Virtual Continuous CWmin Control Scheme of WLAN

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1. Introduction

IEEE 802.11 distribution control function (DCF) is a carrier sense based medium access control (MAC) protocol defined by the IEEE 802.11 standard [1] and has been widely used in wireless local area networks (WLANs). A WLAN is one of the most promising candidates for constructing a home area network (HAN) connecting various home electronics and sensors.

In WLANs based on the IEEE 802.11 standard, each WLAN station (WS), including an access point (AP) and stations (STAs), has the same transmission opportunity [2]. Therefore, unfairness between the uplink and the downlink flows arises in networks wherein many STAs belong to a single AP [3]. As a solution to this problem, a minimum contention window size (CWmin) control has been studied [4]–[6].

Abeysekera et al. showed that fairness between the up-
ffect does not occur, i.e., no WSs can obtain information at the instant a frame collision occurs. In this paper, we assume saturated traffic load conditions for simplicity: that is, the transmission queues of the AP and STAs are always nonempty. The propagation delay of each WS is negligible. In order to evaluate the throughput performance in the MAC layer, it is assumed that all the WSs generate user datagram protocol (UDP) traffic. We consider a WLAN based on the IEEE 802.11a standard, the parameters of which are listed in Table 1. We define an unidirectional throughput as

$$\min\{S_{\text{up}}, S_{\text{down}}\},$$

where $S_{\text{up}}$ and $S_{\text{down}}$ denote the uplink and downlink throughput, respectively. The fairness between the uplink and the downlink flows can be achieved by maximizing the unidirectional throughput. In this paper, the purpose of CWmin control is to maximize the unidirectional throughput, and it is considered that the system is optimized when the unidirectional throughput is maximized.

### 3. Conventional Scheme

The conventional dynamic CWmin control (DCC) scheme [6] and its problems are described in this section. In the conventional DCC scheme, to solve an unfairness problem between the uplink and the downlink flows, the CWmin value of the AP is determined according to the number of STAs that belong to a single AP. The backoff period when the WS waits before the frame transmission is depends on each WS’s CWmin value. The frame transmission opportunity of the WS increases with a decrease in the WS’s CWmin value. The CWmin values of the AP and the STA are expressed as CWminAP and CWminSTA, respectively. The fairness between the uplink and the downlink flows can be achieved when the AP has the same transmission opportunity as all the STAs that belong to the AP. This is achieved by deriving the optimum CWminAP value on the basis of CWminSTA value and other parameters. To evaluate the numerical value of the optimum CWminAP, the default value of CWminSTA that is defined in the IEEE 802.11 standard was used [6].

Figure 2 shows the throughputs with the conventional CWmin control according to CWminAP value when the number of STAs is 10. The downlink throughput $S_{\text{down}}$ decreases and the uplink throughput $S_{\text{up}}$ increases monotonously with an increase in CWminAP value. The unidirectional throughput can be maximized if CWminAP value is set between three and four, as shown in Fig. 2. However, CWminAP value should be an integer. Thus, according to Fig. 2, the optimized CWminAP is four. 

### 4. Proposed Scheme

In this section, the new CWmin control method (VCCC scheme) that can virtually realize CWmin value as a non-negative real number is proposed.

#### 4.1 Virtual Continuous CWmin Control (VCCC)

An AP that employs the basic access mechanism of IEEE 802.11 DCF resets its contention window size when the frame transmission is successful or the retry limit is reached. In the case of the legacy DCF, the CW value is reset at $l$, which has a nonnegative integer value.

