A New IEEE 802.11 DCF Utilizing Freezing Experiences in Backoff Interval and Its Saturation Throughput

Katsumi Sakakibara and Jumpei Taketsugu

Abstract: **IEEE 802.11 defines distributed coordination function (DCF), which is characterized by CSMA/CA and binary exponential backoff (BEB) algorithm. Most modifications on DCF so far have focused on updating of the contention window (CW) size depending on the outcome of own frame transmission without considering freezing periods experienced in the backoff interval. We propose two simple but novel schemes which effectively utilize the number of freezing periods sensed during the current backoff interval. The proposed schemes can be applied to DCF and its family, such as double increment double decrement (DIDD). Saturation throughput of the proposed schemes is analyzed by means of Bianchi's Markovian model. Computer simulation validates the accuracy of the analysis. Numerical results based on IEEE 802.11b show that up to about 20% improvement of saturation throughput can be achieved by combining the proposed scheme with conventional schemes when applied to the basic access procedure.**

Index Terms: **Carrier sense mechanism, contention window, IEEE 802.11 distributed coordination function (DCF), Markovian model saturation throughput.**

I. INTRODUCTION

IEEE 802.11 standard [1] is a world-wide and promising technique for wireless LANs. Two coordination functions are defined in the standard: The mandatory contention-based distributed coordination function (DCF) and the optional contention-free point coordination function (PCF). The key feature of IEEE 802.11 DCF is the combinatorial use of carrier-sense multiple-access with collision avoidance (CSMA/CA) and the binary exponential backoff (BEB) algorithm.

In IEEE 802.11 DCF, each node controls its frame transmission with CSMA/CA and the BEB algorithm in a distributed manner [1]. Before attempting to transmit a frame, a node is required to insert a random backoff interval according to its current contention window (CW) size w.[1] A backoff interval is represented by a random integer k (backoff counter) in $[0, w-1]$.[2] The backoff counter k is decreased at every idle slot, while it is frozen when the channel is busy and resumed when the channel turns to idle for the distributed inter-frame space (DIFS). The frame is transmitted when the backoff counter k equals zero. The destination node sends back an acknowledgment (ACK) frame following the short inter-frame space (SIFS), if it successfully receives the transmitted frame. After receiving the ACK frame, the source node initializes the CW size w to the prescribed minimum $\mathrm{CW}_{\min}$. On the other hand, if the source node does not receive the ACK frame, it doubles the CW size w up to the predefined maximum $\mathrm{CW}_{\max}$ and reschedules retransmission according to the similar backoff procedure.

It has been pointed out that throughput can be improved by properly updating the CW size, in particular, under heavy traffic [2]–[9]. In the legacy DCF, a small fraction of successful nodes might repeatedly grab the channel for a moment while other nodes back off their frame transmissions for a long time. Upon this observation, a number of modifications have been proposed [2]–[10]. In [2], multiplicative increase linear decrease (MILD) was proposed, in which a successful node linearly decreases its CW size. Natkaniec and Pach [3], [4] proposed double increment double decrement (DIDD), where a successful node rather halves its CW size than initialization. An equivalent algorithm was independently proposed by Wu *et al.* [5]. Then, a number of generalizations of DIDD were proposed, for example, by Song *et al.* [6], Ni *et al.* [7], and Ki *et al.* [8], which are referred to as exponential increase exponential decrease (EIED), slow CW decrease (SD), and binary negative-exponential backoff (BNEB), respectively. In EIED, the CW size increases and decreases with some prescribed exponential factor, r_I and r_D (not limited to two). In SD, a successful node decreases its CW size by a factor 2^{-j}, where j is a positive integer. In BNEB, a colliding node maximizes its CW size and successful transmission halves the CW size. Wang *et al.* [9] proposed gentle DCF (GDCF) where a successful node keeps its CW size unchanged until it consecutively succeeds ℓ times. Cali *et al.* [10] proposed a dynamic tuning algorithm of the CW size, which is adaptively adjusted by mean of the frame transmission probability. It should be noticed here that the CW size of MILD, EIED and the algorithm in [10] may be beyond the BEB policy, that is, their CW size may take an integer other than $2^m\mathrm{CW}_{\min}$ for some integer m. Also, the CW size should be shared among nodes in MILD and the algorithm in [10]. Among these modifications, DIDD [3], [4] is known as a simple and effective one which is subject to the BEB policy. Note that DIDD is equivalent to EIED [6] for $r_I = r_D = 2$, SD [7] for $j = 1$, and GDCF [9] for $\ell = 1$.

However, in most modifications in the literature [2]–[9], a node updates its CW size depending on the outcome of own frame exchange and makes no use of the freezing experiences in a backoff interval. A node should suppose that more number of nodes might contend for the channel in the case that it has ex-

Manuscript received June 14, 2008; approved for publication by Constantinos B. Papadias, Division II Editor, November 19, 2009.

A part of this work was presented in the 3rd IEEE International Symposium on Communications, Control, and Signal Processing (ISCCSP2008), St. Julians, Malta, March 2008 and was supported by Japan Society for the Promotion of Science under Grant-in-Aid for Scientific Research (C).

The authors are with the Department of Communication Engineering, Okayama Prefectural University, Japan, email: {sakaki, taketugu}@c.oka-pu.ac.jp.

[1] In the standard [1], the CW size w is defined to take an integer power of 2, minus 1, in accordance with the physical specification. However, for the sake of mathematical tractability, we assume that the CW size is an integer power of 2 as in the literature [6], [7], [10], [11].

[2] A set of consecutive integers $\{a, a+1, \ldots, b\}$ is abbreviated to $[a, b]$.

1229-2370/10/$10.00 © 2010 KICS

perienced freezing many times in the backoff interval (from the update of w to its own frame transmission) than the case of no freezing. Hence, a node involved in collision after experienced a large number of freezing periods in the backoff interval should increase its CW size much more in rescheduling retransmission.

In this paper, we propose two novel schemes which effectively take into account the number of freezing experiences during the current backoff interval. The proposed schemes can be applied to any conventional backoff algorithms, such as DCF and DIDD. Saturation throughput of the proposed schemes is analyzed by means of Bianchi's Markovian model [11]. The accuracy of the analysis is validated by computer simulation. Hereafter, we consider DCF and DIDD as conventional backoff algorithms.

