

# Interclass Collision Protection for IEEE 802.11e Wireless LANs

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Distributed Coordination Function (DCF) in IEEE 802.11 and Enhanced Distributed Channel Access (EDCA) in IEEE 802.11e are contention-based access mechanism in wireless LAN. Both DCF and EDCA reduce collisions based on inter-frame space (IFS) and backoff mechanisms. However, collisions are unavoidable even with the two mechanisms. Especially, in the EDCA, collisions can be classified into interclass and intra-class collision. To eliminate interclass collision in wireless LAN, we propose an interclass collision protection (ICP) scheme by employing collision protection period (CPP) after backoff. Different number of backoff time-slots is inserted to each class. Higher class stations are allowed to transmit before lower class stations end backoff period. Analysis is performed with one dimensional discrete-time markov chain for the EDCA and proposed ICP-based EDCA. Collision probability and throughput of each channel access is examined. Throughput increase is more than doubled with reduced collision probability when the system is saturated.

Keywords: wireless LAN, EDCA, interclass collision, orthogonal backoff signal, markov chain

## I. Introduction

Wireless local area network (WLAN) is rapidly growing due to technological development in supporting mobility. The last few years have seen growth in the installation of access points (APs) based on IEEE 802.11 WLAN [1] to support data communications. Its advantages are low cost and simple deployment. With the increasing expectation of voice over Internet Protocol (VoIP), WLAN looks forward to providing real-time service in addition to data service. However, IEEE 802.11 WLAN is below the level of quality of service (QoS) requirements to provide real-time services [3]. To support

QoS requirements in medium access control (MAC) level, the standardization committee has proposed IEEE 802.11e [2]. The IEEE 802.11e MAC protocol employs a hybrid coordination function (HCF) that includes enhanced distributed channel access (EDCA). Although the EDCA provides different QoS for each class by differentiating the inter-frame space and contention window size, system performance cannot provide pertinent QoS for voice service. This is because the number of collisions increases with the number of contending stations. That is, collisions are still an impediment because EDCA is a contention-based mechanism

analogous to DCF.

The DCF and EDCA implement a binary exponential backoff by increasing the contention window size exponentially for each transmission failure in order to reduce collisions. However, in certain situations, this exponential backoff causes unnecessary idle duration such that the channel is utilized inefficiently. Due to the aforementioned facts, it is well known that the throughput performance gets severely compromised when the number of contending stations increases [4, 5, 6]. The performance degradation due to collisions becomes more severe as the frame size increases since the bandwidth waste by collisions becomes relatively large. Moreover, retransmissions due to collisions waste communication energy, thus reducing the lifetime of battery-powered wireless devices.

In this paper, we propose a novel contention-based MAC model by enhancing the 802.11e EDCA, followed by analysis. Our motivation is that interclass collision can be eliminated by suppressing the transmission of lower class stations. A collision occurs when two or more stations transmit simultaneously. When a collision occurs among stations in the same class, it is hard to select a station to transmit because all stations have equivalent transmission priority. On the other hand, in the case of interclass collision, class priority can play a role of different transmission opportunity with each station. That is, if a station in the highest class priority has transmission opportunity,

interclass collision does not occur. The proposed contention-based MAC is interclass collision protection (ICP) model. In the ICP, each station recognizes the class of other stations which transmit simultaneously by use of control signal and only the highest class station is allowed to transmit.

The remainder of this paper is organized as follows. Section II introduces IEEE 802.11e EDCA and a signal-based collision avoidance scheme. In Section III, we present the basic idea and operation of ICP. Throughput analysis is presented in Section IV with numerical results in Section V. Finally, Section VI concludes the paper.

## II. Related Works

### 1. IEEE 802.11e EDCA

EDCA is designed to enhance the DCF mechanism by supporting service differentiation among categories and distributing these categories in the channel access. EDCA consists of four access categories (ACs). Each AC has different priority with different initial contention window size ( $CW_{i,min}$ ), maximum contention window size ( $CW_{i,max}$ ) and arbitration inter-frame space ( $AIFS_i$ ). Different parameter settings play a role of giving higher AC more statistical opportunity to access the channel. That is, if a class sets smaller parameters than other classes, stations of the class has a better chance to access the wireless medium.

The basic operation of EDCA is similar to IEEE 802.11 DCF. If a station of  $AC_i$  has a frame to transmit, it checks the

medium status for idleness. If the medium is sensed to be idle, the station immediately proceeds with its transmission after waiting  $AIFS_i$ . If the medium is sensed to be busy, the station defers its access until the medium is determined to be idle for  $AIFS_i$  interval, and then it starts a backoff procedure.

A backoff procedure starts by setting its own backoff timer by uniformly choosing a random value from the range  $[0, CW_{i,j}-1]$ , where  $CW_{i,j}$  is the current contention window size, and determined by  $AC_i$  and backoff stage  $j$ . It is an integer value within the range of  $CW_{i,min}$  and  $CW_{i,max}$ . Backoff stage is defined as the number of retransmissions in a station. The backoff counter is decreased by a slot time as long as the channel is sensed idle, while it is frozen when the channel is sensed busy. The backoff counter count-down is resumed after the channel is sensed to be idle for a AIFS interval. When the backoff counter reaches zero, the station starts its data frame transmission. If the source successfully receives an acknowledgment (ACK) frame after a short inter-frame space (SIFS) idle period, the transmission is assumed to be successful.

