Doctoral Dissertation

Reservation-based MAC Protocol for Crowded Wireless LAN using Full-Duplex Radio

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밀집된 환경에서 전이중라디오를 사용하는 무선랜을 위한 예약기반의 매체 접근 제어 프로토콜에 관한 연구

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by

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The undersigned have examined this dissertation and hereby certify that it is worthy of acceptance for a doctoral degree from POSTECH

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ABSTRACT

Recently, the number of stations using Wireless Local Area Networks(WLAN) is increasing rapidly and the usage of WLAN traffic per station is also increased. It means that an access point (AP) associates with the number of stations. Because conventional WLAN is not designed for these densely crowded WLAN, when the stations using WLAN are densely deployed, performance is degraded seriously. To solve the performance degradation, several researches are proposed for conventional WLAN. Nowadays, researches trying to employ new physical technologies such as directional antenna, Orthogonal Frequency Division Multiplexing Access (OFDMA) and full-duplex radio technology are now in progress to improve throughput of WLAN. Especially, in-band simultaneous transmission between an AP and a device was enabled by recent full-duplex radio communication research. Because, in theoretically, full-duplex radio technology may double the throughput of half-duplex radio, we expected full-duplex radio communication to be an appropriate technology to solve throughput degradation of WLAN.

While this event was expected to increase throughput within the feasibility of full-duplex radio communication, the conventional Medium Access Control (MAC) protocol as Distributed Coordination Function (DCF) for WLAN limits the performance enhancement. Each station competes for transmission opportunities because DCF is based on half-duplex communication principles. Although DCF offers fair opportunities for stations through the competition, the competition among stations and an AP creates excessive overhead and many collisions. The characteristics of DCF lead throughput degradation seriously as the number of devices increases.

In this dissertation, we suggest a MAC protocol called Reservation-Based Medium-Access Control (RMAC) based on station reservation in WLAN with full-duplex radio. In particular, RMAC protocol is targeted at densely deployed stations and heavy traffic stations which means that devices try to uplink (send a frame from station to AP) frequently. RMAC is designed to be backward compatible with DCF because RMAC does not require any modification of legacy devices. RMAC decreases collisions by reducing the number of competing stations and increases throughput by reducing competition overhead. Our RMAC assures stations a transmission opportunity without collision if a station has several packets to send. We show that RMAC achieves at least 86.3% more throughput than full-duplex radio based on DCF. The RMAC protocol also maintains high throughput even in cases of dense station deployment.

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I. Introduction

1.1 Backgrounds

1.1.1 WLAN

Recently, the number of mobile stations using WLAN is increased rapidly such as laptop, smartphone, and tablet [1]. As shown in Fig. 1.1, it is predicted that the number of mobile stations is reached about 11.6 billion at 2021. In addition, as Internet of Things (IoT) which connects everything (i.e, refrigerator, TV, washing machine, etc.) through the internet is lately trend, it is easy to predict that more and more stations connect and communicate through WLAN (Fig. 1.2). As a result, the traffic of mobile data will be grown rapidly also. As increasing the mobile traffic, the traffic of WLAN is also increased because more than half perof mobile traffic. It means that the weight of WLAN is more important than that of before as time passed (Fig. 1.3). To cover the increased number of mobile stations and traffic demands, a WLAN with higher throuhput is needed.

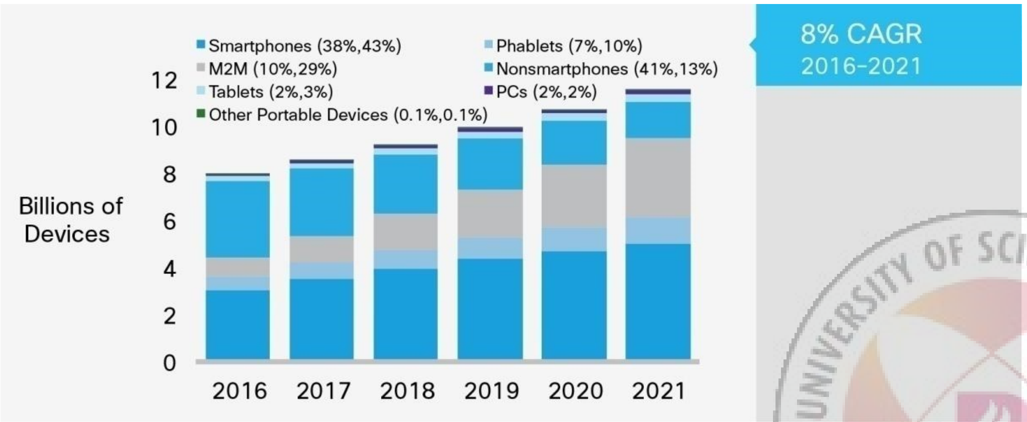


Figure 1.1: Global mobile devices and connections growth

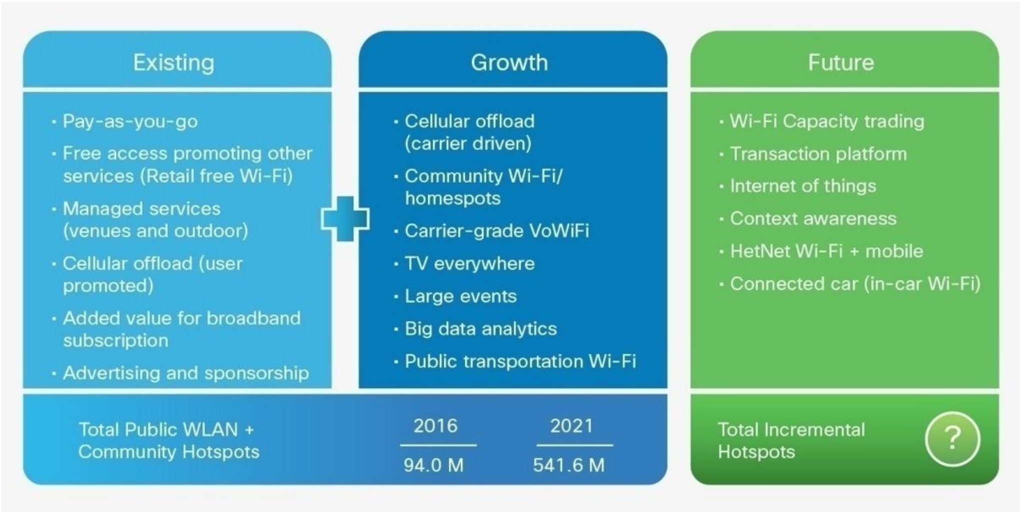


Figure 1.2: Global Wi-Fi hotspot strategy and 2016-2021 forecast

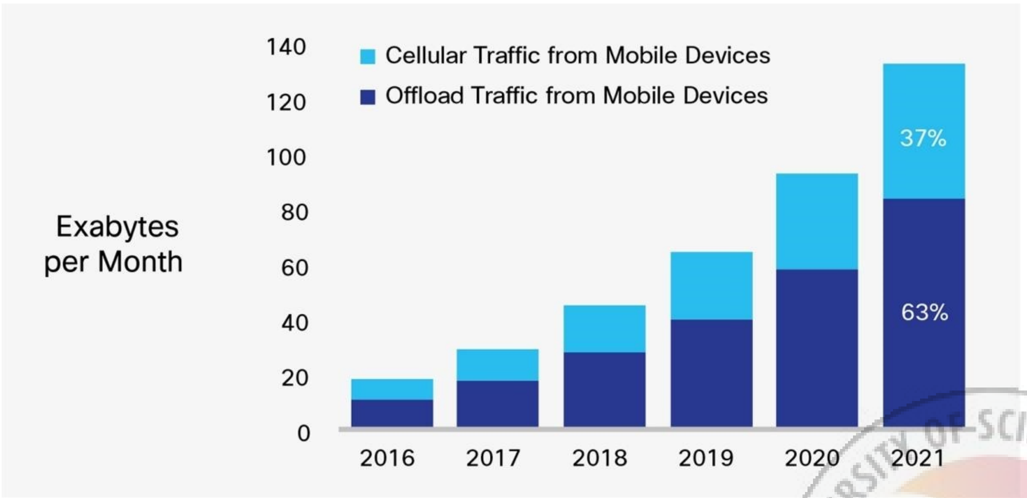


Figure 1.3: Percentage of offloaded traffic from total mobile data traffic

In general, one AP is associated with many stations; therefore, relatively, AP competes more frequently to get more transmission opportunities. However, nowadays, it is popularized using various applications such as video, cloud service, audio. VoIP and file sharing [2]. Especially, as shown in Fig. 1.4, some applications, such as peer-to-peer services (e.g., file sharing), VoIP (e.g., skype), and cloud storage (e.g., google drive) require more uplink transmission opportunities and have more uplink traffic volume [3]. VoIP or applications requiring short-interval and continuous transmission incur continuous station competition; therefore, the weight of uplink transmissions will increase to satisfy various application requirements. When the number of uplink transmission attempts increases, throughput seriously degrades because of the collision increment among stations. Therefore, new WLAN is needed to solve these problems.

The latest commercial standard for WLAN is IEEE 802.11ac [4]. In IEEE 802.11ac standard, as shown in Fig. 1.5, three factors (channel bandwidth, Data bits per subcarrier, number of spatial streams) were considered to improve WLAN throughput [5]. It means that IEEE 802.11ac mostly focused on the enhancement of physical data rate. Despite of improved physical data rate up to 6.8 Gbps with

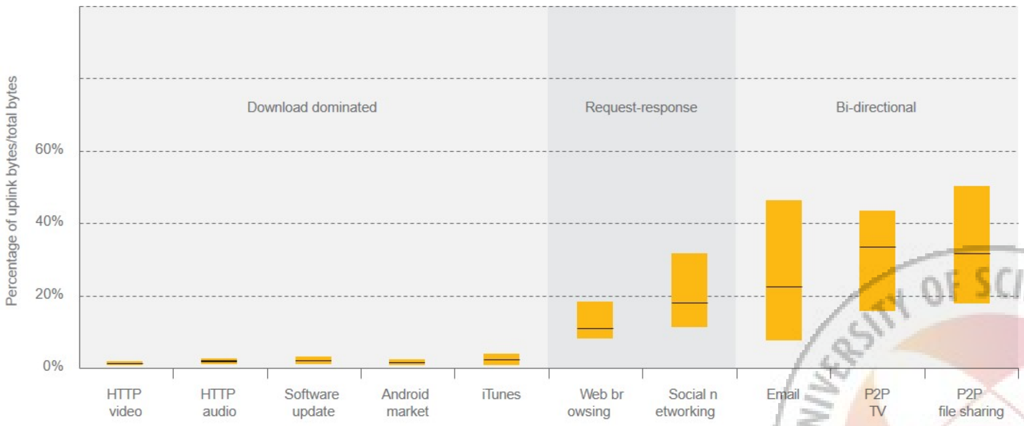


Figure 1.4: Ratio of uplink traffic volume for different applications

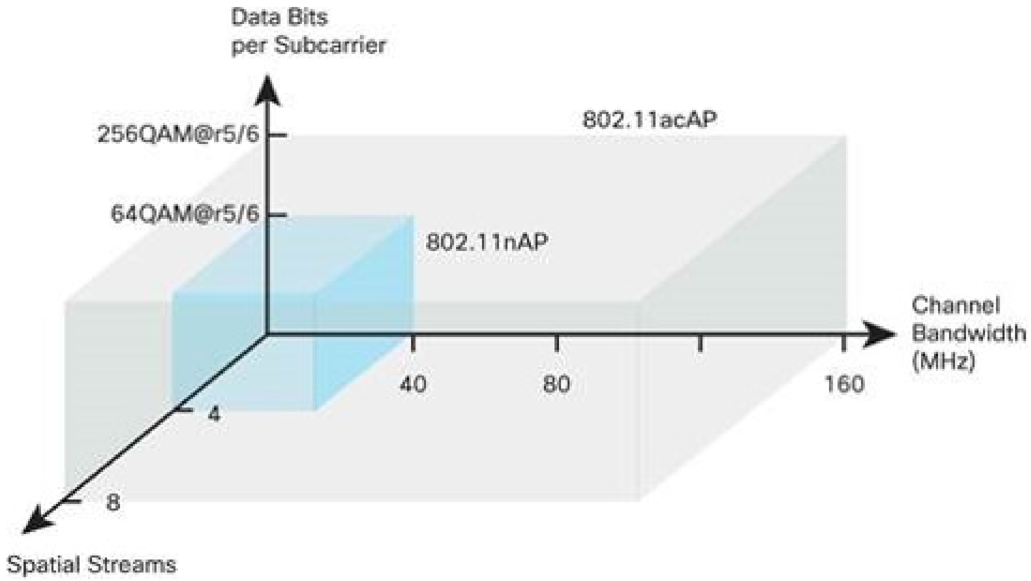


Figure 1.5: Three factors of direction of IEEE 802.11n/ac improvement

8×8 MIMO and 160 MHz bandwidth in IEEE 802.11ac standard, it cannot satisfy the demand of increased number of mobile stations and increased traffic because of legacy MAC protocol of WLAN.

