A Time Fairness-Based MAC Algorithm for Throughput Maximization in 802.11 Networks

Yuan Le, Liran Ma, *Member, IEEE*, Wei Cheng, Xiuzhen Cheng, *Senior Member, IEEE*, and Biao Chen, *Member, IEEE*

Abstract—This paper focuses on designing a distributed medium access control algorithm for fairly sharing network resources among contending stations in an 802.11 wireless network. Because the notion of fairness is not universal and there lacks a rigorous analysis on the relationships among the four types of most popular fairness criteria, we first mathematically prove that there exist certain connections between these types of fairness criteria. We then propose an efficient medium access algorithm that aims at achieving time fairness and throughput enhancement in a fully distributed manner. The core idea of our proposed algorithm lies in that each station needs to select an appropriate contention window size so as to fairly share the channel occupancy time and maximize the throughput under the time fairness constraint. The derivation of the proper contention window size is addressed rigorously. We evaluate the performance of our proposed algorithm through an extensive simulation study, and the evaluation results demonstrate that our proposed algorithm leads to nearly perfect time fairness, high throughput, and low collision overhead.

Index Terms—Wireless LANs, MAC protocol, time-fairness, contention window, throughput enhancement

1 Introduction

A fundamental problem in 802.11 wireless networks is how to design medium access control algorithms for sharing network resources among contending stations. The primary objective is to fully utilize all available resources (such as channel access opportunity or channel occupancy time) while maintaining a certain "fairness" in the allocations among different stations. There exist four types of popular fairness criteria: throughput fairness, time fairness, max-min fairness, and proportional fairness. Throughput fairness and time fairness try to distribute the resources—throughput or channel occupation time—to all stations equally [1]. Max-min fairness and proportional fairness, on the other hand, are defined as optimization problems. A common understanding of max-min fairness [2] is that resources are allocated in a way such that the minimum share in a network is maximized. In contrast, proportional fairness [3] argues that resources should be shared so as to maximize an objective function describing the overall utility of the contending stations.

There are many proposed algorithms in the literature that either explicitly or implicitly satisfy one or more types of the four fairness criteria. For example, it is well known that the default 802.11 standard [4] employs the Distributed Coordination Function (DCF) as its Medium Access Control (MAC) method. To be specific, DCF utilizes a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme along with an exponentially increased Contention Window (CW). It has been shown that DCF provides an equal long-term transmission opportunity to each station in the network [5]. If each station has the same bitrate and uses the same frame size, throughput fairness can be achieved.

However, there are multiple bitrates defined in the 802.11 standard so as to adapt to channel condition dynamics. Some studies [6], [7] have revealed that in a multi-rate environment, throughput fairness (i.e., the equal transmission opportunity) can sometimes severely degrade the overall network performance. The main reason for the performance degradation lies in the fact that the channel can be excessively occupied by slow bitrate stations because it takes longer time for them to transmit the frame of the same size than high nitrate stations. To remedy this problem, many algorithms that target different types of fairness have been proposed. For an instance, Banchs et al. proposed a throughput allocation criterion and two allocation schemes that are based on the proportional fairness in [8]. Another proportional fairness based algorithm is proposed in [9]. To further improve the performance, *Idle Sense* is proposed in [10] where the contention windows size is adjusted based on an estimation of the number of idle slots and station bitrates. Idle Sense is able to closely balance the channel occupancy time among stations in certain scenarios, and thus is regarded as one of the arguably best time fairness based channel access algorithms.

With these fairness criteria and their associated medium access control algorithms, it becomes imperative to find a way to rigorously evaluate their performance and potentials. There exist a few previous work attempting to address this

- *Y. Le and X. Cheng are with the Department of Computer Science, The George Washington University, Washington, DC 20052. E-mail: ppzt@gwmail.gwu.edu; cheng@gwu.edu.*
- *L. Ma is with the Department of Computer Science, Texas Christian University, Fort Worth, TX 76129. E-mail: l.ma@tcu.edu.*
- *W. Cheng is with the Department of Computer Science, Virginia Commonwealth University, Richmond, VA 23284. E-mail: ian.w.cheng@gmail.com.*
- *B. Chen is with the Department of Computer and Information Science, University of Macau, Macau, China. E-mail: bchen@umac.mo.*

Manuscript received 06 Oct. 2012; revised 27 Aug. 2013; accepted 02 Sep. 2013. Date of publication 12 Sep. 2013; date of current version 12 Dec. 2014. Recommended for acceptance by K. Li.
For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TC.2013.186

problem. For instances, Tan et al. [6] show that time fairness provides better performance over throughput fairness in a multi-rate WLAN environment, and in [11], a MAC algorithm that can achieve proportional fairness is proposed and compared with various algorithms that achieve different fairness criteria in an 802.11e test-bed. However, the relationships among these fairness criteria have never been mathematically studied in the literature. The primitive question of which fairness criterion is better remains unanswered. In addition, it is difficult to precisely design and comprehensively evaluate medium access control algorithms without knowing which fairness criterion should be preferred over some other types of fairness criteria.

Bearing these challenges in mind, our paper begins with a study of the four types of fairness criteria. We are the first to mathematically prove that there exist certain relationships among the four types of fairness criteria. Specifically, max-min fairness leads to throughput fairness in a saturated network, and proportional fairness leads to time fairness if a network is saturated and stable. With the knowledge on these relationships, we propose a novel time fairness based medium access algorithm for a multi-rate wireless LAN. The core idea of our proposed algorithm is that each station needs to select an appropriate contention window size so as to jointly achieve fair sharing of channel occupancy time and throughput maximization. We rigorously derive the formula to calculate the contention window size. In addition, we evaluate the performance of our algorithm via a comprehensive comparative simulation study. The evaluation results demonstrate that our proposed algorithm possesses the following nice features: i) Channel occupancy time is nearly equally shared among stations; ii) Throughput can be significantly improved under the fairness constraint; iii) Collision overhead is greatly reduced when the network presents rich bitrate diversity; iv) The optimal content window size can be calculated by each station in a fully distributed manner.

The rest of the paper is organized as follows. Section 2 discusses the related work. Preliminary knowledge is illustrated in Section 3. Our fairness analysis is presented in Section 4. Section 5 describes the design of our proposed algorithm. We detail the evaluation settings and results in Section 6 and Section 7, respectively. Finally, we conclude the paper in Section 8.

2 Related Work

In this section, we summarize the related work under the categories of fairness studies and medium access control algorithms. There exist four widely used fairness criteria: throughput fairness, time fairness, max-min fairness, and proportional fairness. Jain et al. proposes a formal way to define and evaluate resource (such as throughput and channel access time) sharing fairness in [1]. The basic idea of max-min fairness is to maximize the minimum share in a network [2]. In [3], Kelly et al. propose the proportional fairness criterion that maximizes a logarithm utility function. There exist some work such as [6], [12] attempting to address the relationships between different types of fairness. However, the studies from the previous work lack rigorous proof.

There are many studies on the default 802.11 medium access control algorithm (i.e., DCF) [5]-[7], [13]-[16] in the literature. In one of the earlier seminal work [5], *Bianchi* evaluates the throughput and frame transmission probability of the 802.11 DCF using a *Markov* chain. In this work, an analytical model with ideal channel conditions is adopted and station bitrates are assumed to be identical. It concludes that 802.11 DCF provides throughput fairness to all stations if they have the same bitrate and adopt the same frame size. However, there are multiple bitrates defined in the 802.11 standard. Because of the rich dynamics of the wireless channel [13], a station needs to transmit at an appropriate bitrate so that the bit error rate can be controlled in an acceptable level. Generally, stations that are far away from an AP may select a low bitrate, while stations close to the AP may select a high bitrate. This leads to bitrate diversity where contending stations associated to the same AP use different bitrates [14]. Previous work [6], [7] indicate that in a bitrate diverse environment, algorithms that offer equal transmission opportunities can significantly degrade the overall performance.

To address the performance degradation problem, several algorithms are proposed to improve the performance of the default 802.11 DCF by dynamically adjusting the contention window size. A method of estimating the number of active stations using the a *Kalman* filter is proposed in [17]. Based on the estimated number of stations, a suitable contention window size can be calculated. To further improve the performance, Cal et al. derive the average size of the contention window that can maximize the throughput in [18]. With this average contention window size, a distributed algorithm is proposed to enable each station to tune its backoff algorithm at run-time. In [19], stations can exponentially decrease their backoff timer after observing a number of empty slots, and thus the channel utilization is enhanced. Aad et al. propose a simple slow contention window decrease function in [20], in which the contention window size is reduced by half instead of being reset to the initial value after a successful transmission.