After a successful transmission, the source resets its contention window to the minimum value  $CW_{i,min}$ , and performs another backoff process irrespective of whether it has another frame to transmit or not. It prevents a station from performing consecutive immediate access. On the other hand, if a frame transmission fails, the  $CW_{i,j}$  is increased by  $CW_{i,j+1}$  with the maximum

value  $CW_{i,max}$ . The station attempts to transmit the frame again by recalculating a backoff counter value from contention window increase,  $CW_{i,j+1}$ . After the number of failures reaches a retry limit, the station drops the frame.

The  $CW_{i,j}$  for priority class  $i$  in backoff stage  $j$  is determined as follows [5].

$$CW_{i,j} = \begin{cases} \sigma_i^j CW_{i,0}, & \text{for } j=0,1,\dots,m_i-1, & \text{if } R_i > m_i \\ \sigma_i^{m_i} CW_{i,0} = CW_{i,max}, & \text{for } j=m_i, m_i+1, \dots, R_i, & \text{if } R_i > m_i \\ \sigma_i^j CW_{i,0}, & \text{for } j=0,1,\dots,R_i, & \text{if } R_i \leq m_i \end{cases} \quad (1)$$

where  $\sigma_i$  is the contention window (CW) increasing factor of class  $i$  (for example, the increasing factor of DCF is 2), and  $CW_{i,min}$  and  $CW_{i,max}$  are minimum and maximum CW size of class  $i$ .  $R_i$  is the retry limit of class  $i$  and  $m_i = \log_{\sigma_i}(CW_{i,max} / CW_{i,min})$ . Backoff period is randomly chosen in the range of  $[0, CW_{i,j}-1]$ . The AIFS is applied to achieve differentiation of each class. The AIFS for a given AC is determined by the following equation.

$$AIFS_i = SIFS + AIFSN_i \times \delta \quad (2)$$

where  $AIFSN_i$  is AIFS Number of  $i$ th AC ( $AC_i$ ) determined by the AC and physical setting of IEEE 802.11e standardization [2].  $\delta$  is the duration of a time slot. The AC with the smallest AIFS has the highest priority.

## 2. Signal Based Collision Avoidance

A collision occurs when two or more stations transmit data simultaneously on the same channel. IEEE 802.11 standardization [1] proposed DCF based on carrier sensing

multiple access with collision avoidance (CSMA/CA) mechanism. The CSMA/CA utilizes the random backoff prior to each frame transmission attempt. While the random backoff can reduce the collision probability, it cannot completely eliminate the collisions since two or more stations can finish their backoff procedures simultaneously. Thus the collision is unavoidable in a distributed system, even if the hidden terminal problem can be solved with the Request-To-Send (RTS) and Clear-To-Send (CTS) messages. The DCF implements a binary exponential backoff by increasing the contention window size exponentially for each transmission failure in order to reduce consecutive collisions. However, the performance degradation due to the collisions becomes more severe as the number of contending station increases. Many literatures have studied the method of reducing collision in WLAN [6, 7, 8, 9]. Especially, collision avoidance by use of a dummy signal achieves practical results. Blackburst (BB) contention scheme [7] and busy tone multiple access (BTMA) [9] is representative of a signal based collision avoidance scheme.

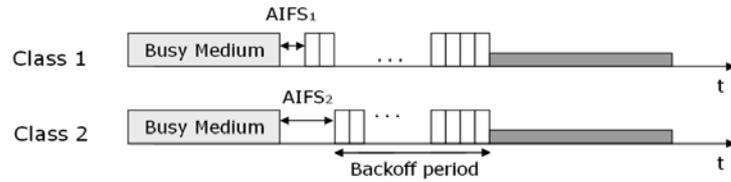
### III. Interclass Collision Protection

#### 1. Basic idea of ICP

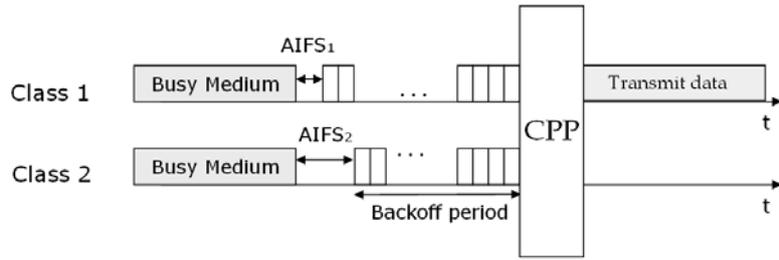
In the enhanced MAC, any collision among ACs in a station can be handled by a virtual collision handler. However, the virtual collision handler cannot eliminate the interclass collision among stations. The

purpose of ICP is the elimination of interclass collision with an appropriate collision protection period after the backoff. Figure 1 (a) illustrates the case of interclass collision in EDCA. Under EDCA, interclass collision occurs when the backoff period of two or more stations belonging to different AC ends simultaneously. This interclass collision can be avoided by using a control scheme that grants a preferential transmission right to the highest priority station among stations of collision as in Figure 1 (b). The control scheme guarantees to grant greater channel access priority to the higher class station by using collision protection period (CPP).

