Group-Based Medium Access for Next-Generation Wireless LANs

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Abstract

Recently, there has been extensive research interest in increasing the data rates supported by IEEE 802.11 wireless LANs. For this purpose, IEEE 802.11 formed Task Group N to develop specifications for high-data-rate wireless LANs. The medium access in the legacy 802.11 is not scalable as it exhibits a large control overhead when the data rates increase and a large collision rate when the number of stations is large. In this paper, we introduce a Group-based Medium Access Control (GMAC) protocol for wireless LANs with high data rates and a large number of stations. With GMAC, stations are divided into groups that are free of hidden nodes. Each group has a leader and only group leaders contend using CSMA/CA. Once a group leader wins the contention, it reserves transmission time for all the stations in its group and issues a polling packet specifying the group's schedule. Stations in the same group transmit after their leader according to the polling packet. GMAC achieves significant throughput gain over DCF by reducing the collision rate and the control overhead. Simulation studies show that GMAC maintains a high throughput as the data rates and the number of stations increase.

1 Introduction

Recently, there has been extensive research interest in increasing the data rates supported by IEEE 802.11 wireless LANs (WLANs). Higher rates enhance end-user performance and enable new multimedia applications. For this purpose, IEEE 802.11 formed Task Group N (TGn) to develop new 802.11n standard specifications that achieve a maximum throughput over 100 Mbps. The latest proposals for 802.11n physical layer (PHY) [1] and the medium access control sublayer (MAC) [2] were proposed by the Enhanced Wireless Consortium (EWC), an industry-backed group.

In next-generation WLANs, a single cell can support a large number of stations due to the availability of bandwidth. However, the distributed coordination function (DCF) of 802.11 [3], the most popular access mode currently, does not perform well with a large number of stations since its collision rate becomes high. This trend was demonstrated in analytic- and simulation-based studies [4], [5], [6].

In addition, DCF does not scale well with high data rates due to its large overhead. With DCF, a station transmits one data packet upon winning the contention. The overhead for a data packet includes interframe spaces (DIFS, SIFS), backoff slots and control packets (RTS, CTS, ACK). The RTS/CTS packets are used to combat hidden nodes and to reduce the collision time; they are omitted in the basic access mode. As the data rate increases, the data transmission time decreases but the control overhead cannot be decreased by the same factor since control packets are transmitted at a low rate so they can be received correctly by all the stations. Thus, the overhead of the medium access protocol should be reduced to benefit from the increase in data rates. In [7], it is shown that the throughput of DCF reaches an upperbound even if the data rate increases infinitely. In [8], it is shown that the overhead of RTS/CTS becomes very large with high data rates, and in most cases, the basic access mode (without RTS/CTS) yields a higher throughput even in heavy load conditions with hidden nodes.

In this paper, we introduce a Group-based Medium Access Control (GMAC) protocol for wireless LANs with high data rates and a large number of stations. With GMAC, stations are divided into groups based on their locations in the WLAN so that groups are free of hidden nodes. Each group has a leader and only group leaders participate in the contention for the medium. When a group leader wins the contention, it reserves time for all the stations in its group via RTS/CTS and it transmits a polling packet that contains the group's schedule. Stations in the same group are within the communication range of each other, thus they transmit in a contention-free and hidden-node-free environment without requiring RTS/CTS exchanges. GMAC achieves gain over DCF by allowing fewer stations to contend and by reducing the number of control packets. Further, GMAC is interoperable with legacy 802.11 devices; when all the stations are group leaders, GMAC is reduced to DCF. Simulation results show

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that GMAC maintains a high throughput as the data rates and the number of stations increase.

The rest of this paper is organized as follows. Section 2 presents the system model and background information. Section 3 describes the group-based medium access control protocol for next-generation WLANs and Section 4 presents the simulation results. The paper concludes in Section 5 with summarizing remarks.

2 System Model and Background

In this section, we present the system model and review the limitations of DCF in next-generation WLANs. Then, we present previous related work.