Additionally, there exist access control algorithms that are directly based on certain types of fairness such as time fairness and proportional fairness. For example, the long term fairness of DCF is investigated through the conditional probabilities of the number of inter-transmissions in [9]. In [21], a priority-based fair MAC algorithm is proposed to jointly consider weighted fairness and throughput enhancement. In [22], a centralized flow coordination approach is proposed to achieve proportional fairness in enterprise wireless mesh networks. Another proportional fairness based allocation algorithm is proposed in [8]. In this allocation algorithm, a station sets the initial contention window size inversely proportional to its bitrate. In contrast to adjusting the contention window size, a rate control based access scheme is proposed in [23], in which several rate control mechanisms are combined to achieve proportional fairness. However, this algorithm is not suitable for a network with self rate adaptation. Another time fairness based resource allocation algorithm is developed in [6]. This algorithm runs on each AP to regulate the frame transmissions. The channel occupation time is equally distributed to each station. However, this algorithm requires a centralized control unit on the AP side, and thus it is not adaptive to dynamic environment. In [24], the concept of

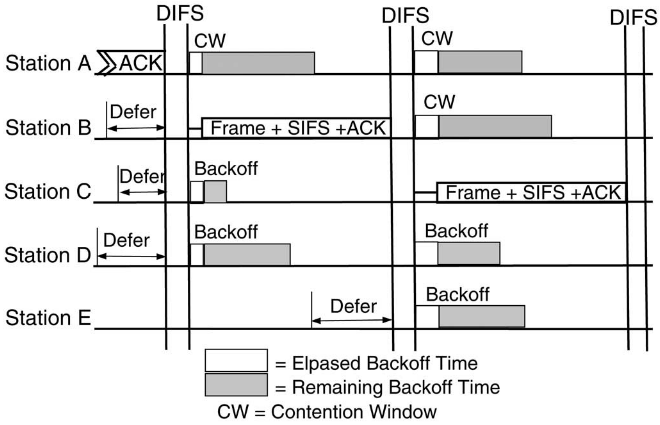


Fig. 1. 802.11 DCF Backoff Procedure.

transmission opportunity is adopted to provide equal channel transmission time in an 802.11e network. Recently, another time fairness based algorithm is devised in [10] where the contention window size is adjusted based on the number of idle slots. Specifically, each station monitors the channel status and evaluates the number of continuous idle slots. The contention window size is increased or decreased if the estimated number of idle slots is greater or less than a predefined target value, respectively. We show that our proposed algorithm outperforms both [8] and [10] through an extensive simulation study.

3 Preliminary

We begin by introducing some basic knowledge related to the default 802.11 medium access control and describing our network model.

3.1 802.11 DCF

According to the 802.11 standard, DCF employs the CSMA/CA with binary exponential backoff to regulate medium access. To be specific, a station first senses the channel before transmitting a frame. If the channel is busy, the station defers the transmission and continuously senses the channel. Once the channel is free for a Distributed Inter Frame Space (DIFS) duration, the station can start the transmission after a backoff period. The duration of the backoff period is randomly chosen from a uniform distribution in the range of [0, CW], where CW is the current contention window. During the backoff period, the backoff counter is decreased by one for each time slot in which the channel is free. Otherwise, the backoff counter is frozen until the channel becomes free again for a DIFS duration. When the backoff counter reaches zero, the station can begin its transmission.

After a frame has been correctly received at the destination station for a Short Inter Frame Space (SIFS) duration, an ACK frame needs to be sent back to the sender. If the ACK frame is received by the sender correctly, the frame transmission is considered successfully completed. Subsequently, the sender will reset its CW value to CW_{min} and enter the next transmission competition cycle. On the other hand, if the ACK frame is not received after a timeout period, a collision is assumed to have occurred. Thus, the sender executes exponential backoff by doubling its CW value and begin another transmission attempt. By default, CW_{min} is 31 and CW_{max} is 1023. An example backoff procedure with 5 competing stations is listed in Fig. 1.

TABLE 1
Notations and Definitions

symbol	Semantics
U	Set of stations
n	Number of stations, $n = \|U\|$
W	The aggregate throughput
W_i	The throughput of station i
s_i	The average package size of station i
r_i	The bitrate of station i
r_c	The basic bitrate for transmitting the ACK frame
T_t^i	Transmission duration of station i
T_f	Average duration of failure transmission
T_s	Idle slot duration
P_e^i	Attempt probability of station i
P_t	Aggregate successful transmission
P_t^i	Successful transmission probability of station i
P_{idle}	Channel idle probability
P_f	Failure transmission probability
CW_i	Contention window size of station i

In addition to the backoff procedure, Request To Send (RTS) and Clear to Send (CTS) may be enabled to further reduce collisions. However, RTS/CTS may incur prohibitive overhead in certain situations. Hence, we assume the RTS/CTS option is disabled in our model and analysis.

3.2 System Model

We model a typical 802.11 multi-rate wireless LAN by one AP and n competing stations. Each station is associated with the AP and shares the same channel with the other stations. We assume the network is saturated so that each station always has some frames to transmit. The notations and definitions are summarized in Table 1.

In our model, we adopt the basic DCF CSMA/CA protocol with no exponential backoff after a failure transmission. That is because such exponential backoff is the major source of short-term unfairness in DCF [10]. We denote the attempt probability P_e^i of a station i as the probability that station i attempts to transmit a frame. As the stations may have different contention window sizes, the attempt probability P_e^i can be calculated as in [7]:

$$P_e^i = \frac{2}{CW_i + 1}. \tag{1}$$

For a station that attempts to transmit a frame. The station can successfully transmit the frame if and only if it is the only station that attempts to transmit. Thus, the probability of station i to transmit successfully is:

$$P_t^i = P_e^i \cdot \prod_{j \neq i} (1 - P_e^j). \tag{2}$$

Similarly, the channel is idle if and only if no station is in transmission. Hence we can compute the probability of the channel being idle as:

$$P_{idle} = \prod_{i=1}^{n}(1 - P_e^j). \tag{3}$$

And the probability of a failure transmission, caused by collision, is:

$$P_f = 1 - \sum_{i=1}^{n} P_t^i - P_{idle}. \tag{4}$$

In our paper, we adopt a similar throughput definition as that in [5]. Consider a station's transmission in a unit time slot, the expectation of its transmission payload can be expressed as

$$E(L) = P_t^i s_i, \tag{5}$$

and the average length of a unit time slot can be calculated by:

$$E(T_{slot}) = \sum_{j=1}^{n}(P_t^j T_t^j) + P_f T_f + P_{idle} T_s. \tag{6}$$

As a result, the throughput of station i can be expressed as the ratio:

$$W_i = \frac{E(L)}{E(T_{slot})} = \frac{P_t^i s_i}{\sum_{j=1}^{n}(P_t^j T_t^j) + P_f T_f + P_{idle} T_s}. \tag{7}$$

And the aggregate throughput is the sum of the per station throughput:

$$W = \frac{\sum_{i=1}^{n} P_t^i \cdot s_i}{\sum_{i=1}^{n} P_t^i T_t^i + P_f T_f + P_{idle} T_s}. \tag{8}$$

We assume the following parameters are known constants in our analysis: the transmission duration T_t^i of a station i, the average duration of a failure transmission T_f, and the idle slot duration T_s. T_t^i depends on the bitrate of station i and the average packet size s_i. For convenience, we further assume that all the stations have the same s_i. Similarly, T_f is represented by the maximum time cost incurred by a failure transmission. T_s is defined by the IEEE 802.11 standard.

4 Fairness Analysis

In this section, we study the relationships among the four types of widely used fairness: throughput fairness, max-min fairness, time fairness, and proportional fairness. It is obvious that the time fairness and throughput fairness are equivalent if and only if the bitrates of all the stations are identical. Hence, in this section we focus on the following two pairs of relationship: the throughput fairness versus the max-min fairness, and the time fairness versus the proportional fairness. Specifically, we show that in a saturated network, all the stations in a max-min fairness should have equivalent throughput, and thus prove that the max-min fairness leads to the throughput fairness. Similarly, channel occupation time of stations in a proportional fairness should be equal to each other in a saturated wireless network, so the proportional fairness can lead to the time fairness under certain constraints.

From the two pairs of relationships, we can infer that the proportional fairness outperforms the max-min fairness in a multi-rate wireless network. This inference is consistent with the current research results [8]-[10], [25]. Furthermore, the time and throughput fairness is easy to achieve and implement, while the max-min and proportional fairness are NP-hard problems. The inner connections between these fairness criteria provide a possible idea to approximately achieve the max-min and proportional fairness. That is, we can achieve the throughput or time fairness first, then try to optimize the objective function to achieve the max-min or proportional fairness.

