Carrier Sense Multiple Access with Collision Resolution

Hyun-Ho Choi, *Member, IEEE*, Jung-Min Moon, *Student Member, IEEE*, In-Ho Lee, *Member, IEEE*, and Howon Lee, *Member, IEEE*

***Abstract*—We propose a distributed medium access control (MAC) protocol called carrier sense multiple access with collision resolution (CSMA/CR) by extending the wireless CSMA/CD protocol. The proposed CSMA/CR protocol identifies a collision by additional sensing after data transmission starts. If one station detects a collision, it transmits a jam signal to stop the other stations' transmissions and then retransmits the data without backoff, which resolves the next collision that may occur. The throughput analysis shows that the proposed CSMA/CR protocol outperforms other conventional CSMA-based MAC protocols.**

***Index Terms*—Carrier sense multiple access (CSMA), collision avoidance, collision detection, collision resolution.**

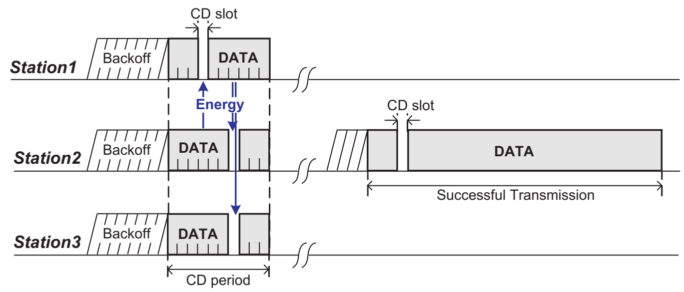

Fig. 1. Operation of WCSMA/CD.

I. Introduction

IN THE carrier sense multiple access with collision detection (CSMA/CD) protocol, a transmitting station can detect a collision while transmitting a data frame by comparing the transmitted signal level with the received one. The station that detects the collision transmits a jam signal to inform the other stations that they must stop transmitting. This terminates the transmission as soon as the collision is detected; thus, the time required before a retry shortens and the CSMA performance significantly improves [1]. However, the CSMA/CD protocol is only possible in a wired network. In a wireless network, it is impossible to simultaneously sense the channel while transmitting because the receiver of the transmitting station is overwhelmed by its own transmission power (a.k.a., deafness problem).

Despite the deafness problem, in order to achieve the performance gain, the wireless CSMA/CD (WCSMA/CD) protocol has been proposed in [2] and references therein. The WCSMA/CD protocol enables the collision detection in a fully connected single-hop network environment (i.e., the topology of complete graph). Its operation is depicted in Fig. 1. Each station allocates a short CD slot randomly within a fixed CD period after starting data transmission and senses the channel at the selected CD slot to determine whether a collision occurs or not. The collision is detectable if all the colliding stations do not choose the same CD slot. If a station perceives a higher energy level than the threshold during the CD slot, it aborts its transmission after the CD period ends and tries again after a random backoff time. Otherwise, the station continues data transmission and successfully completes it.

In the future, everything in the human living space will have wireless capability and this will increase the node density per unit area [3]. Numerous wireless devices will increase access collisions. However, the typical CSMA with collision avoidance (CSMA/CA) protocol is very vulnerable to the collision. Although the CSMA/CA using a ready-to-send (RTS) and clear-to-send (CTS) option can reserve the channel and transmit the data frame without collision, its added overhead for an RTS/CTS transmission modulated with the lowest rate is not negligible, especially at a high data transmission rate [4], [5]. Moreover, the RTS/CTS-based CSMA/CA protocol solves the hidden and exposed node problems, but a number of commercial WLAN applications seldom encounter such problems because they are generally used for wireless access in a small cell by assigning an orthogonal channel not used in adjacent cells or used for direct communication between nodes within a visible range [2]. Furthermore, the lower frequency-based WLAN standards of IEEE 802.11af using TV white spaces [6] and IEEE 802.11ah using sub-1-GHz bands [7] are in progress to offer one-hop coverage among stations within a cell. In such environments, it is realistically expected that every station has a single-hop distance and forms a fully connected network in either infrastructure or ad hoc mode.