On the other hand, CW is determined probabilistically as follows in the proposed VCCC scheme. The proposed method is applied to the AP.

$$\text{CWmin}_{\text{AP}} = \begin{cases} \frac{l}{\alpha_{\text{HP}}} & \text{(Probability of } \alpha_{\text{HP}}), \\ \frac{l + 1}{1 - \alpha_{\text{HP}}} & \text{(Probability of } 1 - \alpha_{\text{HP}}) \end{cases}$$

where $\alpha_{\text{HP}}$ that is in the range of $0 < \alpha_{\text{HP}} \leq 1$, is the probability that CWminAP value becomes $l$. Figure 3 shows the procedure of the proposed VCCC scheme. Once an AP sets CWminAP value to $l$ or $l+1$, the AP uses the same CWminAP value until it resets its CW next time after a successful transmission or reaching the retry limit. The AP of the proposed VCCC scheme has two states and repeats them probabilistically. If the AP set CWminAP value to small value $l$, the AP has a high priority state (HP). If the AP set CWminAP value to large value $l + 1$, the AP has a low priority state (LP). The expected value of CWminAP with the proposed VCCC scheme is expressed as
When we determine the expected value of $CW_{\text{minAP}}$, which is a nonnegative real number, we derive the value of $l$ that is determined by Eq. (3) when $E[CW_{\text{minAP}}]$ are given.

\begin{equation}
\begin{aligned}
E[CW_{\text{minAP}}] &= l \cdot \alpha_{\text{HP}} + (l + 1)(1 - \alpha_{\text{HP}}) \\
&= l - \alpha_{\text{HP}} + 1.
\end{aligned}
\end{equation}

When we determine the expected value of $CW_{\text{minAP}}$, which is a nonnegative real number, we derive the value of $l$ that is given by the following equation:

\begin{equation}
\begin{aligned}
l &= \lfloor E[CW_{\text{minAP}}] \rfloor,
\end{aligned}
\end{equation}

where $\lfloor z \rfloor$ stands for the maximum integer that is not greater than $z$ which is a real number. The value of $\alpha_{\text{HP}}$ is determined by Eq. (3) when $l$ and $E[CW_{\text{minAP}}]$ are given.

### 4.2 Theoretical Analysis

Tinnirello et al. proposed an accurate analytical model of IEEE 802.11e enhanced distributed channel access (EDCA) [8]. In this section, we propose an analytical model, which is expanded from Tinnirello’s model and can express the throughput performance of the proposed VCCC scheme.

#### 4.2.1 Analytical Model of IEEE 802.11

Figure 4 shows an example of the IEEE 802.11 DCF and the cycle introduced in [8]. The channel access of the IEEE 802.11 DCF is considered as a repetition of a cycle. A cycle starts from the end of a DIFS period and terminates at the end of the next DIFS. Each cycle consists of an initial random waiting time plus one transmission event or a frame collision event. A discrete-time $t$ denotes the start of a $t$th cycle.

Let $x(t)$ be the duration of the initial random time in cycle $t$ expressed in number of backoff slots. A saturated traffic load condition is assumed, and all the WSs compete persistently under that condition. $x(t)$ is expressed as

\begin{equation}
x(t) = \min_{\Phi} (b_\Phi(t)),
\end{equation}

where $b_\Phi(t)$ is the backoff counter value of WS$_\Phi$ at time $t$. The WS$_\Phi$ is considered as AP$_{HP}$, AP$_{LP}$, or STA in the case of the proposed VCCC scheme. As described in Fig. 3, AP$_{HP}$ and AP$_{LP}$ represent as the AP with the HP and LP states, respectively. Tagged station index $k$ is used in [8]; however, we use the WS index $\Phi$ in place of index $k$. The transmission event occurring in cycle $t$ depends on the natural number $y$, which is the number of WSs whose backoff counter value is $x(t)$. Successful transmission event occurs if $y = 1$, and the frame collision event occurs if $y > 1$. Thus, we can know the event occurring in the cycle $t$ if $b_\Phi(t)$ is obtained.

Let $B_\Phi(j)$ be the steady-state distribution of the WS$_\Phi$’s backoff counter. $B_\Phi(j)$ is defined as

\begin{equation}
B_\Phi(j) = \lim_{t \to \infty} Pr\{b_\Phi(t) = j\}.
\end{equation}

The existence of such a steady-state distribution is described in [8]. $B_\Phi(j)$ depends on the WS$_\Phi$’s parameters, such as $CW_{\text{min}}$ and $CW_{\text{max}}$ values.