4.1 Throughput Fairness Versus Max-Min Fairness

The max-min fairness [2] allocates resources as equal as possible subject only to the constraints imposed by link capacities. To be specific, it allocates the throughputs among stations in a manner such that the stations with the minimum throughput cannot gain any more by reducing the throughput of some other stations with higher throughput. Thus, the max-min fairness allocation can be expressed as

$$\max\min(W_i). \tag{9}$$

Compared with the throughput fairness, we have:

Theorem 1. *If a network is saturated and stable, max-min fairness can lead to throughput fairness.*

Proof. Assume that A is a max-min fairness throughput allocation, and A does not achieve throughput fairness. Let i be the station with the minimum throughput W_i in A. From the assumption we have:

$$\exists 1 \leq j \leq n, j \neq i, W_j > W_i.$$

Subsequently, by comparing W_i with W_j, we have $P_t^i < P_t^j$, and thus $P_e^i < P_e^j$.

Consider another throughput allocation A'. In A' we reduce the attempt probability of station j to the same value as that of station i, and keep the attempt probabilities of the remaining stations unchanged. As W_i is the minimum throughput in A, we have $P_t^i \leq P_t^k, \forall k \neq i$. Hence, in allocation A', station i should have the minimum throughput as well. We denote this throughput as W_i'. Now we show that W_i' must be greater than W_i. Before comparing W_i and W_i', we can simplify W_i first. Consider W_i, we have:

$$\begin{aligned} s_i/W_i &= \frac{\sum_{i=1}^{n} P_t^i T_t^i + P_f T_f + P_{idle} T_s}{P_t^i} \\ &= \frac{\sum_{k\neq j} P_t^k T_t^k - T_f \sum_{k\neq j} P_t^k + (T_s - T_f) P_{idle}}{P_t^i} && (*) \\ &\quad + \frac{P_t^j T_t^j}{P_t^i} && (**) \\ &\quad + \frac{(1 - P_t^j) T_f}{P_t^i}. && (***) \end{aligned}$$

We can see that portion (*) is independent of P_e^j. In addition, portion (**) is decreased if we reduce the attempt probability of station j from P_e^j to P_e^i. Subsequently, we only need to examine portion (***). For convenience, we denote $\pi_0 = \frac{(1-P_t^j)}{P_t^i}$, and let π_0' be the corresponding π_0 after we decrease the P_e^j to P_e^i. By adopting Eq. (2) to portion (***), we have:

$$\pi_0 = \frac{1 - P_e^j \prod_{k \neq j} (1 - P_e^k)}{P_e^i \prod_{k \neq i} (1 - P_e^k)},$$
$$\pi_0' = \frac{1 - P_e^i \prod_{k \neq j} (1 - P_e^k)}{P_e^i (1 - P_e^i) \prod_{k \neq i,j} (1 - P_e^k)},$$
$$\frac{\pi_0}{\pi_0'} = \frac{(1 - P_e^i)[1 - P_e^j \prod_{k \neq j} (1 - P_e^k)]}{(1 - P_e^j)[1 - P_e^i \prod_{k \neq j} (1 - P_e^k)]}. \quad (10)$$

We further denote $\Delta_1 = (1 - P_e^i)[1 - P_e^j \prod_{k \neq j} (1 - P_e^k)]$ and $\Delta_2 = (1 - P_e^j)[1 - P_e^i \prod_{k \neq j}(1 - P_e^k)]$. Then we have:

$$\begin{aligned}\Delta_1 - \Delta_2 &= -P_e^j \prod_{k \neq j}(1 - P_e^k) - P_e^i + P_e^i \prod_{k \neq j}(1 - P_e^k) + P_e^j \\ &= (P_e^j - P_e^i)[1 - \prod_{k \neq j}(1 - P_e^k)] > 0. \quad (11)\end{aligned}$$

From Eqs. (10) and (11) we observe that by reducing P_e^j to P_e^i, the portion (***) is decreased as well, so the throughput of station i is increased. This is contradict to the basic assumption of max-min fairness. Hence, we have proved that max-min fairness leads to throughput fairness in a saturated network. □

4.2 Time Fairness Versus Proportional Fairness

In the proportional fairness allocation [3], each station is assigned with a priority ω_i. Resources are allocated to stations in a manner such that the utility function $U = \sum_{i=1}^n \omega_i \ln W_i$ is maximized. Compared with the time fairness, we have:

Theorem 2. *If a network is saturated and stable, and all stations have the same priority ω_i, then the proportional fairness leads to the time fairness.*

Proof. For each station, the throughput can be expressed as:

$$W_i = \frac{P_t^i T_t^i r_i}{\sum_{j=1}^n (P_t^j T_t^j) + P_f T_f + P_{idle} T_s},$$

where r_i is the bitrate of station i and $P_t^i T_t^i$ is the expectation of transmission time. Consequently, the expectation of the channel occupation ratio of station i can be expressed as:

$$t_i = \frac{P_t^i T_t^i}{\sum_{j=1}^n (P_t^j T_t^j) + P_f T_f + P_{idle} T_s}. \quad (12)$$

Thus, we have $W_i = t_i r_i$. Since the network is saturated, the overall channel occupation ratio converges to a constant when the network is stable. Hence, we have $\sum_{i=1}^n t_i = c$, where c is a constant that is smaller than 1. In order to guarantee proportional fairness, we need to maximize the utility function:

$$\max \sum_{i=1}^n \ln(r_i t_i). \quad (13)$$

It is equivalent to maximize

$$\prod_{i=1}^n (r_i t_i) = \prod_{i=1}^n r_i \cdot \prod_{i=1}^n t_i.$$

As the $\{r_i\}$ are pre-defined constants, $\prod_{i=1}^n r_i$ is a constant as well. With the constraint that $\sum_{i=1}^n t_i = c$, we have that $\prod_{i=1}^n t_i$ can be maximized if and only if

$$t_1 = t_2 = \ldots = t_n. \quad (14)$$

This proves that proportional fairness leads to time fairness when the network is saturated and stable. □

5 Our Algorithm

The core idea of our proposed algorithm is straightforward: each station needs to select an appropriate contention window size so as to jointly achieve time fairness and throughput enhancement. We choose time fairness over other types of fairness for the following two reasons. Firstly, it has been shown that time fairness provides better performance in a multi-rate WLAN environment [6]. Secondly, we have proved that the proportional fairness leads to the time fairness in a saturated network.

5.1 Analysis of Contention Window Size

In this section, we illustrate how to compute the appropriate contention window size for each station so as to achieve both time fairness and throughput improvements. Let us start with the time fairness. If any two stations i and j fairly share the channel access time, we have:

$$T_t^i P_t^i = T_t^j P_t^j. \quad (15)$$

According to Eq. (2), we have:

$$\frac{P_t^i}{P_t^j} = \frac{P_e^i \cdot \prod_{k \neq i} (1 - P_e^k)}{P_e^j \cdot \prod_{l \neq j} (1 - P_e^l)} = \frac{P_e^i (1 - P_e^j)}{P_e^j (1 - P_e^i)}. \quad (16)$$

Next, applying Eq. (1) into Eq. (16), we obtain:

$$\begin{aligned}\frac{P_t^i}{P_t^j} &= \frac{\frac{2}{CW_i+1} \cdot (1 - \frac{2}{CW_j+1})}{\frac{2}{CW_j+1} \cdot (1 - \frac{2}{CW_i+1})} \\ &= \frac{(CW_j + 1) \cdot (\frac{CW_j - 1}{CW_j + 1})}{(CW_i + 1) \cdot (\frac{CW_i - 1}{CW_i + 1})} \\ &= \frac{CW_j - 1}{CW_i - 1}. \quad (17)\end{aligned}$$

Combining Eqs. (15) and (17), we have:

$$\frac{CW_i - 1}{CW_j - 1} = \frac{P_t^j}{P_t^i} = \frac{T_t^i}{T_t^j}. \quad (18)$$

Thus, for two arbitrary stations i and j that fairly share the channel access time, their contention window sizes have the following relationship:

$$CW_j = 1 + \frac{T_t^j}{T_t^i}(CW_i - 1). \quad (19)$$

With this relationship, we now can show how to calculate the appropriate contention window size for each station so as to maximize the aggregate throughput. Recall the aggregate throughput expression in Eq. (8) and notice that $P_t^i T_t^i = P_t^j T_t^j$ for all i and j. Maximizing the aggregate throughput is equivalent to minimize the following cost function:

$$\begin{aligned}
&\frac{nP_t^iT_t^i + P_fT_f + P_{idle}T_s}{\sum_{j=1}^n P_t^j} \\
&= \frac{nP_t^iT_t^i + (1-\sum_{j=1}^n P_t^j - P_{idle})T_f + P_{idle}T_s}{\sum_{j=1}^n (\frac{P_t^iT_t^i}{T_t^j})} \\
&= \frac{1}{\sum_{j=1}^n (1/T_t^j)} - T_f + \frac{(1-P_{idle})T_f + P_{idle}T_s}{P_t^iT_t^i \sum_{j=1}^n (1/T_t^j)}.
\end{aligned} \tag{20}$$

In Eq. (20), T_t^j and T_f are constants for a given network. According to 802.11 DCF, T_t^j, the average time cost of a successful transmission for station j, can be expressed as:

$$T_t^j = DIFS + SIFS + s_j/r_j + ACK/r_c. \tag{21}$$

And, T_f, the maximum time cost for a unsuccessful transmission, can be calculated as:

$$T_f = DIFS + SIFS + s_{max}/r_{min} + ACK/r_c. \tag{22}$$

where s_{max} is the maximum packet payload and r_{min} is the minimum possible bitrate.

