IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received December 21, 2018, accepted January 5, 2019, date of publication January 14, 2019, date of current version February 4, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2892760

A Differentiated Reservation MAC Protocol for Achieving Fairness and Efficiency in Multi-Rate IEEE 802.11 WLANs

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This work was supported in part by the National Science Foundation of China under Grant 61602073 and in part by the Natural Science Foundation of Chongqing under Grant cstc2014kjrc-qnrc40002.

ABSTRACT This paper focuses on designing a medium access control and channel usage algorithm in multi-rate wireless local area networks for improving the efficiency and fairly sharing channel resources among the contending nodes. Aiming for the problems that the high collision is often caused by binary exponential backoff mechanism in the legacy IEEE 802.11 and the shared channel can be overused by low bitrate nodes, we propose a differentiated reservation (DR) algorithm to reduce the collision among the contending nodes by setting their backoff counter as a deterministic value once accessing successfully to the channel. Furthermore, to eliminate the performance anomaly, some nodes are permitted to send multiple packets in one transmission opportunity according to their feature. Moreover, we present the implementation of the DR algorithm that is readily applied to both the existing 802.11 DCF and 802.11e EDCA networks with minimum modification. In addition, we also investigate the limitation of the DR algorithm and propose a group-based differentiated reservation (GDR) algorithm applied to high dense scenarios. The results of the theoretical analysis and simulation validate that our proposed algorithms (DR and GDR) can obtain high throughput, good airtime fairness, and low collision rate.

INDEX TERMS WLANs, MAC, collision mitigation, airtime fairness.

I. INTRODUCTION

In recent years, WiFi has become a backbone of network connectivity alongside cellular 3G and 4G technologies. According to the Cisco Global Mobile Data Forecast [1], WiFi is projected to carry approximately 53% of the total IP traffic by 2019. The IEEE 802.11 distributed coordination function (DCF) has been widely used as a dominant MAC protocol in WiFi WLANs because of its simplicity and low-cost implementation [2]. The IEEE 802.11 DCF uses a Binary Exponential Backoff (BEB) mechanism that offers equal transmission opportunities to all contending nodes regardless of their differentiation. Bianchi [3] evaluates the throughput and packet transmission probability of the IEEE 802.11 DCF under ideal channel conditions using a Markov chain model. In their works, it concludes that the DCF provides throughput fairness to all nodes if they have the same bitrate and adopt the same packet size. However, there are multiple bitrates defined in the legacy IEEE 802.11 and the nodes may use different bitrates according to their scenarios in real deployments. The bitrate of the node can be affected by multiple factors, such as the configuration of hardware and the current channel environment. A node will choose an appropriate transmission bitrate so that its throughput can be maximized and the bit error rates (BER) can be restrained in an acceptable level [4]. However, the scenario with diverse bitrate coexisting also leads to the problem of *performance anomaly* due to the equal transmission opportunities offered by the 802.11 DCF mechanism [5]. Accordingly, high bitrate nodes cannot get the corresponding higher throughput because the shared channel is overused by the low bitrate nodes, which degrades the overall performance, especially in the dense scenarios.

In addition, another bottleneck of DCF is its nature that is prone to collisions with the ever-growing throughput demands from upper layers and more contention nodes under crowded and dense scenarios. The standardization communities have propose or envision some new standards to enhance the service, such as 802.11aa for strengthening audio or video streams, 802.11ah for enhancing power saving mechanisms under dense conditions and 802.11ax for extent the features for dense areas. However, when a proposal deviates too much from DCF, or some critical operations are modified, its hardware implementation often becomes unlikely, with the standardization process also taking many years. In addition, these new implementation as a replacement must also serve existing users, which means they should be backwards compatible.

A replacement based on the current 802.11 DCF is desired to provide advantages in terms of channel utilization, aggregated throughput, airtime fairness and backwards compatible. In this paper, we propose a sophisticated and distributed MAC protocol named DR (Differentiated Reservation) algorithm, which can improve the system throughput and reduce the collision rate by setting its backoff counter as a deterministic value. Moreover, it also can achieve significant airtime fairness and channel utilization by permitting a node to transmit multiple packets during a successful channel access opportunity according to its feature. Meanwhile, to ensure the performance of DR algorithm that will not be worse than that in the legacy IEEE 802.11 DCF, the node also may revert to the standard random BEB backoff mode in the case of a failed packet transmission occurring. In particular, the DR algorithm is readily applied to both the existing 802.11 DCF and 802.11e EDCA networks with the minimum modification. In detail, the contributions of this paper are summarized as follows:

- First, we propose a general framework to implement the DR algorithm for different nodes in WLANs. It does not require any modification to existing hardware, and incurs backward compatible with legacy IEEE 802.11.
- Second, we present the detail of DR algorithm to integrate it into the 802.11 DCF and 802.11e EDCA mechanisms, and also demonstrate that the DR can achieve the better system throughput and airtime fairness by some extensive evaluation simulations.
- Third, we develop an analytical model of the DR to validate the improvement of airtime fairness and system throughput in theory. In addition, this analytical model also can be used to predict the performance in some non-ideal situations.
- Finally, we also further discuss the situation applied to some high dense scenarios, and investigate the limitation of basic DR algorithm and present an enhanced Group-Based Differentiated Reservation (GDR) algorithm to improve its performance under high dense scenarios.

The rest of this paper is organized as follows. Section II presents the related work. The design of DR algorithm is described in Section III and the analysis is presented in Section IV. Section V presents the simulation results. An enhanced algorithm to DR is studied in Section VI. Section VII discusses some non-ideal cases. Finally, we conclude the paper in section VIII.

II. RELATED WORK

The simplicity and flexibility of BEB contribute to the popularity of 802.11 DCF/EDCA. However, some analytical studies [3], [6] reveal that BEB mechanism suffers high collision rate in the case of heavy traffic loads and leads to performance anomaly in conventional multi-rate IEEE 802.11 WLANs. To address these problems, many research works concentrate on improving the performance of the legacy IEEE 802.11 by reducing the collision rate and allocating fairly the airtime to all contending nodes.

