Fair Medium Access in 802.11 based Wireless Ad-Hoc Networks

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Abstract— **The Medium Access Control (MAC) protocol through which mobile stations can share a common broadcast channel is essential in an ad-hoc network. Due to the existence of hidden terminal problem, partially-connected network topology and lack of central administration, existing popular MAC protocols like IEEE 802.11 Distributed Foundation Wireless Medium Access Control (DFWMAC) [1] may lead to "capture" effects which means that some stations grab the shared channel and other stations suffer from starvation. This is also known as the "fairness problem". This paper reviews some related work in the literature and proposes a general approach to address the problem. This paper borrows the idea of fair queueing from wireline networks and defines the "fairness index" for ad-hoc network to quantify the fairness, so that the goal of achieving fairness becomes equivalent to minimizing the fairness index. Then this paper proposes a different backoff scheme for IEEE 802.11 DFWMAC, instead of the original binary exponential backoff scheme. Simulation results show that the new backoff scheme can achieve far better fairness without loss of simplicity.**

I. INTRODUCTION

An ad-hoc network is a dynamic multi-hop wireless network that is established by a group of mobile stations without the aid of any pre-existing network infrastructure or centralized administration. It can be installed quickly in emergency or some other special situations and is self-configurable, which makes it very attractive in both civilian and military applications [2].

An efficient medium access control (MAC) protocol through which mobile stations can share a common broadcast channel is essential in an ad-hoc network because the medium or channel is a scarce resource. Due to the limited transmission range of mobile stations, multiple transmitters within range of the same receiver may not know one another's transmissions, and thus are in effect "hidden" from one another. When these transmitters transmit to the same receiver at around the same time, they do not realize that their transmissions collide at the receiver. This is the so-called "hidden terminal" problem [3] which is known to degrade throughput significantly.

To address the hidden terminal problem, various distributed MAC protocols were proposed in the literature [1], [4], [5], [6]. Among them, IEEE 802.11 Distributed Foundation Wireless Medium Access Control (DFWMAC) is a proposed standard for wireless ad-hoc and infrastructure LANs and is commonly used in testbeds of wireless ad-hoc networks for research in routing for example [2]. DFWMAC is a kind of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocols and provides basic and RTS/CTS access method. The basic access method includes only exchange of data packet and acknowledgment packet between a pair of source and destination stations. The RTS/CTS access method is used to combat the hidden terminal problem and requires additional handshake, namely short Request-to-Send (RTS) and Clear-to-Send (CTS) packets between a pair of source and destination stations before actual data packet transmission. RTS and CTS packets include a field called Network Allocation Vector (NAV). It is used to inform stations who overhear the RTS and/or the CTS packets how long they should defer access to the channel. Although the RTS/CTS access method can alleviate hidden terminal problem leading to an increased throughput [7], DFWMAC still suffer from the fairness problem which was first investigated in MACAW [4] (short for Multiple Access with Collision Avoidance for Wireless) which is another protocol proposed for wireless LANs.

In MACAW, additional control packets and a different backoff algorithm named Multiplicative Increase and Linear Decrease (MILD) with a backoff copy scheme are used to increase throughput and alleviate fairness prob-

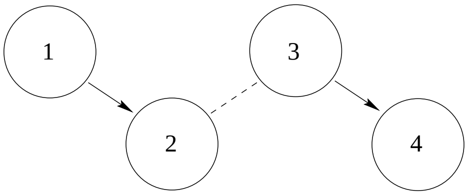

Fig. 1. Sample network

lem. In addition, "per stream" fairness is introduced in MACAW. It means that each stream that originates from either the same station or different stations should be treated equally and given equal share of the channel capacity. This is different from "per station" fairness which accords channel capacity to individual stations instead of individual streams. For multiple streams that originate from a station, MACAW keeps separate queues for each stream and runs backoff algorithms independently for each stream. However, MACAW still left some problems unsolved. For example, in the configuration shown in Fig. 1, station 1 has load for station 2 and station 3 has load for station 4. When the load increases to a certain degree, station 3 will "capture" the channel and station 1 will suffer severe degradation in throughput. DFWMAC faces the same problem as well because it uses a binary exponential backoff which always favors the last succeeding station. This has been pointed out in MACAW. Another problem for MACAW is that backoff copy scheme only works when congestion is homogeneous which is not necessarily the case in ad-hoc networks. For more details about these problems, readers can refer to MACAW paper [4].