The present paper is organized as follows: The algorithm to update the CW size for the legacy DCF and DIDD is summarized in Section II. The proposed schemes are described in Section III in conjunction with the legacy DCF and DIDD. Section IV provides the system model. Saturation throughput is analyzed in Section V by means of Bianchi's Markovian model [11] and the accuracy of the analysis is verified in Section VI. Section VII concludes the present paper with further studies.

II. CONVENTIONAL SCHEMES

The update of the CW size w at each node can be expressed by the following equations according to the outcome of its frame exchange; success or failure.

A. Legacy DCF

Upon a successful frame exchange, a node resets its CW size w to $\mathrm{CW}_{\min}$ and it doubles its CW size until it reaches $\mathrm{CW}_{\max}$ if its frame exchange fails. Hence, the relation

$$w = \begin{cases} \mathrm{CW}_{\min}, & \text{success,} \\ \min\left[2w,\ \mathrm{CW}_{\max}\right], & \text{failure} \end{cases} \tag{1}$$

holds [1], [11].

B. DIDD

In DIDD [3]–[5], a successful node halves its CW size rather than initialization, until it reaches $\mathrm{CW}_{\min}$. A node doubles its CW size when its frame exchange fails. Thus, we have

$$w = \begin{cases} \max\left[\frac{w}{2},\ \mathrm{CW}_{\min}\right], & \text{success,} \\ \min\left[2w,\ \mathrm{CW}_{\max}\right], & \text{failure.} \end{cases} \tag{2}$$

III. PROPOSED SCHEMES

The key idea of the proposed schemes is that a node involved in collision should increase its CW size much more in rescheduling retransmission, if it has experienced a large number of freezing periods in the current backoff interval.

Let b and c denote the number of freezing periods and the number of frame collisions experienced in the current backoff interval by a certain node (from the update of the CW size w to its following frame transmission). It is clear that $0 \le c \le b \le k < w$, since an initial backoff interval k is randomly chosen in $[0, w-1]$, where w is the current CW size. In the following, we describe two proposed schemes, named as Schemes Busy and Coll, which take into account b and c in updating the CW size, respectively.

A. Scheme Busy

In Scheme Busy, a node updates the CW size w depending not only on the outcome (success or failure) of its own frame transmission, but also on the value of b. Scheme Busy can be implemented by adding a counter for freezing in a backoff interval, since the freezing mechanism has already regulated. Note that Scheme Busy is equivalent to the conventional one, DCF or DIDD, if a node encounters no freezing, $b = 0$. An algorithm to update the CW size w follows when we apply Scheme Busy to DCF and DIDD.

A.1 DCF with Scheme Busy (DCF+Busy)

A successful node initializes its CW size according to the legacy DCF in spite of the value of b. On the other hand, the CW size is doubled $b+1$ times on transmission failure. Hence, we have

$$w = \begin{cases} \mathrm{CW}_{\min}, & \text{success,} \\ \min\left[2^{b+1}w,\ \mathrm{CW}_{\max}\right], & \text{failure} \end{cases} \tag{3}$$

for the combination of Scheme Busy with DCF.

A.2 DIDD with Scheme Busy (DIDD+Busy)

A successful node halves its CW size after it doubles the CW size b times. As a result, we have

$$w = \begin{cases} \max\left[\frac{\min\left[2^{b}w,\ \mathrm{CW}_{\max}\right]}{2},\ \mathrm{CW}_{\min}\right], & \text{success,} \\ \min\left[2^{b+1}w,\ \mathrm{CW}_{\max}\right], & \text{failure} \end{cases} \tag{4}$$

for the combination of Scheme Busy with DIDD.

B. Scheme Coll

In Scheme Busy, a freezing period due to successful transmission may urge a node to increase its CW size.

In Scheme Coll, a node uses the number of sensed collisions c, instead of b in Scheme Busy. It should be emphasized that in Scheme Coll, a node needs to distinguish frame collisions among other nodes from a successful transmission. It can be implemented, for example, by overhearing the ACK frame during the freezing period. A freezing node perceives that another node succeeds in transmission if it can overhear the ACK frame. Note that Scheme Coll is reduced to the conventional one, DCF or DIDD, if $c = 0$. Furthermore, Scheme Coll becomes equivalent to Scheme Busy if a node can not distinguish a busy channel due to frame collision from a successful transmission. An algorithm to update the CW size w can be obtained by substituting c for b in (3) and (4) when Scheme Coll is applied to DCF and DIDD, respectively.

IV. SYSTEM MODEL

Consider a wireless LAN with N saturated nodes operating in the ad-hoc mode, that is, each node always possesses a frame to transmit (saturation conditions) and it can overhear frame exchanges among other nodes [5], [7]–[9], [11]. According to the BEB policy, we let $W_m = 2^m \mathrm{CW}_{\min}$ be a possible CW size for $m \in [0, M]$, where M is a non-negative integer [5], [8], [9]. Then, we have $W_M = \mathrm{CW}_{\max}$ and every node can be modeled by a two-dimensional Markovian process with its backoff stage m and backoff counter k [7], [9], [11].

A node with the CW size $w = W_m$ is said to be in *stage* m. Stage m consists of W_m states, $\mathrm{B}(m,k)$, according to its backoff counter $k \in [0, W_m - 1]$ [7], [9], [11]. Each node is always in one of $\mathrm{B}(m,k)$ for $m \in [0, M]$ and $k \in [0, W_m - 1]$ under saturation conditions. We ignore frame discard due to the retry limit. No channel noise is considered, so that a frame transmission fails if and only if it collides with simultaneously transmitted frames from other nodes. The ACK frames are assumed to be received with no errors.

Complete Markovian models under these assumptions for the legacy DCF and DIDD can be found in [11] and [5], respectively.

V. SATURATION THROUGHPUT

We denote by $b_{m,k}$ the ratio of nodes in state $\mathrm{B}(m,k)$ [11]. Then, the normalized condition

$$\sum_{m=0}^{M} \sum_{k=0}^{W_m - 1} b_{m,k} = 1 \tag{5}$$

holds under saturation conditions. The ratio τ of transmitting nodes is given by

$$\tau = \sum_{m=0}^{M} b_{m,0}, \tag{6}$$

since only nodes with $k = 0$ are permitted to transmit their frame. By assuming the independent operation among nodes and the independence of transmission failure of stages [5], [7]–[9], [11], the probability of transmission failure can be expressed by

$$\varepsilon = 1 - (1 - \tau)^{N-1}. \tag{7}$$

In the following, we evaluate saturation throughput by means of the equilibrium point analysis (EPA) [12]. In the EPA, it is supposed that an in-flow and an out-flow at each state are always balanced.