The Task Group (TG) for a new WLAN standard IEEE 802.11ax called as high efficiency WLAN (HEW) is organized to accomodate latest requirements for WLAN. The goal of 802.11ax is throughput improvement when a number of stations are densely deployed [6]. However, because it is hard to achieve this goal with previous hardware, new physical technology which is orthogonal frequency divison multple access (OFDMA) is produced. Even if 802.11ax enhances the ability of multiple communication by allowing sending or receiving packet with OFDMA technology, because of constraints to use OFDMA and backward compatibility requirement [7], it is hard to enhance throughput drastically; therefore, we expected full-duplx radio which is realized technology recently [8] to be a new approach for WLAN enhancement because simultaneous sending and receiving are allowed in full-duplex radio.

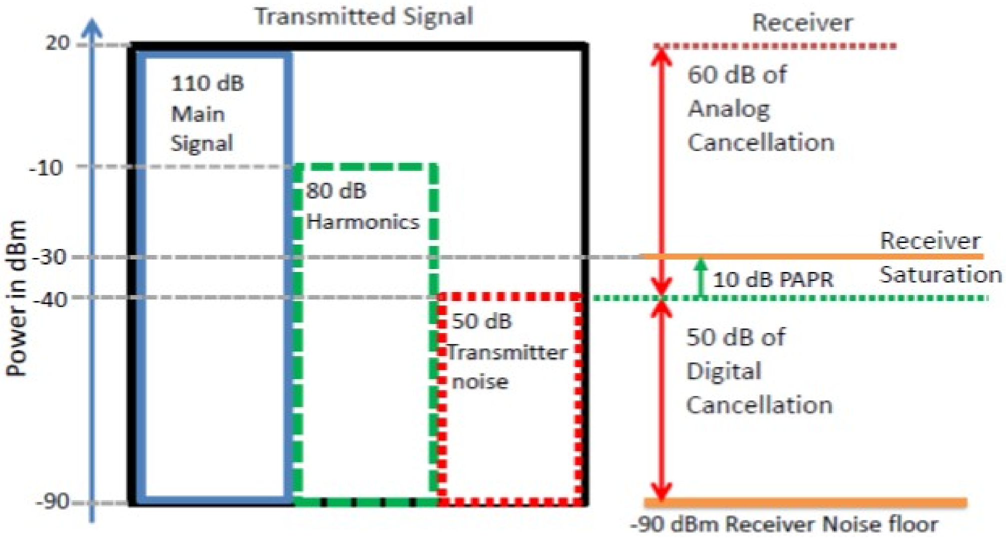


Figure 1.6: Cancellation technology of transmitted signal

1.1.2 Full-duplex radio

In full-duplex radio, because it enables simultaneous transmission and reception, full-duplex radio doubles the throughput of the half-duplex radio theoretically; therefore, several researches had proposed to reallize full-duplex technology [9, 10] enabling simultaneous transmission and reception. To enbale full-duplex radio technology, the full-duplex radio eliminates its own transmission signal from the received signal. Self-Interference Cancellation (SIC) which is recently introduced [8] is developed to enable in-band full-duplex radio technology. As shown in Fig. 1.6, SIC is consisting of analog cancellation and digital cancellation [8]. In digital cancellation, baseband signal T_b is utilized before converting analog signal, and converted analog signal is used to analog cancellation. Inversed analog signal which is generated by analog cancellation circuit offset the 60 dB of analog signal. The remainder 50 dB signal of analog cancellation is eliminated by digital cancellation. As a result, [8] obtained 110 dB cancellation (60 dB of analog cancellation and 50 dB of digital cancellation) for single antenna.

In recently, several enhanced full-duplex radio technologies have been proposed [11, 12, 13, 14] such as full-duplex MIMO and full-duplex applications in 5G. These researches show that full-duplex radio has possibility that to full-duplex radio can be applied to WLAN and other wireless communication devices.

1.2 Problem statement and research goals

In previous WLAN standards, stations are equipped with half-duplex radio. Because stations cannot transmit and receive simultaneously using half-duplex radio, WLAN stations need a channel access mechanism such as DCF [15]. DCF is based on the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) method and is a widely used MAC protocol in several wireless communication standards.

In DCF, to send a data packet, each station chooses the back-off number randomly in the interval [0, CW -1] where CW is contention window value from CW_{min} which is the initial value of CW (16 or 32, depends on IEEE 802.11 standard) to CW_{max} which is the maximum value of CW, 1024. This randomly generated back-off number reduces the collision probability. After choosing the back-off number, each station starts back-off procedure and performs carrier sensing to check whether the channel state is busy or idle. If the channel is idle for a duration called the DCF interframe space (DIFS), the back-off number is decremented by a slot time (9 μs). This procedure is halted and the back-off number is frozen when the channel is sensed to be busy. Station restarts back-off number decrement when the channel is idle during DIFS. Each station waits until the back-off number is zero then it transmits a data packet. If station fails to receive acknowledgement (ACK) corresponding its transmitted packet, it considers that the transmission is collided. After collision, to avoid consecutive collision, the station doubles CW until it reaches the CW_{max}. The station chooses new back-off number randomly in the interval [0, CW-1] and repeat back-off procedure to retransmit a packet. When the station receives ACK frame from receiver, it resets CW to CW_{min}. This procedure avoids collisions in a distributed manner by inducing different channel access time. Despite the collision avoidance mechanism,

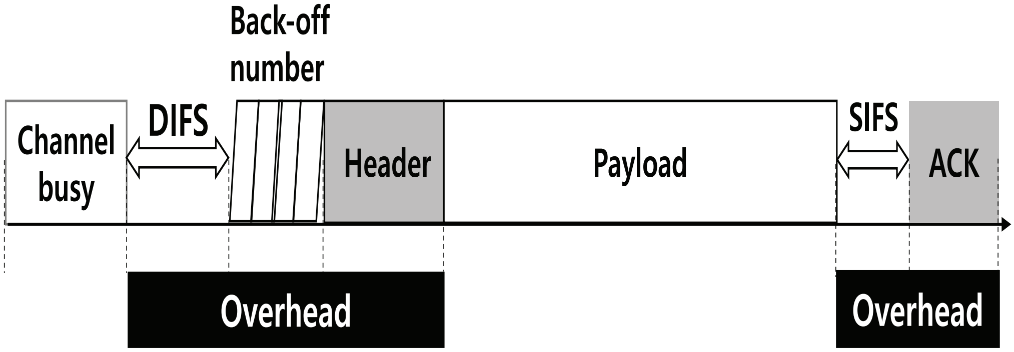


Figure 1.7: A schematic of DCF

DCF cannot assure communication without collisions because some stations may access the channel simultaneously. As the number of WLAN stations increases, the number of competing stations increases. As a result, the probability of simultaneous transmission among stations also increases. It means that when a number of stations are densely deployed in WLANs, the efficiency of DCF is degraded because the competition and collision probability among stations have increased [16, 17].

With in-band full-duplex radio, a station's ability to transmit and receive simultaneously not only improves throughput but also enables continued operation even when the stations are densely deployed. In addition, station transmission competition is halved during competition. Since competition among stations must be settled within a fixed time, the amount of competition becomes more important as the transmission rate increases. However, since DCF was designed for the half-duplex radio environment, it limits the performance enhancement of full-duplex radio; thus giving rise to the need for developing a new MAC protocol for full-duplex radio. Several MAC protocols have been proposed, but prior research [18, 19, 20, 21, 22] focused on full-duplex communications, especially asymmetric transmission as shown in Fig 1.8(b). We focused on full-duplex ra-

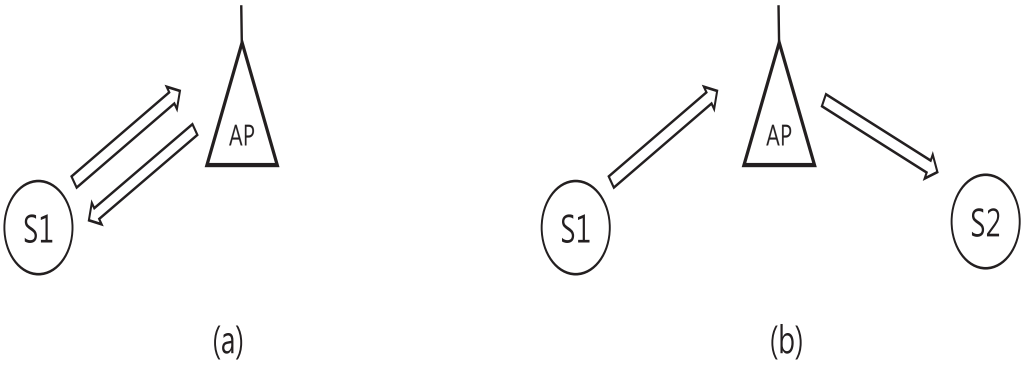


Figure 1.8: Full-duplex communication cases (a) bi-directional transmission (b) asymmetric transmission

dio applications to enhance transmission performance even if the stations were densely deployed because stations equipped for full-duplex radio can send and receive simultaneously on the same channel.

In this dissertation, in order to solve the inefficiency which occur when IEEE 802.11 DCF is applied for full-duplex WLAN, we propose a simple and efficient MAC protocol based on a reservation scheme for full-duplex WLANs. In our research, we choose the environment containing one AP with full-duplex radio and stations equipped with either full-duplex or half-duplex radio transmission capability. Our dissertation satisfies the three system problems of design, wasted computational time, and determinism to improve data throughput as described below.

1. Reduce waste time: Using full-duplex radio, our RMAC protocol reduces competition among stations to decrease collision probability even when stations are densely deployed. It has been proven that collision probability is affected by the number of stations [23, 24]. In our research, the number of stations vying for the right to transmit is decreased, so the competition time is reduced.

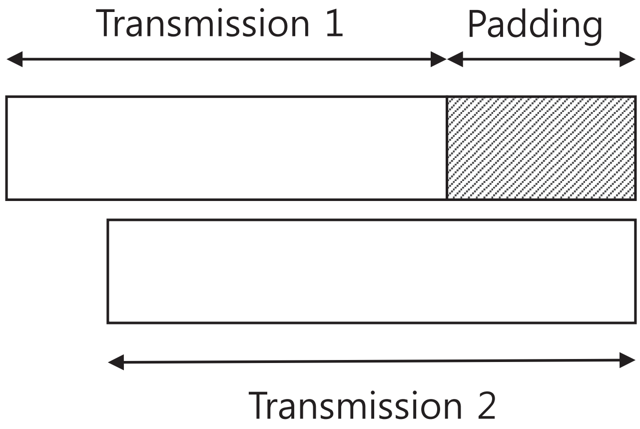


Figure 1.9: Padding transmission example for full-duplex radio

2. Deterministic full-duplex transmission: For full-duplex transmission to maximize its full-duplex radio performance, an AP needs to recognize with low overhead whether a station has a packet to send. In our research, we used a single bit contained in the MAC header for full-duplex transmission. With this, we support deterministic full-duplex transmission between an AP and a station.
3. Compatible design: Our proposed MAC protocol operates even when stations with full-duplex radio coexist with stations with half-duplex radio using DCF in the same network. Stations with half-duplex radio capability operate well without any modification.

To achieve the above goals, we had to make reasonable assumptions that can be applied in any practical environment.

1. Bi-directional transmission: As shown in Fig. 1.8, there are two types of full-duplex radio communication. Bi-directional transmission is an ideal transmission case because an AP and a station communicate without collisions during full-duplex transmission. In contrast, asymmetric transmission

can be applied more frequently in practical environments. However, to support asymmetric transmission, an AP must be able to identify the location of hidden stations. Despite this requirement, it is difficult to completely prevent collisions during full-duplex transmission. Since collisions degrade throughput, we considered bi-directional transmission only in our research.

2. Padding: If successive transmissions in either the downlink or uplink do not terminate simultaneously, then transmission padding is added to the shorter packet so that both packets terminate simultaneously as shown in Fig. 1.9.
3. Hidden station problem. We assumed that the problem of hidden stations was negligible because a full-duplex radio AP is able to detect hidden stations without any additional method (e.g., RTS/CTS) as depicted in Fig. 1.10.

Given the above assumptions, our RMAC achieves high throughput compared with the DCF technique based on both half-duplex radio and full-duplex radio.

The remainder of this dissertation is organized as follows. We briefly discuss related research in Section 2, our RMAC protocol design is described in Section 3, evaluation results are presented in Section 4, and conclusions in Section 5.