More recently, Ozugur et. al [8] proposed a p_{ij}-persistent CSMA based backoff algorithm. This paper first defined the fairness index to be the ratio of maximum link throughput to minimum link throughput. Then it proposed that each station calculates a link access probability p_{ij} for each of its links based on the number of connections from itself and its neighbors(connection based), or based on the average contention period of its and other stations' individual links(time based). Whenever its backoff period ends, station i will send RTS packet to j with probability p_{ij} or back off again with probability $1-p_{ij}$. The proposed scheme relies on periodic broadcast packets in the time-based approach or on aperiodic broadcast packets in the connection-based approach whenever the network topology changes. This paper also investigated the effects of combination of contention window[1] exchange with either connection-based or time-based approach. However, none of the schemes can achieve the best results for all network configurations investigated in [8] and sometimes the best results are achieved when these schemes are in fact not used. In addition, broadcast packets are unreliable to disseminate information to neighbors. As the RTS/CTS access method cannot be used and no acknowledgment packet can be sent in this case, no one can ensure if broadcast packets can be delivered to all the sending stations' neighbors, which makes the performance of this method tightly coupled to the successful dissemination of the information in the network.

In the ongoing research work of Vaidya and Bahl [9], they identified the difficulties in defining fairness itself in multi-hop networks and defined a Generalized Resource Sharing (GPS) algorithm which needs further investigation as it includes sorting flows which requires global information. In addition, a distributed fair scheduling algorithm is also proposed to achieve fairness on local area networks (one hop) and its performance was evaluated.

The goal of this paper is to address the fairness problem in multi-hop ad-hoc networks with a general and more practicable approach. This paper will present preliminary results as this is still ongoing work. Section 2 first defines new metrics for measuring fairness and then proposes a different backoff scheme for the DFWMAC protocol. Section 3 evaluates the performance of the proposed scheme and compares its performance to those obtained from the original backoff scheme using several ad-hoc network configurations. Section 4 concludes this paper.

II. Estimation-based Fair Medium Access

In this paper, we want to address the fairness problem in a general approach. We define fairness in the sense of fair queueing as defined in [10]. To facilitate the discussion, we introduce the following notation:

ϕ_i : a pre-defined fair share that station i should receive. Normally, it should be determined at admission control, i.e. when the node joins the ad-hoc network, and can be readjusted for example when a node becomes a router. How to choose this parameter, how to do admission control and how to adjust the parameter, are still open research problems.
W_i : The actual throughput achieved by station i;
L_i : Station i's offered load.

A fair MAC protocol should have the following properties. When stations' offered load to the channel is much

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[1] Backoff timer is generated from the uniform distribution which ranges from 0 to the size of the current contention window.

lower than the channel capacity, each station's request for transmission should be met. This means that for any station i, $W_i = L_i$. When stations' offered load exceeds the channel capacity, each station should be able to get its fair share of the channel, i.e, proportionally to ϕ. This means that for any station i and j, $\frac{W_i}{\phi_i} = \frac{W_j}{\phi_j}$. This is just for ideal situations. In reality, we want to bound the value of $|\frac{W_i}{\phi_i} - \frac{W_j}{\phi_j}|$ by the smallest possible value. Instead of working with absolute values, we define the fairness index, *FI*, to be:

$$FI = max\{\forall i, j : max(\frac{W_i}{\phi_i}, \frac{W_j}{\phi_j})/min(\frac{W_i}{\phi_i}, \frac{W_j}{\phi_j})\}$$

Therefore, our goal becomes the design of a distributed MAC protocol that can minimizes *FI* and thus achieve fairness for all the stations in an ad-hoc network.

There comes the problem of how to choose ϕ_i for any station i. As mentioned previously, this is an admission control problem which is beyond the scope of this paper, however, in situations where the ad-hoc network is open to everyone without admission control, which can happen in situations where all the stations are trusted and known not to misbehave, the following approach can be used. If each station is considered to be a greedy source and wants to get the same share as all other stations as a whole, then it can just set $\phi = 0.5$ regardless of the number of its neighbors. As to any station, say i, it requests the same share as all the others in its vicinity. These stations have a total share of $\phi_o = 1 - \phi_i = 0.5$, which equals to this station's share ϕ_i. This can be interpreted as a per-station fairness. If a station has two active links (or streams in MACAW's terminology), which can happen when a station acts as a router in an ad-hoc network, it can set ϕ_i to meet :

$$\frac{\phi_i}{\phi_o} = \frac{\phi_i}{(1 - \phi_i)} = \frac{2}{1} \Rightarrow \phi_i \approx 0.67,$$

which shows simply that the station (router) wants to obtain two times as much share of bandwidth as other stations' to function as a router properly. This can be interpreted as MACAW's per-stream fairness.

