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RegionDCF: A Self-Adapting CSMA/Round-Robin MAC for WLAN

Javier Gomez[1] · **Alberto Riggi**[2]

Abstract This paper presents RegionDCF, a self-adapting Media Access Control protocol for WLAN that seamlessly behaves as either CSMA or round-robin access methods simultaneously taking advantage of their most effective properties. In contrast to preceding works in this area that focused on enhancements of a particular access protocol, or on a mechanism that switches between different access protocols, this paper proposes a single access protocol capable of behaving simultaneously as a pure contention-based (e.g., CSMA) and as a round-robin-based protocol depending on traffic conditions. The main building block of the proposed protocol is the *region*, a cluster of nodes that establishes orderly access to the channel. Once a member of a region gains channel access through a contention-based protocol, it allows contention-free transmission to all other members of the region in a round-robin manner. The functionality of the protocol for UDP and TCP traffic is discussed. Simulation results show that RegionDCF outperforms standard CSMA-based IEEE 802.11 Distributed Coordination Function in many aspects, including higher throughput and channel efficiency.

Keywords RegionDCF · DCF · CSMA · TDMA · Round-robin · Hybrid MAC · IEEE 802.11

1 Introduction

Wi-Fi technology has spread extensively and gained commercial success in recent years. However, unsolved performance issues regarding this technology remain, particularly in areas where many nodes contend for the channel, such as public hot spots. Wi-Fi uses the

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✉ Javier Gomez
javiergo@gmail.com

Alberto Riggi
alberto.riggi@gmail.com

[1] Telecommunications Engineering Department, National Autonomous University of Mexico, Av. Universidad 3000, 04510 Coyoacan, D.F., Mexico

[2] Information Engineering Department, University of Pisa, Lungarno Pacinotti, 43, 56126 Pisa, Italy

Distribution Coordination Function (DCF) as its main access method, relying on Channel Sense Multiple Access with or without collision avoidance (CSMA/CA) in order to inform nodes whether or not the channel is available for transmission. To reduce collisions among contending stations, DCF employs an exponential backoff mechanism (EB) that introduces some time randomness so stations do not transmit at the same time, thereby causing a collision. The EB mechanism doubles, on the average, the time interval in which a node defers transmission of a packet after each collision. In cases where many nodes contend for the channel, deferral intervals are likely to increase, thus increasing the associated delay involved in the successful transmission of each packet. This access delay heavily impacts the use of the channel, having a negative impact on user experience. As a result, it becomes necessary to modify IEEE 802.11 in order to reduce contention delays and improve channel use, especially in the presence of many contending nodes.

A possible solution to this problem, widely used in cellular systems, is to apply a TDMA approach. With TDMA, time is divided into time slots and each node has pre-assigned time slots during which nodes can transmit in a contention-free manner. With TDMA there are no wasted deferral intervals as each node receives its own transmission opportunities. A drawback of TDMA, however, is its lack of flexibility. That is, if a node does not have anything to transmit during its assigned slots, then such slots are wasted since no other node can use them. Many TDMA protocols use an on-demand slot assignment to avoid wasting unused data slots. In this approach, there is a reservation phase where nodes request data-slots in predefined request-slots. If the request is successful, the node obtains contention-free slots to transmit data. When more than one node submits its request in the same request-slot there is a collision, and provision for solving collisions during the reservation phase is needed [1]. However, even if this method alleviates the problem of unused slots, it suffers an increased overhead due to the signaling needed to request slot assignments (by nodes) and to announce them (by base stations). Furthermore, with TDMA, time is divided into fixed-length time slots, resulting in bad channel utilization in the presence of heterogeneous packet sizes. Other approaches consider an access method that switches between CSMA and TDMA access protocols, depending on the number of contending stations and traffic patterns. These proposals basically use CSMA when a few stations are contending for the channel, and switch to TDMA when many contending stations are present.

The solution proposed in this paper is a self-adapting access method called RegionDCF, which is based on standard IEEE 802.11 DCF. RegionDCF is a single-access protocol that seamlessly behaves as either CSMA or round-robin (RR), depending on the current number of contending stations. While round-robin is not the same as TDMA, it allows for orderly contention-free access to the channel, being less complex to implement and manage compared with TDMA. RegionDCF takes advantage of the most effective properties of CSMA and TDMA simultaneously. On one hand, it behaves like a pure contention-based access method when few stations contend for the channel. On the other hand, it behaves like a round-robin-access method when many stations contend for the channel. The key idea behind RegionDCF is the concept of *region*, which is a cluster of stations that can communicate with each other, at least at the basic rate. Once a member of a region successfully transmits a packet using a standard DCF method, it grants contention-free orderly access to the channel to all other members of the region in a round-robin manner. The contention delays associated to gaining channel access, except for the first packet, are thus eliminated resulting in lower contention delays and better channel utilization. In RegionDCF, channel contention moves from individual nodes as in 802.11 DCF to regions.

The rest of the paper is organized as follows: Sect. 2 briefly refers to what motivated this work, and reviews related work in this area of research focusing on the operation of DCF and ways in which TDMA has been implemented using IEEE 802.11 hardware. Section 3 presents a detailed explanation of the operation of RegionDCF, discussing both uplink and downlink cases. Section 4 presents the results of various simulation experiments of RegionDCF under various network conditions. Section 5 presents and discusses an algorithm to create and maintain regions. Finally, Sect. 6 presents our conclusions.

2 Motivation and Related Work

The Distributed Coordination Function (DCF) is the main access method defined by the IEEE 802.11 standard [2], and it is based on CSMA/CA. In CSMA, the time each node takes to transmit a packet is determined by a backoff timer, which is obtained from a uniform distribution between 0 and $CW - 1$, where CW is the current contention window size. For every transmission failure, the contention window doubles its current value until a successful transmission occurs, in which case the CW takes again its minimum value or CW_{min}. In the presence of a few contending nodes, the CW value remains around CW_{min}. However, as more nodes contend for the channel, the probability of a collision increases, thus increasing the CW value. A higher CW has a twofold aspect. On the one hand, it reduces packet collision. But on the other hand, it makes other nodes spend more time waiting (because of higher backoff timers) before they can access the channel. In order to illustrate how the number of contending nodes impacts performance, we evaluated a delay model for DCF presented in [3] and [4] under saturation conditions and ideal channel conditions. In particular, the access delay model given by [4] computes the average delay per node ($\overline{T}$) experienced by a node in the presence of n backlogged contending nodes as:

$$\overline{T} = \overline{T}_B + \overline{T}_S \tag{1}$$

where $\overline{T}_B$ is the average contention time and $\overline{T}_S$ is the average time during which the channel is busy due to successful transmission (Transmission Time). In Fig. 1, $\overline{T}_B$ and $\overline{T}_S$ are plotted against n contending nodes, thus varying the transmission rate. Table 1 shows the values of $\overline{T}_B$ and $\overline{T}_S$ for 64 and 1024 byte packets when there are 20 contending nodes in the network. Results from Fig. 1 and Table 1 confirm that nodes could spend more time contending for the channel than transmitting packets. In fact, for 20 contending nodes there is a 1-2 orders of magnitude difference between $\overline{T}_S$ and $\overline{T}_B$.

