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Cross layer access point selection mechanisms for a distributed queuing MAC protocol

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Abstract The Distributed Queuing with Collision Avoidance (DQCA) Medium Access Control (MAC) protocol has been presented in the literature as a high-performance protocol for WLANs. Previous work regarding DQCA is focused on the operation of a single cell, where no interaction with neighboring sites is considered. In this paper, we define specific handoff procedures (channel sensing, discovery and reassociation functions) that enable the roaming of users in a scenario consisting of several DQCA access points (APs) deployed in a specific area using non-overlapping channel frequencies. Furthermore, we introduce a number of AP selection mechanisms in order to provide efficient reassociation decision criteria in the context of DQCA. These mechanisms are based either on a single metric such as the Signal to Noise Ratio (SNR) or the traffic load, or on cross-layer design by combining the information from different layers. Finally, our proposed solutions are evaluated by means of computer simulations.

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1 Introduction

Distributed Queuing with Collision Avoidance (DQCA) is a distributed Medium Access Control (MAC) protocol for Wireless Local Area Networks (WLANs) that offers near optimum performance [1]. The protocol implements a reservation scheme that ensures collision-free data transmission for high traffic load and switches smoothly and automatically to a random access mechanism when the traffic load is light, improving the delay performance under these conditions. The protocol rules described in [1] specify how stations get access to the uplink of a single AP. However, no handoff procedure or AP selection mechanisms that must be carried out in multi-site environments where several APs are present and users can freely roam have been yet defined for DQCA. This is the main motivation for the work presented in this paper, where we propose and evaluate the performance of smart handoff mechanisms for a DQCA network with more than one AP.

Traditionally, handoff decisions rely upon measurements of the Received Signal Strength Indicator (RSSI). Specifically, a station moving away from the current AP reassociates with another AP whose control signaling is received with stronger signal power than that of the current AP [2, 3]. However, it has been shown that AP selection mechanisms simply based on the RSSI lead to poor network performance [4, 5] and highly unbalanced load distribution among APs [6]. Indeed, several solutions have been proposed in the literature trying to efficiently balance the traffic load in the network. The authors in [7] try to optimize the AP selection decision using an estimation of the packet delay, which reflects the load of each AP. In [8], Koutsopoulos et al. jointly address the problem of AP selection and channel assignment by executing load balancing algorithms in order to satisfy a given user load. In their work, they group in the same "clique" the set of cells that interfere with each other. Therefore, the key idea behind these algorithms is that AP allocation at each step should attempt to balance the clique loads as much as possible. In [9], authors estimate the available bandwidth of an AP based on the delay of the received beacon frames and use this value to make the AP decision with the aim to avoid congestion. Karetsos et al. [10] present some techniques in order to minimize the handover latency in heterogeneous wireless environments. Furthermore, they propose a hybrid approach (combination of centralized and distributed approaches) in order to facilitate the implementation of load balancing and fair resource sharing. The main drawback of these mechanisms focused on load balancing is that they generally ignore the channel conditions and the signal strength, leading to high probability that a mobile station associates with a low-loaded AP but with weak signal strength, thus degrading the performance of the network. Note that this performance degradation is induced by the performance anomaly problem of multi-rate networks that select the transmission rate as a function of the RSSI [11].

In order to overcome these problems, some works introduce cross-layer design in the handoff procedure. In [12], a cross layer partner-based fast handoff mechanism, called PHMIPv6, is presented. PHMIPv6 exploits information obtained from the MAC and network layers in order to accurately predict which the next AP will be, thus minimizing the handoff delay time and the packet loss rate. Another practical cross layer handoff mechanism is presented by Song et al. [13]. In their paper, authors try to improve the success rate of mobility prediction by combining information from both the link and network layers. Lee et al. [14] propose a new mobility management scheme that accelerates the handover control procedure with cross-layer interaction operations. The proposed scheme introduces a signaling architecture which logically separates a control plane from a data plane in order to support fast and reliable control message delivery. The aforementioned cross layer-based works achieve enhancements in terms of throughput and delay by improving the packet loss rate or the success rate of mobility prediction. However, their main drawback is that they either require changes in the topology (partner stations) or base their operation on specific protocols (IPv6).

Motivated by the lack of a definition of handoff procedures for a multi-cell DQCA-based network and taking into account the pros and cons of existing handoff processes, and particularly the suitability of using mechanisms based on a cross-layer design, we present in this paper specific handoff mechanisms for a DQCA network with multiple APs. The operation of DQCA inherently provides stations with valuable cross-layer information that can be exploited to implement smart AP selection mechanisms that lead to high performance through a balanced share of the stations among the different APs.

The rest of the paper is organized as follows. In Sect. 2 we briefly review the operation of DQCA. In Sect. 3, we describe the general functions that have to be considered in a handoff process. Based on this, Sect. 4 describes the specific DQCA handoff functions required to allow the roaming of users among different APs in a multiple-cell site. Section 5 defines three generic AP selection criteria, while Sect. 6 presents the proposed DQCA AP selection mechanisms. The simulation scenario along with the performance results are presented in Sect. 7. Finally, Sect. 8 concludes the paper.

2 DQCA overview

The purpose of this section is to highlight the basic features of DQCA which are essential for the understanding of the proposed handoff procedures. A detailed explanation of DQCA, along with the protocol operating rules, can be found in [1]. As demonstrated there, DQCA outperforms the widely commercially spread Distributed Coordination Function (DCF) of the IEEE 802.11 Standard [15] and remains stable even when the traffic load occasionally exceeds the channel capacity.

DQCA is a MAC protocol designed to manage the access to the uplink channel of an infrastructure WLAN. Time is divided into MAC frames, and each frame is divided in three parts separated by a Short Inter Frame Space (SIFS) necessary to tolerate turnaround times, as well as propagation and processing delays. The three parts, depicted in Fig. 1, are:

i. A Contention Window (CW) further divided into m access minislots where the stations can send a short chip sequence named Access Request Sequence (ARS) to request access to the channel. An ARS is a short chip sequence that contains no explicit information, but it has a specific and predefined pattern that allows the AP to distinguish between an *idle* minislot, the presence of just one ARS (*success*), and the occurrence of a *collision* between two or more simultaneous ARS. A mechanism to operate with these ARS is the subject of a patent [16].
ii. A data slot reserved for the transmission of data packets.
iii. A feedback part where the AP broadcasts a Feedback Packet (FBP) that contains the data acknowledgment, the state of each of the minislots of the CW for the contention resolution algorithm and a 'final message bit' that is enabled (set to one) by the AP to identify the last data packet (fragment) of a message. The stations also include a 'final message bit' in their data packet transmissions in order to advertise the transmission of