In this letter, we propose a distributed medium access control (MAC) protocol by extending the WCSMA/CD protocol. Unlike the WCSMA/CD protocol, one station that first detects a collision transmits a jam signal and the other stations that recognize this jam signal immediately stop their ongoing transmissions, analogous to the original CSMA/CD protocol. In addition, the first collision-detecting station that transmits the jam signal during a predetermined period is allowed to retransmit its data without the backoff procedure and the other stations automatically defer accessing. This ensures a successful transmission for the retransmission after

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H.-H. Choi, I.-H. Lee, and H. Lee (corresponding author) are with the Department of Electrical, Electronic, and Control Engineering, and the Institute for Information Technology Convergence, Hankyong National University, Anseong 456-749, Korea (e-mail: {hhchoi, ihlee, hwlee}@knuu.ac.kr).

J.-M. Moon is with the Department of Electrical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 305-701, Korea (e-mail: jmmoon@comis.kaist.ac.kr).

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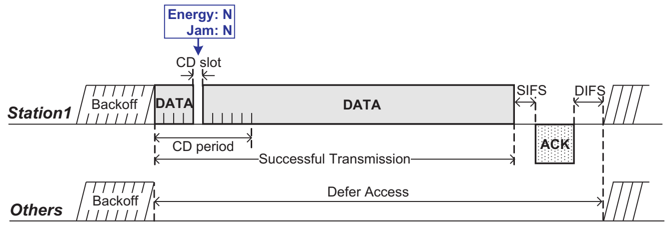


Fig. 2. Operation of CSMA/CR when no collision occurs.

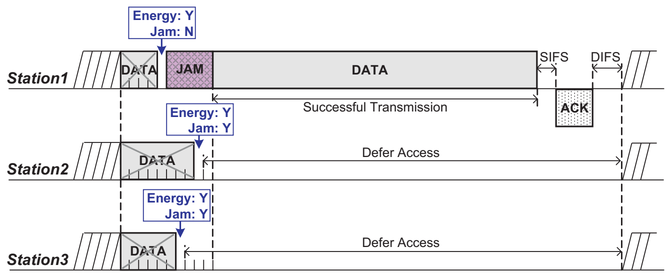


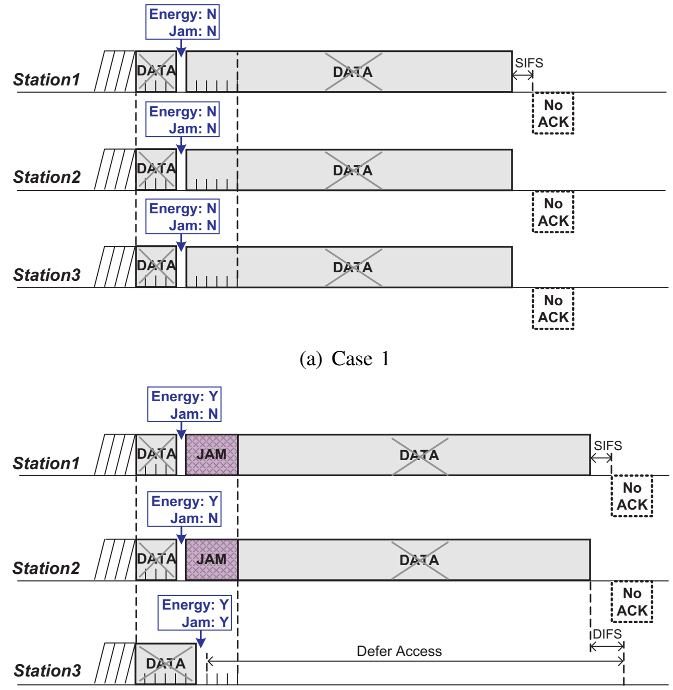
Fig. 3. Operation of CSMA/CR when a collision is detected.

a collision is detected, which is a key feature of the proposed MAC protocol. Therefore, we name it *CSMA with collision resolution (CSMA/CR)*.

II. CSMA/CR Protocol

Fig. 2 shows the operation of CSMA/CR protocol when no collision occurs. This operation is the same as that of WCSMA/CD. If the channel is idle, the station starts a data transmission, selects a CD slot randomly within the fixed CD period, and senses once again at the selected CD slot. When no collision occurs, neither energy nor a jam signal are detected. So, the station continues its data transmission and receives the acknowledgement (ACK) frame from its receiver. Here, the length of the CD period is the predetermined parameter and is set equally in all stations. The length of the CD slot should be shorter than the distributed inter-frame space (DIFS) in order that other stations do not intervene during a CD slot. The CD slot should also be longer than the time required for Tx/Rx and Rx/Tx switching and the jam signal sensing, which corresponds to the implementation issue. Furthermore, at the first slot in the CD period, the preamble and the information of the selected CD slot number should be transmitted to ensure the synchronization and the data integrity at the receiving side.