These results emphasize the need to reduce contention delays in IEEE 802.11 networks, particularly in areas of high user demand. The problem with having large contention delays in IEEE 802.11 has been studied by many authors. Most of these works focus on optimizing the exponential backup process. Unfortunately, the optimal value of various parameters involved in the exponential backoff process depends closely on the present number of contending stations, which in practice is a rather difficult parameter to estimate [5] [6], and can vary significantly over time. Some authors have proposed different techniques to adjust the backoff process parameters without requiring the number of contending stations. For example, the work in [7] proposes to divide the previous contention window over a constant decrease factor to compute the new CW after each successful transmission, rather than using the default CW_{min}. Similarly, the authors in [8] used a record of previous values of the contention window used in successful packet transmissions in order to estimate a new value of the contention window for the next

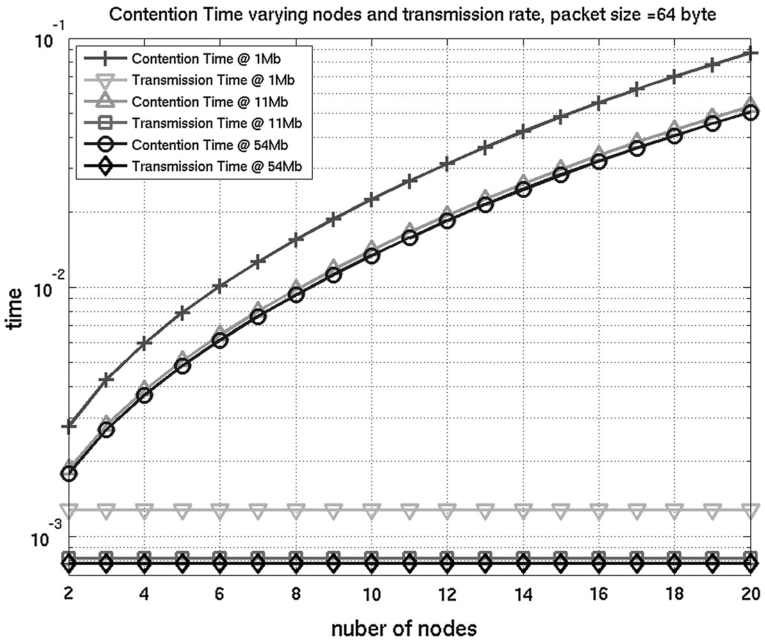


Fig. 1 Contention time versus transmission time for 64-byte packets

Table 1 64-byte (top) and 1024-byte (bottom) packet size

Rate	$\overline{T}_B$	$\overline{T}_S$
1 Mbps	0.0872	0.0013
11 Mbps	0.0530	0.0008
54 Mbps	0.0503	0.0008
1 Mbps	0.125	0.0018
11 Mbps	0.0564	0.0009
54 Mbps	0.0510	0.0008

transmission attempt. Underlying this operation is the assumption that the number of contending stations is the same as in the previous and current transmission attempts, which it is not always true. In [9], the authors propose a mechanism that exponentially decreases the backoff timer when a certain number of consecutive idle slots are detected. However, this behavior leads to unfairness as stations that already transmitted a packet re-enter the contention process with smaller backoff timers. Although the contention-based component of RegionDCF assumes the standard operation of 802.11 DCF, it can easily accommodate any modification in the operation of DCF without modifying its core operation.

Point Coordination Function (PCF) is an optional access method specified by the original IEEE 802.11 standard [10]. PCF is supported only by infrastructure-mode networks because it uses a Point Coordination (PC) that resides in the AP to establish which station can transmit. PCF is based on polling, where PC is the polling master. PCF provides contention-free periods (CFP) alternating with contention periods (DCF). Channel access is guaranteed because the PC waits for the channel to be idle for an Inter-Frame Space

(PIFS), which is shorter than the DIFS period used by other terminals. This prevents any other node from gaining access to the channel before the PC. During the CFP, the PC sends a poll to every station (or a set of stations if a Polling List is used), and the polled station replies by transmitting a data packet back to the AP.

The IEEE 802.11e standard [6] is an amendment to the original IEEE 802.11 draft that defines a new coordination function called Hybrid Coordination Function (HCF), which supports Quality of Service (QoS). HCF provides two access methods: Enhanced Distributed Channel Access (EDCA) and HCF Controlled Channel Access (HCCA). QoS is obtained by classifying traffic into different Access Categories (AC). EDCA is a contention-based access method founded on DCF that provides differentiated access to each AC. For each AC, a station uses a different EDCA Function (EDCAF), characterized by a different set of parameters ($CW_{min/max}$, duration of a transmission opportunity (TOp); etc.) that varies according to each priority. In [11], the authors proppposed a round-robin technique to achieve fair throughput with QoS guarantees in WLANs. The IEEE 802.11n [12] standard, on the other hand, introduced frame aggregation and Block ACK. These mechanisms enable a node to transmit multiple back-to-back packets, thus increasing MAC efficiency.

Regarding the use of TDMA employing IEEE 802.11 hardware, two main approaches can be found in the literature: pure TDMA methods or hybrid methods that switch between TDMA and other MACs. In [13], the authors describe the protocols and algorithms to implement TDMA in hardware using an Atheros wireless device. The access method chosen for this work is a pure TDMA access method for long distance Wi-Fi networks in order to bypass hidden terminal problems. In [14], the authors propose Soft-TDMAC, a software-based TDMA for wireless mesh networks that takes advantage of commodity IEEE 802.11 hardware under Linux OS by disabling CSMA/CA. This method provides tight synchronization between node pairs in the network, thus building a synchronization tree in which every node is synchronized with its parent. Precise synchronization decreases transmission overhead, thus improving network performance. In [15], the authors proposed the use of STDMA, a pure software TDMA access method to support VoIP applications over wireless LANs. The authors of [16] propose MultiMac, a framework that allows the concurrent operation of many MACs and frame transmission from different access methods within the same framework. The drawbacks of approaches that switch among different MACs are: the need for constant monitoring of traffic; the signaling overhead needed to inform all nodes about the change in MAC operation; and the overall complexity of the algorithm.

3 RegionDCF

As reviewed in the previous section, most related proposals either emulate TDMA or switch among different MAC protocols on 802.11 hardware. In Opposition, RegionDCF is a single-access method capable of behaving seamlessly either as a pure contention-based or a round-robin-based protocol, depending on present traffic conditions [17]. More importantly, RegionDCF achieves this behavior without requiring the protocol to identify the present number of contending stations. RegionDCF automatically adapts to traffic conditions without needing to switch between protocols, or to signal stations that there is a change in the access method, thus maintaining low complexity in the access protocol. However, CSMA characteristics are preserved in RegionDCF, especially when few nodes contend for the channel. While RegionDCF can be adapted to ad hoc topologies, it is a protocol initially designed for infrastructure-based networks. In fact, it takes advantage of the particular traffic patterns of these networks where it is common that all traffic be directed exclusively to the Access Point.