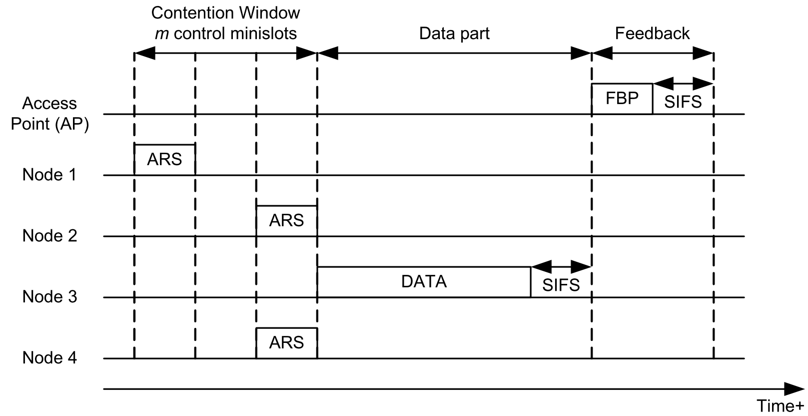


Fig. 1 DQCA frame structure

the final fragment of each message. This is the only information necessary for the proper execution of the protocol rules in a distributed manner (locally by each station).

The execution of the protocol is based on two concatenated distributed queues, the Collision Resolution Queue (CRQ) and the Data Transmission Queue (DTQ). The CRQ is responsible for the resolution of collisions among ARS (following a tree-splitting collision resolution algorithm [17–19]), while the DTQ handles the data transmission. The number of occupied positions (or elements) in each queue is represented by an integer counter (RQ and TQ for the CRQ and the DTQ, respectively). Both counters have the same value for all the stations in the system and are updated according to a set of rules at the end of each frame using the information attached to the FBP broadcast by the AP. In addition, each station maintains and updates another pair of integer counters that reveal its position in the queue (pRQ and pTQ for the CRQ and the DTQ, respectively). The *position* refers to the relative order of arrival (or age) of the station in the respective queue. In the CRQ, each position (or element) is occupied by a set of stations that suffered an ARS collision (i.e., attempted an ARS transmission in the same access minislot of the same CW). All the stations within the first position in the CRQ attempt to solve their collision by resending an ARS within the next frame in a newly randomly selected minislot. Therefore, a tree-splitting collision resolution algorithm is executed and, indeed, collisions are solved much faster than the actual transmission of data. In its turn, each position in the DTQ contains exactly one station that has successfully reserved the channel through an ARS. Within each frame, the station at the first position of the queue is allowed to transmit data. According to this operation, the collision resolution and the transmission of data occur simultaneously and they are based on the distributed update of the logical queues facilitated by the control information broadcast by the AP.

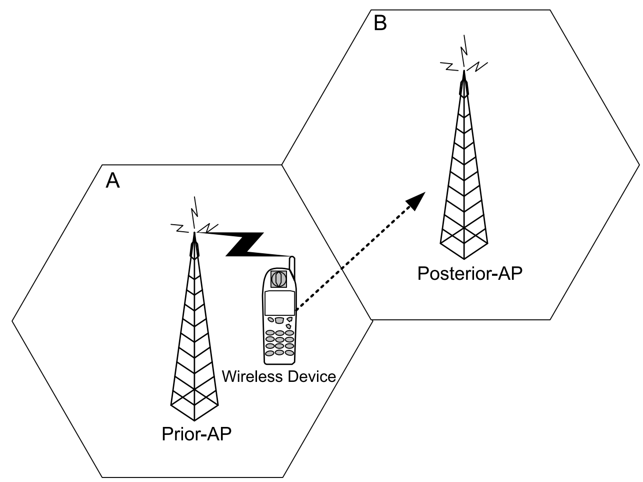


Fig. 2 Entities involved in a handoff process

3 Logical functions in a handoff process

A handoff algorithm refers to the mechanisms performed to transfer the connectivity of a mobile device from one AP to another. Handoff is a layer-2 function that involves at least three entities, namely the wireless device (mobile station), a prior-AP (or current AP), and a posterior-AP (Fig. 2). The prior-AP is the AP that the station was connected to before the handoff procedure, while the posterior-AP is the AP that the wireless device gets connected to after the handoff process.

In general, a roaming station performing a handoff process must carry out three interrelated functions (see Fig. 3):

(1) *Link Status Monitoring* (*LSM*): This function defines the procedure through which a station monitors the quality and the availability of the connectivity with a certain AP. In the wireless channel, the received signal strength and/or the signal-to-noise ratio (SNR) of the signal received from the current AP may degrade due to mobility, channel fading or inter-cell interference. Accordingly, as soon as the quality of a con-

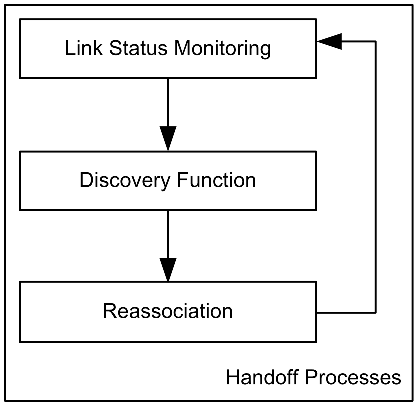


Fig. 3 Handoff processes

nection degrades below a certain threshold (also defined by the LSM function), the station should initiate a discovery process to obtain information related to other available APs that may provide better connectivity. Therefore, it is necessary to keep track of the status of the wireless links from neighbor APs, as well as from the current AP. In general, the LSM functions can be based on any individual parameter, such as the received signal strength, the SNR, the bit error rate, or a combination of them. The most common option is to perform the LSM decisions based on the information obtained by means of beacon packets broadcast by the APs.

(2) *Discovery*: This function is performed by a station when it is essential to reassociate with another AP due to a bad connectivity with the current AP (as indicated by the LSM function). During the discovery (or scanning) phase, the station listens to the channel, waiting for the reception of beacon messages broadcast by APs operating in other channels. Therefore, it can create an ordered list of candidate APs prioritized according to some criteria defined by the LSM function, such as the received signal strength. Just as an example, there are two kinds of scanning methods defined in the 802.11 Standard: active and passive. The passive scanning mode implies that stations just listen to beacon messages transmitted from the APs and infer the channel quality from the received signals. In the active mode, in addition to the listening of the beacon messages, stations transmit additional *probe broadcast packets* on each channel and receive responses from APs.

