisms perform similarly under the studied scenario in terms of throughput and mean delay. Nevertheless, slight differences appeared with respect to mean delay results. When the traffic load increases up to the point beyond the stable zone, #5 maintains slightly lower mean delay values than those obtained with #4. This behavior that previously differed these two mechanisms, is now emphasized when this Cross-Layer scheduling and selection mechanisms #6 and #7 are applied. This result can be explained following the next reasoning:

- Mechanism #4 did not required extra control information to be included in the FBP packet, that is, system overhead was not increased due to its use. Otherwise, AP selection mechanism #5 did required extra information to be attached to the FBP, hence, system overhead had to be slightly augmented. Specifically, this mechanism required that the FBP includes all R_b values of the nodes in DTQ.

- In order to implement the previously described Cross-Layer scheduling technique it is necessary to increase the DQCA frame overhead. Thus, this technique requires extra control information (R_b of the nodes in DTQ) to be included in the FBP.

- Note that both the Cross-Layer scheduling and the AP mechanism #5 require exactly the same amount of extra feedback information to be included in the FBP.

- Thus, regardless of the AP selection mechanism employed (#4 or #5), when the Cross-Layer scheduling is applied, the same amount of overhead is required so that neither mechanisms takes advantage with respect to the other in terms of overhead.

In conclusion, mechanism #6 is outperformed by #7 in terms of mean delay more significantly. That is, when the Cross-Layer scheduling technique is used, differences between mechanisms #4 and #5 (that correspond to #6 and #7 respectively) are more noticeable as in this case the system overhead is the same for both mechanisms. Additionally, as mechanism #7 is based on a smarter AP affiliation decision based on the different metrics (*SNR*, *TQ* and *EQD*) it is able to slightly improve mean message delay results.

Finally, it is worth remarking that using the presented Cross-Layer scheduling technique, the AST mechanism can be easily implemented in the system. Note that the AST requires that the FBP packet includes the value of the available R_b of the node in DTQ's first position. As the Cross-Layer technique requires that all R_b values of nodes in DTQ are included in the FBP, this information inherently includes the feedback information required in order to implement the AST.

6.6. Summary of results of the proposed AP selection mechanisms

So far, several AP selection mechanisms have been proposed and analyzed by means of computer simulation. These mechanisms specify the criteria that DQCA nodes within a WLAN multi-cell system must follow in order to decide which AP to associate with. The first mechanisms (#1, #2 and #3) are based on a single metric such as SNR (#1 and #2) or an AP traffic load estimation (#3). Next, a dual metric selection mechanism was proposed which is based on both SNR and AP traffic load estimation (#4). Mechanism #5 is jointly based on three parameters: SNR, AP traffic load estimation and expected queuing delay (EQD). Finally, performance of mechanism #4 and #5 has been assessed when they are applied along with a scheduling Cross-layer technique based on an PHY-MAC interaction. As a consequence of this combination, mechanisms #6 and #7 were proposed.

Next, the main conclusions extracted from the results analysis are listed:

- Mechanisms #6 and #7 provide the best performing results both in terms of throughput and mean messages delay with regard to the rest of proposed AP selection mechanisms. This enhancement is essentially due to the application of a scheduling Cross-Layer technique.

- Regarding the rest of mechanisms, which are not applied along with a Cross-Layer technique, mechanisms #1, #4 and #5 provide the best results in terms of throughput.

- Regarding the rest of mechanisms, which are not applied along with a Cross-Layer technique, mechanisms #3, #4 and #5 provide the best results in terms of mean messages delay.

- Considering overall throughput and mean messages delay results, it can be concluded that mechanisms based on multiple metrics, i.e. mechanisms #4 and #5, allow achieving the best performance although requiring an increase of the system overhead.

- Finally, it is worth recalling that the obtained results when applying the AST have shown that this mechanisms allows obtaining a net increase of system efficiency even though it requires a slight extra overhead to be included.

CHAPTER 7. CONCLUSIONS AND FUTURE RESEARCH LINES

7.1. Final Conclusions

Under the perspective of the current growth that markets related to wireless communications are experiencing and especially those related with Wireless Local Area Networks, this work has focused on the proposal and study of novel techniques in order to achieve a more efficient use of the scarce resources in 802.11b WLAN multi-cell systems. Computer simulations have been carried out in order to evaluate the benefits and performance of the proposed techniques and mechanims.