CPP is an extra period which is inserted at the end of a backoff period of each station. By using the CPP, only the highest class station transmits when backoff periods of different class stations finish simultaneously. That is, the highest class station transmits a frame and others wait until the channel is idle. CPP follows a signal based collision avoidance scheme. CPP uses a special signal to protect interclass collision, named orthogonal backoff signal (OB signal). OB signal is defined as a busy signal that has no effect on any other signal to guarantee orthogonality. It is a busy tone to inform all other stations that the channel is busy as in [9]. For example, let station A transmit OB signal when station B transmits a data signal to station C and all stations are located in interference range. In a casual situation, a collision occurs because station C receives signal from both stations A and B



(a) Interclass collision in EDCA



(b) ICP-based EDCA

Figure 1 EDCA vs. ICP-based EDCA

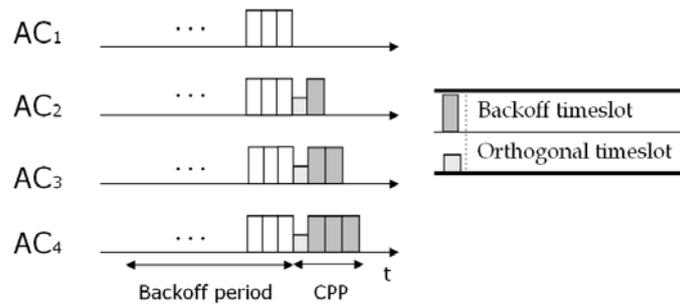


Figure 2 Basic operation of ICP in four-class model

simultaneously.

However, by the definition of OB signal, the signal of station A does not affect the signal of station B, so station C is able to receive the signal of station B.

CPP consists of two elements; backoff timeslot and orthogonal timeslot as in Figure 2. Backoff timeslot proceeds as a timeslot of backoff period. In other words, each backoff timeslot checks whether the channel is busy or not. If the channel is idle at the last backoff timeslot, a station transmits at the next timeslot. Otherwise, a station freezes its backoff period until the channel becomes idle. Orthogonal timeslot is the timeslot to

transmit orthogonal backoff signal.

Orthogonal timeslot performs two roles. First, the highest AC station transmits its data when interclass collision has occurred. It is deeply related to the definition of OB signal. While lower class stations transmit OB signal, the highest class station transmits data signal with no interference. Second, when the backoff period of lower AC station finishes earlier than higher ACs, OB signal from the lower class station occupies the channel and the higher class stations backoff counter freezes until the channel is idle again.

Figure 2 illustrates the ICP of each class. CPP is inserted after the backoff period. To

prevent interclass collision, each AC has different time duration of CPP. Let the total number of AC be  $N$  and  $AC_i, i=1, \dots, N$  has higher priority than  $AC_{i+1}$ . CPP of the highest AC ( $AC_1$ ) does not have an additional timeslot. The highest class station transmits data without additional delay. CPP of  $AC_i$  consists of one orthogonal timeslot and  $i$  backoff timeslots. Different number of CPP backoff timeslots allows higher class stations to transmit before lower class stations end backoff period.

## 2. ICP procedure

Figure 3 illustrates the flow diagram of ICP. ICP procedure is similar to IEEE 802.11e EDCA, but ICP adopts the concept of virtual collision. Virtual collision occurs when the backoff counters of interclass stations finish simultaneously. Virtual collision follows the concept of interclass collision in EDCA. In ICP, when virtual collision occurs, the highest class station transmits, and lower class stations wait until the highest station finishes transmission and restarts backoff procedure without increasing the CW size. In this case, a new backoff counter must be

provided to lower class stations because the backoff counter of lower class stations has ended. The new backoff counter is calculated on the same backoff stage. It gives lower priority class stations more transmission opportunity than in EDCA. In EDCA, when collision occurs, the contention window size doubles in the backoff procedure by increasing backoff stage. The bigger contention window size causes a larger backoff counter and the station which gets the larger backoff counter needs more waiting time to transmit. Therefore, ICP efficiently reduces waiting time by not increasing the backoff stage when virtual collision occurs.

Figure 4 shows how ICP avoids interclass collision. In the figure, station 1 is  $AC_1$ , station 2 is  $AC_2$ , station 3 is  $AC_3$ , and station 4 is  $AC_4$ . Figure 4 (a) shows the case of the highest class station (station 1) transmitting when the backoff period of every station finishes simultaneously. After the backoff period, station 1 transmits the data signal and others transmit orthogonal backoff signal. The receiving station or AP receives the data signal of station 1 with no interference by the