(3) *Reassociation*: This function is comprised of two parts, namely, the reauthentication and the reassociation of a station to a new AP. The reauthentication process typically involves a message exchange performing an authentication and a reassociation to the posterior-AP. The reauthentication phase also includes the transfer of credentials and other state information from the prior-AP to the posterior-AP.

4 DQCA handoff processes

In this section we specify the handoff operations in the context of a DQCA multi-cellular WLAN system, taking into account the general handoff functions described in the previous section.

4.1 Link status monitoring (LSM) function

The frame structure of DQCA facilitates the design of specific LSM functions. The FBP broadcast by the AP at the end of each frame can be used as an implicit beacon for the LSM function. This packet can be used by all stations in order to obtain information regarding the link status with the AP on a frame-by-frame basis. This information may be the received signal strength. However, in the case of DQCA, the values of the TQ and RQ counters of each AP can be also considered in order to select the best AP not only in terms of channel quality, but in terms of traffic load as well. Note that the values of TQ and RQ are representative values of the traffic load of an AP. Therefore, by efficiently managing the information regarding the state of the distributed queues, it is possible to attain efficient load balancing in a multi-cell DQCA network.

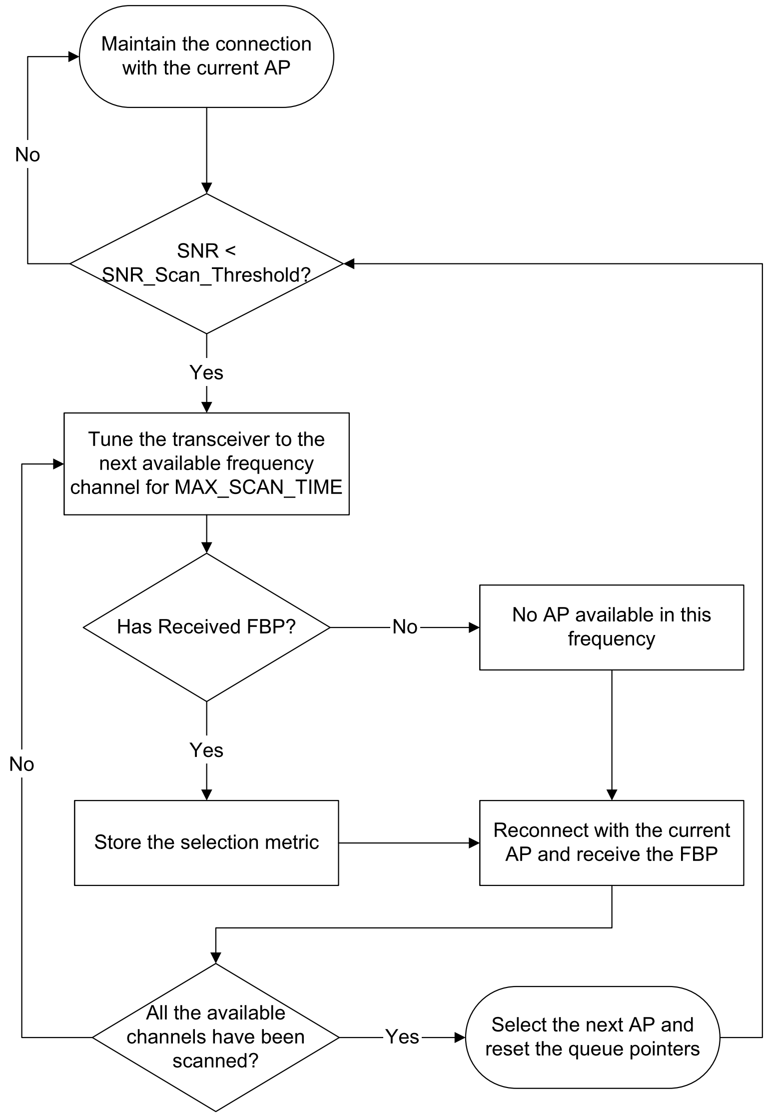
In addition to the specific criteria to quantify the *eligibility* of an AP, it is necessary to establish a criterion to decide when a station should initiate the discovery function and start searching for a new AP. Towards this, a parameter called *SNR_Scan_Threshold* is defined in DQCA. Each station continuously compares the SNR measured from the reception of each FBP with the value of this threshold. When the SNR falls below the *SNR_Scan_Threshold*, the station initiates a discovery process. In order to set the value of this parameter, a tradeoff should be managed:

1. The threshold should be high enough to allow a station to initiate the discovery phase before losing the connection with the current AP.
2. A very high threshold may result in stations initiating a scanning process too frequently. As a result, system efficiency would decrease as stations spend too much time seeking for other available resources instead of transmitting their information messages.

4.2 Discovery function

The discovery function is initiated once a station has determined that it is necessary to scan for other available APs, seeking for a better connection. The information regarding

Fig. 4 DQCA discovery phase (flowchart)



the quality of each neighbor AP is obtained through the LSM function described above.

One of the main constraints that have to be taken into account for the discovery process is that stations must keep updated some control state information (positions in the queues and queues sizes) of the current AP through the feedback information broadcast by the AP at the end of each frame. This means that any station must receive the FBPs from its current AP despite scanning for new candidate APs operating at different frequency bands.

Accordingly, assuming that all stations know all the possible frequency channels in the system, we establish the following steps for the discovery function, whose block diagram is shown in Fig. 4:

Step 1: Once a station has determined that it must initiate the scanning process, it has to tune its transceiver to the next available frequency channel at the beginning of the next frame. Then, it waits for the reception of the FBP from the AP at this new frequency for a certain period of time denoted by MAX_SCAN_TIME. If the station receives a FBP, it measures and stores a certain selection metric (e.g., the received SNR from the FBP). However, the station may not receive any FBP due to the fact that either the scanning station is not within the radio range of any other AP or the FBP transmission from the scanned AP has not coincided in time with the scanning period of the station. In any of these two cases, the scanning station interprets that no AP is available on this frequency.

Step 2: After the scanning period, the station 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 its current AP, the station must tune its radio transceiver to the next frequency channel in the list of available channels and perform the same procedure described in step 1. The available chan-

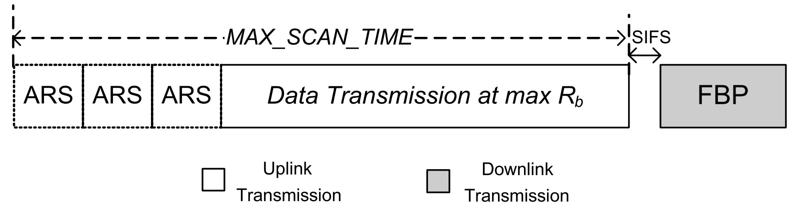


Fig. 5 MAX_SCAN_TIME duration and DQCA frame

nels in the system are scanned consecutively. For example, if the WLAN system is configured to operate on channels 1, 6, and 11 and a given station 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 for the reception of the FBP, it will continue scanning on channel 1, and so on.