Some literatures focus on reducing the collision rate. Reference [7] proposes a distributed carrier sense multiple access with enhanced collision avoidance (CSMA/ECA) to reduce the collision by utilizing a deterministic backoff mechanism. But the CSMA/ECA does not take into account the loss of the transmission opportunity for colliding nodes, thus cannot provide the fair channel utilization. Thus, in [8], they further propose two extensions of CSMA/ECA, Hysteresis and Fair Share, which support a large number of contenders and mitigate the impact of the collision on the nodes. To some extent, these algorithms can improve the system throughput and short-term throughput fairness. Similarly, [9] proposes a semi-random backoff (SRB) method that enables resource reservation in 802.11 WLANs, which can greatly reduce the collision, but does not take into account the fairness between contending nodes. Reference [10] proposes a semi-distributed backoff (SDB) algorithm, which performs deterministic backoff from opportunistic access mode. Reference [11] proposes a centralized random backoff (CRB). In CRB, the access point (AP) allocates a unique backoff state to the nodes after it receives successfully a data frame from these nodes. Both [10] and [11] can mitigate the collision problem to some extent at their own cost, such as extra controlling overhead from the AP. Reference [12] proposes a new backoff freezing process: each node runs its backoff process by a backoff probability, which can reduce the number of contending nodes. Reference [13] proposes a similar idea and attaches a method to calculate the value of backoff probability. Both approaches need to recalculate the parameters when the state of network changes. Reference [14] proposes the enhanced backoff (EBO) mechanism to migrate the collision by limiting the value of backoff counter. And, [15] also reduces effectively the collision by tuning the backoff counter according to the state of network. Reference [16] proposes a backoff algorithm to set an optimal contention window (CW) updating factor based on the theoretical analysis. Reference [17] proposes a distributed algorithm that enables each node to dynamically adapt its CW according to the channel congestion status. Both [16] and [17] can reduce the collision by tuning CW, but they need to recalculate the CW frequently. In despite, these works offer some valuable theoretical insights and approaches, they require radical changes to the standard and also are unknown under dense scenarios, and thus their adoptions are uncertain for real deployments.

Reference [18] reveals that algorithms offer equal transmission opportunities can significantly degrade the overall performance in a multi-rate WLAN environment. Therefore, some fairness algorithms by allocating fairly the airtime to all contending nodes are proposed to provide the better channel utilization. Reference [19] first proves mathematically that there exists certain correlation among four types of popular fairness criteria and proposes a distributed MAC algorithm that aims at achieving airtime fairness by selecting an appropriate CW size for each node. In [20]–[23], these authors also propose some CW tuning schemes to control the airtime. These algorithms can improve the airtime fairness to some extent. However, they need to calculate frequently the value of CW with the change of network environment. Reference [24] proposes a distributed FA algorithm to improve the airtime fairness by employing a two-level frame aggregation such as A-MSDU and A-MPDU. However, its accuracy and flexibility cannot be guaranteed, and with a high retransmission overhead. Lee *et al.* [25] and Hu *et al.* [26], the authors propose two algorithms tuning the size of packets according to the bitrates of the nodes. However, they will suffer a failed big size packet transmission. Reference [27] controls the airtime of each nodes by the Arbitration Inter frame Space (AIFS). But it requires recalculating the AIFS frequently. Reference [28] employs Transmission Opportunity (TXOP) to control the airtime of all nodes. However, it is not suitable to the delay-sensitive traffic. Therefore, Lin *et al.* [29] propose an airtime fairness algorithm for some delay-sensitive applications. Reference [30] presents a novel distributed airtime fairness algorithm, which runs multiple instances in a standard DCF backoff mechanism according to their bitrates. Because of multiple standard DCF processes operating in each node, it will result in a high collision rate. Besides, some cross-layer solutions [31], [32] also are proposed that involves both MAC and transport layers. But they are often inadequately and too complicated for implementation.

The aforementioned works can improve the performance of the system to some extent, but they usually only focus on the one aspect of collision rate or performance anomaly. It should be noticed that a comprehensive algorithm aiming simultaneously to these two problems can obtain the significant system performance. Therefore, we propose the DR algorithm, which can reduce the collision and improve the airtime fairness. Crucially, it can be readily applied to the legacy 802.11 DCF or EDCA mechanisms without any extra modifications on hardware.

III. DIFFERENTIATED RESERVATION (DR) ALGORITHM

A. DR ALGORITHM DESCRIPTION

As shown in Fig.1, we consider a network model with many nodes connecting to an AP. In the legacy 802.11 DCF, each node selects a random number as its backoff count, which means all nodes will always be in an intense contention. In this paper, we propose DR algorithm, in which all nodes can perform the transmission orderly after a series of successful contention. The main idea of the DR is setting backoff counter as a deterministic value and sending multiple packets once accessing to the channel upon a successful packet transmission. Compared to the legacy 802.11 DCF, it has the following features:

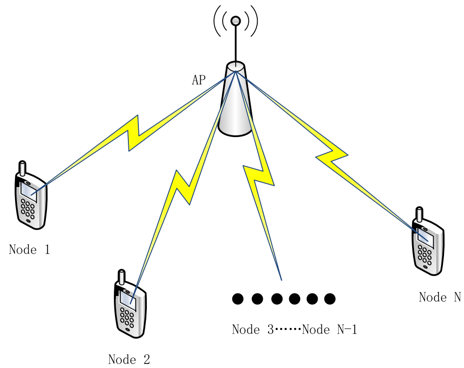

FIGURE 1. Network topology.

1) In DR, contending nodes will set its backoff counter to a deterministic value (DRV, Deterministic Reservation Value) after successful transmissions, and the DRV can be related to the value of Contention Window (CW) or independent on it.

2) The DR always seeks a suitable and relatively fixed time slot for the data transmission of each node, and thus collisions can be avoided when all the nodes seek out the corresponding time slots.

3) In DR, the CW is only a time-varying parameter adjusted among nodes that can be controlled by different random backoff methods, such as BEB, Exponential Increase Exponential Decrease (EIED) [33] and Linear Increase Linear Decrease (LILD) [34].

4) More significantly, the nodes operating DR can be reserved with different airtime for data transmission according to their features, such as their bitrates and traffic types. For example, if the airtime of differentiated reservation for each node is proportional to the bitrate of node, the airtime fairness can be easily achieved. Similarly, it is assigned based on the bitrate and the business category simultaneously, the performance and QoS (Quality of Service) can be governed evenly.

The detailed description for DR with BEB is shown in Algorithm 1. The DR is a fully decentralized and collision-free MAC mechanism. If the last transmission is successful and node i will transmit a unicast frame, the CW will be set to CW_{min} and the value of the backoff counter for node i in slot n (denoted as $S_i(n)$) a deterministic value DRV. Simultaneously, multiple packets can be transmitted during this successful channel access slot. If the last transmission is successful but node i will transmit broadcast/multicast frames, the CW will be set to CW_{min} and the $S_i(n)$ will be set to a random value in the range [0, CW]. In addition, if the last transmission is failed, the CW will be doubled, and the $S_i(n)$ will be set to a random value in the range [0, CW]. Therefore, the DR includes two states: reservation state and random state. In reservation state, the $S_i(n)$ of a node is set to a deterministic value DRV, otherwise it falls into random state. A node can switch to the reservation state from random state once it competes for the channel and performs a successful transmission. Then it sets the backoff counter as a deterministic value and can transmit multiple packets during its next accessing period.