Next, the studied proposals and results are summarized:

- Based on the benefits that the Distributed Queuing Collision Avoidance (DQCA) MAC protocol offers within single cell WLAN scenarios, an adaptation of this protocol has been proposed to multi-cell scenarios. In such scenarios several Access Point offer radio coverage with several independent DQCA engines running on each one. As nodes move freely around the scenario handoff processes are performed. In this sense, a handoff process has been designed considering the operation of DQCA and the benefits that it inherently provides.

- An enhancement for the designed DQCA handoff process has been proposed. It has been called the Advanced Scanning Technique (AST) and it is based on the use of extra control information transmitted whithin the FBP. This mechanism allows nodes to scan on each channel in a more efficient manner. Computer simulations results have shown that although the AST requires certain extra overhead information, this technique effectively improves the DQCA scanning process especially in terms of messages mean delay.

- Seven AP selection mechanisms have been proposed. These mechanisms specify different criterion decisions in order to allow a scanning node to choose the most appropriate AP to associate with. Single metric, dual metric and multiple metric based criterions have been proposed and analyzed. The main conclusion that can be drawn from the obtained results is that AP selection mechanisms that are based on multiple metric criterions allow performing smarter AP selection decicions. Thus, even though the extra overhead required, these mechanisms allow achieving better system performance both in terms of throughput and messages mean delay.

- The interaction of certain selection mechanisms with a Cross-Layer scheduling has been studied. In this sense, mechanisms #4 and #5 have been redefined the mechanisms #6 and #7 have resulted. Computer simulations have shown that mechanisms #6 and #7. Mechanism #7 slightly outperforms #6, especially in terms of messages mean delay.

- o In order to evaluate the benefits of the proposed techniques and mechanisms, a DQCA multi-cell simulator has been developed using the object-oriented language C++.

In short, several techniques have been proposed and studied that aim at improving the performance and efficiency of WLAN infrastructure systems when multi-cell scenarios are considered. The benefits of the proposals have been assessed under relevant scenario conditions by means of computer simulations. The subsequent analysis of the obtained results has allowed evaluating the goodness of the proposals. The main advantage of these techniques is the easiness of practical implementation and the significant performance enhancements that these achieve.

Because all of this, it can be finally concluded that after the carrying out of this final career project the objectives that were initially established have been fully achieved.

7.2. Future Research Lines

This final section is devoted to providing possible future research lines within the context of DQCA WLANs, AP selection mechanisms and Cross-Layer Design. These future lines are briefly described next:

- **DQCA multi-cell scenarios with heterogeneous traffic**: This work has focused on WLAN multi-cell scenarios where a single class of traffic is present. However, within actual WLAN deployments several types of traffic patters are present, such as voice, video and data traffic. Each of these classes of traffic show different QoS requirements that must be met. Of special interest are those handoff processes related to time-critical applications such as voice or video. In this regard, efforts should be focused on providing efficient DQCA handoff procedures while keeping QoS requirements.

- **Study of interaction between AP selection mechanisms and other Cross-Layer scheduling techniques**: In this work, it has been studied the interaction of several AP selection mechanisms with a Cross-Layer scheduling technique. In this sense, of special interest is to study the interaction of these (and others) AP selection mechanisms with different Cross-Layer scheduling techniques. Different CL scheduling techniques may include those proposed in [22].

- **Proposal and study of other AP selection mechanisms**: In view of the promising performance that multiple-metric AP selection mechanisms have shown, research efforts should be focused on proposing and studying novel mechanisms that take into account different metrics jointly in order to achieve the best AP selection decisions. For instance, a new metric may take into account the number of packets that each node in DTQ will transmit as it is directly related with the time required for a newly arrived node to reach the head of the DTQ.

- **Study of alternative multi-cell scenarios**: Of particular interest is the extension of the proposed enhancements to alternative WLAN DQCA multi-cell scenarios. In this sense, changes in the scenario layout may be appropiate in order to fully evaluate the benefits of the proposed techniques. These changes may include increasing the number of present APs, varying distances between APs, APs' locations, channel and mobility models, number of available radiofrequency channels, extension to OFDM-based 802.11 PHY layers such as 802.11g or 802.11a, etc.

