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A New Backoff Algorithm for the IEEE 802.11 Distributed Coordination Function

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***Abstract*— In the IEEE 802.11 Wireless Local Area Networks (WLANs), network nodes experiencing collisions on the shared channel need to backoff for a random period of time, which is uniformly selected from the Contention Window (CW). This contention window is dynamically controlled by the Binary Exponential Backoff (BEB) algorithm. The BEB scheme, as shown in some studies in the literature, suffers from a fairness problem and low throughput under high traffic load. In this paper, we propose a new backoff algorithm, termed the Linear/Multiplicative Increase and Linear Decrease (LMILD) backoff algorithm, for use with the IEEE 802.11 Distributed Coordination Function. In the LMILD scheme, colliding nodes increase their contention windows multiplicatively, while other nodes overhearing the collisions increase their contention windows linearly. After successful transmissions, all nodes decrease their contention windows linearly. Our preliminary study shows that the LMILD scheme out-performs the BEB scheme employed in the IEEE 802.11 MAC standard and the Multiplicative Increase Linear Decrease (MILD) scheme over a wide range of network sizes.**

***Index Terms*— Wireless Local Area Networks (WLAN); IEEE 802.11 Distributed Coordination Function (DCF); Medium Access Control (MAC); Contention Window; Backoff Algorithm**

I. Introduction

Wireless Local Area Networks (WLANs) have recently received considerable attention as a means to provide ad hoc wireless connectivity of mobile communication devices. The IEEE 802.11 WLAN MAC/PHY specification [1] is one of the recommended international standards for WLANs. The standard contains technical details for the Medium Access Control layer (MAC) and the Physical layer (PHY) of the communication protocol.

Two coordination functions are defined in the IEEE 802.11 MAC/PHY standard: the *Point Coordination Function (PCF)* and the *Distributed Coordination Function (DCF)*. In the PCF mechanism, a polling technique is employed by the access points or base stations to query network nodes for any traffic they may have to send. In the DCF medium access mode, active nodes compete for the use of the channel in a distributed manner via the use of the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) scheme. The CSMA/CA scheme uses both physical and virtual carrier sensing with the help of the optional Request-To-Send/Clear-To-Send (RTS/CTS) dialogue. The RTS/CTS dialogue was designed to mitigate the so-called hidden-terminal and exposed-terminal problems for WLANs [2].

Packet collisions are not completely eliminated in the IEEE 802.11 MAC/PHY standard due to the distributed nature of the competing nodes and the bursty traffic arrival at the nodes. In the IEEE 802.11 DCF scheme, the senders of the colliding packets need to refrain from immediate retransmissions in order to avoid repeated collisions. Thus, each competing node sets up a backoff timer according to a randomly selected backoff time period and enters the backoff state. This backoff time period is selected uniformly between 0 and the Contention Window (CW). In the IEEE 802.11 DCF scheme, the CW is dynamically controlled by the backoff algorithm; the *Binary Exponential Backoff (BEB)*. In the BEB algorithm, the contention window is doubled every time a node experiences a packet collision, i.e., when the CTS packet or the ACK reply are not received before a timeout occurs. If a node is successful in its packet transmission, the contention window is reset to the minimum value. In order to avoid the contention window from growing too large or shrinking too small, two bounds on CW are defined: the maximum contention window (CW_{max}) and the minimum contention window (CW_{min}).

However, the BEB scheme suffers from a fairness problem; some nodes can achieve significantly larger throughput than others. The fairness problem occurs due to the fact that the scheme resets the contention window of a successful sender to CW_{min}, while other nodes continue to maintain larger contention windows, thus reducing their chances of seizing the channel and resulting in channel domination by the successful nodes [3] [4]. The selection of CW_{min} and CW_{max} also has significant impact on the performance of the IEEE 802.11 DCF scheme, as reported in [5]. Other backoff algorithms have been proposed, such as the Multiplicative Increase and Linear Decrease (MILD) algorithm in [3]. However, as we will show in Section IV, the performance of these backoff schemes are still quite far away from the maximum utilization of the IEEE 802.11 MAC scheme.