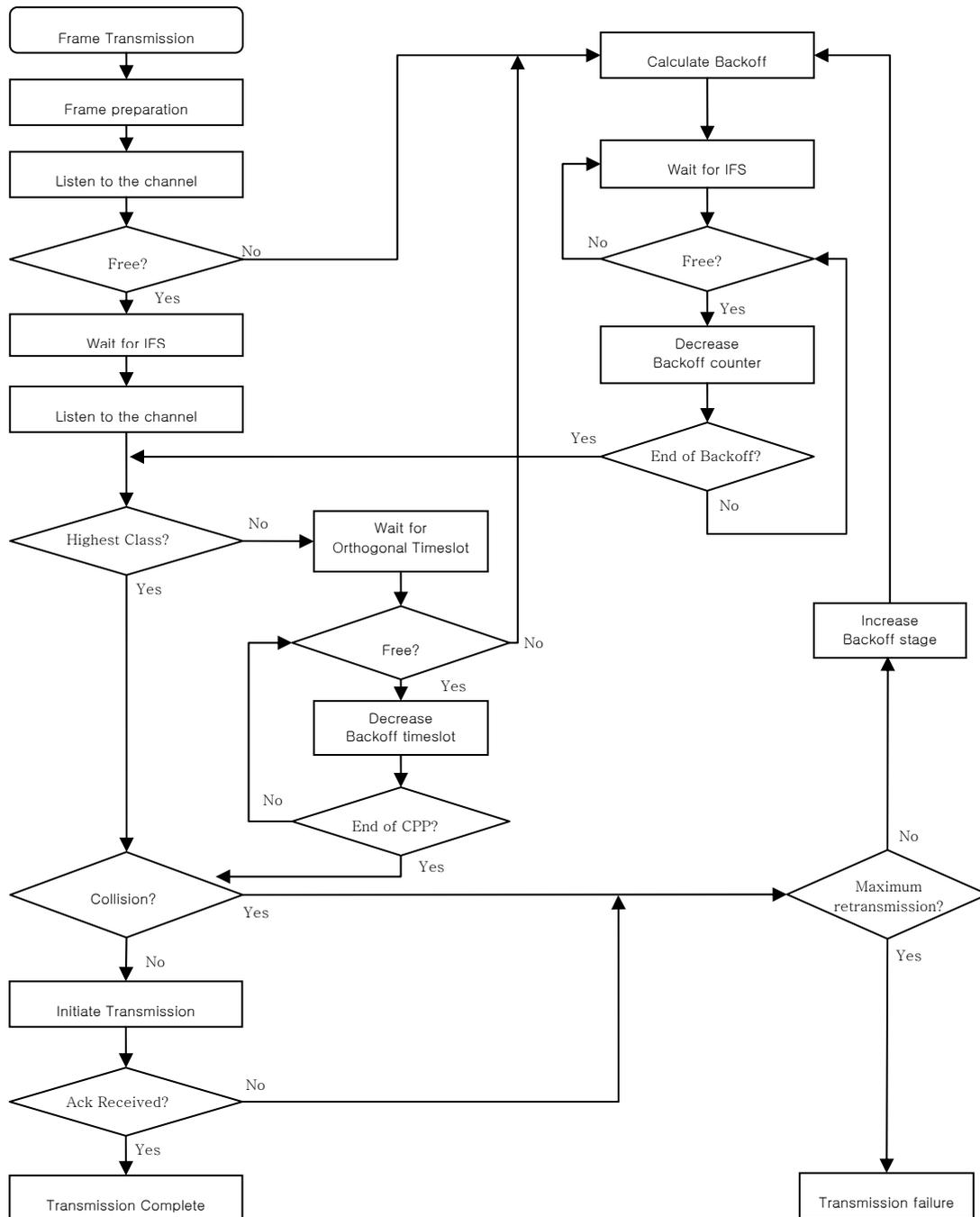


Figure 3 Flow diagram of ICP

definition of orthogonal backoff signal. After the orthogonal timeslot, lower class stations sense the busy channel and recognize the occurrence of virtual collision and freeze backoff counter until the channel is idle.

Figure 4 (b) shows the data transmission by station 3 when the virtual collision is caused by stations 3 and 4. For station 3 to transmit data signal, higher class stations should have remaining backoff timeslot when

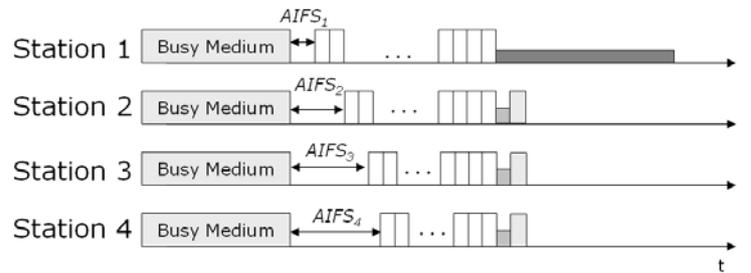
backoff period of station 3 is finished. In the figure, backoff period of stations 1 and 2 are not finished when station 3 finishes its backoff period.

After the last backoff timeslot, station 3 transmits an orthogonal backoff signal and the remaining backoff timeslot of higher class stations are frozen until channel is idle. In the figure, station 4 has a lower class priority than station 3, so the number of CPP backoff timeslot is more than that of station 3. By the different number of backoff timeslots, station 3 transmits before station 4 finishes

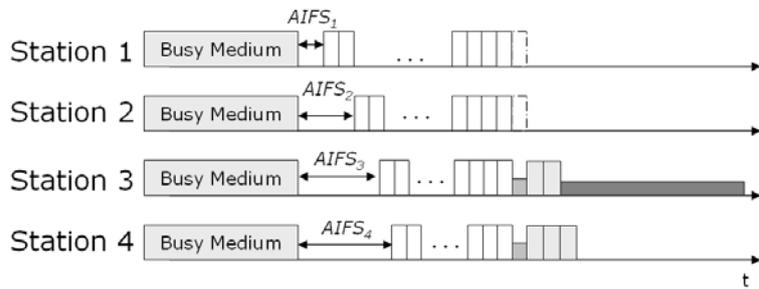
CPP. Therefore, station 3 transmits and other stations freeze their backoff period until the medium is idle.