#### 4.2.2 Definition of Variables

WS$_\Phi$ has the following set of MAC parameters:

- $R_\Phi$: Retry limit of WS$_\Phi$.
- $m_\Phi$: Maximum number of retransmissions until a frame is discarded. Thus, $m_\Phi$ is $R_\Phi - 1$.
- $W_{s_{t_{\Phi}}}$: CW value used in backoff stage of $s$.
- $W_{\Phi_{\text{max}}}$: CWmax value of WS$_\Phi$.
- $s_\Phi(t)$: Backoff stage value of WS$_\Phi$ when DIFS duration ends. $s_\Phi(t)$ has a value in the range of $[0, m_\Phi]$.
- $b_\Phi(t)$: Backoff counter value of WS$_\Phi$ after DIFS duration. $b_\Phi(t)$ is randomly selected from the range of $[0, W_{\Phi_{\text{max}}}]$.

Let $\Pi_\Phi(s, j)$ be a distribution such as

\begin{equation}
\Pi_\Phi(s, j) = \lim_{t \to \infty} Pr\{s_\Phi(t) = s, b_\Phi(t) = j\}.
\end{equation}

$\Pi_\Phi(s, j)$ denotes the probability that the WS$_\Phi$ has a backoff stage value of $s \in [0, m_\Phi]$ and a backoff counter value of $j \in [0, W_{\Phi_{\text{max}}}]$ in the steady-state cycle. By using $\Pi_\Phi(s, j)$, $B_\Phi(j)$ defined in Eq. (6) is expressed as

\begin{equation}
B_\Phi(j) = \sum_{s \in [0, m_\Phi]} \Pi_\Phi(s, j).
\end{equation}

Let us focus on WS$_\Phi$. Two probabilities that determine the states of other competing WSs are defined as follows.

- $Q_\Phi(i)$: The probability that no competing WSs transmit
before the occurrence of the slot index $i$. Slot index $i$ is defined as the $i$th slot time after the DIFS period. $i$ is greater than or equal to zero.

- $T_\Phi(i)$: The probability that the transmission of the other competing WSs occurs in a cycle exactly at slot index $i$.

It can be known that if WS$_\Phi$’s transmission succeeds or fails according to the probabilities of $Q_\Phi(i)$ and $T_\Phi(i)$. The cumulative distribution $\beta_\Phi(i)$ is defined as follows to obtain $Q_\Phi(i)$.

$$\beta_\Phi(i) = \begin{cases} 0 & (i \leq 0), \\ \sum_{j=0}^{i-1} B_\Phi(j) & (i > 0). \end{cases}$$

$\beta_\Phi(i)$ represents the probability that WS$_\Phi$ transmits a frame before the occurrence of slot index $i$. By using $\beta_\Phi(i)$, $Q_\Phi(i)$ is calculated as

$$Q_\Phi(i) = \left\{ \begin{array}{ll} Q_{AP,HP}(i) = \{1 - \beta_{STA}(i)\}^n, & \\
Q_{STA}(i) = [1 - (\beta_{AP,HP}(i) + \beta_{STA}(i))]\{1 - \beta_{STA}(i)\}^{n-1}, & 
\end{array} \right.$$  

(9)

where $Q_\Phi(0) = 1$. By using $Q_\Phi(i)$, $T_\Phi(i)$ is calculated as

$$T_\Phi(i) = Q_\Phi(i) - Q_\Phi(i + 1).$$

(10)

Note that the probabilities defined above can be expressed by using $P_\Phi(s, j)$.

4.2.3 Event Formularization with Proposed Scheme

The proposed VCCC scheme can realize the $E[CWmin]$ value as a nonnegative real number by changing the CWmin values probabilistically. The system proposed by Tinmirello can be used when CWmin has a fixed value. In this section, we propose the modified system that can be applied to the proposed VCCC scheme.

The state transition probability between $\{s_\Phi(t), b_\Phi(t)\}$ and $\{s_\Phi(t + 1), b_\Phi(t + 1)\}$ depends on the occurrence of the four following cases.

**case 1** The backoff counter of WS$_\Phi$ resumes. It does not reach zero because of a transmission or collision event by the other WSs.

