A Novel Backoff Algorithm based on the tradeoff of Efficiency and Fairness for Ad hoc Networks

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Abstract

Since the wireless medium is a scarce resource, design of efficient medium access control (MAC) protocols with both high throughput and high fairness is significantly important for distributed ad hoc networks. Many current MAC protocols use an exponential backoff mechanism. In that mechanism, a node picks a random backoff time uniformly in an interval that doubles in size after a collision or decreases to the minimum value after a successful transmission. It can cause unfairness problem to some nodes. In this paper, we propose a novel and efficient contention-based backoff mechanism for wireless ad hoc networks, namely, the adaptive efficiency-fairness tradeoff (AEFT) backoff algorithm, which provides not only a higher throughput and a larger fairness index, but also a tradeoff between efficiency and fairness. We increase the contention window when the channel is busy, and use an adaptive window to fast decrease the backoff time when the channel is idle by fair scheduling. The fair scheduling mainly adopts maximum successive transmission and collision limit to finish the fairness.

1. Introduction

A key characteristic of Wireless ad hoc networks is their operation without infrastructure support or central administration. Each node in these networks may work as a router to relay connections or data packets to their destinations and randomly enter or leave networks without informing other nodes but not destroy the communication networks. For these special issues, ad hoc networks are widely used in the military, commercial and residential areas and have been regarded as one of the key features of beyond 3G systems [1]. In these networks, the medium access control (MAC) protocols that are used to share common channel resources among wireless nodes are responsible for coordinating the access from active nodes since the wireless medium is a scare resource and inherently prone to errors. Although a lot of research has been conducted on MAC protocols, the various issues involved have mostly been presented in isolation of each other such as hidden terminal, exposed terminal and collision problems. To solve those problems, researchers have proposed some MAC protocols based on carrier sensing medium access/collision avoidance (CSMA/CD) and others. The IEEE802.11DCF is a widely used access protocol in test beds and simulations for wireless networks [2]. The sender must defer a random time which is known as the backoff algorithm and the random time is called backoff time (BT) before retransmission in order to resolve medium conflicts. The backoff time relates directly to the ability to access to the channel for mobile nodes, lower backoff time means more chance to succeed in channel contention. Thus it can be seen that selection of backoff algorithm is crucial for all networks performance.

Although many innovative distributed contention-based backoff algorithms have been proposed, very few backoff algorithms satisfy simultaneously all desirable properties such as high throughput and good fairness while maintaining the simplicity of implementation in real wireless ad hoc networks. In this paper, we will focus on the backoff algorithm and design a novel adaptive efficiency-fairness tradeoff (AEFT) backoff algorithm, which provides not only a higher throughput and a larger fairness index, but also a tradeoff between efficiency and fairness. We increase the contention window (CW) when the channel is busy while reduce CW to zero upon successful transmission for high throughput, and use an adaptive window to fast decrease the backoff time when the channel is idle by fair scheduling. The fair scheduling mainly adopts maximum successive transmission and collision limit to finish the fairness.

The rest of the paper is organized as follows. Section II reviews the related work that has been done to improve backoff algorithm and analyzes their
deficiency. Section III introduces the AEFT. Section IV evaluates the performance of this new algorithm via computer simulation. At last, section V concludes this paper.

2. Related work

Binary exponential backoff (BEB) algorithm is the most popular instrument for collision resolution in multiple access protocols and regarded as the standard in IEEE802.11DCF MAC. A node which has a low backoff value contends more aggressively for the medium than a node which has a high backoff time, and has a higher probability of accessing the medium. Thus, the goal of collision resolution algorithms is to set the backoff time of a node to reflect the contention for the channel in the locality of the node. In BEB which is described in formula (1), a sender which detects a collision of its packet doubles its CW, while a transmitter which detects successful transmission of its packet resets its backoff time CWmin. This algorithm essentially favors the last transmitter to aggressively contend for the channel again since it has a low backoff the next time around and thus leads to unfairness, particularly when the offered load is high [3].