To achieve the fairness goal, we propose a different backoff scheme. In this scheme, each station will estimate its share and other stations' share of the channel and then adjust the contention window accordingly. We use the following notations in fair share estimation algorithm:

W_{ei} : The estimated share of the estimating station itself;
W_{eo} : The estimated share of other stations;
T_{type} : Time to transmit a packet of type *type*.

Algorithm 1 shows how estimation works. The basic idea is that from the point of view of station i, it sees that it is sharing the channel with a group of "belligerent" stations who are competing with it for channel access. Thus we have the notion of "me, and the others". Stations estimate dynamically what throughput they get and what throughput "others" get, and then adjust their contention window according to the fairness index defined. In other words the contention window is adjusted in order to equalize the throughput obtained by the different stations. A station can estimate roughly how much bandwidth "others" obtain by looking at the packets in its vicinity. For example (the details can be seen in the algorithm) an RTS packet that station i sends leads to an increase of its obtained throughput since it used the channel, a received RTS means "others" are trying to obtain the channel and thus it increases "others" obtained throughput, etc.

Algorithm 1 Fair share estimation

```
switch (received packet type) {
case RTS:
    if (destID != localID) $W_{eo}$ += $T_{rts}$
    else {send CTS packet;
        $W_{eo}$ += $(T_{rts} + T_{cts})$}
case CTS:
    if (destID != localID) $W_{eo}$ += $(T_{rts} + T_{cts})$
    else {send DATA packet;
        $W_{ei}$ += $(T_{rts} + T_{cts} + T_{data})$}
case DATA:
    if (destID != localID)
        $W_{eo}$ += $(T_{rts} + T_{cts} + T_{data})$
    else {send ACK packet;
        $W_{ei}$ += $(T_{rts} + T_{cts} + T_{data} + T_{ack})$}
case ACK:
    if (destID != localID)
        $W_{eo}$ += $(T_{rts} + T_{cts} + T_{data} + T_{ack})$
    else {$W_{ei}$ += $(T_{rts} + T_{cts} + T_{data} + T_{ack})$}
}

Whenever sending an RTS packet, $W_{ei}$ += $T_{rts}$
```

In this algorithm, RTS and CTS packets' transmission is counted towards the estimated share because RTS and CTS packets are used as a channel reservation scheme and consume channel resource as well.

With this estimation, we modify the binary exponential backoff scheme used in DFWMAC. We define the estimated fairness index to be: $FI_e = (\frac{W_{ei}}{\phi_i})/(\frac{W_{eo}}{\phi_o})$ and the adjustment of contention window is shown in Algorithm 2.

Algorithm 2 Contention window adjustment

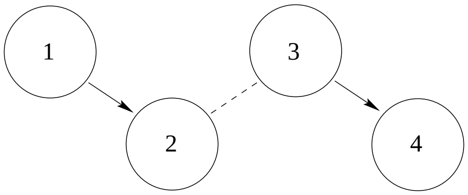
```
switch ($FI_e$) {
case $>C$:
    $CW_{new} = min(CW_{new} \times 2, CWMAX)$
case $(1/C, C)$:
    $CW_{new} = CW_{old}$
case $<1/C$:
    $CW_{new} = max(CW_{old}\ /\ 2, CWMIN)$
}
```

In Algorithm 2, C is a constant used to adjust the adaptativity of the algorithm. The smaller the value of C, the more aggressively is the contention window size adjusted and vice versa. However, the choice of C is rather limited. For example, if we choose $C = 2$, stations would not change their contention windows when estimated *FI* is between $(0.5, 2)$ and probability of collision may be high when the number of competing stations is large and load to channel is high. On the other hand, if C is too close to 1, say 1.01, stations may be busy adjusting their contention windows all the time and the algorithm becomes instable. The calculation shows that if a station estimates that it has got more share than it should get, it will double its contention window size until it reaches a maximum value (CWMAX) so that its neighbors can have more chances to recover earlier from backoff procedure and win access to the channel and vice versa. If a station estimates that it has got only its fair share, it will hold onto its current contention window size.