- **Study of Advanced Transmission Techniques**: With the increasing research interest regarding advanced transmission techniques such as Smart Antennas and MIMO technologies, of special interest may be to include these advanced transmission techniques within the WLAN DQCA-based multi-cell scenario. Hence, novel handoff algorithms may be proposed that take advantage of these techniques. In this regard, with the advent of the MIMO-based standard for WLAN, 802.11n, may trigger significant research efforts towards this direction.

- **Inclusion of Cooperative Transmission schemes within DQCA-based WLAN multi-cell scenario:** Cooperative transmission techniques are innovative within wireless communicactions systems. Next generation systems incorporate this kind of techniques that allow distant nodes from a base station or AP to transmit using higher data rates by using an intermediate node (relay). The role of these techniques within WLAN multi-cell scenarios poses interesting novel challenges.

7.3. Environmental impact

The proposed mechanisms and techniques, as well as providing significant enhancements to WLAN systems, they allow minimizing the environmental impact caused by the operation of such systems.

Analyzing the obtained results, these proposals have been proved to make a more efficient use of the available resources so that they reduce power consumption and increase batteries' life. Moreover, with the proposed mechanisms a more efficient use of the radiofrequency spectrum is achieved which results in a reduction of electromagnetic pollution.

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ANNEXES

ANNEXE 1. 802.11 MAC

1.1. 802.11 Basic Network Layout

The IEEE 802.11 standard defines two types of networks: Adhoc and Infrastructure. Adhoc networks are self-configuring networks between mobile and portable wireless clients. Infrastructure networks use fixed, interconnected access points to provide connectivity to mobile and portable wireless clients. Infrastructure based wireless networks need to provide some level of service, either in terms of coverage area or in network performance, or in both.

1.2. MAC Layer Packet Structure

The basic format of packets passed to the PHY layer from the MAC layer is shown in Figure 1.2.1 . Note that this is the basic format for all packets sent by the MAC layer. Some actual packets do not actually contain all of the fields. However, all fields are present in all data packets. Up to four addresses are needed because it is sometimes necessary to identify the address of the access point used by the transmitter or receiver. Thus, if two wireless LAN users are sending packets to one another but each is using a diferent access point, the 802.11 MAC address of both access points and both clients will be present in the four address fields.

Frame Control 2 bytes	Duration and ID 2 bytes	Address 1 6 bytes	Address 2 6 bytes	Address 3 6 bytes	Sequence Control 2 bytes	Address 4 6 bytes	Frame Body 0 to 2312 bytes	Frame Check Sequence 4 bytes

to check if anyone is transmitting just before transmitting a packet of data. This only partially avoids the possibility of packets being transmitted by two users at the same time. When two or more packets are transmitted simultaneously, or overlapping in time, a 'collision' is said to have taken place. In wired Ethernet connections a user is able to detect when a collision has taken place because a network card is setup to be able to transmit and receive on different physical wires that make up the actual Ethernet cable. This is not possible in wireless Ethernet because when a wireless LAN card is transmitting it can not listen to detect if packets collide.

To partially cope with the inability to detect a collision, the IEEE 802.11 standard attempts to avoid collisions using carefully designed waiting periods that allow multiple users to defer access to the shared wireless channel to one another. That is, IEEE 802.11 clients will always ensure a channel has been idle for a certain period of time before transmitting. The process of deciding how long to wait as governed by the basic DCF is illustrated via a flowchart in Figure 1.3.1.

