AUB: A Full-Duplex MAC Protocol for the Efficient Utilization of the Idle Uplink Period in WLAN

Hyeongtae Ahn, Harim Lee, and Young Deok Park

Abstract—**Recently, full-duplex radio has attracted attention as a solution for wireless local area networks (WLANs) where traffic is exploding but available frequency bands are insufficient. Full-duplex radio exploits various self-interference cancellation technologies to transmit and receive signals concurrently in the same frequency band. Thus, the efficiency of the frequency band is doubled compared with that of conventional half-duplex radios. However, to effectively exploit full-duplex radio, new problems that do not exist in conventional half-duplex radio, such as full-duplex link setup, inter-node interference avoidance, and idle uplink period (IUP), must be addressed. We propose a full-duplex medium access control (MAC) protocol to effectively exploit full-duplex radio by addressing these problems. In particular, our MAC protocol uses an IUP to transmit an acknowledgment (ACK) frame and report the buffer information of nodes. Accordingly, an access point can gather the node's buffer information during the IUP and schedule the transmission of nodes without competition. In addition, because the uplink ACK frame is transmitted during the IUP, additional channel usage time for the uplink ACK frame transmission is not required. Therefore, the proposed MAC protocol improves the WLAN throughput by reducing the number of control frame transmissions and the IUP. The results of our performance analysis and simulation show that the MAC protocol achieves throughput improvements compared with those of previous studies.**

Index Terms—**Full-duplex radio, IEEE 802.11 DCF, medium access control.**

I. INTRODUCTION

RECENTLY, the amount of traffic in wireless local area networks (WLANs) has rapidly increased; however, frequency bands remain scarce [1], [2]. Thus, full-duplex radio is attracting attention as a solution because it doubles the efficiency of the frequency bands. Conventional half-duplex radio cannot transmit and receive signals concurrently in the same frequency band because the transmitted signal strongly interferes with the signal received. However, full-duplex radio uses combined self-interference cancellation (SIC) technology to cancel self-interference signals to the noise floor level [3], [4], allowing signals to be transmitted and received concurrently in the same frequency band.

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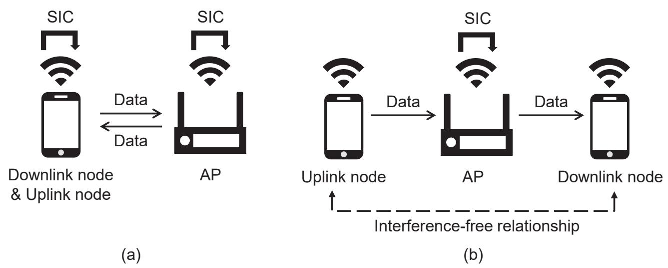

Fig. 1. Full-duplex link types: (a) A symmetric full-duplex link; the uplink and downlink nodes are the same; and (b) an asymmetric full-duplex link; the uplink and downlink nodes are different and should have an interference-free relationship.

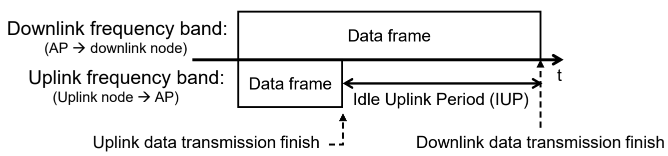

Fig. 2. Idle uplink period on a full-duplex link.

To exploit full-duplex radio in WLANs, a full-duplex link setup process is required to determine an uplink node and a downlink node; the uplink node transfers data to an access point (AP), and the downlink node receives data from the AP. A full-duplex link can be established in two manners according to the relationship between the uplink and downlink nodes. If both nodes are the same node, a symmetric full-duplex link (SFL) is set up (Fig. 1(a)); the AP and the node that is both an uplink and downlink node concurrently transfer data frames to each other. By contrast, an asymmetric full-duplex link (AFL) is set up when both nodes are different (Fig. 1(b)); the uplink node transfers a data frame to the AP, and simultaneously, the AP transfers a data frame to the downlink node. The uplink and downlink nodes should be outside each other's interference zones to avoid interference with each other. In this study, the relationship between both nodes in an AFL is referred to as an interference-free relationship (IFR).

To effectively exploit full-duplex radio in WLANs, new

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problems that do not exist in conventional half-duplex radio, such as full-duplex link setup, IFR reporting, and idle uplink period (IUP), should be solved. In particular, the IUP is a major factor that degrades the efficiency of the uplink frequency band. The IUP is the period of an uplink frequency band on a full-duplex link in which uplink data transmission is completed but downlink data transmission continues (Fig. 2). In WLANs, the length of an uplink data frame is generally shorter than that of a downlink data frame [1]. Consequently, IUPs occur frequently and many uplink frequency bands are wasted on full-duplex links. However, during an IUP, a node that has an IFR with the downlink node can transfer signals to the AP without interfering with the downlink node, such as an AFL. We define an uplink transmission candidate node (UC node) as the node that has an IFR with the downlink node and has data to send. Consequently, to improve the efficiency of the uplink frequency band, UC nodes must be able to utilize the IUP.