The variables in Eq. (20) are P_t^j and P_{idle}. Based on Eqs (2) and (19), P_t^j can be expressed as a function of CW_i. Similarly, P_{idle} can also be expressed as a function of CW_i according to Eqs. (3) and (19). As a result, the aggregate throughput expression can be expressed as a function of CW_i. Specifically, minimizing Eq. (20) is equivalent to minimizing the following cost function:

$$\begin{aligned}
\frac{T_f + (T_s - T_f)P_{idle}}{P_t^i} &= \frac{T_f}{P_t^i} + (T_s - T_f)\frac{P_{idle}(1-P_e^i)}{P_e^iP_{idle}} \\
&= \frac{T_f}{P_t^i} + (T_s - T_f)\frac{CW_i - 1}{2} \\
&= \frac{T_f}{P_e^i \cdot \prod_{j=2}^n (1-P_e^j)} + (T_s - T_f)\frac{CW_i - 1}{2} \\
&= \frac{T_f}{\frac{2}{CW_i+1} \cdot \prod_{j\neq i} \frac{T_t^j(CW_i-1)}{2T_t^i + T_t^j(CW_i-1)}} \\
&\quad + (T_s - T_f)\frac{CW_i - 1}{2} \\
&= \frac{T_f \prod_{j=1}^n [(CW_i - 1) + \frac{2T_t^i}{T_t^j}]}{2(CW_i-1)^{n-1}} \\
&\quad + (T_s - T_f)\frac{CW_i - 1}{2}.
\end{aligned} \tag{23}$$

Let $\lambda_j = \frac{2T_t^i}{T_t^j}$, and define C_k to be:

$$C_k = \sum_{j_1=1}^{n-k+1} \sum_{j_2=j_1+1}^{n-k+2} \cdots \sum_{j_k=j_{k-1}+1}^{n} \prod_{l=1}^{k} \lambda_{j_l},\ k = 1,2,3\ldots. \tag{24}$$

After applying C_k, Eq. (23) can be simplified as follows:

$$= \frac{T_s}{2}(CW_i - 1) + \frac{T_f}{2}\sum_{k=1}^n C_k (CW_i - 1)^{1-k}. \tag{25}$$

Next, we show that the minimum value of the cost function (i.e., Eq. (25)) uniquely exists.

Theorem 3. *Let $f(CW_i)$ be the function defined by Eqs. (25) and (24), and T_t^j, T_s and T_f are parameters defined by the 802.11 standard. The optimal CW_i that minimizes the cost function exists uniquely.*

Proof. It is clear that $C_k > 0$ for $k = 1,2,3\ldots$. Consider the first and second derivative of the cost function, we have:

$$\begin{aligned}
f'(CW_i) &= T_s - C_2(CW_i - 1)^{-2} - 2C_3(CW_i - 1)^{-3} \\
&\quad - \ldots - (n-1)(CW_i - 1)^{-n},
\end{aligned} \tag{26}$$

$$\begin{aligned}
f''(CW_i) &= 2C_2(CW_i - 1)^{-3} + 6C_3(CW_i - 1)^{-4} \\
&\quad + \ldots + n(n-1)(CW_i - 1)^{-n-1}.
\end{aligned} \tag{27}$$

Assume that the maximum bitrate of a station is 54Mbps[1] and the minimum bitrate is 1Mbps. We have $T_t^i/T_t^j \geq 1/54$, for any $i,j = 1,2,3\ldots n$.

Consider $f'(2)$ and $\lim f'(+\infty)$, we have:

$$\begin{aligned}
f'(2) &= T_s - \sum_{k=2}^n C_k \leq T_s - C_2 \\
&\leq T_s - \sum_{j_1=1}^{n-1}\sum_{j_2=j_1+1}^{n} \frac{4(T_t^i)^2}{T_t^{j_1}T_t^{j_2}} \\
&\leq T_s - \frac{4(T_t^i)^2}{T_t^iT_t^j} \\
&\leq T_s - \frac{2}{27},
\end{aligned} \tag{28}$$

$$\lim f'(+\infty) = T_s > 0. \tag{29}$$

Since T_s is the duration of a slot time, we have $T_s \ll \frac{2}{27}$ and thus $f'(2) < 0$. Therefore, we can always find a $CW_{opt} \in [2, +\infty)$ such that $f'(CW_{opt}) = 0$.

In addition, according to Eq. (27), we can see that $f''(CW) > 0$ for $CW \in [2, +\infty)$. Hence, equation $f'(CW) = 0$ has a unique solution CW_{opt} in the range $[2, +\infty)$. □

The root of equation $f'(CW_i) = 0$ uniquely exists. We can apply numerical analysis techniques such as the *Newton's method* to calculate the numerical value of the optimized contention window size given the values of T_t^j, T_f, and T_s. Via applying the optimized contention window size, each station is guaranteed to fairly share the channel in time and the aggregate throughput is significantly improved.

5.2 Design

To reduce the implementation overhead in practice, our algorithm design is adopted from the default 802.11 DCF with two major changes. Firstly, each station needs to disable the exponential backoff after a failure transmission because it is the major cause of the short-term unfairness in DCF [10].

1. Note that the maximum bitrate depends on the specific 802.11 standard. Here, we assume that the 802.11b/g compatible mode is adopted. A higher maximum bitrate such as 150Mbps in 802.11n does not affect the correctness of our proof.

Secondly, each station calculates its optimized contention window size based on the cost function described in Eq. (25).

In order to calculate the optimized contention window size, our algorithm requires each station to know the bitrates of the stations that are within its communication range. Due to the broadcast nature of the wireless medium, a station is able to receive all frames that are within its communication range. As a result, a station can learn the bitrates of its neighboring stations by observing the on-going transmissions. To be specific, the MAC frame header contains the information about the bitrate of the transmitter. Each station needs to continuously monitor all frames in the air and decapsulate the headers of these frames. The obtained $< MAC\_address$, $Bitrate >$ tuples can be stored in a local table (say $Table\_t$). If a new station arrives or there are changes to the existing tuples, a new contention window size needs to be calculated by calling the contention window calculation function (say CW_Cal). The CW_Cal function can apply the Newton's method to get a numerical value for minimizing the cost function in Eq. (25). To discover an absent station, a Time-to-Live (TTL) field is included in the table for each entry. If there is no packet received from a certain station within a TTL period, the corresponding entry is removed from the table. The value of TTL can be adjusted based on the network scenarios. For instance, a large TTL value can reduce the computation overhead in a static network, while a small TTL value is more suitable for a dynamic network that stations may join and leave frequently. The pseudo-code of optimal contention window size calculation appears in Algorithm 1.

Algorithm 1. Optimal CW Calculation.

```
Insert self MAC address and bitrate into Table_t;
for each received frame do
    Get the sender's MAC address addr and bitrate r from
    the frame header;
    Search the MAC address addr in Table_t;
    if addr is not in Table_t then
        Insert the tuple of <addr, r> to Table_t;
        CW ← CW_Cal(Table_t);
    else
        Get the stored bitrate r';
        Renew the Time-to-Live field TTL;
        if r' ≠ r then
            Update r' with r;
            CW ← CW_Cal(Table_t);
        end if
    end if
end for
```

The fact of using a universal function CW_Cal for contention window size calculation makes our proposed algorithm simple and efficient. This universal function is one of the most important characteristics of our design. In addition, each station is able to compute its contention window size in a fully distributed manner based on the local bitrate table. We note that the bitrate table construction merely requires receiving carrier signal and decoding the MAC frame header. Hence, it does not require any additional hardware support but driver firmware tweaks. Lastly, our design only needs to revise a small portion of the default 802.11 DCF code, which makes our proposed algorithm easy to implement in commodity wireless devices.

TABLE 2
Bitrate of the 5 Competing Stations

Station	1	2	3	4	5
Bitrate	36Mbps	48Mbps	36Mbps	24Mbps	12Mbps

5.3 An Example

Consider the following example deployment scenario in 802.11g mode with 5 competing stations. The bitrates of these stations are listed in Table 2. We use Station 1 as an instance to show the procedure of computing the optimized contention window size step by step.