\[ CW = \min\{2 \times CW, CW_{\text{max}}\}, \text{ if collision} \]
\[ CW = CW_{\text{min}}, \text{ if success transmission} \]

Where \( CW_{\text{max}} \) and \( CW_{\text{min}} \) is the maximum value, minimum value of \( CW \) respectively. And

\[ \text{Backoff Time (BT)} = \text{Random}[0, CW] \times \text{a Slot time} \]

Where Random [ ] is an integer randomly chosen from a uniform distribution over the interval \([0, CW]\). A gentler version of BEB is MILD (Multiplicative Increase Linear Decrease) backoff, wherein a transmitter which detects a collision of its packet multiplies it backoff by a factor \( \alpha \) (upper bounded by a \( CW_{\text{max}} \)), while a transmitter which detects a successful transmission of its packet decreases its backoff by \( \beta \) (lower bounded by a \( CW_{\text{min}} \)). This algorithm still favors a successful transmitter to contend more aggressively the next time around, but since the backoff reduction is only by a constant \( \beta \), the fairness properties of MILD are much better than BEB. EIED [4] use the same principle with MILD.

Brahim et al. proposed a estimation-based fair medium access [5] in which each node 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 node’s individual links (time based). Whenever its backoff period ends, node \( i \) will send RTS packet to \( j \) with probability \( p_{ij} \) or backoff 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. Similarly literature [7-10] all improved the fairness of the backoff by dynamic adjusting CW.

However, none of [4-8] can achieve the best tradeoff for the network configurations and sometimes will cause the aggregated throughput to degrade badly. In addition, these schemes would slow down the collision resolution. Moreover, broadcast packets are unreliable to disseminate information to neighbors as the sender cannot elicit acknowledgment packets from its neighbors to ascertain if its packet has been successfully received by all of them. [9-10] construed the basic channel operation performance of CSMA/CA and put forward two major factors affecting the throughput in the 802.11DCF, then attempted to resolve collisions quickly by FCR. This measure obtained maximum throughput and low latency in wireless LANS. While deficiency in [9] was that the adaptive backoff threshold was not very good for our self-organized environment and not fairness for all nodes because one node monopolized channel in existence. [10] modified the self-clocked fair queuing (SCFQ) algorithm and incorporated it into FCR algorithm, still favor the last transmitter to aggressively contend for the channel since it has a low backoff time although it gave the maximum successive transmission limit for fairness but did not give chance to the continuous deferring or collision nodes. Also the backoff threshold was static without taking into account channel load.

Based on these analyses, we will propose a novel backoff algorithm based on the tradeoff of efficiency and fairness for ad hoc networks that incorporates the algorithms mentioned above to build a robust, efficient, and fair wireless medium access protocol. We setup two special counters in each node as the maximum successful transmission or collision. Via the fair scheduling, we simulate and analyze the algorithm performance, resulting high throughput and high degree of fairness.
3. Adaptive efficiency-fairness tradeoff (AEFT) backoff algorithm

3.1. Preliminary Part

Before the research of backoff algorithm, we should review the basic operations of CSMA/CA in IEEE 802.11 DCF, which are shown in Figure 1. The main performance impairment of throughput comes from packet collisions and wasted idle slots in each contention cycle. If the channel is highly loaded, the throughput of station $i$ can be expressed as [10]:

$$\rho = \frac{E(N\cdot T_r + T_{IFS} + T_{DFS}) + E(2\cdot T_{IFS} + T_{IFS} + T_{SIFS} + T_{ACK} + T_{DFS})}{E(N\cdot T_r + T_{IFS} + T_{DFS})}$$  \hspace{1cm} (3)

Where $E(N)$ is the average number of collisions in a virtual transmission time, $E(T)$ is the average number of idle slots resulting from backoff for each contention period, $T_{IFS}$ is the length of a slot, i.e. $aSlotTime$, and $E(P)$ is the average packet length.