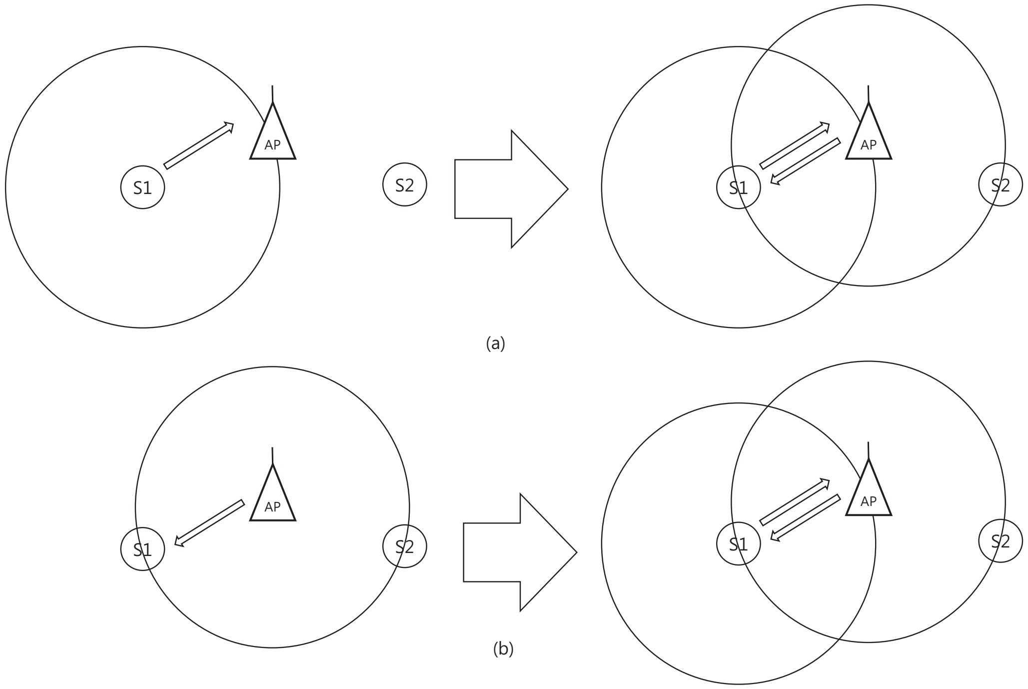


Figure 1.10: Principle of hidden node detection in full-duplex WLAN (a) uplink is the preceding transmission (b) downlink is the preceding transmission

II. Related Work

Most MAC protocols for full-duplex radio support asymmetric transmission. Because of the collision probability during asymmetric transmission, stations should be hidden during asymmetric transmission. In most schemes [19, 21, 22, 25], to realize asymmetric transmission, information exchange between an AP and a station is required. In this process, symmetric/asymmetric link is established. In [19], stations used a busy-tone signal during the time between reception of the MAC header and the data for information exchange. In [22], stations exchanged signatures before sending a packet. In [19, 22], it was important to synchronize stations to implement both time-sensitive schemes. In [21], stations used RTS and modified CTS (FCTS) to set link-establishments for both bi-directional and asymmetric transmission. Before sending a packet, stations (bi-directional and asymmetric) send an RTS or an FCTS signal. RTS/FCTS signals in [21] suppressed collisions during asymmetric transmission despite the RTS and FCTS exchange overhead. In [25], stations set link by composing of three consecutive contention rounds. During three contention rounds, stations operate step-by-step, then one link is established. In [26], it used two OFDM symbol time and OFDMA technology to exchange information and establish link. As described above, [19, 21, 22, 25, 26] are focused on link establishment for full-duplex communication.

In [27], full-duplex radio is used for collision detection. If the station employs full-duplex radio, then it can sense the signal during its own transmission. If the station senses the collided signal, it recognizes that other station is tranmitting now and stops its transmission. This process prevents long collision duration.

In [18, 20], the authors claimed that stations could decode by using a capture effect method. Using a capture effect method, when a station receives two colliding packets, it is able to decode the stronger packet of the colliding packets. In these schemes, stations use a modified RTS frame to report the signal-to-interference ratio (SIR) and make an SIR map for the establishment of asymmetrical dual links. With this information, an AP can determine whether a station receives a packet from the AP or is sending a packet to the AP.

In [28, 29], an orthogonal frequency division multiplexing (OFDM) subcarrier was used to solve the transmission inefficiency resulting from uneven packet sizes between the uplink and downlink. This scheme supports asymmetric transmission without information exchange for finding hidden stations. By using an OFDM subcarrier, stations receiving a packet from an AP can recognize collisions. Although this scheme offers additional transmission opportunities, when the stations are densely deployed, throughput improvement is limited.

In [30], Janus, an AP-based MAC protocol with reservation like our RMAC, was employed. Janus consists of three phases. In Phase 1, the scheduling preparation period, an AP queries all stations to determine whether they have packets to send. After gathering information from stations, the AP schedules the transmission sequence and transmission time for stations and then broadcasts a scheduling packet containing the schedule information. In Phase 2, the AP and stations exchange packets by following the AP schedule. In this period, asymmetric transmission is allowed because the AP has scheduled and notified all stations as to when they are to start sending a packet. In Phase 3, the AP and stations transmit a Request Acknowledgement (RA) and ACK during packet-exchange period. Since the AP is centralized, the Janus protocol supports asymmetric transmission with efficient performance, however, it has limitations. First, the Janus protocol requires excessive overhead because an AP must gather information packets from all candidate stations. In addition, the AP schedules stations efficiently, even if the transmissions of stations are overlapped. This requires a highly complex AP. Also, as the number of stations increases, the information gathering and scheduling time increases. Second, since Janus is a full-duplex MAC protocol, it is not compatible with the half-duplex DCF technique. Our RMAC, however, not only minimizes the information gathering overhead but also enhances compatibility. We summarize the characteristics of the full-duplex MAC protocols surveyed in this section in Table 2.1.

Table 2.1: Full-duplex MAC protocol characteristics

MAC	Control overhead	Information gathering	MAC architecture	Scheduling	Optimization
RCTC [22]	fixed	no	distributed	no	no
RTS/FCTS [21]	fixed	no	distributed	no	no
A-duplex [20]	fixed	yes	distributed	no	no
Janus [30]	variable	yes	centralized	yes	yes
RCFD [25]	variable	no	distributed	no	no
CSMA/CA [27]	fixed	no	distributed	no	no

III. Proposed Method

Our RMAC protocol based on the station reservation approach was designed for full-duplex WLANs. Because our RMAC uses a centralized AP scheme, APs need to recognize when a station has a packet to send for deterministic full-duplex transmission. In addition, an AP negotiates the sequence of transmission to stations and the time to transmit. In this section, we describe our experimental environment and the details of our RMAC.

3.1 Overview

In our RMAC scheme, we assume that the APs are equipped with in-band full-duplex radios and the stations are equipped with either full-duplex radio or half-duplex radio. Our RMAC scheme has two types of periods, one being a contention period for stations equipped with both a full-duplex and a half-duplex radio, and the other a reservation period for stations equipped with a full-duplex radio only.

During the contention period, the AP operates in half-duplex communication mode when it communicates with a station equipped with a half-duplex radio. On the other hand, when the AP communicates with a station equipped with full-duplex radio, it performs full-duplex transmission. During communication with full-duplex stations, the AP gathers information to determine whether a station has more than one frame in its buffer. To minimize the information gathering overhead, we used the More Data bit in the frame control field of the 802.11 MAC header (Fig. 3.1) [15]. In the previous 802.11 standard, the More Data bit was used to notify a station using Power Save (PS) mode that an AP had more data to send. In our RMAC protocol, we used the More Data bit to check whether a station buffer contained several frames. If the station sends a frame with its More Data bit set, then it considers itself reserved and does not compete during the contention period because our RMAC protocol promises reserved stations a transmission opportunity without competition or collisions. As a result, the number of competing stations is reduced.

Bits :	2	2	4	1	1	1	1	1	**1**	1	1
	Protocol version	Type	Subtype	To DS	From DS	More Frag	Retry	Pwr Mgt	**More Data**	WEP	Rsvd

Figure 3.1: Structure of Frame Control field in 802.11 MAC header.

During the reservation period, the AP sends a frame (data or poll) sequentially to a reserved station. When the station receives a frame from the AP, it has an immediate full-duplex transmission opportunity. If the AP sends and receives frames with all reserved stations, the AP sets the time for the next reservation period and automatically begins the contention period. In our RMAC protocol, since all stations do not require information for each period, the AP does not send a notification control frame for each period.

3.2 RMAC protocol design

Since a reservation period is required only for full-duplex transmission, it is important to determine the duration of each period. Although stations communicate with APs without collision in the reservation period, it is also important to reduce collisions in the contention period because half-duplex stations, unreserved full-duplex stations, and new incoming stations can use a channel only during the contention period. In our RMAC protocol, we classified stations as reserved and unreserved. Reserved stations include stations that succeed in sending a frame with the More Data bit set as 1.

3.2.1 AP operation

In RMAC, reservation period and contention period is appeared iteratively as shown in Fig. 3.2. The length of reservation period is decided by the downlink and uplink duration of reserved station and AP. The length of contention period is decided by the number of non-reserved station. When the reservation period is terminated, the AP calculates immediately the time for next reservation period. Detail description about each period is explained at Period decision.

To give the uplink transmission opportunity to reserved station, AP should store and update the list of reserved stations (Reservation list) whenever state of station changed from unreserved to reserved or from reserved to unreserved. The order of Reservation list is first come first serve principle. As shown in Fig. 3.3 (a), when a station state changed from unreserved to reserved, it is added in the rear of Reservation list. As shown in Fig. 3.3 (b), if the station state changed from reserved to unreserved, it is removed in Reservation list. If the station state changed from unreserved to reserved again, it is added at rear of Resrvation list.

Period decision

During the reservation period, the AP sends a frame to all reserved stations consecutively. Predicting the length of the reservation period is difficult because the AP cannot estimate the uplink duration of a reserved station. Alternatively, our RMAC protocol defines the start time of the reservation period as T_r.

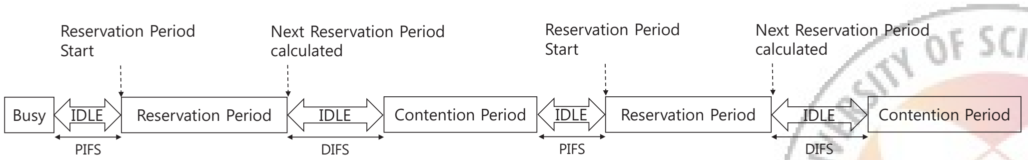


Figure 3.2: Reservation period and contention period appear iteratively.

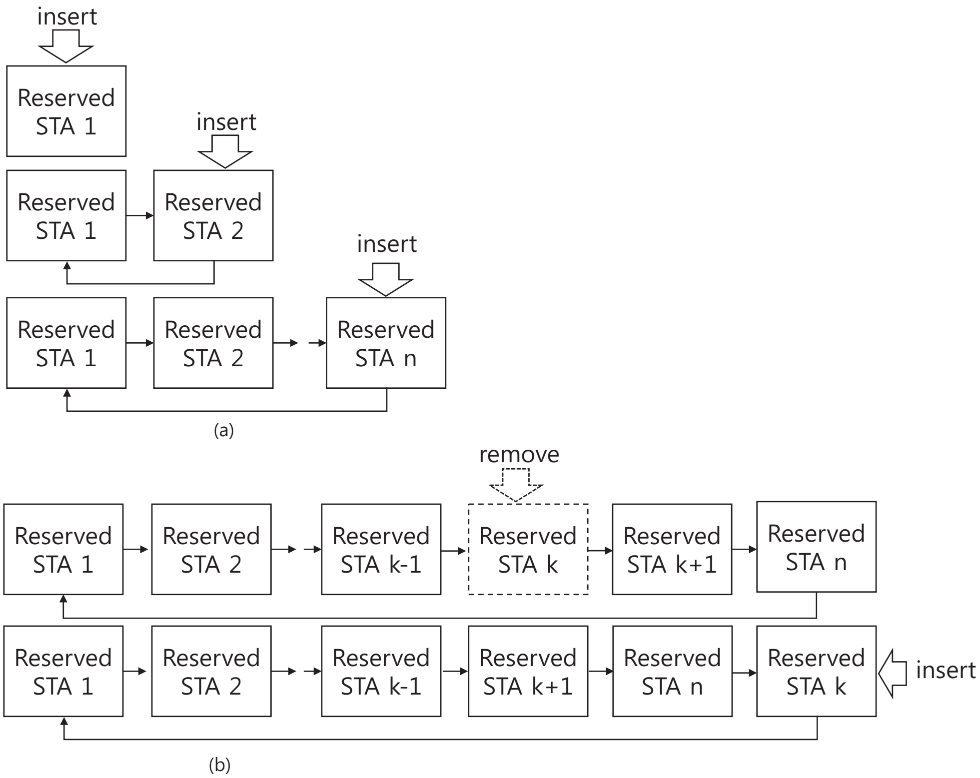


Figure 3.3: Reservation list management; (a) insert a new incoming reserved station, (b) remove reserved station from the reservation list and re-insert it

We define T as the current time and T' as the reservation period finish time. T' is updated and T_r is calculated when a reservation period finishes. When the AP starts, it sets T' to T to initiate reservation period. Then the AP calculates T_r. $|N_{all}|$ is the total number of stations, and $|N_r|$ is the number of reserved stations. T_{DIFS} is the duration of the DIFS (DCF interframe space) interval, and $T_{Slottime}$ is the duration of the slot time.