Algorithm 1 The DR With BEB Algorithm

```
while the device is on do
    CW = CW_min
    flag = 0
    backoff stage = 0
    while there are packets to transmit do
        repeat
            if S_i(n) >0
                wait 1 slot
                S_i(n) = S_i(n) − 1
            else
                if flag = 1
                    transmit multiple packets
                else
                    transmit 1 packet
                if collision then
                    backoff stage = backoff stage + 1
                    CW = min(CW∗2+1,CW_max)
                    S_i(n) = rand(0,CW)
        until backoff stage == 7 or success
        backoff stage = 0
        if success then
            S_i(n) = DRV
            flag = 1
        else
            discard 1 packet
            S_i(n) = rand(0,CW)
wait until there are packets to transmit
```

With the operation of this algorithm, the more nodes will fall into the reservation state and thus the fewer collisions will occur in the network. If all nodes get into the reservation state, they will form a virtual ring for sharing the channel in an orderly manner. And the nodes in the reservation state will allow transmitting several packets during an accessing opportunity, which can reduce the collision and provide airtime fairness. The number of continuous transmitting packets (Nct) can be determined by the bitrate of nodes. Accordingly, the high bitrate nodes can get more airtime, and simultaneously it also avoids overusing of the shared channel by low bitrate nodes. In addition, in terms of the complexity, the DR algorithm has almost no extra complexity compared to the legacy 802.11. It just needs to judge whether the node's last transmission is successful, and then takes corresponding measures.

B. DR IMPLEMENTATION IN 802.11 NETWORKS

In this subsection, we discuss how to integrate DR into the legacy 802.11 DCF and 802.11e EDCA in multi-rate WLANs. Since both DCF and EDCA compete for the channel based on BEB mechanism, we concentrate on how to combine the DR with the BEB. For convenience, we use the prefix DR to note the algorithms, such as DR-DCF and DR-EDCA.

1) DR IN 802.11 DCF

To support the backward compatibility to DCF, the DR-DCF is modified as little as possible and only the CW value of BEB is changed. The reservation parameter DRV is set as $\lfloor (CW_{\min} + 1)/2 \rfloor$, since it is the average interval between the two packets successfully transmitted in BEB mechanism. In addition, we also let the number of continuous transmitting packets Nct be proportional to the bitrate of the node. For instance, the value of Nct is set as $\lfloor R_i/10^6 \rfloor$, where R_i represents the bitrate of node i. Thus, the nodes with high bitrates can send more packets at one channel accessing opportunity. This sophisticated assignment may result in the fair channel utilization finally, which will be analyzed and demonstrated theoretically in the section IV. For simplicity, when each node finds a suitable transmission time slot, a node with bitrate of R_i can transmit $\lfloor R_i/10^6 \rfloor$ packets at one time, so that it is easy to achieve airtime fairness and solve the problem of performance anomaly. The pseudocode for DR-DCF is shown in Algorithm 2.

Algorithm 2 The DR-DCF Algorithm

```
while the device is on do
    CW = CW_min
    flag = 0
    backoff stage = 0
    Nct = ⌊R_i/10^6⌋
    DRV = ⌊(CW_min + 1)/2⌋
    while there are packets to transmit do
        repeat
            if S_i(n) >0
                wait 1 slot
                S_i(n) = S_i(n) − 1
            else
                if flag = 1
                    transmit Nct packets
                else
                    transmit 1 packet
                if collision then
                    backoff stage = backoff stage + 1
                    CW = min(CW∗2+1,CW_max)
                    S_i(n) = rand(0,CW)
        until backoff stage == 7 or success
        backoff stage = 0
        if success then
            S_i(n) = DRV
            flag = 1
        else
            discard 1 packet
            S_i(n) = rand(0,CW)
wait until there are packets to transmit
```

To illustrate this algorithm, we also give an example shown in Fig. 2, where four nodes compete for the channel, and with bitrates of 1, 2, 5.5 and 11 Mbps respectively. One node can start to transmit packets once its backoff counter reduces

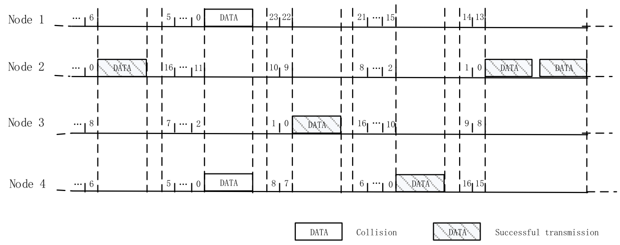

FIGURE 2. An example of the DR-DCF with 4 contention nodes.

to zero. Thus, node 2 first gets the transmission opportunity. After successful transmission, it sets its backoff counter to a deterministic value. Node 2 can transmit two packets at next transmission opportunity due to its bitrate (2Mbps). Owing to the same backoff counter value, node 1 and node 4 will collide each other. Thus, they revert to the standard random backoff mode and set the value of the backoff counter value in the range [0, CW]. Eventually, all nodes can enter a collision-free mode and perform orderly transmission, their sequences are node 2(2), node 3(5), node 1(11) and node 4(1). The number in the parenthesis represents the number of transmitting packets during a transmission opportunity.

2) DR IN 802.11e EDCA

The EDCA attempts to provide a prioritized channel access to all nodes according to their business category rather than the fairness of the channel. Thus, in DR-EDCA, the channel utilization will be governed simultaneously by the Access Category (AC) and the bitrate of the node. For the legacy EDCA, we use a parameter $Num(node_i)$ to denote the the number of packets that can be transmitted in a limited Transmission Opportunity (TXOP) time by node i. Since the Nct should be related to the bitrate of node and the AC of business simultaneously, for simplicity, it is set as the maximum value from $\lfloor R_i/10^6 \rfloor$ and $Num(node_i)$. Therefore, DR-EDCA solves the problem of performance anomaly and considers the QoS of business. In addition, in DR-EDCA, the CW varies based on the BEB mechanism. Due to the very small CW_{min} in EDCA, the reservation parameter *DRV* is initiated temporarily to $CW_{min}(AC) + 1$. Ultimately, the nodes with high priority business or high bitrate are expected to achieve high throughput. The pseudocode for DR-EDCA is shown in Algorithm 3.

Analogously, we also demonstrate an example in the Fig. 3, where four nodes with bitrate of 1, 2, 5.5 and 11 Mbps transmit respectively four kinds of business data (VI, BE, BK and VO). As shown, node 3 can transmit 5 packets at a transmission opportunity after it falls into the reserved state.

Algorithm 3 The DR-EDCA Algorithm

```
while the device is on do
    CW = CW_min
    flag = 0
    backoff stage = 0
    Nct = max{⌊R_i/10^6⌋, Num(node_i)}
    DRV = CW_min(AC) + 1
    while there are packets to transmit do
      repeat
          if S_i(n) >0
            wait 1 slot
              S_i(n) = S_i(n) − 1
          else
            if flag = 1
                transmit Nct packets
              else
                  transmit 1 packet
            if collision then
                  backoff stage = backoff stage + 1
                CW = min(CW∗2+1,CW_max(AC))
                 S_i(n) = rand(0,CW)
      until backoff stage == 7 or success
      backoff stage = 0
      if success then
          S_i(n) = DRV
          flag = 1
      else
          discard 1 packet
          S_i(n) = rand(0,CW)
wait until there are packets to transmit
```

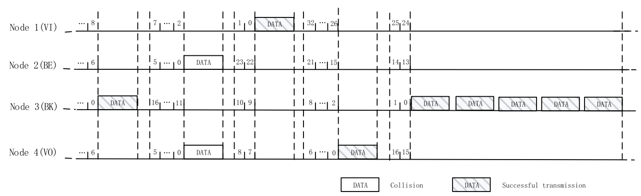

FIGURE 3. An example of the DR-EDCA with 4 contenders.