Fig. 3 shows the operation of the CSMA/CR protocol when a collision is detected and the transmission is successful. Simultaneously accessing stations select a CD slot randomly within the CD period and sense the channel at the selected CD slot. The station that selects the earliest CD slot (i.e., Station 1) can detect the energy but not the jam signal. This station is the first station that detects the collision and so transmits the jam signal instead of the data during the remaining CD period. As a result, the other stations that select a later CD slot can detect both the energy and the jam signal, and this makes their on-going transmissions stop immediately. If the CD period ends, only the station that has transmitted the jam signal retransmits its data promptly without backoff. The other



(a) Case 1

(b) Case 2

Fig. 4. Operations of CSMA/CR in two cases that a collision is not detected.

stations automatically defer accessing and perform the backoff procedure.

Fig. 4 shows the operation of the CSMA/CR protocol in two cases in which a collision is not detected and the transmissions fail. In the first case, all stations select the same CD slot, so they do not detect the energy and continue their transmissions. This leads to the failure of all transmissions. In the second case, two or more stations select the same earliest CD slot. Thus, they detect only the energy and so transmit the jam signal and retransmit their data frames simultaneously, which also leads to a transmission failure.[1] When the transmission fails, the transmitter identifies it by receiving no ACK and then retries after backoff.

III. Implementation Issue

We need to consider how to design the jam signal and decide the length of the CD slot for its reliable detection. The IEEE 802.11 standard specifies the clear channel assessment (CCA) method. This judges that the channel is busy through a energy sensing or a carrier sensing or both [9]. Here, the carrier sensing detects a carrier signal with a specific pattern, such as the preamble in the physical (PHY) layer or the direct sequence spread spectrum (DSSS) signal in the DSSS mode. Considering this CCA method, the 802.11 standard presents a required CCA time ($aCCATime$) and defines a slot time ($aSlotTime$) as a basic time unit required for the channel sensing and accessing, as follows:

$$\begin{aligned} aSlotTime = {} & aCCATime + aRxTxTurnaroundTime \\ & + aAirPropagationTime + aMACProcessingDelay \quad (1) \end{aligned}$$

[1] In this case, the station selecting the later CD slot (i.e., Station 3) detects the overlapped jam signal. Because an overlapped signal with the same pattern is detectable in general [8], it can stop the transmission.

where $aRxTxTurnaroundTime$ is the maximum time that the PHY requires to change from receiving to transmitting, $aAirPropagationTime$ is the maximum propagation time for a signal to travel between two stations at the maximum distance within the network, and $aMACProcessingDelay$ is the maximum time required for the MAC to issue a request primitive to the PHY.

For the CSMA/CR protocol, we can design the jam signal pattern similar to but distinguishable from the preamble in the IEEE 802.11 standard. Then, it is possible to detect this jam signal within $aCCATime$. However, the CSMA/CR protocol needs a Tx-Rx-Tx transition for sensing in the middle of transmission. To perform this, a Tx/Rx turnaround time should be added to the basic slot time. Thus, the required minimum length of CD slot becomes $aSlotTime + aTxRxTurnaroundTime$. Moreover, the length of CD slot must be shorter than the DIFS time, which is defined as $TxSIFS + 2 \cdot aSlotTime$. Therefore, a CD slot time ($aCDSlotTime$) should satisfy

$$\begin{aligned} & aSlotTime + aTxRxTurnaroundTime \\ & \leq aCDSlotTime < TxSIFS + 2 \cdot aSlotTime. \end{aligned} \tag{2}$$

IV. Throughput Analysis

Let n be the number of contending stations and let m be the number of available CD slots. From the Bianchi's CSMA/CA analysis [10], we derive the probability τ that a station transmits in a generic slot time. Then, the probability P_{tr} that in a slot time there is at least one transmission, given n contending stations, is readily obtained as

$$P_{tr} = 1 - (1-\tau)^n. \tag{3}$$

The probability P_s that a transmission is successful, i.e., the probability that only one station tries to access, is obtained as

$$P_s = \frac{\binom{n}{1}\tau^1(1-\tau)^{n-1}}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n}. \tag{4}$$

Moreover, the probability $P_c(i)$ that transmission is collided as i stations among the total n stations access simultaneously is given by

$$P_c(i) = \frac{\binom{n}{i}\tau^i(1-\tau)^{n-i}}{P_{tr}} = \frac{\binom{n}{i}\tau^i(1-\tau)^{n-i}}{1-(1-\tau)^n},\ i = 2, 3, \cdots, n. \tag{5}$$