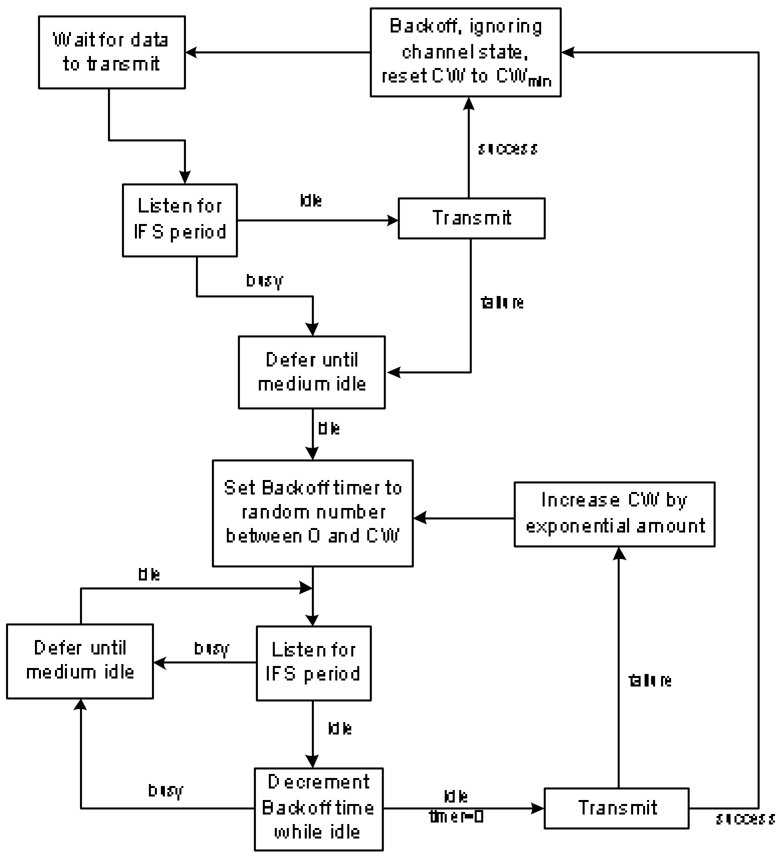

Figure 1.3.1 Flow chart of the process of sending data packets under the CSMA/CA based Distributed Coordination Function (DCF).

The following presents a basic overview of how the DCF progresses:

1. In Figure 1.3., flow begins at the top left portion of the diagram. When a data packet is ready for transmission, a client will first sense the medium.

If it is idle and remains so for a period of time known as the Interframe Spacing (IFS) period, the packet can be immediately transmitted. A standard, unicast packet (called a directed MSDU or MAC Service Data Unit) needs to be acknowledged by the receiver by a short ACK packet. If this transmission fails by the ACK not being received, the client enters the same defer state as if the medium was initially detected to be busy during the IFS period.

2. If the medium was not idle or the transmission fails, the client must defer until the medium is free. This is done using a special timer known as the Network Allocation Vector (NAV). To set this timer the client reads a field in the header of the packet currently being transmitted that tells the client how long the current user will continue to use the medium, through the current transmission, or through the current transmission and immediate transmissions after the current transmission. In this way the client does not need to continue to sense the state of the channel until the NAV timer has expired.

3. After the NAV timer has expired or the client has sensed that the channel is no longer busy, the client will calculate a backoff interval. This backoff interval is a uniform random number. This number is chosen from the interval between 0 and the value of the Contention Window (CW) inclusive. The contention window is initially set to be equal to CW_{min} which is a value defined by the PHY layer.

4. After calculating the value of the backoff interval to use, the client senses the channel for an IFS period. If the channel is idle at the end of this period the client will set a backoff timer equal to the value of the backoff period calculated previously. This timer is periodically decremented while the channel continues to stay idle. If the channel becomes busy either during the IFS period or during while the backoff counter is being decremented but before it reaches zero, the client goes into a defer state without changing the value of the backoff timer.

5. If the client goes back into a defer state it goes through the same process as before in which the client waits for the medium to become idle by first sensing the medium and then by setting the NAV timer. When the medium returns to an idle state, the client must wait for an additional IFS period before continuing to decrement the backoff counter.

6. When the medium has been idle for an IFS period and the backoff counter reaches zero, the client will transmit it's data.

7. If the client discovers that the transmission has failed then the client must exponentially increase the value of CW using next equation:

$$CW_{new} = \min(2\times(CW_{old}+1)-1, CW_{\max})$$

As a result, if the medium is very busy, exponential increases in the maximum backoff delay will occur and the probability of packet collisions will decrease. After increasing CW, the client generates a new value for the backoff interval and re-senses the state of the channel.

8. After either of the two transmit states have been completed successfully (by having been properly acknowledged by the receiver using an ACK packet), several things happen. First, the value of CW is reset to CW_{min} after successful transmission occurs. Second, the client goes through a mandatory backoff interval in which the state of the medium is ignored. The client then goes back to the initial state in which the client waits for data to be ready for transmission.

