Group-Based Medium Access Control for IEEE 802.11n Wireless LANs

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Abstract—The latest generation of Wireless Local Area Networks (WLANs) is based on IEEE 802.11n-2009 Standard. The standard provides very high data rates at the physical layer and aims to achieve a throughput at the Medium Access Control (MAC) layer that is higher than 100 Mbps. To do that, the standard introduces several mechanisms to improve the MAC efficiency. The most notable ones are the use of frame aggregation and Block-ACK frames. The standard, however, does not introduce a mechanism to reduce the probability of collision. This issue is significant because, with a high data rate, an AP would be able to serve a large number of stations, which would result in a high collision rate. In this paper, we propose a Group-based MAC (GMAC) scheme that reduces the probability of collision and also uses frame aggregation to improve the efficiency. The contending stations are divided into groups. Each group has one station that is the group leader. Only the leader stations contend, hence, reducing the probability of a collision. We evaluate the performance of our scheme with analytic and simulation results. The results show that GMAC achieves a high throughput, high fairness, low delay and maintains a high performance with high data rates.

Index Terms—Computer networks, wireless LAN, medium access control, IEEE 802.11n standard

1 Introduction

The latest generation of Wireless Local Area Networks (WLANs) is based on the IEEE 802.11n-2009 Standard [1], [2], [3]. The 802.11n standard provides very high data rates at the physical (PHY) layer by using the latest advances in wireless communication. The high data rates are achieved with the Multi-Input Multi-Output (MIMO) PHY layer. MIMO systems use multiple antennae at the transmitting and receiving stations to increase the range and the link capacity. The goal of the 802.11n standard is to leverage the high data rates at the PHY layer to obtain a throughput at the Medium Access Control (MAC) layer that is higher than 100 Mbps. To do that, the Medium Access Control scheme should be efficient with high data rates.

Prior to 802.11n, the highest data rate at the PHY layer was 11 Mbps in the 802.11b standard and 54 Mbps in the 802.11a and 802.11g standards. The new 802.11n standard provides data rates at the PHY layer that are higher than 100 Mbps. There are even configurations to provide a rate of 600 Mbps. The MAC schemes that were designed for the low data rates are not efficient anymore with the high data rates. Previous MAC schemes include the standard's Distributed Coordination Function (DCF) which is the practically used scheme in the devices. There are also several other approaches in the literature that work with low data rates, such as our scheme in [4]. The previous MAC schemes are not efficient with high data rates as the research has shown [3], [5]. When the data rates are increased, the time to transmit the data decreases. However, the time to transmit the control frames (RTS, CTS, ACK) and the time used in the interframe spaces and contention does not necessarily decrease. The control frames are typically transmitted at a low data rate in order to be received reliably by all the stations. Accordingly, most of the time would be spent in transmitting control frames. As a result, the proportion of time used to transmit data is reduced, so the efficiency becomes lower.

The 802.11n standard introduces several mechanisms to improve the efficiency of the MAC scheme. The most notable ones are the use of frame aggregation and Block-ACK frames. When a station gets access to the channel, it has the right to transmit more than one data frame. The recipient station waits for all the data to be transmitted and replies with one Block-ACK frame. These mechanisms improve the efficiency since the overhead per data frame is reduced. There are also other mechanisms introduced in the standard which we describe in the next section. The 802.11n standard, however, does not introduce a mechanism to reduce the probability of collision. The probability of collision is related directly to the number of stations in the network. Previous research has shown that the standard's MAC scheme has a high probability of collision when the number of stations is large [4], [6]. This issue is significant because when the Access Point (AP) has a high data rate, it is able to serve a large number of stations, so the MAC scheme of 802.11n should be able to accommodate a large number of stations.

In this paper, we introduce a MAC scheme that reduces the probability of collision and also uses frame aggregation to improve the efficiency. The scheme we propose is called Group-based MAC (GMAC). Our scheme divides the contending stations into groups. Out of each group, only one station will contend. This station is called the leader of the group. Since fewer stations are contending, the probability of collision is reduced. When the leader of a group

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gains access to the channel, it reserves time for all the stations in its group via an RTS/CTS exchange with the AP. The leader also transmits the schedule of the group. Hence, the other stations in the group do not need to contend and do not need to transmit RTS/CTS. This reduction in control frames increases the throughput of the MAC scheme.

The stations in a group rely on the RTS frame transmitted by the leader. They also rely on hearing each other's transmissions. Hence, the condition is that a group should be free of hidden nodes. All the stations in the group should be able to hear each other's transmissions. Accordingly, the stations in a group should be in close proximity.

Our scheme provides performance gain over the standard's DCF since it has a lower probability of collision. Our scheme also uses aggregation of data frames and the Block-ACK mechanism.

We evaluate the performance of our scheme with analytic and simulation results. We compare our scheme to the 802.11n standard's DCF and to other schemes from the literature. The simulation results show that our scheme provides a significant increase in throughput. Our scheme also has one of the lowest collision rates. The results also show that our scheme has good delay characteristics and provides a high fairness to the users.

The rest of this paper is organized as follows: Section 2 presents the related work and Section 3 presents the system model. The proposed scheme is presented in Section 4 and the analysis is presented in Section 5. Finally, the simulation results are presented in Section 6 and the conclusion of the paper is in Section 7.

2 Related Work

In this section, we present an overview of the 802.11n standard and of other schemes in the literature.

2.1 The IEEE 802.11n Standard

The IEEE 802.11n Standard [1] presents several improvements to deal with the high data rates. First, a new Interframe Space (IFS), called Reduced Interframe Space (RIFS), is defined to reduce the amount of time between frames. RIFS may be used instead of Short Interframe Space (SIFS) to separate multiple transmissions of a single station. These frames must be destined to the same recipient. Also, the station using RIFS must support the high data rates (i.e., it is not a legacy station). In 2.4 GHz band, RIFS is $2\ \mu s$, whereas SIFS is $10\ \mu s$.

The standard also supports Aggregate MSDUs (A-MSDU) in order to increase the efficiency. The MSDUs in an A-MSDU should be transmitted to the same receiver. The aggregated MSDUs should also have the same priority parameters. The lifetime timer of the A-MSDU expires when the timers of all MSDUs in it expire. The standard also supports the transmission of Aggregate MPDUs (A-MPDU). When the transmitter of the A-MPDU is the AP, the MPDUs can be addressed to multiple recipients.

Another mechanism in 802.11n is called Dual CTS Protection. It is used when the stations use the technique of Space Time Block Coding (STBC). STBC increases the range of the BS, however, this type of transmission is not understood by legacy devices. Thus, when STBC is used, a station would transmit an RTS frame to the AP, the AP would reply with a CTS frame in STBC, followed by another CTS frame in non-STBC.

The standard introduces a Block ACK mechanism that aggregates ACK frames that are destined to a recipient. The ACK frames in a Block ACK should be in response to frames that have the same priority parameters. There are two variants of Block ACK. The Immediate Block ACK technique specifies that the sender transmits a number of data frames. They are followed by a Block ACK Request frame. The receiver then immediately transmits the Block ACK frame after an SIFS duration. The Delayed Block ACK mechanism specifies that the sender, after transmitting a number of data frames, transmits a Block ACK Request frame. The receiver replies with an ACK frame to acknowledge receiving the Block ACK Request. The Block ACK may be transmitted in subsequent TXOPs. In the meanwhile, the sender can transmit more data frames to the same recipient.

Another mechanism in the standard is called the Reverse Direction Protocol. This mechanism allows the transmission of data in both ways during a TXOP (originally, only the owner of the TXOP used to transmit data). To initiate this mechanism, the TXOP holder includes in a PPDU a Reverse Direction Grant. This allows the receiver station to transmit data frames in the TXOP.

The standard also introduces a 20/40 MHz BSS operation mode. In this mode, the AP and the associated stations of the BSS transmit either in a 20 MHz channel (the primary channel) or in a 40 MHz channel (the primary and secondary channels). The 20/40 MHz mode also defines measures to avoid interference with other BSSs. For example, if an AP is operating in the 20/40 MHz mode and detects an overlapping BSS whose primary channel is the AP's secondary channel, this AP will switch to 20 MHz mode. The AP might later switch to another pair of channels. The switching between the 20 MHz mode and 20/40 MHz mode and the switching to another pair of channels should happen after notifying all the associated stations, including the ones using the power-save mode that could be temporarily sleeping.