IV. NUMERICAL ANALYSIS

In this section, we theoretically analyze the throughput and the airtime fairness of DR algorithms. We consider a single 802.11 BSS (Basic Service Set) network consisting of one AP and several multi-rate contending nodes. Suppose that each node transmits the saturated unicast data and the length of each packet is the same.

A. THROUGHPUT

Firstly, we make an assumption that n nodes stay in the reservation state and the remaining N-n nodes stay in the random state. As mentioned above, there are *DRV* time-slots too. Therefore, the collision probability that n nodes stay in the reservation state can be calculated as follows.

$$P_{coll}(n) = 1 - \sum_{k=1}^{N} \frac{k}{N}\psi_n(k) \tag{1}$$

where, k is the number of collision-free time-slots in *DRV* time-slots and $\psi_n(k)$ is the probability for k collision-free time-slots in *DRV* time-slots when n nodes stay in the reservation state. We denote l as the expectation of a successful transmission payload size for all nodes when they stay in the reservation state, which can be calculated as follows:

$$l = E(l_i) = \sum_{i=1}^{N} \frac{l_i}{N} \tag{2}$$

where, l_i is the payload size of a successful transmission for node i. We can calculate l_i by: $l_i = l_{Basic} \cdot \lfloor R_i/10^6 \rfloor$, where l_{Basic} is the payload size of a packet.

Similarly, we also can calculate the expectation of a successful transmission time for all nodes when they stay in the reservation state by the following equation:

$$T_s = E\left(T_s^i\right) = \sum_{i=1}^{N} \frac{T_s^i}{N} \tag{3}$$

where, T_s^i is a successful transmission time of node i, which is given by:

$$T_s^i = \left\lfloor \frac{R_i}{10^6} \right\rfloor \cdot (T_{header}^i + T_{packet}^i + 2SIFS + T_{ACK}^i) - SIFS + DIFS \tag{4}$$

where, T_{ACK}^i, T_{header}^i and T_{packet}^i are transmission time for ACK (acknowledgement frame), header (includes PHY and MAC header), payload respectively. T_{packet}^i can be calculated as follows:

$$T_{packet}^i = \frac{l_{Basic}}{R_i} \tag{5}$$

Analogously, we calculate the expectation of a failed transmission time of all nodes caused by collision or channel errors as follows:

$$T_c = E\left(T_c^i\right) = \sum_{i=1}^{N} \frac{T_c^i}{N} \tag{6}$$

where, T_c^i is a failed transmission time of node i, which is given by:

$$T_c^i = T_{header}^i + T_{packet}^i + SIFS + ACK_{Timeout} \tag{7}$$

where, ACK_{Timeout} is the longest time for the node to wait for an ACK frame. We regard it as a failed transmission if the node has not received the ACK frame after ACK_{Timeout} expires. Thus, we have the system throughput, (8), as shown at the bottom of this page, where, σ is the minimum duration of a physical time-slot. P_{FER} is the probability of packet loss due to channel errors.

Fig. 4 shows that the system throughput of DR-DCF varies with the increase of the number of nodes. We add nodes in groups with 4 nodes for each group. The bitrates are 1Mbps, 2Mbps, 5.5Mbps and 11Mbps respectively. We can obtain the ideal result for DR-DCF algorithm when all nodes stay in the reservation state, which is denoted as Analytical-Max in Fig. 4. Analogously, we can obtain the extremely bad throughput Analytical-Min when all nodes stay in the random state. The simulation result also is given in Fig. 4 and confirms the analysis.

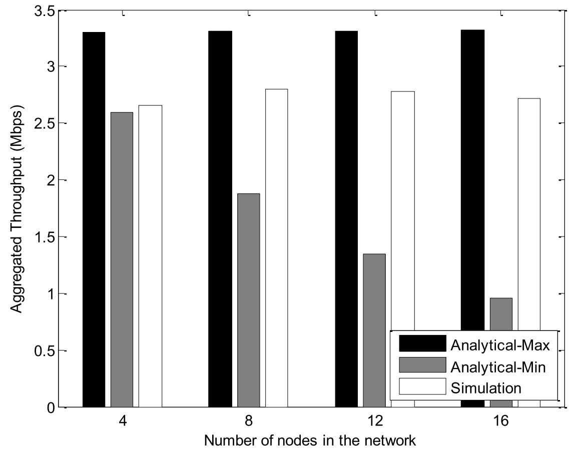

FIGURE 4. Analytical versus simulation throughput of DR-DCF.

B. FAIRNESS

We also analyze the airtime fairness of DR-DCF algorithm according to the Jain's Fairness Index (JFI) [35]. The fairness index that ranges from 0 to 1 and reflects the node fairness in time is defined as follows:

$$JFI(n) = \frac{\left(\sum_{i=1}^{N} T_{i,n}\right)^2}{N \sum_{i=1}^{N} T_{i,n}^2} \tag{9}$$

where, $T_{i,n}$ is the allocated airtime for node i.

In DR-DCF, node i sends only one packet when it stays in the random state, thus its duration's length is $T_{header}^i + T_{packet}^i + SIFS + ACK_{Timeout}$. Node i sends $\lfloor R_i/10^6 \rfloor$ packets in an accessing opportunity when it stays in the reservation state, and the duration's length is $\lfloor R_i/10^6 \rfloor \cdot \left(T_{header}^i + T_{packet}^i + 2SIFS + T_{ACK}^i\right) + DIFS - SIFS$. So we have:

$$\begin{aligned} T_{i,n} = {} & (P_{coll}(n) + P_{FER}) \\ & \cdot \left(T_{header}^i + T_{packet}^i + SIFS + ACK_{Timeout}\right) \\ & + (1 - P_{coll}(n) - P_{FER}) \\ & \cdot (\left\lfloor \frac{R_i}{10^6} \right\rfloor \cdot \left(T_{header}^i + T_{packet}^i + 2SIFS + T_{ACK}^i\right) \\ & + DIFS - SIFS) \end{aligned} \tag{10}$$

For simplicity, we ignore some terms such as T_{header}^i, T_{ACK}^i, SIFS, and DIFS since they are much smaller than T_{packet}^i. Analogously, we deal with the P_{FER} rather than $P_{coll}(n)$ too. Thus, we have:

$$T_{i,n} = (P_{coll}(n) - \left\lfloor \frac{R_i}{10^6} \right\rfloor \cdot P_{coll}(n) + \left\lfloor \frac{R_i}{10^6} \right\rfloor) \cdot \frac{l_{Basic}}{R_i} \tag{11}$$

$$S_{N,DRV,n} = \frac{(l \cdot (1 - P_{coll}(n) - P_{FER}) + l_{Basic} \cdot (P_{coll}(n) + P_{FER})) \cdot (1 - P_{coll}(n) - P_{FER})}{\frac{DRV}{N} \cdot \sigma + T_s \cdot (1 - P_{coll}(n) - P_{FER}) + T_c \cdot (P_{coll}(n) + P_{FER})} \tag{8}$$

TABLE 1. Simulation parameters.