2.1 System Model

We consider an infrastructure-based WLAN with an access point (AP) supporting high data rates. We consider two configurations for the data rates from the PHY proposal in [1]. One configuration provides a single spatial stream between the transmitting and receiving ends and provides rates between 13.5 Mbps and 135 Mbps. The second configuration has two spatial streams and provides rates between 27 Mbps and 270 Mbps. Typically, stations close to the AP transmit at high rates while stations further away from the AP transmit at lower rates. We consider that a large number of stations might be connected to the AP. In the WLAN, there is a direct link between the AP and any station, but two stations in the WLAN might be hidden from each other. The transmissions are either destined to the AP (uplink) or originated from the AP (downlink). We assume that stations are mainly static and thus remain in the same location for a long time, relative to MAC operation. Finally, we assume that stations are able to localize themselves with an error upperbound δ, for any reasonable value of δ as in current localization technologies.

2.2 DCF in Next-Generation WLANs

Scalability with Respect to the Number of Stations: The efficiency of contention resolution with DCF decreases as the number of stations becomes large, as shown in [4], [5]. This is a limitation for next-generation WLANs as the high bandwidth can support a large number of stations. Figure 1 shows simulation results for the collision rate of DCF (simulation parameters are the same as in Section 4). The number of stations increases up to 500 and the collisions are caused solely by DCF operation (there are no hidden nodes). The collision rate is 40% with 100 stations and 50% with 200 stations.

Scalability with Respect to High Data Rates: When the data rates increase with DCF, the data transmission time decreases. However, the overhead time does not decrease by the same factor as control packets are transmitted at a low rate so they are received correctly by all the stations. Consider a simple scenario where stations are saturated with packets. In the case where there are no collisions, the maximum throughput of DCF is achieved and is given by Equation (1). We assume that the number of backoff for each access is $\frac{CW_{min}}{2}$. The length of the data packets and the data rate are given by l_{data} and r_{data}, respectively.

$$\rho = \frac{l_{data}}{difs + \frac{CW_{min}}{2} + rts + cts + \frac{l_{data}}{r_{data}} + ack + 3sifs} \quad (1)$$

Based on Equation (1), Figure 2 shows the maximum throughput with various data rates (the control rate is 6 Mbps). We use data rates that are defined in [1]. The upperbound on the throughput of DCF is 36.8 Mbps for packet sizes of 1500 bytes even if the data rate increases infinitely.

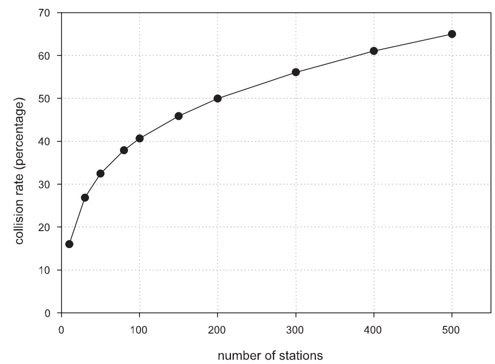

Figure 1. Simulation results for the collision rate of DCF with no hidden nodes.

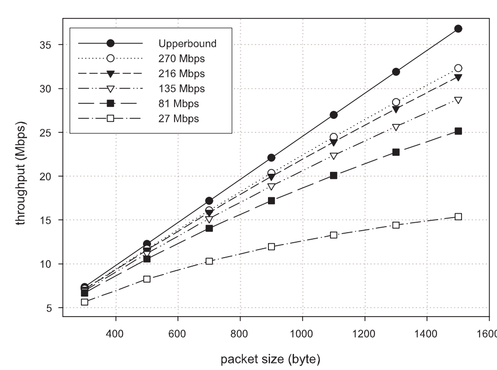

Figure 2. Upperbound on the throughput of DCF with control rate of 6 Mbps.