In this study, we propose a new full-duplex medium access control (MAC) protocol to effectively exploit full-duplex radio by addressing the problems in WLANs. Our protocol is based on the IEEE 802.11 distributed coordination function (DCF) and uses a request-to-send (RTS)/clear-to-send (CTS) mechanism [5] to identify IFRs between nodes. In particular, during the transmission of one downlink data frame, the proposed MAC protocol allows the transmission of an Acknowledgment (ACK) frame, an Uplink data frame, and Buffer information frames (AUB). Thus, our MAC protocol, called AUB, effectively reduces the IUP compared with methods proposed in previous studies. To transmit an uplink ACK frame during the IUP, the AP can request the downlink node to delay sending the ACK frame until data frame transmission begins on the next full-duplex link. However, because the uplink ACK frame transmission cannot be delayed indefinitely, the AUB protocol is designed to use delayed uplink ACK frame transmission only when the next full-duplex link can be immediately established to transmit the uplink ACK frame. Accordingly, the uplink ACK frame is transmitted simultaneously with the downlink data frame of the next full-duplex link. During the remaining IUP after the ACK and data frames are transmitted, UC nodes can report buffer information to the AP, as in [6].

The contributions of this study are as follows. First, we propose a method of reducing the IUP by sending an ACK frame. Thus, the efficiency of the uplink frequency band is improved. Second, the AUB MAC protocol exploits a newly defined control frame combined with a CTS and ACK frame to reduce the number of control frames transmitted. Consequently, our MAC protocol improves the WLAN throughput by reducing the number of control frame transmissions and the IUP.

II. Related Works

Recently, many full-duplex MAC protocols have been proposed for exploiting full-duplex radio [7]–[11]. However, most studies do not consider the IUP problem by assuming that the downlink and uplink have the same amount of data. In real WLAN traffic, the amount of data on the downlink is overwhelmingly greater than the amount of data on the uplink [1], making the IUP problem very common on full-duplex links. As a result, most existing studies significantly reduce the gains of full-duplex radio in real WLAN traffic.

There are only a few studies to address the IUP problem. In [12] and [13], the AP sequentially gathered buffer information from all nodes and scheduled node's data transmissions without competition. Thus, to reduce IUPs, multiple uplink data frame transmissions are performed while the same downlink data frame is transmitted. However, because the AP schedules all the transmissions, the existing WLAN nodes have no chance to transmit, making it difficult to commercialize. In [14]–[16], whenever the AP senses an IUP, it transfers a signal over the control subchannel, allowing the UC node that received the signal to transmit an uplink data frame. However, these IUP solutions, which transmit multiple uplink data frames per downlink data frame transmission, are not suitable for real WLAN traffic, where the data frame ratio of uplink and downlink is almost one-to-one [17] and most WLAN traffic has a request-response pattern [1]. Thus, these IUP solutions are only effective in very limited scenarios where a node sends two or three data frames and receives only one data frame in response from the server. In [18], a frame aggregation method is used to reduce an IUP. However, the frame aggregation method can be used in limited scenarios, such as real-time communications, where a node has many uplink data frames. Also, as with the previous IUP solutions, multiple downlink data frames may be generated in response, which can create additional IUPs. In [19], if the IUP problem is severe, it avoids the IUP problem by sending uplink and downlink data frames sequentially, as in a half-duplex link, instead of simultaneously. The BRU MAC protocol [6] uses an IUP in a different approach. UC nodes report buffer information to the AP during the IUP, allowing the AP to establish a full-duplex link without competition. This increases the WLAN throughput by reducing competition overhead. However, because the IUP is only used to report buffer information of UC nodes, the uplink frequency band may still be wasted if UC nodes report very little buffer information. Thus, it cannot be guaranteed to reliably reduce the IUP.

To address the limitations of the existing studies on the IUP problem, the proposed MAC protocol is basically based on IEEE 802.11 DCF, which is the current WLAN operation. In addition, to reduce an IUP, our MAC protocol sends one uplink data frame and one ACK frame instead of sending multiple uplink data frames that do not match the real WLAN traffic pattern. Sending an ACK frame can reliably reduce an IUP, and the IUP remaining after transmitting uplink data and ACK frames is utilized by UC nodes to report buffer information to the AP as in [6].