1. During the initialization phase, Station 1 inserts itself (i.e., the tuple of $<$ MAC_Station_1, 36Mbps $>$.) into the bitrate table. Its default CW is set to 31.
2. Assume Station 3 starts to transmit a frame to the AP. Station 1 overhears the transmission, and gets the MAC address and the bitrate of the transmitter. Station 1 then updates the bitrate table by adding the $<$ MAC_Station_3, 36Mbps $>$ tuple into the table.
3. Since $<$ MAC_Station_3, 36Mbps $>$ is a new entry, the optimized CW needs to be re-calculated. By calling the CW_Cal function, Station 1 gets its new optimized CW of 15.
4. Next, Station 1 overhears the transmission from Station 2 and inserts a new entry $<$ MAC_Station_2, 48Mbps $>$ to the table. The CW of Station 1 is then updated to 26.
5. Eventually, Station 1 has the bitrates of all the other 4 stations. As a result, the final CW value is 46 in this particular scenario.

6 Evaluation Settings

We compare the performance of our proposed algorithm with that of the following three widely accepted algorithms: i) the default 802.11 DCF backoff algorithm [4]; ii) the proportional fair throughput allocation algorithm (referred as *proportional*) proposed in [8]; iii) one of the arguably best time fairness algorithms: Idle Sense [10].

6.1 Configuration

We use the Omnet++ and its INETMANET framework as our simulation environment [26]. The INETMANET framework is shipped with the default 802.11 DCF backoff algorithm. We implement the proportional, Idle Sense, and our proposed algorithm. In our implementation, the MAC and PHY parameters have values defined in the 802.11 standard. For example, the basic MAC layer and PHY layer parameters of 802.11b

TABLE 3
$802.11b$ MAC and PHY Parameters in Omnet++

Slot Time (μs)	SIFS (μs)	DIFS (μs)
20	10	50
ACK Length (bits)	MAC Header (bits)	PHY Header (bits)
112	272	192
Bitrate of ACK	Bitrate of PHY Header	
2Mbps	1Mbps	

are listed in Table 3. In addition, the IP payload size is fixed to be 1500 bytes that is the Maximum Transmission Unit (MTU) for Ethernet.

In our simulation, we place all the stations randomly in the simulation area and assume that all stations are static; thus we disable rate adaptation. Please note that the rate adaptation shall have little impact on the performance of our algorithm in theory. Hence, our simulation results are still valid in a real system with rate adaptation enabled. The bitrate of each station is set at the initialization phase and remains the same throughout the entire simulation period. All the stations have the same transmit power and the same signal-to-interference-plus-noise ratio (SINR) threshold for correctly receiving a frame. All data frames are transmitted to the AP from the stations. In addition, we disable the RTS/CTS options since they are not widely used in practice.

6.2 Methodology

Our evaluation is conducted under two different settings. The first setting is a fully connected environment where all stations can hear transmissions from each other. As a result, each station can obtain a complete view of the contending stations in the network. In this setting, we adopt five popular deployment modes: 802.11b only, 802.11g only, 802.11n only, 802.11b/g compatible, and 802.11b/g/n compatible. For each type of the deployment modes, we consider two types of scenarios. The first scenario is introduced in [10] where one slow station competes with $n-1$ fast stations. On the other hand, each station in the second scenario transmits at a unique bitrate. Hence, the number of stations depends on the number of available bitrates of a given mode. The first scenario studies the impact of varying numbers of contending stations, while the second scenario scrutinizes the impact of bitrate diversity.

Contrary to the first setting, the second setting is a non-fully connected environment where a station cannot obtain a complete view of the contending stations in the network. Such an incomplete view may cause the hidden terminal problem and/or the exposed terminal problem. We begin with studying scenarios that consist exactly one of the two problems. Additionally, we investigate scenarios that consist both of the two problems. By doing so, we are able to comprehensively scrutinize the impact of these two problems on the performance of the four algorithms.

7 Evaluation Results

We detail the evaluation results in terms of time fairness, throughput, and collision overhead under the aforementioned two settings as follows. All of our results presented are averaged over 10 simulation runs. Each simulation run lasts 20 seconds.

7.1 Fully Connected Environment

As it is stated in Section 6.2, there are two scenarios for the fully connected environment. In Scenario I, one slow station competes with $n-1$ fast stations. The values of n are set to be 2, 3, 4, 5, 10, and 20 for each deployment mode. The slow station transmits at 1Mbps in 802.11b, 802.11b/g, and 802.11b/g/n modes, 6Mbps in 802.11g mode, and 15Mbps in 802.11n mode, respectively. The fast stations transmit at 11Mbps in 802.11b mode, 54Mbps in both 802.11g and 802.11b/g modes, and 150Mbps in both 802.11n and 802.11b/g/n modes, respectively. In Scenario II, the number of stations equals the number of available bitrates of a given mode. For example, there are 4 stations in the 802.11b mode, 8 stations in the 802.11g mode, and thus, 12 stations in the 802.11b/g mode.

7.1.1 Time Fairness

We measure the fairness of the channel occupation time among contending stations with the Jain's fairness index (JFI) [1]. The JFI values are plotted in Fig. 2. We observe that the JFI values of our proposed algorithm consistently approach 1 in all cases, which significantly outperforms the other three algorithms. Such a high level of time fairness closely matches our theoretical analysis in Section 5. In addition, we notice that the fairness improvement is higher when the bitrate diversity is higher. For example, the biggest improvement is achieved at the 802.11b/g/n mode under Scenario II as shown in Fig. 2e.

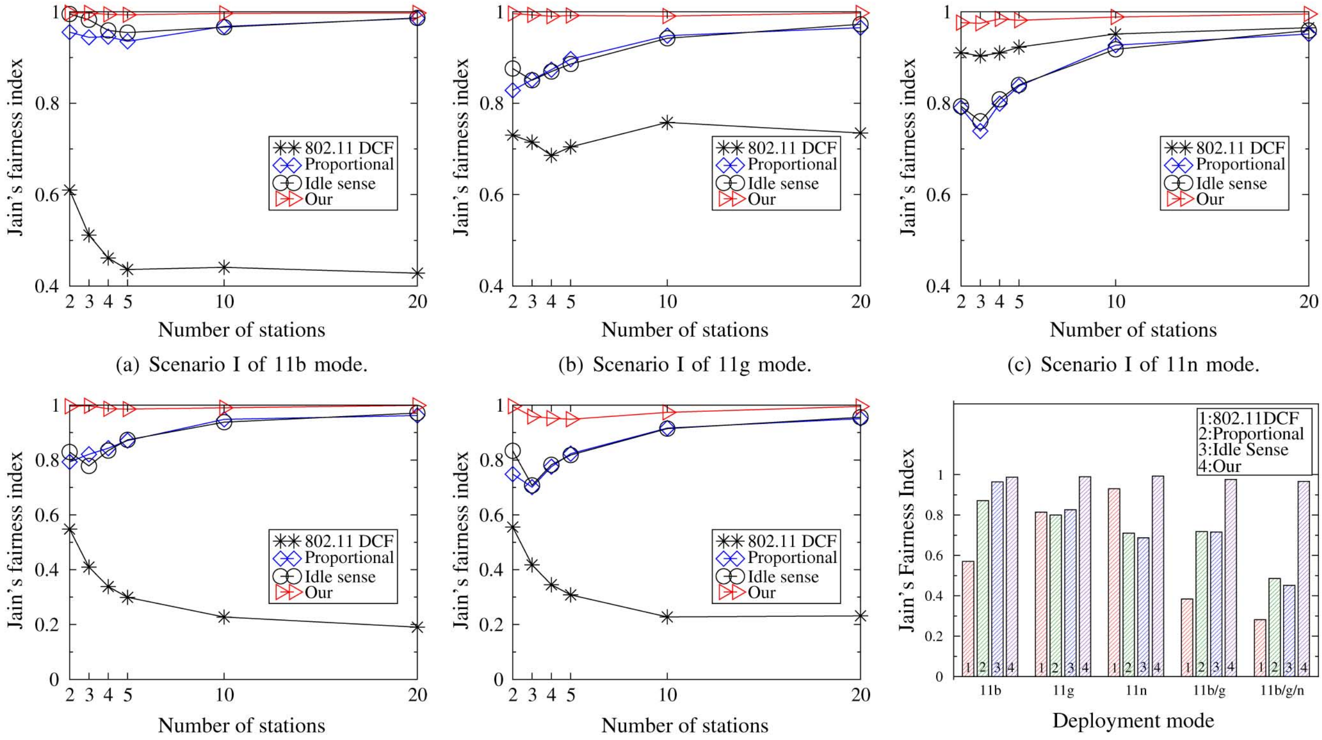
7.1.2 Throughput

The aggregate throughput of the four algorithms is presented in Fig. 3. We can see that our proposed algorithm significantly outperforms the default 802.11 DCF algorithm in this measure. The throughput improvement is achieved by allocating fair channel access time to all stations. We also notice that Idle Sense and Proportional obtain similar throughput to that of our proposed algorithm in most cases. Nevertheless, the throughput improvement of Idle Sense and Proportional is obtained at the cost of scarifying time fairness as it is shown in Fig. 2.