Let the previous state of WS$_\Phi$ be $\{s_\Phi(t) = s, b_\Phi(t) = b + r\}$, where $r \in [0, W_{\Phi,s} - b]$. In this case, the backoff counter value of WS$_\Phi$ will be decremented by $r$, but it will not reach zero before cycle $t$ ends. The probability which WS$_\Phi$ ends in state $\{s_\Phi(t + 1) = s, b_\Phi(t + 1) = b\}$ is $T_\Phi(r)$.

$$T_\Phi(r).$$

Thus, $P_\Phi,BO(s, j)$, which denotes the contribution of case 1 to $P_\Phi(s, j)$, is expressed as follows,

$$P_\Phi,BO(s, j) = \sum_{r=0}^{W_{\Phi,s} - j} P_\Phi(s, j + r)T_\Phi(r).$$

(11)

**case 2** The cycle ends with a collision event involving WS$_\Phi$, while WS$_\Phi$ has not yet reached its retry limit of $R_\Phi$.

In this case, the backoff stage value of WS$_\Phi$ is incremented. If the previous state is $\{s_\Phi(t) = s - 1, b_\Phi(t) = j\}$, with $s - 1 < m_\Phi$, the transition probability to state $\{s_\Phi(t + 1) = s, b_\Phi(t + 1) = b\}$ is given by

$$\frac{1}{W_{\Phi,r} + 1} T_\Phi(j).$$

(12)

$P_\Phi,US(s, j)$, which denotes the contribution of case 2 to $P_\Phi(s, j)$, is expressed as follows,

$$P_\Phi,US(s, j) = \frac{1}{W_{\Phi,r} + 1} \sum_{r=0}^{W_{\Phi,s} - j} P_\Phi(s - 1, i)T_\Phi(i).$$

(13)

**case 3** The cycle ends with a collision event involving WS$_\Phi$, while WS$_\Phi$ has reached its retry limit of $R_\Phi$.

In this case, the frame is dropped, a new frame is scheduled for the next transmission, and the backoff stage value is set to zero. For the previous state $\{s_\Phi(t) = m_\Phi, b_\Phi(t) = j\}$, the transition probability to state $\{s_\Phi(t + 1) = 0, b_\Phi(t + 1) = b\}$ is

$$\frac{1}{W_{\Phi,0} + 1} T_\Phi(j).$$

(14)

Let us consider $P_\Phi,RL(s, j)$, which denotes a contribution of case 3 to $P_\Phi(s, j)$. In the case 3, WS$_\Phi$ resets its CW. $P_{STA,RL}(s, j)$ denotes the contribution of case 3 to $P_{STA}(s, j)$ and is expressed as

$$P_{STA,RL}(s, j) = \frac{1}{W_{STA,0} + 1} \sum_{i=0}^{W_{STA,\max}} P_{STA}(m_{STA}, i)T_{STA}(i).$$

(15)

On the other hand, an AP is applied to the proposed VCCC scheme, and it resets its CW according to the procedure shown in Fig. 3. Considering that the AP occupies the AP,HP state with the probability of $\alpha_{HP}$, $P_{AP,HP,RL}(s, j)$, which denotes the contribution of case 3 to $P_{AP,HP}(s, j)$, is expressed as

$$P_{AP,HP,RL}(s, j) = \frac{\alpha_{HP}}{W_{AP,HP,0} + 1} \sum_{i=0}^{W_{\Psi,\max}} P_{\Psi}(m_{\Psi}, i)T_{\Psi}(i),$$

where $\Psi \in AP,HP, AP,LP$.  

(16)

Considering that the AP occupies the AP,LP state with a probability of $1 - \alpha_{HP}$, $P_{AP,LP,RL}(s, j)$ which denotes the contribution of case 3 to $P_{AP,LP}(s, j)$, is expressed as

$$P_{AP,LP,RL}(s, j)$$

(17)
\[
\Pi_{\Phi}(0, j) = \Pi_{\Phi, BO}(0, j) + \Pi_{\Phi, RL}(0, j) + \Pi_{\Phi, ST}(0, j).
\]

\[(25)\]

c) For \(1 \leq s \leq m_{\Phi}, j = 0\) (case 2):
\[
\Pi_{\Phi}(s, 0) = \Pi_{\Phi, US}(s, 0).
\]

\[(26)\]

d) For \(1 \leq s \leq m_{\Phi}, 1 \leq j \leq W_{\Phi, \max}\) (cases 1 and 2):
\[
\Pi_{\Phi}(s, j) = \Pi_{\Phi, BO}(s, j) + \Pi_{\Phi, US}(s, j).
\]

\[(27)\]