A. Equations in Equilibrium

Let $p_{i,m}$ be the stage transition probability from stage i to stage m after frame transmission, where

$$\sum_{m=0}^{M} p_{i,m} = 1 \tag{8}$$

for $i \in [0, M]$.

The in-flow to stage m is randomly divided into W_m states, as shown in Fig. 1. Hence, the flow balance at $\mathrm{B}(m,k)$ can be

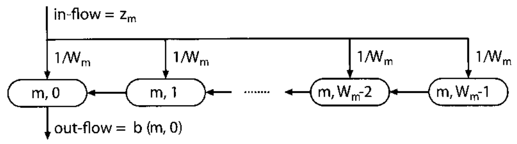


Fig. 1. State transitions in stage m.

equated as

$$b_{m,k} = \begin{cases} b_{m,k+1} + \dfrac{z_m}{W_m}, & \text{for } k \in [0, W_m - 2], \\ \dfrac{z_m}{W_m}, & \text{for } k = W_m - 1 \end{cases} \tag{9}$$

for $m \in [0, M]$, where z_m is the average in-flow to stage m, which is given by

$$z_m = \sum_{i=0}^{M} p_{i,m} b_{i,0}. \tag{10}$$

Summing (9) on k, we have

$$z_m = b_{m,0}. \tag{11}$$

Also, the relation

$$b_{m,k} = \frac{W_m - k}{W_m} z_m \tag{12}$$

for $k \in [0, W_m - 1]$ can be derived from the recursive relation in (9). Then, we obtain

$$\sum_{k=0}^{W_m - 1} b_{m,k} = \frac{W_m + 1}{2} b_{m,0} \tag{13}$$

for $m \in [0, M]$. It follows from (10) and (11) that for given $p_{i,m}$, we can obtain $\{b_{0,0}, b_{1,0}, \cdots, b_{M,0}\}$ as a root of the system of linear equations

$$\begin{bmatrix} b_{0,0} \\ b_{1,0} \\ \vdots \\ b_{M,0} \end{bmatrix} = \begin{bmatrix} p_{0,0} & p_{1,0} & \cdots & p_{M,0} \\ p_{0,1} & p_{1,1} & \cdots & p_{M,1} \\ \vdots & \vdots & \ddots & \vdots \\ p_{0,M} & p_{1,M} & \cdots & p_{M,M} \end{bmatrix} \begin{bmatrix} b_{0,0} \\ b_{1,0} \\ \vdots \\ b_{M,0} \end{bmatrix} \tag{14}$$

under the constraint condition

$$\sum_{m=0}^{M} \frac{W_m + 1}{2} b_{m,0} = 1 \tag{15}$$

which can be obtained by substituting (13) into (5).

B. Stage Transition Probabilities

In order to solve (14) with (15), the stage transition probabilities, $p_{m,n}$, should be derived. Here, we separate $p_{m,n}$ into two parts as

$$p_{m,n} = (1 - \varepsilon) p_{m,n}^{(S)} + \varepsilon p_{m,n}^{(C)} \tag{16}$$

for $m \in [0, M]$ and $n \in [0, M]$, where $p_{m,n}^{(S)}$ and $p_{m,n}^{(C)}$ are the conditional stage transition probabilities on successful frame exchange and on transmission failure, respectively, and ε is the probability of transmission failure, given by (7). Due to the limitation of pages, we show non-zero $p_{m,n}^{(S)}$ and $p_{m,n}^{(C)}$ for six respective algorithms of DCF and DIDD with and without Schemes Busy/Coll in the following.

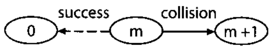


Fig. 2. Stage transitions from stage m for legacy DCF.

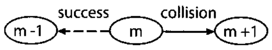


Fig. 3. Stage transitions from stage m for DIDD.

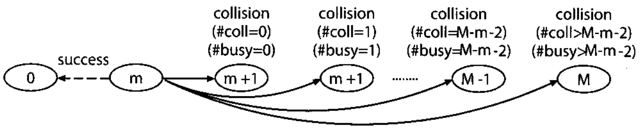


Fig. 4. Stage transitions from stage m for DCF with Busy/Coll.

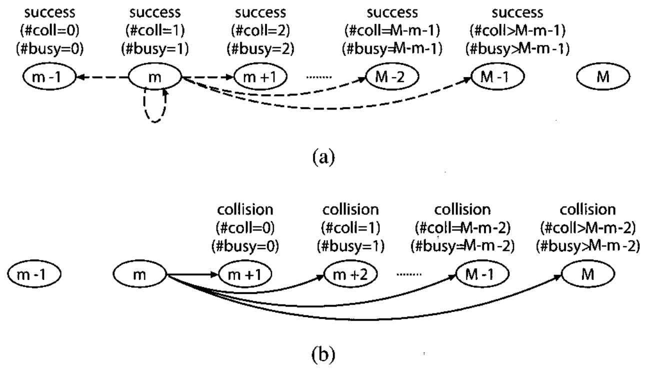


Fig. 5. Stage transitions from stage m for DIDD with Busy/Coll: (a) Case of successful frame exchange and (b) case of frame exchange failure.

B.1 Legacy DCF

In the legacy DCF, a successful node initializes its stage m to zero and a colliding node increases m by one, as shown in Fig. 2. Then, the non-zero conditional stage transition probabilities are given by

$$p_{m,0}^{(S)} = p_{m,\min[M,m+1]}^{(C)} = 1 \tag{17}$$

for $m \in [0, M]$.

B.2 DIDD

The stage transitions from stage m are shown in Fig. 3 for DIDD. The non-zero conditional stage transition probabilities are given by

$$p_{m,\max[0,m-1]}^{(S)} = p_{m,\min[M,m+1]}^{(C)} = 1 \tag{18}$$

for $m \in [0, M]$.