Step 3: Once all the available channels in the system have been scanned, the station selects the best AP to associate with. Note that, to this end, a neighbor AP table should be maintained by the station during the discovery phase.

Step 4: The station tunes its transceiver to the selected AP channel. In the case that the selected AP is different from the current one, the station resets its queue pointers (TQ = RQ = pTQ = pRQ = 0) and waits for the first FBP broadcast by the new AP in order to properly adjust the queue pointers.

It is worth mentioning that the value of MAX_SCAN_TIME is critical as it defines the duration of the scanning period that a station spends on each frequency channel. As with the *SNR_Scan_Threshold*, a tradeoff must be managed:

(1) The scanning period must be long enough so that a scanning station can receive and demodulate a complete FBP packet from the scanned AP. The duration of the scanning period has to be at least equal to the duration of a FBP packet plus the time needed to perform the channel switches. We have to take into account that the shorter the duration of the scanning process, the lower the probability that a FBP from a neighboring AP can be received.

(2) The scanning period must be short enough to allow a station to reconnect to the channel at which it is currently connected once the scanning period has elapsed. Note that the longer the scanning period, the higher the probability that a scanning user detects the presence of an existing AP.

These lower and upper bounds for the value of MAX_SCAN_TIME can be formulated as:

$$\begin{aligned} T_{FBP} + T_S &\leq MAX\_SCAN\_TIME \\ &\leq (T_{frame} - T_{FBP}) + T_S, \end{aligned} \tag{1}$$

where T_{FBP} is the duration of a FBP, T_{frame} is the duration of a DQCA frame, and T_S represents the switching time required to change the frequency of the receiver to scan in different channels. In order to maximize the probability that an existing AP is detected by a station executing the discovery function, the scanning time should be maximized and thus should be set as close as possible to the upper bound expressed in (1). However, due to the variable packet-lengths of different applications and the adaptive rate capability of 802.11-like systems, the duration of a DQCA frame is not constant. This means that a station in the discovery phase is not able to have any knowledge of the maximum periods of time that it can be scanning another frequency channel. In order to cope with this problem, a conservative approach can be adopted by setting the value of MAX_SCAN_TIME equal to the duration of the control minislots plus the minimum data slot duration. The minimum data slot duration can be computed using the highest available data rate with the shortest data packet. In addition, it is worth noting in the right condition of (1) that the duration of a FBP is subtracted from T_{frame}. This subtraction is necessary to ensure that a scanning station can receive and demodulate the complete FBP packet at the end of the frame. Figure 5 illustrates the conservative MAX_SCAN_TIME duration with respect to the DQCA frame duration.

Figure 6 shows an example of operation of the discovery function where a station initiates the scanning process. First, the station associated to AP1 scans the frequency channel of AP2 for MAX_SCAN_TIME seconds and receives an FBP. Next, the station reconnects to AP1 channel frequency in order to receive the FBP necessary to maintain its DQCA state.

Then, the scanning station tunes its transceiver to the AP3 channel frequency and receives another FBP. At this point the station has finished the scanning process and is able to choose the most appropriate AP to associate with. In this example, the station executing the discovery function receives FBPs in each scanning period. However, it may occur that the transmissions of the FBP from the scanned AP channels do not coincide temporarily with the interval of time during which the scanning station listens to that AP.

In addition, it has to be mentioned that this discovery process has some impact on the protocol rules of DQCA, which have to be slightly extended to consider the roaming between APs. Indeed, a station initiating a discovery phase

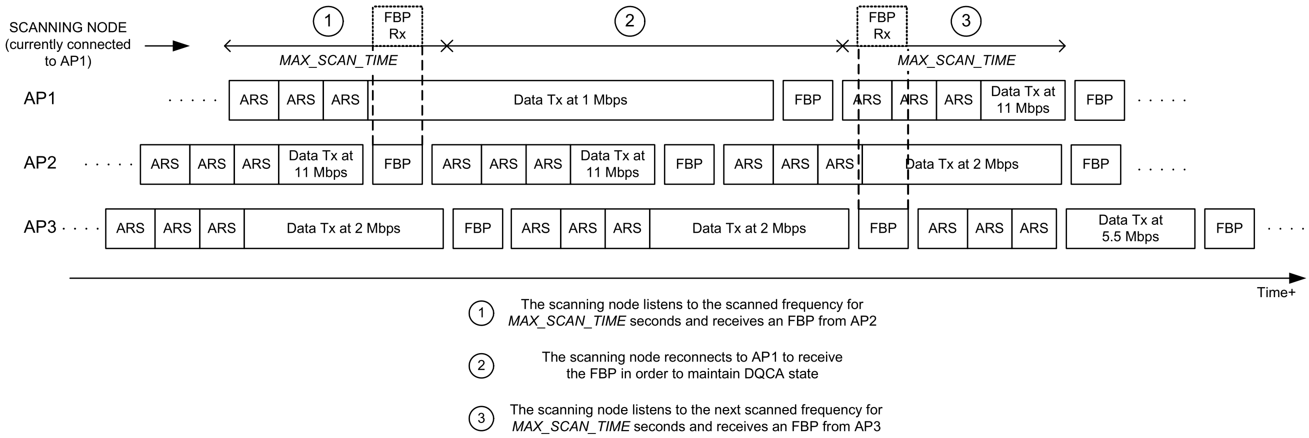


Fig. 6 Example: discovery process

can be in one of the following states (regarding the DQCA rules execution and the state of the queues):

(a) The station has no position in either the DTQ or the CRQ (pTQ = 0 and pRQ = 0).
(b) The station has a position in the CRQ and the resolution of a previously collided ARS (pTQ = 0, pRQ > 0) is pending.
(c) The station has a position in the DTQ, but it is not currently transmitting data (pTQ> 1, pRQ = 0).
(d) The station is transmitting a message because it occupies the first position in the DTQ (pTQ = 1, pRQ = 0).

The first case (a) is transparent to the execution of the rules of DQCA. In case (b), if the station initiates the discovery phase having a position in the CRQ, it should reset the value of pRQ to zero and reinitiate the contention resolution process as soon as it reassociates to another AP.