Fairness in a Multi-Rate Environment: With DCF, a station transmits one data packet upon access, hence

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DCF mandates a throughput-based fairness policy. In a multi-rate environment, the aggregate throughput degrades significantly if a throughput-based fairness policy is used since stations with low rates occupy the channel for long durations of time and stations with high rates spend most of the time waiting. This trend is shown in [9] and [10]. To leverage the performance through high data rates, a time-based fairness policy is more suitable, as argued in [10]. With GMAC, we use a time-based fairness policy. Upon access, each station is allocated a transmission time that is sufficient to transmit one data packet at the lowest data rate. If the station can transmit at a higher rate, it aggregates multiple MPDUs into a single PSDU and it receives an aggregate ACK packet.

2.3 Related Work

The proposal of EWC for the MAC layer specifications [2] presents several enhancements to the 802.11 standard and its amendments 802.11a/b/g. The enhancements include aggregating data packets (MSDUs or MPDUs) to reduce the MAC and PHY overhead. ACK packets are also aggregated and a station indicates if it is willing to receive delayed ACKs to reduce the overhead further. A *Long-NAV* mode is introduced in which a single RTS/CTS exchange protects the transmission of multiple data packets in a transmission opportunity (TXOP). However, the EWC proposal does not specify mechanisms to reduce the collision rate when the number of stations is large.

In [11], a medium access scheme is presented for next-generation WLANs that reduces the overhead by aggregating data packets (MSDUs and MPDUs) and by providing access through a polling scheme. This work does not specify a distributed mode of operation as it relies mainly on the AP to coordinate access.

In [7], an analysis on DCF is presented that derives the throughput upperbound and the delay lowerbound. This paper also presents a medium access scheme that enhances the throughput of DCF via the transmission of a burst of packets upon access.

An access scheme is introduced in [12] where the AP broadcasts a *reference data rate* and a *reference burst size*. Stations contend using CSMA/CA. When a station wins the contention, it transmits only if it is able to transmit at a rate higher than the reference data rate; otherwise, the station gains credit. Once the station has enough credit, it transmits upon winning contention at any data rate it is capable of.

In [13], an *Adaptive Coordination Function* is introduced where the AP schedules the access of several stations and transmits the schedule in a polling-like fashion. Another enhancement is introduced, called *Reverse Direction Scheduling*, allows a station to use its allocated time to transmit as well as receive data packets.

The schemes above focus mainly on reducing the overhead and do not consider the scalability of the access scheme as the number of stations becomes high (except [11] which is a polling scheme). Most of them keep the classic CSMA/CA algorithm unchanged. GMAC reduces the time spent in contention and the collision rate by allowing fewer stations to contend. In addition, GMAC reduces the control overhead by using a single RTS/CTS exchange to protect the transmission of multiple stations.

3 Group-Based Medium Access

In this section, we present the group-based medium access control scheme (GMAC) in details. First, we describe how stations can be divided into groups that are free of hidden nodes. Then, we describe the contention of group leaders and the polling-based transmission of non-leaders. Finally, we discuss how groups are maintained when stations fail or withdraw from the network.

3.1 Overview

The key ideas of GMAC are:

- Stations are divided into groups based on their locations in the WLAN so that groups are free of hidden nodes. Each group has a station designated as leader.
- Only group leaders contend for the medium using CSMA/CA. When a leader wins the contention, it reserves transmission time for its group and transmits a polling packet that contains the group's schedule.
- Stations in the same group transmit according to the polling packet transmitted by their leader. There is no need for RTS/CTS exchange as the leader has reserved time for the entire group.
- Every station is allocated a time period that is sufficient to transmit one data packet at the lowest rate (time-based fairness). If a station can transmit at a higher rate, it aggregates multiple MPDUs for which it receives a single aggregate ACK packet.