III. AUB MAC Protocol

A. IFR Reporting

When establishing a full-duplex link, the AP must know the IFR among nodes to appropriately choose an uplink or

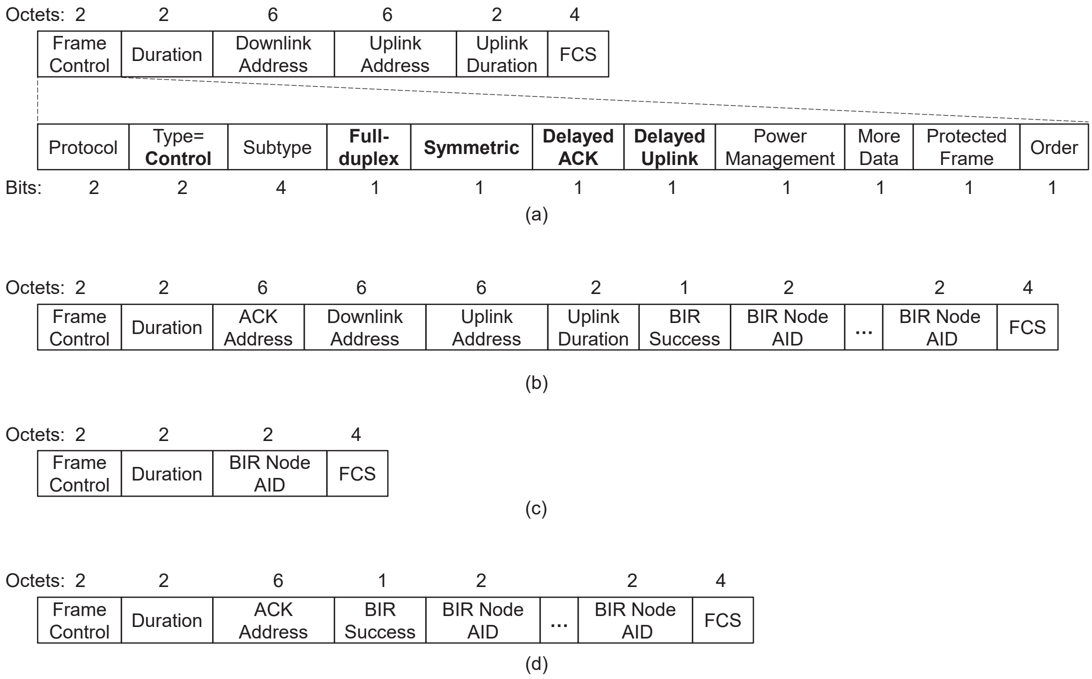

Fig. 3. Newly defined control frame formats of the AUB MAC protocol: (a) FCTS frame; (b) FACTS frame; (c) BIR frame; and (d) FACK frame.

downlink node. Nodes can estimate the interference strength of another node by overhearing the frame exchange, such as in the RTS/CTS mechanism. The RTS and CTS frames contain the address of the node communicating with the AP. Thus, the other nodes measure the received signal strength indicator (RSSI) of the RTS and CTS frames sent by the node and AP, respectively, as in [7], [8], to figure out the interference strength caused by the node. Similar to the hidden node problem, if the other nodes do not detect any RTS frame, but do detect a CTS frame, they know that the uplink node whose address is included in the CTS frame is not causing interference [15]. They continue to overhear the RTS/CTS handshaking and gather a list of nodes that cause less interference and their RSSI information. The nodes then report the interference information with other nodes that they have collected so far to the AP in a data frame, and the AP can learn some IFRs among nodes. As a result, over time, the AP learns most of the IFRs among nodes. Therefore, the proposed protocol also uses the RTS/CTS mechanism for IFR reporting.

B. Full-Duplex Link Setup with Competition

In the AUB MAC protocol, the AP and nodes basically compete for access to the same channel based on the IEEE 802.11 DCF. When a node successfully transfers an RTS frame to the AP through competition, the AP attempts to establish a full-duplex link by choosing a downlink node. If the AP cannot choose a downlink node, i.e., both SFL and AFL setups are impossible, the AP and uplink node operate as conventional WLANs using the half-duplex radio. Otherwise, the AP chooses a downlink node and transfers an FCTS frame (Fig. 3(a)) in response to an RTS frame. The FCTS frame is an extension of the CTS frame for full-duplex link setup, containing additional information related to full-duplex link setup, and is used in the same way as the CTS frame; other nodes can set the NAV value through the Duration field in the FCTS frame; the Downlink and Uplink Address fields indicate the addresses of the downlink and uplink nodes on a full-duplex link, respectively. The Uplink Duration field indicates the time required to transmit an uplink data frame. Note that when a legacy IEEE 802.11 frame is set as the control type, most subfields of the Frame Control field, that is, To DS, From Ds, More Fragments, Retry, More Data, Protected Frame, and Order subfields, are unused and always set to zero [20]. Thus, in the AUB MAC protocol, when sending a control frame, the unused subfields can indicate information related to the full-duplex link setup. The Full-duplex subfield indicates that a full-duplex link is established. The Symmetric subfield indicates whether this full-duplex link is an SFL. The Delayed ACK subfield indicates whether the Delayed ACK method is used. If the Delayed ACK subfield is set to one, the downlink node delays sending an ACK frame until the transmission of a downlink data frame begins on the next full-duplex link. After the FCTS frame transmission completes, the uplink node transfers a data frame to the AP, and the AP transfers a data frame to the downlink node simultaneously. If the Delayed ACK method is not used, the AP and downlink node concurrently transfer ACK frames. Both ACK frames are decoded correctly by the AP and uplink node using the full-duplex radio or IFR, respectively. Subsequently, the AP and nodes compete again for channel access based on the IEEE 802.11 DCF.