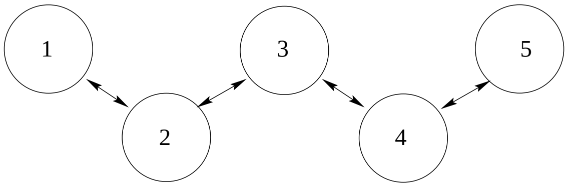
III. Simulation Results

In our experiments, we investigate some configurations of wireless ad-hoc networks used in MACAW and p_{ij}-persistent CSMA. These are the 4-station, 5-station and 6-station scenarios. They are shown in Fig. 2, where arrow lines indicate that there is traffic between stations and dashed lines indicate that the stations are within communication reach of each other but no traffic flows between them.

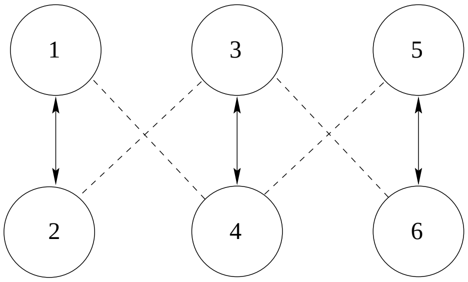
We assume a 1Mbps ideal channel with zero preamble and processing overhead and a propagation delay of about 6μ seconds. We have performed different sets of simulations with OPNET Modeler/Radio and we compare our results with the original IEEE 802.11 DFWMAC protocol[2]. Table I lists the parameters used to generate the simulations results. As we ignore the extra time incurred by hardware and software, the different InterFrame Spaces (IFSs) in IEEE 802.11 are reduced accordingly and they are also shown in Table I. Unless otherwise specified, all stations will use a fair share $\phi = 0.5$.



(a) 4-station



(b) 5-station



(c) 6-station

Fig. 2. Network configurations

In the 4-station scenario, station 1 and 3 generate Poisson traffic with the same mean rate, and results are shown in Fig. 3. Figure 3 shows that DFWMAC will have serious fairness problem when the offered load is high enough, which can be explained as follows. Most of the time station 1's transmission may coincide with station 3's trans-

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[2] We use its specification for Direct Sequence Spread Spectrum when applicable.