In this paper, we propose a new backoff algorithm for the IEEE 802.11 DCF scheme. Our algorithm is termed the *Linear/Multiplicative Increase and Linear Decrease (LMILD)*. Similar to the MILD scheme, we use a linear decrease mechanism to avoid channel domination, instead of the reset mechanism of the BEB scheme. However, the main difference

between the LMILD and the MILD schemes is that the LMILD scheme uses an additional piece of information – the overheard collisions – available in the IEEE 802.11 WLANs. This is in contrast with the MILD scheme which uses a backoff copy technique to make sure that every neighboring node copies the contention windows of the successful nodes. In the LMILD scheme, colliding nodes increase their contention windows multiplicatively, while other nodes overhearing the collisions increase their contention windows linearly. After a successful transmission, all nodes decrease their contention windows linearly.

Our work is inspired by the following observation regarding IEEE 802.11 WLANs: network nodes compatible with the IEEE 802.11 MAC/PHY standard are able to observe packet collisions taking place on the channel. While it is considered generally difficult for wireless network nodes to perform collision detection during transmissions, it is more practical for non-transmitting nodes to *observe* packet collisions. In IEEE 802.11 WLANs, all nodes are capable of performing physical carrier sensing. When a node senses the channel busy for the duration equal to a packet transmission time, but it does not receive or overhear a successful packet,[1] the node concludes that a packet collision has taken place.

The paper is organized as follows. Section II briefly reviews related work. The details of the LMILD scheme are presented in Section III. In this section, we also present our analysis on the optimum contention windows in a fully connected network with a known number of active nodes. Section IV discusses our numerical and simulation results. Section V concludes the work.

II. Related Work

The BEB scheme is widely used in MAC layer protocols due to its simplicity [6]. In this scheme, each node doubles its contention window, CW, up to the maximum contention window (CW_{max}) after a collision occurs and resets its CW to the minimum value (CW_{min}) after a successful transmission:

$$\begin{cases} CW \leftarrow min(2 \cdot CW, CW_{max}) & \text{upon collision} \\ CW \leftarrow CW_{min} & \text{upon success} \end{cases} .$$

The values of the CW_{min} and CW_{max} are pre-determined based on the expected range of the number of active nodes and the traffic load of the network. As we have pointed out, the BEB scheme suffers from fairness issues under high traffic load and low throughput problems when network size is large.

To address the fairness problem in the BEB scheme, the Multiplicative Increase and Linear Decrease (MILD) algorithm was introduced in the MACAW scheme [3]. In the MILD scheme, a collided node increases its CW by multiplying it by 1.5. A successful node decreases its CW by one unit, where a unit is defined as the transmission time of the RTS packet. The MACAW protocol assumes that a successful node has a CW value that is related to the contention level of the local area. The current CW is included in each transmitted packet and a contention window copy mechanism is implemented at each overhearing node to copy the CW of the overheard successful transmission into its local CW. The operation of the MILD scheme can be summarized as follows:

$$\begin{cases} CW \leftarrow min(1.5 \cdot CW, CW_{max}) & \text{upon collision} \\ CW \leftarrow CW_{packet} & \text{upon overhearing} \\ & \quad \text{successful packets} \\ CW \leftarrow max(CW - 1, CW_{min}) & \text{upon success} \end{cases} ,$$

where CW_{packet} is the CW value included in the overheard (successful) packet. Besides increasing the header size of the RTS packets, the MILD scheme may also suffer from the migration of the CW value into areas with different contention levels that do not match the CW values [7].

In [8], an analytical model was proposed to predict and study the performance of the IEEE 802.11 DCF scheme. It was found that the performance of the basic scheme (without the RTS/CTS dialogue) is strongly dependent on the system parameters, mainly the minimum contention window and the number of active stations. It was, however, found that the performance is only marginally dependent on these system parameters when the RTS/CTS mechanism is employed. Reference [9] presented an analytical model and its results. This model considered the busy medium conditions and how they would affect the use of the backoff mechanism.

A similar approach was presented in [10] without the fairness considerations. The proposed scheme eliminates the contention window reset process of the IEEE 802.11 DCF scheme and uses a multiplicative increase and multiplicative decrease (MIMD) algorithm to change the contention window; i.e., the contention window is doubled(halved) when a node experiences collisions(successful transmissions.)