C. Delayed ACK Method

The Delayed ACK method can reduce the IUP and control frame transmission. After data frames are transmitted on a

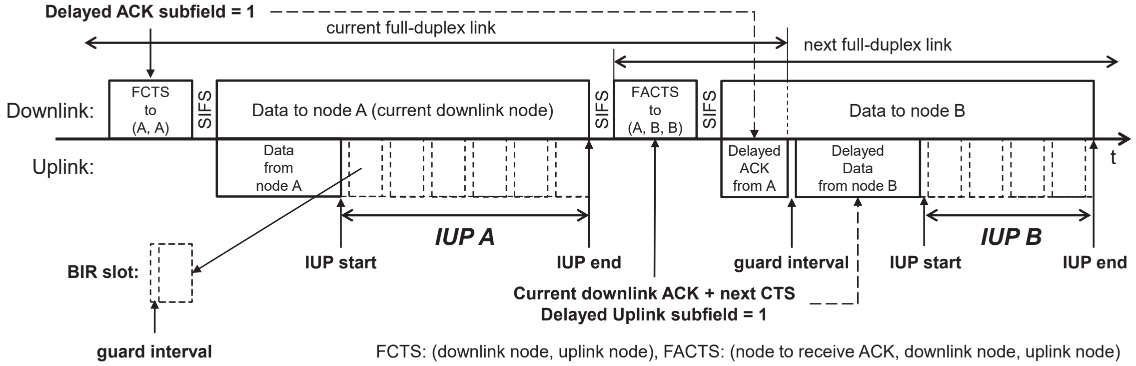

Fig. 4. The first (current) full-duplex link is established through competition, and the second (next) full-duplex link is established through the Delayed ACK method. Nodes A and B have an IFR with each other and the AP knows that node B has data to send; node A is the downlink node; node B is a UC node in the current full-duplex link. $IUPA$: without the delayed uplink ACK frame transmission during an IUP; $IUPB$: with the delayed uplink ACK frame transmission during an IUP.

full-duplex link, the downlink ACK frame is transmitted by combining the CTS frame of the next full-duplex link, and the uplink ACK frame is transmitted simultaneously with the downlink data frame of the next full-duplex link (Fig. 4).

To exploit the Delayed ACK method, we define a new control frame called the FACTS (full-duplex ACK and CTS) frame (Fig. 3(b)), which combines an ACK frame and an FCTS frame. When the AP successfully receives the uplink data frame, the ACK Address field of the FACTS frame serves as an ACK frame by indicating the uplink node address. If the Delayed Uplink subfield is set to one, the uplink node of the next full-duplex link begins its data frame transmission after the delayed uplink ACK frame transmission completes (Fig. 4). Therefore, using the FACTS frame reduces the number of control frame transmissions.

The Delayed ACK method can be used if the following three conditions are satisfied. First, the AP establishes a full-duplex link by sending an FCTS or FACTS frame with the Delayed ACK subfield set to one. Second, the AP must have data to send to a UC node of the current downlink node. Third, when the UC node becomes the downlink node on the next full-duplex link, the AP must be able to choose an uplink node having data to send. i.e., the downlink node on the current full-duplex link must be able to transmit its ACK frame on the next full-duplex link. The Delayed ACK method can be utilized whenever these three conditions are satisfied. Therefore, in the Delayed ACK method, if a full-duplex link is established through competition, several nodes can continuously transfer data frames without competition. To avoid the starvation problem on other basic service sets (BSSs) using the same channel, the AP may stop using the Delayed ACK method even if the conditions are satisfied. However, to choose an appropriate uplink node that has data to send on the next full-duplex link, the AP must know which nodes have data to send.