7.1.3 Collision Overhead

We measure the collision overhead via the ratio of total collisions experienced by the default 802.11 DCF scheme to those of the other three algorithms, denoted as *collision ratio*. The number of total collisions is acquired by summing all the collisions recorded on each station for each algorithm. Note that we skip the case of two competing stations because neither of the two stations is able to report collisions properly.

We report the collision ratios among the four algorithms in Fig. 4. Since the default 802.11 DCF algorithm is used as the baseline, its collision ratio is always 1. A ratio below 1 represents a decrease of collision overhead, while a ratio above 1 indicates an increase of collision overhead.

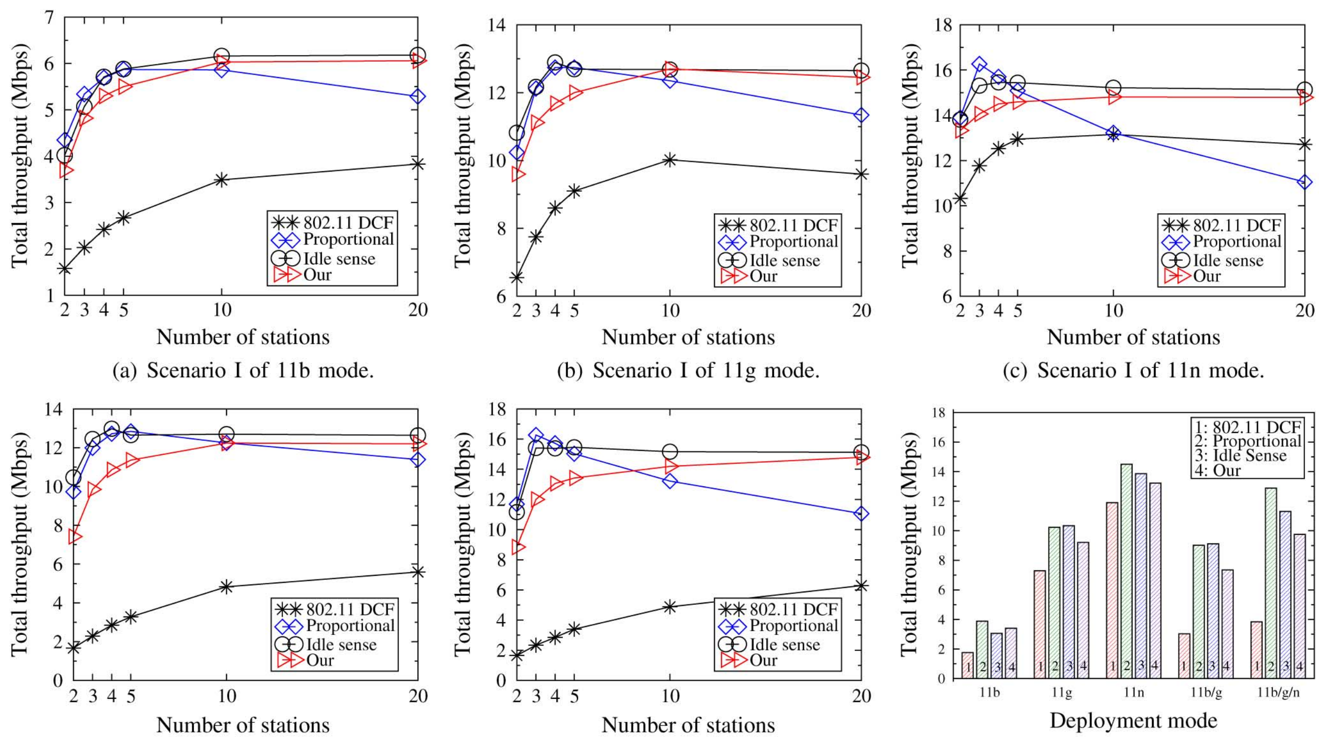


(a) Scenario I of 11b mode. (b) Scenario I of 11g mode. (c) Scenario I of 11n mode.

(d) Scenario I of 11b/g mode. (e) Scenario I of 11b/g/n mode. (f) Scenario II of all deployment modes.

Fig. 2. Jain's fairness index under the fully connected environment: (a) scenario I of 11b mode, (b) scenario I of 11g mode, (c) scenario I of 11n mode, (d) scenario I of 11b/g mode, (e) scenario I of 11b/g/n mode, and (f) scenario II of all deployment modes.

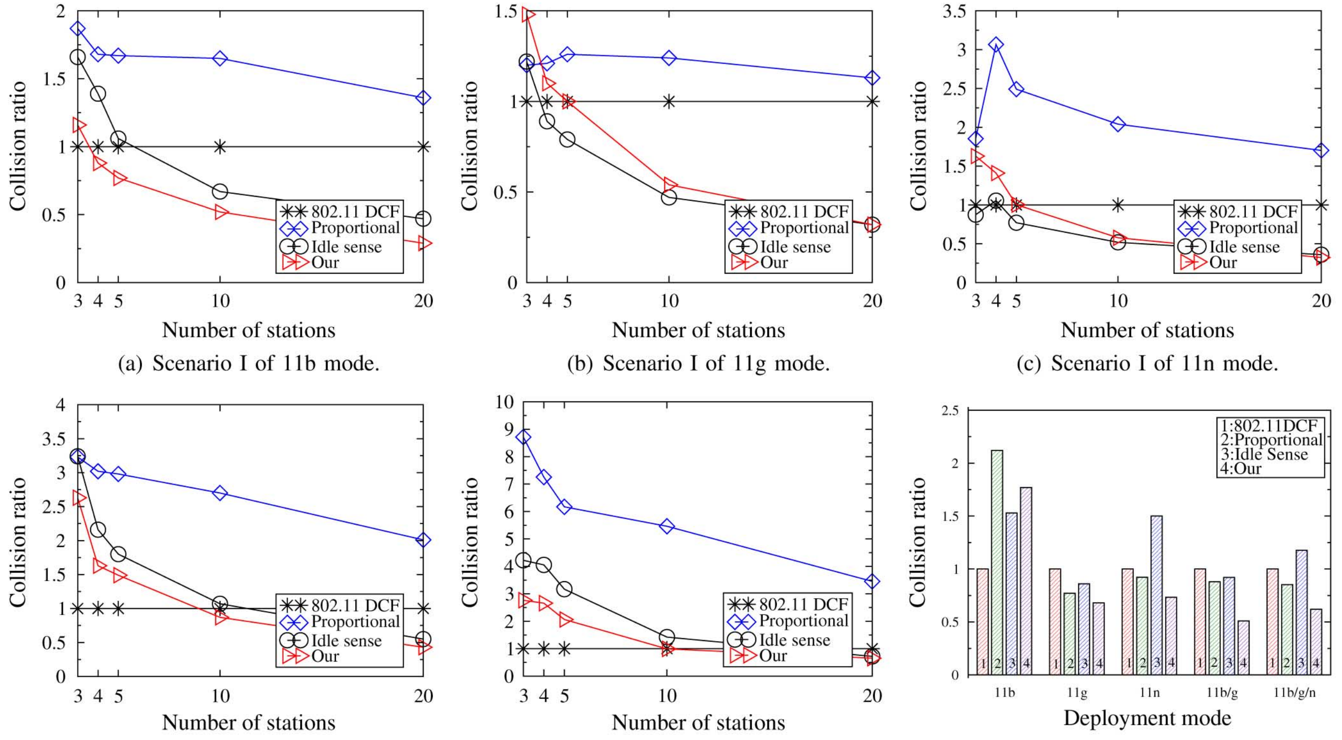
We notice that the default 802.11 DCF scheme introduces the least collision overhead when the number of competing stations is small (i.e., less than 5). This seemingly anti-intuitive result is due to the fact that the other three algorithms transmit up to 5 times more frames than those of the default 802.11 DCF (as it is shown in Fig. 3). When the number of competing



(a) Scenario I of 11b mode. (b) Scenario I of 11g mode. (c) Scenario I of 11n mode.

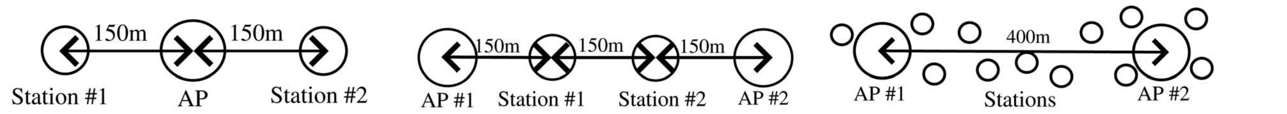
(d) Scenario I of 11b/g mode. (e) Scenario I of 11b/g/n mode. (f) Scenario II of all deployment modes.

Fig. 3. Throughput under the fully connected environment: (a) scenario I of 11b mode, (b) scenario I of 11g mode, (c) scenario I of 11n mode, (d) scenario I of 11b/g mode, (e) scenario I of 11b/g/n mode, and (f) scenario II of all deployment modes.