III. The Linear/Multiplicative Increase and Linear Decrease Backoff Algorithm

In this section, we present the details of the proposed Linear/Multiplicative Increase and Linear Decrease (LMILD) backoff algorithm for the IEEE 802.11 DCF scheme. The operation of the LMILD scheme is based on an additional piece of information available to network nodes in the IEEE 802.11 WLANs. This additional information is the knowledge of the packet collisions on the channel. Note that we do not assume that network nodes are capable of performing collision detection while transmitting packets. According to the IEEE 802.11 MAC/PHY standard, every node is capable of physical carrier sensing. When a backoff or idle node senses the channel busy for a period of the RTS packet transmission time but the packet header is not detected and reported by the physical layer, it knows that an RTS packet collision has taken place. The senders of the colliding RTS packets will become aware of the collision when the CTS reply is not received before timeout occurs. In addition to this information, nodes will also overhear successful packet transmissions.

In the LMILD scheme, each node experiencing an RTS collision increases its CW by multiplying it by the factor

[1] More precisely, the header of the incoming packet is not reported by the physical layer. These two primitives are specified in [1] in the PHY-CCA.indication service specification in Section 12.3.5.10 and the PHY-RXSTART.indication service specification in Section 12.3.5.11.

m_c. Any node overhearing a collision with the help of the above-mentioned technique increases its CW by ℓ_c units (slots). When a successful RTS transmission takes place, all nodes (including the sender, the receiver, and all overhearing neighbors) decrease their CWs by ℓ_s units. Thus, the operation of the LMILD algorithm can be summarized as follows:

$$\begin{cases} CW \leftarrow min(m_c \cdot CW, CW_{max}) & \text{upon collisions} \\ CW \leftarrow min(CW + \ell_c, CW_{max}) & \text{upon overhearing collisions} \\ CW \leftarrow max(CW - \ell_s, CW_{min}) & \text{upon experiencing or overhearing success} \end{cases} .$$

In the LMILD scheme, the failed senders increase their CWs multiplicatively, while neighboring nodes increase their CWs linearly. Upon successful transmission of an RTS packet, which will most likely result in a successful DATA packet transmission, every node decreases its CW linearly. The ℓ_c parameter allows non-colliding nodes to react to packet collisions on the shared channel, similar to the way they react to successful transmissions on the shared channel with parameter ℓ_s. Note that the LMILD scheme does not employ the contention window (backoff interval) copy mechanism that is used in the MILD scheme. In our LMILD scheme, every node knows the status of the channel as idle, success, or collision, $(0, 1, e)$.

The values of m_c and ℓ_c control how fast nodes increase their $CW s$ in the case of packet collisions. Similarly, the value of ℓ_s allows nodes to lower their CWs when a successful channel access takes place. We set the m_c to 2 and leave discussion of the other two parameters to Section IV. The goal of the LMILD scheme is to dynamically maintain the CW values of all nodes close to the optimum CW value, which maximizes the throughput of the IEEE 802.11 network given a fixed number of competing nodes. In the following subsection, we derive the length of the optimum fixed contention windows.

A. Optimum Fixed Contention Windows

We assume that there are altogether N active nodes competing for the use of the shared channel in an IEEE 802.11 WLAN. Each of these nodes uses a fixed CW. Our objective is to find the optimum value for CW, CW^*, which maximizes the channel throughput of the IEEE 802.11 WLAN.

The probability of each active node sending an RTS packet in a particular slot is given by [8]:

$$p \approx \frac{2}{CW + 1} \quad . \tag{1}$$

Note that (1) is more accurate when N is large. For a small N, e.g., $N = 2$, the approximation becomes less accurate.

For large N and CW, the events of different nodes sending RTS packets in a slot are mutually independent. The probability that there will be a successful RTS packet transmission on the channel in a slot is $P_s = \binom{N}{1} p(1-p)^{N-1}$. A slot will be left idle with probability $P_i = (1-p)^N$. The probability that RTS packet collisions take place on the channel in a slot is $P_f = 1 - P_s - P_i = 1 - (1-p)^{N-1}(Np + 1 - p)$.