D. Buffer Information Reporting (BIR)

Nodes having data to send can utilize the characteristics of full-duplex radio to report buffer information to the AP with minimal overhead. Several methods have been proposed for reporting buffer information on full-duplex links using IUPs [6], ACK frames [21], and collisions [22]. To report the node's buffer information, as in [6], the AUB MAC protocol exploits the remaining IUP after transmitting uplink data and ACK frames. Fig. 4 shows two examples of IUPs. $IUPA$ is an IUP without an uplink ACK frame transmission. $IUPB$ is an IUP with an uplink ACK frame transmission. Nodes can calculate the start and end times of the IUP using the value of the Uplink Duration field (T_u) of an FCTS or FACTS frame. T_u indicates the time required to transmit the uplink data frame. T_u is obtained as follows:

$$T_u = RTS_{dur} - T_{cts} - 3T_{sifs} - T_{ack}, \tag{1}$$

where RTS_{dur} denotes the Duration field value of an RTS frame, T_{sifs} is the short inter-frame space (SIFS) [5], T_{cts} and T_{ack} indicate the time required to transmit a legacy CTS and ACK frame, respectively. If the nodes receive a FACTS frame in which the Delayed Uplink subfield is set to zero or an FCTS frame ($IUPA$ in Fig. 4), they calculate the IUP start time (IUP_{start}) and IUP end time (IUP_{end}), based on the time when the FCTS or FACTS frame has completed reception, as follows:

$$IUP_{\text{start}} = T_{sifs} + T_u + T_{\text{guard}} \tag{2}$$

$$IUP_{\text{end}} = CTS_{dur} - T_{sifs} - T_{\text{ack}}, \tag{3}$$

where T_{guard} indicates an interval used to prevent collisions between frames due to propagation delays. CTS_{dur} is the Duration field value of the FACTS, FCTS, and CTS frames. If the nodes receive a FACTS frame in which the Delayed Uplink subfield is set to one ($IUPB$ in Fig. 4), they calculate the IUP_{start} as follows:

$$IUP_{\text{start}} = T_{sifs} + T_{\text{ack}} + T_u + 2T_{\text{guard}}, \tag{4}$$

where IUP_{end} is calculated in the same manner as in (3).

The IUP, from IUP_{start} to IUP_{end}, is divided into buffer information reporting (BIR) slots. Each BIR slot consists of the time to transfer one BIR frame (Fig. 3(c)) and one T_{guard}. Thus, a UC node randomly chooses a BIR slot and transfers a BIR frame containing its association ID (AID) and the Duration field value of an RTS frame. The BIR is

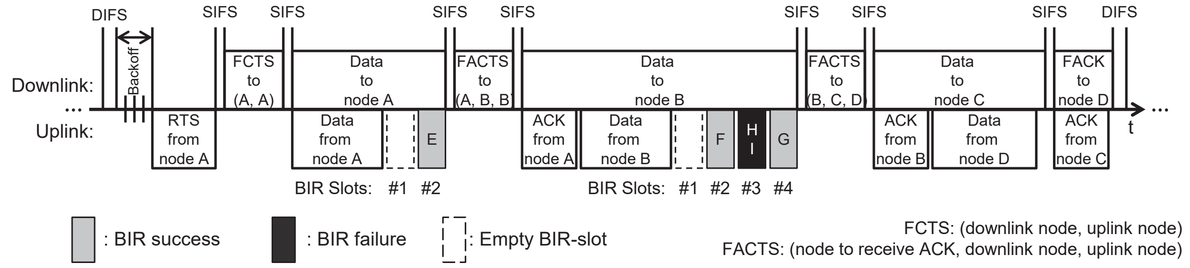

Fig. 5. An operation example of the AUB MAC protocol. Node A transfers a data frame through competition, and nodes B and D transfer data frames without competition using the Delayed ACK method. Meanwhile, nodes E, F, and G report buffer information to the AP during the IUPs.

successful if only one BIR frame is transmitted in one BIR slot. However, if two or more UC nodes choose the same BIR slot, their BIR fails. In the FACTS and FACK (full-duplex ACK) (Fig. 3(d)) frames, the BIR Success field indicates the number of successful BIR nodes, and the BIR Node AID fields represent the node list of successful BIRs. Thus, when the AP transfers a FACTS or FACK frame, the BIR-try nodes will know whether their BIR is successful. The BIR-success nodes can participate in the channel access competition or wait for the AP to grant a transfer opportunity. Accordingly, the AUB MAC protocol can exploit IUPs for the BIR of nodes, as in [6]. The nodes having data to send can report their buffer information to the AP with minimal overhead, and based on the reported buffer information, the AP can determine which nodes have data to send. Consequently, the AP can appropriately choose either an uplink or downlink node when establishing a full-duplex link.

The AP can transfer an RTS frame first because it also participates in the channel access competition by default. When the AP transfers the RTS frame first, the reported buffer information and IFRs are useful for establishing a full-duplex link. If the AP knows that the downlink node has data to send, it can easily establish an SFL. Otherwise, the AP can choose another node that has data to transmit as the uplink node to establish an AFL. In the case in which the AP does not know the buffer information of the nodes, an SFL or half-duplex link is established depending on whether the downlink node has data to transmit. The downlink node transfers an FCTS or CTS frame in response to the RTS frame from the AP. However, UC nodes may not receive this frame. Therefore, the Delayed ACK and BIR methods cannot be utilized, and a half-duplex link or SFL is established. Note that, to exploit the Delayed ACK and BIR methods, the AP may additionally transfer an FCTS frame after receiving a CTS or FCTS frame from the downlink node.