On the other hand, the summation of the state probabilities for all WSs equals one. Thus, the following equations are given.
\[
\sum_{j=0}^{m_{\Phi}} \sum_{s=0}^{W_{\Phi, \max}} \Pi_{\Phi}(s, j) = 1,
\]

where \(\Psi \in \{\text{AP, LP}\}\).

\[
\sum_{j=0}^{m_{\Phi}} \sum_{s=0}^{W_{\Phi, \max}} \Pi_{\Phi}(s, j) = 1.
\]

\[(28)\]
\[(29)\]

The system that is expressed as Eqs. (24)–(29) can be solved by using a fix-point iteration similar to that presented in [8]. We use the function “fsolve” in the MATLAB [9] to solve these equations. The solutions of \(\Pi_{\Phi}(s, j), \Pi_{\Phi, AP}(s, j), \) and \(\Pi_{\Phi, \text{STA}}(s, j)\) are iteratively obtained. \(B_{\Phi}(\cdot), \beta_{\Phi}(\cdot), \Omega_{\Phi}(\cdot),\) and \(T_{\Phi}(\cdot)\) are derived from Eqs. (8), (9), (10), and Eq. (11), respectively using the solutions of \(\Pi_{\Phi}(s, j)\).

4.2.4 Calculation of Throughput

This section explains how to calculate the throughput of the proposed model. Let \(P_{\text{succ}}(\Phi)\) be the probability that WS\(_{\Phi}\)'s transmission succeeds in the cycle, i.e., only WS\(_{\Phi}\) can transmit a data-frame in the cycle and \(P_{\text{succ}}(\Phi)\) is derived as
\[
P_{\text{succ}}(\Phi) = \sum_{j=0}^{W_{\Phi, \max}} B_{\Phi}(i) Q_{\Phi}(i + 1).
\]

\[(30)\]

The probability \(P_{\text{succ}}\) that success transmission occurs in the cycle is expressed as
\[
P_{\text{succ}} = n \cdot P_{\text{succ}}(\text{STA}) + P_{\text{succ}}(\text{AP, HP}) + P_{\text{succ}}(\text{AP, LP}).
\]

\[(31)\]

Following variables are defined as:

- \(E[x]\): Expected value of the number of backoff slot in one cycle.
- \(\sigma\): Slot time.
- \(T_{\text{succ}}\): Duration of a successful transmission event.
- \(T_{\text{coll}}\): Duration of a collision event.

The expected value of one cycle duration is calculated as
\[
E[\text{cycle}] = E[x] \sigma + P_{\text{succ}} T_{\text{succ}} + (1 - P_{\text{succ}}) T_{\text{coll}}.
\]

\[(32)\]

Let \(Q_{\Phi}(j)\) be the probability that no WSs transmit before the occurrence of backoff slot \(j\) and it is computed as
\[ Q_0(j) = \left[ 1 - (\beta_{AP,HP}(j) + \beta_{AP,LP}(j)) \right] \left[ 1 - \beta_{STA}(j) \right]^n. \]  

(33)

The probability that the transmission event occurs in a cycle exactly at slot index \( j \) is

\[ T_0(j) = Q_0(j) - Q_0(j+1). \]  

(34)

On the other hand, \( T_0(j) \) is the probability that there are \( j \) backoff slots. Thus, the expected value of the number of backoff slot in one cycle is calculated as

\[ E[x] = \sum_{j=0}^{L} j \cdot T_0(j). \]  

(35)

where \( L \) is the minimum of \( CW_{max} \) value in the WSs.