(a) Scenario I of 11b mode. (b) Scenario I of 11g mode. (c) Scenario I of 11n mode. (d) Scenario I of 11b/g mode. (e) Scenario I of 11b/g/n mode. (f) Scenario II of all deployment modes.

Fig. 4. Collision overhead under the fully connected environment: (a) scenario I of 11b mode, (b) scenario I of 11g mode, (c) scenario I of 11n mode, (d) scenario I of 11b/g mode, (e) scenario I of 11b/g/n mode, and (f) scenario II of all deployment modes.



(a) Hidden terminal scenario. (b) Exposed terminal scenario. (c) Combination scenario.

Fig. 5. Scenarios of the non-fully connected environment: (a) hidden terminal scenario, (b) exposed terminal scenario, and (c) combination scenario.

stations exceeds 5, both Idle Sense and our proposed algorithm start introducing lower collision overhead compared to that of the default 802.11 DCF scheme. It is worth noting that our proposed algorithm incurs a lower collision overhead compared to that of Idle Sense and Proportional for most cases.

7.2 Non-Fully Connected Environment

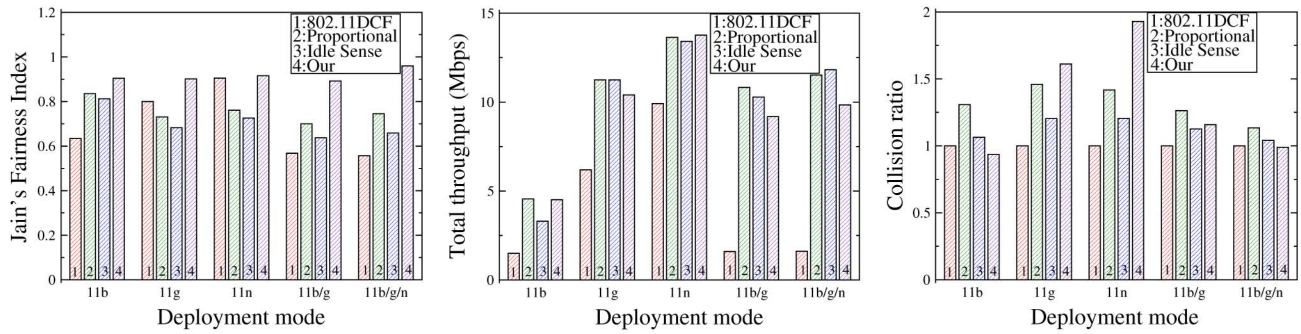
There are three scenarios investigated under the non-fully connected environment, namely, hidden terminal only, exposed terminal only, and a combination of both, which are shown in Fig. 5. For each scenario, we explain the scenario generation followed by the detailed evaluation results, respectively.

7.2.1 Hidden Terminal

We generate a network with one AP and two stations as shown in Fig. 5a. The two stations are placed 300m apart. The AP is stationed at the middle location between the two stations (i.e., the AP is 150m apart from each station). Since the transmission range is 200m, the two stations can communicate to the AP, while these two stations cannot decode frames from each other correctly. Hence, these two stations are "hidden" from each other. The evaluation results are illustrated in Figs. 6a-6c, representing Jain's fairness index, throughput, and collision overhead, respectfully. We can see that our algorithm outperforms the other three algorithm in the Jain's fairness index, and achieves a much higher aggregate throughput than the default 802.11 DCF. We also see that our algorithm incurs slightly higher collision overhead compared the that of the other three algorithms.

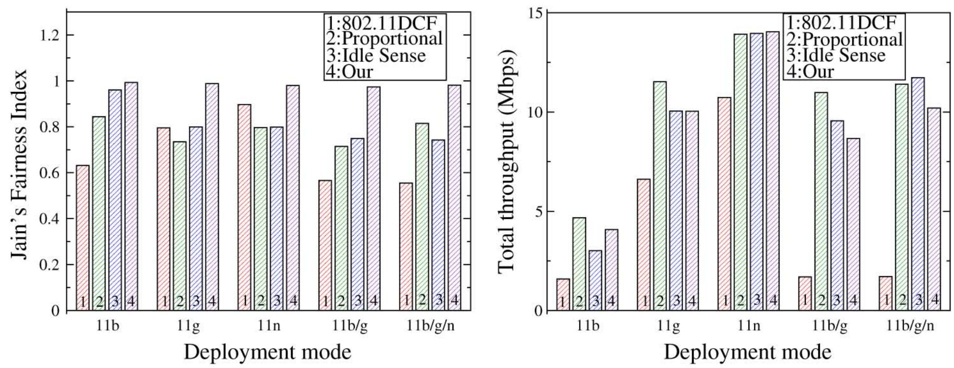
7.2.2 Exposed Terminal

We generate a network with two APs and two stations in a straight line as shown in Fig. 5b. We place these four devices equally apart (150m) in the following order: AP number one, station number one, AP number two, and station number two. Since the transmission range is 200m, each station can associate to only one AP. In this network, the two stations are prohibited to simultaneously transmit frames to their



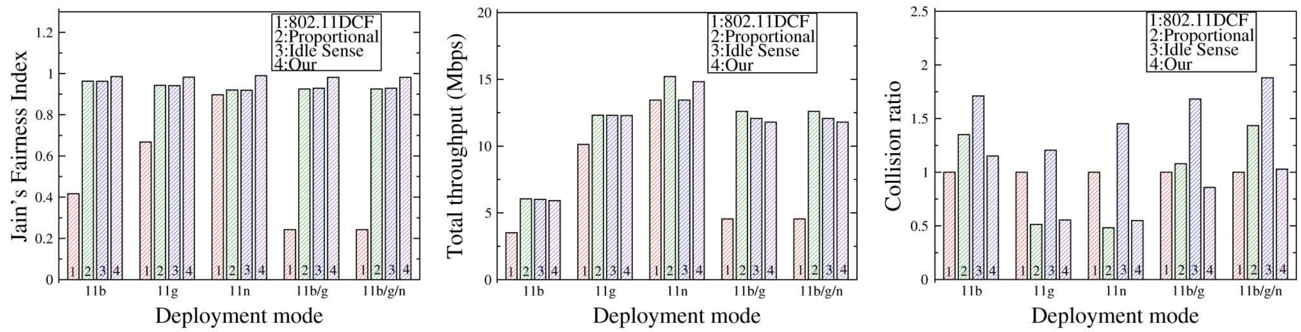
(a) JFI. (b) Throughput. (c) Collision.

Fig. 6. Hidden terminal scenario: (a) JFI, (b) throughput, and (c) collision.



(a) JFI. (b) Throughput.

Fig. 7. Exposed terminal scenario: (a) JFI and (b) throughput.



(a) JFI. (b) Throughput. (c) Collision.

Fig. 8. Combination of hidden terminals and exposed terminals: (a) JFI, (b) throughput, and (c) collision.

associated APs due to exposed terminal problem. The evaluation results are shown in Figs. 7a and 7b. Note that due to the nature of the hidden terminal problem, there is no collision overhead in this scenario.

7.2.3 Combination of Hidden and Exposed Terminals

We generate a network that contains both hidden terminals and exposed terminals as shown in Fig. 5c. Specifically, there are two APs and 10 stations in the network. The distance between the two APs are set to $400\mathrm{m}$. We randomly place the 10 stations around the two APs. Each station is set to associate with its nearest AP. The evaluation results are shown in Figs. 8a-8c. We can see that our proposed algorithm can achieve better fairness in such a randomly generated network, compared with the other three algorithms. Also the aggregate throughput of our algorithm is higher than that of the default 802.11 DCF algorithm.

7.3 Summary

The evaluation results demonstrate that our proposed algorithm outperforms the other three algorithms in the following aspects: i) The channel occupancy time of our algorithm is almost equally shared (i.e., the Jain's fairness index approaching one) among stations for all cases; ii) Our proposed algorithm significantly improves the aggregate throughput under the time fairness constraint; iii) Our algorithm is capable of reducing collision overhead when the network exhibits complexity such as a rich bitrate diversity.

8 Conclusion

In this paper, we study the relationships among the four types of fairness criteria. We are the first to rigorously prove that there exist certain connections among these fairness criteria. Furthermore, we propose a novel distributed time fairness based MAC algorithm for multi-rate wireless LANs. Our proposed algorithm is able to achieve fair sharing of the channel occupancy time as well as throughput maximization by enabling each station to select an appropriate contention window size. We evaluate the performance of our algorithm thru a comprehensive comparative evaluation study. The evaluation results demonstrate that our proposed algorithm greatly outperforms three other popular medium access algorithms in the literature. As a part of our future work, we plan to implement our proposed algorithm in commodity 802.11 hardware and test its performance using real world experiments.