Fig. 5 shows an operation example of the AUB MAC protocol. This example assumes that the AP has data for nodes A, B, and C, and nodes B and D previously reported buffer information to the AP; node A has an IFR with nodes B and E; node B has an IFR with nodes A, C, F, G, H, and I; node C has an IFR with nodes B and D. Node A's backoff timer reaches zero and successfully transfers an RTS frame. The AP first checks whether the three conditions of the Delayed ACK method are satisfied and recognizes that the Delayed ACK method is possible. Thus, the AP responds with an FCTS frame with the uplink and downlink nodes set to node A and the Delayed ACK subfield set to one; that is, node A does not immediately transmit the uplink ACK frame, even if it successfully receives the downlink data frame. Through the FCTS frame, node E detects that an IUP with two BIR slots has occurred. Node A and the AP establish an SFL for transmitting data frames to each other. During the IUP, node E randomly chooses the second BIR slot and successfully transfers a BIR frame to the AP. The AP knows that the Delayed ACK method is available on the next full-duplex link and transfers a FACTS frame with the Delayed ACK and Delayed Uplink subfields set to one, respectively. This FACTS frame includes a variety of information: node A's uplink data frame transmission was successful; the uplink and downlink nodes are set to node B on the next full-duplex link because the AP already knows that node B has an IFR with node A and has data to send; node E's BIR was successful; and an IUP with four BIR slots occurs. Through the FACTS frame, nodes E, G, H, and I recognize that the IUP has occurred. While the AP transfers a downlink data frame to node B, node A first sends an ACK frame to the AP, and node B then transfers an uplink data frame to the AP. During the IUP, each UC node randomly chooses a BIR slot; the second and fourth BIR slots are chosen only by node F and node G, respectively. Thus, nodes F and G successfully report their buffer information to the AP, and the AP knows that the two nodes have data to send. By contrast, nodes H and I fail to report buffer information because they choose the same BIR slot. After completing the transmission of the downlink data frame, the AP checks whether the three conditions of the Delayed ACK method are satisfied and recognizes that the three conditions are unsatisfied. i.e., the AP has no more data to send to nodes B and D, which have an IFR with the downlink node C. Thus, to establish a next full-duplex link, the AP sends a FACTS frame in which the Delayed ACK subfield is set to zero; however, the Delayed Uplink subfield is set to one. This FACTS frame provides a variety of information: Node B's uplink data frame transmission was successful; the downlink and uplink nodes are nodes C and D, respectively; BIRs of nodes F and G were successful; and lack of an IUP. While the AP transfers a downlink data frame to node C, nodes B and A sequentially send an ACK and uplink data frame. After both data frame transmissions are complete, the AP sends a FACK frame; simultaneously, node C sends a legacy ACK frame. Subsequently, the AP and nodes compete for channel access based on the IEEE 802.11 DCF.

IV. Performance Analysis

In this section, we use the Markov chain model [23] to analyze the saturated throughput performance of the AUB MAC protocol under saturated traffic conditions. We assume that a single BSS consists of one AP and n non-AP nodes. All non-AP nodes have a one-hop relationship with the AP. All nodes, including the AP, are equipped with full-duplex radio; the AP always has data for k nodes randomly chosen from among n nodes, and the n nodes always have data to send immediately. The probability that each non-AP node has an IFR with another non-AP node is h. Thus, on average, each non-AP node has $h(n-1)$ non-AP nodes outside the interference zone in the BSS. To focus on our contributions and simplify the performance analysis, we assumed the following: channel conditions are ideal; no transmission failures except collision; if a collision is detected during transmission, the transmission is stopped immediately; only a single spatial stream is used; self-interference signals are completely canceled; the AP randomly chooses a downlink node among the nodes that can establish a full-duplex link; and the AP sufficiently knows the buffer information and IFRs of nodes through BIR and IFR reporting.

Let τ be the probability that a node transfers in a backoff slot. Following the Markov chain model [23], τ is given by:

$$\tau = \frac{2}{1 + CW_{\min} + pCW_{\min} \sum_{i=0}^{m-1} (2p)^i}, \quad (5)$$

where CW_{min} is the minimum contention window, m is the maximum backoff stage, and p is the collision probability of the transmitting node. When a node transfers a frame in a backoff slot, a collision occurs if any of the remaining nodes transfer a frame. Thus, p is obtained by

$$p = 1 - (1-\tau)^n. \quad (6)$$

The values of p and τ can be derived from (5) and (6) using numerical techniques.

