Improving Throughput in Wireless Networks Using MIMD Backoff Window Control Method

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Abstract

The backoff window control mechanism in 802.11 DCF is closely related to the transmission performance. In the standard 802.11 DCF, a crossover station which bridges two different wireless channels has less chances for winning channel accesses than the non-crossover stations. In order to improve the throughput of the crossover stations, the crossover stations should be favored to win channel accesses.

In this paper, we describe a multiplicative-increase multiplicative-decrease (MIMD) based backoff window control mechanism. The window increase rate is determined based on the number of direct and indirect neighbors: it is proportional to the number of direct neighbors and inversely proportional to the number of indirect neighbors. A station with more number of indirect neighbors is more likely to act as a potential frame relay for other stations. Hence, the more the number of indirect neighbors is, the more modest a station increases its backoff window. Under this backoff window control mechanism, the average throughput of a wireless station is made proportional to the number of indirect neighbors.

Index Terms

Media Access Control, IEEE 802.11 protocols, Ad Hoc Wireless Networks, MIMD, Stability
I. INTRODUCTION

Improving the end-to-end throughput is one of the key research topics in ad hoc routing in wireless networks, especially for streaming media over multiple hops in wireless networks. The end-to-end throughput under an ad hoc routing protocol is jointly determined by the efficiency of the routing protocol which operates at the network layer and the performance of the underlying media access control (MAC) mechanism which operates at the link layer [9]. Traditionally, ad hoc routing protocols focus on specifying methods of route discovery without explicitly taking into account the interactions with the underlying medium access control (MAC) protocols. The MAC protocols, however, largely affect the overall performance of ad hoc routing protocols because the MAC protocols adjudicate the successful transmission of packets sent by the routing protocols. Failure of sending/receiving packets to/from the underlying wireless channel compromises the efficiency of a routing protocol. Packet losses at the link layer compromise the end-to-end throughput of multiple-hop connections much more than that of single-hop connections. Therefore, it is important to strengthen the design of the MAC protocols for improving the end-to-end throughput.

IEEE 802.11 series standards [12], [6], [21] have been widely used as the MAC protocol at the link layer in wireless networks, which specify the arbitration channel access contentions among multiple wireless transmission devices. A crucial component in these standards is the Distributed Coordination Function (DCF) which is implemented in each wireless transmission device (a.k.a. station). A DCF is a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism [15], [4]. Under a CSMA protocol, only one station is allowed to transmit at a time, and a station can transmit only when the channel is idle. Compared with collision resolution in a wireline channel, contention resolution in wireless channels is more difficult.

A crossover station stays at the intersection of multiple channels, and it is similar to a bridge linking different local area networks (LANs). A crossover station serves to relay packets for other stations. It can only make a transmission when all channels, in which it is involved, become idle at the same time. The chance that multiple channels become idle simultaneously is certainly less than the chance that a single channel becomes idle. Therefore, it is more difficult for crossover stations to win a channel access. Chances for the crossover stations to win channel accesses closely relate to the end-to-end throughput of multiple-hop transmissions. Hence, favoring the crossover stations to win channel accesses needs to be considered in MAC protocols.

In this paper, we present a multiplicative-increase multiplicative-decrease (MIMD) based backoff window control method for favoring crossover wireless stations to access the channel.

\[ W_{n+1} = \begin{cases} 
(1 + \alpha)W_n, & \text{upon a collision} \\
(1 - \beta)W_n, & \text{upon a successful transmission} 
\end{cases} \]

where \( \alpha \) and \( \beta \) are backoff window increase and decrease rates, respectively. The values of \( \alpha \) and \( \beta \) rely on keeping track of the number of two-tier neighbors. For a wireless station, its two-tier neighbors are those stations which can be reached in no more than two hops, \textit{i.e.}, the direct and indirect neighbors (ref. Fig. 1). When \( d \) and \( i \) are denoted as the number of direct and indirect neighbors, respectively, the value of \( \alpha \) is determined by

\[ \alpha = \frac{d}{i + 1}. \]

The value of \( \beta \) is determined by

\[ \beta = 1 - \frac{1}{(1 + \alpha)^s} \]

where \( s \) is a parameter called the service capability. Each station keeps track of its two-tier neighbors by snooping on the MAC layer frames (RTS,CTS, DATA, and ACK frames). The goal of this backoff window control method is to reduce the backoff time experienced by the crossover stations, such that the crossover stations are favored in channel accesses. The chance for a wireless station to win a channel access should be proportional to the number of its indirect neighbors and inversely proportional to the number of its direct neighbors.