2.2 Schemes in the Literature

The scheme Token-Coordinated Random Access MAC (TMAC) was presented in [7] in which the stations are divided into groups. When a station joins the WLAN, the AP assigns the station to a group such that the groups are of equal sizes. The AP passes a token among the groups in a round-robin way. When a group has the token, its stations transmit by contention. The maximum number of stations in a group is 15 to limit the contention. Also, a station contends at most once during a token period, which is at most $35\ \mathrm{ms}$. A station that collides doubles its contention windows for its next contention, with only two contention stages used (so the stations doubles its contention window at most twice). When a station gets access to the channel, if its rate, r_i is higher than a reference rate, R_f, (chosen to be a high rate among the supported rates), the station transmits for a duration of $r_i/R_f * 2\ \mathrm{ms}$. Otherwise, the stations transmits for at most a duration of 2 ms. TMAC uses the Block ACK mechanism and the maximum number of ACK frames in the Block ACK is two. Finally, if all the stations in the group finish their transmission before the $35\ \mathrm{ms}$ limit, the token is passed to the next group.

The scheme Enhanced Grouping-based Distributed Coordination Function (E-GDCF) was proposed in [8], which is an enhancement of the earlier Grouping-Based DCF (GB-DCF) by the same authors [9]. In E-GDCF, when the number of active stations is larger than eight, a grouping mechanism is used. The groups are formed based on the parameters N and k that are transmitted by the AP. N designates the number of groups. The stations are divided based on their MAC addresses by looking at $log_2 N$ bits of their MAC address. If $k = 0$, then the groups are divided based on their least significant $log_2 N$ bits. If $k = 1$, then we use the $log_2 N$ bits starting from the second bit on the right side. For example, if $N = 4$ and $k = 0$, stations with MAC address ending with 00 belong to group 0. But if $N = 4$ and $k = 1$, stations with MAC address ending with 110 are in group 11. The target of E-GDCF is to have two stations in each group. Thus, the AP will use $N = \lfloor M/2 \rfloor \geq 1$ and will consider all the values of k. The AP selects the value of k that minimizes the standard deviation in the group sizes; this encourages the groups to have equivalent sizes, as much as possible. A group cycle in E-GDCF starts with a DIFS. Then, one station from every group transmits. The stations in a group transmit by contention, using $CW_{min} = CW_{max}$ equal to 8 as the preferred value. Each station transmits one data frame only upon access. After all the groups have finished transmission (one station transmitted from every group), the AP sends a Block ACK that contains an ACK frame for every station that has transmitted in this cycle.

In [10], we presented an early version of our scheme, GMAC, in a conference paper. In [11], the MAC scheme gives the priority of transmission to stations with high data rates. In [12], the MAC scheme delays the transmission of the data to allow more data frames to arrive from higher layers so that frame aggregation can be used. In [13], a polling scheme was proposed. In [14] and [15], the reverse direction protocol of 802.11n is evaluated. In [16], [17], and [18], frame aggregation mechanisms are evaluated. In [19], a Block ACK scheme is presented and analyzed. In [20] and [21], performance evaluation of 802.11n is presented. In [22], multiple stations are allowed to transmit simultaneously by using features from the MIMO PHY layer. In [23], a station is able to use a subset of the channels upon access. This allows multiple stations to transmit simultaneously. In [24] and [25], the 20/40 MHz mode of the 802.11n is used.

From the related work, we selected TMAC and E-GDCF to compare to our scheme since they use similar grouping mechanisms.

3 System Model

This section presents the network configuration that we consider for the WLAN system.

3.1 Network

We consider a WLAN in which the AP connects to wireless devices which are the end users. The number of connected stations is potentially large due to the large bandwidth that is available at the AP. The transmissions are either form the station to the AP or from the AP to the station.

3.2 Distance Estimation

In our scheme, any group of stations should be free of hidden nodes because the stations should hear the leader's RTS frame. The stations in a group should also be able to detect each other's transmissions.

To have the groups remain free of hidden nodes, a station estimates its distance to the leader of a group before joining its group. If the distance R is considered to be a reliable distance for two stations to hear each other's transmissions, then a station will join a group if its distance to the leader is $R/2$ or less. This way, the distance between any two stations in a group is less than R. Our scheme tolerates the presence of error in the distance estimation procedure. If the largest error in the distance estimation is δ, then the distance between a leader and a stations should be at most $R/2 - \delta$.

The value of R should be determined based on measurements of the signal strength in the devices. The value of R is selected conservatively. If, for example, two stations at a distance $R = 100$ ft have a signal strength in the interval [80 and 120 percent], where 100 percent is the signal strength required to decode a transmission, then we cannot use $R = 100$ ft because the signal might fall to 80 percent. So, we use a smaller R, say $R = 80$ ft. If, for example, $R = 80$ ft gives a signal strength in the interval [120, 160 percent], then, we can use this value of R since it provides a signal strength that is at least 120 percent of the required strength to decode a transmission. The specific environment, such as indoor or outdoor, influences the choice of R. However, our scheme can accommodate these factors since, once an appropriate value of R is found, it can be broadcast by the AP and be used by all the stations.

There are several schemes in the literature that provide distance estimation and localization. Some of the existing schemes are [26], [27], [28], which provide localization and positioning based on the Receive Signal Strength (RSS) capability that is available in the devices.

3.3 Use of Time-Based Fairness

In the WLAN, if every station transmits the same number of frames upon access, this is called throughput-based fairness. With this policy, if the stations obtained access to the channel for the same number of times, they will achieve the same throughput. An alternative policy is called time-based fairness in which every station transmits for the same duration of time when it accesses the channel. With time-based fairness, if a station is able to transmit at a high data rate, it will achieve a high throughput; however, if a station only manages to transmit at a low data rate, it will have a lower throughput. Previous research [29], [30], [31] has shown that in WLANs where there is a great variation among the stations' data rates, the time-based fairness policy provides a significantly greater overall throughput. In such an environment with great data rate variation, if a throughput-based fairness policy is used (all the stations transmit the same number of frames), the stations with the low rates would take most of the transmission time and the stations with the high rates would wait most of the time for the slow stations to finish.

In our scheme, we use the time-based fairness policy since the data rates in the next-generation WLANs are high and there will be a great variation in the data rates that are achieved by the stations. We present a simple analysis that

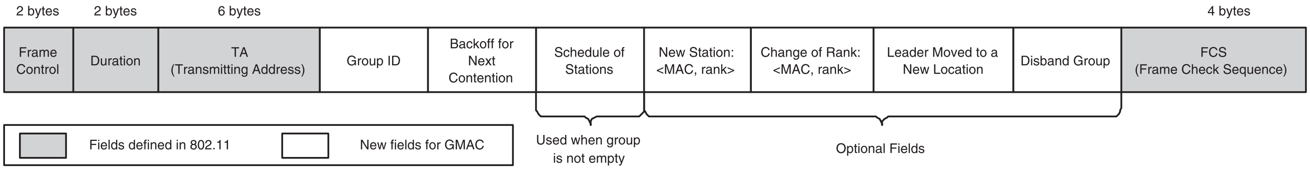


Fig. 1. Polling frame of GMAC.

quantifies the difference between the time-based fairness policy and the throughput-based fairness policy. We consider a WLAN with two stations, one that is transmitting at a high rate, r_{big}, and one that is transmitting at a low rate, r_{small}. With the throughput-based fairness policy, the overall throughput would be $\rho_{through} = \frac{2 \times r_{big} \times r_{small}}{(r_{big} + r_{small})}$. With the time-based fairness policy, the overall throughput would be $\rho_{time} = \frac{r_{big} + r_{small}}{2}$.

Numerically, if $[r_{big}, r_{small}]$ are equal to [11, 11], there is no difference between time-based and throughput-based policy; the same throughput is achieved by both. However, if the rates are [11, 54], the throughout-based policy achieves a throughput of 18.27 Mbps versus 32.5 Mbps for the time-based policy, which is 1.77 times more. If the rates are [11, 130], the throughput-based policy achieves a throughput of 20.28 Mbps versus 70.5 Mbps for the time-based policy, which is 3.47 times more. Finally, if the rates are [11, 216.7], the throughput-based policy achieves a throughput of 20.93 Mbps versus 113.85 Mbps for the time-based policy, which is 5.43 times more. In conclusion, the time-based fairness provides a larger overall throughput and the difference becomes significant when the variation in the rates increases.

4 Proposed Scheme

In this section, we present the Group-based MAC scheme in details.