Since the reservation and contention periods are iterated, to minimize the wasting time when no stations contend, we define $|T_w|$, the interval time between two reservation periods, as Eq. 3.1

$$|T_w| = T_{DIFS} + (|N_{all}| - |N_r| + 1) \times T_{Slottime} \tag{3.1}$$

Then, T_r is calculated by Eq. 3.2. Note that, $|T_w|$ is the minimum duration for the contention period.

$$T_r = T' + |T_w| \tag{3.2}$$

Furthermore, if all stations associated with an AP use the full-duplex radio mode and are reserved, then the number of unreserved stations ($|N_{all}| - |N_r|$) is 0. Even if $|N_{all}| = |N_r|$ is satisfied, an AP needs time of at least $T_{DIFS} + T_{Slottime}$ to associate with new incoming stations because they follow DCF protocol to associate with an AP [31]. $|T_w|$ is recalculated whenever the reservation period finishes because the number of reserved stations can change.

T_r is determined by Eq. 3.1 and Eq. 3.2. A reservation period can begin only if the following conditions in Eq. 3.3 are verified:

$$\begin{cases} T > T_r \\ N_r > 0 \\ T_{idle} > T_{PIFS} \end{cases} . \tag{3.3}$$

where T_{idle} is the duration time that a channel is kept idle, and T_{PIFS} is the duration of the PIFS (PCF interframe space) interval.

The AP waits during T_{PIFS} when it begins the reservation period in order to avoid collisions with the ACK frame or data frames during the contention period (see Fig. 3.4). However, if RMAC protocol coexists with any scheme using PIFS such as Point Coordination Function (PCF), it may occur collision; therefore, in this case, RMAC may require new IFS having longer duration than PIFS and shorter duration than DIFS.

The reservation period is finished when the one of following conditions is satisfied:

1. AP transmits a frame to every reserved station
2. AP fails to receive an uplink frame from reserved station during the reservation period

Condition 2 means that if the AP receives an uplink frame, it keeps reservation period up irrespective of whether the AP receives an ACK from reserved station or not.

When the reservation period finishes, the AP begins its contention period. If a channel is idle during the DIFS, the AP and unreserved stations begin competition automatically. Modification of half-duplex stations is not required because the reservation period is the same as the channel-busy state.

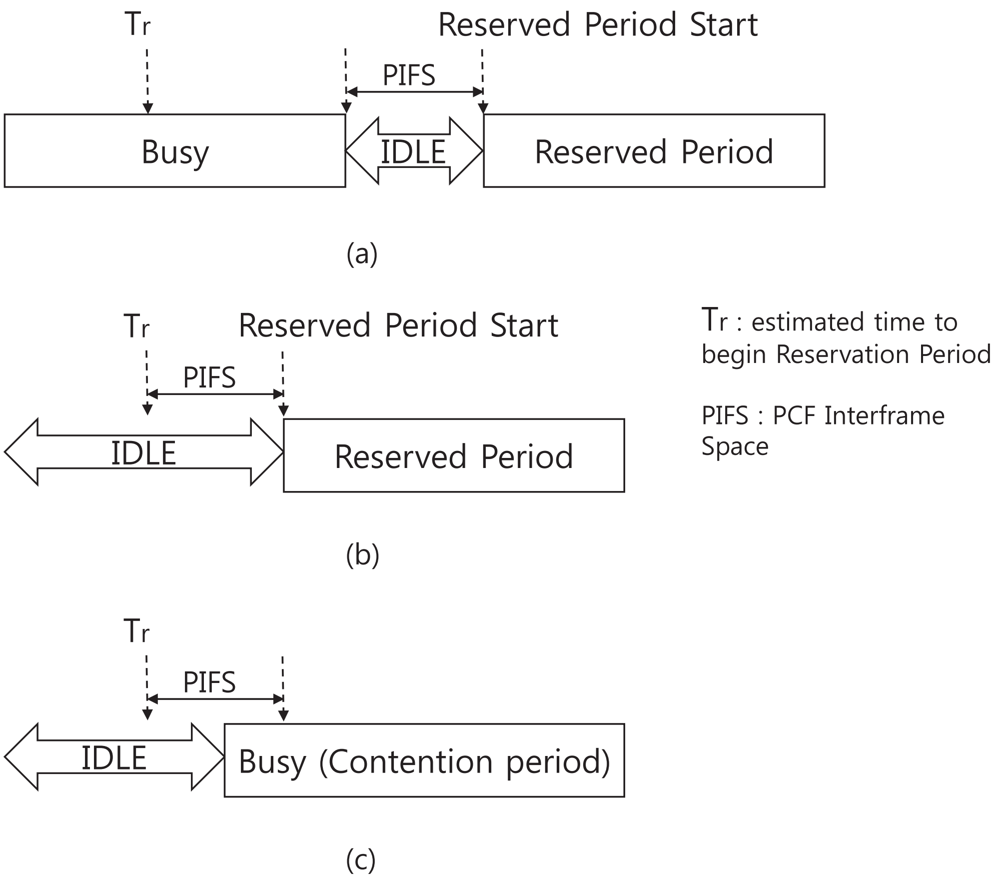


Figure 3.4: Example of beginning reservation period for each case: (a) If the channel is busy when the time has arrived to begin the reservation period, the AP waits until the channel is idle and then starts the reservation period after sensing the channel during PIFS; (b) If the channel is idle when the time has arrived to begin the reservation period, the AP waits during PIFS to begin the reservation period; and (c) If the channel is busy when the AP senses the channel state during PIFS, it waits until the channel is idle and operates like case (a).

Competition and transmission

During contention period, AP competes to transmit a frame as following DCF mechanism. During reservation period, the AP continues to transmit one frame to all the reserved stations from the front station of the Reservation list without competition. If AP transmits one frame to every reserved station during previous reservation period, it starts transmitting the first reserved station in this reservation period (Fig. 3.5 (a)). As shown in Fig. 3.5 (b), if the transmission during reservation period is interrupted during transmitting and receiving with any reserved station, reserved station is the rear of the Reservation list and the next reserved station is the front of the Reservation list. When the AP begins the next reservation period, it starts transmitting a frame to station located at the front of Reservation list. If the AP does not have a data frame for a reserved station, it sends a null data frame (MAC header plus padding bits only) to provide transmission opportunity for other reserved stations.

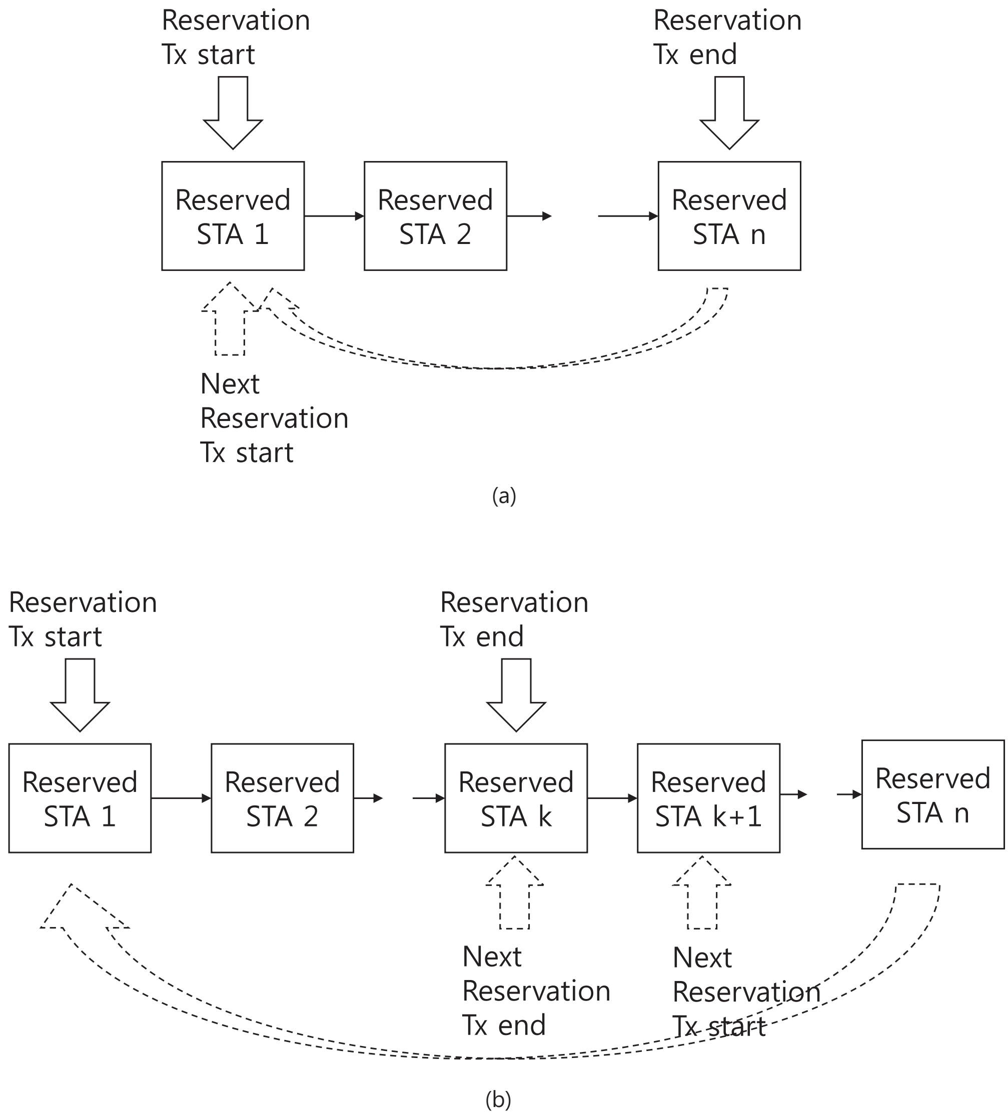


Figure 3.5: Starting point of reserved station for transmission at next reservation preiod; (a) AP transmits a frame for every reserved station (b) AP stop transmitting a frame at any reserved station

3.2.2 Non-AP station

In RMAC protocol, non-AP station equipped full-duplex radio has two states; reserved and unreserved state. Non-AP station equipped half-duplex radio has only one state; unreserved state.

Competition and transmission

There is no competition during the reservation period. When the reserved station receives a data frame from the AP, the station receiving the downlink frame starts transmitting a data frame without competition. Because unreserved stations operate same as DCF, these stations need idle time longer than DIFS to get transmission opportunity, but there is no idle time longer than DIFS during reservation period; therefore, unreserved station cannot participate during reservation period automatically (Fig. 3.7).

If a station has more frames in its buffer, it can retain its reserved state by setting its More Data bit to '1', thereby allowing it to have a transmission opportunity at the next reservation period without the threat of collision. On the other hand, if a reserved station has no frames in its buffer, it sets its More Data bit to '0'. Then this station is unreserved state and is removed from Reservation list of the AP. When this station has frames to transmit, it participates in competition during contention period.

During the contention period, only unreserved stations and the AP compete as following the DCF for the right to transmit. Since reserved stations do not compete during the contention period, the collision probability decreases because the number of competition stations has reduced. In this period, if a full-duplex station receives a downlink frame, it has an opportunity to transmit. Before transmitting a frame, stations check whether or not they have more frames in