Parameter	Value
Slot time	20μs
DIFS	50μs
SIFS	10μs
ACK	112bits
CW_{min}	31
CW_{max}	1023
$CW_{min}(AC)$	{7,15,31,31}
$CW_{max}(AC)$	{15,31,1023,1023}

Evidently, the lower the collision rate is, the better the airtime fairness is. Thus, the fairness will be declined as the density of node increases since it will result in higher collision. In dense network, our DR-DCF still can obtain the better fairness compared to the legacy 802.11 DCF algorithm The Fig. 5 shows the JFI of DR-DCF varying with the increase of the number of nodes, which demonstrates that our DR-DCF always obtains the better fairness even though it falls in the worst case (Analytical-Min: all nodes stay in the random state). We also present the simulation results to confirm this analysis.

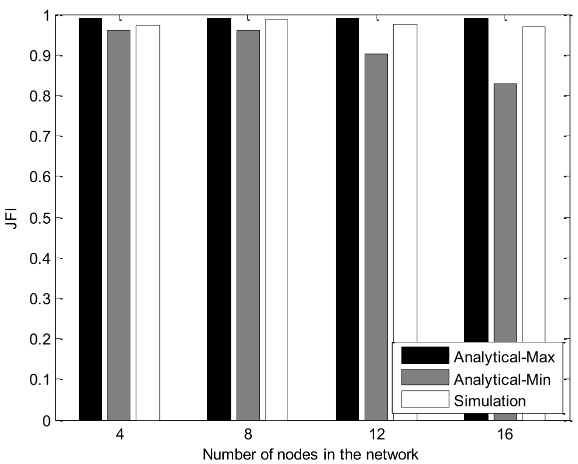

FIGURE 5. Analytical versus simulation JFI of DR-DCF.

V. SIMULATION RESULTS

To validate the numerical analysis, we have developed an algorithm library for DR-DCF and DR-EDCA based on the Matlab and compared them with the legacy IEEE 802.11 DCF, EDCA and SRB algorithms proposed in [9]. Our simulation considers a typical 802.11 WLAN scenario which contains an AP and some mobile nodes associating with it. Suppose that there is no hidden node and exposed node problem and each node also transmits the saturated unicast packet with fixed size of 1024 bytes. The other PHY and MAC parameters used in simulation are detailed in Table 1. Some unspecified parameters follow the IEEE 802.11n (2.4 GHz) amendment.

A. DR-DCF

In DR-DCF, we add nodes in groups and each group includes 4 nodes with bitrates of 1Mbps, 2Mbps, 5.5 Mbps and 11 Mbps respectively. Each simulation lasts 200 seconds and repeated 20 times. Finally, we average the simulation results.

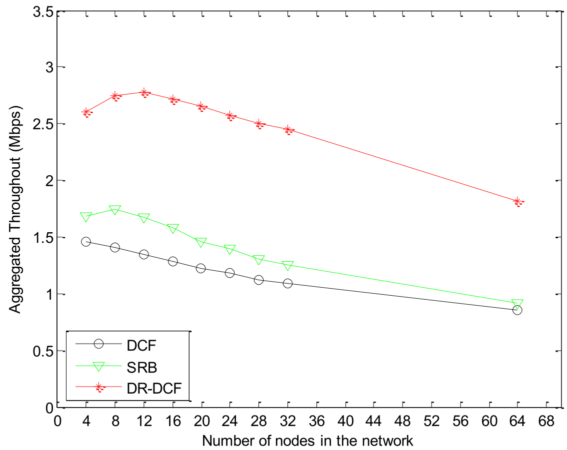

FIGURE 6. System throughput under various network densities.

1) THROUGHPUT AND COLLISION RATES

We first examine the throughput of the DR-DCF, legacy DCF and SRB algorithms under various node densities, which are shown in Fig.6. We note that the DR-DCF significantly outperforms the DCF and SRB due to its lower collision rate occurrence and the fair airtime allocation mechanism. The collision rate (the ratio of the number of collisions to the overall transmission attempts) also is shown in Fig.7. As indicated, the DR-DCF performs almost similar with the SRB, but rather than legacy 802.11 DCF. In particular, the DR-DCF almost operates without collision when the number of nodes is 4, but the collision rate of the DCF is close to 0.1. The collision rate of DR-DCF is still lower than that of DCF even under the 64 nodes scenario.

2) AIRTIME FAIRNESS

We also measure the airtime fairness among contending nodes, which is plotted in Fig. 8. The JFI of DR-DCF deceases with the increase of the density of nodes, but always keeping above 0.9 even when the number of nodes is 64. However, the JFI of DCF and SRB only keep on 0.65. This is due to the mechanism the continuous packet transmission is exploited in high bitrate nodes.

3) DOWNLOAD SCENARIOS

We also simulate the file download scenario with one AP and several contending nodes and each node downloads a 5MB file through the AP. The Fig.9 shows the maximum, average and minimum completion time for all nodes governed by three algorithms of DCF, SRB and DR-DCF, respectively. Though the fairness mechanism of DR-DCF results in the much difference completion time between high and low

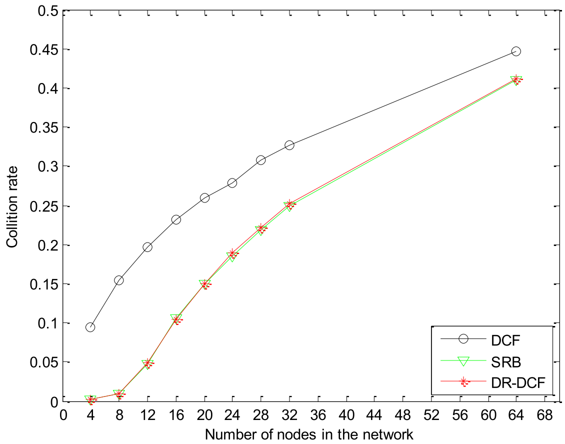

FIGURE 7. Collision rate under various network densities.

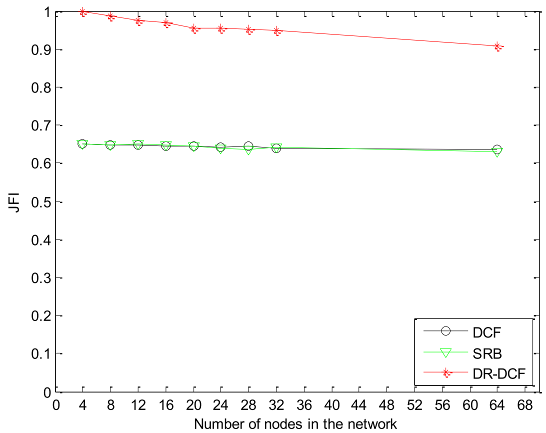

FIGURE 8. Airtime fairness.