Acknowledgment

This work was supported in part by the National Basic Research Program of China (No. 2011CB302702), the US National Science Foundation (CNS-1162057, CNS-1265311, and CNS-1352726), the Macau Science and Technology Development Fund (009/2010/A1, 061/2011/A3, and 021/2009/A1), and the NPST program by King Saud University (Project No. 10-INF1184-02).

References

[1] R. Jain, D. Chui, and W. Hawe, "A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Systems," Digital Equipment Institution, technical report, 1984.

[2] D. Bertsekas and R. Gallager, *Data Networks*. Prentice-Hall, 1987, pp. 524-529.

[3] F. Kelly, "Charging and Rate Control for Elastic Traffic," *European Trans. Telecomm.*, vol. 8, no. 1, pp. 33-37, 1997.

[4] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Std 802.11-2007, pp. 1-1076, 12 June 2007, http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4248378&isnumber=4248377.

[5] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE J. Selected Areas in Comm.*, vol. 18, no. 3, pp. 535-547, Mar. 2000.

[6] G. Tan and J. Guttag, "Time-Based Fairness Improves Performance in Multi-Rate WLANs," *Proc. Ann. Conf. USENIX Ann. Technical Conf.* USENIX Association, pp. 269-282, 2004.

[7] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda, "Performance Anomaly of 802.11b," *Proc. Int'l Conf. Computer Comm. (INFOCOM'03)*, vol. 2, pp. 836-843, 2003.

[8] A. Banchs, P. Serrano, and H. Oliver, "Proportional Fair Throughput Allocation in Multirate IEEE 802.11e Wireless LANs," *Wireless Networks*, vol. 13, no. 5, pp. 649-662, 2007.

[9] L.E. Li, M. Pal, and Y.R. Yang, "Proportional Fairness in Multi-Rate Wireless LANs," *Proc. Int'l Conf. Computer Comm. (INFOCOM'08)*, pp. 1004-1012, Apr. 2008.

[10] M. Heusse, F. Rousseau, R. Guillier, and A. Duda, "Idle Sense: An Optimal Access Method for High Throughput and Fairness in Rate Diverse Wireless LANs," *Proc. Conf. Applications, Technologies, Architectures, and Protocols for Computer Comm. (SIGCOMM'05)*, pp. 121-132, 2005.

[11] V.A. Siris and G. Stamatakis, "Optimal CWmin Selection for Achieving Proportional Fairness in Multi-Rate 802.11e WLANs: Test-Bed Implementation and Evaluation," *Proc. 1st Int'l Workshop Wireless Network Testbeds, Experimental Evaluation & Characterization (WiNTECH'06)*, pp. 41-48, 2006.

[12] L. Massoulié and J. Roberts, "Bandwidth Sharing: Objectives and algorithms," *IEEE/ACM Trans. Networking*, vol. 10, no. 3, pp. 320-328, 2002.

[13] A. Miu, G. Tan, H. Balakrishnan, and J. Apostolopoulos, "Divert: Fine-Grained Path Selection for Wireless LANs," *Proc. 2nd Int'l Conf. Mobile Systems, Applications, and Services (MobiSys'04)*, pp. 203-216, 2004.

[14] D. Kotz, C. Newport, R.S. Gray, J. Liu, Y. Yuan, and C. Elliott, "Experimental Evaluation of Wireless Simulation Assumptions," *Proc. 7th ACM Int'l Symp. Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM'04)*, pp. 78-82, 2004.

[15] Y. Jian and S. Chen, "Can CSMA/CA Networks Be Made Fair?" *Proc. 14th ACM Int'l Conf. Mobile Computing and Networking (MobiCom'08)*, pp. 235-246, 2008.

[16] S. Ganu, K. Ramachandran, M. Gruteser, I. Seskar, and J. Deng, "Methods for Restoring MAC Layer Fairness in IEEE 802.11 Networks with Physical Layer Capture," *Proc. 2nd Int'l Workshop Multi-Hop Ad Hoc Networks: From Theory to Reality (REALMAN'06)*. ACM, pp. 7-14, 2006.

[17] G. Bianchi and I. Tinnirello, "Kalman Filter Estimation of the Number of Competing Terminals in an IEEE 802.11 Network," *Proc. Int'l Conf. Computer Comm. (INFOCOM'03)*, vol. 2, pp. 844-852, 2003.

[18] F. Cal, M. Conti, and E. Gregori, "Dynamic Tuning of the IEEE 802.11 Protocol to Achieve a Theoretical Throughput Limit," *IEEE/ACM Trans. Networking*, vol. 8, no. 6, pp. 785-799, Dec. 2000.

[19] Y. Kwon, Y. Fang, and H. Latchman, "A Novel MAC Protocol with Fast Collision Resolution for Wireless LANs," *Proc. Int'l Conf. Computer Comm. (INFOCOM'03)*, pp. 793-807, 2003.

[20] I. Aad, Q. Ni, C. Barakat, and T. Turletti, "Enhancing IEEE 802.11 MAC in Congested Environments," *Computer Comm.*, vol. 28, no. 14, pp. 1605-1617, 2005.

[21] D. Qiao and K. Shin, "Achieving Efficient Channel Utilization and Weighted Fairness for Data Communications in IEEE 802.11 WLAN Under the DCF," *Proc. 10th IEEE Int'l Workshop Quality of Service*, pp. 227-236, 2002.

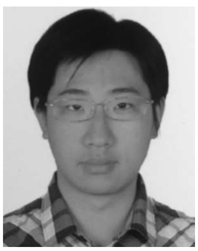
[22] J.-Y. Yoo and J.W. Kim, "Centralized Flow Coordination for Proportional Fairness in Enterprise Wireless Mesh Networks," *SIGMOBILE Mobile Computing and Comm. Rev.*, vol. 14, no. 3, pp. 52-54, http://doi.acm.org/10.1145/1923641.1923660, Dec. 2010.

[23] Y. Jian, M. Zhang, and S. Chen, "Achieving MAC-Layer Fairness in CSMA/CA Networks," *IEEE/ACM Trans. Networking*, vol. 19, no. 5, pp. 1472-1484, http://dx.doi.org/10.1109/TNET.2011.2116124, Oct. 2011.

[24] I. Tinnirello and S. Choi, "Temporal Fairness Provisioning in Multi-rate Contention-Based 802.11e WLANs," *Proc. 6th IEEE Int'l Symp. World of Wireless Mobile and Multimedia Networks (WOWMOM'05)*. IEEE Computer Society, pp. 220-230, 2005.

[25] W. Li, Y. Cui, S. Wang, and X. Cheng, "Approximate Optimization for Proportional Fair ap Association in Multi-Rate WLANs," *Proc. 5th Int'l Conf. Wireless Algorithms, Systems, and Applications (WASA'10)*. Springer-Verlag, pp. 36-46, 2010.

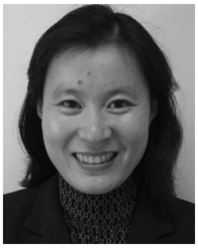
[26] "OMNeT++ home page," http://www.omnetpp.org, 2010.



Yuan Le received the MS degree in computer science from The George Washington University in 2010. He is a PhD candidate in computer science at The George Washington University. His current research interests include wireless protocol design and analysis, cognitive radio networks, and mobile computing.

Liran Ma received the doctoral degree in computer science from The George Washington University in 2008 He is an assistant professor in the Department of Computer Science at Texas Christian University, Fort Worth. His current research interests include wireless networking, network and system security, and mobile computing.

Wei Cheng received the PhD degree in computer science from The George Washington University in 2010, and the BS degree in applied mathematics and MS degree in computer science both from National University of Defense Technology, China, in 2002 and 2004, respectively. Currently, he is an assistant professor at Virginia Commonwealth University, Richmond. He has worked as a postdoc scholar at University of California Davis. His research interests span the areas of wireless networking, cyber-physical networking system, and algorithm design and analysis.



Xiuzhen Cheng received the MS and PhD degrees in computer science from the University of Minnesota—Twin Cities, Minneapolis, in 2000 and 2002, respectively. She is a professor in the Department of Computer Science, The George Washington University. Her current research interests focus on cognitive radio networks, mobile handset networking systems (mobile health and safety), wireless and mobile computing, sensor networking, wireless and mobile security, and algorithm design and analysis. She has served on the editorial boards of several technical journals and the technical program committees of various professional conferences/workshops. She also has chaired several international conferences. She worked as a program director for the US National Science Foundation (NSF) from April to October in 2006 (full time), and from April 2008 to May 2010 (part time). She received the NSF CAREER Award in 2004. She is a member of ACM.

Biao Chen received the BS degree in computer science from Fudan University, China, and the MS degree in mathematics and PhD degree in computer science from Texas A & M University, College Station, respectively. After graduation, he joined the Department of Computer Science, the University of Texas at Dallas, as a faculty member. Currently, he is a visiting professor in the Department of Computer and Information Science, University of Macau, China. His research interests include distributed systems, networking, and security. He is a member of Sigma Xi and ACM.