In RegionDCF, nodes are organized into *regions*. In order to join a region, a node must be able to communicate with other nodes in the region at least at the basic rate. The main goal of a region is to allow contention-free transmission of one packet by all its members in a round-robin manner once one member has gained access through standard DCF. This period is called Region Burst (RB). The region burst does not have a predetermined duration because it depends on the number of backlogged members in a region and the length of the packet transmitted by each member. With RegionDCF, access to the channel is still initially gained through using a contention method such as DCF, but this contention moves from individual nodes to regions.

In RegionDCF, there is no pre-allocated time for the transmission of packets as in TDMA. If a member of a region does not transmit because it has no traffic at the moment, there is only a wasted SIFS interval, which is much shorter than a wasted data slot, as in TDMA-based protocols. The resulting access scheme is a dynamic round-robin system that seamlessly evolves to CSMA, depending on present traffic conditions.

3.1 Region Header

In order to implement the concept of region in IEEE 802.11 a new region header is proposed, it is a modified MAC header that includes a Reservation sub-header (RSH) as the one shown in [18] and [19]. This sub-header is transmitted at a basic rate so that all other members of the region can decode it correctly. Fields of the RSH header are shown in Fig. 2. Each region has a unique ID inside the WLAN (RegionID), and each node within a region has a unique member ID in case a node belongs to more than one region. The RegionID is a positive integer that can assume values in the interval [1–255].

The Reserved Slot Field has a different meaning depending on the node decoding it: for nodes in the same region it indicates how many transmission opportunities (TOp) are available during the current region burst. For the AP, it indicates the number of SIFS intervals it must wait for before sending an Ack. Finally, for other nodes outside the region, it indicates the amount of time (in terms of SIFS) that the channel must be considered to be busy.

3.2 Uplink

When a region member gains channel access through DCF, it sets the RSH's Reserved Slot Field of the transmitted packet to the number of members in the region that have not

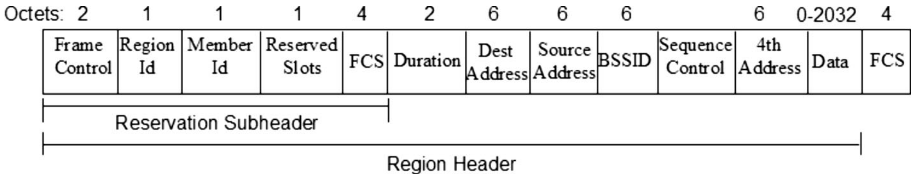


Fig. 2 Region header

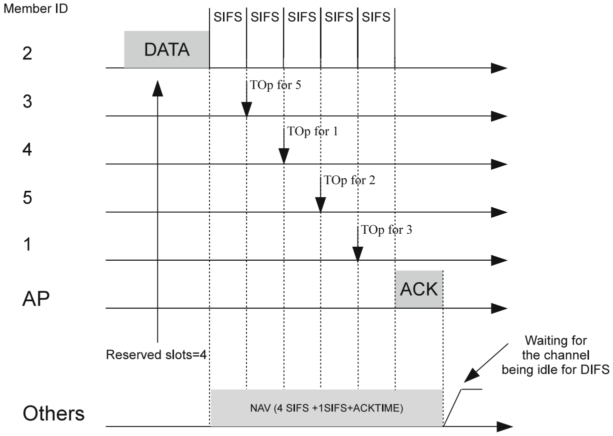
transmitted yet during the current region burst. Every time a member of a region transmits a packet, the timing of transmissions of other nodes in the region is consequently updated. However, only the start of the TOp for the next member is known for certain (after a SIFS). RegionDCF is based on two timers: a backoff and a deferral timer. The former, inherited from DCF, is used to gain channel access by the node that initiates a region burst. Once a member of a region gains access to the channel through DCF, all other region members freeze their backoff timers and individually start a deferral timer by setting this timer to their calculated TOp start value. Members of a region freeze their deferral timer while the channel is being used by another region member, and this timer is reactivated as soon as the channel is sensed to be idle again. If a transmission from a different region or a collision occurs, the deferral timer stops, and the backoff timer procedure is reactivated again in order to restart contention for the channel in DCF mode.

Within a region burst there is a TOp after every SIFS, and all TOps are sorted using a round-robin scheme. Once a node transmits a packet using its corresponding TOp, it sets the Reserved Slot Field to the value of the Reserved Slot Field of the previous packet, minus the calculated distance between nodes (see Fig. 4). During a region burst, nodes outside the region update their NAV with the value of the Reserved Slot Field. The channel is thus dynamically reserved until a region burst ends.

The algorithm that determines the time it takes each region member to access the channel is a round-robin scheme based on the ascending order of Member IDs. Hence, the first region member to transmit automatically fixes the transmission order of the remaining nodes in the region. When a member of a region gains access through DCF, it sets the Reserved Slot Field of the RSH to the number of region members that have not transmitted yet during the present region burst. Nodes that do not belong to the same region set their NAV to the value: Reserved Slot Field + SIFS + AckTime (see Fig. 3). To illustrate this, let us consider a region formed by the nodes shown in Fig. 3. In this figure, when node 2 gains access to the channel, the next node to transmit will be node 3, followed by node 4, etc. If node 5 is the one that gains access through DCF, it will be followed by node 1 and then by node 2, etc. Hence, the first region member to transmit establishes the transmission order of remaining nodes in the region, according to the relative distance of their Member IDs.

It is important to note that even if it seems redundant to iterate the members because the distance could be calculated with a formula, it is important to use the formula in case

Fig. 3 RegionDCF TOp



member IDs are not contiguous. Although the duration of a region burst depends on the number of backlogged region members and the size of the packets being transmitted, it automatically lasts enough time to permit the transmission of one packet by every backlogged member in a region (see Fig. 4).

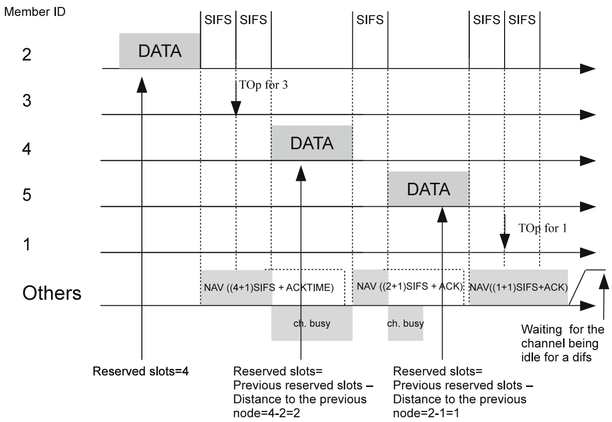
3.3 Aggregate Ack

Once a region burst finishes, the AP sends an aggregated Ack to all members of the region after a SIFS period. We call this aggregate Ack, the Region Ack (RA). This is shown in Fig. 5, where the RegionID field is an integer greater than zero. Region Ack differs from a legacy IEEE 802.11 Ack given the presence of the Region ID field that indicates the region where the Ack packet is addressed. There is also a difference in the way the receiving address (RA) field is used. In 802.11, the RA field is a unicast address to which the packet is addressed. In RegionDCF, the RA field is used as a bit mask that indicates which members of the region are acked. The aggregated Ack is sent at a basic rate so that all nodes in the region can decode the Ack packet properly. When a unicast Ack is needed, the RA field is used as a normal MAC address and, to indicate that the packet is unicast, the Region Id field is set to 0. The unicast Ack is used when a station sends an Ack to the AP upon receiving data from it.