4.1 The Polling Frame

When a leader gets access to the channel, it transmits the polling frame. The leader transmits the polling frame even if it does not have a data frame since the polling frame distributes the schedule of the stations in the group. The leader also transmits the polling frame even if its group is empty because the polling frame advertises that there is a leader present in this area; new stations joining nearby should join the existing leader. The format of the polling frame is in Fig. 1. It contains the Group ID, the backoff slots that the leader uses in its next contention and the group schedule when the group is not empty. Other optional fields are used when a new station joins the group, the group changes the rank of the stations, the leader moves to a new location or the leader disbands the group. The scenarios for these events are presented in this section.

4.2 Formation of Groups

The stations are divided into groups that are free of hidden nodes. To achieve this, a new station joins a group if its distance to the leader is smaller or equal to $R/2$, where R is a reliable communication distance. In this way, the maximum distance between any two stations in a group is R. When there are several leaders within $R/2$ of the new station, the group with the closest leader is selected. The new station listens initially for a period of T_{listen} and estimates its distance to the group leaders that it can hear. Our scheme tolerates the presence of error in the distance estimation procedure. If the largest error is δ, then a station joins a group when its distance to the leader is smaller than $R/2 - \delta$. This will exclude some eligible stations from joining the group, but it ensures that the group does not have hidden nodes.

In the Association Request frame that the new station sends to the AP, the new station indicates which leader it would like to join. This information is repeated in the Association Response frame as a confirmation that the AP received the requested group. The group leader decodes the association frames and takes note of the new station joining its group. The group leader assigns a rank for the station. The rank will be used for the transmission, as explained later. Next time the group leader transmits a polling frame, it uses the "New Station" field and indicates the MAC address and the rank of the new station. This tells the new station that it is now part of the group.

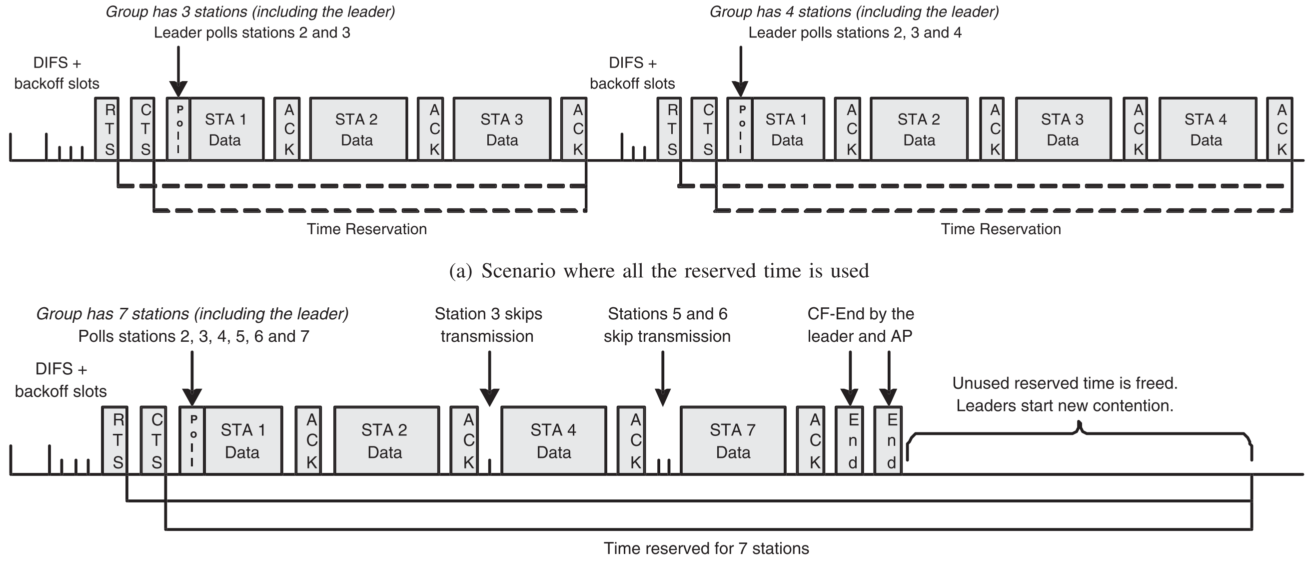
If the new station cannot find a group leader within a distance of $R/2$ from it, it will use group ID -1 in the Association Request frame to say that there is no existing group that it can join. The AP assigns a group ID and includes it in the Association Response frame. This means that the new station starts a new group and becomes its leader. From now on, this station will transmit a polling frame when it accesses the channel. The procedure for a new station to join a group is shown in Fig. 3a.

4.3 Contention of the Group Leaders

The group leaders contend using a modified version of the standard's DCF scheme. The modification we use is that the contending stations, which are the leaders, include in the polling frame the value of the Back-Off (BO) timer that they will use in the next contention. This mechanism was proposed in [32] and [33] to allow the contending stations to know each other's BO timers. In GMAC, the BO timer of the leader is transmitted in the field "Backoff for Next Contention" in the polling frame. This field is used by the stations in the leader's group to detect if the leader has left the network without a formal Disassociation Request. This mechanism is presented later in this section in the maintenance discussion.

When a leader gets access to the channel by winning the contention, it reserves time for itself and for all the stations in its group via an RTS/CTS exchange with the AP. All the stations in the WLAN (such as other groups) hear the CTS and refrain from transmission. The reserved time is dedicated for the current group.

There are two scenarios that could happen, as shown in Fig. 2. In Fig. 2a, all the stations have data to transmit, therefore, all the time that was reserved was used. In Fig. 2a, in the first transmission, the leader reserves time for the



(a) Scenario where all the reserved time is used

(b) Scenario where some stations don't have data frames to transmit

Fig. 2. Transmission of GMAC.

three stations in the group. When the last station receives the ACK frame, the reserved time finishes. However, in Fig. 2b, some stations do not have data to transmit. The leader has reserved time for the seven stations in its group. Since stations 3, 5, and 6 do not have data, not all the reserved time is used. The leader is able to detect this event since it can hear all of the stations in its group. The leader then transmits a CF-End (Contention-Free END) frame that is defined in the standard. The AP repeats the CF-END frame after an SIFS duration so that all the stations in the WLAN hear it. The medium is then open for a new contention by the leaders.

The time reserved for each station is sufficient to transmit the largest data frame (2,346 bytes) at the lowest rate supported by the PHY layer. The reserved time also accommodates the SIFS durations and the transmission of the ACK frame. If a station is able to transmit at a rate that's higher than the minimum rate, it has the right to transmit an Aggregate-MSDU (A-MSDU) frame for which it receives a Block ACK frame.

Upon winning the contention, if the leader does not have data to transmit, it transmits the polling frame. If the group consists only of the leader, the polling frame will contain the Group ID and no schedule is included. The transmission of the Group ID serves to let new stations in the vicinity see the presence of the leader.

4.4 Transmission of Stations in a Group

When a leader wins the contention, it initiates an RTS/CTS exchange with the AP to reserve time for all the stations in the group. Then, the leader transmits a polling frame. If the leader has data to transmit, the polling frame is aggregated in an A-MPDU to the data frame. The polling frame contains the schedule of transmission for the stations in the group. The schedule contains the ranks of all the stations in the group in ascending order. All the stations are included since they have the same priority.

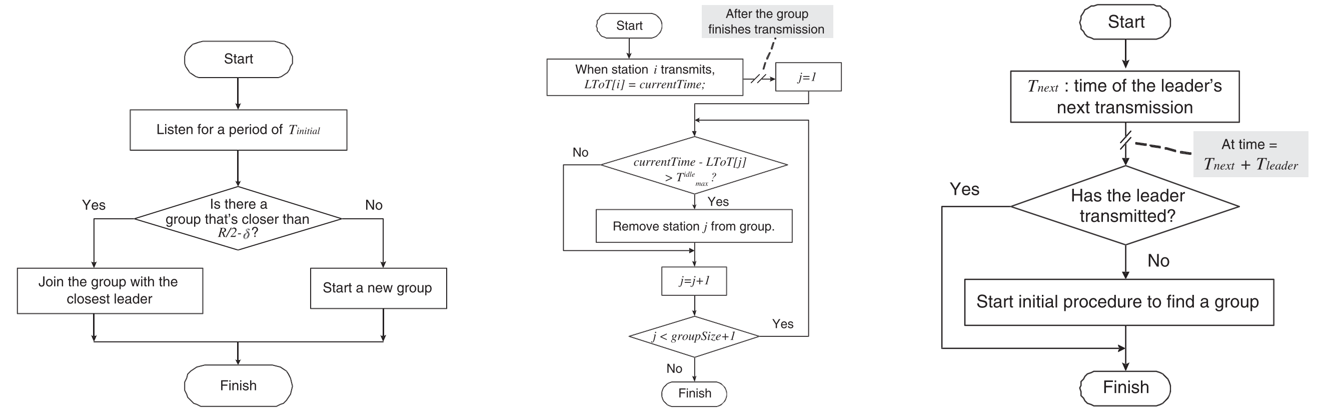
The stations in the group transmit one after the other by leaving SIFS durations between consecutive transmissions, as shown in Fig. 2a. An SIFS duration is also left between the data frame and the ACK frame (or between the A-MSDU and the Block ACK frame). The stations in a group do not need to transmit an RTS/CTS exchange with the AP since the group is free of hidden nodes. The purpose of the RTS/CTS exchange is to inform all the stations in the WLAN of the upcoming transmission. However, the stations in other groups are refraining from transmission based on the RTS/CTS exchange that the leader has initiated. Since the stations in the group can hear each other, no RTS/CTS exchange is required.