Let p_{tr} be the probability that at least one transmission is performed in a chosen backoff slot and p_s be the probability of successful transmission in p_{tr}. In addition, $n+1$ nodes, including the AP, compete for channel access, and each node attempts to transmit with probability τ in the chosen backoff slot. Thus, p_{tr} is given by

$$p_{tr} = 1 - (1-\tau)^{n+1}. \quad (7)$$

For a successful transmission, only one node attempts to transmit in the chosen backoff slot, and the other nodes must remain silent. Thus, p_s is obtained by

$$p_s = \frac{(n+1)\tau(1-\tau)^n}{p_{tr}}. \quad (8)$$

To apply the Delayed ACK method, a full-duplex link is first established, and the AP has data for the nodes having an IFR with the current downlink node. Thus, if only a half-duplex link setup is possible, then the Delayed ACK method cannot be applied. We define p_h as the probability that a half-duplex link is established when the non-AP node wins the competition, and the AP has data for randomly chosen k nodes. p_h is calculated as follows:

$$p_h = \frac{n}{n+1}(1 - \frac{k}{n} - (1 - \frac{k}{n})(1 - (1-h)^k)), \quad (9)$$

where $n/(n+1)$ is the probability that a non-AP node wins the competition, k/n is the probability of establishing a symmetric full-duplex link with the winner, and $(1-(1-h)^k)$ is the probability of establishing an asymmetric full-duplex link with the winner.

If a full-duplex link has already been established, the next full-duplex link can be established without competition whenever the three conditions of the Delayed ACK method are satisfied. Thus, after a full-duplex link is established once through competition, several full-duplex links are established continuously with the Delayed ACK method. Let $e_{(k,i)}$ be the probability that i full-duplex links are established continuously when a full-duplex link is established through competition and the AP has data for k nodes. $e_{(k,i)}$ is given by

$$e_{(k,i)} = e_{(k,i-1)}(1 - (1-h)^{k-i}) \quad (k > 0, e_{(k,0)} = 1), \quad (10)$$

where $(1-(1-h)^{k-1})$ denotes the probability that AP has at least one data frame for the node that has an IFR with the current downlink node among $k-i$ nodes. Let e_k be the estimated number of continuously established full-duplex links when a full-duplex link is established through competition and the AP has data for k nodes; e_k can be calculated as follows:

$$e_k = \sum_{i=1}^{k-1} e_{(k,i)}. \quad (11)$$

The saturated throughput (S) of the AUB MAC protocol can be calculated by

$$S = \frac{p_h D_u + (1-p_h)(1+e_k)(D_u+D_d)}{\frac{(1-p_{tr})\sigma}{p_{tr}p_s} + (p_h T_h + (1-p_h)(T_f + e_k T_{aub})) + \frac{(1-p_s)T_c}{p_s}}, \quad (12)$$

where σ denotes the period of an idle back-off slot, D_u and D_d are the payloads of the uplink and downlink data frames, respectively. T_{aub} is the time required to transmit data through the Delayed ACK method on a full-duplex link, T_f is the time required to transmit data through competition on a full-duplex link, T_h is the time required to transmit data through competition on a half-duplex link, and T_c is the channel time wasted when a collision occurs. T_{aub}, T_f, T_h, and T_c are obtained as follows:

$$\begin{aligned} T_{aub} &= T_{facts} + \max(T_u, T_d) + 2T_{sifs} \\ T_f &= T_{difs} + T_{rts} + T_{fcts} + \max(T_u, T_d) + \\ &\quad T_{fack} + 3T_{sifs} \\ T_h &= T_{difs} + T_{rts} + T_{cts} + T_u + T_{ack} + 3T_{sifs} \\ T_c &= T_{difs} + 2OFDM_{dur}, \end{aligned} \quad (13)$$

where T_{facts}, T_d, T_{rts}, T_{fcts}, and T_{fack} denote the time required to transmit a FACTS, downlink data, legacy RTS, FCTS, and FACK frame, respectively; T_{difs} denotes the distributed inter-frame space (DIFS) [5], and $OFDM_{dur}$ denotes

TABLE I
EVALUATION PARAMETERS IN THE SIMULATOR.

Parameters	Values
Channel frequency	5 GHz
Channel bandwidth	20 MHz
Data transmission rate	39 Mbps (16-QAM 3/4)
Basic transmission rate	6 Mbps (BPSK 1/2)
Back-off window size	From 15 to 1023
OFDM symbol duration	4 μs
DIFS, SIFS	34, 16 μs
Back-off slot	9 μs
BIR slot	40 μs
PLCP transmission time	20 μs
MAC header & frame check sum	34 bytes
Downlink payload	1500 bytes
Uplink payload	250 bytes
RTS, CTS, ACK	20, 14, 14 bytes
Number of non-AP nodes, n	From 11 to 51
Number of data frames held by the AP, k	From 4 to 25
IFR ratio, h	From 0.05 to 0.5

the symbol duration of orthogonal frequency division multiplexing (OFDM), assuming that two OFDM symbol periods are required to stop transmitting RTS frames in the event of a collision.