Therefore, when there is at least one transmission, the collision probability of CSMA/CA is given by

$$P_c^{ca} = \sum_{i=2}^{n} P_c(i) = 1 - P_s. \tag{6}$$

The collision in the WCSMA/CD protocol occurs when all i stations accessing simultaneously select the same CD slot among the total m slots, as shown in Fig. 4(a). This collision probability is obtained as

$$P_c^{cd}(i) = m \cdot \left(\frac{1}{m}\right)^i = m^{(1-i)}, \quad i = 2, 3, \cdots, n. \tag{7}$$

So, the collision probability of WCSMA/CD is expressed as

$$P_c^{cd} = \sum_{i=2}^{n} P_c(i) P_c^{cd}(i). \tag{8}$$

Now the collision detection probability of WCSMA/CD is obtained as

$$P_d^{cd} = 1 - P_s - P_c^{cd}. \tag{9}$$

On the other hand, the collision in the CSMA/CR protocol occurs when j with $j > 1$ stations among i stations accessing simultaneously select the same earliest CD slot among the total m slots, as shown in Fig. 4. This collision probability is calculated as

$$P_c^{cr}(i) = \frac{\sum_{j=2}^{i}\sum_{k=1}^{m}\binom{i}{j}(m-k)^{(i-j)}}{m^i}, \quad i = 2, 3, \cdots, n. \tag{10}$$

Therefore, the collision probability of CSMA/CR is given by

$$P_c^{cr} = \sum_{i=2}^{n} P_c(i) P_c^{cr}(i). \tag{11}$$

Moreover, from (8) and (11), the collision probabilities of the first and second cases in Fig. 4 are respectively given by

$$P_{c1}^{cr} = P_c^{cd}, \tag{12}$$

$$P_{c2}^{cr} = P_c^{cr} - P_c^{cd}. \tag{13}$$

Finally, the collision resolution probability of CSMA/CR is given by

$$P_r^{cr} = 1 - P_s - P_c^{cr}. \tag{14}$$

Let Ψ be the random variable representing the number of consecutive idle slots between two consecutive transmissions on the channel. It is given by

$$E[\Psi] = \sum_{k=1}^{\infty}(1-P_{tr})^k = \frac{1}{P_{tr}} - 1. \tag{15}$$

The normalized system throughput, S is defined as the fraction of time the channel is used to successfully transmit payload bits, as follows: [10]

$$S = \frac{E[\text{time used for successful transmission in interval}]}{E[\text{length of a renewal interval}]}. \tag{16}$$

Then, the throughput of CSMA/CA is expressed as

$$S_{ca} = \frac{P_s E[P]}{E[\Psi] + P_s T_s + P_c^{ca} T_c} \tag{17}$$

where $E[P]$ is the average packet length, T_s is the average time the channel is busy because of a successful transmission, and T_c is the average time the channel is busy due to a collision. The times $E[P]$, T_s and T_c must be measured in slot times, as this is the time unit of $E[\Psi]$. In the basic and RTS/CTS-based CSMA/CA schemes, T_s and T_c are respectively described as

$$T_s^{bas} = H + E[P] + SIFS + \delta + ACK + DIFS + \delta \tag{18}$$

$$T_c^{bas} = H + E[P^*] + DIFS + \delta \tag{19}$$

$$\begin{aligned} T_s^{rts} = {} & RTS + SIFS + \delta + CTS + SIFS + \delta + H \\ & + E[P] + SIFS + \delta + ACK + DIFS + \delta \end{aligned} \tag{20}$$

$$T_c^{rts} = RTS + DIFS + \delta \tag{21}$$

where H is the packet header given by $H = PHY_{hdr} + MAC_{hdr}$, δ is the propagation time, and $E[P^*]$ is the average length of the longest packet payload involved in a collision.