#### IV. Analytical Model and Throughput Analysis

The analytical model of IEEE 802.11 DCF proposed by Bianchi [4] and Bianchi and Tinnirello [11] becomes a motivation for numerous analyses of 802.11 DCF and IEEE 802.11e EDCA. The main framework of the analytical model is two dimensional Markov Chain (MC) organized by backoff counter



(a) Transmission by Class 1 station



(b) Transmission by Class 3 station

Figure 4 Examples of ICP

and backoff stage. This two dimensional MC is simplified to one dimensional MC [11] by separating the backoff stage and backoff counter.

### 1. IEEE 802.11e EDCA model

To analyze the performance of IEEE802.11e EDCA with one dimensional MC, we assume that stations transmit in ideal condition with no errors in the channel and no hidden stations. Also, we assume that the channel is saturated and collision probability of a transmitted packet is constant and independent of the retransmissions.

Let  $\tau_i$ , that is  $P(TX_i)$ , be the probability that a station of  $AC_i$ , is transmitting a frame in a timeslot. Also, let  $P(s_i=j)$  be the probability that a station of  $AC_i$  is in backoff stage  $j$ . Then, we can obtain Equation (3) by the definition of conditional probability.

$$P(s_i = j, TX_i) = P(TX_i)P(s_i = j | TX_i) = P(s_i = j)P(TX_i | s_i = j) \quad (3)$$

By Equation (3),  $P(s_i=j)$  can be represented as follows.

$$P(s_i = j) = P(TX_i) \frac{P(s_i = j | TX_i)}{P(TX_i | s_i = j)}, \quad i \in (1, \dots, N), j \in (0, \dots, R_i) \quad (4)$$

Because a station of  $AC_i$  transmits a data frame in stage  $j$ ,  $j \in (0, \dots, R_i)$  with  $\sum_{j=0}^R P(s_i = j) = 1$ ,  $i \in (1, \dots, N)$ , we can obtain transmission probability  $\tau_i$  as follows.

$$\tau_i = P(TX_i) = \frac{1}{\sum_{j=0}^{R_i} \frac{P(s_i = j | TX_i)}{P(TX_i | s_i = j)}}$$

$$i \in (1, \dots, N) \quad (5)$$

In Equation (5),  $\tau_i$  is computed with the sum of  $P(s_i=j|TX_i)$  and  $P(TX_i|s_i=j)$ .

$P(s_i=j|TX_i)$  represents the probability that a station of  $AC_i$  being transmitting is found in stage  $j$ . This probability is the steady state probability of a discrete-time Markov chain  $s_i(k)$ , describing the backoff stage during the station's transmission instant  $k$ , whose non-null one-step transition probability is given as in Equation (6).

$$\begin{cases} P(s_i(k+1) = j | s_i(k) = j-1) = p_i & j=0, \dots, R_i \\ P(s_i(k+1) = 0 | s_i(k) = j) = 1-p_i & j=0, \dots, R_i-1 \\ P(s_i(k+1) = 0 | s_i(k) = R_i) = 1 & j=R_i \end{cases} \quad (6)$$

where the conditional collision probability  $p_i$  is the collision probability when the packet is transmitted on the channel. From (6) we can get  $P(s_i=j|TX_i)$ .

$$P(s_i = j | TX_i) = \frac{(1-p_i)P_i^j}{1-p_i^{R_i+1}} \quad i \in (1, \dots, N), j \in (0, \dots, R_i) \quad (7)$$

$P(TX_i|s_i=j)$  in Equation (5) is the probability that a station of  $AC_i$  transmits a frame in backoff stage  $j$ . From [11], given backoff stage  $j$ ,  $P(TX_i|s_i=j)$  is obtained by dividing the average number of slots spent by the station during the interval of its backoff counter which is called a cycle.

$$P(TX_i | s_i = j) = \frac{1}{1 + \alpha_i + E[b_{ij}]}, \quad i \in (1, \dots, N), j \in (0, \dots, R_i) \quad (8)$$

$E[b_{ij}]$  is the average value of the backoff counter extracted by a station of  $AC_i$  entering stage  $j$ .  $\alpha_i$  is the difference between minimum AIFS ( $AIFS_0$ ) and  $AIFS_i$ . It is used to compensate the difference of AIFS of each

class. Namely, if all stations have the same length of IFS, which is same as the size of  $AIFS_0$  in EDCA, we can think of the station of  $AC_i$  as having additional timeslots, the size of  $\alpha_i$ , during one cycle. By doing this, the IFS mechanism of DCF enhances AIFS mechanism of EDCA without loss. Substituting Equation (7) and (8) into (5), it can be written as.

$$\tau_i = P(TX_i) = \frac{1}{\sum_{j=0}^{R_i} \frac{P(s_i=j|TX_i)}{P(TX_i|s_i=j)}} = \frac{1}{1 + \alpha_i + \frac{1-p_i}{1-p_i^{R_i+1}} \sum_{j=0}^{R_i} p_i^j E[b_j]}$$

$$i \in (1, \dots, N), j \in (0, \dots, R_i) \quad (9)$$

When a station of  $AC_i$  transmits, a collision occurs if one or more stations transmit into the medium. It is the same as the definition of  $p_i$ , and it is represented as follows.

$$p_i = 1 - (1 - \tau_i)^{n_i-1} \prod_h^{i-1} (1 - \tau_h)^{n_h} \quad i \in (1, \dots, N) \quad (10)$$

where  $n_i$  denotes the number of stations of class  $i$ .