![Fig.1. Basic operations of CSMA/CA in IEEE 802.11 DCF](image)

From this above expression, we can see that the throughput of station $i$ will be best if there are not collisions and idle slots in a virtual transmission time. We all know the transmission probability of station $i$ bears upon its priority. The station with high priority has high transmission probability, and small contention windows. So we may draw a conclusion that small contention windows should be for the successfully transmitted stations to decrease idle slots and large contention windows should be for the deferring or collision stations to decrease the collision probability, to achieve high throughput. Since the time delay is another important parameter for the throughput in ad hoc networks, Fast Collision Resolution (FCR) algorithm [10] decreased the wasted idle slots fast. Our paper also makes use of this point.

3.2. Protocol Operation

The detailed AEFT algorithm is described as follows.

1) A station desiring to transmit packets shall invoke the carrier sense mechanism to determine the busy/idle state of the medium. If the medium is idle, the station invokes the backoff procedure immediately with random backoff time (BT) determined from the initial contention window range, i.e. in this paper, $BackoffTime(BT) = Random[0,CW]*aSlotTime$ while if the medium is busy, the station defers till it becomes idle. Then it will start decrementing its backoff timer by a slot time, that is to say,

$$BT_{new} = BT_{old} - aSlotTime$$  \hspace{1cm} (4)

If a number of consecutive idle slots are detected and the remaining backoff timer value is less or equal than the backoff time Threshold $BT_{Th[i]}$ value which is different from literature [9](in this paper, we will explain why our $BT_{Th[i]}$ is better than the $BT_{Th[i]}$ of literature[9]) ,our algorithm will decrease faster(exponentially) the backoff timer:

$$BT_{new} = BT_{old}/2$$

if $BT_{new} < aSlotTime$, then $BT_{new} = 0$  \hspace{1cm} (5)

In the process of backoff procedure, we can not transmit RTS packet transitorily until the channel is idle and the backoff timer reaches zero.

2) In each station, there need set up two counters $n_s$, $n_f$ for recording the number of continuous successful transmissions and continuous deferring or collision respectively. Initial value all equals to zero. Counter $n_s$ will reset to zero after each collision or overrunning the threshold $n_s_{Th}$, also counter $n_f$ will reset to zero after each successful transmission or overrunning the threshold $n_f_{Th}$. The two thresholds are determined by the channel load.

3) If a station transmitted a packet successfully, then its contention window size will be reduced to zero, that is to say, $CW = 0$. This behavior has two meanings. First, it will decrease the idle slots and improve the total throughput. Second, it will decrease the collision probability to the newly entering stations which have small contention window size. In the same time, the counter $n_s$ will add one, i.e. $n_{snew} = n_{sold} + 1$. When there is a collision or overruns the threshold $n_s_{Th}$, Counter $n_s$ will reset to 0. But the contention window size will be increased to $CW_{max}$ if $n_s$ overruns the threshold $n_s_{Th}$.

4) If a station failed because of packet collision or deferring, then its contention window size will be doubled, the same as in FCR [10] and EDCF [9].

$$CW_{new} = \min(CW_{max}, 2\cdot CW_{old})$$  \hspace{1cm} (6)

However, in this paper, we add a counter $n_f$ for
recording the number of continuous deferring or collision. This behavior mainly aims to guarantee fairness to all the station and gives each station chance to transmit packet. At the time, the counter $n_f$ will add one, i.e. $n_{new} = n_{old} + 1$. When there is a successful transmission or overrunning the threshold $n_f - Th$, counter $n_f$ will reset to zero. But the contention window size will be decreased to $CW_{min}$ if $n_f$ overruns the threshold $n_f - Th$.

There are some issues to analyze from the items hereinbefore. First, the backoff time threshold $BT_{Th[i]}$ value is related to the channel load. The relation is that in the environment with many competing nodes, it requires small value of $BT_{Th[i]}$ relative to current CW to reduce collisions and in the environment with a few competing nodes, it requires high value relative to current CW to fast collision resolution in Figure 2.