B.3 DCF with Scheme Busy (DCF+Busy)

The stage transitions from stage m for DCF with Scheme Busy are shown in Fig. 4. Similarly to the legacy DCF, a successful node initializes its CW size, so that

$$p_{m,0}^{(S)} = 1 \tag{19}$$

for $m \in [0, M]$.

Let us suppose that a node in stage m fails its frame exchange after it has sensed b freezing periods in the backoff interval. Then, the stage level of the node moves from m to $\min[m+b+1, M]$. From the independent node operation assumption, the probability that a node senses a frame collision is given by

$$\delta_B = 1 - B(N-1, 0, \tau) \tag{20}$$

where $B(i, j, p)$ is the binomial distribution

$$B(i, j, p) = \binom{i}{j} p^j (1-p)^{i-j} \tag{21}$$

for $j \in [0, i]$ and $0 \le p \le 1$. The conditional probability that the node in stage m senses b freezing periods, given that it has selected the backoff interval k ($k \in [0, W_m - 1]$), is $B(k, b, \delta_B)$ for $b \in [0, k]$. Averaging on k, we can evaluate the probability that a transmitting node in stage m has detected b freezing periods as

$$q_B(b \mid m) = \sum_{k=b}^{W_m - 1} \frac{B(k, b, \delta_B)}{W_m} \tag{22}$$

for $b \in [0, W_m - 1]$, since k is randomly chosen in $[0, W_m - 1]$. Then, the non-zero conditional probability $p_{m,n}^{(C)}$ is given by

$$p_{m,n}^{(C)} = \begin{cases} q_B(n-m-1 \mid m), & \text{for } n \in [m+1, M-1], \\ \displaystyle\sum_{b=M-m-1}^{W_m-1} q_B(b \mid m), & \text{for } n = M \end{cases} \tag{23}$$

so that (19) and (23) provide the conditional non-zero stage transition probabilities.

B.4 DIDD with Scheme Busy (DIDD+Busy)

The stage transitions from stage m for DIDD with Scheme Busy are shown in Figs. 5(a) and (b) for a successful and a colliding node, respectively.

Let us consider a successful node in stage m with detection of b freezing periods in the backoff interval. The probability distribution of b is given by (22). A successful node decreases its stage level by one after increasing the stage level by b. Then, for a successful node, the non-zero conditional stage transition probability is given by

$$p_{m,n}^{(S)} = \begin{cases} q_B(0 \mid 0) + q_B(0 \mid 1), & \text{for } m = n = 0, \\ q_B(n-m+1 \mid m), & \\ \quad \text{for } m \in [1, M] \text{ and } n \in [m-1, M-2] & \\ \quad \text{and for } m = 0 \text{ and } n \in [1, M-2], & \\ \displaystyle\sum_{b=M-m}^{W_m-1} q_B(b \mid m), & \text{for } n = M-1. \end{cases} \tag{24}$$

Note that no transitions can occur from m to M for any value b, since a successful node lastly halves its CW size. In a similar manner, we can obtain the non-zero conditional stage transition probability for a colliding node as follows:

$$p_{m,n}^{(C)} = \begin{cases} q_B(n-m-1 \mid m), \\ \quad \text{for } m \in [0, M-2] \text{ and } n \in [m+1, M-1], \\ \displaystyle\sum_{b=M-m-1}^{W_m-1} q_B(b \mid m), \\ \qquad\qquad \text{for } m \in [0, M-2] \text{ and } n = M, \\ 1, \qquad\quad \text{for } m = M-1, M \text{ and } n = M \end{cases} \tag{25}$$

with the aid of Fig. 5(b).

B.5 DCF with Scheme Coll (DCF+Coll)

The probability $p_{m,n}^{(S)}$ for DCF with Scheme Coll equals to (19). Corresponding to (20), the probability that a node senses a frame collision is given by

$$\delta_C = 1 - B(N-1, 0, \tau) - B(N-1, 1, \tau). \tag{26}$$

Hence,

$$q_C(c \mid m) = \sum_{k=c}^{W_m-1} \frac{B(k, c, \delta_C)}{W_m} \tag{27}$$

provides the probability that a node in stage m has experienced collision c times in the backoff interval for $c \in [0, W_m - 1]$. Then, $p_{m,n}^{(C)}$ can be obtained by replacing $q_B(b \mid m)$ in (23) by $q_C(c \mid m)$ (see Fig. 4).

B.6 DIDD with Scheme Coll (DIDD+Coll)

Similarly to the previous case, the probabilities $p_{m,n}^{(S)}$ and $p_{m,n}^{(C)}$ for DIDD with Scheme Coll can be obtained by replacing $q_B(b \mid m)$ in (24) and (25) by $q_C(c \mid m)$, respectively.

C. Non-Linear Equations for τ and ε

At this point, we have obtained the stage transition probability $p_{m,n}$ as a function of τ. As a result, $b_{m,0}$'s are also evaluated as a function of τ by solving (14) with (15). The ratio of transmitting nodes τ and the probability of transmission failure ε can be obtained by solving the non-linear equations (6) and (7).

D. Saturation Throughput

Once the ratio of transmitting nodes τ is obtained, saturation throughput can be given by

$$S = \frac{N\tau(1-\tau)^{N-1}\mathrm{E}[\text{payload}]}{\left[\begin{array}{l}(1-\tau)^N T_{\text{slot}} + N\tau(1-\tau)^{N-1}T_S \\ +\{1-(1-\tau)^N - N\tau(1-\tau)^{N-1}\}T_C\end{array}\right]} \tag{28}$$

where T_{slot}, T_S, and T_C are the slot duration, the average duration of a successful transmission, and the average duration of frame collision, respectively [11]. For the basic access procedure, T_S and T_C are evaluated as

$$T_S = 2T_{\text{PHY}} + T_{\text{MAC}} + \mathrm{E}[\text{payload}] + T_{\text{ACK}} + T_{\text{SIFS}} + T_{\text{DIFS}} \tag{29}$$

$$T_C = T_{\text{PHY}} + T_{\text{MAC}} + \mathrm{E}[\text{payload}] + T_{\text{DIFS}} \tag{30}$$

respectively, where T_{PHY}, T_{MAC}, T_{ACK}, T_{DIFS}, and T_{SIFS} are the duration of PHY header, MAC header, ACK frame, DIFS duration, and SIFS duration [11]. Here, we ignore the propagation delay between transmitting and receiving nodes for simplicity. For the RTS/CTS access procedure, we have

$$T_S = 4T_{\text{PHY}} + T_{\text{MAC}} + \mathrm{E}[\text{payload}] + T_{\text{ACK}} + T_{\text{RTS}} + T_{\text{CTS}} + 3T_{\text{SIFS}} + T_{\text{DIFS}} \tag{31}$$

$$T_C = T_{\text{PHY}} + T_{\text{RTS}} + T_{\text{DIFS}} \tag{32}$$

respectively, where T_{RTS} is the duration of RTS frame and T_{CTS} is that of CTS frame.