Situations (c) and (d) can lead to degradation in the system performance due to the fact that they yield empty data frames, as we will explain following. However, they can be easily handled by exploiting the 'final message bit' attached to the FBP. First, in situation (c), a scanning station which reaches at the first position of the DTQ will not transmit even the first packet and, as a result, some empty data frames will occur in the system, thus reducing the throughput of the network. In this case, the AP sets the 'final message bit' to one in the first FBP upon the occurrence of an empty data slot, hence allowing the rest of stations in the DTQ to "gain" one position in the queue. Therefore, the number of empty data slots is reduced to one. Furthermore, this loss of efficiency can be significantly improved if the time interval that the AP needs to decide that a data slot is empty is minimized by defining a *data timeout* after which, if no data transmission has been sensed, the frame is finished with the immediate transmission of a FBP by the AP.

The same mechanism can be also applied to solve situation (d). Let us recall that in this situation the station initiates the discovery process during the transmission of a data message. In this case, the station aborts the data transmission and empty data slots occur in the system. Similarly to the previous case, the AP detects the situation and sets the 'final message bit' to one in the next FBP. The scanning station will reset its pTQ counter to zero in order to leave the DTQ. It is worth mentioning that, since the station has not finished the transmission of the entire message, it should broadcast a request access for the pending part of the message. The reconstruction of a message received through different APs is out of the scope of the paper and constitutes an interesting line for future research.

4.3 Reassociation function

The reassociation function defines the message exchange devoted to authorizing and reassociating a station with an AP. As in 802.11, we define two procedures for the DQCA reassociation process: the authentication process and the reassociation process. These processes are represented in Fig. 7.

Once the station has found an available AP and decides to associate to it, it initiates the authentication process. This process consists in exchanging information (proof of knowledge of a given password) between the AP and the station. When the station is authenticated, the association process is started. This process consists in exchanging information regarding the station and AP capabilities. Once the association process is completed, the station is capable of transmitting and receiving data frames.

5 Access point selection criteria

The selection of a new AP is the primary mission of the discovery phase. There are several factors that affect the con-

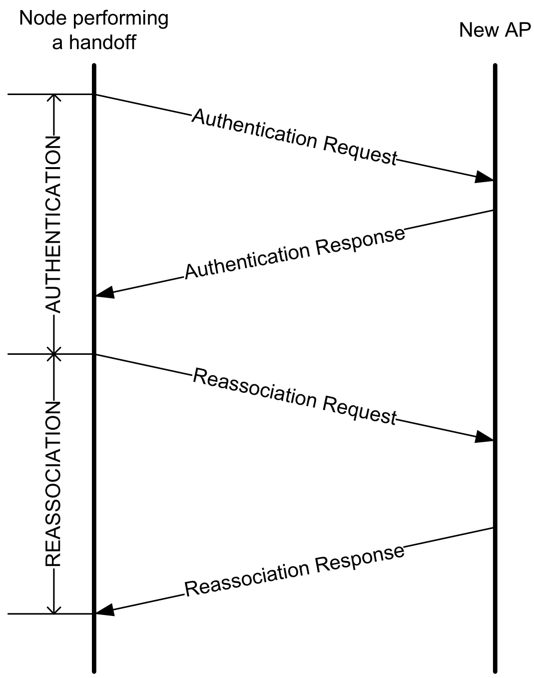


Fig. 7 Authentication and reassociation process

nectivity and the quality of service that a mobile station experiences. The main metrics that have been identified as critical factors during the AP selection are:

(1) *Received Signal Strength Indicator* (*RSSI*): This is the most commonly used parameter regarding user affiliation decisions as higher received signal strength implies higher transmission rates for a particular station and more reliable transmissions.
(2) *Signal-to-Noise Ratio* (*SNR*): Similar to the RSSI, it is a critical factor that affects the transmission data rates between the station and the eligible AP.
(3) *Traffic Load*: The traffic load an AP experiences is directly related with the quality of service that a network can provide. Overloading conditions at the MAC layer may lead to increasing number of collisions and subsequently to bad quality of service (e.g., higher transmission delays, lower throughput, etc.).
(4) *Expected Queueing Delay* (*EQD*): EQD aims to capture the average amount of time that a scanning station would need to spend before it is allowed to transmit data information messages if it gets associated to a given AP. This factor depends both on the traffic load of the AP and the transmission rates available for the existing stations in the cell.

Based on these metrics, we propose in the next section various AP selection mechanisms for DQCA based on different decision criteria.

6 DQCA access point selection mechanisms

The proposed mechanisms can be classified into two main categories: Single Metric-based and Cross-Layer mechanisms.

6.1 Single metric-based AP selection mechanisms

In this subsection, we present three different AP selection mechanisms that are based on a single metric to govern the decision-making process:

(1) *Opportunistic SNR AP Selection Mechanism (#1)*

In this mechanism, a scanning station selects the AP whose beacon frames (FBPs) have been received with the highest SNR after having scanned all the available channels. A parameter called *Delta_SNR* is introduced to define a hysteresis mechanism. The purpose of this parameter is to protect the stations from a "ping-pong" effect between different APs due to the fluctuations of the channel quality. *Delta_SNR* specifies the minimum SNR difference between the prior and the posterior AP that is needed in order for the handoff process to begin.

(2) *First Better SNR AP Selection Mechanism (#2)*

This mechanism is also based on SNR values. A scanning station reassociates with the first AP found along the discovery process that presents better SNR than the one of the current AP. Therefore, the scanning of the whole available frequency band is no longer a prerequisite, thus reducing the delay of the handoff process and the energy expenditure associated to the whole handoff process.

(3) *Traffic Load-based AP Selection Mechanism (#3)*

This mechanism has been designed to implement traffic load-based AP selection decisions. The amount of traffic load that a DQCA AP is serving is directly related to the value of TQ, whose value corresponds to the number of stations waiting for transmission in the Data Transmission Queue (DTQ). Therefore, it is possible to implement a traffic load-based mechanism without inserting any extra overhead. The selection of the AP can be simply based on the AP with the lowest value of TQ (i.e., with the lowest number of users waiting to transmit).

6.2 Cross layer AP selection mechanisms

It has been shown in the literature that the use of cross layer techniques allow for the design of smart selection decisions that combine information obtained from different layers and can outperform single-metric based algorithms. Indeed, the operation of DQCA facilitates the implementation of novel cross layer mechanisms that we present herein.