Sometimes, a station in the group does not have data to transmit. This is detected by the other stations in its group since all the stations can hear each other. The procedure is demonstrated in Fig. 2b. After the ACK frame is received by station 2, we expect station 3 to start transmitting its data after an SIFS duration. However, the channel remains silent. All the stations in the group detect that station 3 does not have data. After another SIFS, station 4 starts transmitting its data. Later in Fig. 2b, stations 5 and 6 do not have data and thus an SIFS duration is left idle for every one of these stations.

In this procedure, an SIFS duration is left idle for every stations that does not have data, however, the duration of SIFS is very small. Also, our scheme eliminates the contention of the stations in the group, therefore, several slots are saved from being wasted. We also note that when several SIFS slots are left idle, the stations from other groups will not detect this event as an idle DIFS since they have set their NAVs, so they will not start contention.

4.5 Group Maintenance

There are several events that require the maintenance of groups in our scheme. A station, whether a leader or not, might leave the network. The station might leave the network by observing the protocol, i.e., issuing a Disassociation Request. In another event, the station might run out of battery or the system on it might crash; thus the station



(a) Procedure for a station to find a group

(b) Procedure done by a leader when it gets access to the channel

(c) Procedure done by a station when it receives a poll frame

Fig. 3. Procedures to maintain the groups in GMAC.

might leave without disassociating from the network. In addition, a station, whether a leader or not, might move within the WLAN area. Hence, the groups need to be maintained so that they stay free of hidden nodes. This part considers these scenarios and presents the corresponding procedures in these cases.

4.5.1 A Station Issues a Disassociation Request

In this event, the station issues a Disassociation Request frame and leaves the network. This is the normal way of leaving the network. If this station is a nonleader, then the leader of its group will know that this station has left because the leader decodes the association and disassociation frames. In this case, there might be a gap in the ranks of the stations. If the ranks of the group are 1, 2, 3, 4, and 5, and station 3 leaves the network, then the ranks will be 1, 2, 4, and 5. To avoid having an SIFS duration wasted in every transmission of the group, the leader will take the station with the highest rank (station 5) and change its rank to that of the station that has left (station 3). This is done with the "Change of Rank" field of the polling frame; the MAC address of station 5 and its new rank (equal to 3) are indicated. If the station with the highest rank (station 5) has left, then no action is needed.

If the station leaving the network is a leader, then its group is disbanded by using the "Disband Group" field of the polling frame. The stations of this group will join existing groups or form new groups according to the initial procedure in Fig. 3a.

4.5.2 A Station Leaves without Issuing a Disassociation Request

A station might leave the network without issuing a Disassociation Request. This might happen if the operating system on the station crashes or if its battery runs out. For a nonleader station, this event is detected as the following. When the station is idle for a duration that is greater than the parameter, T_{idle}^{max}, the leader assumes that the station has left the network without a Disassociation Request. The group leader keeps a table that has the Last Time of Transmission (LToT) for every station in its group. When the station with rank i in group j transmits data at time t, then the leader of group j records in the table $LToT_i^j = t$. Every while, the leader subtracts the $LToT$ of the stations from the current time $(currentTime - LToT_i^j)$ for all the entries in the table. If the obtained result is greater than T_{idle}^{max}, it means the corresponding station has been idle for a long time and it is removed from the group. This procedure is shown in Fig. 3b. If a station is idle for a while and does not wish to be removed from the group, then it can transmit an empty frame to itself periodically every T_{idle}^{max} to avoid being removed.

If a leader leaves the network without issuing a Disassociation Request, the stations in its group cannot transmit. This event is detected by having the stations observe the backoff timer that the leader will use in the next contention. This value is transmitted in the field "Backoff for Next Contention" in the polling frame. Using this field, the stations of the group can predict when the leader will transmit. If they do not hear the leader, then they will wait for a period of T_{leader} before assuming that the leader has left the network. This wait period will be also useful if the leader has collided and has not, in fact, left the network. This procedure is shown in Fig. 3c. The value of T_{leader} should not be very large since it affects the user experience. During a wait of this period, the user might not receive service. It could be set to 1 or 2 seconds; such a duration is tolerable by the end user but is considered a large duration in the MAC operation.

4.5.3 A Station Moves in the Network Area

The stations might move within the WLAN area while remaining associated to the same AP. The mobility of the stations might introduce hidden nodes in the groups. When a nonleader station moves, it will find its new distance to the leader. If the distance remains smaller or equal to $R/2$, then the station does not need to change anything. However, if the distance to its leader becomes larger than $R/2$, then the station will perform the initial procedure of joining a group as described in Fig. 3a. The station does not need to inform the leader. It will be dropped from the group after a duration of T_{idle}^{max}.

If a leader stations moves, it will find out if it can join an existing group. If this is the case, the leader will disband its group by using the "Disband Group" field of the polling frame and it will join an existing group. However, if the leader moved its location and could not find an existing group in the new location, then it will remain a group leader. In this case, the leader will notify the stations in its group that it has moved by using the field "Leader Moved to a New Location." The stations in the corresponding group that are still within a distance of $R/2$ to the leader will remain in the group. The stations that are not within a distance of $R/2$ to the leader will perform the initial procedure described in Fig. 3a.

4.6 Discussions

Below are discussions that are related to the proposed scheme.

4.6.1 Dividing the Stations into Groups

We divided the stations into groups based on a station's distance to the group leader. We selected the communication range, R, conservatively to ensure that two stations in a group can hear each other. There are also other alternatives for dividing the stations into groups. Our scheme can work with other approaches as well. One approach is to have the stations in the same room belong to the same group. For a room of normal size, like an office, a lounge, or a classroom, the stations in the same room would be able to hear each other. However, if the room is unusually large, like an auditorium, the stations in the same room might be too far away and out of range. However, in most cases, the stations in the same room are in range of each other. When a station joins the group leader that's in the same room, this does not guarantee the shortest distance to the group leader. There might be a leader in an adjacent room that's closer and can provide a higher signal strength. Another consideration for this approach is the distribution of users in the rooms. If a floor level has multiple offices with one user in each office, then we would have many groups with one user each. This is not good for our scheme since there will be a lot of contention. However, if there are a few rooms with multiple users in each room, there will be multiple stations in each group and this will reduce the collisions and the overhead.

4.6.2 Interoperability with Legacy 802.11

Right from its outset, the 802.11n standard was designed to provide interoperability with legacy 802.11 devices. One example is the dual CTS mechanism that we mentioned in Section 2.1. In this scenario, the High-Throughput (HT) stations are using the advanced STBC technique that cannot be understood by legacy devices. So the AP replies with an STBC-encoded CTS to HT stations followed by another non-STBC CTS for legacy devices. So the CTS is used to defer legacy devices while the high-throughput stations are transmitting. In a similar way, our proposed scheme is interoperable with legacy devices that do not implement GMAC. At first, during the contention, the group leaders will contend with the legacy devices to access the channel. If a legacy device gets access to the channel, it transmits and all the other devices (including the leaders and nonleaders) refrain from transmission. When a group leader wins the contention, it transmits. Its CTS reply from the AP will make the legacy devices refrain from transmission and they will not interfere with the 802.11n stations using our scheme.

4.6.3 User Mobility

In our scheme, when users are mobile the groups and group membership will change. The movement of a station will only affect itself, but the movement of a group leader will affect its whole group. We considered a WLAN network and the stations could be moving at human speed. That is, a person who's holding the wireless station could be walking in the WLAN coverage area. Typically, a person would sit down for a while after a movement and not keep moving all the time. In such a setting, our scheme accommodates the user mobility since the events in the MAC operation happen during very small time durations, in nanoseconds or microseconds; so the system is fast enough the update its state and the user will not feel a prolonged service interruption.