![Fig. 2. Backoff Time Threshold](image)

We use the following expression to determine the backoff time threshold

$$BT_{Th} = \sqrt{\frac{CW_{max} - CW_{min}}{CW_{max}}} \cdot CW \cdot aSlotTime$$  

This expression is self-regulating and the ratio of $BT_{Th[i]}$ and contention window size is constant. But when contention window size is large, the difference of two values is large too, and the relative $BT_{Th[i]}$ value is small. When channel load decreases and the backoff time decrements its CW value, the difference of CW and $BT_{Th[i]}$ decreases too and relative $BT_{Th[i]}$ to CW is increasing. For example, in 802.11DCF, $CW_{max} = 1023$, $CW_{min} = 31$, if a station has CW 1023, here, $BT_{Th} = \sqrt{\frac{1023 - 31}{1023}} \cdot 1023 \cdot aSlotTime = 1067 \cdot aSlotTime$.

the difference of CW and $BT_{Th[i]}$ is 16. When CW equals to 31, $BT_{Th} = \sqrt{\frac{1023 - 31}{1023}} \cdot 31 \cdot aSlotTime = 31 \cdot aSlotTime$, the difference of CW and $BT_{Th[i]}$ is 0. So we can see that the $BT_{Th[i]}$ is adaptive based on the channel load.

In literature [9],

$$BT_{Th} = \frac{CW_{max} - OW_{max} \cdot OW \cdot aSlotTime}{CW_{max}} = \frac{1023 - 31}{1023} \cdot 31 \cdot aSlotTime = 31 \cdot aSlotTime$$

with CW equals to 1023, and

$$BT_{Th} = \frac{CW_{max} - OW_{max} \cdot OW \cdot aSlotTime}{CW_{max}} = \frac{1023 - 31}{1023} \cdot 31 \cdot aSlotTime = 31 \cdot aSlotTime$$

with CW equals to 31, $BT_{Th} = \text{Random}[0, 31] \cdot aSlotTime$. From the result, we find out the maximum $BT_{Th[i]}$ is 31, this contradicts our intent of fast collision resolution. Literature [10] used a static backoff threshold that can not reflect the channel load.

Second, whenever a station need the channel for packets transmission, the maximum successive transmission or continuous deferring or collision limit is determined by the $n_s - Th$ and $n_f - Th$. The two thresholds aim to give other stations higher probabilities to transmit their packets and make each station fairly use the channel. These two values also correlate with channel load. Basically, they should increase during high contention periods and decrease during low contention periods. If we know the number of current active stations in a distributed dynamic environment, the $n_s - Th$ and $n_f - Th$ values would be adjusted in real time. Literature [8] proposed a method to calculate the active number while it required filters and expensive to precisely precise value for stations frequently move about in ad hoc networks. In this paper, we adopt the way in literature [7] to show the relation of the parameter $n_s - Th$, $n_f - Th$ and the number of competing stations. We find the optimal range and emulate the algorithm. Since decreasing backoff time process is fast, the idle slots is too small to impact the networks performance.

Third, in item 4), the deferring station also doubles its contention window size which is different from 802.11 DCF to make the same priority has the similar CW for guaranteeing the fairness and decreasing collision probability.

4. Performance evaluation

4.1. Simulation Environment

We evaluate performance of the proposed AEFT algorithm using a network simulator NS-2 [11] and investigate some media parameters in ad hoc networks with different channel loads. In our simulations, the system parameters based on 802.11DCF network configurations [12] are given in Table I. For reducing the effect of TCP congestion control mechanism, simulation experiments select UDP data flows as our data source. From the previous section, we know the
values of $n_s\_Th$ and $n_f\_Th$ will highly influence the throughput performance and vary with the channel load. But the strict function relation of the two values and number of competing stations is difficult to obtain although literature [7] gave some advice. Considering the cost and the paper length, we do a lot of simulations and compare the different threshold values based on the conclusion [7]. At last, we choose $n_s\_Th =8$, $n_f\_Th =4$ as our simulation thresholds.