Table 1. Values of parameters in numerical example.

Minimum CW (CW_{min})	32	
Maximum CW (CW_{max})	1024	
Number of stages (M)	5	
Channel bit rate (R)	11	[Mbps]
Slot duration (T_{slot})	20	[μsec]
SIFS (T_{SIFS})	10	[μsec]
DIFS (T_{DIFS})	50	[μsec]
PHY header (T_{PHY})	192	[μsec]
MAC header ($T_{\text{MAC}}R$)	28	[byte]
Payload length	1500	[byte]
ACK ($T_{\text{ACK}}R$)	14	[byte]
RTS ($t_{\text{RTS}}R$)	20	[byte]
CTS ($t_{\text{CTS}}R$)	14	[byte]

VI. NUMERICAL EXAMPLE

We examine the derived expressions through a numerical example with the values of parameters shown in Table 1. These values are chosen based on the basic access procedure in IEEE 802.11b standard [1]. We verify the accuracy of the expressions by means of extensive computer simulations. The simulation program was written in C language and 10^8 virtual time-slots were simulated.

A. Probability of Transmission Failure

In order to validate the accuracy of the analysis, the probability of transmission failure ε is demonstrated with the results of computer simulations in Fig. 6. Theoretical results obtained as a root of the non-linear equations, (6) and (7), are indicated by lines. The points denote the results obtained from computer simulations. From Fig. 6, we can observe good agreement between theoretical and simulation results, so that the accuracy of the system model is verified. The proposed schemes succeed in reducing ε of the legacy DCF below the standard DIDD. Among the six cases, DIDD with Scheme Busy exhibits the smallest ε.

By applying the proposed schemes, a node with transmission failure tends to expand its CW size much more than the standard BEB algorithm. This may relax a possibility to re-collide with other frame transmissions. As a result, the proposed schemes can improve the probability of transmission failure. Note here that the probability of transmission failure ε is independent of

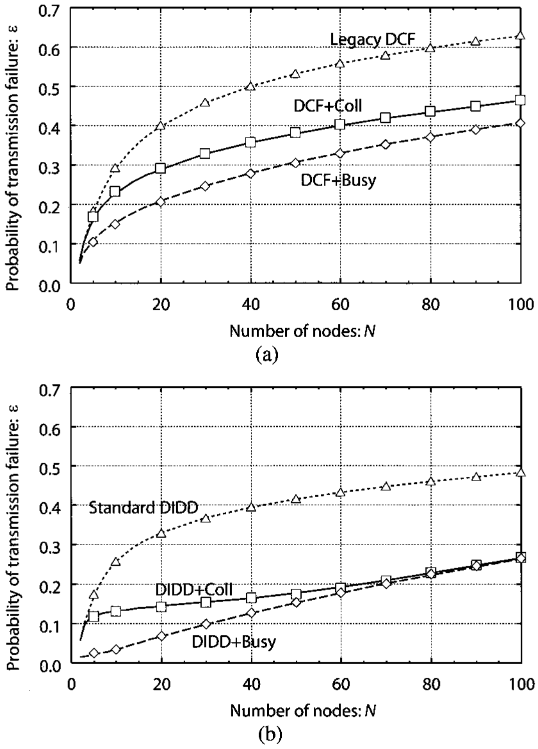


Fig. 6. Probability of transmission failure: (a) DCF with proposed schemes and (b) DIDD with proposed schemes.

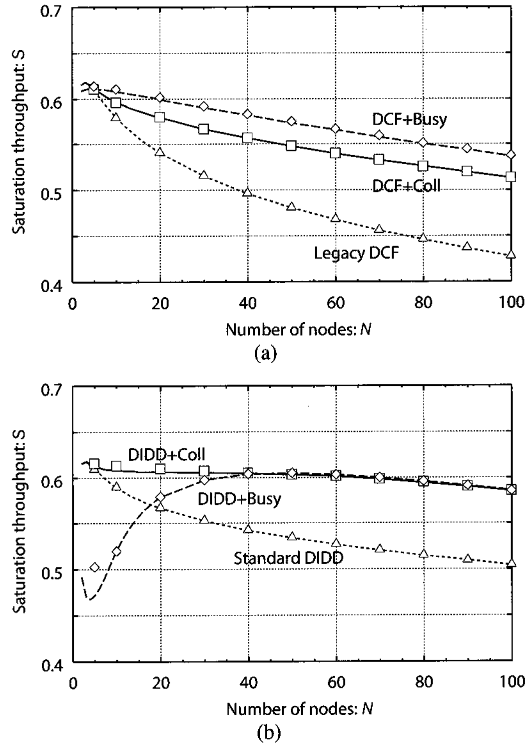


Fig. 7. Saturation throughput for basic access procedure: (a) DCF with proposed schemes and (b) DIDD with proposed schemes.

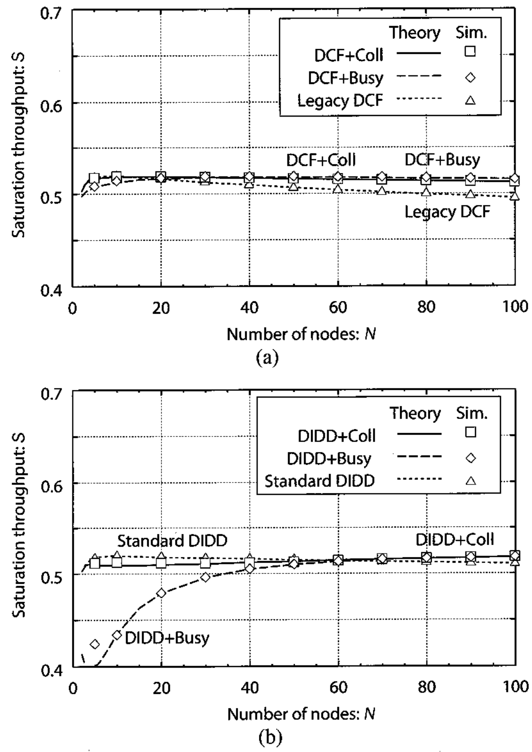


Fig. 8. Saturation throughput for RTS/CTS access procedure: (a) DCF with proposed schemes and (b) DIDD with proposed schemes.

which access procedure is employed, basic or RTS/CTS, since it can be obtained without relying on (29)–(32).