RTS	CTS	DATA	ACK
25-byte	20-byte	500-byte	20-byte

CWMIN	CWMAX	C	backoff unit time
31	1023	1.1	6μsec

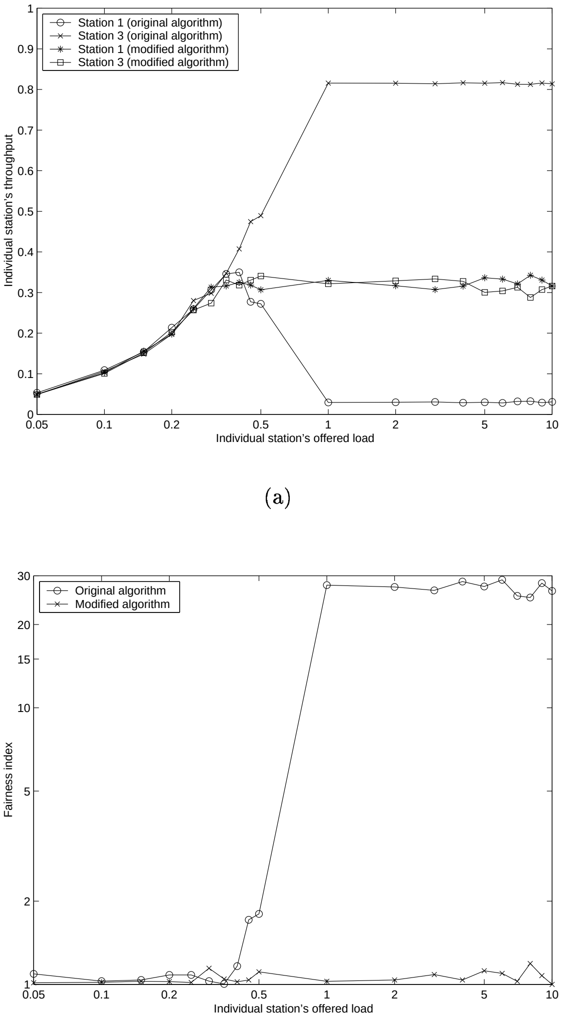
DIFS	SIFS	EIFS
12μsec	0μsec	1.3msec

TABLE I

Protocol configuration parameters

mission as they are hidden from each other. Station 2 will not be able to receive station 1's packet due to station 3's concurrent transmission. However, station 4 can still receive station 3's transmission successfully and reply to station 3 thereafter. According to the binary exponential backoff (BEB) scheme used in DFWMAC, a station's contention window size will be doubled after unsuccessful transmission and will return to the minimum value if a data packet is successfully transmitted. Therefore station 3 usually enjoys a much smaller contention window, thus statistically shorter backoff timer than station 1. When the load is high, station 3 will *capture* the channel eventually. In our backoff scheme, if station 3 overhears a few packets transmitted from station 2 (in this case, either CTS or ACK packet), its estimatition will show that it has obtained more bandwidth share than what it should have and will increase its contention window size[3] accordingly. With the ever increase of station 3's contention window, station 1 will get more chances to transmit packets to station 2. In the end, the station 1's throughput can be balanced with station 3's throughput, so this scheme can achieve far better fairness than the BEB.

In the 5-station scenario, we investigate two cases. In the first case, each station generates Poisson traffic with the same mean rate. For station 2, 3 and 4, each has two active links to its neighbors. For each packet that is generated, these stations will randomly choose a neighbor as destination. For this case, we consider per-station fairness only and aggregate the two links' throughputs as the corresponding station's throughput. The results are shown in Fig. 4. Due to symmetry, we show results for station 1, 2 and 3 only. In this case, edge stations (1 and 5) face less congestion and their packets are easier to get through. As the binary exponential backoff always favors the last succeeding station, the edge stations will get much higher throughput than other stations. Our scheme works much better to achieve fairness because station 1 and 5 will yield the channel to other stations when they estimate that they obtained extra share than what they should get.



(a)

(b)

Fig. 3. (a) Station throughput, (b) fairness index versus station's offered load for the 4-station scenario.

In the second case, each station generates Poisson traffic for each link with the same mean rate. Therefore, stations 2, 3 and 4, require equal fair share for each of their links. We experiment with two situations. One is

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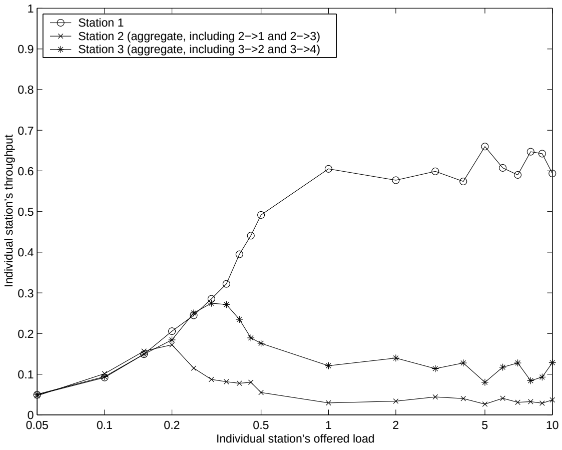
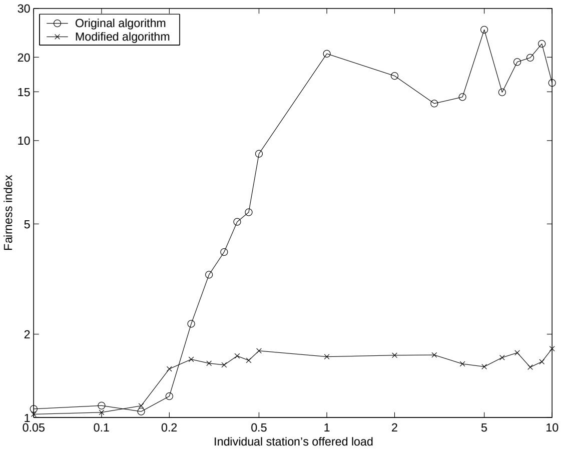
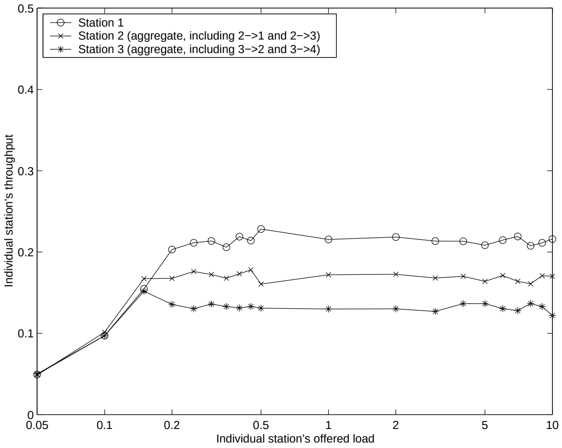
[3] Here station 3 does not even need not know the fact that station 1 has packets for station 2.