## 2. ICP-based EDCA Model

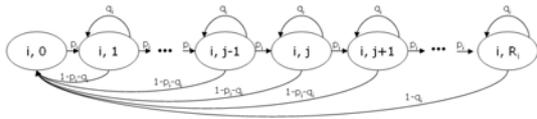


Figure 5 Transition diagram of  $P(s_i=j|TX_i)$  of ICP

An analytical model of ICP is an enhanced version of the EDCA model. The major difference between ICP and EDCA is virtual collision. As explained in Section III. 2, the virtual collision occurs when backoff period of interclass stations finishes simultaneously. Actually, virtual collision probability is the probability

only applied to lower class stations. The highest class station transmits frames in virtual collision, but lower class stations precede new backoff procedure in the same backoff stage.

In ICP-based EDCA model,  $P(s_i=j|TX_i)$  is given as in Equation (11) with transition diagram in Figure 5.

$$\begin{cases} P(s_i(k+1) = j | s_i(k) = j-1) = p_i, & j=0, \dots, R_i \\ P(s_i(k+1) = 0 | s_i(k) = j) = 1 - p_i, & j=0, \dots, R_i-1 \\ P(s_i(k+1) = 0 | s_i(k) = R_i) = 1, & j=R_i \\ P(s_i(k+1) = j | s_i(k) = j) = q_i, & j=0, \dots, R_i \end{cases} \quad (11)$$

where  $q_i$  is the virtual collision probability. From (11) we can get  $P(s_i=j|TX_i)$ .

$$P(s_i = j | TX_i) = \frac{\left(1 - \frac{p_i}{1-q_i}\right) \left(\frac{p_i}{1-q_i}\right)^j}{1 - \left(\frac{p_i}{1-q_i}\right)^{R_i+1}}$$

$$i \in (1, \dots, N), j \in (0, \dots, R_i) \quad (12)$$

$P(TX_i|s_i=j)$  is the same as the EDCA model in Equation (8). From Equation (5), (8), and (12)  $\tau_i$  is obtained as follows.

$$\tau_i = P(TX_i) = \frac{1}{\sum_{j=0}^{R_i} \frac{P(s_i=j|TX_i)}{P(TX_i|s_i=j)}} = \frac{1}{1 + \alpha_i + \frac{1 - \left(\frac{p_i}{1-q_i}\right)}{1 - \left(\frac{p_i}{1-q_i}\right)^{R_i+1}} \sum_{j=0}^{R_i} \left(\frac{p_i}{1-q_i}\right)^j E[b_j]}$$

$$i \in (1, \dots, N), j \in (0, \dots, R_i) \quad (13)$$

In ICP, all actual collisions are intraclass collisions, since all interclass collisions are eliminated by using CPP. Namely, the actual collision occurs in  $AC_i$  when the backoff period of two or more stations of the same  $AC_i$  end simultaneously but no higher class station ends at the same time. Therefore, the collision probability is calculated as,

$$p_i = \left(1 - (1 - \tau_i)^{n_i-1}\right) \prod_h^{i-1} (1 - \tau_h)^{n_h}, \quad i \in (1, \dots, N) \quad (14)$$

Also, the virtual collision probability is computed as

$$q_i = 0, \quad q_i = (1 - (1 - \tau_i)^{n_i}) \left(1 - \prod_{h=1}^{i-1} (1 - \tau_h)^{n_h}\right), i \in (1, \dots, N) \quad (15)$$

Equation (13), (14), and (15) form a nonlinear system with the same number of variables and equations. This system can be solved by utilizing a numerical method which has a unique solution in the range of  $\tau_i, p_i, q_i \in [0, 1]$  for  $i \in (1, \dots, N)$ .

### 3. Throughput analysis

Let the probability  $p_{S,i}$  and  $p_{C,i}$  be successful transmission and collision probability of  $AC_i$  respectively. Also, let  $p_b$  be the busy channel probability. Then, we have

$$p_{S,i} = n_i \tau_i (1 - \tau_i)^{n_i - 1} \prod_{h=0}^{i-1} (1 - \tau_h)^{n_h}, \quad i \in (1, \dots, N) \quad (16)$$

$$p_{C,i} = \frac{n_i(n_i - 1)}{2} \tau_i^2 (1 - \tau_i)^{n_i - 2} \prod_{h=0}^{i-1} (1 - \tau_h)^{n_h}, \quad i \in (1, \dots, N) \quad (17)$$

$$p_b = \sum_{i=1}^{N-1} (p_{S,i} + p_{C,i}), \quad i \in (1, \dots, N) \quad (18)$$

Let  $S_i$  denote the normalized throughput of  $AC_i$ . Then the throughput  $S_i$  is given as follows.

$$S_i = \frac{E(\text{payload transmission time in a slot time for the class } i)}{E(\text{length of a slot time})} \\ = \frac{p_{S,i} T_{E(L)}}{(1 - p_b) \delta + \sum_{i=0}^{N-1} (p_{S,i} T_{S,i} + p_{C,i} T_{C,i})}, \quad i \in (1, \dots, N) \quad (19)$$

$\delta, T_{E(L)}, T_{S,i}$ , and  $T_{C,i}$  in the above equation denote the duration of empty timeslot, the

time to transmit an average payload, the average transmission time of  $AC_i$ , and the average collision time of  $AC_i$ , respectively.