1.4. RTS/CTS and the Hidden Terminal Problem

The DCF implementation of IEEE 802.11 does not handle a problem referred to as the hidden terminal problem. This problem occurs when a mutual receiver is in range of two transmitters which are not in range of one another. In this case attempting to detect if the medium is free does not necessarily work because the two transmitters can not detect one another's transmissions. Thus the packets from the two transmitters will collide at the common receiver. To combat this problem, IEEE 802.11 adds an optional RTS/CTS mechanism. In this technique instead of transmitting a data packet after waiting for a free medium, a client will transmit a short Ready To Send (RTS) packet to request the use of the medium. If this succeeds, the receiver will quickly (after a SIFS period) reply with a short Clear To Send (CTS). After the successful exchange of an RTS/CTS pair the actual transmission takes place. This method allows hidden terminals to hear either a CTS or an RTS packet and know to difer access using the NAV functionality described previously. It also means that if packets do collide only a short RTS or CTS packet is lost rather than a long data packet. It is important to note though that this mechanism is optional to include and is enabled in one of three modes: always on, always off or on for packet sizes above a certain threshold.

ANNEXE 2. DQCA MAC

2.1. DQCA Description

DQCA is a distributed high-performance medium access protocol designed for WLAN environments that behaves as a random access mechanism under low traffic conditions and switches smoothly and automatically to a reservation scheme when traffic load grows. DQCA has the following main features:

- It eliminates back-off periods and guarantees collision-free data transmissions for high traffic loads.
- It performs independently of the number of nodes transmitting in the system.
- Its performance is not degraded under high traffic conditions like slotted Aloha, but a maximum throughput is achieved and maintained even when the traffic load exceeds the channel capacity.

The main idea of DQCA is that the nodes may ask for channel access in a reserved time interval, confining collisions almost only to this part of the frame which can be extremely short with respect to the data transmission part having into account that the channel access message actually does not need to carry any explicit information, only its mere existence as a detectable energy burst is sufficient. Any collisions are resolved by a blocked access m-ary tree-splitting collision resolution algorithm (CRA) in a FIFO order, managed by a distributed queue. Once having successfully sent an access request, a node waits for its turn to transmit data in another distributed queue devoted to the scheduling of collision-free data transmission.

Next, a thorough description of the DQCA protocol is given.

Let us consider an infrastructure network in which N nodes share a wireless channel in order to communicate with an Access Point (AP). The time axis is divided into continuous DQCA frames which consist of three parts of different duration, as depicted in Figure 2.1. The first two parts are devoted to the uplink communication from the nodes to the AP while the third part is reserved for the downlink broadcast of control information by the AP (FBP).

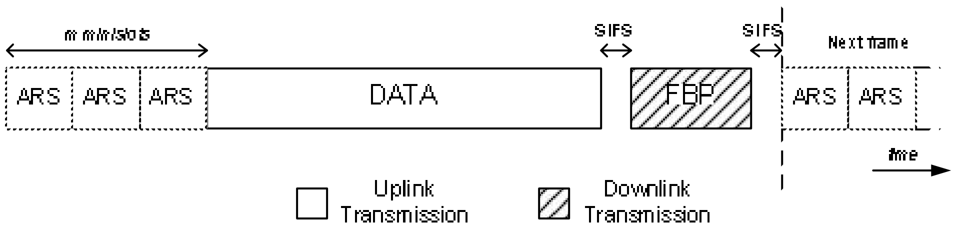

Figure 7.2 DQCA frame structure

The first part, also referred to as Contention Window (CW) is divided into *m* control minislots, during which those nodes with data to transmit may request access to the channel by sending an Access-Request Sequence (ARS) to the AP as long as no previous collisions in the system are pending to be resolved (blocked-access CRA).

The operation of DQCA is based on the use of m-ternary feedback information on the state of the CW. The AP must be able to distinguish between idle, success and collision state for each control minislot and must broadcast this information at the end of each frame. Therefore, the ARS is not required to contain any kind of actual information but must be properly selected in order to enable collision detection.

The second part of the frame is reserved for the almost collision-free transmission of data packets by one node at a time. This part is of fixed byte length (the time duration will depend on the actual transmission rate, allowing therefore the implementation of bit rate adaptation techniques) and large messages have to be fragmented into smaller packets. In any case, the frame could be easily adapted to support variable length data packets.

In the last part of the frame the AP broadcasts a Feedback Packet (FBP) that contains:

- Ternary feedback information on the state of all access minislots
- An acknowledgement (ACK) to verify the correct receipt of the previous data packet.
- A final-message bit which is set to 1 when the last packet of a message has been received and to 0 when more packets of the same message are expected to follow.

In certain configurations, the FBP may contain additional information, as it will be explained later. Moreover, any possible ARQ strategy may be used regarding the ACK part of the FPB.