3.2 Formation of Groups

GMAC requires that stations are divided into groups that are free of hidden nodes. For this purpose, it is sufficient that a station joins a group if its distance to the group leader is smaller than $\frac{R}{2}$, where R is the communication range. A new station waits initially for a period $T_{initial}$ to obtain information about neighboring groups. The new station listens to the polling packets (shown in Figure 3) which contain information such as leader location, current group size and maximum group size. The station might join a group if its estimated distance to the leader is $d_{est} < \frac{R}{2} - 2\delta$, where δ is the upperbound on the localization error, and if the group is not full, i.e., *groupSize* $<$ *MaximumSize*. In addition, a station favors a

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group leader that is close to itself to enhance the reliability of polling. In the *association request* with the AP which is transmitted through CSMA/CA contention, the new station indicates which group leader it wants to join. In the *association response,* the AP assigns the new station a *rank*, which is used in the polling packet. The group leader takes note of the new joining station since stations are required to overhear all packets transmitted by the AP. If the station cannot find a group leader according to the criteria above, it becomes a group leader itself.

Implementation: Practically, localization technologies are becoming cheaper and more accurate, which makes it easier to estimate the distance between stations. Localization technologies based on Received Signal Strength (RSS) and GPS are typical. The papers [14], [15], [16] present localization schemes based on RSS that can be implemented with off-the-shelf 802.11 devices. The basic idea of those schemes is that stations measure the RSS from several reference stations and the values are stored in an RSS database, which is used to estimate the locations. The RSS database might be built off-line (before localization begins) or on-line. RSS-based schemes provide an accuracy of sub-10 meters and are suitable to be used with GMAC. Alternatively, GPS computes positions in three dimensions using four satellite signals and provides an accuracy of 1-3 meters. Variants of GPS, such as A-GPS (Assisted GPS) and E-GPS (Enhanced GPS), relieve the line-of-sight (LOS) requirement to allow operation indoors and improve in the computation time.

3.3 Contention of Group Leaders

Group leaders contend using the CSMA/CA algorithm as defined in DCF [3]. When a leader wins the contention, it reserves the medium for itself and for all the stations in its group through an RTS/CTS exchange. For each station, the leader reserves a time duration that is sufficient to transmit one data packet at the lowest rate and receive the corresponding ACK. If a station is capable of transmitting at a high rate, it aggregates multiple MPDUs (to the same destination) for which it receives a single aggregate ACK packet. If some stations don't have data to transmit, then the time reserved by the leader should be ended sooner. For this purpose, the group leader monitors the transmission of its group and transmits an *End-NAV* packet (a small packet similar to CTS) in case some stations skip transmission, as shown in Figure 4. In the figure, stations 2, 3, 4, 5, 6 and 7 are polled but stations 3, 5 and 6 don't have data packets to transmit. The reserved time is ended earlier by the *End-NAV* packet.

3.4 Polling of Non-Leaders

Upon winning the contention, a group leader polls all the stations in its group in a polling packet that is aggregated to its data packet. The format of the polling packet, shown in Figure 3, is based on the control frames defined in the 802.11 standard. Stations transmit according to the order in the polling packet and a duration of SIFS is left idle between the transmission of consecutive stations. There is no need for RTS/CTS exchanges as the leader has reserved time for the entire group. If a station doesn't have packets to transmit, it remains idle. After the elapse of an additional SIFS time from the previous ACK, the subsequent station transmits, as illustrated in Figure 4. If the leader station doesn't have packets to transmit, it contends and transmits the polling packet.

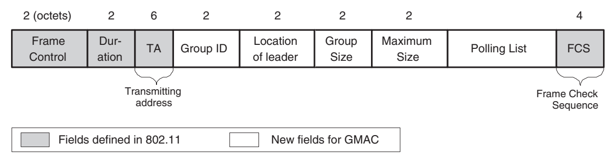


Figure 3. Format of the polling packet based on IEEE 802.11 control frame format.

3.5 Group Maintenance

Group maintenance is required when stations withdraw from the network or fail without disassociating.

Station Withdraws: When a leader station withdraws from the network transparently, i.e., by issuing a *disassociation request*, the group is disbanded and the stations affiliate with a new group according to the initial procedure. It is not correct to relegate the role of group leader to another station in the group as the group may no longer be free of hidden nodes. If the withdrawing station is non-leader, the group leader updates the polling list.