TABLE I
PARAMETER SETUP

PHY mode	FH (frequency hopping)
MAC header	272 bits
PHY header	128 bits
ACK length	112 bits + PHY header
RTS length	160 bits + PHY header
CTS length	112 bits + PHY header
Channel bit rate	1 Mbps
Propagation time	1 μs
SIFS	28 μs
Slot time	50 μs
DIFS	128 μs
RxTx/TxRx turnaround time	20 μs
CD slot time	70 μs
Mininum/Maximum CW size	31 / 255
Payload size	512 bytes

Similarly, the throughput of WCSMA/CD is expressed as

$$S_{cd} = \frac{P_s E[P]}{E[\Psi] + P_s T_s^{cd} + P_c^{cd} T_c^{cd} + P_d^{cd} T_d^{cd}} \quad (22)$$

where

$$T_s^{cd} = T_s^{bas} + CDS \quad (23)$$
$$T_c^{cd} = T_c^{bas} + CDS \quad (24)$$
$$T_d^{cd} = CDP = (m+1)CDS \quad (25)$$

where CDS is the length of CD slot and CDP is the length of CD period. Here, CDP is given by $(m+1)CDS$ because the first slot in the CD period cannot be used for sensing. In the same way, the throughput of CSMA/CR is described as

$$S_{cr} = \frac{(P_s + P_r^{cr})E[P]}{E[\Psi] + P_s T_s^{cr} + P_{c1}^{cr} T_{c1}^{cr} + P_{c2}^{cr} T_{c2}^{cr} + P_r^{cr} T_r^{cr}} \quad (26)$$

where

$$T_s^{cr} = T_s^{bas} + CDS \quad (27)$$
$$T_{c1}^{cr} = T_c^{bas} + CDS \quad (28)$$
$$T_{c2}^{cr} = T_c^{bas} + (m+1)CDS \quad (29)$$
$$T_r^{cr} = T_s^{bas} + (m+1)CDS. \quad (30)$$

Note that S_{cr} additionally contains the collision resolution probability P_r^{cr} in the numerator, unlike S_{ca} and S_{cd}.

V. RESULT AND DISCUSSION

Table I summarizes the used parameters. We mostly choose the same values used in [10]. In addition, we set that $aTxRxTurnaroundTime$ is equal to $aRxTxTurnaroundTime$ of the standard [9] and the CD slot time is $aSlotTime + aTxRxTurnaroundTime$ as discussed in Section III. Here, we assume that every station always has packets to be delivered and all packets have the same fixed size. We perform Monte Carlo simulations to validate the analysis.

Fig. 5 shows the normalized throughput versus the number of stations. The throughput of the basic CSMA/CA protocol sharply decreases with an increase in the number of stations because of the repeated collision and backoff. The RTS/CTS-based CSMA/CA protocol shows the lowest throughput at a small number of stations because of its RTS/CTS overhead; however, its throughput slightly decreases with an increase in the number of stations because of its reservation-based data transmission. The WCSMA/CD protocol generally outperforms the RTS/CTS scheme, but this is reversed in a large number of stations due to the increased collisions. The proposed CSMA/CR shows better throughput than the other schemes due to its collision resolution mechanism. The throughputs of both the WCSMA/CD and CSMA/CR protocols are affected by the number of available CD slots (m). We could numerically find the optimal value of m that maximizes the throughput according to the number of stations. Compared the optimal m with an appropriate fixed m (e.g., m = 10), there is little performance degradation. This implies that we can appropriately choose a fixed value of m, which approaches the achievable throughput.

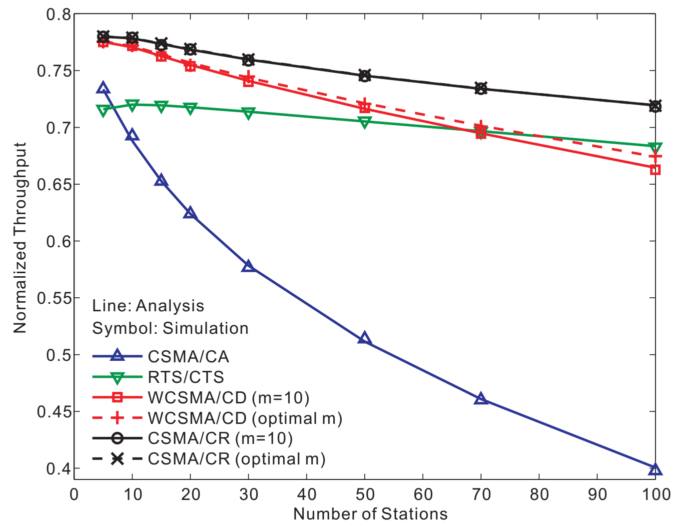


Fig. 5. Normalized throughput vs. number of stations.

VI. CONCLUSION

We proposed a new CSMA/CR protocol that realizes the function of collision resolution by transmitting a jam signal when a collision is detected. In view of its compatibility, practicality, and performance improvement, we expect that the CSMA/CR protocol can be applied to future WLAN systems although it increases complexity at the transmitter.

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