When the AP receives a packet from a region member, it sets its deferral timer to a number of SIFS equal to the value of the Reserved Slot Field contained in the RSH field plus one. During the transmission of other region members in the current region burst, the AP stops the deferral timer and reactivates it with the new value contained in RSH once the current transmission is over. The AP waits an additional SIFS applied to its deferral timer in order to ensure that the last node in the region burst has completed its transmission.

Every member of a region that transmits a packet during a region burst uses the Ack timeout to determine whether a collision has occurred, like in legacy DCF. The only difference in RegionDCF is that the timeout must include the time needed for the TOp of other region members that have not transmitted during the current region burst. For this reason, a node sending a packet during the region burst sets the relative Ack timeout to the value of the RSH's Reserved Slot Field. When the same node overhears a packet from another member of the same region, it freezes its Ack timeout and reactivates it as soon as the channel becomes idle. At the end of a region burst, all region members have the Ack

Fig. 4 RegionDCF channel reservation



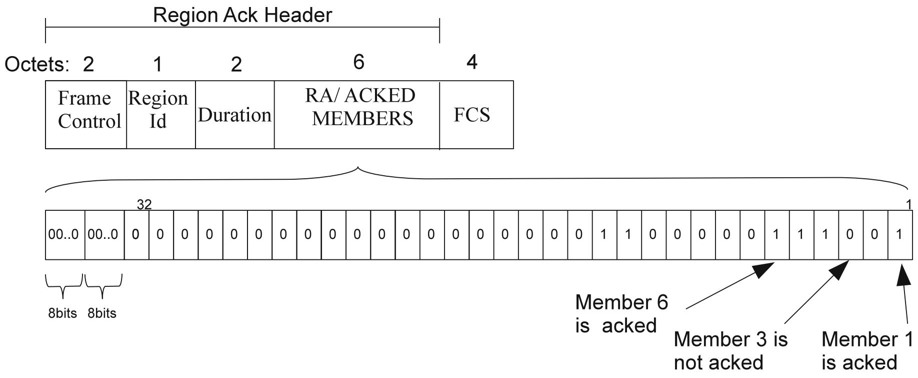


Fig. 5 Region ack

timeout with the same value so they are all waiting for the same aggregated Ack from the AP.

3.4 Downlink

In the case of downlink, the AP contends for the channel like any other node in DCF mode in order to transmit its own traffic. Compared to other nodes, however, the AP is less likely to access the channel since it cannot take advantage of other nodes gaining access to the channel as nodes in the uplink case do within a region burst. This access unfairness experienced by the AP creates problems in RegionDCF, especially when downlink traffic affects uplink traffic, such as TCP. A region member transmitting a TCP packet can potentially wait for a long period of time before receiving the associated TCP Ack. This delay includes not only the time needed for other members to transmit their packets within the current region burst, but also the time used by other region bursts in case the AP does not immediately gain access to the channel to transmit the aggregate Ack. For TCP, which is based on timers and contention windows, long and variable delays while receiving TCP Acks significantly affect TCP performance. As a result, it becomes necessary to give the AP some transmission priority equivalent to the priority given to region members within a region burst. In this way, RegionDCF provides a contention-free period for the AP, called AP burst. During the AP burst, the AP can send one packet to each member of a chosen region. Initially, we considered a strategy where the AP burst served the region of the previous region burst. However, such a strategy led to access unfairness among regions. We thus chose a strategy where the region chosen for the AP burst is the one to which AP buffer’s first packet destination node belongs. If the destination node of the packet belongs to more than one region, the chosen region would be the one that has not been served for the longer period of time. Once a region is chosen, the AP transmits one packet to each region member. In case the AP has no packets in its queue addressed to a region member in the current AP burst, it simply skips that node and moves to the next member in the region.

An AP burst can start after an aggregated Ack or when the AP gains channel access through DCF. If the AP has traffic to send to other stations, it waits for a SIFS after the transmission of the aggregated Ack and then starts the AP burst. Packets sent by the AP have all the RSH field set to 0 so that none of the non-AP stations can hook up to the transmission which is generating errors. Every packet sent by the AP must be acked by the destination node (after a SIFS). Acks sent by non-AP stations have the RegionID field set to 0 in order to indicate that they are unicast Acks.

3.4.1 Collision Management

In RegionDCF, a collision may happen only during the contention period in the DCF mode. This situation is managed by normal DCF mechanisms. That is, colliding nodes will start a backoff procedure and the region burst will not start (i.e., the channel is not reserved because other nodes of the region cannot decode the region information correctly due to the collision). Once a node successfully transmits a packet through DCF, no collision can occur in the following round-robin phase since nodes inside and outside the sender's transmission range are prevented from accessing the channel during the region burst. Nodes that are within transmission range can decode the RSH field since it is transmitted at the basic rate, in order that they are able to set their NAV properly. Regarding nodes located outside transmission range, they are still placed within sensing range so they thus receive a packet in error. Like in DCF, when a station does not receive a packet correctly, it waits for the idle channel to have an Extended Inter Frame Space (EIFS), where a EIFS has a duration equivalent to SIFS + DIFS + AckTime. An EIFS allows enough time for the receiver station to acknowledge the frame. The worst case regarding a node in sensing range is found when only one of the region's nodes transmits while other members in the region have no packets to transmit. In this case, a node located in sensing range of the transmitting node should consider the channel busy for an amount of time equal to SIFS*(number of members in the region), even if it does not sense any transmission thereafter. Because an EIFS is about 21 times the length of a SIFS, an EIFS is long enough to prevent a collision during a region burst that could include as many as 20 members, in the worst of cases. The critical period, the period during which the channel must be considered busy even if there are no transmissions, becomes smaller at every turn corresponding to each region member. This makes the EIFS large enough to protect all transmissions during a region burst. Besides, it is also likely that not all of the packets in a region burst are received incorrectly by the same node since each packet is sent by a different region member. It may happen, in fact, that a node is inside sensing range of one part of a region while it is inside the transmission range of the rest of the region. This node, hence, can decode the RSH of some packets and use the reservation mechanism through NAV, as already seen. If the node receives a further packet that cannot be decoded during the reserved time, it assumes that the packet comes from the same region and overrides the normal normal EIFS-based mechanism. This node, in fact, saves the current NAV value, waits for the transmission to be completed (that can be known through sensing the channel idle) and sets the NAV with the saved value.

Unlike the region burst, there is no additional mechanism to protect the AP burst. AP Transmission is guaranteed because the AP waits for the channel to become idle only for a SIFS while other stations, which are in the contention phase, wait for a DIFS. Consequently, the AP can send many packets during the AP burst without contending for the channel. The AP burst can start either after the transmission of an aggregated Ack or after gaining access to the channel in DCF mode. If the AP burst starts after a contention period, there might be a collision, which is processed by the DCF's normal recovery procedure. The AP burst ends when the AP stops transmitting packets. If a collision occurs, the AP burst ends because the AP stops transmitting. Hence, the channel is left idle and a new contention period follows.