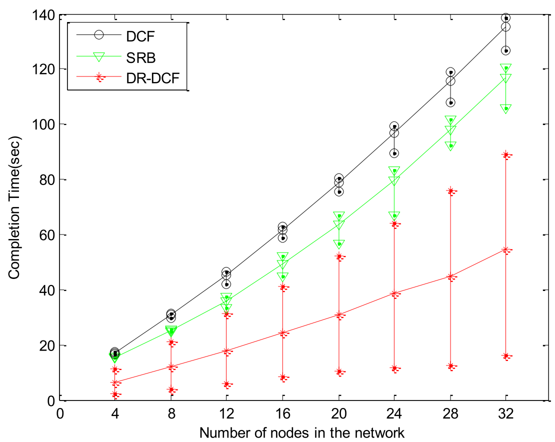

FIGURE 9. Completion time for all nodes download a 5MB file.

bitrate nodes, the average complete time of DR-DCF is much less than that of DCF and SRB. And in DR-DCF, the lowest bitrate node still completes the download task in a shorter time than all nodes operating in DCF and SRB algorithms do, which fully validates the efficient channel utilization of DR-DCF algorithm in a large download task.

B. DR-EDCA

We perform the DR-EDCA simulation by utilizing almost similar parameters with DR-DCF. Besides, we add 8 nodes to the simulation scenario each time, which considers two cases: the single-traffic case and the mixed-traffic case. We use best-effort (BE) or video (VI) data as the delivery traffic in the single-traffic case and mix half of each in the mixed-traffic case. In addition, for convenience of comparison, all traffic use the same AIFS (AIFS=2).

1) SINGLE-TRAFFIC CASE

Fig. 10(a), (b) and (c) show the throughput, JFI and collision rate in the single BE traffic case for the three algorithms. Similar to DR-DCF, DR-EDCA also exhibits a very good comprehensive performance compared with SRB and legacy EDCA in various network densities. In particular, the throughput of DR-EDCA is always highlighted due to its airtime fairness mechanism and low collision rates. As shown in Fig. 10(d), (c) and (f), in the single VI traffic case, the DR-EDCA outperforms the other two algorithms when the number of nodes is less than 16. Nevertheless, for dense scenarios (24 and 32 nodes), the collision rate of DR-EDCA increases sharply and its throughput and JFI are close to or even lower than that of the other two algorithms. The reason is that the EDCA enables the TXOP for VI traffic, which may result in a little confusion for several continuous packet transmissions during one channel access in dense scenarios.

2) MIXED-TRAFFIC CASE

We also study the mixing of BE plus VI traffic. In this mixed traffic case, half of the nodes in a group send high priority traffic (VI), and the other half send low priority traffic (BE). As indicated by Fig. 11, the DR-EDCA can improve significantly the throughput and JFI, and reduce the collision rates, especially in low density scenarios.

VI. GROUP-BASED DIFFERENTIATED RESERVATION (GDR) ALGORITHM

According to the above analysis and simulations, it is obvious that the performance of DR suffers from an increasing network density. Due to the more collision occurring, many nodes cannot get into the reservation state successfully after several turns of contention. As validated by the above numerical analysis, the JFI also cannot be guaranteed. Therefore, in this section, we also present a Group-Based Differentiated Reservation algorithm (GDR) to improve the performance under dense scenarios.

A. GDR DESCRIPTION

In GDR, all contending nodes are divided into several groups according to their bitrates. To reduce the collision, the number of nodes for each group should not be more than the Maximum Number Threshold (MNT). Each group is privileged a transmitting duration that is related to the number of nodes. The transmission procedures are almost similar to

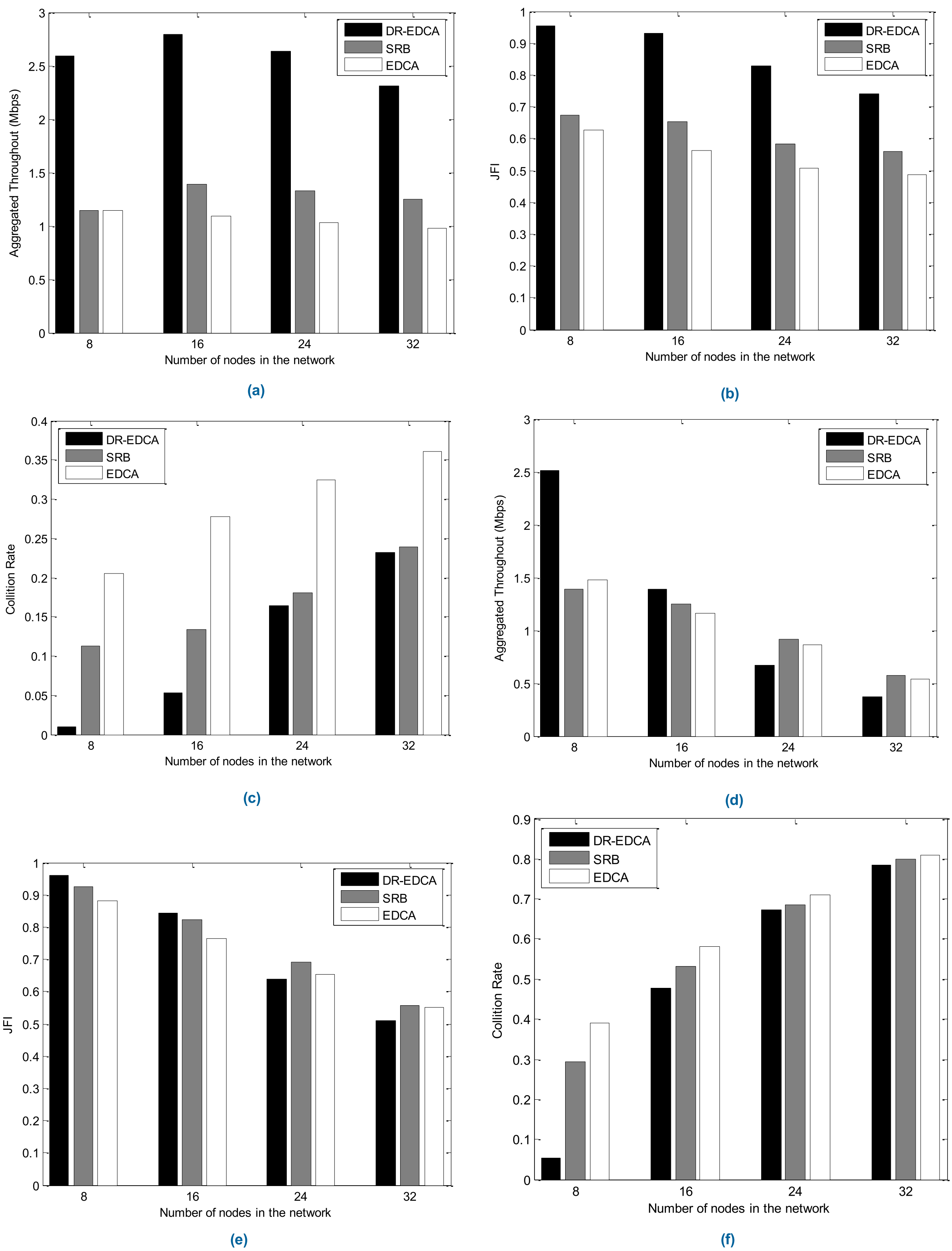

FIGURE 10. **(a) Throughput in the single BE traffic. (b) JFI in the single BE traffic. (c) Collision rate in the single BE traffic. (d) Throughput in the single VI traffic. (e) JFI in the single VI traffic. (f) Collision rate in the single VI traffic.**

the DR algorithm during each privilege transmitting duration. The GDR algorithm is detailed as follows:

1) When a node associates with an AP, it will get the grouping information from the AP.