Leader Fails: If a leader station fails without requesting a disassociation, the stations in its group cannot transmit. We use a simple modification to DCF that allows non-leader stations to detect the failure of their leader quickly. Using the idea presented in [17], a station contending with DCF appends the value of the backoff counter that it will use in the next contention so that neighboring stations know the backoff counters of each other and avoid collisions. We use this idea so that non-leader stations can detect the failure of their leader. Based on the backoff counter of the leader, if the leader is supposed to transmit but it doesn't, then the leader has failed. If a collision is heard, the leader is not assumed to have failed and the stations wait for a guard time (T_{guard}) before considering that the leader has failed. When the leader fails, the group is disbanded and the stations affiliate with a new group.

Non-leader Fails: When a non-leader station fails, other stations are able to transmit. However, a time duration of SIFS is wasted by waiting for the failed station to transmit. The failure of a non-leader station is detected

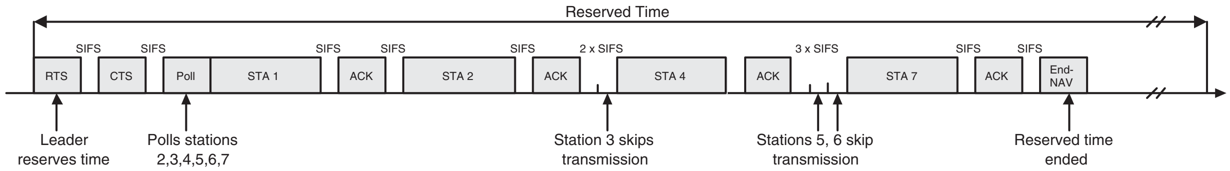


Figure 4. The group leader (station 1) reserves transmission time for its group and polls stations 2, 3, 4, 5, 6, 7. Stations 3, 5, 6 don't have packets. The reserved time is ended with an *End-NAV* packet by the leader.

using a counter, *Counter-Skip-Max*, that is stored at the leader and initiated to a preset value. When a station skips transmission, the counter is decremented by one and when a station transmits, the timer is reset to the initial value. A station with no data should transmit an empty packet periodically to avoid being removed from the polling list of its group.

4 Simulation Results

In this section, we present the simulation results that evaluate the performance of GMAC with high data rates and a large number of stations. The simulations were conducted with a custom simulation program that simulates the MAC operations of GMAC and DCF.

4.1 Configuration

We use the PHY characteristics, summarized in Table 1, that are presented in the PHY proposal [1] of EWC and the underlying standard 802.11g [18]. We consider two configurations for the high rates from [1]. One configuration with two antennas at each station allows a single stream to be transmitted and provides rates between 13.5 Mbps and 135 Mbps, called *single-stream rates.* The other configuration with four antennas at each station allows two streams to be transmitted and provides rates between 27 Mbps and 270 Mbps, called *double-stream rates.* The rates are listed in Table 2. The data rate of a station depends on its location in the WLAN, as shown in Figure 5. The WLAN area is divided into eight areas, $A1$ through $A8$, by eight concentric circles with radii incrementing by $\frac{R}{8}$, where R is the communication range of the AP. In the simulations, the control packets are transmitted at 6 Mbps and the data packet size is 1024 bytes. In this study, stations are placed randomly in the WLAN area, according to a uniform distribution, and we do not limit the group size.

4.2 Scalability with the Data Rates

We measure the throughput of GMAC and DCF as the data rates increase. In this evaluation, we use a small network size of 20 stations. We use the method below to increase the average data rate in the WLAN.