The rest of this paper is organized as follows. The related work is presented in Section II. The analytical method of modeling the operation of the MIMD-based backoff window control mechanism is debriefed in
Section III. The MIMD-based backoff window control mechanism is described in Section IV. The evaluation of the efficiency of the MIMD-based backoff window control mechanism is demonstrated in Section V. Our work is summarized in Section VI.

II. RELATED WORK

Modeling the saturation transmission throughput of the CSMA/CA mechanism [5], [8], [20] is based on several assumptions: 1) ideal channel conditions; 2) finite but a large number of contending stations; 3) each station is ready to transmit data frames whenever it is allowed to access the medium (the channel); and 4) a frame transmitted by a station collides with other frames with a constant probability which is only dependent on the size of its backoff window. The backoff algorithm used in IEEE 802.11 MAC protocol is a significant factor affecting the transmission throughput. The bounded binary backoff (BEB) [15], [4] algorithm is commonly used in CSMA protocols. The main advantage of adopting the BEB algorithm is to achieve a stability on throughput, i.e., BEB guarantees a certain amount of throughput no matter how many contending stations are present in a network [23]. However, this stability is an asymptotic behavior, when there are infinite backoff stages and the number of contending stations are very large.

Improving the throughput of 802.11 DCF through modifications to the original BEB algorithm has been studied in a number of works. The collision-minimizing CSMA [24] is a new backoff scheme which adopts a nonuniform probability distribution used to randomly select contention slots. This probability distribution is the unique probability distribution that minimizes collisions between contending stations. The multiplicative increase multiplicative/linear decrease (MIMLD) algorithm [22] is to add a linear decrement operation used to automatically adjust the initial contention window size to the “optimal” window size contingent to the actual collision status in a wireless channel. The linear/multiplicative increase and linear decrease (LMILD) backoff algorithm [10] adopts mixed multiplicative/linear increase and linear decrease on contention windows size. A medium access diversity (MAD) scheme [14] to adapt to different requirements on transmission rate by aggressively exploiting multiuser diversity. In this scheme, data frames are selectively transmitted to their destinations based on the instantaneous channel condition information probed from ongoing transmission, in order to largely eliminate the unfairness of winning the access to the medium among multiple stations. A receiver-based auto-rate MAC protocol [11] makes sender stations to adapt to the rates of receiver stations in order to achieve a higher overall throughput compared to the throughput achieved under a sender-based auto-rate MAC protocol.

III. BASIC MODEL

The modeling of the throughput of a wireless station is made in two steps. First, the average backoff window size is modeled. Second, the average throughput of a wireless station is modeled based on the average backoff window size.
A. Modeling the Backoff Window Size

A backoff window size is dynamically updated by

\[ W_{n+1} = \begin{cases} 
(1 + \alpha)W_n, & \text{upon a collision}, \\
(1 - \beta)W_n, & \text{upon a successful transmission}, 
\end{cases} \tag{III.A} \]

where \( 0 < \alpha, \beta < 1 \).

Following the same analytical approach developed in [2], [3], the operation of a wireless channel is assumed independent of the operation of wireless stations. The state of a wireless channel oscillates between idle and collision, and it can be modeled by a Markov chain shown in Fig. 2. The probability of an occurrence of a collision is

\[ P_c = \frac{1 - P_1}{(1 - P_1) + (1 - P_2)} \]

Combined with the fact that a backoff window size is always bounded between two limits: \( W_{\min} \) and \( W_{\max} \), expression (III.A) is written into

\[ W_{n+1} = \begin{cases} 
\min\{(1 + \alpha)W_n, W_{\max}\}, & \text{w.p. } P_c, \\
\max\{(1 - \beta)W_n, W_{\min}\}, & \text{w.p. } (1 - P_c). 
\end{cases} \tag{III.B} \]