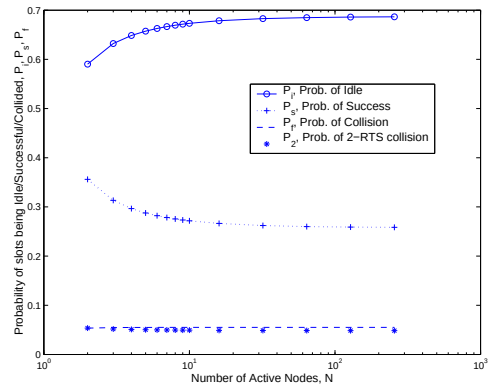

Fig. 1. Probability of Idle, Success, and Collision

According to the derivation in the Appendix and in [8], the optimum transmission probability that maximizes the throughput for the IEEE 802.11 DCF scheme is:

$$p^* \approx \frac{1}{N\sqrt{T_c/2}} \quad , \tag{2}$$

where T_c is the duration of packet collisions on the channel in the terms of the number of time slots. The value of T_c is 13 slots in an IEEE 802.11 WLAN with 11 Mbps data rate.[2]

Based on (1), the optimum CW, CW^*, for a fully connected network with exactly N active nodes is [8]:

$$CW^* \approx \sqrt{2T_c}N = 5.1N \quad . \tag{3}$$

In Fig. 1, we show the probability of a slot being idle, with successful transmission, and with packet collisions (P_i, P_s, and P_f) when CW is set to CW^* according to (3). We observe that P_i and P_s approach 0.68 and 0.26, respectively, as N increases. Interestingly, the P_f curve is relatively flat at the value of 0.06 for different values of N.[3] In Fig. 1, we also draw the probability of a specific type of RTS packet collisions, P_2, the probability of exactly two RTS packets colliding with each other. Observing that the P_2 and P_f curves almost coincide with each other, we conclude that, when an IEEE 802.11 WLAN operates with CW^*, the probability of having more than 2 nodes colliding with each other is relatively small.

IV. Performance Evaluation

In order to evaluate the performance of the proposed LMILD scheme, we used the NS-2 simulator to perform simulations of the IEEE 802.11 WLANs under various network assumptions. The channel data rate is assumed to be 11 Mbps. The propagation times are assumed to be negligible. All nodes are in the range of each other and are stationary.

[2]The physical layer overhead is 192 μsec. The RTS packet is 20 bytes (15 μsec). The Distributed InterFrame Spacing (DIFS) is 50 μsec. The slot length is 20 μsec. Thus, each collided RTS packet uses 13 slots [1].

[3]Indeed, according to (5) in the Appendix, $(1-p^*)^N = \frac{T_c}{T_c-1}(1 - Np^*)$. From the equation of P_f and (2), we have $P_f = 1 - \frac{T_c}{T_c-1}\frac{(1-Np^*)(Np^*+1-p^*)}{1-p^*} \approx 1 - \frac{T_c}{T_c-1}\left[1-(Np^*)^2\right] \approx \frac{1}{T_c-1}$ is not related to N. The discrepancy between this result and 0.06 shown in Fig. 1 is due to the approximation in (2).

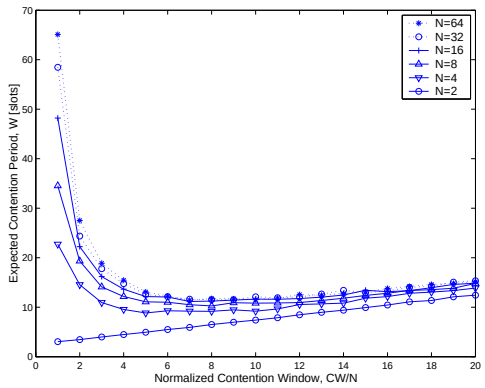

Fig. 2. Expected Contention Period

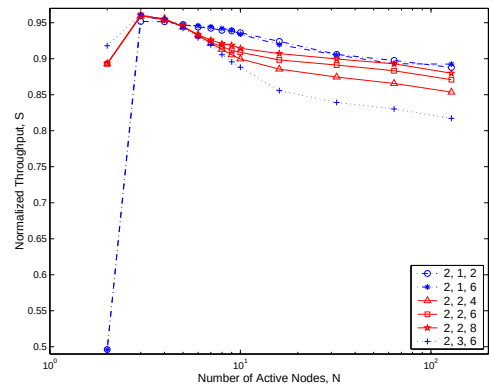

Fig. 3. Throughput Comparisons of Different LMILD Schemes

The number of active nodes, N, is varied in our simulations. These N nodes can hear each other directly, similar to what was assumed in [8] and [9]. In order to study the performance of the backoff schemes, our simulations are performed under saturated conditions [8] [9]; i.e., active nodes always have data packets to send. The values of CW_{min} and CW_{max} are assumed to be 15 and 1023, respectively, unless specified otherwise.