Table 1 Summary of the proposed AP selection mechanisms

AP selection mechanism	Cost function (F)	Extra overhead
Opportunistic SNR #1	Best SNR	No
First Better SNR #2	First Better SNR	No
Traffic Load #3	Minimum value of TQ	No
SNR-TQ #4	$F=\frac{SNR}{1+pTQ'}$	No
SNR-EQD #5	$F=\frac{SNR}{1+EEQD}$	$[\log_2(n)xTQ]$ bits, n the number of available data rates

(4) *SNR-TQ AP Selection Mechanism (#4)*

We introduce a cost function associated to each available channel i by combining both SNR measurements and traffic information. This cost function, expressed in vector form to include the information of all the available channels, is defined as

$$F(i)=\frac{SNR(i)}{1+pTQ'(i)}, \tag{2}$$

where SNR represents the Signal-to-Noise Ratio and pTQ' is the position that the station will occupy in the DTQ if it associates to the ith AP. Note that the value of pTQ represents the number of stations in the DTQ that will transmit with equal or higher data rate comparing to the potential data rate of the scanning station, as the users in the DTQ can be sorted by decreasing achievable transmission rate [1]. According to this mechanism, a scanning station reassociates with the AP that holds the highest value of F.

(5) *SNR-EQD AP Selection Mechanism* (#5)

So far, all the proposed mechanisms do not require any extra packet overhead (additional information). However, it is possible to design enhanced AP selection mechanisms if we allow the addition of some extra overhead bits to the control packets of DQCA. This overhead can be used to provide the stations with more qualitative information related to, for example, the data rates (R_b) at which the stations in the DTQ will transmit. R_b can be represented by a total number of $\log_2(n)$ bits, being n the total number of available transmission rates.

In order to exploit this extra information, we can define the Equivalent EQD (EEQD) as

$$EEQD=\sum_{j=1}^{TQ-1}\frac{1}{R_{b_j}}, \tag{3}$$

where R_{b_j} corresponds to the available transmission rate for the station in the pTQth position of the DTQ. This EEQD constitutes a proportional measure of the queuing delay that the station can expect in a certain channel. The actual value of the delay will depend on the number of data packets that each station transmits when it gets to the first position of the DTQ and on the length of the data packets. In case that both the number of packets that can be transmitted per channel invocation and the length of the data packets are constant, then the EEQD will be equal to the expected queuing delay.

The EEQD allows the definition of a new cost function that takes into account the expected queuing delay to make the AP decision:

$$F(i)=\frac{SNR(i)}{1+EEQD(i)}. \tag{4}$$

7 Performance evaluation

In order to evaluate the performance of the proposed AP selection mechanisms (summarized in Table 1), we have implemented a C++ system level simulator that executes the rules of the mechanisms in a multi-cell DQCA network.

According to the LSM function described before, a mobile station initiates a new scanning process when the channel conditions with the current AP degrade and the SNR drops below a specified value. Therefore, the radio propagation model used to evaluate the performance of the AP Selection mechanisms presented in this paper plays a key role. For this reason, we have considered a realistic wireless channel that suffers from path-loss and log-normal shadow-fading. More precisely, we have considered the path-loss dual-slope breakpoint model presented in [20] combined with a log-normal shadowing variation that takes into account the effects of the surrounding environment [21]. A breakpoint model is characterized by a breakpoint distance that separates the propagation properties in the regions close to and far from the transmitter. Typically, the free space loss distance exponent ($\gamma=2$) is used in the adjacent region, while a larger distance exponent is considered beyond the breakpoint distance. Reference [20] 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 $\gamma=3.5$ beyond that distance. The average loss at a distance d expressed in dB using this model, valid for operation at 2.4 GHz, can be expressed as:

$$\overline{L}(d)=\begin{cases}40+20\log(d),\ (dB) & d\le 5\text{ m}\\ 54+10\gamma\log(\frac{d}{5}),\ (dB) & d>5\text{ m}\end{cases} \tag{5}$$

Furthermore, measurements in [20] have shown that at any value of d, the path loss $\overline{L}(d)$ at a particular location is

Table 2 SNR thresholds for rate selection

Data rate	1 Mbps	2 Mbps	5.5 Mbps	11 Mbps
SNR threshold	$2-4dB$	$4-7.5dB$	$7.5-11$	$>11dB$

random and log-normally distributed (normal in dB) around the mean distance value:

$$L(d)[dB] = \overline{L}(d) + X_\sigma, \tag{6}$$

where X_σ is a zero-mean Gaussian distributed random variable (expressed in dB) with standard deviation σ (also in dB). The log-normal distribution describes the random shadowing effects that 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 considered a zero-mean log-normal shadowing with a standard deviation $\sigma = 5dB$ [21]. Furthermore, it is assumed that each new value of this log-normal attenuation is computed whenever a moving station travels 5 m. For example, at a speed of 10 m/s, shadowing attenuation varies every 0.5 s (slow fading).

7.1 Simulation scenario

The scenario under study is an 802.11b-like WLAN system [15] in infrastructure mode with three APs operating at the "non-overlapping" channels 1, 6, and 11 corresponding to a center-frequency of 2412, 2437 and 2462 GHz, respectively. The main reason for simulating with 802.11b rather than 802.11g (with higher transmission rates) is the fact that we are on the process of developing a testbed with actual equipment that can only work with the *b* extension. Our aim is to be able to compare in the future the simulated results with the actual measurements.

Accordingly, the transmission powers of the stations and the APs have been set to 20 dBm (100 mW), while the transmission rates have been fixed to 1, 2, 5.5 and 11 Mbps. The MAC protocol executed for the uplink is the DQCA. A set of SNR thresholds have been defined in order to select the appropriate data rate for PHY transmissions. Table 2 presents

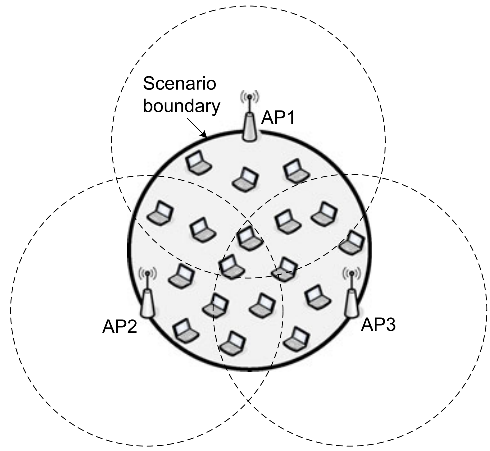


Fig. 8 Simulation scenario

these thresholds that have been selected based on the results presented in [22]. We assume in all cases that an ideal SNR detection and perfect rate selection scheme exist for the 802.11 MAC operations (ideal link adaptation).