When \( \{A_n, n \geq 0\} \) is denoted as a sequence of i.i.d. random variables with \( A_n \) defined by

\[ A_n = \begin{cases} 
(1 + \alpha), & \text{w.p. } P_c, \\
(1 - \beta), & \text{w.p. } (1 - P_c), 
\end{cases} \]

expression (III.B) is written into

\[ W_{n+1} = \begin{cases} 
\min\{A_nW_n, W_{\max}\}, & \text{w.p. } P_c, \\
\max\{A_nW_n, W_{\min}\}, & \text{w.p. } (1 - P_c) 
\end{cases} \tag{III.C} \]

If the sequence \( \{A_n\} \) is assumed stationary and ergodic, then there exists a unique stationary ergodic process \( \{W_n^*\} \) for \( W_n \) defined in (III.C) [3].

Let us introduce a transformation that has been used in [3]:

\[ Y_n = \frac{\log(W_n) - \log(W_{\min})}{\log(1 + \alpha)}. \tag{III.D} \]

When \( s = \frac{-\log(1 - \beta)}{\log(1 + \alpha)} \) is assumed an integer, the value of \( Y_n \) is an integer because the space of \( W_n \) is of the form \( \{W_{\min}^i(1 + \alpha)^i, i = 0, 1, \ldots, L\} \). We also denote \( L = \frac{\log(W_{\max}) - \log(W_{\min})}{\log(1 + \alpha)} \), and the value of \( L \) is an integer. Expression (III.B) is transformed into

\[ Y_{n+1} = \begin{cases} 
\min\{Y_n + 1, L\}, & \text{w.p. } P_c \\
\max\{Y_n - s, 0\}, & \text{w.p. } (1 - P_c) 
\end{cases} \tag{III.E} \]
Expression (III.E) characterizes a discrete-time GI/D/s/1/L single server queueing system with a finite buffer space \( L \). In this case, time is divided into service epochs, and a service epoch is defined as the time interval between two consecutive successful transmissions. The customer arrival pattern follows a general inter-arrival (GI) distribution, and the number of arrival customers in an epoch is an integer ranging between 0 and \( L \). The number of arrival customers in an epoch is assumed stationary. The service is only made at the beginning of each epoch. The number of customers that can be served in an epoch is a constant \( s \), if there are sufficient customers; otherwise, only the customers currently in the system are served.

When \( B_n \) is denoted as the amount of arrivals in the \( n \)-th epoch, the number of customers in the GI/D/s/1/L system at the end of the \( n \)-th epoch is denoted as \( Y_n \), we have

\[
Y_n = \min \{ \max \{ Y_{n-1} - s, 0 \} + B_n, L \}.
\]

Since \( B_n \) is assumed stationary, we denote \( B_0 = \lim_{n \to \infty} B_n \). When \( E[B_0] < s \), a stationary queue length distribution has been shown to exist in a \( M/D/1/\infty \) system [7] and in a \( GI/D/1/\infty \) system [17], [19]. Thus, \( Y_n \) converges to \( Y_0 = \lim_{n \to \infty} Y_n \).

### B. Stationary Distribution of \( Y_n \)

When the steady state distributions of \( Y_0 \) is denoted as \( y_j = P\{Y_0 = j\} \) \((0 \leq j \leq L)\), \( y_j \)'s satisfy the following equalities:

\[
y_j = \begin{cases} 
  \sum_{i=s}^{s+j} y_i \cdot b_{j-(i-s)} + \sum_{i=0}^{s-1} y_i \cdot b_j, & \text{if } 0 \leq j \leq L-s, \\
  \sum_{i=s}^{L} y_i \cdot b_{j-(i-s)} + \sum_{i=0}^{s-1} y_i \cdot b_j, & \text{if } L-s + 1 \leq j \leq L-1, \\
  \sum_{i=s}^{L} \left( y_i \cdot \left[ \sum_{m=0}^{\infty} b_{(j-(i-s)+m)} \right] \right) + \sum_{i=0}^{s-1} \left( y_i \cdot \left[ \sum_{m=0}^{\infty} b_{(j+m)} \right] \right), & \text{if } j = L.
\end{cases}
\]