B. Saturation Throughput

Saturation throughput for the basic and RTS/CTS access procedures are shown in Figs. 7 and 8, respectively. The accuracy of the analysis can be validated again.

From Fig. 7(a), saturation throughput of DCF for the basic access procedure combined with the proposed schemes exceeds that of the standard DIDD. In particular, DCF with Scheme Busy can achieve the highest saturation throughput. For large N, the proposed schemes can improve throughput up to about 20%. Scheme Coll may exhibit little effect for small N, since packet collisions may hardly occur. Thus, it will be rare for a node to detect frame collisions among other nodes in a backoff interval. For small N, e.g., $N = 2, 3$, Scheme Busy provides a little worse throughput than the legacy DCF, since successful transmissions of other nodes may eventually doubles the CW size.

In the case of DIDD, it follows from Fig. 7(b) that Scheme Coll can improve saturation throughput for any N and that it can keep high throughput for up to about $N = 60$. However, DIDD with Scheme Busy degrades the performance for small N, although it can achieve the smallest probability of transmission failure, as shown in Fig. 6. In DIDD with Scheme Busy, one can easily expect that the CW size at a node may rapidly reach to the maximum CW_{max} even for small N, since every freezing experience in a backoff interval doubles the CW size regardless of success or collision. Enlarging the CW size not only reduces the probability of frame collision, which may improve throughput, but also increases the number of idle time-slots at a time, which may decrease throughput.

Next, saturation throughput for the RTS/CTS access procedure is presented in Fig. 8. Notice that the RTS/CTS access

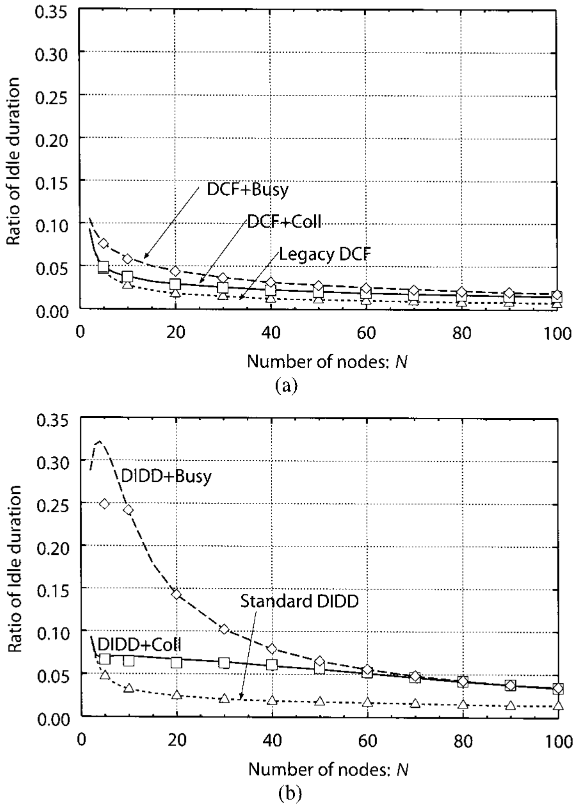


Fig. 9. Ratio of idle duration for basic access procedure: (a) DCF with proposed schemes and (b) DIDD with proposed schemes.

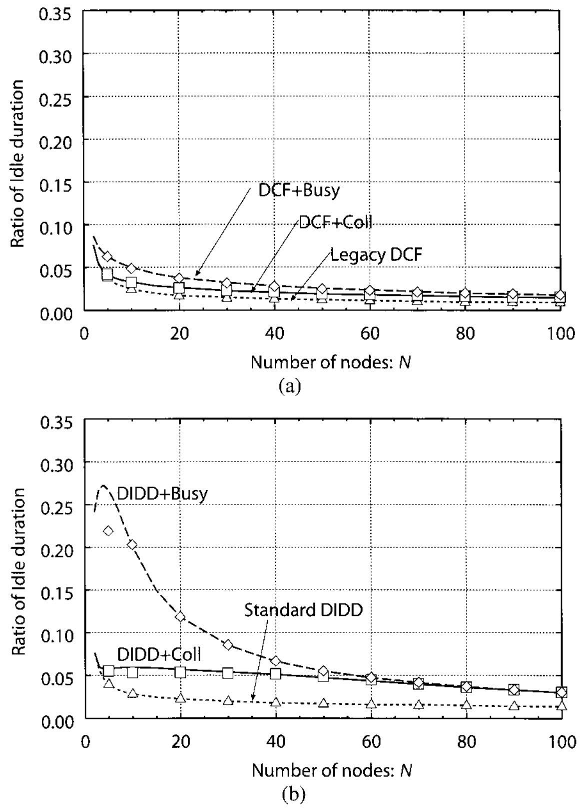


Fig. 10. Ratio of idle duration for RTS/CTS access procedure: (a) DCF with proposed schemes and (b) DIDD with proposed schemes.

procedure may introduce excessive overhead, since no hidden nodes are assumed in our system model. In fact, saturation throughput for small N in Fig. 8 is lower than that in Fig. 7. It is apparent from Fig. 8 that the gain obtained from the proposed schemes for the basic access procedure vanishes for the RTS/CTS procedure. This is because in the case of the RTS/CTS access procedure, the reduction of the collision period T_C has a more effect on saturation throughput than the control of the CW size. It follows from Fig. 8(b) that saturation throughput for DIDD with Scheme Busy also decreases for small N similarly to Fig. 7(b).