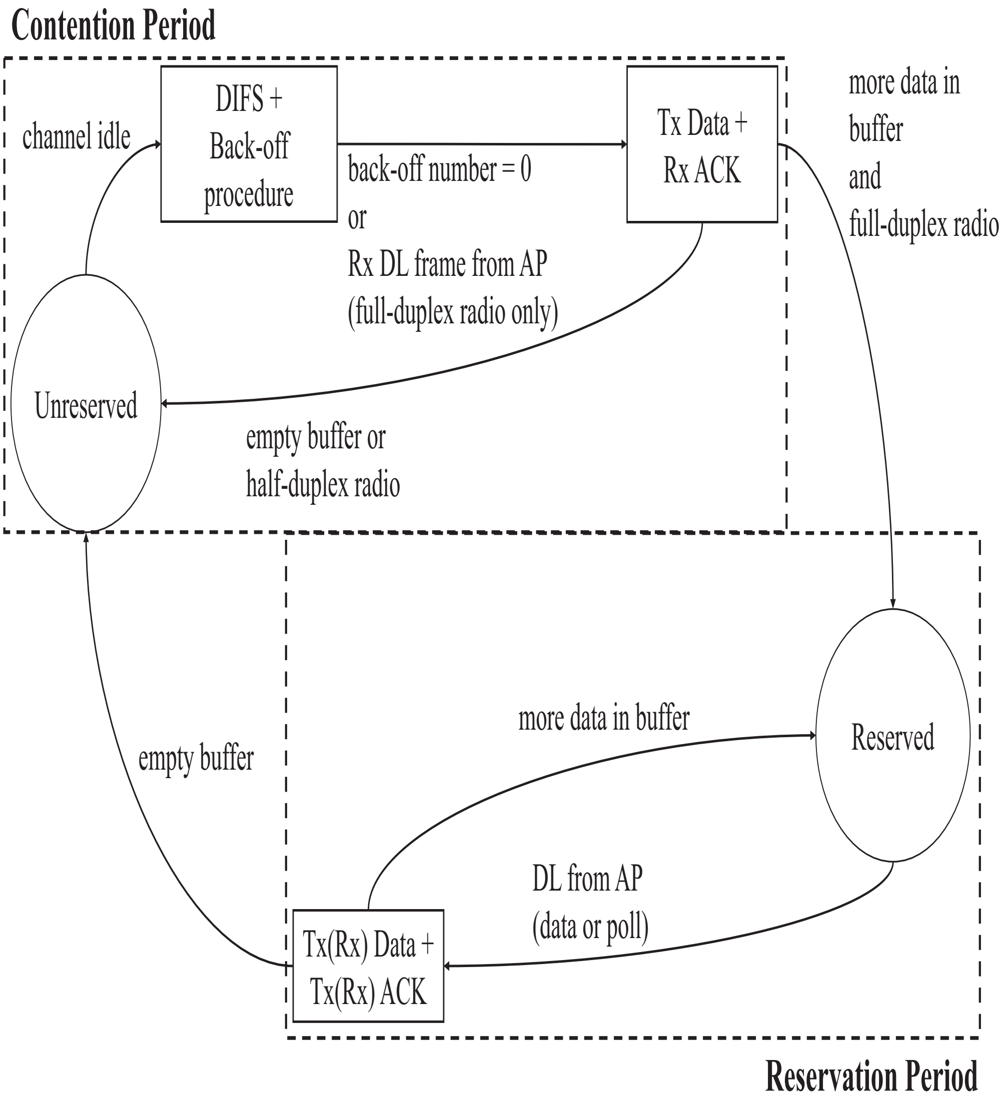


Figure 3.6: State diagram of non-AP station

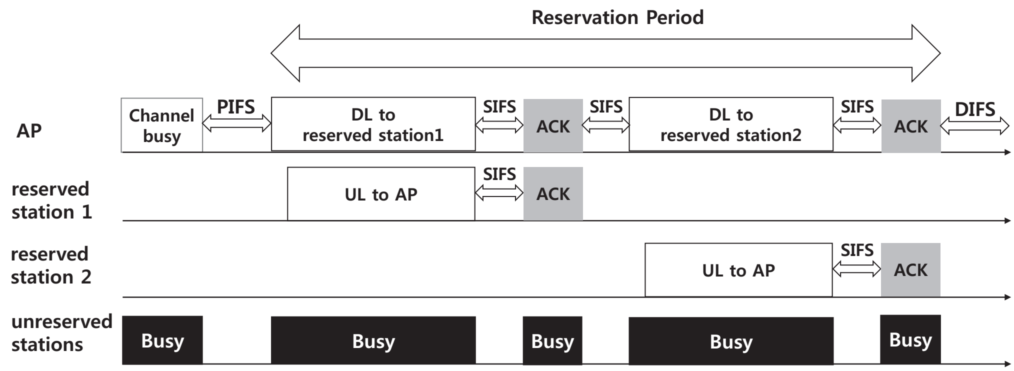


Figure 3.7: Channel state of each station (AP, reserved station and unreserved station)

their buffers. During the contention period, new reserved stations can be added.

The overall operation is described in Fig. 3.8 when one AP and three full-duplex stations and one half-duplex station are deployed. When the AP initiates RMAC protocol, there is no reserved station so AP finishes reservation period immediately and sets the duration of contention period for next reservation period. During contention period, if any station succeeds to transmit the uplink frame to AP, it obtains an opportunity to reserve itself for next transmission. If contention period setted by the AP is finished, AP transmits the donwlink frames to every reserved station in order of sequence of Reservation list. If any reserved station does not have a frame to transmit in buffer, it sets 'More data bit' as 0 when it transmits the last frame and changes its state as unreserved. Then, this station attend competition during contention period when it has frames in buffer. As shown in Fig. 3.8, contention period and reservation period are repeated iteratively.

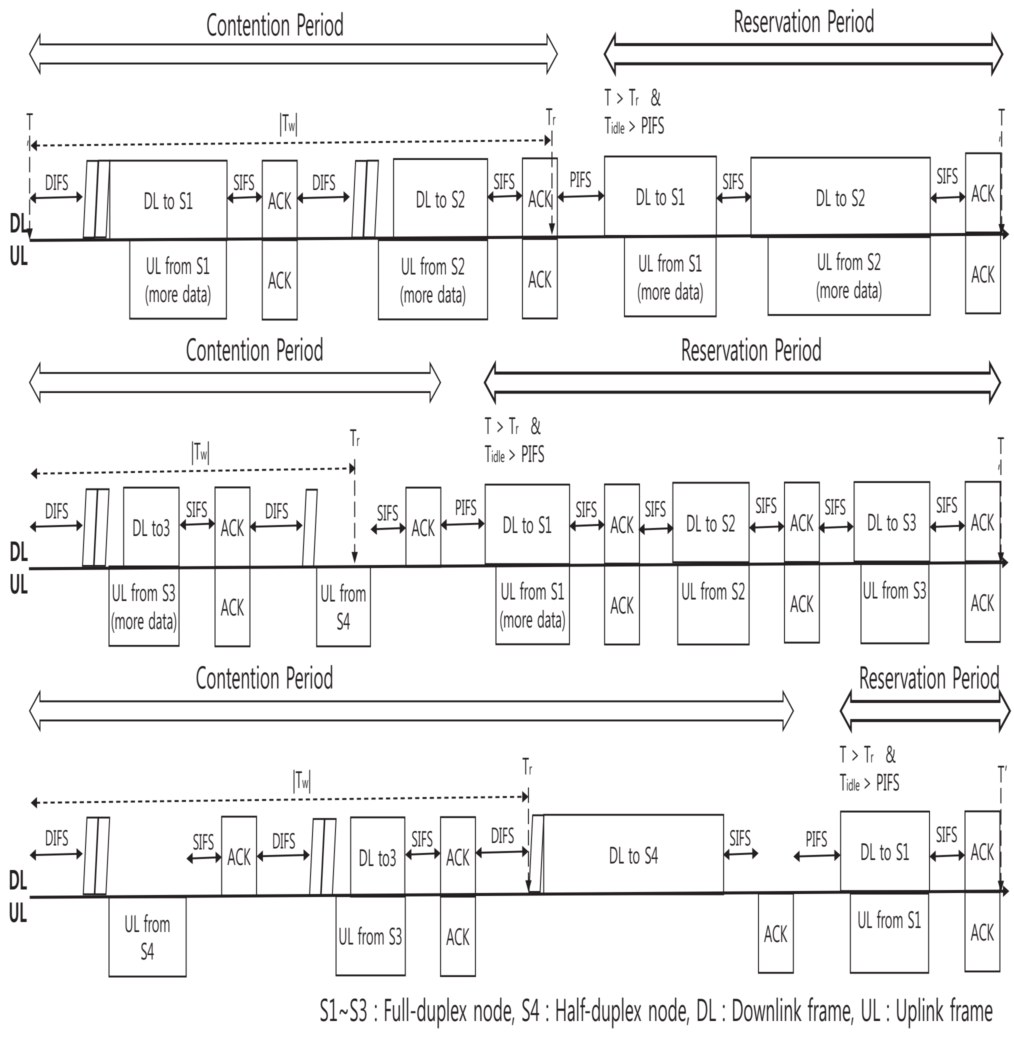


Figure 3.8: Operation example of RMAC with three full-duplex stations (S1, S2, S3) and one half-duplex station (S4)

3.3 Overhead

In this section, we compare network overhead during competition in several cases. We compared half-duplex and full-duplex based on the DCF technique and the RMAC protocol. We assumed that half-duplex stations and full-duplex stations followed the IEEE 802.11 DCF without the use of RTS/CTS signals. In addition, we used an expected value of contention window (CW) defined as E[CW] (i.e., E[16] = 8) for simplification. The denotations used in our analysis are provided in Table 3.1.

In our analysis, one round consisted of N_{all} times of downlink and N_all times of uplink, therefore, $2 \times N_{all}$ data frames were exchanged in one round. We analyzed the overhead of each case for K rounds.

When a station sends a frame in the half-duplex mode, the transmission time T was calculated with Eq. 3.4 as referred to in [32],

$$T = T_{DIFS} + E\left[CW\right] + (T_{DL}|T_{UL}) + T_{SIFS} + T_{ACK} \tag{3.4}$$

The number of all stations was set as $N_{all} = N_h$ when all stations were equipped for half-duplex transmission. During one round, at least $2 \times N_{all}$ competitions occurred, and overhead during one round ($O_(h-1)$) was calculated as

$$O_{h1} = (T_{DIFS} + E\left[CW\right] \times T_{slottime} + T_{SIFS} + T_{ACK}) \times 2N_{all} \tag{3.5}$$

Overhead during K rounds (O_{hK}) was simply calculated as

$$O_{hK} = O_1 \times K = (T_{DIFS} + E[CW] \times T_{slottime} + T_{SIFS} + T_{ACK}) \times 2KN_{all} \tag{3.6}$$

If half-duplex radio stations successfully transmitted without collision, the overall overhead was calculated with Eq. 3.6. If we consider collisions during DCF, then $2KN_{all}$ in Eq. 3.6 is replaced by $(2KN_{all} + N_{col})$, where N_{col} is the number of collisions depending on the number of stations.

The overhead of full-duplex with DCF (O_{f1}) and that of RMAC (O_{r1}) are the same at the first round because the number of reserved stations is zero.

Therefore, the competition overhead of both cases is calculated as

$$O_{r1} = O_{f1} = (T_{DIFS} + E[CW] \times T_{slottime} + T_{SIFS} + T_{ACK}) \times N_{all} \qquad (3.7)$$

where the number of stations is set to $N_{all} = N_f$. In Eq. (7), the full-duplex overhead is halved compared to the half-duplex operation because the number of competitions required for the same number of transmissions is reduced by simultaneous transmission. However, the number of reserved stations changes as the transmission proceeds, thereby creating a difference between the overhead of full-duplex with DCF and that of RMAC. When K rounds occur, the overhead of full-duplex with DCF is calculated as

$$O_{fK} = O_{r1} \times K = (T_{DIFS} + E[CW] \times T_{slottime} + T_{SIFS} + T_{ACK}) \times N_{all} \times K \quad (3.8)$$

To calculate the overhead of the RMAC protocol, the number of stations was set to $N_{all} = N_f$ and the number of reserved stations was set to $N_r = N_f$ because all stations will be reserved after the first round finished and traffic is saturated. In this case, the overhead of the RMAC protocol was calculated as

$$
\begin{aligned}
O_{rK} = (T_{DIFS} + E[CW] \times T_{slottime} + T_{SIFS} + T_{ACK}) \times N_{all} \\
+(T_{PIFS} + T_{SIFS} + T_{ACK}) \times (K-1) \\
+(T_{SIFS} + T_{SIFS} + T_{ACK}) \times (N_{all}-1) \times (K-1) \\
+(T_{DIFS} + T_{slottime}) \times (K-1)
\end{aligned}
\tag{3.9}
$$

In Eq. 3.9, in the first round, all stations need competition overhead $(T_{DIFS}+ E[CW] \times T_{slottime} + T_{SIFS} + T_{ACK}) \times N_{all}$ to be included in the reservation period. After finishing the first round, because all stations are reserved, the AP begins transmitting after waiting a PIFS time interval during (K-1) rounds. After sending the first transmission of each round, the AP uses an SIFS time interval to send the downlink frame. When each reservation period is finished, the AP waits a minimum time equal to the sum of the DIFS time interval and one slot time for the contention period. When we use the RMAC protocol, the overhead decrement compared with full-duplex with DCF is calculated as

$$
\begin{aligned}
O_{fK} - O_{rK} &= (T_{DIFS} - T_{SIFS} + E[CW] \times T_{slottime}) \times (N_{all}-1) \times (K-1) \\
&\quad +((E[CW]-1) \times T_{slottime} - T_{PIFS}) \times (K-1) \\
&= ((E[CW]+2) \times T_{slottime}) \times (N_{all}-1) \times (K-1) \\
&\quad +((E[CW]-1) \times T_{slottime} - T_{PIFS}) \times (K-1)
\end{aligned}
\tag{3.10}
$$

As presented in Eq. 3.10, when a round proceeds in saturated traffic, the RMAC protocol reduces overhead more efficiently than full-duplex using DCF.