The pgf of \( Y_0 \) is defined as \( Y(z) = \sum_{j=0}^{L} y_j \cdot z^j \). Combined with Equations (III.F), \( Y(z) \) is expressed as

\[
Y(z) = \sum_{j=0}^{L-s} \left[ \sum_{i=s}^{j+s} y_i \cdot b_{j-(i-s)} + \sum_{i=0}^{s-1} y_i \cdot b_j \right] \cdot z^j + \sum_{j=L-s+1}^{L-1} \left[ \sum_{i=s}^{L} y_i \cdot b_{j-(i-s)} + \sum_{i=0}^{s-1} y_i \cdot b_j \right] \cdot z^j + \sum_{i=s}^{L} \left( y_i \cdot \left[ \sum_{m=0}^{\infty} b_{(L-(i-s)+m)} \right] \right) + \sum_{i=0}^{s-1} \left( y_i \cdot \left[ \sum_{m=0}^{\infty} b_{(L+m)} \right] \right) \cdot z^L.
\]

(III.G)

In order to derive a closed form of \( Y(z) \), we denote by \( B_L(z) \) the truncated pdf’s for \( B_0 \) as

\[
B_L(z) = \sum_{i=0}^{L-1} b_i \cdot z^i + \sum_{i=L}^{\infty} b_i \cdot z^L.
\]

(III.H)

The pgf \( B_L(z) \) characterizes a new random variable \( C \) with finite support, and the probability density of r.v. \( C \) is

\[
c_0 = b_0, c_1 = b_1, \cdots, c_{L-1} = b_{L-1}, c_L = \sum_{i=L}^{\infty} b_i.
\]

The r.v. \( C \) characterizes the truncated amount of customer arrivals which impact the queue length. The mean amount of truncated customer arrivals within an epoch is

\[
\mu_C = \frac{d}{dz} B_L(z)|_{z=1} = \sum_{i=0}^{L-1} i \cdot b_i + L \cdot \sum_{i=L}^{\infty} b_i.
\]

(III.I)
In the rest description, we shorthand $B'_L(1)$ for $\frac{d}{dz}B_L(z)|_{z=1}$. We also denote by $Y_s(z)$ the pgf of r.v. $\max\{Y_0-s,0\} + s$ as

$$Y_s(z) = \sum_{j=0}^{L-s} y_{i+s} z^{i+s}.$$  

We can relate $Y_s(z)$ with $Y(z)$ by

$$Y(z) = Y_s(z) + \sum_{i=0}^{s-1} y_i z^i.$$  

It is apparent that both $Y_s(z)$ and $B_L(z)$ are analytic for $|z| < 1$ and continuous for $|z| \leq 1$.

Based on the pdf of $Y_0$ defined in (III.F), the truncated pgf of r.v. $Y_0 + \max\{Y_0-s,0\} + s$ is defined as

$$B_L(z)Y_s(z) = \sum_{j=0}^{L-s} \sum_{i=0}^{L} y_{i+s} b_{j-i} z^{i+s} z^{j-i} + \sum_{j=L-s+1}^{L} \sum_{i=0}^{L-s} y_{i+s} b_{j-i} z^{i+s} z^{j-i} + \sum_{j=L+1}^{\infty} \sum_{i=0}^{L-s} y_{i+s} b_{j-i} z^{i+s} z^{L-i}.$$  

Next, $z^sY(z)$ can be expressed in terms of $B_L(z)Y_s(z)$ as

$$z^sY(z) = \sum_{j=0}^{L-s} \sum_{i=0}^{L} y_{i+s} b_{j-i} z^{i+s} z^{j-i} + \sum_{j=L-s+1}^{L} \sum_{i=0}^{L-s} y_{i+s} b_{j-i} z^{i+s} z^{j-i} + \sum_{j=L+1}^{\infty} \sum_{i=0}^{L-s} y_{i+s} b_{j-i} z^{i+s} z^{L-i} + \sum_{i=0}^{\infty} y_i z^i \left[ \sum_{j=0}^{L} b_j z^j + \sum_{j=L+1}^{\infty} b_j z^L \right].$$

$$= B_L(z)Y_s(z) + \sum_{i=0}^{s-1} y_i z^i \cdot B_L(z).$$

Therefore, $Y(z)$ can be expressed as

$$Y(z) = \frac{B_L(z) - \sum_{i=0}^{s-1} y_i (z^i - z^i)}{z^s - B_L(z)}, \text{ for } |z| \leq 1 \quad (III.J)$$