2) The AP broadcasts periodically beacon frame that contains a group number, which indicates some nodes belonging to the same group can compete for the channel in this duration.

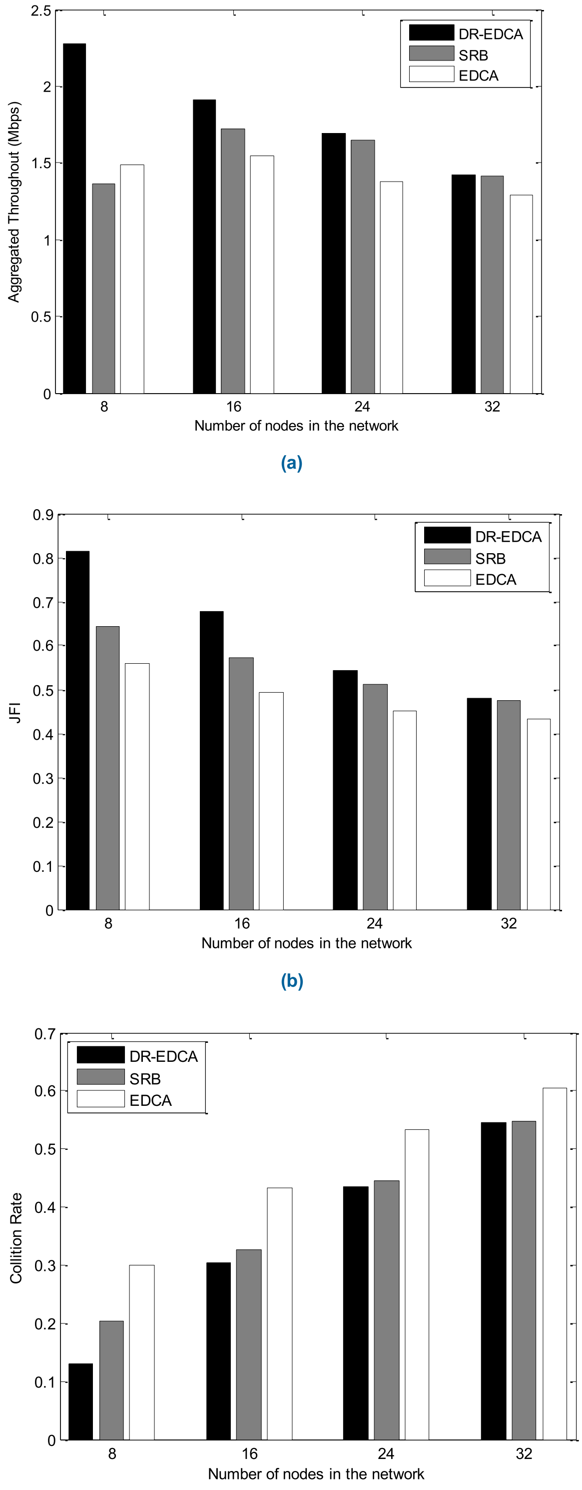

FIGURE 11. (a) Throughput in the mixed VI and BE traffic case. (b) JFI in the mixed VI and BE traffic case. (c) Collision rates in the mixed VI and BE traffic case.

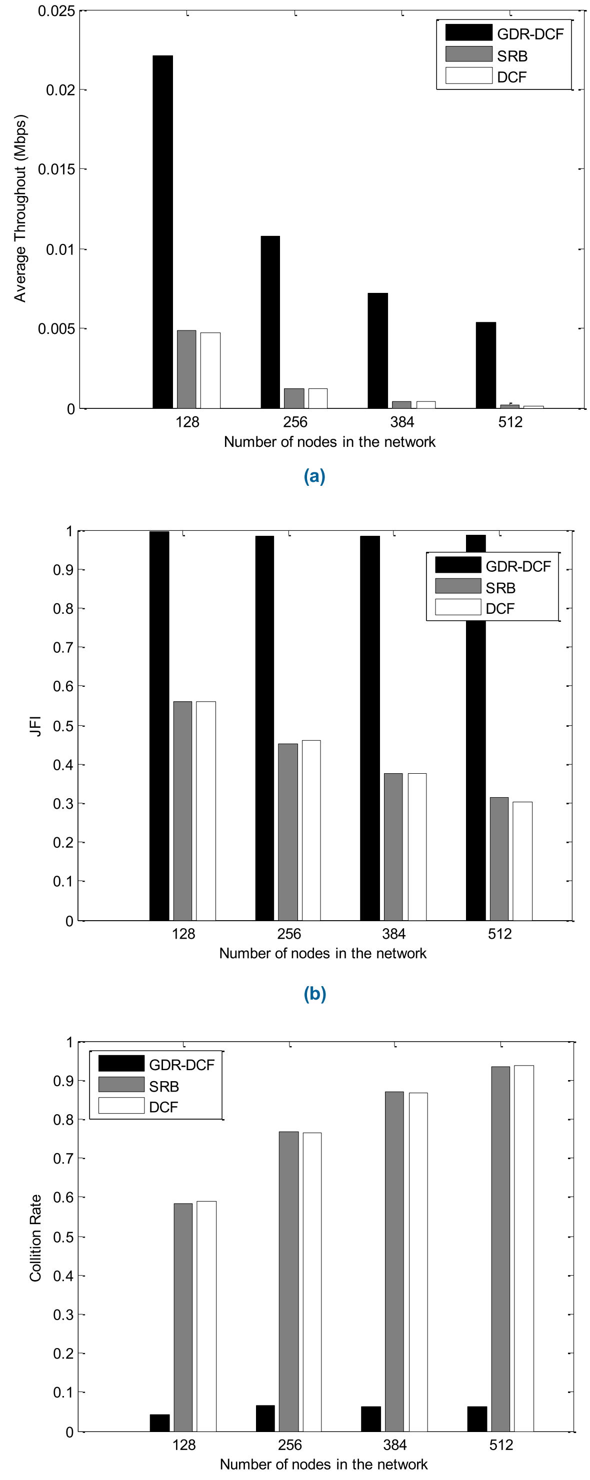

FIGURE 12. (a) Throughput of GDR-DCF under high dense scenarios. (b) JFI of GDR-DCF under high dense scenarios. (c) Collision rate of GDR-DCF under high dense scenarios.

3) The broadcasting interval of beacon frames is determined by the length of privilege transmitting duration.

4) The active group will freeze the backoff counters of all nodes and wait for their next active time at the end of current privilege transmit duration.