4 Validation Tests

RegionDCF was implemented in network simulator NS2 in order to validate its operation and study the impact of various protocol parameters. We used the ns-miracle extension library [20] to support IEEE 802.11bg rate adaptive functionality. This rate adapter sets the actual data rate depending on the distance, as in [21], for a Free-Space propagation model and error-free channel conditions. Transmission range and sensing range were set at 250 and 550 m, respectively. All measured metrics have been evaluated with a 95 % confidence interval being 5 or 10 % of the mean value through ns-measure [22]. The tests focused on two types of traffic: Constant Bit Rate (CBR) and File Transfer Protocol (FTP). We chose these applications because they allow for the injection of heavy traffic in the network, maintaining nodes constantly backlogged. CBR application allows for the isolation of uplink traffic in order to analyze uplink performance only, while FTP permits the study of the presence of concurrent uplink and downlink traffic. We considered 20 static nodes randomly placed in the network area connected to one Access Point located at the center. The results presented in this section are expressed in terms of percentage gain, comparing the performance of RegionDCF with standard IEEE 802.11bg. That is, for a certain metric we computed the percentage gain as:

$$PercentageGain = \left(\frac{Metric_{RegionDCF}}{Metric_{DCF}} - 1\right)100 \tag{2}$$

In the experiments we measured the following performance metrics: Channel utilization is the percentage of time during which the channel is busy due to successful packet transmissions. Contention Time is the time that elapses from the moment a node attempts the transmission of a packet to the moment in which the first byte of the packet is transmitted. Delay is the time interval that elapses between the arrival of a packet at the the sender’s queue from upper layers to the time the last byte is received by the destination. Throughput is the number of bits received correctly per unit of time.

4.1 CBR

4.1.1 Scenario 1

First we studied how the number of members in a region affected uplink CBR traffic performance. We considered a network of 200 × 200 m to explore what happened when all nodes were within transmission range of each other. In this scenario, the number of members in each region was determined by their relative position and the following two conditions:

- A node can participate in one region only.
- If the distance between every possible pair of nodes in the region is less than a specific value, a region can be formed by two or more nodes.

This configuration determines that it is possible, in this scenario, to have a region that includes all 20 nodes. We considered CBR traffic with packet sizes of 64, 512 and 1024 bytes, respectively. CBR rate was chosen at 0.6 Mbit/s so nodes were always backlogged. We analyzed RegionDCF performance for 2, 3, 4, 5, 6, 10 and 20 members per region. Figure 6 shows the behavior of various performance metrics for the three packet sizes being considered. The first point to note from these figures is that the smaller the packet size, the better the performance of RegionDCF over IEEE 802.11bg (see Fig. 6a). This behavior was to be expected since smaller packet sizes result in higher packet overhead introduced by the exponential backoff mechanism in IEEE 802.11bg. On the contrary, RegionDCF performs better for small packets because it eliminates contention access delays during region bursts (see Fig. 6c). As shown in Fig. 6a, the best configuration is the one with the highest number of region members. A node in a region with more members has a higher probability to access the channel in a round-robin manner. The throughput improvement shown in Fig. 6a is related to reduced contention times and smaller delays (see Fig. 6c), which translates into better channel utilization (see Fig. 6b).

4.1.2 Scenario 2

In this scenario, we considered a network of 400x400 meters so all nodes are within sensing range of each other but not all nodes are within transmission range of each other. In this scenario, the number of members in a region was determined by the relative position of nodes. All nodes are allowed to participate in every region as long as they satisfy the following rules:

- If the distance between every possible pair of nodes in the region is less than a specific value, a region can be formed by two or more nodes.
- There cannot be two regions constituted by the same nodes. The rationale underlying this rule is that two regions constituted by the same nodes do not yield any real advantage, but introduce higher overhead and complexity while maintaining regions.
- There cannot be a region formed by a subset of nodes found in another region. For this, consider the following example: if nodes A, B, and C form a region, nodes A and B cannot form another region unless another node, say node F, is included and node F is not present in any other region together with nodes A and B.

Each node generates CBR traffic destined to the AP with a fixed packet-size of 512 bytes. CBR rate was again 0.6 Mbit/s so nodes were always backlogged. Simulations ran for 100 s.

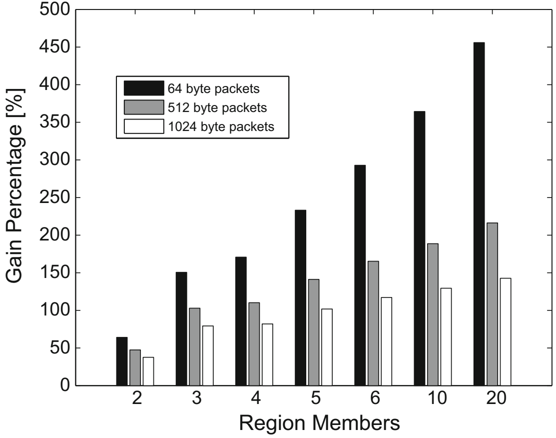
Table 2 shows a comparison of various performance metrics obtained from this scenario using either IEEE 802.11bg or RegionDCF for 512 byte packets only. As can be seen in this table, RegionDCF was able to achieve 89 % more aggregate throughput than IEEE 802.11bg. This result again is a direct consequence of eliminating contention delays within region bursts, resulting in better channel utilization. Besides, RegionDCF achieved fewer collisions and shorter delays. However, throughput of individual nodes in RegionDCF suffered from unfairness as can be seen in Fig. 7 where some nodes achieved higher throughput than others. This unfairness was caused by region configuration. As shown in Fig. 7, node 13 has the highest throughput, while node 20 has the lowest. Node 13, indeed, happens to be the only node that belonged to four regions, while node 20 was the only node belonging to one region only. This configuration determines that node 13 has a higher probability to access the channel than other nodes. This behavior shows the link between the number of regions a node belongs to and the throughput it achieves.

4.2 FTP

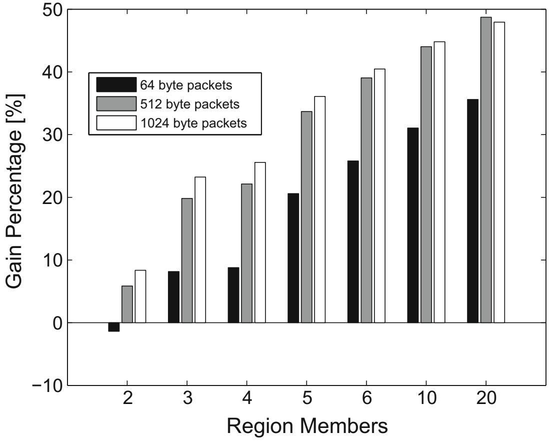
This section presents the results of experiments for FTP/TCP traffic. The FTP application consisted of the transmission of an infinite-sized file, so nodes were always backlogged.