Equation (III.J) resembles the pgf of the queue length of a discrete-time $GI/D^s/1$ system with unbounded buffer space. When $X_0$ represents the stationary number of customers in a $GI/D^s/1$ system, its steady-state distribution is denoted as $x_j = P\{X_0 = j\}$ and expressed as

$$x_j = \sum_{i=s}^{s+j} x_i b_{j-(i-s)} + \sum_{i=0}^{s-1} x_i b_j. \quad (III.K)$$

The pgf of $X_0$ has been shown in [25], [13] to be in the form of equality (III.L).

$$X(z) = \frac{B(z) \sum_{i=0}^{s-1} x_i (z^i - z^i)}{z^s - B(z)}, \text{ for } |z| \leq 1 \quad (III.L)$$

where $B(z)$ is the pgf of $B_0$ which is the stationary number of customer arrivals to the $GI/D^s/1$ system in each epoch.

The $s$ unknown variables $y_0, \cdots, y_{s-1}$ in Equation (III.J) can be determined using the $s$ zeros of the denominator $z^s - B(z)$ [25], [13], [1]. From the definition of $B_L(z)$, we know that $B_L(z)$ is analytic in
|z| \leq 1 + \epsilon (\epsilon > 0). Making use of this fact, it can be shown that \( z^s - B_L(z) \) has \( s \) zeros on and within the unit circle using Rouché’s theorem [16]. The validity of this result relies on the assumption that \( \frac{d}{dz} B_L(z) \big|_{z=1} < s \).

**Lemma 1:** Assuming that \( \frac{d}{dz} B_L(z) \big|_{z=1} < s \). The equation \( z^s - B_L(z) \) has \( s \) zeros in \(|z| \leq 1 \).

**Proof:** This proof makes use of the Rouché’s theorem.

**Rouché’s Theorem:** [18] Let the bounded region \( D \) have as its boundary a simple closed contour \( C \). Let \( f(z) \) and \( g(z) \) be analytic both in \( D \) and on \( C \). Assume that \(|f(z)| \leq |g(z)|\) on \( C \). Then \( f(z) - g(z) \) has the same number of zeros as \( g(z) \) inside \( C \).

Define the functions \( f(z) = B_L(z) \) and \( g(z) = z^s \). Both \( f(z) \) and \( g(z) \) are analytic for \(|z| \leq 1 + \epsilon \). Since \( f(1) = g(1) \) and \( f'(1) = \frac{d}{dz} B_L(z) \big|_{z=1} < s = g'(1) \), we know that a sufficiently small \( \epsilon \) \((\epsilon > 0)\) can be found to make \( f(1 + \epsilon) < g(1 + \epsilon) \) to be satisfied. For any \( z \) with \(|z| = 1 + \epsilon \), using Equation (III.H), we have that

\[
|f(z)| = \left| \sum_{i=0}^{L} b_i z^i + \sum_{i=L+1}^{\infty} b_i z^i \right|
\leq \sum_{i=0}^{L} |b_i| |z|^i + \sum_{i=L+1}^{\infty} |b_i| |z|^i
= f(1 + \epsilon).
\]

We also have \(|g(z)| = |z|^s = g(1 + \epsilon)\). Then, \(|f(z)| < |g(z)|\) is satisfied because that \( f(1 + \epsilon) < g(1 + \epsilon) \). By Rouché’s theorem, \( g(z) \) and \( f(z) - g(z) \) have the same number of zeros in \(|z| \leq 1 + \epsilon \). Since \( g(z) = z^s \) has \( s \) zeros in region \(|z| \leq 1 \), when \( \epsilon \) approaches 0, \( g(z) \) and \( f(z) - g(z) \) have the same \( s \) zeros for \(|z| \leq 1 \).