TABLE 1. PHY Characteristics

Characteristics	Value	Comments
tSlotTime	9 μs	Slot time
tSIFSTime	10 μs	SIFS time
tDIFSTime	28 μs	DIFS = SIFS + 2 $\times$ Slot
aCWmin	15	min contention window size
aCWmax	1023	max contention window size
tPLCPOverhead	41.6 μs	PLCP overhead

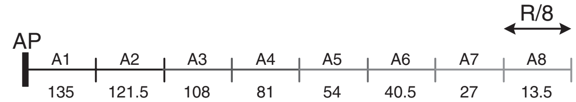
TABLE 2. Data Rates

Config.	Rates (Mbps)
Single-stream	13.5, 27, 40.5, 54, 81, 108, 121.5, 135
Double-stream	27, 54, 81, 108, 162, 216, 243, 270

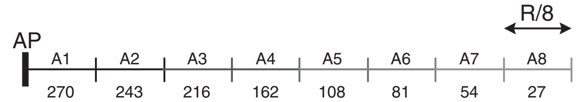
Method to Increase the Average Data Rate: We increase the average data rate in the WLAN in eight steps. First, all the stations, independently of their locations, transmit at the rate of $A8$, which is the lowest rate. We measure the throughput for this case. Then, we introduce the rate of $A7$, that is, stations in areas $A1$ through $A7$ transmit at the rate of $A7$ and stations in $A8$ transmit at the rate of $A8$. In this way, we increase the average data rate gradually in eight steps as we measure the throughput in each step.

Figures 6 and 7 show the throughput results for GMAC and DCF as the average data rate increases in eight steps as described above. Figure 6 shows the results for the single-stream rates and Figure 7 shows the results for the double-stream rates. In those figures, the number of stations is 20. The eight scenarios in the figures correspond to the same positions of the stations.

In Figure 6, the average data rate varies from 13.5 Mbps to 62.7 Mbps. The throughput of GMAC varies from



(a) *Single-stream* rates (Mbps)



(b) *Double-stream* rates (Mbps)

Figure 5. Distribution of data rates in the WLAN.

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8.9 Mbps to 47.3 Mbps and the throughput of DCF varies from 4.5 Mbps to 6.1 Mbps. In Figure 7, the average data rate varies from 27 Mbps to 125 Mbps. The throughput of GMAC varies from 19 Mbps to 94 Mbps and the throughput of DCF varies from 5.4 Mbps to 6.5 Mbps. The results indicate that GMAC scales well with respect to high data rates due to reducing the overhead (backoff slots, interframe spaces and control packets). With 20 stations, the performance bottleneck is caused by the overhead and not by the collision rate.

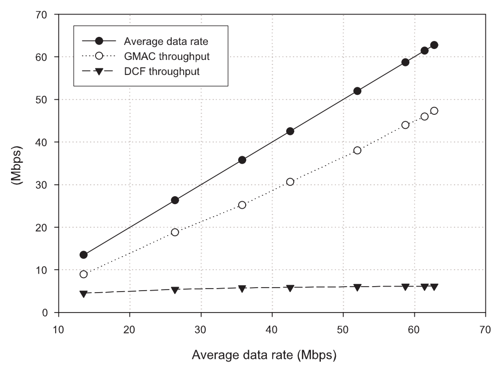

Figure 6. Throughput with single-stream rates and 20 stations.

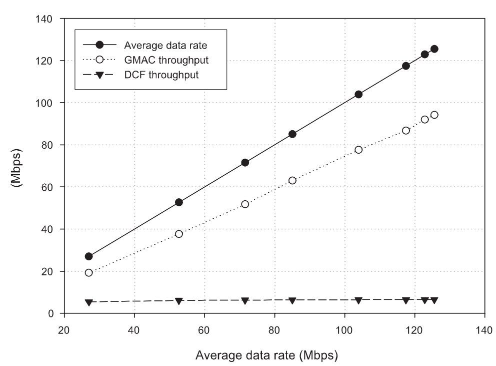

Figure 7. Throughput with double-stream rates and 20 stations.

4.3 Scalability with the Number of Stations

In this part, we evaluate the throughput of GMAC and DCF as the number of stations increases. We consider scenarios with up to 1000 stations. In this evaluation, the data rates are assigned according to the distribution in Figure 5. The throughput results are shown in Figure 8 for single-stream rates, and in Figure 9, for double-stream rates. For each simulation run, a new set of stations is randomly placed in the WLAN.