Fig. 6 RegionDCF performance for 64, 512 and 1024 byte packets

(a) Throughput



(b) Channel Utilization



(c) Contention Time

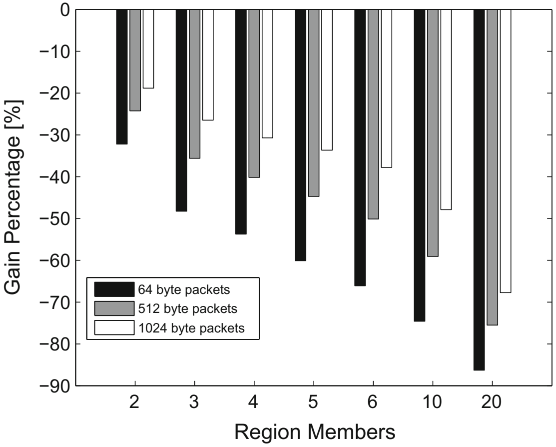


Table 2 Collected metrics for CBR traffic, packet size 512 bytes

Metric	IEEE 802.11bg	RegionDCF	RegionDCF gain (%)
Throughput (byte/s)	314434.5	595333.02	+89
Node delay (s)	0.318382	0.2375688	−25
Contention time (s)	0.018843	0.0153837	−20
Channel utilization (%)	61.89 %	69.79 %	+12
Number of collisions	34,870	29,955	−14

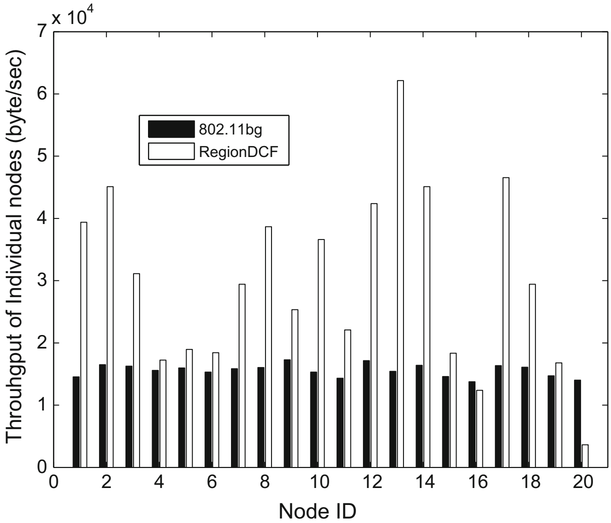


Fig. 7 Unfairness when regions are of different sizes

TCP fragmented the file into packets with a size equal to the maximum transfer unit (MTU), which in this case corresponded to 1500 byte frames. To make TCP experiments more realistic, wireless stations established an FTP connection with a remote node belonging to a wired network connected to the Access Point (see Fig. 8). As sketched in Fig. 8, every wireless station sent FTP traffic to a different node in the wired segment of the network. Each wired node is connected to the AP through a link that has a delay that varies from one node to another. In this way, both uplink and downlink traffic experience different delays. In general, results for FTP traffic confirm that RegionDCF achieves better performance over IEEE 802.11bg. Figure 9 shows the individual throughput of nodes with IEEE 802.11bg and RegionDCF configured with five members per region. The wired links connecting the AP with the wired nodes were configured in such a way that link 2 has a higher delay than link 1. Link 3 has a higher delay than link 2 and so on. The effect of each particular delay can be seen in the individual throughput obtained under IEEE 802.11bg in Fig. 9. Nodes with traffic passing through links with higher delays experience lower throughput. RegionDCF, instead, is more resilient to this problem, as it provides similar throughput to all nodes.

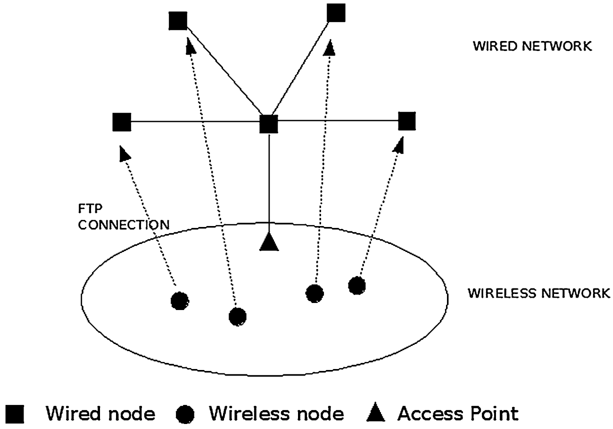


Fig. 8 Wired-wireless scenario

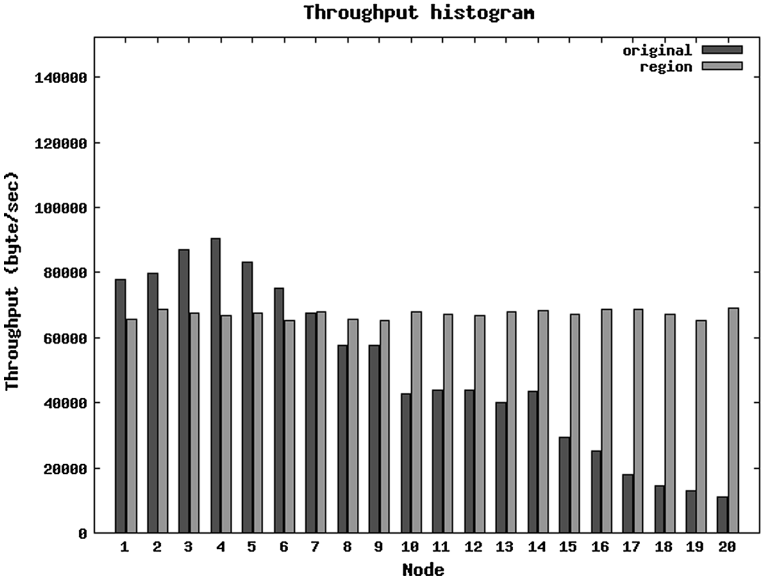


Fig. 9 Individual throughput in five-member regions and FTP traffic

Figure 10 shows the aggregated throughput for the three packet sizes being considered, while Table 3 shows a comparison of various performance metrics as region size varies for the same experiment illustrated in Fig. 10, however, this is applicable only to packets of 512 bytes. As can be observed in Fig. 10 and Table 3, contention times, channel utilization and delays consistently achieve better performance in larger regions in RegionDCF, compared with IEEE 802.11bg. This is a trend already observed for CBR traffic.