When the \( s \) zeros in \(|z| \leq 1 \) are denoted as \( z_0, z_1, \cdots, z_{s-1} \), the expression (III.J) can be written into

\[
Y(z) = \frac{B_L(z)(z-1)(s-\mu(B_L))}{z^s - B_L(z)} \prod_{i=1}^{s-1} \frac{z - z_i}{1 - z_i}, \quad \text{for } |z| \leq 1
\]

(III.M)

where \( \mu(B_L) \) is the mean value of the truncated customer arrivals defined in Equation (III.I). Combining

**C. Mean and Variation of Queue Length \( Y_0 \)**

The mean and variation of \( Y_0 \) are denoted as \( \mu(Y_0) \) and \( \sigma^2(Y_0) \), respectively. They can be derived from pgf \( Y(z) \). We shorthand \( Y'(1) \) for \( \frac{d}{dz} Y(z) \big|_{z=1} \) and \( Y''(1) \) for \( \frac{d^2}{dz^2} Y(z) \big|_{z=1} \). Then, \( \mu(Y_0) \) and \( \sigma^2(Y_0) \) can be expressed as \( Y'(1) \) and \( Y''(1) + Y'(1) - Y'(1)^2 \), respectively. \( Y'(1) \) and \( Y''(1) \) are expressed as follows.

\[
\mu(Y_0) = \frac{\sigma^2(B_L)}{2(s - \mu(B_L))} + \frac{1}{2} \mu(B_L) - \frac{1}{2} (s - 1) + \sum_{i=1}^{s-1} \frac{1}{1 - z_i}
\]
\[
\sigma^2(Y_0) = \sigma^2(B_L) + \frac{B''_L(1) - s(s-1)(s-2)}{3(s - \mu(B_L))} + \frac{B'_L(1) - s(s-1)}{2(s - \mu(B_L))} + \sum_{i=1}^{s-1} \frac{z_i}{(1 - z_i)^2}.
\]

The values of \( z_i \)'s can be evaluated through fixed-point iterations [13]; however, the derivation of these values might take many iterations.

**D. Average Backoff Window Size**

From the expression of \( Y_0 \) defined in Eq. (III.D), the expectation of random variable \( \log W_0 \) is expressed as

\[
\mu(\log(W_0)) = \mu(Y_0) \cdot \log(1 + \alpha) + \log(W_{\min}).
\]

(III.N)

By Jensen’s inequality \( \log \mu(W_0) \leq \mu(\log(W_0)) \), Eq. (III.N) is further expressed into

\[
\log \mu(W_0) \leq \mu(Y_0) \cdot \log(1 + \alpha) + \log(W_{\min})
\]
and
\[ \mu(W_0) \leq W_{min} \cdot (1 + \alpha)^\mu(Y_0). \] (III.O)

E. Modeling the Average Throughput

Efforts on modeling the performance of the 802.11 DCF under saturated traffic have been made in [5], [8], [9]. The basic idea of the modeling is to first model the average time duration spent between two DATA frames that are successfully transmitted. This average time duration is the average time duration for successfully transmitting a DATA frame under saturated transmission, i.e., a sender station always has pending data frame to transmit. Then, the average throughput of the saturated transmission is estimated as the ratio of the average size of DATA frames to the average time duration for successfully sending one DATA frame. The time duration wasted in failed transmissions of DATA frames has not been considered in the modeling in previous studies. The transmission of a DATA frame is given up after a certain number of transmission attempts have been made. In our modeling, such wasted transmission time has been taken into account.

Our modeling of the average throughput still follows the Poisson assumption made in [5], i.e., the event of a current frame being collided is independent to the occurrence of past collision events. The state of a wireless channel can be in the idle state or in the busy state. When a wireless channel is in a busy state, it is either experiencing a collision or is performing a collision-free transmission. The state transition of a wireless channel is suitably modeled as a batch process. Based on the Poisson assumption, the state of a wireless channel can be modeled as a Poisson batch process. In this process, the arrivals of busy periods are mutually independent, and the average interval between two consecutive busy periods is finite. The average time duration of a busy state is also assumed to be finite.