4.6.4 Effect of the Distance Estimation Error

The distance estimation error, δ, has an effect on the grouping in GMAC. We initially seek to form groups of radii equal to $R/2$ after obtaining R from the characteristics of the WLAN propagation environment. The groups are formed with radii of $R/2 - \delta$ to account for the error in distance estimation. Accordingly, the groups are smaller than they could have been if the distance estimation had no error. As a result, this could lead to more groups in the WLAN and this leads to more contention and the performance would drop a bit when the error, δ, increases. In the extreme case, if δ approaches $R/2$, then the stations can no longer form a group since $R/2 - \delta$ is equal to zero. However, the distance estimation algorithms have a much smaller error. In [34], the error reported is smaller than 0.5 ft for 90 percent of the time and smaller than 1 ft for 100 percent of the time in a WLAN environment. This is suitable for our scheme since the value of R could range from around 35 up to 100 ft and such values of δ will not reduce the radius of the group by much.

5 Analysis

This section presents an analysis that demonstrates the benefit of the frame aggregation mechanism that was introduced in the 802.11n standard. We also show the benefit of the grouping mechanism in our scheme which reduces the probability of collision. The analysis compares the throughput of three schemes: our scheme GMAC, the DCF scheme with frame aggregation (we call it DCF-Agg) as in the 802.11n standard and the regular DCF scheme without frame aggregation.

5.1 Performance Gain

We relate the performance of GMAC and DCF-Agg to the performance of the regular DCF scheme. The transmission of GMAC, DCF-Agg, and DCF is shown in Fig. 4.

Let $\eta(n, b, T)$ be the number of frames transmitted successfully when n stations contend using DCF over a time duration T and each station transmits an A-MSDU that contains b data frames. In the regular DCF scheme, a station transmits one frame upon access. However, in the DCF-Agg scheme, each station transmits an A-MSDU that contains b

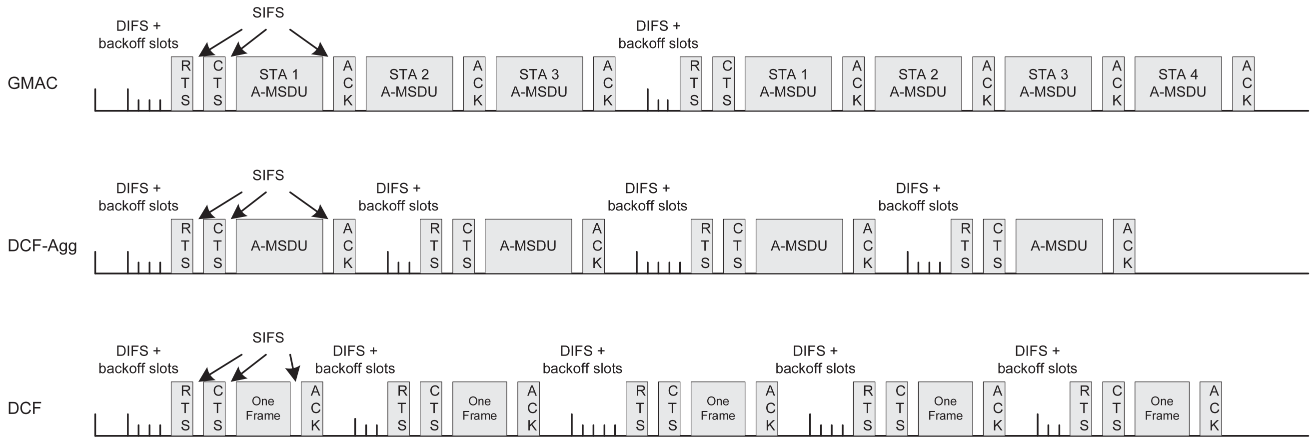


Fig. 4. Transmission of GMAC, DCF-Agg, and DCF.

frames. The performance gain of DCF-Agg over DCF is the following:

$$\gamma_{\mathrm{DCF}}^{\mathrm{DCF\text{-}Agg}} = \frac{\eta(n, b, T)}{\eta(n, 1, T)}. \quad (1)$$

In this analysis, we consider that there are n stations that are using GMAC. These stations are divided into g groups of equal size. Every station transmits an A-MSDU with b frames upon access. Thus, the number of contending stations is g and the number of data frames transmitted after each contention is $(n/g).b$. The performance gain of GMAC over DCF is the following:

$$\gamma_{\mathrm{DCF}}^{\mathrm{GMAC}} = \frac{\eta(g, \frac{n}{g}.b, T)}{\eta(n, 1, T)}. \quad (2)$$

Equations (1) and (2) indicate that the throughput gain in DCF-Agg comes from transmitting more frames per contention while, on the other hand, the performance gain in GMAC comes from reducing the number of contending stations and from transmitting more frames per contention.

5.2 Time Utilization

The time utilization of the regular DCF scheme was found in [6]. It is given as the following. Let the minimum Contention Window be CW_{min} and the maximum backoff stage be m, then the time utilization of the DCF scheme is given by

$$\mu = \frac{P_s.P_{tr}.T_{payload}}{(1 - P_{tr})\sigma + P_{tr}.P_s.T_s + P_{tr}.(1 - P_s).T_c}. \quad (3)$$

In this equation, P_{tr} is the probability that a station transmits in a slot and P_s is the conditional probability of a successful transmission in a slot given that at least one station tries to transmit. The term T_s is the time consumed by a successful transmission. The term T_c is the time consumed by a collision event and σ is the duration of a backoff slot.

The expressions for P_{tr} and P_s are the following:

$$P_{tr} = 1 - (1 - \tau)^n, \quad (4)$$

$$P_s = \frac{n.\tau.(1 - \tau)^{n-1}}{P_{tr}}. \quad (5)$$

The expression of τ is the following:

$$\tau = \frac{2(1 - 2p)}{(1 - 2p)(CW_{min} + 1) + p.CW_{min}(1 - (2p)^m)}, \quad (6)$$

$$p = 1 - (1 - \tau)^{n-1}. \quad (7)$$

5.3 Applying to GMAC, DCF-Agg, and DCF

To use the result above, we need to find T_s and T_c for each of the three schemes. For DCF, we have the following equations where $t_{data(1)}$ is the time to transmit one data frame

$$T_s^{\mathrm{DCF}} = t_{difs} + t_{slots} + t_{rts} + t_{cts} + t_{data(1)} + t_{ack} + 3.t_{sifs}, \quad (8)$$

$$T_c^{\mathrm{DCF}} = t_{difs} + t_{slots} + t_{RTS}. \quad (9)$$

For DCF-Agg, the difference from the two equations above is that we have an A-MSDU of b frames that is transmitted on every access. We have $T_c^{\mathrm{DCF\text{-}Agg}}$ is the same as T_c^{DCF} and $T_s^{\mathrm{DCF-Agg}}$ is the following equation where $t_{data(b)}$ is the time to transmit an A-MSDU that contains b data frames

$$T_s^{\mathrm{DCF\text{-}Agg}} = t_{difs} + t_{slots} + t_{rts} + t_{cts} + t_{data(b)} + t_{ack} + 3.t_{sifs.} \quad (10)$$

For GMAC, after every contention the stations in a group transmit. We assume in the analysis that there are $\frac{n}{g}$ stations in a group. Each one transmits an A-MSDU that contains b frames. There are $\frac{n}{g}$ Block ACK frames transmitted, assuming that no erroneous transmissions occur, and $(\frac{n}{g} + 1)$ intermediate SIFS durations. We have T_c^{GMAC} is the same as T_c^{DCF} and T_s^{GMAC} is the following:

$$T_s^{\mathrm{GMAC}} = t_{difs} + t_{slots} + t_{rts} + t_{cts} + \frac{n}{g}.t_{data(b)} + \frac{n}{g}.t_{ack} + \left(\frac{n}{g} + 1\right).t_{sifs.} \quad (11)$$

The number of frames transmitted in duration T by n contending stations where b frames are aggregated in each access is

$$\eta(n, b, T) = \frac{\mu.T.r_{avg}}{L}. \quad (12)$$

In the equation above, r_{avg} is the average data rate and L is the average frame length in bytes.