Fig. 2 compares the expected contention periods as a function of different CWs for different N. In these simulations, we fix CW of all active nodes and investigate the expected time of the contention periods (in time slots). When the value of relative CW, CW/N, is too small (e.g., 2), there are too many RTS packet collisions on the channel, leading to longer expected contention periods. The expected contention period decreases as CW/N increases. However, as CW/N increases after a certain point, the expected contention period increases from the minimum value. Interestingly, we observe that the optimum CW/N is not exactly 5.1 as specified in (3). However, the expected contention period is relatively constant when CW/N changes from 5 to 18. The expected contention period is slightly larger for networks with larger N. This is due to the increase of randomness from competing nodes with larger N. In Fig. 2, the $N = 2$ curve is different from other curves because (1) does not model the transmission probability in a network with $N = 2$ active nodes accurately.

In Fig. 3, we compare the throughput performance[4] of the LMILD scheme with different parameters. The legends shown in the figure represent the LMILD schemes with different parameters of (m_c, ℓ_s, ℓ_c). From this figure, it can be observed that the throughput of the LMILD schemes with large values of ℓ_s, e.g., $\ell_s = 3$, suffers from low throughput for networks with large N. This is due to the fact that nodes decrease their CWs too quickly in case of successful transmissions, leading to more packet collisions. Lowering the value of ℓ_s may help to improve the throughput, however, as we will see in the following discussion on fairness, this may lead to unfair channel allocation. Increasing the ℓ_c value improves the throughput of the LMILD scheme slightly. However, when ℓ_c is too high, some nodes may have an extremely small chance to access the channel successfully, due to the fact that they increase their CWs too fast when overhearing collisions.

[4]The throughput is presented as normalized to the throughput of a network with no contention resolution at all [11].

TABLE I

FAIRNESS OF LMILD SCHEMES AND BEB SCHEME

(2,1,2)	(2,1,6)	(2,2,4)	(2,2,6)	(2,2,8)	MILD	BEB
0.12	0.13	0.71	0.64	0.59	0.75	0.58

In Table I, we compare the Fairness Index (FI) of the LMILD schemes with different parameters, the MILD scheme, and the BEB scheme employed in the IEEE 802.11 DCF scheme for $N = 10$. The value of FI is calculated as the ratio of the minimum number of packets sent by any individual node to the maximum number of packets sent by any individual node. Thus, this index demonstrates how fairly the channel is shared among the active nodes in the presence of a backoff scheme. Obviously, for a perfectly fair network, FI should be 1. The lower the FI value is, the more unfair the system is. From Table I, we can see that the parameter sets of $(2, 1, 2)$ and $(2, 1, 6)$ for the LMILD scheme, which provides slightly higher throughput, as shown in our simulation results in Fig. 3, have very poor fairness performance. When the value of ℓ_s is increased to 2, the fairness performance of the LMILD scheme is vastly improved. This table and results to be presented in Fig. 4 show the superiority of our scheme compared with the BEB scheme, as the LMILD scheme with parameters set to $(2, 2, 6)$ provides higher throughput for a wide range of N and better fairness than the BEB scheme. Note that the MILD scheme has better fairness performance than both the LMILD and the BEB schemes due to its CW copy mechanism. From Table I and Fig. 3, we recommend setting the parameters of the LMILD scheme at $(2, 2, 6)$, considering both throughput and fairness performance. Further increasing ℓ_c may improve the throughput slightly, but resulting in degradation in the fairness index as well.