$T_{S,i}$  and  $T_{C,i}$  are calculated as

$$\begin{cases} T_{S,i} = H + T_{E(L)} + SIFS + ACK + AIFS_i \\ T_{C,i} = H + T_{E(L)} + SIFS + ACK + AIFS_i + (i+1)\delta, \quad i \in (2, \dots, N) \end{cases} \quad (20)$$

$$\begin{cases} T_{C,1} = H + T_{E(L^*)} + E(IFS) \\ T_{C,i} = H + T_{E(L^*)} + E(IFS) + E(N_{i, \text{retry}}) \delta, \quad i \in (2, \dots, N) \end{cases} \quad (21)$$

If a transmission successfully ends (or collides),  $T_{S,i}$  (or  $T_{C,i}$ ) requires extra time to process CPP compared to EDCA model. To get the average collision time, we need to know the average number of retries,  $E(N_{i, \text{retry}})$ , which is given as

$$E[N_{i, \text{retry}}] = \sum_{j=0}^{R_i} \frac{j(p_i + q_i)^j (1 - p_i - q_i)}{1 - (p_i + q_i)^{R_i + 1}}, \quad i \in (1, \dots, N) \quad (22)$$

## V. Numerical Results

We examine system performance through two scenarios. Scenario 1 illustrates throughput variation by increasing the total number of stations from one to 40. Each station generates traffics in four different classes. Scenario 2 illustrates throughput variation by increasing the number of stations of one class. We fix the total number of stations in the system to 60 which is considered to be sufficiently saturated. The computational result is based on IEEE 802.11b [14] and IEEE 802.11e

Table 1 Simulation parameters for IEEE 802.11b

Parameter	Value
SIFS	10 $\mu$ sec
DIFS	50 $\mu$ sec
Slot time	20 $\mu$ sec
aPreambleLength	144 $\mu$ sec
aPLCPHeaderLength	48 $\mu$ sec
SIFS	10 $\mu$ sec
Data transmission	11 Mbps
ACK transmission	2 Mbps
aCWmin	64
aCWmax	256
Retry limits	{4, 7, 10, 14}

Table 2 EDCA Parameter settings

Access	$CW_{min}$	$CW_{max}$	AIFSN
AC_BK ( $AC_4$ )	aCWmin	aCWmax	7
AC_BE ( $AC_3$ )	aCWmin	aCWmax	3
AC_VI ( $AC_2$ )	aCWmin/2	aCWmin	2
AC_VO ( $AC_1$ )	aCWmin/4	aCWmin/2	2

standard [2]. The parameters are shown in Table 1 and 2. To compare the performance, IEEE 802.11e EDCA and ICP are solved with MATLAB programmed numerical method, which is executed at 3.0 GHz CPU.

Figure 6 shows the result of Scenario 1. The throughput given by IEEE 802.11e EDCA is also compared with ICP. The figure shows the improvement of total throughput by the ICP model through intraclass collision elimination. The increase of total throughput is more than doubled when the number of stations in each class exceeds 20. Figure 7

shows the difference of collision probability between EDCA and ICP. The collision probability by ICP is reduced by more than 20% as the channel congestion increases. Figure 6 and 7 clearly show that total throughput and collision probability are closely related and they are inversely proportional. In ICP, the most portion of throughput improvement is contributed by  $AC_1$ . It is because ICP provides higher priority to the highest class when virtual collision occurs. Another important point proven by the figures is that the throughput

improvement of  $AC_1$  does not degrade that of the lower class.

Figure 8 and 9 illustrate Scenario 2. All figures show total throughput improvement of ICP compared to EDCA. A large portion of total throughput improvement occurs in  $AC_1$  while the throughput of other classes maintains the level of EDCA. It is because ICP enhances system performance by eliminating interclass collision and provides more priority to  $AC_1$  than other classes.

Figure 8 shows an increase in the number of stations of  $AC_1$  while the total number of stations is fixed at 60. The number of stations of  $AC_1$  ranges [3, 57] as multiples of three. In each case the remaining stations are equally distributed into three other classes. In the Figure, when the number of stations of  $AC_1$  is smaller than 10, the throughput of  $AC_1$  increases with the number of  $AC_1$  stations, but the total throughput is decreased by the loss of lower class throughputs. When the number of  $AC_1$  stations is greater than 10, total throughput is decreased by excessive

congestion. Moreover, throughput in Figure 8 is not better than that in Figure 6, even if the total number of stations in Figure 8 is smaller than Figure 6. The reason is that the increase of collision and virtual collision is seriously affected by the number of stations of  $AC_1$  rather than the total number of stations. It is also related to the contention window size in Table 2, the contention window size of  $AC_1$  is the smallest. A small contention window size guarantees large transmission opportunity, but causes extra collisions when the number of  $AC_1$  stations increases.