### TABLE 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phy layer</td>
<td>DSSS</td>
</tr>
<tr>
<td>Packet size</td>
<td>11680bits</td>
</tr>
<tr>
<td>Router protocol</td>
<td>DSR</td>
</tr>
<tr>
<td>MAC overhead</td>
<td>224bits</td>
</tr>
<tr>
<td>PHY header</td>
<td>192μs</td>
</tr>
<tr>
<td>A preamble length</td>
<td>144bits</td>
</tr>
<tr>
<td>A PLCP header length</td>
<td>48bits</td>
</tr>
<tr>
<td>ACK</td>
<td>14 bytes</td>
</tr>
<tr>
<td>RTS</td>
<td>20 bytes</td>
</tr>
<tr>
<td>CTS</td>
<td>14 bytes</td>
</tr>
<tr>
<td>Channel bit rate</td>
<td>2Mpbs</td>
</tr>
<tr>
<td>Propagation delay</td>
<td>1μs</td>
</tr>
<tr>
<td>A slot time</td>
<td>20μs</td>
</tr>
<tr>
<td>SIFS</td>
<td>10μs</td>
</tr>
<tr>
<td>DIFS</td>
<td>50μs</td>
</tr>
<tr>
<td>CWmin</td>
<td>31</td>
</tr>
<tr>
<td>CWmax</td>
<td>1023</td>
</tr>
</tbody>
</table>

To compare fairness, we use the following fairness index defined in [13] by Jain et al.:

$$FairnessIndex(FI) = \left( \frac{\sum T_i}{\phi_i} \right)^2$$

(8)

Where $T_i$ and $\phi_i$ are the throughput and weight of flow $i$ respectively, and $n$ is the number of flows. We all know, $\phi_i$ of all flows are equal. Our intuition is that $FI=1$ represents the optimal fairness. A closer value of $FI$ to 1 implies a higher the degree of fairness. It means all stations have the basic same chance accessing channel.

### 4.2. Simulation Results and Analysis

Figure 3 shows that AEFT provides obviously more throughput results than FS-FCR and 802.11DCF with different offered loads. Especially, in low load situations, AEFT executes well because it transmits packets continuously and low backoff time threshold economizing lots of wasted slots while FS-FCR has static backoff time threshold and need some slot time waiting with CW equal to CW$_{min}$ after successful transmits so in low offered load case, it need more time to wait. And 802.11DCF reduces its CW slowly and when contention stations increase, the collision chance increases too. This is the main reason that 802.11 shows very poor throughput performance with the contention stations increase. Moreover, we can see from this figure that in high offered load, AEFT does not obviously improve the total throughput value compared to FS-FCR. We analyze this situation carefully and find the whys. In our AEFT algorithm, we set two maximum successive transmission or continuous deferring or collision limit $n_s\_Th$, $n_f\_Th$. When a station continuously defers or conflicts $n_f\_Th$ times, our system can give it chance to transmit packet. It influences the total throughput value. However, we aim to achieve a tradeoff between efficiency and fairness so in a certain extent we must ensure fairness. Figure 4 shows the time delay of UDP flow results varied with offered load. From above introduction, we understand the result easily and this also testifies the correctness of our methods. AEFT clearly reduces the unnecessarily wasteful times in 802.11DCF and is as much as FS-FCR.
In this paper, we proposed AEFT (adaptive efficiency-fairness tradeoff) backoff algorithm, which provides not only a higher throughput and a larger fairness index, but also a tradeoff between efficiency and fairness, a simple framework for ad hoc networks with heterogeneous stations. We increase the contentention window when the channel is busy, and use an adaptive window to fast decrease the backoff time when the channel is idle by fair scheduling. The fair scheduling mainly adopts maximum successive transmission and collision limit to finish the fairness. The simulation results which we obtained in ns-2 simulator show that the new algorithm can achieve improved total throughput compared with 802.11 and other proposed MAC protocols such as FS-FCR and also obtain the almost same chance to access the shared channel.

Ongoing work includes addressing the continuous maximum successive transmission and the deferring or collision limit problem, by a simple method to gain the function which the adaptive limit and the active contention stations.

6. References