Through detailed modeling, the average time duration for successfully sending one DATA frame mainly consists of backoff time. When the average backoff time spent in successfully sending one DATA frame is denoted by \( \bar{U} \), the average saturation throughput \( \bar{\rho} \) can be approximated by \( S/\bar{U} \) where \( S \) is the average size of DATA frames. Furthermore, the average throughput \( \bar{\rho} \) satisfies:
\[ \bar{\rho} \approx \frac{2S}{\mu(W_0) \cdot \tau} \geq \frac{2S}{\tau \cdot W_{min} \cdot (1 + \alpha)^\mu(Y_0)}. \] (III.P)

IV. THE MIMD BACKOFF WINDOW CONTROL MECHANISM

The MIMD backoff window control mechanism determines the MIMD parameters \( \alpha \) and \( \beta \) based on the detection of direct and indirect neighbors.

A. Determination of parameters \( \alpha \) and \( \beta \)

When the service capability is denoted by \( s \), the values of \( \alpha \) and \( \beta \) satisfy \( s = \frac{\log(1 - \beta)}{\log(1 + \alpha)} \). If \( \alpha \) is defined as \( \frac{d}{i+1} \) (\( d \) and \( i \) are the numbers of direct and indirect neighbors, respectively), then the value of \( \beta \) is \( 1 - \frac{1}{(1+\alpha)^i} \). The intuition of setting \( \alpha \) to be \( \frac{d}{i+1} \) is that a backoff window should be proportionally increased, upon collisions, with the number of direct neighbors. In the meantime, a backoff window should be inverse-proportionally increased with the number of indirect neighbors. The existence of indirect neighbors makes a station a potential forwarder of frames for other stations. Hence, a potential forwarder station should be favored in accessing the channel by increasing its backoff window moderately. Moreover, when the number of indirect neighbors is zero, the backoff window is doubled upon collisions just as standard 802.11 backoff window control mechanism does.

For two stations with their direct and indirect neighbors being denoted by \( (d_1, i_1) \) and \( (d_2, i_2) \), respectively, their \( \alpha \) parameters are \( \alpha_1 = \frac{d_1}{i_1+1} \) and \( \alpha_2 = \frac{d_2}{i_2+1} \), respectively. Let us assume that the operations of backoff windows of both stations share the same service capability \( s \) and the same arrival pattern to their individual GI/D^s/1 systems. Hence, their average backoff window sizes \( \mu(W^{(1)}) \) and \( \mu(W^{(2)}) \) are related by
\[ \frac{\mu(W^{(1)})}{\mu(W^{(2)})} = \left( \frac{1 + \alpha_1}{1 + \alpha_2} \right)^\mu(Y_0) \]
\[ = \left( \frac{1 + i_2}{1 + i_1} \cdot \frac{1 + d_1 + i_1}{1 + d_2 + i_2} \right)^\mu(Y_0). \] (IV.Q)
Therefore, the ratio of two average backoff window sizes is jointly depended on the ratio of indirect neighbors and the ratio of the number of two-tier neighbors. For example, when two stations have the same number of two-tier neighbors, the average backoff window size of a station is smaller if the station has more indirect neighbors. The more the number of indirect neighbors are, the higher the chance of acting as a crossover station is. In the meantime, the number of two-tier neighbors also impact on the average backoff window size in the way that the average backoff window size is proportional to the number of two-tier neighbors.

B. Detection of Direct and Indirect Neighbors

Neighbors can be detected by snooping on RTS or DATA frames. The identifiers of the sender station and the receiver station are specified in an RTS or a DATA frame. When receiving an RTS or a DATA frame, a station treats the sender station of the frame as one of its current neighbors. A neighbor remains its validity for only a short period of time following the most recent detection.

Indirect neighbors are also detected by snooping on CTS or ACK frames in which only the identifier of the receiver station is specified. When capturing a CTS or ACK frame, a station treats the receiver station of the CTS or ACK frame as one of its indirect neighbor. An indirect station is also only valid for a short period of time following the most recent detection.

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The impact of the MIMD backoff window control mechanism on the network performance is evaluated in two networks with fixed topologies. The performance improvement under the new MIMD-based backoff window control mechanism is demonstrated by a comparison with the performance under the standard 802.11 backoff window control mechanism.