With the single-stream rates, the average data rate ranges from 56 Mbps to 49 Mbps. GMAC maintains a throughput close to 40 Mbps and the throughput of DCF drops from 6.2 Mbps to 4.1 Mbps. With double-stream rates, the average data rate ranges from 113 Mbps to 98 Mbps. The throughput of GMAC varies from 81 Mbps to 74 Mbps and the throughput of DCF varies from 6.5 Mbps to 4.3 Mbps. The throughput of GMAC remains almost unaffected as the network size increases since only few stations contend for the medium, hence scaling the contention resolution. Meanwhile, the collision rate of DCF increases significantly as the number of stations increases.

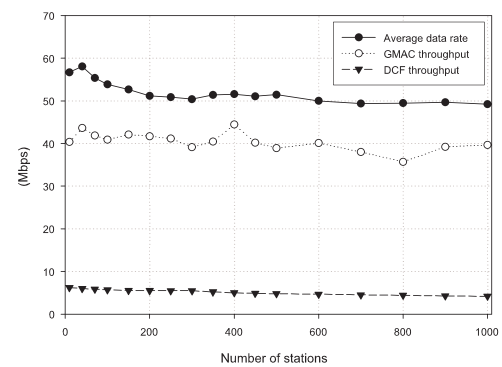

Figure 8. Throughput as the number of stations increases. Scenario with single-stream rates.

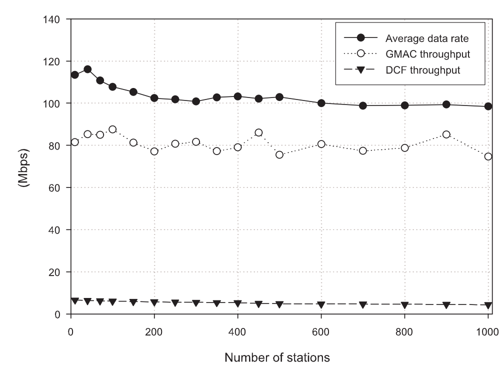

Figure 9. Throughput as the number of stations increases. Scenario with double-stream rates.

4.4 Dependency on the Average Data Rate

With GMAC, the throughput depends mostly on the average data rate in the network. For various positions of the stations in the WLAN, the average data rate changes. We measure the throughput of GMAC with 20 stations for several random topologies using the single-stream rates. Figure 10 shows the average data rate and the throughput for each topology. The average rate varies between 37 Mbps and 62 Mbps and the throughput varies between 25 Mbps and 48 Mbps while following closely the average data rate.

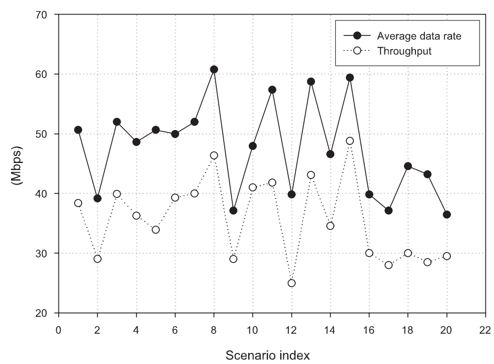

Figure 10. Throughput and average data rate. Scenario with 20 stations and single-stream rates.

5 Conclusion

In this paper, we showed the limitations of the medium access with DCF in the next-generation WLANs environment with high data rates and a large number of stations. We introduced a grouped-based medium access control (GMAC) protocol that enhances the performance by reducing the contention and control overhead. GMAC reduces the collision rate and the time spent on backoff slots by allowing group leaders to contend on behalf of other stations. GMAC reduces also the use of control packets as non-leader stations transmit without requiring RTS/CTS exchanges. In the simulation results, we considered scenarios with increasing data rates and scenarios with an increasing number of stations and showed that GMAC maintains a high throughput. Finally, the simulation results showed that the throughput of GMAC depends closely on the average data rate in the WLAN.

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