Table 3.1: Denotation for analysis

Parameter	Description
N_{all}	The number of all non-AP nodes
N_f	The number of full-duplex nodes (without AP)
N_h	The number of half-duplex nodes (without AP)
N_r	The number of reserved nodes (without AP)
N_{nr}	The number of unreserved nodes (without AP)
T_{DL}	Downlink frame transmission time
T_{UL}	Uplink frame transmission time
T_{ACK}	ACK frame transmission time
T_{DIFS}	Duration of DIFS (SIFS + 2 slot times)
T_{PIFS}	Duration of PIFS (SIFS + slot time)
T_{SIFS}	Duration of SIFS
$T_{slottime}$	Duration of slot time

3.4 RMAC protocol for overlapping BSS

In general, basic service set (BSS) consiting of one AP and one or more stations is the basic unit of WLAN. When BSS (AP) overlaps with other BSS (AP) because of neighboring deployment, it called as overlapping BSS (OBSS). In OBSS, generally, WLAN throughput is degraded [33] because of various reasons such as hidden terminal problem, exposed terminal problem, and the increment of collision probability. In RMAC protocol, because the AP decides the reservation period and contention period and starts the downlink transmission during reservation period, the location of AP is important factor to identify the RMAC operation in OBSS scenario. There are two cases of OBSS type as shown in Fig. 3.9. In fully overlapped case (Fig. 3.9 (a)), AP2 can sense the transmitting signal of neighboring AP 1. In fully overlapped case (Fig. 3.9 (a)), AP can sense the signal from overlapping AP, so AP can recognize whether the channel is idle or busy. In partially overlapped case (Fig. 3.9 (b)), AP2 cannot sense the transmitting signal of neighboring AP1, but AP1 can interfere with S2 when S2 receives a downlink frame from AP2.

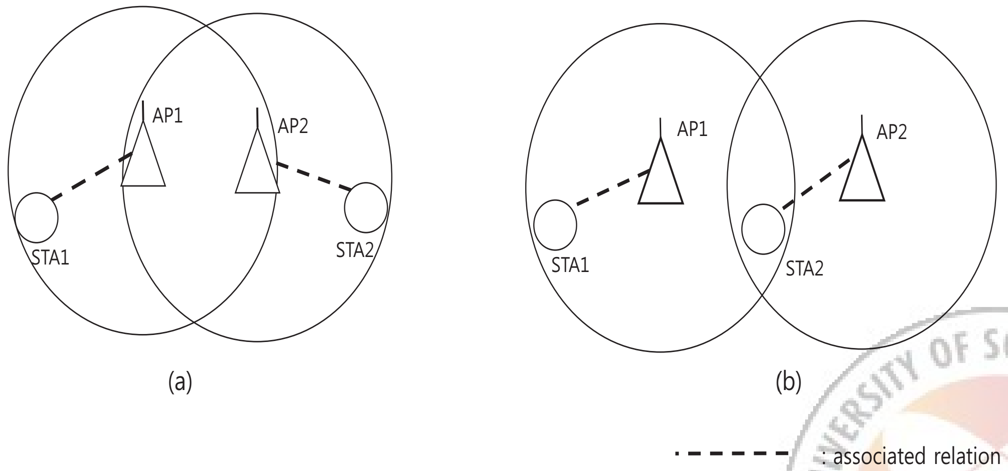


Figure 3.9: OBSS types; (a) fully overlapped (b) partially overlapped

We categorize and analyze several transmission cases to identify whether RMAC protocol provides transmission opportunities during reservation period in OBSS environments or not. In this analysis, we assumed that two APs are deployed to simplify the explanation of each case.

3.4.1 Fully overlapped

In this section, we describe and anlyze several cases when APs are overlapped fully as shown in Fig. 3.9 (a) and sense each other. In RMAC protocol, because the AP drives downlink and uplink transmission during reservation period, the timing of transmission of each AP is important in this scenario to check whether the transmission is available or not.

Case 1-1 *One of two APs transmits prior to another AP*
If one of APs transmits a downlink frame to its reserved station early, it proceeds with full-duplex transmission without competition during its reservation period. On the other hand, another AP cannot transmit because it senses the channel is busy and it cannot satisfy the starting condition $T_{idle} > T_{PIFS}$ in Eq. 3.3. In this case, when AP finished the reservation period, another AP has an opportunity to begin its reservation period. As shown in Fig. 3.10, each AP proceeds downlink and uplink transmission sequentially during its own reservation period.

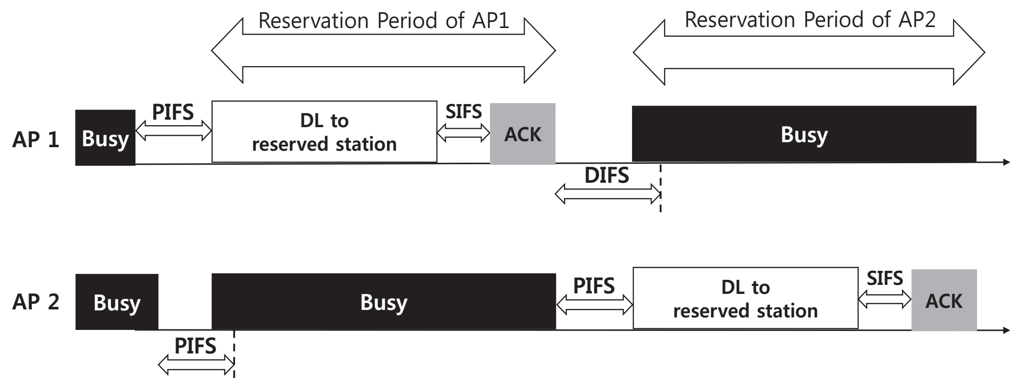


Figure 3.10: Operation example of RMAC when two APs overlapped fully and one of APs transmits earlier

Case 1-2 *Simultaneous transmission in two APs*

If two APs transmit a downlink frame to reserved station at the same time, unfortunately both APs cannot decode the uplink frame irrespectively of the location of reserved station. Even if the reserved station success to decode the downlink frame and transmit the uplink frame, AP receives the mixture of the uplink frame from its reserved node and the downlink frame from another AP. This collision enforce suspending reservation period of both APs. In this collision scenario, we categorized two cases whether the interval time T_w of each AP is same or not. If the number of unreserved station of both APs is different, the interval time T_w which is derived from Eq. 3.1 is different; therefore, the starting time of reservation period of each AP is different (Fig. 3.11 (a)). As shown in Fig. 3.11 (b), if the interval time T_w is same because the number of unreserved station of each AP is same, consecutive collision can occur. However, in general, the current time T' is different because the finish time of each downlink is different. Then, althrough the interval time T_w of each AP is same, T_r which is start time of the next reservation period is different by calculated in Eq. 3.3. As shown in this analysis, RMAC protocol operates with OBSS scenario regardless of the inter time T_w.

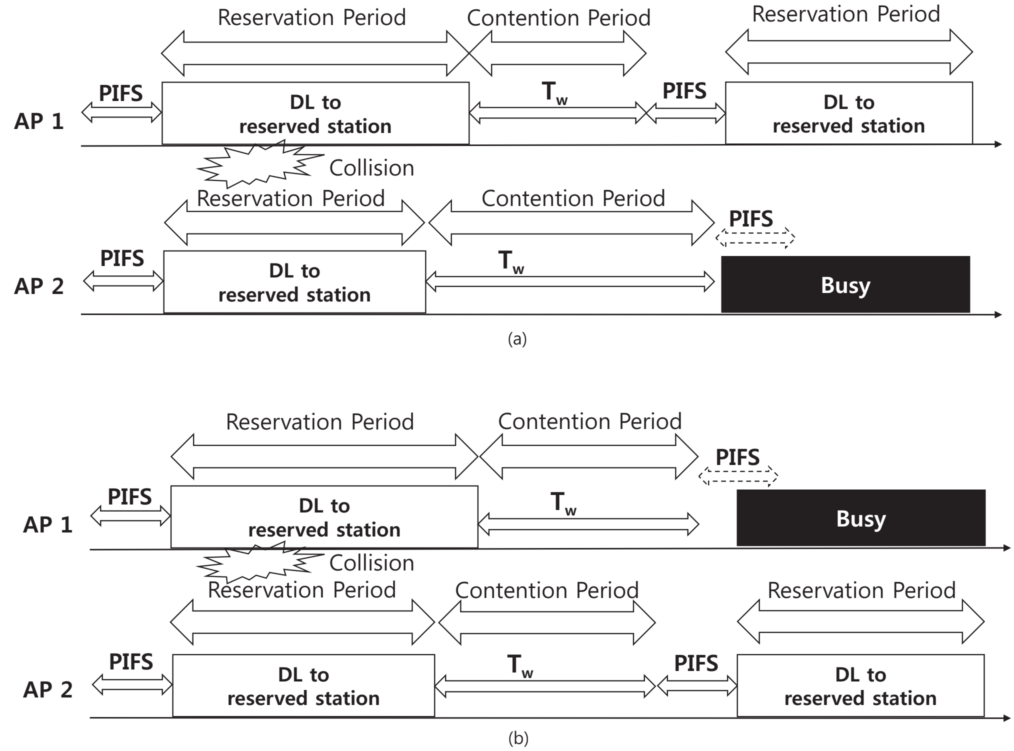


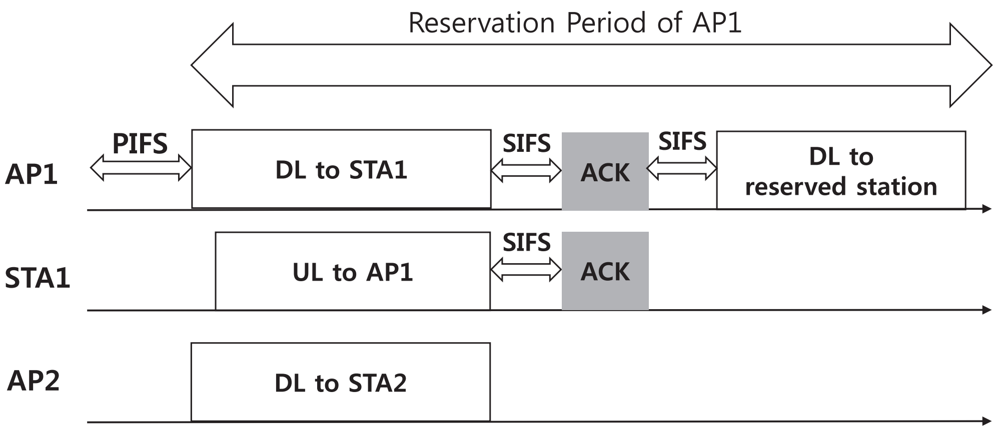
Figure 3.11: Operation exmple of RMAC when two APs overlapped fully and both APs transmits simultaneously; (a) each AP has different interval time T_w, (b) each AP has same length of interval time T_w

3.4.2 Paritially overlapped

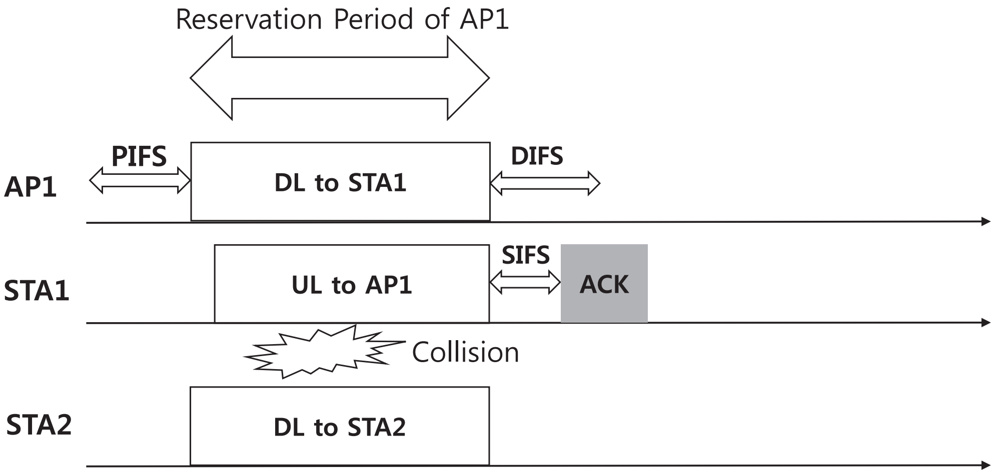
In this section, we describe and anlyze several cases when APs overlap partially as shown in Fig. 3.9 (b). In this case, the location of reserved station and the timing of transmission are very important to decide whether the reservation period continues or not.

Case 2-1 *reserved station is located at out of range of the another (unassociated) AP*

If reserved station is located at out of transmission range of another AP such as S1 in Fig. 3.9 (b), it is free to interfere from another AP. This station receive downlink frame successfully from associated AP and transmit the uplink frame to the AP during reservation period even if both APs start reservation period at the same time (Fig. 3.12 (a)). However, although the reserved station receives the downlink frame and transmits a uplink frame, the AP cannot assure that it proceeds the reservation period or not because it may suffer from interference. For example, in Fig. 3.9 (b), if the timing of tranmission of AP1 is same the timing of transmission of S2, then S1 can receive and decode the downlink frame from AP1; therefore, S1 starts transmitting uplink frame to AP1. However, AP1 cannot decode the uplink frame from S1 because it receives the mixture of uplink frame of S1 and S2. As a result, AP1 terminates its reservation period by condition 2 in Eq. 3.3 (Fig. 3.12 (b)) although it receives ACK successfully corresponding the downlink frame.