The evaluation is performed by ns-2 simulations. Each wireless station is equipped with only one IEEE 802.11 wireless interface. Each wireless interface is configured using the parameters shown in Table I. This set of parameters is abstracted from a 914MHz Lucent WaveLAN DSSS radio interface. The 802.11 DCF is run under the mixed basic and optional mode, i.e., data packets are sent using RTS-CTS-DATA-ACK four-way handshaking. In the simulations, routing oriented management packets are sent under the basic mode, and user data packets are sent under the optional mode.

The impact of the MIMD backoff window control mechanism on the transmission performance has been tested under the fixed network topology shown in Fig. 3. The comparison of the average bytes sent and received at the MAC layer under two different backoff window control mechanisms is shown in Fig. 4. The MIMD backoff window control mechanism improves the transmission performance by enhancing the hop-by-hop transmission (ref. Fig. 4 (1)), while the average DATA bytes sent or relayed by a station is restrained (ref. Fig. 4 (2)).

Under the MIMD backoff window control mechanism, the average backoff window size has been generally restricted (ref. Fig. 5). In particular, the average backoff window size of station 8 is made the smaller than the
<table>
<thead>
<tr>
<th>APPLICATION (cbr)</th>
<th>Packet Size</th>
<th>512 bytes</th>
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<tbody>
<tr>
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<td>TRANSPORT UDP</td>
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<tr>
<td>ROUTING</td>
<td>Source-initiated On-demand Ad Hoc Routing Protocols (DSR)</td>
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<td>LL and ifq</td>
<td>Queuing Model</td>
<td>CMUPriQueue</td>
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<td></td>
<td>Queue Size</td>
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<tr>
<td>MAC</td>
<td>Slot Time</td>
<td>20 $\mu$s</td>
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<td></td>
<td>Min. Backoff Window Size</td>
<td>32 slots</td>
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<td></td>
<td>Max. Backoff Window Size</td>
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<td>MAC Header Size</td>
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<td>RTS Packet Size</td>
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<td>CTS Packet Size</td>
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<td>ACK Packet Size</td>
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<td>Basic Rate</td>
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<tr>
<td></td>
<td>Data Rate</td>
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<tr>
<td></td>
<td>Packet Reception Model</td>
<td>BER</td>
</tr>
</tbody>
</table>

**TABLE I**
The configuration parameters of an IEEE 802.11b wireless interface.

Window sizes of other stations which are actively involved in sending or forwarding DATA frames, *i.e.*, stations $1, 3, 5, 7, 9, 11, 13, 15$. The MIMD-based backoff window control mechanism makes the backoff window size restrained on crossover stations. The restrained backoff window size helps crossover stations to win channel accesses, and the throughput on crossover stations is improved.

**VI. CONCLUSIONS**

The end-to-end throughput is jointly determined by the efficiency of the routing protocol and the performance of the underlying media access control (MAC) mechanism. A crossover wireless station which links two different channels has less chances to win a channel access than those non-crossover stations. Crossover stations serve to relay packets for other stations, and it can only make a transmission when all channels, in which it is involved, become idle at the same time. Chances for the crossover stations to win channel accesses closely relate to the end-to-end throughput of multiple-hop transmissions. Hence, the crossover stations should be favored to win channel accesses.

In this paper, we presented a multiplicative-increase multiplicative-decrease (MIMD) based backoff window control mechanism for favoring channel accesses by crossover wireless stations. The increase and decrease rates of a backoff window size rely on the number of two-tier neighbors. For a wireless station, its two-tier neighbors are those stations which can be reached in no more than two hops. The two-tier neighbors are detected by snooping on the MAC layer frames (RTS, CTS, DATA, and ACK frames). The goal of this backoff window control mechanism is to reduce the backoff time experienced by the crossover stations, such that the crossover stations are favored in channel accesses. The chance for a wireless station winning a channel access should be proportional to the number of its indirect neighbors and inversely proportional to the number of its direct neighbors. Evaluation results show that the MIMD-based backoff window control mechanism improves the throughput of crossover stations by reducing the average backoff time.

**REFERENCES**

Fig. 4. Comparison of the average amount of DATA Bytes Sent and Received at the MAC Layer under the standard 802.11 mechanism and the new 802.11 MIMD mechanism. Each data point in a history plot represents a mean metric value which is averaged across all stations in a 0.5 second interval.

Fig. 5. The average backoff window size of each station over an 100-second simulation period (under topology 1).