4.3 Inactive Region Members

In all the experiments so far we have considered that all nodes always have a packet in their buffer ready to be transmitted (i.e., nodes are backlogged). However, this assumption

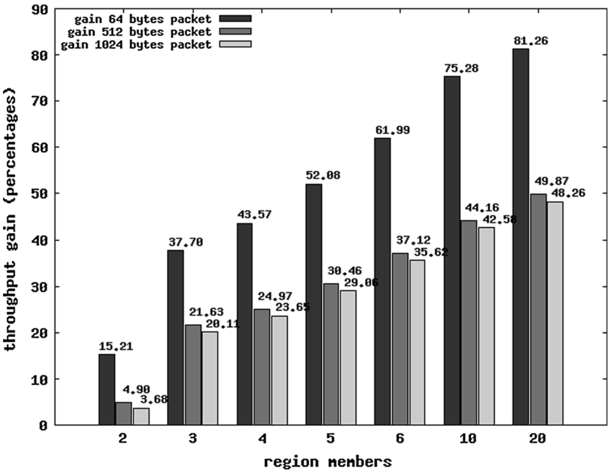


Fig. 10 Wired-wireless scenario: aggregated throughput

does not always hold, as nodes will also experience times when their transmitting buffer is empty. In this case, we consider a node to be inactive when it has no packets to transmit. The transitions from having packets to transmit to having no packets in the buffer will ultimately depend on the particular applications running on the mobile device. The presence of inactive nodes represents wasted periods within a region burst. An inactive region member negatively impacts its region in two ways: First of all, active region members will need to wait for an additional SIFS in order to find out whether the next member in turn has no packet to transmit. Secondly, inactive nodes do not gain access to the channel through the DCF mode so other region members can benefit by transmitting in a round-robin manner. This situation leads to both a decrease in performance and potential unfairness problems, due to regions having a different number of active members. This problem becomes critical when most nodes in a region are inactive since active nodes cannot take advantage of other region members gaining the channel for them and, at the same time, the AP waits in vain for a SIFS period for every inactive region member, before sending the aggregate Ack.

Figure 11 show the performance of RegionDCF in a network having 20 nodes connected to the AP as the number of active nodes for regions of different sizes was varied. The *R*–*M* legend on the horizontal axis in these figures means there are *R* regions having *M* members in each region so all 20 nodes are included. For this study we used the same network settings as in the CBR experiments described previously for Scenario 1 in Sect. 4.1.1.

In the first experiment, Fig. 11a, we tested the performance of RegionDCF as we varied the size of regions, but there was only one active node out of 20 nodes in the network. In this figure, we can observe how RegionDCF throughput decreases as regions become larger compared with IEEE 802.11bg. This behavior is expected since the only active member has to gain access to the channel by itself using DCF, and the AP waits as many SIFS periods as the number of inactive region members before sending the Ack. The worst performance in this figure is obtained with a region having 20 members where RegionDCF gets 22 % less throughput compared with IEEE 802.11bg.

Figure 11b shows the performance of RegionDCF when only two nodes out of 20 are active (i.e., backlogged), and the two active nodes are distributed homogeneously in

Table 3 Collected metrics for FTP traffic, packet size 512 bytes

Metric	802.11bg	RegionDCF 2 members	RegionDCF 5 members	RegionDCF 10 members	RegionDCF 20 members
Contention time (s)	0.007362	0.005578	0.004069	0.003012	0.001803
		−32.18 %	−44.73 %	−59.09 %	−75.51 %
Channel utilization (%)	58.23 %	61.64 %	77.84 %	83.86 %	86.60 %
		+5.86 %	+33.68 %	+44.02 %	+48.72 %
Delay (s)	0.096906	0.058810	0.044426	0.030665	0.035963
		−33.22 %	−64.03 %	−75.17 %	−70.89 %

different-sized regions. As we can see in this figure, throughput of RegionDCF decreases again for larger regions compared with IEEE 802.11bg up to a region configuration having 20 members, where RegionDCF achieves a better performance compared with IEEE 802.11bg. The reason why performance increased for a 20-node region is that the two active nodes were located in the same region, and while one node transmitted its packet in DCF mode, the other node transmitted its packet in round-robin mode, thus eliminating the associated contention delay. We can observe a similar behavior in, for example, Fig. 11d, where four active nodes were distributed homogeneously in regions of various sizes. In this figure, we can observe how throughput decreased again for small regions compared with IEEE 802.11bg up to a network configuration having four regions with five members. For this region configuration, there were three regions with one active node each while the fourth region had two active nodes. Again, because there was one region with two or more active nodes within a region burst, there was a better throughput of RegionDCF compared with IEEE 802.11bg. Observing the other graphs in Fig. 11, we note that the region configuration for which the throughput performance of RegionDCF changes from negative to positive compared with IEEE 802.11bg, occurs in a region configuration in which there is at least one region with two active nodes. This result is very important because it shows RegionDCF exhibits a performance decrease compared with IEEE 802.11bg when there is only one active member within a region burst. This problem, however, can be alleviated with proper region configuration, as we discussed in the following section.

5 Region Configuration

Given that RegionDCF targets infrastructure networks, the AP is the entity that can better accomplish the task of creating and maintaining regions. In fact, due to the network's topology, all traffic usually passes through the AP. The only information that is not available to the AP is the relative distance among nodes. The following protocol can be implemented in order to obtain this information. When a node joins the network, it sends a broadcast packet to its neighbors to request information about regions they currently belong to. Nodes receiving the request reply with a small packet containing only the RegionDCF header. These response packets are sent at the basic rate directly to the new node without passing through the AP. In this way, the new node can estimate the possible achievable rate of each reply packet through the signal strength of the received reply packets. The new node sends a packet to the AP that contains a list of all responding nodes and their associated rates. The AP can then assign the new node to a region as long as all members of a candidate region are present in the information packet sent by the new node, or in the database information regarding the new node.

Once the AP acquires information about all candidate region membership for each node in its domain, important questions appear: how many regions should a node join? What size should the regions be? When should a node join a new region or leave an existing region? In the rest of this section, these questions will be answered and a region maintenance algorithm that maximizes RegionDCF performance and usability will be proposed.

5.1 One Region Versus Many Regions?

When studying scenario 2 in Sect. 4.1.1, we partially answered this question regarding how many regions a node should join. In that scenario, we allowed nodes to join as many regions as possible, which resulted in a serious unfairness behavior as nodes belonging to more regions obtained higher throughput compared with nodes belonging to fewer regions. As a result, it becomes important that nodes belong to one region only in order to thus avoid unfair behavior of the protocol.

5.2 Region Size?

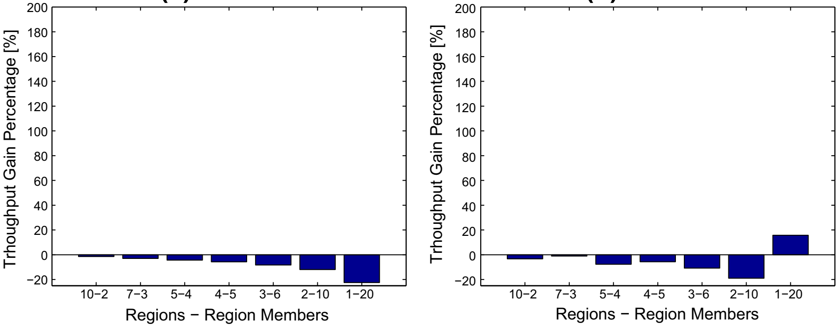
Having decided that nodes join one region only, the next important issue is what should region size be. The graphs in Fig. 11 show that for a fixed number of active nodes, the best performance of RegionDCF always happened in larger regions rather than smaller regions. This situation occurs because even when there are a few active nodes in the network, as long as we put those few active nodes in the same region they will take advantage of transmitting their packets in a round-robin mode, thus eliminating the associated contention delays. In this way, a node should join the candidate region with the most members. The exception to this rule is the case where there is only one active node in the network, where performance worsens as regions become larger. We will show that this worst case scenario can be prevented by removing inactive nodes from regions as explained below.