TABLE 1
Throughput Comparison of GMAC, DCF-Agg, and DCF

n	b	g	$\gamma_{\text{DCF}}^{\text{DCF-Agg}}$	$\gamma_{\text{DCF}}^{\text{GMAC}}$	$\gamma_{\text{DCF-Agg}}^{\text{GMAC}}$
10	5	2	3.00	4.55	1.38
20	5	4	3.03	4.24	1.39
40	5	5	3.07	4.53	1.47
60	5	5	3.10	4.75	1.53
100	5	5	3.15	5.03	1.59

5.4 Analysis Results

Using the results of the analysis, we find the throughput gain of DCF-Agg and GMAC with respect to that of DCF, given by the terms $\gamma_{\text{DCF}}^{\text{DCF-Agg}}$ and $\gamma_{\text{DCF}}^{\text{GMAC}}$, respectively. We also show the throughput gain of GMAC over DCF-Agg, indicated by the term $\gamma_{\text{DCF-Agg}}^{\text{GMAC}}$. The numerical results are in Table 1. For these results, the data rate is 116 Mbps, the control rate is 6.5 Mbps and the frame size is 1,000 bytes.

As in Table 1, DCF-Agg achieves a throughput gain over DCF by a factor of about 3. This gain is achieved by the frame aggregation mechanism used in DCF-Agg. In DCF-Agg, a station transmits an A-MSDU that contains $b = 5$ data frames upon access. However, in DCF, a station transmits one data frame only. The throughput gain of GMAC over DCF is a factor of about 4.5 to 5. This gain is achieved since GMAC reduces the number of contending stations (n/g instead of n) and also uses frame aggregation ($b = 5$ data frame in an A-MSDU).

Finally, the throughput gain of GMAC over DCF-Agg is a factor of about 1.3 to 1.5. Both GMAC and DCF-Agg allow the stations to transmit an A-MSDU of five frames upon access. However, in GMAC a fewer number of stations contends and, therefore, the collision rate is smaller. Also, with GMAC an RTS/CTS exchange is used for every group which contains n/g stations. On the other hand, an RTS/CTS exchange is used for every station in DCF-Agg. The throughput gain in DCF-Agg comes from reducing the collisions and from using less control frames. The numerical results for the throughput gain of GMAC over DCF-Agg shown here agree with the simulation results that we present in the next section.

6 Simulation Results

In this section, we present the simulation results which compare the 802.11n standard, our scheme GMAC and two schemes from the literature TMAC [7] and E-GDCF [8]. We wrote our own simulation code which simulates the MAC layer of the WLAN. All of the schemes were tested in the same environment and using the same physical layer. Hence, this ensures that the comparison is fair and focuses on the MAC scheme performance. For TMAC and E-GDCF, we used the parameters that were presented in their original publications as given in Section 2.

TABLE 2
Physical Layer Characteristics

Characteristics	Value	Description
Slot Time	9 μs	Contention slot time
RIFS	2 μs	Reduced Inter-Frame Space
SIFS	10 μs	Short Inter-Frame Space
DIFS	28 μs	DCF Inter-Frame Space
CW_{min}	15	Minimum contention window size
CW_{max}	1023	Maximum contention windows size

TABLE 3
Data Rates (in Mbps)

Control Frames	Data Frames
6.5	21.7 – 43.3 – 65.0 – 86.7 – 130.0 – 173.3 – 195.0 – 216.7

The physical layer characteristics are presented in Table 2. These characteristics are used for the 802.11n DCF scheme and for GMAC. For TMAC and E-GDCF, we use the values from this table when applicable, otherwise, we use the values presented in the respective original papers. For example, TMAC and E-GDCF use DIFS which we take from this table. However, TMAC and E-GDCF define their own CW_{min} and CW_{max} values, which we set as defined by the schemes' authors.

The data rates that we use in the simulation are shown in Table 3. These rates are defined in the 802.11n standard [1]. In the standard, rates are defined for several configurations. The rates in this table correspond for three spatial streams between the sender and the receiver. This means a MIMO-based physical layer is used with three antennae at each end. The bandwidth used to support these rates is 20 MHz.

In the simulation results, the control frames are transmitted at the control rate, which is 6.5 Mbps. Each station in the WLAN is assigned a data rate from Table 3 that it uses for all of its data transmission. There are eight rates in Table 3 and, in our simulation, we always have the number of stations in the WLAN to be a multiple of eight. Therefore, each rate is used by the same number of stations. For example, when there are 40 or 120 stations in the WLAN, each rate is used by 5 or 15 stations, respectively. Accordingly, the average rate in the network is the average of all the data rates in the table, which is 116.46 Mbps.

6.1 Collision Rate

First, we measure the collision rate for each of the schemes: GMAC, DCF of 802.11n, TMAC and E-GDCF. The collision rate is the number of collisions divided by the total number of contention resolutions. The results are in Fig. 5. The simulation time is 1,200 seconds and the frame size is 1,000 bytes. First, we notice that the collision rate of DCF grows to be the highest. It reaches more than 40 percent when there are 120 stations in the WLAN. This is because the mechanisms introduced in DCF focus on reducing the overhead (such as using RIFS instead of SIFS) and improving the efficiency by aggregating the frames. However, DCF does not introduce a mechanism to reduce the probability of collision. As a result, its collision rate is acceptable with a low number of stations but it becomes large when the number of stations increases.

The collision rate of E-GDCF is almost constant and does not depend too much on the number of stations in the WLAN. It is equal to about 34.6 percent. The collision rate does not change when the number of stations increases because the collision in E-GDCF happens between the

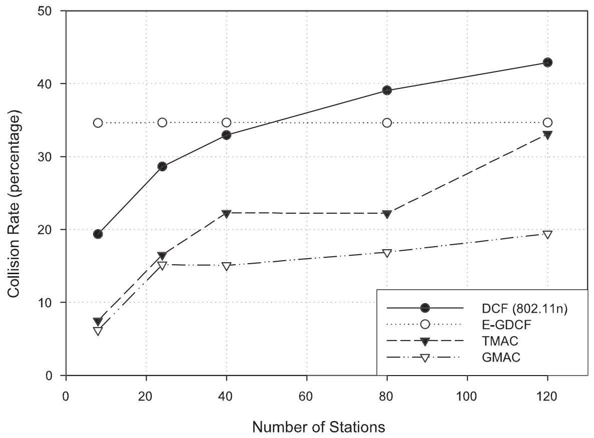


Fig. 5. Collision rate.

stations that are in the same group. E-GDCF aims at having two stations in each group. The number of groups is $M = \lfloor n/2 \rfloor \geq 1$ and the parameters that divide the stations into groups, (n, k), are selected such as there is minimal variation in the group sizes. Accordingly, when the number of stations in the WLAN is small or large, most likely, the contention happens between two stations that use $CW_{min} = CW_{max} = 8$. While the collision rate of E-GDCF does not increase when the number of stations increases, it is still a high collision rate when compared to the other schemes. TMAC and GMAC always have a lower collision rate in Fig. 5 and DCF have a lower collision rate in some cases.

The collision rate of TMAC increases when the number of stations increases. However, the collision rate of TMAC is always smaller than that of DCF and E-GDCF in Fig. 5. TMAC uses contention like DCF. But in TMAC, the contention is limited to at most $\overline{N}_V = 15$ stations that are in the same group. The collision rate in TMAC depends on the number of stations in the group. Fig. 5 shows five instances of the collision rate of TMAC when the number of stations is 8, 24, 40, 80, and 120. The stations are distributed to the groups equally. With eight stations, there is one group with eight contending stations. With 24 stations, there are two groups with 12 stations each. Thus, the collision rate increases since now there are 12 stations contending together instead of 8. In the third point on the graph, there are 40 stations. Thus, there are three groups; two groups have 13 stations each and one group has 14 stations. In the fourth point on the graph, there are 80 stations that are divided over six groups; four groups have 13 stations and two groups have 14 stations. As a result, the third and fourth points on the graph have 13 or 14 stations in each group, and thus, they have similar collision rates. So even though the number of stations increased between these cases, the collision rate stayed the same. Finally, with 120 stations, there are six groups with 15 stations each. In this case, the collision rate is the highest since 15 stations contend together.

The collision rate of GMAC is the smallest among the four schemes. In GMAC, only the leaders are contending. In Fig. 5, when the number of stations is 8, 24, 40, 80, and 120, the number of groups is 2, 3, 3, 5, and 6, respectively. The number of stations contending in our scheme is smaller than that of TMAC. Hence, our scheme has a smaller collision rate. In our scheme, the number of groups is likely to remain small. When we put 300 stations in the WLAN at random locations, the number of groups obtained was 10 to 12 groups in different simulation runs. The number of groups does not grow too much since a new station tries first to join an existing group. The new station will start a group only if it's not able to find an existing group nearby. Accordingly, when the number of stations grows, there will be groups that are covering most of the WLAN area. Since the number of groups does not grow too much, the collision rate remains small.