(a)

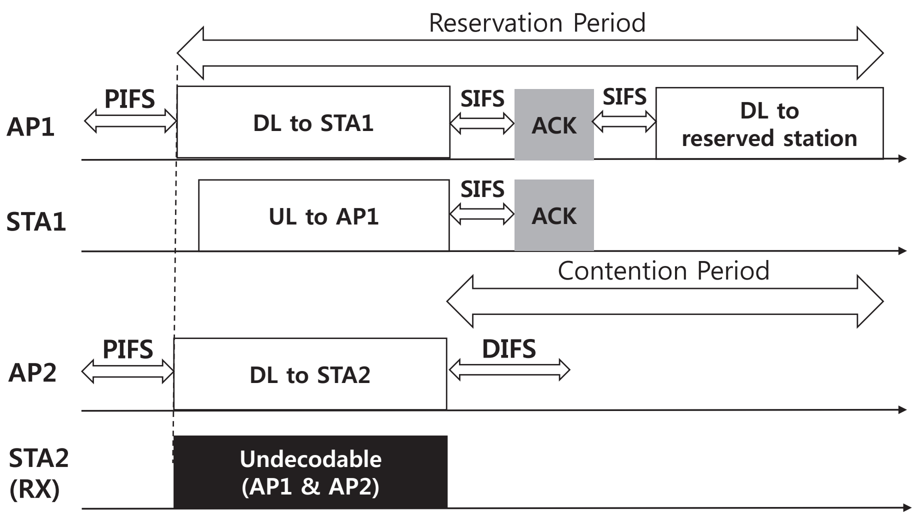


(b)

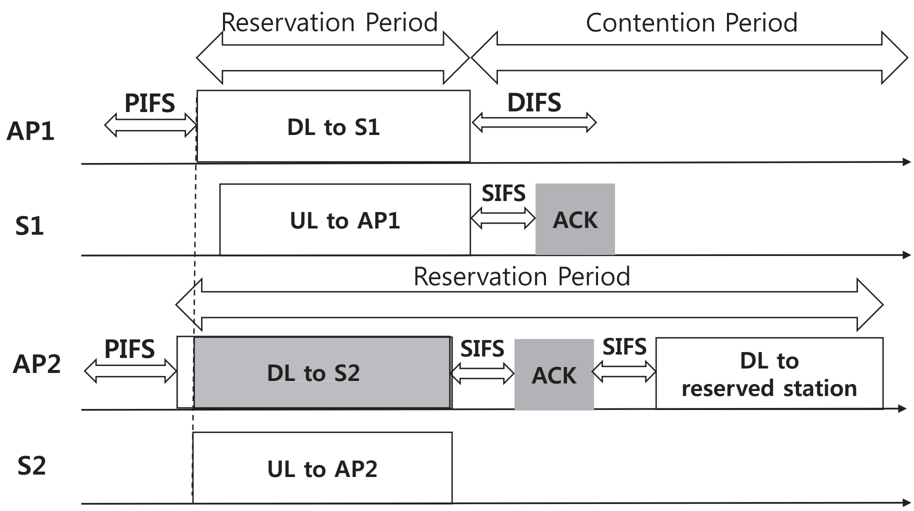
Figure 3.12: Operation example of RMAC when two APs overlapped paritially and reserved station located at out of overlapping range; (a) successful transmission case, (b) transmission failure case

Case 2-2 *reserved station is located at overlapping range of both APs*
When the reserved station is located at overlapping range of both APs, it may suffer from interference from neighboring transmission (i.e., S2 in Fig. 3.9 (b)). When the station located at overlapping range starts transmitting earlier, it can communicate susscessfully. If both AP enter the reservation period at the same time, reserved station located at overlapping range cannot receive and decode the downlink frame form associated AP. For example, in Fig. 3.9 (b), if AP1 and AP2 transtmit downlink frame to their reservation station, S2 cannot decode the downlink frame so it cannot transmit the uplink frame to AP2. Then AP2 stops next transmission and terminates its reservation period (Fig. 3.13 (a)). When AP1 and S2 transmits at the same time, AP1 cannot decode the uplink frame from its reserved station because it receives the mixture signal of uplink frame of S1 and S2. If S2 decodes the downlink frame from AP2 successfully, it transmits the uplink frame to AP2. Later, if the downlink frames from AP2 and AP1 overlap, S2 fails to decode collided part of the downlink frame from AP1 and AP2, but AP2 receives the uplink frame from S2 successfully because AP2 is not interfered from AP1. Because AP2 receives the uplink frame during its downlink transmission, it continues its reservation period (Fig. 3.13 (b)).

We analyzed RMAC operation in OBSS scenario above. As shown in several cases, RMAC operates even if collision occur because of OBSS environment. However, limitations of RMAC in OBSS scenario exist. Collision during reservation period can be resolved during next reservation period, but the length of contention period can be deducted. It may restrict the incoming of new reserved station.



(a)



(b)

Figure 3.13: Operation exmple of RMAC when two APs overlapped partially and reserved station located at the overlapping range; (a) S1 receives successfully the downlink frame from AP1 and S2 recevies collided frame from both APs when both AP transmit at the same time, (b) AP2 and S1 receive the frame from S2 and AP1 respectively, AP1 receives the collided frame from S1 and S2 and S2 receives collided frame from both APs when AP1 and S2 transmits a frame at the same time

IV. Performance evaluation

In this section, we describe the evaluation of our RMAC protocol to prove the performance improvement. To evaluate RMAC, we developed a WLAN simulator that supports full-duplex radio communication based on SIC by using C++ and compared the RMAC with IEEE 802.11 DCF with half-duplex radio and full-duplex radio. We considered the metrics of normalized throughput and fairness for evaluation. The simulation environment and experimental results are described in sections 4.1 and 4.2, respectively.

4.1 Simulation environment

When we simulated IEEE 802.11 DCF with half-duplex radio and full-duplex radio and RMAC, we considered only a single AP with multiple stations. We assumed that the size of network is $25 \times 25(m^2)$ and the coverage of each station including AP is $37(m)$ to cover the whole network. The AP was located at the center of the network, and the stations were located at random positions in the network. During MAC-protocol simulation, we changed the number of stations from 5 to 60, and we measured the performance degradation when stations were densely deployed. In addition, we assumed saturated traffic. When the AP and stations generated packets, the packet size was decided by the distribution shown in Fig. 4.1 based on [34, 35], so the frame size of the uplink and downlink was different. Theoretically, the throughput of the full-duplex radio was twice as large as that of the half-duplex radio if the frame size of the uplink and downlink were equal. However, in a practical environment as shown in Fig. 4.1, the downlink frame size was larger than that of the uplink. Therefore, the increased downlink traffic of a practical environment achieved a higher throughput. In addition, we considered only a 20-MHz channel bandwidth with a single stream because channel extension schemes can be used in specific environments (i.e., multiple channels are idle).

Since we assumed that all stations were one-hop, all stations were able to receive or overhear and decode all frames in the network. Therefore, when we simulated IEEE 802.11 DCF with half-duplex radio, we did not employ RTS/CTS. Other simulation parameters are described in Table 4.1.

For precise simulation results, we created two scenarios. First, when we simulated IEEE DCF with half-duplex radio, the AP and all stations operated only in the half-duplex mode. On the other hand, when IEEE 802.11 DCF with

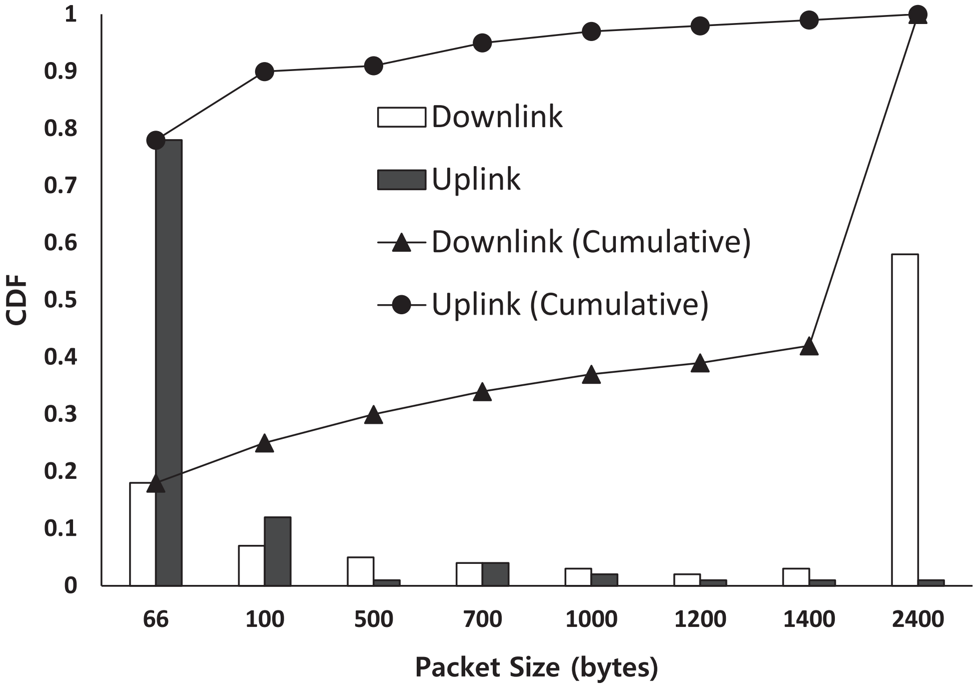


Figure 4.1: Packet size distribution

full-duplex radio and RMAC were simulated, the AP and all stations had the capability of supporting full-duplex communication.

Second, we compared two MAC protocols (DCF and RMAC). The two MAC protocols operated with various numbers of full-duplex stations and half-duplex stations. This scenario proved the ability of full-duplex stations to coexist with half-duplex stations.

Table 4.1: Parameters for simulation

Description	Value
Duration of simulation	10 (s)
Physical overhead (header, preamble, signal)	40 (μs)
Data rate	65 (Mbps)
Slot time	9 (μs)
SIFS	16 (μs)
PIFS	25 (μs)
DIFS	34 (μs)
Contention Window size [Minimum/Maximum]	[16 / 1024]
ACK	14 (bytes)

4.2 Simulation result

In this section, the normalized throughput of each MAC protocol and the average number of uplink transmissions are compared. Fig. 4.2 shows the normalized throughput as the number of stations was increased. As shown in Fig. 8, the normalized throughput of DCF with full-duplex stations was 167.7 % and 61.4% greater than that of DCF with half-duplex stations when the number of stations was 5 and 60, respectively. Since the number of downlinks of full-duplex radio was more than that of the half-duplex radio as mentioned in Section 4.1, the normalized throughput of DCF with full-duplex stations was more than double that of the half-duplex stations. In addition, the RMAC protocol throughput with full-duplex stations only (presented as RMAC-P in Fig. 4.2) outperformed that of the DCF with full-duplex stations by 86.3 %. Moreover, with 60 network stations, the normalized throughput of DCF with full-duplex stations and half-duplex stations decreased 56.1% and 27.1%, respectively. However, the normalized throughput using the RMAC protocol increased 5.2% because the number of competing stations had decreased and the number of transmission had increased, demonstrating that the RMAC protocol operated well even in a network with a dense station deployment.