Figure 8 represents the considered layout with three APs located such that there are no areas without coverage. The distance between the APs has been set to 300 m. The dashed lines delimit the ideal transmission range (according to the path-loss model, without the shadowing effects) while the solid line represents the physical scenario boundaries wherein stations move according to the following mobility model. The initial position of the stations in the network is random, following a uniform distribution within the scenario boundaries and cells. Once the simulation starts, every 2 μs and with probability 0.2 stations change their direction within a range of ±45° (the initial direction is computed using a uniformly distributed variable between 0 and 2π radians).

Regarding the traffic generation at the stations, the interarrival times follow a Poisson process and the size of the messages follow an exponential distribution with a mean value of $10 \cdot L_d$, where L_d represents the constant data packet length.

Regarding the DQCA configuration, the duration of each ARS packet has been set to 2 μs, and the length of FBP packet has been set to 13 bytes. Each FBP includes:

Table 3 System parameters

Parameter	Value	Parameter	Value
Number of control minislots (m)	3	MAC data packet length	2312 bytes
ARS duration	2 μs	MAC Header	34 bytes
SIFS interval	10 μs	FBP length	13 bytes
Propagation Delay	1 μs	*SNR_Scan_Threshold*	$4dB$
PHY Preamble	96 μs	*Delta_SNR*	$1.5dB$

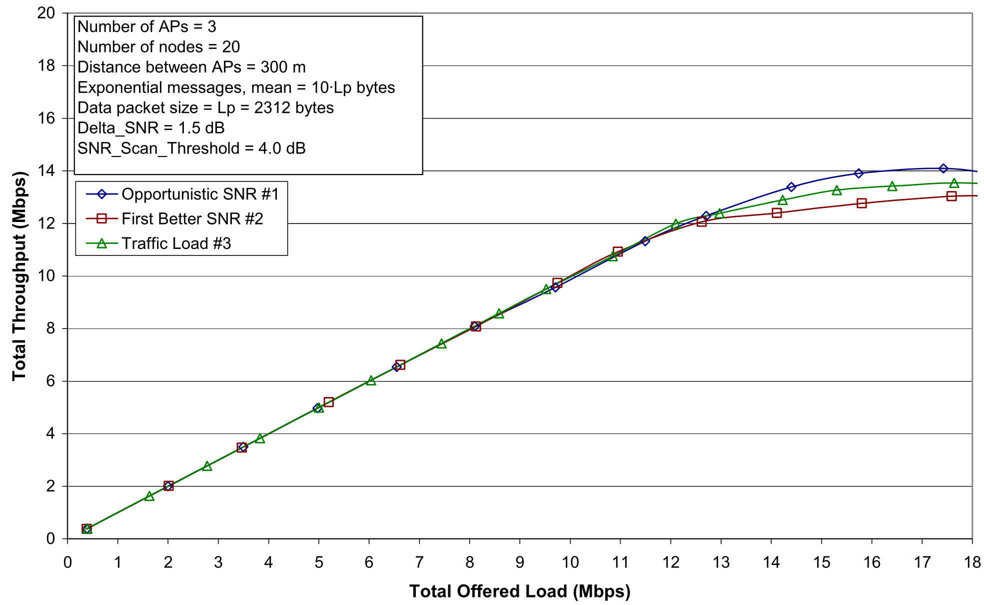


Fig. 9 Throughput (single metric-based mechanisms)

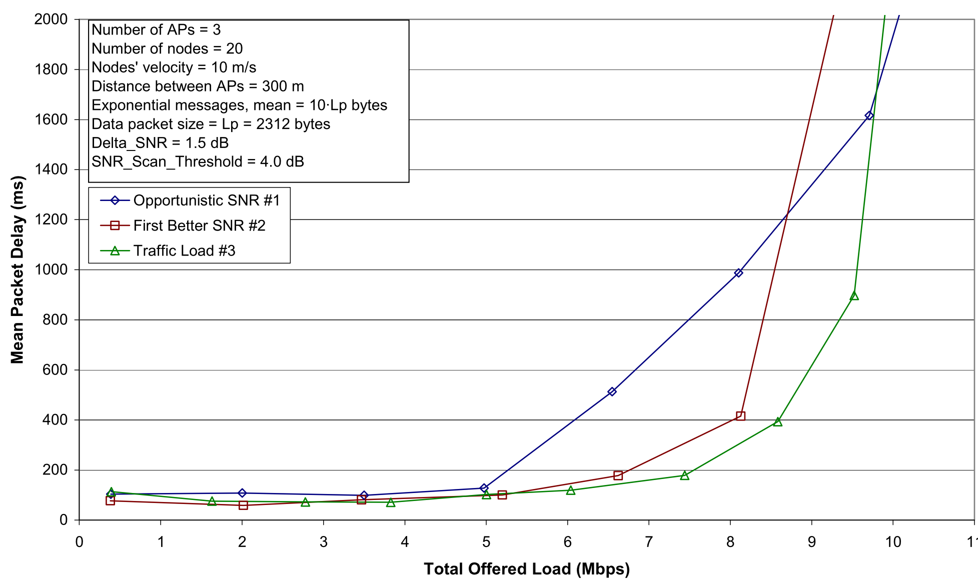


Fig. 10 Mean packet delay (single metric-based mechanisms)

(1) 2 bytes devoted to the *Frame Control* field.
(2) 1 byte for the *ACK*.
(3) 6 bytes for feedback information needed for DQCA operation.
(4) 4 bytes for the *Frame Checksum Sequence* (error control).

It is worth mentioning that the FBP includes the values of TQ and RQ, thus allowing mobile stations capture the MAC state from a certain AP to apply the corresponding DQCA rules. All the selected values of the DQCA parameters along with the physical layer parameters (considering an 802.11b-like radio interface) are summarized in Table 3.

7.2 Simulation results

We have evaluated the five proposed mechanisms with regard to the total throughput and the mean packet delay. The total throughput is defined as the aggregate amount of data bits successfully transmitted (an ACK is received) per second accounting the traffic of all the stations. The mean packet delay is the average duration of time elapsed from the moment that a packet is generated at a station, until the moment when this packet is positively acknowledged by the AP.

Figure 9 shows the simulation results in terms of total throughput using the AP selection mechanisms 1, 2 and 3. We observe that the maximum throughput values are 14, 13.2 and 13.5 Mbps for mechanisms 1, 2 and 3, respectively.