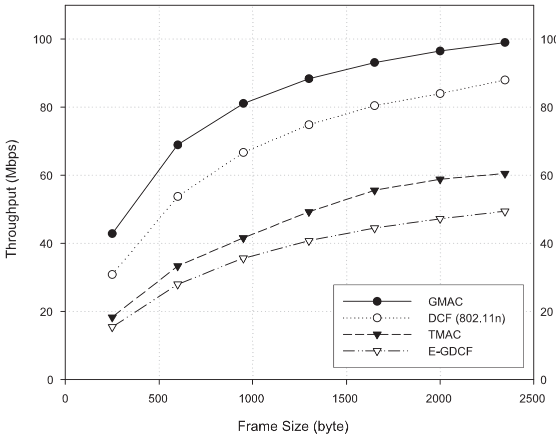
6.2 Throughput

The throughput of the schemes is shown in Fig. 6. The number of stations in the three figures is 8, 40, and 120, respectively. The simulation time is 1,200 seconds. The frame size varies from 300 bytes to the maximum size of 2,346 bytes. The stations always have data to transmit. The three figures are drawn to the same scale for ease of comparison. In TMAC, there is one parameter, R_f, which should be a high rate among the rates supported by the PHY. We set $R_f = 173.3$ Mbps since this is high rate among the rates that we use. When a station in TMAC is able to transmit at a rate r_i that is equal to or higher than R_f, it transmits for a duration of $r_i/R_f.T_f$, where $T_f = 35$ ms. Otherwise, it transmits for a duration of T_f.

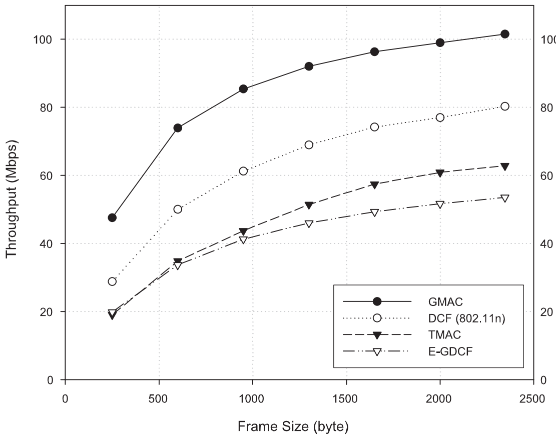
Fig. 6a shows the throughput of the schemes when the number of stations is eight. The throughput of GMAC and DCF is higher than that of TMAC and E-GDCF. Also, the throughput of GMAC is higher than DCF's. The throughput of our scheme ranges from 42 to 99 Mbps. It remains higher than DCF's by about 10 to 15 Mbps as the frame size increases. GMAC has a higher throughput than DCF's because our scheme uses the grouping to reduce the probability of collision. DCF does not use such a mechanism and it has a higher collision rate as we showed earlier.

The throughput of TMAC is smaller than our scheme's and DCF's. It ranges from 18 to 60 Mbps as the frame size increases. One reason why TMAC achieves a smaller throughput than GMAC's and DCF's is because TMAC uses an RTS/CTS exchange for every station. For stations that are transmitting at a high data rate (for example 130 Mbps or more), the overhead of the RTS/CTS exchange becomes very high, since the control frames are transmitted at 6.5 Mbps. Therefore, it might be better to let the data frame collide than to use a long time to transmit the RTS/CTS frames for every station. This phenomenon has been demonstrated in earlier research [35]. However, for stations that are transmitting at a low data rate (for example 21.7 Mbps), the use of the RTS/CTS exchange would be useful since it's better to collide a small RTS frame than to collide a larger data frame.

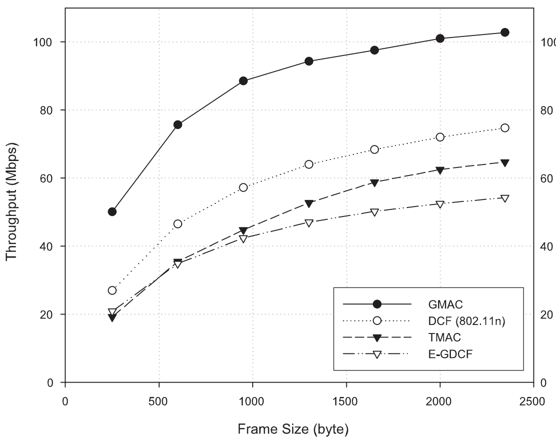
The throughput of E-GDCF is the smallest among the schemes. It ranges from 15 to 49 Mbps. The collision rate of E-GDCF was high as compared to the other schemes. The high collision rate reduces the throughput since the data frames collide. Second, E-GDCF uses frame aggregation for the ACK frame only, but not for the data frame. A group cycle in E-GDCF allows one transmission from each group. At the end of the group cycle, the AP transmits one Block ACK frame that contains an ACK frame for each group. However, E-GDCF does not use frame aggregation for the



(a) Throughput (number of stations is 8)



(b) Throughput (number of stations is 40)



(c) Throughput (number of stations is 120)

Fig. 6. Throughput of DCF (802.11n), GMAC, TMAC, and E-GDCF.

data transmission. Each station transmits only one data frame upon access. On the other hand, the other schemes allowed frame aggregation for the data. Therefore, there is more contention overhead for each data frame in E-GDCF and it achieves the smallest throughput.

Fig. 6b shows the throughput with 40 stations in the WLAN. The order of the schemes remain the same as in the previous figure. However, the throughput achieved changes a little bit for some schemes. The throughput of our scheme increases when the number of stations changes from 8 to 40. With eight stations, there were two groups and with 40 stations, there were three groups. The increase in throughput is because there are more stations per group. Thus, there is less overhead (DIFS duration, contention slots, and RTS/CTS frames) per data frame. The throughput interval[1] for our scheme changes from [43; 99] Mbps to [48; 102] Mbps between Figs. 6a and 6b. The throughput of DCF, on the other hand, decreases when the number of stations increases from 8 to 40. This is because the collision rate increases. The throughput interval for DCF changes from [31; 88] Mbps to [29; 80] Mbps between Figs. 6a and 6b. With TMAC, there is no real trend on the throughput value when the number of stations increases. With E-GDCF, the throughput interval changes from [15; 49] Mbps to [20; 54] Mbps between Figs. 6a and 6b. When there are more stations, the number of groups in E-GDCF increases. The scheme becomes more efficient since a cycle in E-GDCF starts with a DIFS duration followed by one transmission from every group and then ends with a Block ACK frame from the AP. With more groups, the overhead (DIFS duration) per data frame becomes smaller and the throughput increases.

Fig. 6c shows the throughput with 120 stations in the WLAN. The throughput of our scheme increases from [48; 102] Mbps to [50; 103] Mbps between Figs. 6b and 6c. The throughput of DCF decreases from [29; 80] Mbps to [27; 75] Mbps between Figs. 6b and 6c. The throughput of TMAC remains almost the same in the [19; 64] Mbps interval. Finally, the throughput of E-GDCF increases slightly from [20; 54] Mbps to [21; 54] Mbps between Figs. 6b and 6c.

TABLE 4
Delay Average and Standard Deviation (in Milliseconds)

	GMAC	DCF	TMAC	E-GDCF
Average	23.69	31.34	56.12	8.53
Standard Deviation	70.75	153.05	40.58	6.31

6.3 Delay

The delay measurements for our scheme, DCF, TMAC, and E-GDCF are shown in Table 4. The delay of a data frame (or A-MSDU) is measured from the moment the frame arrives at the top of the queue to the moment the frame is received correctly. Like the previous experiments that measure the collision rate and the throughput, the simulation time is 1,200 seconds and the frame size is 1,000 bytes. The results are reported with 40 stations in the WLAN.

Table 4 shows the average delay and the standard deviation on the delay of the schemes. The average delay of our scheme is smaller than DCF's and that of DCF is smaller than TMAC's. The delay of DCF is larger than our scheme because DCF has a larger collision rate. When a frame collides, it has to wait for more time in the queue and thus, this frame will have a long delay. In TMAC, the use of RTS/CTS frames by every station makes the delay longer than that of our scheme and DCF's. The average

1. The interval notation means that our scheme has a throughput of 43 Mbps with the smallest frame size and 99 Mbps with the largest frame size in Fig. 6a.

delay of E-GDCF is much smaller than the other schemes. It is small because E-GDCF allows the stations to transmit only one data frame. Accordingly, a station does not have to wait for a long time to get its next transmission. Overall, the average delay of all the schemes is small and suitable for applications that require low delay such as voice and video streaming applications.