Consequently, only one group of nodes participate in contending for the channel simultaneously, which reduces the collision probability. However, the GDR algorithm also will accommodate some extra cost: (1) a one-byte field should be added to the association response frame and beacon frame to

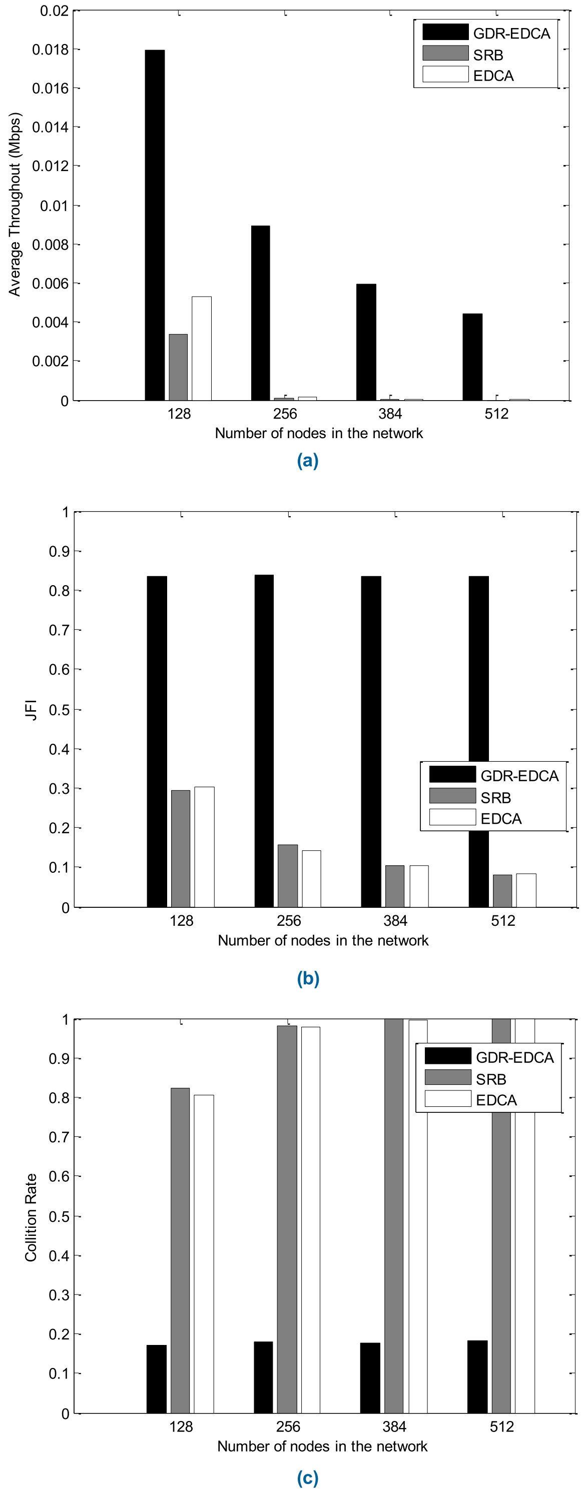

FIGURE 13. (a) Throughput of GDR-EDCA under high dense scenarios. (b) JFI of GDR-EDCA under high dense scenarios. (c) Collision rates of GDR-EDCA under high dense scenarios.

indicate the group number, and (2) the AP should broadcast the beacon frame at intervals. In spite of this extra modification, the GDR algorithm also can be easily applied to legacy 802.11 DCF and 802.11e EDCA. For convenience, we also

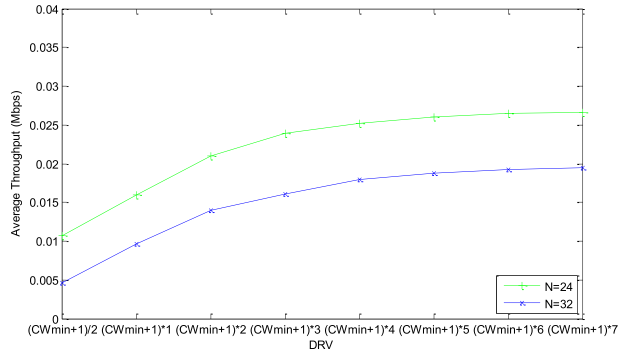

FIGURE 14. Throughput versus DRV under dense scenarios.

use the prefix GDR to note the two algorithms GDR-DCF and GDR-EDCA.

B. SIMULATION VALIDATION

1) GDR-DCF

In GDR-DCF, we increase the density by 4 groups once together, and each group consists of 32 nodes with bitrates of 1Mbps, 2Mbps, 5.5 Mbps and 11 Mbps respectively. Fig. 12(a), (b) and (c) show the throughput, JFI and collision rate respectively for the three algorithms. It is noticed that the GDR-DCF significantly outperforms the DCF and SRB, especially in dense scenarios.

2) GDR-EDCA

In GDR-EDCA, half of the nodes in a group send high priority VI traffic and the other half send low priority BE traffic. Besides, the simulation parameters and methodology is similar to the GDR-DCF. As shown in Fig. 13(a), (b) and (c), the GDR-EDCA also can achieve more significant performance in terms of throughput, JFI and collision rates.

VII. DISCUSSION

A. SYNCHRONIZATION

The DR algorithm builds on the underlying assumption that contending nodes decrease their backoff counters synchronously. However, this assumption does not always hold true in practice. It may break the synchronization due to the timing difference such as the use of AIFS, clock drift, hidden terminals, exposed terminals, carrier-sense errors and so on. These factors can lead to failed transmissions and deteriorate the performance of the DR algorithm. Nonetheless, the DR algorithm still can cope with the temporary extreme case and improve the performance in unsychronization scenario due to its rapid reverting strategies from deterministic backoff to legacy 802.11 random backoff mechanisms.

B. OPTIMIZED DRV

As observed above, the DRV has a significant effect on DR algorithm in terms of the collision rate and channel utilization. Therefore, we also conduct a heuristic experiment to choose a suitable *DRV*. Under 24 and 32 contending nodes scenarios, we observe the tendency of average throughput vary with the change of *DRV*. As shown in Fig.14, the throughput will not be improved and even be degraded when the *DRV* is greater than $(CW_{min}+1) * 4$. Thus, this is referred as the optimized *DRV* value in the aforementioned simulations. Besides, for GDR Algorithm, this experiment also indicates that a group with no more than 32 nodes is suitable capacity, which can balance the collision rate and the broadcast overhead in high dense scenarios.

VIII. CONCLUSIONS

In this paper, we present an elegant and effective DR algorithm in a multi-rate WLAN scenario. The DR algorithm is able to achieve throughput maximization as well as airtime fairness by enabling each node to set its backoff counter to a deterministic value and send multiple packets once accessing to the channel successfully. The theoretical analysis and simulation also validate that our proposed algorithm outperforms the standard 802.11 algorithm and the SRB algorithm. Moreover, we investigate the limitation of the DR algorithm and propose an enhanced GDR algorithm to improve its performance under dense scenarios. As a part of our future work, we plan to implement our proposed algorithms in commodity IEEE 802.11 hardware and test their performance using real-world experiments.

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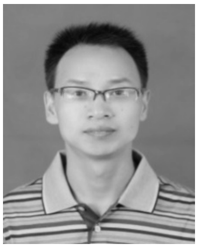

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