We compare the throughput performance of the LMILD scheme with (m_c, ℓ_s, ℓ_c) set to $(2, 2, 6)$, the MIMD scheme, the MILD scheme, and the BEB scheme of the IEEE 802.11 DCF scheme in Fig. 4. This figure also presents the per-

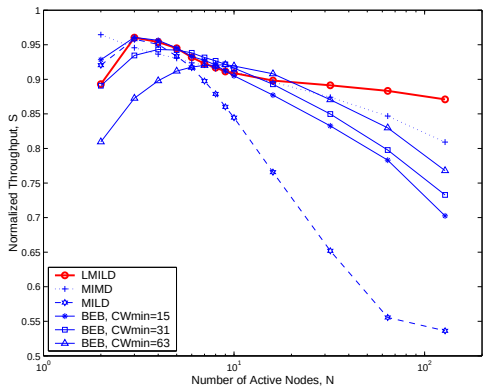

Fig. 4. Comparing the Performance of BEB and LMILD

formance of the IEEE 802.11 DCF scheme with different CW_{min}, as we found that the value of CW_{min} significantly affects the performance of the IEEE 802.11 DCF scheme with the RTS/CTS dialogue. Contrary to the results reported in [8], [5] studied the effects of CW_{min} and CW_{max} in the IEEE 802.11 DCF scheme and showed that the proper choice of these two system parameters has a large influence on the network performance and the choice is highly dependent on the number of contending stations.

The poor throughput performance of the MILD scheme, especially when the number of active nodes is larger as shown in Fig. 4, is due to the resulting low CW with the CW copy mechanism: Nodes with smaller CWs win the contentions with higher probability. All neighboring nodes then copy these low CW values and compete with each other, resulting in high contention collisions and lower throughput. The throughput of the LMILD scheme is generally higher than that of the BEB scheme employed in the IEEE 802.11 DCF scheme. The LMILD scheme maintains a throughput higher than 0.86 for all different values of N shown in the figure, while the throughput of the BEB scheme with $CW_{min} = 15$ has a much lower throughput when N is large. Increasing the value of the CW_{min} may help to improve the throughput in networks with large N. However, the throughput is then lower for networks with fewer nodes, as shown in the figure. Note that the LMILD scheme and the MILD scheme use $CW_{min} = 15$ in these simulations. Thus, the performance in scenarios with smaller N coincides with that of the BEB scheme with the same CW_{min}, except for $N = 2$, where the LMILD scheme has slightly lower throughput than the BEB scheme. When $N = 128$, the LMILD scheme out-performs the BEB scheme in the IEEE 802.11 DCF scheme by 25%. This gain is even higher for larger N. Overall, the performance of the IEEE 802.11 MAC (DCF) scheme with the LMILD backoff scheme is at least 87% of the maximum possible utilization for a wide range of number of active nodes in the network.

V. Conclusions

In the IEEE 802.11 WLANs, packet collisions are not completely eliminated even when the RTS/CTS dialogue option is used by the competing nodes. When access collisions take place, active nodes need to backoff randomly to avoid repeated collisions. This random backoff time is uniformly selected from the contention window, CW, which is dynamically controlled by the Binary Exponential Backoff (BEB) algorithm. However, the BEB scheme suffers from a fairness problem and its throughput performance is unsatisfactory under some circumstances, as shown by our simulation results. Changing the parameters of the BEB scheme cannot improve its performance over a wide range of network operational conditions, such as the number of network nodes. The Multiplicative Increase and Linear Decrease (MILD) backoff algorithm solved the fairness problem of the BEB scheme. However, it suffers from low throughput in networks with large number of active nodes as well.

In this paper, we have introduced a new backoff algorithm, termed the Linear/Multiplicative Increase and Linear Decrease (LMILD), to be used with the IEEE 802.11 DCF scheme. In the LMILD scheme, all nodes decrease their CWs by ℓ_s units (slots) in the case of a successful transmission. The senders of the colliding packets increase their CWs multiplicatively by m_c. All neighboring nodes overhearing the collisions increase their CWs by l_c units (slots). In order to perform such an operation, network nodes make use of the extra information available from the physical layer, which generates physical carrier sensing signal and reports no packet header reception during collisions. This special feature differentiates the LMILD scheme from the MILD scheme.

Our study shows that the LMILD scheme, with correct parameter settings, out-performs the BEB scheme employed in the IEEE 802.11 DCF scheme and the MILD scheme over a wide range of the number of active network nodes. When the number of active nodes in an area reaches 128, the performance of the LMILD scheme is 25% higher than that of the BEB scheme in the IEEE 802.11 DCF scheme. The fairness performance of the LMILD scheme is better than the BEB scheme as well.