The standard deviation on the delay for our scheme is much smaller than that of DCF. In DCF, a station that collides doubles its contention window. Then, the station will have to wait for a long period and thus will have a long delay for its frame. Our scheme reduces the probability of collision, hence, there is less chance that a leader will double its contention window. The delay standard deviation of TMAC is smaller than our scheme's and DCF's. In TMAC, the token is rotated among the groups in a round robin way. So a group will get the token predictably on time. In the contention between the stations in a group, TMAC uses $m = 2$ stages of backoff. This means, a colliding station will double its contention window for up to two times only on consecutive collisions. However, our scheme and DCF have a maximum contention windows size of 1,023, although this number is used only when a station collides for 11 times consecutively. Finally, E-GDCF has a delay standard variation that is much smaller than the other schemes. E-GDCF uses $CW_{min} = CW_{max}$ and thus, no station will have a large contention window. This keeps the delay small.

6.4 Fairness

We evaluate the fairness of the schemes in providing the same level of service to all the stations in the WLAN. In Section 3, we demonstrated the difference between the time-based fairness and the throughput-based fairness policies. We showed that the time-based fairness policy increases the total throughput significantly and therefore, we used a time-based fairness for our scheme. Similarly, the time-based fairness was used for DCF. Accordingly, the evaluation for our scheme aims at finding out if all the stations have transmitted for the same amount of time. When a station gets access to the channel, it gets a Transmission Opportunity, called TXOP, that has a duration. All the TXOPs have the same duration. Therefore, we measure the fairness on the number of TXOPs received by each station.

To measure the fairness, we use Jain's index [36] which is defined as

$$f(x_1, \dots, x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n. \sum_{i=1}^{n} x_i^2}.$$

In this expression, x_i is the number of TXOPs received by station i. Jain's index is a real number in the interval [0; 1]. When the index is 1, the fairness is highest and all the stations have received the same number of TXOPs. Smaller values indicate unfairness which means that some stations received more TXOPs than others. In the fairness measurement, the number of stations is 40. The simulation time is either 60, 300, or 600 seconds to show how the fairness changes with time. Like the previous experiments, the frame size is 1,000 bytes.

Fig. 7a shows the fairness on the number of TXOPs received by the stations. Our scheme and E-GDCF achieve a fairness value of 1 for all the simulation times. In GMAC, all the stations received the same number of TXOPs. Thus, all the stations have transmitted for the same amount of time. In E-GDCF, all the stations have accessed the channel the same number of times. But, E-GDCF is different from GMAC, since a station with E-GDCF transmits only one frame upon access. Therefore, the stations with high data rates transmitted their data quickly and the stations with low data rates took more time to transmit their data. As a result, most of the time in E-GDCF is spent by the transmission of stations with low data rates. This is why E-GDCF has the lowest throughput of the schemes.

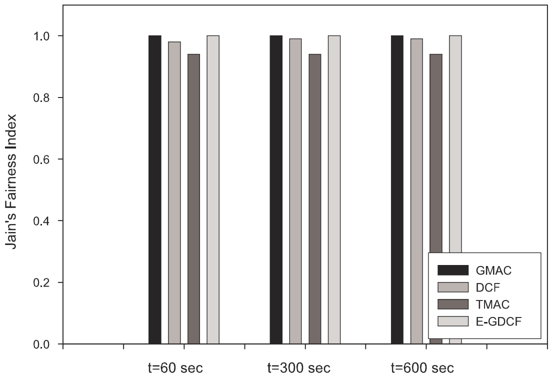
DCF has a fairness value that is 0.98 for the simulation time of 60 seconds and 0.99 for the simulation time of 300 or 600 seconds. This is also considered a high fairness to the stations. The unfairness in DCF happens because of collisions. The colliding stations double their contention windows and, therefore, will have a smaller chance to access the channel. But looking over a long duration, all the stations will have the same chance of colliding since they use the same parameters. Hence, when a longer duration is considered, the fairness improves. Of course it is better to achieve a high fairness even over small durations.

The fairness value for TMAC is 0.94 for all the cases of the simulation time. TMAC gives the token for the groups in a round robin way, so no group is favored over the other. However, within a group, a station attempts transmission only once. If the transmission collides, the colliding stations will not attempt transmission during the current token period. They will remain silent until the next time their group gets the token. Therefore, TMAC will take more time to achieve higher fairness.

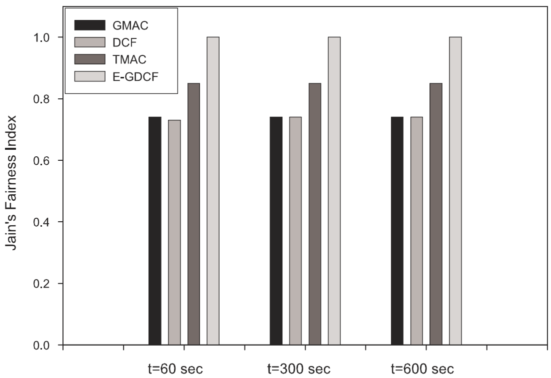
We also evaluate the fairness on the number of frames that was transmitted by the schemes. All the frames have the same size, therefore, this is the fairness on the throughput achieved by the schemes. The results are shown in Fig. 7b. E-GDCF has a value of 1 for all the simulation times. In E-GDCF, when a station gets a TXOP, it transmits one frame only. Therefore, the number of TXOPs is equal to the number of frames transmitted. This is why the result for E-GDCF is the same in Figs. 7a and 7b. However, while all the stations in E-GDCF achieved the same throughput, the total throughput of E-GDCF was the lowest among the schemes.

TMAC has a fairness on the number of frames that is equal to 0.85 for all the simulation times. In TMAC, the stations that have a high rate (higher than the reference rate) transmitted for a longer duration. These stations then get a higher throughput, which is the cause of unfairness. GMAC and DCF have a fairness on the number of frames that is equal to about 0.74 for all the simulation times. Our scheme and DCF have targeted time-based fairness and achieved this goal. They also got the highest total throughput among the schemes. However, with the time-based fairness, the stations with low data rates do not get as much throughput as the stations with high data rates, which is the cause of unfairness.

In conclusion, the simulation results evaluated several criteria in our scheme, DCF, TMAC, and E-GDCF. The collision rate was smallest when the smallest number of



(a) Fairness (Jain's index) on the number of TXOPs obtained by each station



(b) Fairness (Jain's index) on the number of frames transmitted by each station

Fig. 7. Fairness measurement.

stations were contending together. Our scheme achieved the smallest collision rate followed by TMAC, then E-GDCF and DCF. A high throughput was achieved by the schemes that use the frame aggregation for the data frames. E-GDCF obtained the lowest throughput because it does not use frame aggregation. The highest throughput was achieved by our scheme, followed by DCF then TMAC. Since E-GDCF allows the transmission of one frame only, the stations switch transmission frequently. Therefore, a low delay is achieved with E-GDCF (at the expense of the throughput). Among the other schemes, GMAC had the smallest delay average, followed by DCF then TMAC. Finally, our scheme and DCF provided a high level of fairness based on the transmission time. Since the stations have different rates, there was a difference in their throughput. E-GDCF allowed all the stations to transmit the same number of frames. TMAC had the lowest fairness based on the number of TXOPs the stations obtained, but it had higher fairness based on the throughput obtained by the stations.

7 Conclusion

This paper considered the MAC scheme of WLANs that have high data rates as in the IEEE 802.11n Standard. We reviewed the mechanisms that were introduced in the 802.11n standard to improve the efficiency and allow obtaining a high throughput. We proposed a Group-based MAC scheme that groups the stations and reduces the probability of a collision. Our scheme also uses mechanisms that were introduced in the standard such as frame aggregation and Block ACK frames. We presented the details of our scheme and provided an analysis that shows the throughput gain that is obtained by using frame aggregation and Block ACK frames. The analysis also showed the gain that is achieved by reducing the probability of collision in our scheme. In the simulation results, we compared our scheme, DCF and two schemes from the literature, TMAC and E-GDCF. The results showed that our scheme achieved the highest throughput. Our throughput is about 25 percent higher than the next scheme, which is the standard's DCF. Our scheme also had the lowest collision rate and a low delay that allows supporting multimedia-oriented applications. Finally, the results showed that our scheme provides a high fairness to the stations based on the duration of transmission that each station obtained.

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