In order to compensate for propagation delays, turn around times (to switch from receiving to transmit mode), and for processing purposes, the uplink (CW and Data Slot) and downlink (FBP) transmissions are separated by a SIFS (Short Inter Frame Space).

The protocol uses two logical distributed queues: the Collision Resolution Queue (CRQ) and the Data Transmission Queue (DTQ) that handle the collision resolution and the data transmission scheduling, respectively. These two queues do not contain actual packets, but they are just logical representations of distributed queues formed among the buffers of all stations. This representation is made simply by using integer values kept and updated in each station. In fact, it is possible to interchangeably say that a station is in a given queue as well as its messages are in the same queue. Although each ARS is sent for a specific message, the position in the logical queue for that message is maintained by the requesting station as it was the station itself who were within the queue, having into account that this is only a logical allocation.

The two queues are represented at every node by four integer counters denoted by TQ, RQ, pTQ and pRQ. TQ is the number of messages (or nodes) waiting for transmission in the DTQ, while RQ is the number of collisions waiting for resolution in the CRQ. All nodes should have the same TQ an RQ values (i.e. they represent distributed queues). The other two integers, pTQ and pRQ, represent the position of each node within the DTQ and the CRQ respectively and therefore may have different values for each node. They are set to zero whenever a node is in neither queue. Otherwise, their values range from 1 to TQ or RQ respectively, with the value 1 indicating the head of the queues. In principle, every node, including those that do not have a message to transmit, must update these counters upon the reception of the FBP at the end of each frame by executing the set of rules described below. However, it is also convenient to periodically send the TQ and RQ values within the FBP to allow inactive nodes to leave and reenter the system, which in addition will increase robustness against possible miscounting errors for all nodes.

Three sets of rules are defined and executed at each node upon decoding of the FBP. They are, in order of execution, the data transmission rules (DTR), indicating who can transmit data in the following frame, the request transmission rules (RTR), implementing the collision resolution algorithm and the queuing discipline rules (QDR), managing the update of the queues.

1. **DTR (Data Transmission Rules)**

If there are no nodes waiting to transmit (TQ=0) and no collisions to be resolved (RQ=0), every node with a message ready to be sent transmits an ARS in a randomly selected control minislot and the first packet of the message in the data part. This rule is referred to as the immediate access rule, and constitutes the only possible cause of a collision in the data part. However, it avoids an empty data frame and improves the packet transmission delay when the traffic load is low, when the probability of having a collision is also low.

If a node is at the head of the data transmission queue (pTQ=1), it is enabled to transmit a packet in the following frame. If this packet is the last of a message, the node sets the final-message-bit to 1, otherwise it sets it to 0.

2. **RTR (Request Transmission Rules)**

If there are no collisions pending to be resolved (RQ=0) and there are transmissions scheduled (TQ>0), every node that is in neither queue (pTQ=0 and pRQ=0) and which has a message ready to be sent, randomly selects one of the m control minislots and transmits an ARS in the following frame.

If a node is at the head of the collision resolution queue (pRQ=1), it randomly selects one of the m control minislots and transmits an ARS in order to try to resolve the collision in the following frame.

3. **QDR (Queuing Discipline Rules)**

Each node increases the value of TQ by one unit for each control minislot with a successful state (indicating that a new node has entered the DTQ). The value of TQ is reduced by one unit if a data packet has been successfully transmitted and the final-message-bit was set to 1, since the transmitting node will leave the queue.

If there are collisions pending to be resolved (RQ>0) the value of RQ is reduced by one unit, since those nodes at the head of CRQ will try to resolve their collision within the following frame.
The value of RQ is incremented by one unit for each control minislot where an ARS collision occurred.

Each node calculates its own position in the queues (values for pTQ and pRQ). If the node has transmitted an ARS in a particular control minislot and the state of this control minislot was “success” then the node sets its pTQ to the corresponding value at the end of TQ. It should be mentioned that the events of the control minislots are sorted by a time arrival criterion, meaning that a node with successful request at the first control minislot enters the data queue before a node whose request was sent at the second control minislot. If the ARS has collided, the node calculates its position among all the present collisions and sets pRQ to the corresponding value at the end of RQ. If the node has not sent any request, then pTQ and pRQ follow the same update rules as TQ and RQ, respectively, as long as their initial values are non-zero.