As stated before, the uplink throughput \( S_{up} \) and downlink throughput \( S_{down} \) are computed as

\[ S_{up} = \frac{n \cdot P_{suc}(STA) \cdot PSIZE}{E[\text{cycle}]}, \]  

(36)

\[ S_{down} = \frac{P_{suc(AP,HP) + P_{suc(AP,LP)}} \cdot PSIZE}{E[\text{cycle}]}, \]  

(37)

respectively, where \( PSIZE \) denotes the MAC service data unit (MSDU) size.

5. Numerical Results

5.1 Single-rate and saturated traffic condition

In this section, the computer simulation and theoretical analysis results are presented. We assume a saturated traffic load condition. It is assumed that \( CW_{min,STA} \) value is 15, which is the default value in the IEEE 802.11a standard [1]; the MSDU size of a data frame is 1500 bytes, and the PHY data rate is 36 Mbit/s in the network as shown Fig. 1. The basic access mechanism is used whenever a WS transmits a data frame. To evaluate the throughput performance, we employ a simulation platform on a Monte Carlo simulation using the C language. We confirmed that the simulation results of our program are in good agreement with those of QualNet 5.0 [10] under the same conditions explained previously with the conventional scheme described in Sect. 2.

In this study, the purpose of the \( CW_{min} \) control is to maximize the unidirectional throughput to achieve fairness.

Figures 5 and 6 show the throughput performances versus \( E[CW_{min,AP}] \) using the proposed VCCC scheme in the case where 10 and 20 STAs exist, respectively. In the figures, the curved lines represent the throughputs calculated by the theoretical analysis, and the symbols denote those obtained from the computer simulation. In the proposed scheme, the value of \( l \) is given by Eq. (4). It increases in accordance with an increase in \( E[CW_{min,AP}] \) whose range and step size are [0,10] and 0.01, respectively in Figs. 5, 6. Then the value of \( \alpha_{HP} \) is calculated by Eq. (3). These parameters give us the theoretical throughput of each link by Eqs. (36) and (37). Also they give us the simulation results of the throughput. The optimum \( E[CW_{min,AP}] \) value is obtained by the intersection of uplink and downlink throughput curves in Figs. 5, 6. When we derive the optimum \( E[CW_{min,AP}] \) value, we can determine the values of \( l \) and \( \alpha_{HP} \) by using Eqs. (4) and (3), respectively. The conventional scheme cannot maximize the unidirectional throughput, as shown in Fig. 2, because \( CW_{min,AP} \) value has a non-negative integer value. In contrast, the proposed VCCC scheme can realize the \( E[CW_{min,AP}] \) value as a real number and maximize the unidirectional throughput as shown in Fig. 5. The unidirectional throughput is maximized only if the uplink and downlink throughputs are equal. Thus, the proposed VCCC scheme enables accurate control under the constraint that the downlink throughput be exactly equal to the total uplink throughput. The throughputs obtained by the computer simulation are in good agreement with those calculated by the theoretical analysis as shown in Fig. 5. These results reveal that the optimum \( E[CW_{min,AP}] \) value obtained from the computer simulation and theoretical analysis are 3.55 and 3.5, respectively. On the other hand, in the case of 20 STAs, the difference between the throughputs obtained by the computer simulation and the theoretical analysis become large, as shown in Fig. 6. The reason is described later.

Figure 7 shows the steady-state distribution of the
WSN’s backoff counter using the proposed VCCC scheme in the case where 10 STAs exist and $E[CW_{\text{min,AP}}]$ value is 3.55. Figure 8 shows that in the case where 20 STAs exist and $E[CW_{\text{min,AP}}]$ value is 2.11. The numerical values of $B_\Phi(j)$ is derived from Eq. (8). The steady-state distribution of backoff counter obtained by the computer simulation are in good agreement with those calculated by the theoretical analysis, as shown in Fig. 7. As the backoff counter value $j$ becomes small, $B_\Phi(j)$ has a larger and dominant value. The difference between the theoretical analysis results and the computer simulation results of $B_\Phi(j)$ is within 4% in the case where the backoff counter value is less than three and the number of STAs is 10. In the case where more STAs exist, the difference between theoretical analysis and computer simulation results of the throughputs becomes large. The difference is about 8% when 20 STAs belong to the AP.