The proposed LMILD scheme does not require any hardware changes in the IEEE 802.11 MAC/PHY standard. Only software or driver modifications are necessary. The resulting throughput performance is much more stable over a wide range of the number of active nodes. While the LMILD scheme was proposed for the IEEE 802.11 WLANs, it is possible to use it in other similar wireless networks where packet collisions can also be overheard by network nodes.

Compared with the BEB, the MILD, and other backoff schemes in the technical literature, the LMILD scheme operates very well with the parameters we found, for a wide range of number of active nodes in the network. Even though these parameters were found based on simulations instead of analytical study, we believe that they can provide stable throughput for networks with a wide range of active nodes. We leave the analytical study of these parameters to our future work.

In this paper, we have assumed that all neighboring nodes are able to detect the existence of collided packets perfectly.

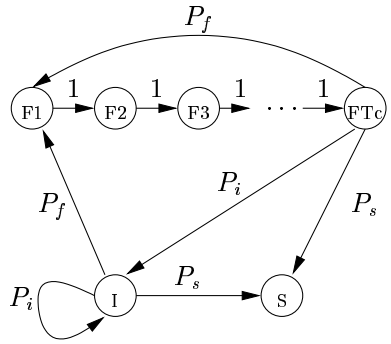

Fig. 5. States of the Channel

This might not be true in a practical IEEE 802.11 WLAN, where the frequency band is shared by other devices, such as bluetooth devices and microwave. The neighboring nodes could fail to detect the collided packets due to channel fading or they could mistaken other signals as packet collisions. These mis-detection and false positive problems may affect the performance of the LMILD scheme. We leave this interesting study to be one of our future work.

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APPENDIX
CALCULATION OF OPTIMUM p

Let $\overline{W}$ denote the expected contention period, the period between the time when the channel becomes available[5] and the time when a successful RTS packet starts. To simplify our study, we further assume that when RTS packets are successfully transmitted and received, DATA packet transmissions will always be successful.

In order to calculate $\overline{W}$, we model the status of the channel with $T_c + 2$ states as shown in Fig. 5, where T_c is the duration of the RTS packet collisions (in the terms of the number of time slots) [8]. The first T_c states, $F1, F2, \cdots, FT_c$, model the T_c slots of collision time on the channel. States I and S model the idle and success states on the channel, respectively. Let W_x denote the expected absorption time to the S state, given that the current slot is in state x, where $x \in \{F1, F2, \cdots, FT_c, I, S\}$. Obviously, $W_S = 0$. Using first step analysis [12], we have the following equations:

$$\begin{cases} W_{F1} = 1 + W_{F2} \\ W_{F2} = 1 + W_{F3} \\ \cdots \\ W_{F(T_c-1)} = 1 + W_{FT_c} \\ W_{FT_c} = 1 + P_i \cdot W_I + P_f \cdot W_{F1} + P_s \cdot W_S \\ W_I = 1 + P_i \cdot W_I + P_f \cdot W_{F1} + P_s \cdot W_S \ . \end{cases}$$

[5]More specifically, it is DIFS seconds after the channel becomes idle [1].

Solving the above equations and noticing that $\overline{W} = W_I - 1$ as we start from an idle slot when calculating W_I, we have:

$$\overline{W} = \frac{P_i}{P_s} + \frac{1-P_i}{P_s} T_c - T_c \ .$$

According to the equations of P_s and P_s, we have:

$$\overline{W} = \frac{1-p}{Np} + \frac{1-(1-p)^N}{Np(1-p)^{N-1}} \cdot T_c - T_c \ . \qquad (4)$$

Taking partial derivative of (4) with respect to p and setting it equal to zero, we find the optimum p, p^*, that minimizes $\overline{W}$. p^* should satisfy:

$$\left[-\frac{(1-p)^{N-1} - (N-1)p(1-p)^{N-2}}{N[p(1-p)^{N-1}]^2} + \frac{1}{Np^2} \right] T_c - \frac{1}{Np^2} = 0 \ ,$$

which is equivalent to

$$\frac{1-Np^*}{(1-p^*)^N} = \frac{T_c - 1}{T_c} \ . \qquad (5)$$

Although we derived (5) using a different approach than that used in [8], this last condition corresponds exactly to equation (27) in [8]. When $Np \ll 1$, we have [8]:

$$p^* \approx \frac{1}{N\sqrt{T_c/2}} \ .$$

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