(a)



(c)



(b)

Fig. 4. (a) Station throughput (original algorithm), (b) station throughput (modified algorithm), (c) fairness index versus station offered load for the 5-station scenario.

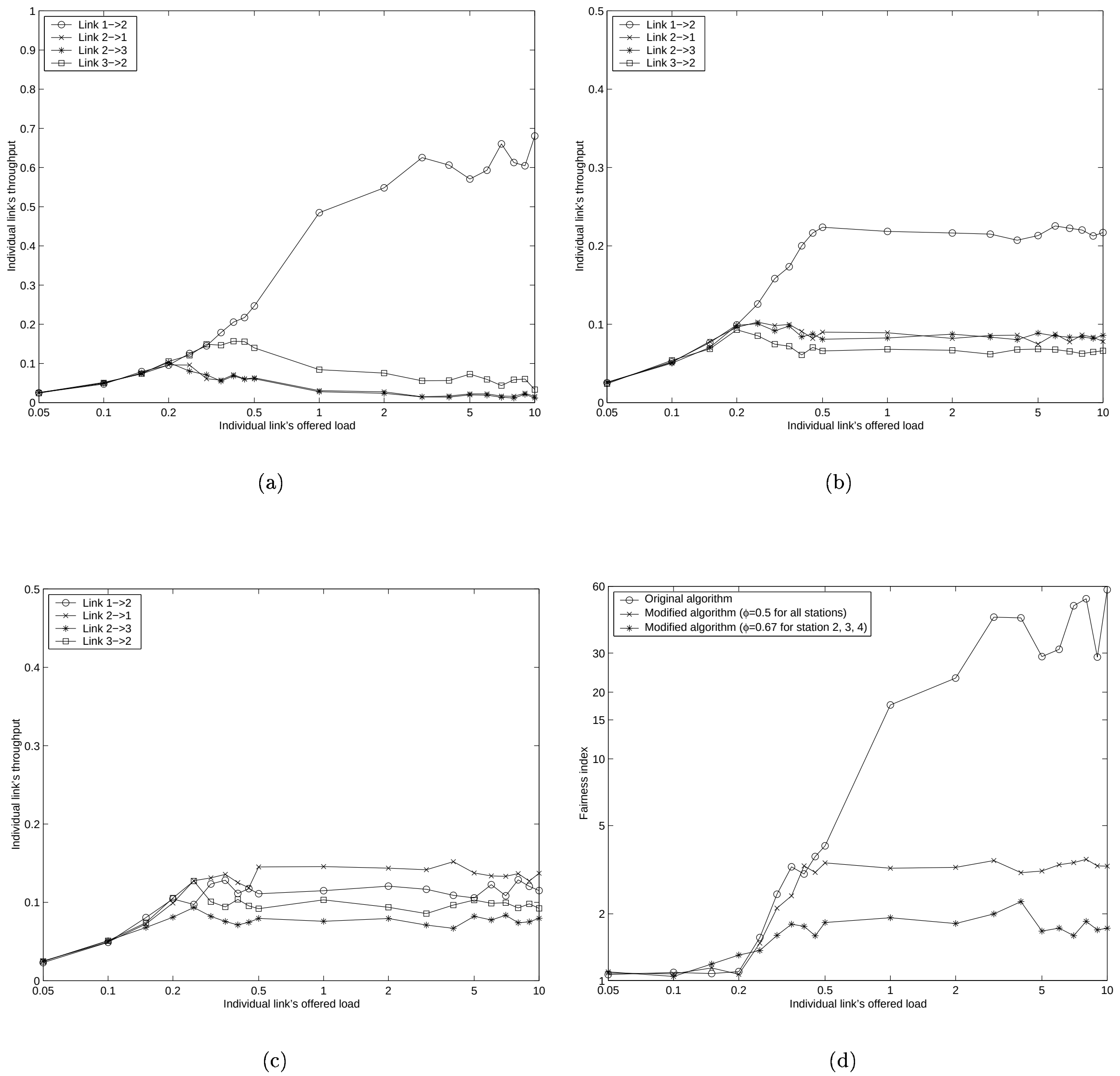
that station 2, 3 and 4 still set $\phi = 0.5$, the other is that these stations set $\phi = 0.67$ which indicates that they require two times the share of other stations as they have two active links. The results are shown in Fig. III. It shows that even if station 2, 3 and 4 do not increase their ϕ, the modified algorithm can still achieve much better fairness than DFWMAC. When they do increase ϕ, the fairness can be further improved.