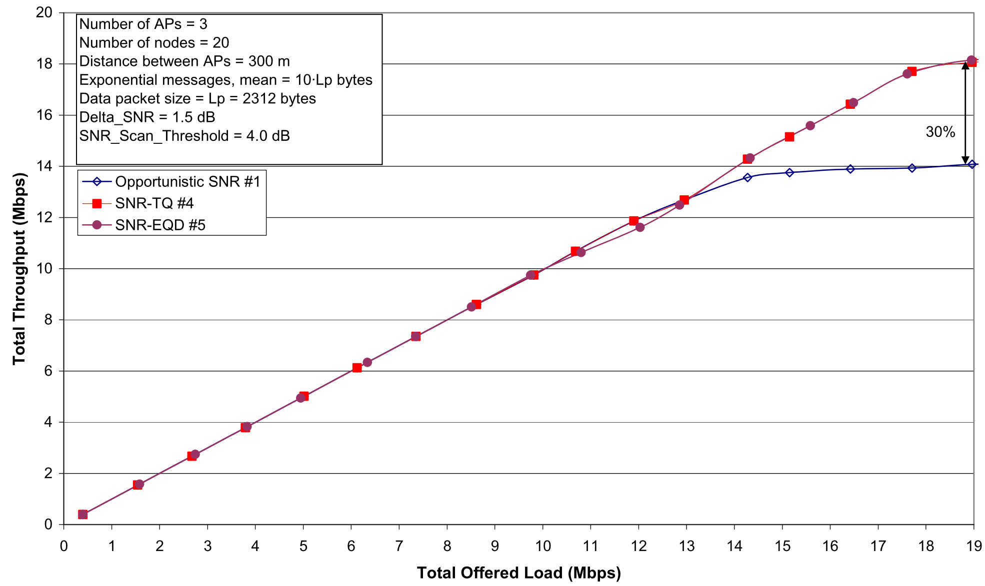


Fig. 11 Throughput (cross layer mechanisms vs best single metric-based mechanism)

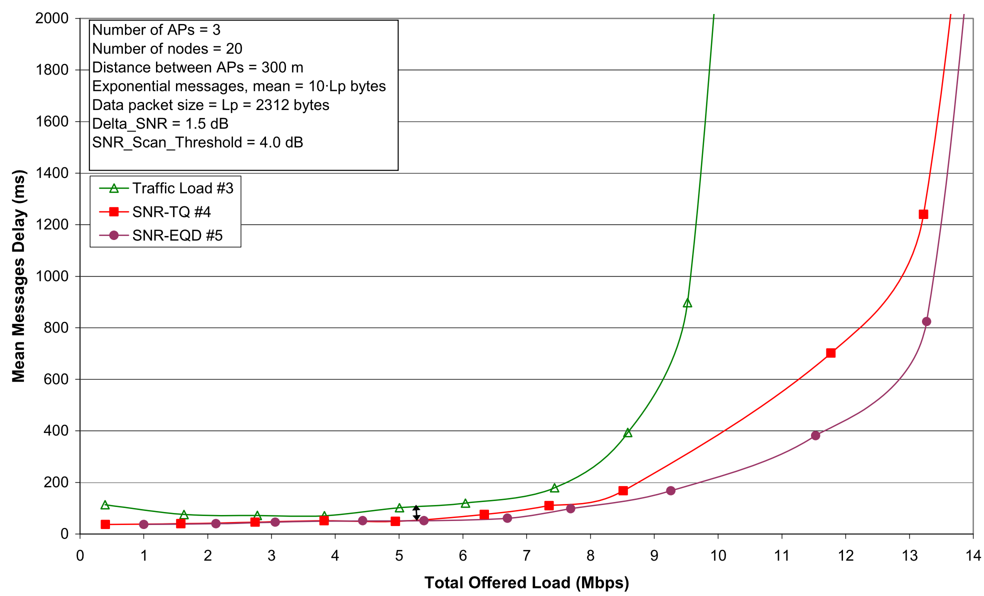


Fig. 12 12 Mean packet delay (cross layer mechanisms vs best single metric-based mechanism)

The difference between the two first mechanisms derives from the fact that in mechanism 1 the stations scan all the available channels, thus obtaining complete information of the available APs, while in mechanism 2 the station directly connects to the first AP that presents better SNR value compared to the SNR with its current AP. We can also see that mechanism 3, which is based exclusively on the estimation of the traffic load, achieves higher throughput compared to mechanism 2, but still does not outperform mechanism 1, which selects the best candidate AP in terms of SNR.

The main advantage of mechanism 3 lies on its delay performance, as it is depicted in Fig. 10. The long period of time that a station executing mechanism 1 devotes to the scanning process is reflected in the average packet delay, which is the highest among the three mechanisms. Mechanism 2 keeps a slightly lower level of mean delay for a wide range of total offered load values. Moreover, the delay in mechanism 2 is almost steady for an offered load up to 7 Mbps, whereas in mechanism 1 the delay increases almost exponentially for offered loads over 5 Mbps.

Therefore, there is a trade off between throughput and mean delay optimization. Mechanism 1 maximizes the achieved throughput at the cost of a higher (scanning) delay, while mechanism 2 minimizes the packet delay at the expense of a lower total throughput. On the other hand, mechanism 3 may not reach the throughput level of mechanism 1, but its delay performance is significantly better compared to the SNR-based approaches.

Regarding the mechanisms based on a cross-layer design, Fig. 11 shows the performance of the two proposed solutions in terms of total throughput. In order to show the throughput enhancement, we compare the cross layer approaches with the Opportunistic SNR AP Selection mechanism, which achieves the best throughput performance among the single metric-based mechanisms. It is clear that we have a significant improvement in the throughput of the system (almost 30 %) by considering various metrics and the information received from different layers in heavy traffic conditions (high offered load).

Although the two cross layer mechanisms have similar throughput performance, the obtained average delay is quite different, as shown in Fig. 12. In this case, the two mechanisms are compared to mechanism 3, which shows the best average delay performance of the single-metric mechanisms. As it can be shown, mechanism 5 is able to slightly improve the mean packet delay by considering more qualitative metrics (SNR, TQ and EQD), thus making smarter AP affiliation decisions. In any case, both cross layer mechanisms outperform the Traffic Load-based mechanism.

8 Conclusions

We have described in this paper the handoff processes for DQCA in a multi-cell environment. The analysis of the high-performance DQCA protocol in multi-cell scenarios had never been evaluated before. Five AP selection mechanisms have been introduced to improve the decision-making process of a station having to select a new AP for roaming purposes. Three of them are based on a single-metric to assist the AP decision-making process, while in two of them a cross-layer approach is employed to improve the performance of the system in terms of both throughput and average packet transmission delay. Computer simulation results show that the best results in terms of throughput and delay are achieved by considering a cross-layer approach where both SNR and traffic load are used as inputs for the AP selection process. Our future work will be focused on including smart scheduling mechanisms and metrics for energy saving into the AP selection process.

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