5.3 Joining/Leaving a Region?

As observed in the graphs of Fig. 11, inactive region members have a negative impact on RegionDCF performance, especially when no other nodes transmit in a round-robin mode after one node transmitted a packet in DCF mode. To address this problem, a policy is needed in order to maintain regions with mostly active nodes. In order to deal with inactive region members, the AP should make sure there is at least one node transmitting in round-robin mode per region burst, on the average. In order to achieve this behavior, we propose that the AP keeps an activity counter for each region member. In the following description, we will be referring in particular to one region having M members only. Let Z_i be a counter for each node in such region ($1 \leq i \leq M$) that is increased or decreased by one every time the region member transmitted or not in round-robin mode, in the previous region burst. The value of Z is reset to zero after M region bursts. The AP decides to keep node i in the region as long as node i transmitted at least one packet in round-robin mode in the past M region bursts (e.g., $Z \geq 1$). Otherwise, node i leaves the region. The rationale underlying this condition is that for RegionDCF to achieve better performance compared with IEEE 802.11 in terms of throughput, RegionDCF needs, on average, that there be at least one node transmitting in round-robin mode for every region burst.

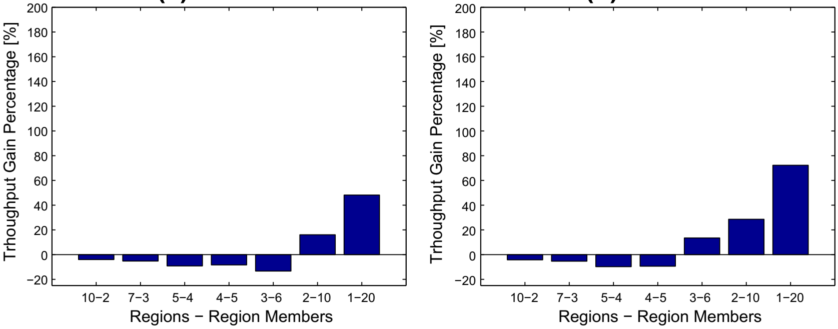
(a) 1 active node

(b) 2 active nodes



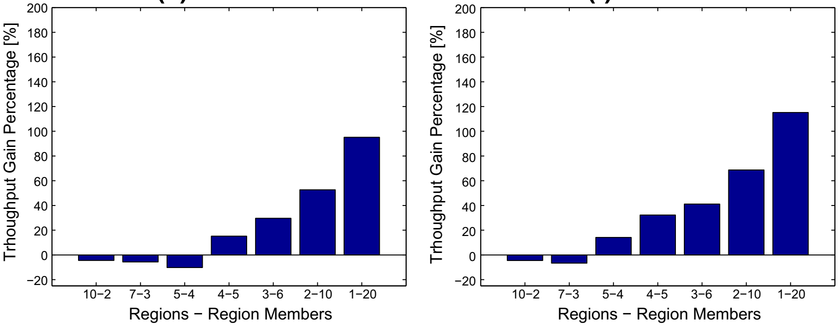
(c) 3 active nodes

(d) 4 active nodes



(e) 5 active nodes

(f) 6 active nodes



(g) 7 active nodes

(h) 11 active node

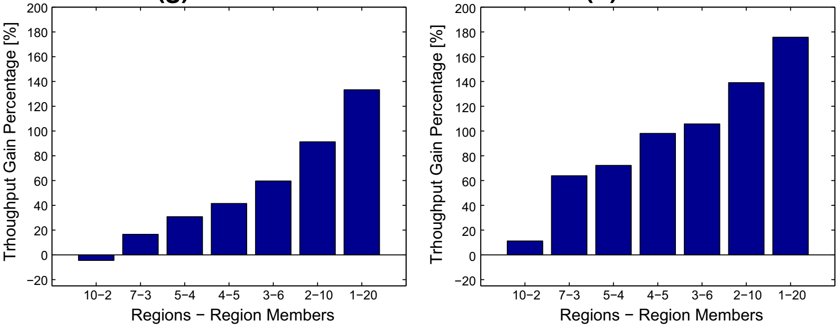


Fig. 11 Throughput gain percentage when the number of active nodes varies

In case a node leaves a region because of recent region inactivity, it will transmit its traffic in DCF mode thereafter, and it will only request to rejoin a region as long as it has had a new packet to transmit during the *M* previous region burst of the region it is targeting to join.

Now, we formalize the region configuration method in Algorithm 1, which encloses the answers to all the questions raised above.

Algorithm 1 Region Membership Configuration

```
1. Joining a region
A node may only be a member of ONE region
The candidate node will join the candidate region with the most members
Define $M$ (number of existing nodes in the region the candidate node is targeting to join)
Let $J = 0$
For each of the next $M$ region bursts increase $J$ by one for each new packet arriving in the candidate node's transmitting buffer
if $J \geq 1$ then
    The candidate node will request the AP to join the targeted region
    The AP will assign region and member IDs to the candidate node and will inform all other nodes in the region regarding the new member
else
    The candidate node remains outside the region and continues transmitting its packets in DCF mode
    The candidate node will go back to state 1
end if
2. Leaving a region
Define $N$ (number of existing nodes in the region of which a node is currently a member)
Let $Z = 0$
For each of the next $N$ region bursts increase $Z$ by one if the node transmitted a packet in round-robin mode
if $Z \geq 1$ then
    The node will remain in the region
    Set $Z$ to zero
    Go back to state 2
else
    The node leaves the region and moves to state 1
end if
```

6 Conclusion

This work presents a new access protocol for wireless local area networks named RegionDCF. RegionDCF is a single-access method that seamlessly behaves as either CSMA or round-robin protocols depending on the traffic conditions present. The key idea of the proposed protocol is the concept of *region*, a cluster of nodes that establishes orderly access to the channel in round-robin manner once one member of the region gains access through DCF mode. Simulation results show that RegionDCF outperforms standard IEEE 802.11 DCF in many aspects, including throughput, contention times and channel efficiency. The proposed access protocol is a feasible alternative to the standard IEEE 802.11bg MAC protocol since it yields a remarkable performance enhancement, yet CSMA characteristics are preserved, especially when there are a few nodes contending for the channel. This work opens new possibilities for WLAN networks because it provides shorter contention delays in populated WLANs as well as improving MAC performance seamlessly for different traffic conditions.

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Javier Gomez received the BSc degree with honors in electrical engineering in 1993 from the National Autonomous University of Mexico (UNAM) and the MSc and PhD degrees in electrical engineering in 1996 and 2002, respectively, from Columbia University and its COMET Group. He was at the IBM T.J. Watson Research Center. His research interests cover routing, QoS, and MAC design for wireless ad hoc, sensor, and mesh networks. Since 2002, he has been a full-time professor with UNAM.

Alberto Riggi is a software engineer working as principal developer and architect in a private company. He studied computer engineering in Italy at university of Pisa. He obtained bachelor degree in computer engineering in 2005 and a master degree in computer engineering with networking curriculum in 2010. His master thesis was written in Mexico at telecommunications department of the National Autonomous University of Mexico (UNAM) under the guidance of professor Javier Gomez.