In the 6-station scenario, each station generates Poisson traffic with the same mean rate and results are shown in Fig. 6. Due to symmetry, we show the results for station 1 and 3 only. As there may be concurrent transmissions between two pairs of edge stations (station 1 and 2, station 5 and 6), inner stations 3 and 4 suffer severe degradation in throughput as in the case of original DFWMAC. Our estimation becomes somewhat inaccurate in this case because some of these concurrent transmissions between edge stations may be interpreted as noise by inner stations and will not be counted in fair share estimation. However, our approach can still achieve far better fairness than DFWMAC.

All the simulations show that we tradeoff some throughput for fairness. As our approach in fact encourages stations to participate in fair competition, some channel bandwidth is lost due to collisions.

IV. CONCLUSION

In this paper, we defined the fairness metrics for wireless ad-hoc networks incorporating both the idea of per-station and per-stream (or per-link) fairness and pointed out that the target to achieve fairness is to minimize fairness index. We then proposed a different backoff scheme for IEEE 802.11 DFWMAC, where each station adjusts its contention window according to the estimated share it obtained and other stations. Simulation results show that this scheme can achieve far better fairness than the original backoff scheme of DFWMAC, despite the fact that it sacrifies some throughput. As this scheme does not assume any knowledge about the network's topology and



(a)

(b)

(c)

(d)

Fig. 5. (a) Link throughput (original algorithm), (b) link throughput (modified algorithm, $\phi = 0.5$ for all), (c) linke throughput (modified algorithm, $\phi = 0.67$ for station 2, 3 and 4), (d) fairness index versus station offered load for the 5-station scenario.

thus does not require broadcast packets to disseminate information to other stations, it is very simple and can be easily overlaid in the existing DFWMAC protocol.

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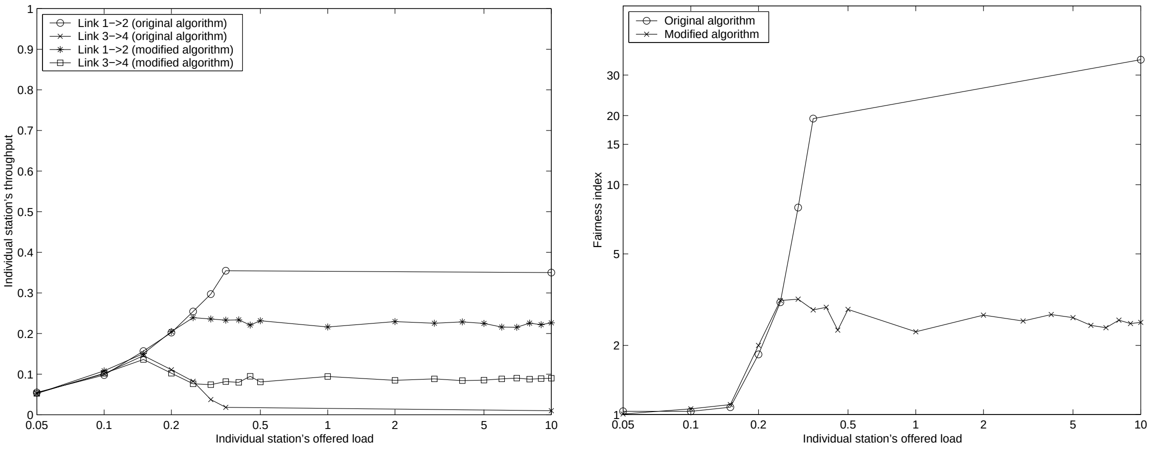

(a)

(b)

Fig. 6. (a) Station throughput, (b) fairness index versus station's offered load for the 6-station scenario.

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