In addition, Fig. 4.3 shows the normalized throughput of a network consisting of an AP, full-duplex stations, and half-duplex stations. During these simulations, we set two scenarios; the number of half-duplex stations is 10 (presented as RMAC-C1 in Fig. 4.3) and the number of full-duplex stations equal to the number of half-duplex stations (presented as RMAC-C2 in Fig. 4.3) to verify that RMAC operates well and maintains throughput when half-duplex stations coexist. In addition, because the number of half-duplex stations affects the period decision, the comparision of fixed number of half-duplex stations and various number of

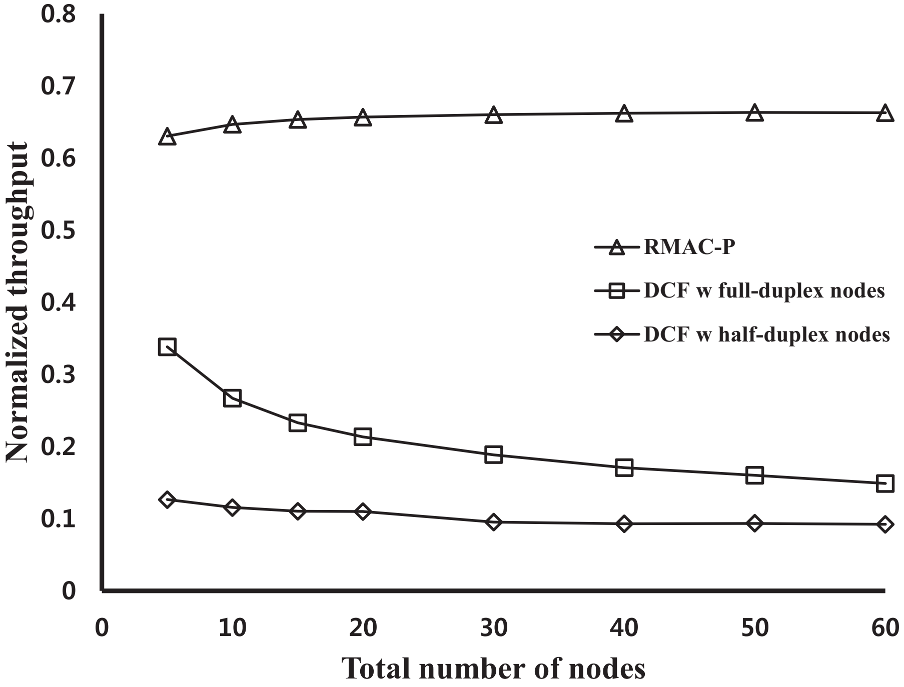


Figure 4.2: Normalized throughput with saturated traffic for several cases; RMAC-P: full-duplex nodes only

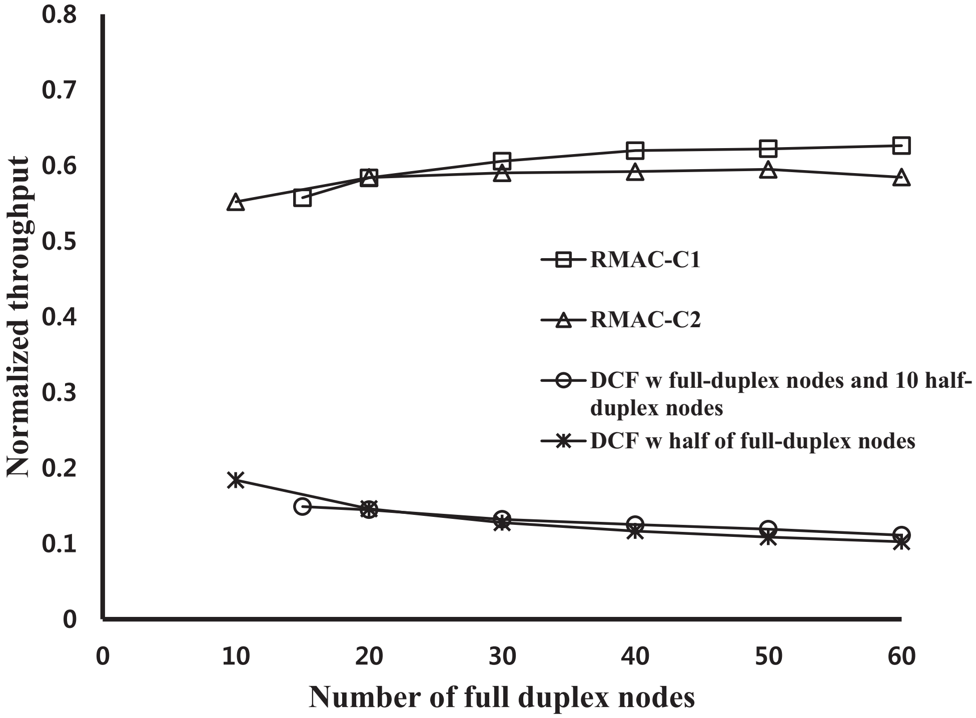


Figure 4.3: Normalized throughput with saturated traffic for several cases; RMAC-C1: mixture of full-duplex nodes and 10 half-duplex nodes; RMAC-C2: mixture of the same number of full-duplex nodes and half-duplex nodes

half-duplex stations shows the effect of the number of half-duplex stations on RMAC protocol. As the number of stations increased, the normalized throughput using DCF decreased because the number of competing stations increased. The greater the number of competing stations, the greater the number of collisions that occurred. On the other hand, using the RMAC protocol shows that as the number of full-duplex stations increased, the normalized throughput also increased as shown in Fig. 4.3 even with the half-duplex stations. As shown in RMAC-C1 and RMAC-C2 of Fig. 4.3, RMAC maintains throughput when not only the number of half-duplex station is fixed but also the number of half-duplex station increases. It means that RMAC is barely affected by the number of half-duplex stations using the RMAC protocol, since the reserved full-duplex stations did not compete during the contention period, the number of competing stations is not proportional to the total number of full-duplex and half-duplex stations, and likewise the collision probability and competition overhead decreased. With saturated traffic, all full-duplex stations will eventually be reserved and transmit without competition during the reservation period with the RMAC protocol. Therefore, the increment of full-duplex stations leads the increment of proportion of the reservation period in one cycle consisting of one reservation period and one contention period.

Fig. 4.4 shows the average number of uplink transmissions of each MAC protocol when the number of stations is 60. In general, DCF provides long-term fairness among stations. The number of uplink transmissions with RMAC protocol was 108.6% and 62.2% greater than that of DCF with full-duplex radio and half-duplex radio, respectively. Furthermore, RMAC protocol achieves the minimum deviation of the number of uplink transmissions because stations already reserved had equitable transmission opportunities during reservation period. As a result, RMAC also provides fairness well among stations.

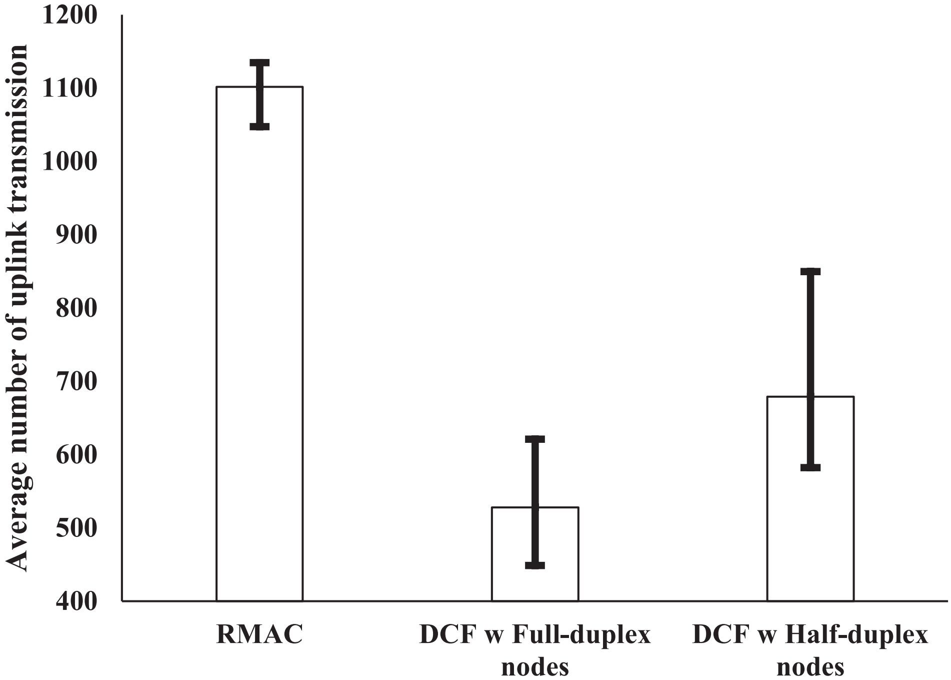


Figure 4.4: The average number of uplink transmission for three MAC protocols (DCF w Full-duplex nodes, DCF w half duplex nodes and RMAC) when the number of nodes is 60

The results of the two scenarios show that the RMAC protocol achieved high throughput when stations frequently sent many frames because the stations remained reserved until their buffers were empty. The efficiency of the RMAC protocol was maintained even when a large number of stations were deployed with heavy traffic.

V. Conclusion

The increasing number of stations in WLANs, the overhead of collision prevention, and the competition among stations are crucial issues to be dealt with in the development of WLAN communication equipment. Despite the advantages of full-duplex radio technology, most prior research has focused on the feasibility of symmetric and asymmetric transmission for frame exchange.

The main contribution of this dissertation is that we considered the WLAN consisting of AP equipped full-dupelx radio and stations equipped full-dupelx radio or half-duplex radio and proposed the corresponding MAC protocol. Our MAC protocol is a RMAC protocol which is reservation-based MAC protocol for full-duplex equipped WLAN (RMAC). Our RMAC protocol reduced competition overhead and collision probability by providing transmission opportunities without competition. We demonstrated that our RMAC protocol performed very well with a large number of stations and heavy traffic. In addition, our RMAC protocol was designed to be compatible with IEEE 802.11 DCF with half-duplex; therefore, we believe our RMAC protocol is suitable for propagating and generalizing full-duplex WLANs.

For the future work, we will consider various aspects such as the performance enhancement, the security, and the applicability to other wireless networks. Since the proposed RMAC covers only symmetric transmissions, it is possible to modify RMAC to support asymmetric transmissions as well. In addition, we may consider Overlapping BSS. Then the modified RMAC may enhance its throughput by mitigating the collision probability further.

요 약 문

최근 무선랜 (WLAN) 을 사용하는 단말 수가 급증하였으며, 각 단말의 무선랜 트래픽 사용량이 급격히 증가하고 있다. 이는 하나의 access point (AP) 에 더 많은 단말들이 연결되며 사용량 역시 증가한다는 것을 의미한다. 기존의 무선랜은 다수의 단말들이 밀집된 환경을 가정하고 설계되지 않았기 때문에, 무선랜을 사용하는 단말들이 밀집된 경우 성능이 심각하게 저하된다. 기존 무선랜의 단말수 증가에 따른 성능 저하 문제를 해결하기 위한 여러 연구들이 제안되었다. 하지만, 기존의 무선랜 기술의 제약으로 발생하는 성능 개선의 한계 때문에, 최근에는 지향성 안테나 (Directional antenna), 직교주파수 분할 다중 접근 (Orthogonal Frequency Division Multiple Access, OFDMA), 전이중 라디오 (Full-duplex radio) 와 같은 새로운 PHY 기술을 도입하여 무선랜에 적용시키는 연구가 진행되고 있다. 특히, 전이중 라디오 통신 기술 연구는 AP와 단말이 동일 대역에서 송수신을 동시에 하는 것을 가능하게 만들었다. 이론적으로 전이중 라디오 기술을 사용할 때 처리량 (throughput) 은 반이중 라디오를 사용할 때 처리량의 2배이기 때문에, 전이중 라디오 기술이 무선랜의 성능 저하 문제를 해결하기에 적합할 것으로 기대하고 있다.

전이중 라디오 통신이 실현된다면 처리량의 급격한 증가를 기대할 수 있지만, 기존의 분산조정함수 (DCF) 라고 불리는 무선랜 매체접근제어 (MAC) 기법은 전이중 라디오 통신을 적용시킨 무선랜의 성능 향상을 제한하는 원인이 된다. 기존의 분산조정함수는 반이중 통신을 기본으로 전제하고 있기 때문에, AP와 각각의 단말들은 전송기회를 얻기 위해서 위해서 경쟁을 필요로 한다. 단말간의 경쟁을 기반으로 하는 매체접근제어를 통해 분산조정함수에서는 단말들에게 공평한 전송 기회를 제공하지만, 단말들간의 그리고 AP와의 경쟁은 매우 큰 오버헤드를 발생시키고 충돌 발생을 증가시키는 원인이 된다. 이러한 분산조정함수의 특성들로 인해 무선랜을

사용하는 단말 수가 증가할 경우 성능을 저하시키게 된다.

본 논문에서는 전이중 라디오 통신을 사용하는 무선랜 환경에서 사용할 수 있는 매체접근제어 기법인 단말 예약 기반의 예약기반매체접근제어기법 (RMAC) 프로토콜을 제안한다. RMAC 프로토콜은 기존의 무선랜의 성능 저하를 유발하는, 단말에서 AP로 전송하는 상향전송 (Uplink transmission) 을 자주 수행하는 트래픽이 많은 단말들이 밀집되어 있는 상황을 주요 환경으로 고려하여 처리량을 개선한다. RMAC 은 IEEE 802.11 표준을 사용하는 기존 단말들의 수정을 필요로 하지 않기 때문에, 기존의 분산조정함수를 사용하는 무선랜 단말들과 호환이 되도록 설계되었다. RMAC 프로토콜에서는 경쟁하는 단말의 수를 감소함으로써 단말간 충돌 발생 확률을 줄이고, 경쟁에서 발생하는 오버헤드를 감소시킴으로써 처리량을 증가시킨다. 또한, RMAC 프로토콜에서는 상향전송에 성공한 단말들이 버퍼에 추가적으로 전송할 패킷이 존재하는 경우 추가적인 경쟁없이 전송할 수 있는 기회를 제공한다. 그 결과, 제안된 RMAC 프로토콜은 시뮬레이션을 통해 전이중 라디오를 사용하는 분산조정함수보다 적어도 86.3% 이상 처리량이 향상된 것을 확인하였다. 또한, RMAC 프로토콜은 다수의 단말들이 매우 밀집된 환경에서도 성능이 저하되지 않고 높은 처리량을 유지하는 것을 확인하였다.

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