In order to reveal the reason for this degradation of DIDD with Scheme Busy for small N, we first present the ratio of the idle duration, which gives the probability that no frame transmissions occur at any time instance, for the basic and RTS/CTS access procedures in Figs. 9 and 10, respectively. The theoretical results can be obtained from

$$\frac{(1-\tau)^N T_{\text{slot}}}{\left[\begin{array}{l}(1-\tau)^N T_{\text{slot}} + N\tau(1-\tau)^{N-1}T_S \\ \quad + \{1-(1-\tau)^N - N\tau(1-\tau)^{N-1}\}T_C\end{array}\right]}. \tag{33}$$

It follows from Fig. 9(b) and Fig. 10(b) that in DIDD with Scheme Busy, the idle duration occupies an extremely large part of time for $N < 20$, compared to the other five schemes, where the ratio of the idle duration is less than 10%. Such a large amount of the idle duration deteriorates saturation throughput of DIDD with Scheme Busy for small N.

Next, for the basic access procedure with the values given in Table 1, the distributions of the CW size at transmitting nodes

$$\Pr[w = 2^m \text{CW}_{\min} \mid \text{transmitting node}] = \frac{b_{m,0}}{\sum_{i=0}^{M} b_{i,0}} \tag{34}$$

for $m \in [0, M]$ are shown in Fig. 11. From Fig. 11, the following observations can be found:

1. The distribution of the CW size for the standard DIDD (Fig. 11(b)) is slightly inclined to larger CW sizes in comparison with that of the legacy DCF (Fig. 11(a)). It follows from Fig. 7 that this slight inclination due to slow decrement of the CW size can succeed in improving saturation throughput.
2. Applying the proposed schemes to DCF, we can observe from Figs. 11(c) and (e) that the CW sizes tend to distribute into two extremes; $\text{CW}_{\min}$ and $\text{CW}_{\max}$. This separation might facilitate short-term unfairness reported for legacy DCF [13], since a node with large CW size has to wait to transmit a frame for a long time during which a node with small CW size may succeed many times. However, it can actually improve saturation throughput, as shown in Fig. 7(a), at the cost of short-term fairness.
3. From Fig. 11(d), the combination of Scheme Coll with DIDD increases the CW size at transmitting nodes. In particular, for large N the CW size of most transmitting nodes is 512 or 1024.
4. The tendency shown in Fig. 11(d) is stressed for DIDD with Scheme Busy, as shown in Fig. 11(f). Most nodes in DIDD

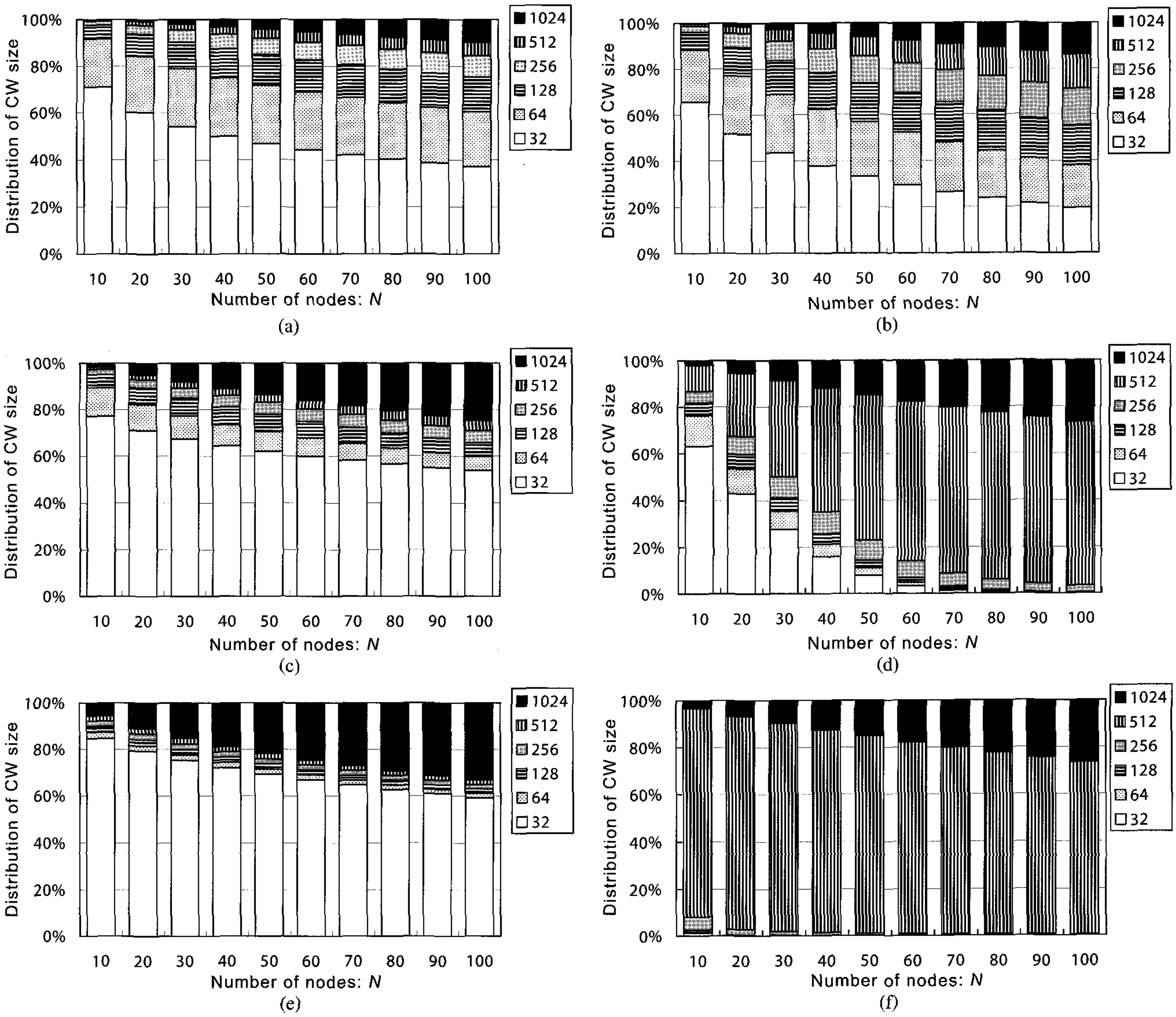


Fig. 11. Distribution of CW size at transmitting nodes for basic access procedure: (a) Legacy DCF, (b) standard DIDD, (c) DCF+Coll, (d) DIDD+Coll, (e) DCF+Busy, and (f) DIDD+Busy.

with Scheme Busy transmit their frame with $w \geq 512$ even for small N. This observation is caused by the combinatorial effect of DIDD and Scheme Busy, that is, only a successful node can halves its CW size and every freezing experience in a backoff interval doubles the CW size in Scheme Busy. This effect enlarges the CW size at a node as a whole. Such a large CW size enhances a long idle period of the channel for small N, as shown in Fig. 9(b), even though it decreases the probability of transmission failure. Therefore, saturation throughput of DIDD with Scheme Busy degrades for small N.