The reason is as follows. In the theoretical analysis, it is assumed that $B_{\text{STA}}(j)$ has a constant value at any AP’s stages. However it is not practical that $B_{\text{STA}}(j)$ always has a constant value. The value of $B_{\text{STA}}(j)$ depends on the AP’s stage. This assumption is the main cause of the difference between the theoretical and the simulation results. Figure 11 shows the probability distribution of STA’s backoff counter according to the AP’s backoff stage where five STAs exist and $E[CW_{\text{min,AP}}]$ value is 5.35. Figure 12 shows those where 20 STAs exist and $E[CW_{\text{min,AP}}]$ value is 2.11. The difference among the probability distribution of STA’s backoff counter becomes large as the number of STAs increases. Thus, theoretical analysis accuracy becomes worse as the

Figures 9 and 10 show the optimum $E[CW_{\text{min,AP}}]$ values and maximized unidirectional throughputs, respectively. Figure 9 shows that the proposed VCCC scheme can realize the expected value of CWmin as a real number. Figure 10 shows that the throughput of the proposed scheme is 31% higher than that of the conventional one when the number of STAs is 18. The difference between theoretical analysis results and computer simulation results of the throughputs is within 1% when 10 STAs exist. However, the number of STAs increases, the difference between theoretical analysis results and computer simulation results of the throughputs becomes large. The difference is about 8% when 20 STAs belong to the AP.

The reason is as follows. In the theoretical analysis, it is assumed that $B_{\text{STA}}(j)$ has a constant value at any AP’s stages. However it is not practical that $B_{\text{STA}}(j)$ always has a constant value. The value of $B_{\text{STA}}(j)$ depends on the AP’s stage. This assumption is the main cause of the difference between the theoretical and the simulation results. Figure 11 shows the probability distribution of STA’s backoff counter according to the AP’s backoff stage where five STAs exist and $E[CW_{\text{min,AP}}]$ value is 5.35. Figure 12 shows those where 20 STAs exist and $E[CW_{\text{min,AP}}]$ value is 2.11. The difference among the probability distribution of STA’s backoff counter becomes large as the number of STAs increases. Thus, theoretical analysis accuracy becomes worse as the
number of STAs increases and CWminAP value decreases.

### 5.2 Multi-rate and Unsaturated Traffic Conditions

The throughput performances for multi-rate networks under saturated or unsaturated traffic conditions are evaluated. The data frame transmission rates of the multi-rate network are 24 Mbit/s and 36 Mbit/s. Half of the STAs have a data rate of 24 Mbit/s and the rest of the STAs have a data rate of 36 Mbit/s. Figure 13 shows the unidirectional throughput for a multi-rate network versus the number of STAs under the saturated traffic condition. In addition, the simulation results for multi-rate networks under the unsaturated traffic condition are shown in Fig. 14. This figure shows the unidirectional throughput versus the offered traffic per STA. These results reveal that the proposed VCCC scheme can be successfully applied to not only single-rate networks under saturated traffic conditions but also multi-rate networks under saturated or unsaturated traffic conditions.

### 6. Conclusions

In this paper, we have proposed a new CWmin control method named the VCCC scheme that can realize $E[CW\min]$ value as a nonnegative real number by changing the CWmin values probabilistically. We have shown that the proposed VCCC scheme can improve the system throughput under the constraint that the downlink throughput be accurately equal to the total uplink throughput. Using a computer simulation, we have estimated the optimized $E[CW\min]$ value and unidirectional throughput, which is the minimum of the uplink and downlink throughputs in a single-hop WLAN network with the proposed VCCC scheme. We clarified that the unidirectional throughput of the proposed VCCC scheme is 31% higher than that of the conventional scheme under the saturated traffic condition, when the number of STAs is 18. Moreover, we have proposed the theoretical analysis model for the proposed VCCC scheme and calculated the optimized $E[CW\min]$ value and unidirectional throughput. The difference between theoretical analysis results and computer simulation results of throughput perfor-
mane is within 1% when 10 STAs exist. Furthermore we have revealed that the proposed VCCC scheme can be applied to not only single-rate networks under saturated traffic conditions but also multi-rate networks under saturated or unsaturated traffic conditions.

References


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