Figure 9 shows an increase in the number of stations of  $AC_2$  while the total number of stations is fixed at 60. Differently from Figure 8 total throughput in Figure 9 maintains almost same level. In the figure, throughput of  $AC_1$  by ICP and EDCA shows different movements. In ICP, when  $AC_2$  is smaller than 45, the throughput maintains about 0.35 regardless of the change in the number of stations, whereas, throughput of EDCA is decreased according to the

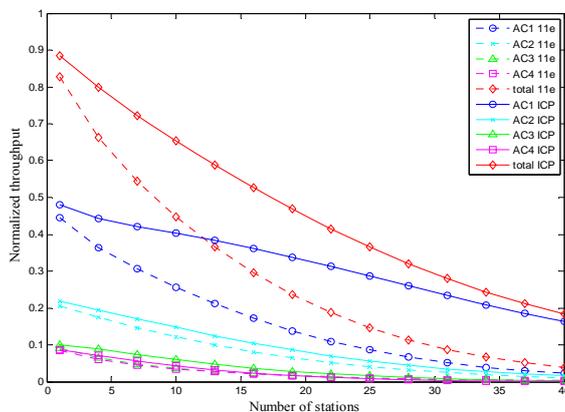


Figure 6 Normalized throughput

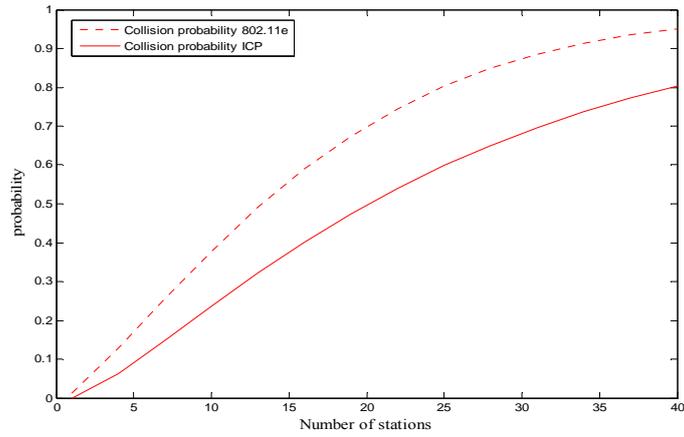


Figure 7 Collision probability

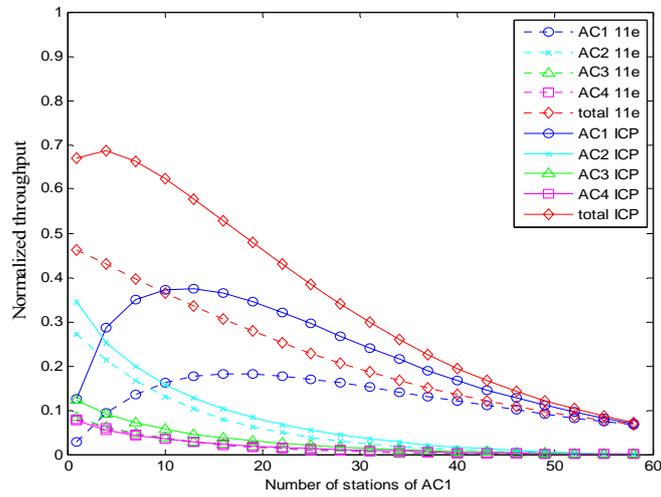


Figure 8 Throughput variation by change of  $AC_1$

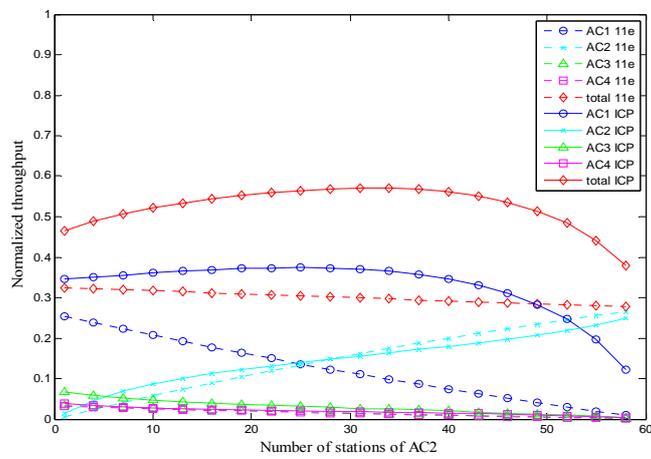


Figure 9 Throughput variation by change of  $AC_2$

increasing number of stations of  $AC_2$ . It is because ICP provides the highest class with more priority to transmit than EDCA.

## VI. Conclusion

In this paper, we have proposed a novel distributed contention-based MAC based on IEEE 802.11e and analyzed the model through analytical model. To eliminate interclass collision, we have proposed the collision protection period. When backoff period of two or more interclass stations finish simultaneously, the highest station transmits and the others wait until the next idle period. We have made an analytical model of ICP and compared it with IEEE 802.11e EDCA. The numerical results show that the ICP model can provide better performance compared to the existing EDCA model.

The proposed collision protection scheme based on the orthogonal backoff signals increases overall throughput without degrading the performance of lower classes. The increase of throughput by the proposed ICP model is more than doubled compared to the EDCA model, when the number of stations in each class exceeds 20. Also, the collision probability by ICP is reduced by more than 20% as the channel congestion increases.

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