In consequence, the proposed schemes are effective in improving saturation throughput of the basic access procedure for DCF with any number of nodes and for DIDD with large number of nodes. However, the performance improvement of the proposed schemes is reduced when they are applied to the RTS/CTS access procedure. Also, Scheme Busy should be carefully incorporated with DIDD, since excessive doubling of the CW size may introduce more idle slots, in particular, for small networks.

VII. CONCLUSION

We have proposed two novel schemes for IEEE 802.11 DCF, which can improve saturation throughput, by effectively utilizing freezing experiences in a backoff interval. One is called Scheme Coll, which makes use of the number of collision periods among other nodes, and the other is called Scheme Busy, which counts the number of freezing. The proposed schemes can be applied to any conventional backoff algorithms, such as DCF and DIDD. Saturation throughput of the proposed schemes has been analyzed by means of Bianchi's Markovian model. The accuracy of the analysis has been validated by computer simulations. Numerical results based on IEEE 802.11b have indicated that up to about 20% improvement of saturation throughput can be achieved for the basic access procedure by combining the proposed scheme, except for DIDD with Scheme Busy for small number of nodes. However, the performance improvement of the proposed schemes is reduced when they are applied to the RTS/CTS access procedure.

Further studies on the proposed schemes include evaluation of i) the energy efficiency, since Scheme Coll needs to distinguish a collision period from a successful period, ii) fairness issues, since the proposed schemes may enhance short-term unfairness, particularly applied to DCF, and iii) robustness against non-ideal scenarios.

REFERENCES

[1] IEEE Standard 802.11, *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, Aug. 1999.

[2] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A media access protocol for wireless LAN's," *ACM SIGCOMM Comput. Commun. Review*, vol. 24, no. 4, pp. 212–225, Oct. 1994.

[3] M. Natkaniec and A. R. Pach, "An analysis of the modified backoff mechanism for IEEE 802.11 networks," in *Proc. PGTS 2000*, Dresden, Germany, Sept. 2000.

[4] M. Natkaniec and A. R. Pach, "PUMA — A new channel access protocol for wireless LANs," in *Proc. WPMC 2002*, Honolulu, HI, Oct. 2002.

[5] H. Wu, S. Cheng, Y. Peng, K. Long, and J. Ma, "IEEE 802.11 distributed coordination function (DCF): Analysis and enhancement," in *Proc. IEEE ICC 2002*, New York, NY, Apr. 2002.

[6] N.-O. Song, B.-J. Kwak, J. Song, and L. E. Miller, "Enhancement of IEEE 802.11 distributed coordination function with exponential increase exponential decrease backoff algorithm," in *Proc. IEEE VTC 2003-Spring*, Jeju, Korea, Apr. 2003.

[7] Q. Ni, I. Aad, C. Barakat, and T. Turletti, "Modeling and analysis of slow CW decrease for IEEE 802.11 WLAN," in *Proc. IEEE PIMRC 2003*, Beijing, China, Sept. 2003.

[8] H. J. Ki, S.-H. Choi, M. Y. Chung, and T.-J. Lee, "Performance evaluation of binary negative-exponential backoff algorithm in IEEE 802.11 WLAN," in *Proc. MSN 2006*, Hong Kong, China, Dec. 2006.

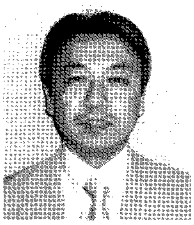
[9] C. Wang, B. Li, and L. Li, "A new collision resolution mechanism to enhance the performance of IEEE 802.11 DCF," *IEEE Trans. Veh. Technol.*, vol. 53, no. 4, pp. 1235–1246, July 2004.

[10] F. Cali, M. Conti, and E. Gregori, "Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit," *IEEE/ACM Trans. Network.*, vol. 8, no. 6, pp. 785–799, Dec. 2000.

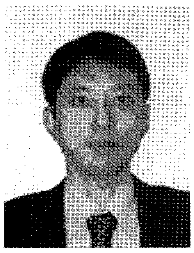
[11] G. Bianchi, "Performance analysis of the IEEE 802.11 distribution coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000.

[12] S. Tasaka, *Performance Analysis of Multiple Access Protocols*, MIT Press, Cambridge, MA, 1986.

[13] C. E. Koksal, H. Kassab, and H. Balakrishnan, "An analysis of short-term fairness in wireless media access protocols," in *Proc. ACM SIGMETRICS 2000*, Santa Clara, CA, June 2000.



Katsumi Sakakibara received the B.Sc., M.Sc., and Ph.D. degrees in Communication Engineering from Osaka University, Suita, Japan, in 1985, 1987, and 1994, respectively. Since 1995, he has been with Okayama Prefectural University, Soja, Japan, where he is currently a Professor in the Department of Communication Engineering. His interests include algebraic coding theory, error-control schemes, random-access protocols and the analysis of communication systems. He is a member of IEEE, the Institute of Electronics, Information, and Communication Engineers (IEICE), the Society of Information Theory and its Applications (SITA), and the Japan Association for Developmental Education (JADE).



Jumpei Taketsugu received the B.Sc. degree in Communication Engineering and the M.Sc., and Ph.D. degrees in Electronic, Information Systems and Energy Engineering from Osaka University, Suita, Japan, in 2000, 2002, and 2005, respectively. Since 2005, he has been with Okayama Prefectural University, Soja, Japan, where he is currently an Assistant Professor in the Department of Communication Engineering. His interests include radio communications in ad-hoc networks and sensor networks. He is a member of IEEE and the Institute of Electronics, Information, and Communication Engineers (IEICE).