We confirmed the throughput improvement of the Delayed ACK method by comparing T_f and T_{aub}. If a full-duplex link is established through competition, to transmit uplink and downlink data frames, three control frames (such as RTS, FCTS, and ACK) must be transmitted, and intervals (one DIFS and three SIFSs) must wait. In addition, the channel time is wasted owing to collisions and idle backoff slots. In contrast, if a full-duplex link is established through the Delayed ACK method, only one control frame (FACTS) is transmitted and waits for two SIFSs. No collisions or idle backoff slots occur because the full-duplex link is established without competition. Consequently, whenever a full-duplex link is established using the Delayed ACK method, the throughput of the AUB MAC protocol is increased by reducing the number of control frame transmissions and competition overhead.

V. SIMULATION EVALUATION

To evaluate the AUB MAC protocol, we implemented an event-driven WLAN simulator, written in C++. The simulator measured the saturation throughput for three MAC protocols (AUB, BRU [6], and A-duplex [8]). The saturation throughput is a very intuitive performance metric and is commonly used in MAC protocol studies, including [23]. Therefore, the simulator measured the total amount of data bytes transferred in 100 seconds under saturated traffic conditions. The BRU MAC and A-duplex MAC protocols are based on the IEEE 802.11 DCF using the RTS/CTS mechanism. The BRU MAC protocol uses only the BIR method to reduce IUPs and is one of the most relevant protocols for this study. The A-duplex MAC protocol is simple, but one of the most cited protocols in the literature, and is designed without considering the IUP problem.

We assumed a simulation environment with a single BSS consisting of one AP and n non-AP nodes. To focus on our contributions and easily compare the results of the performance analysis and simulation, the assumptions of the simulation are the same as those in Section IV. In addition, we assumed that when the AP participates in the channel compete again, data frames to be transmitted to k randomly chosen nodes are generated from the AP's buffer. The simulation parameters follow the IEEE 802.11ac PHY and MAC layer specifications [5], and Table I lists the main parameters.

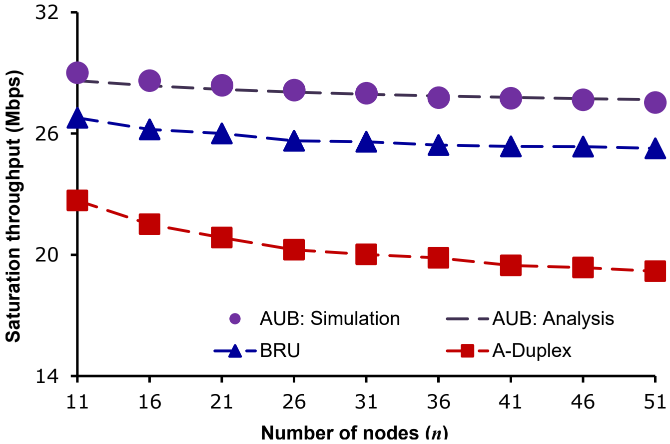

Fig. 6. Saturation throughput results of three MAC protocols according to various numbers of nodes (h = 0.1 and k = 10).

The simulator measured saturation throughput while varying three important parameters: n, k, and h, which are directly related to the full-duplex link setup and the Delayed ACK method. n is the number of nodes competing for channel access. h is the probability that two randomly selected non-AP nodes are outside of each other's interference zone. k is the number of data frames held by the AP. Therefore, when the channel access competition begins, the AP has k data frames to transmit, one to each of the k nodes randomly selected from the n nodes; the probability that each non-AP node has an IFR with another non-AP node is h.

A. Saturation Throughput vs. Number of Nodes (n)

Fig. 6 shows the simulation results for the saturation throughput of three MAC protocols as the number of nodes was changed from 11 to 51 when h was 0.1 and k was 10. When a full-duplex link was established in the simulation, an IUP of 5 or 6 BIR slots occurred. The operation of all MAC protocols is based on IEEE 802.11 DCF using the RTS/CTS mechanism. Overall, the change in throughput with the number of nodes was not significant because all MAC protocols use the RTS/CTS mechanism, which reduces collision overhead. In the A-duplex MAC protocol, all full-duplex links are established through competition. Thus, as the number of nodes increases, its throughput decreases faster than the other MAC protocols. The throughput of the BRU MAC protocol overwhelms the throughput of the A-duplex MAC protocol because it can establish full-duplex links continuously without competition. However, by transmitting a CTS and ACK frame separately, the same physical layer convergence procedure (PLCP) part is transmitted twice, and a waiting time occurs between frames. The AUB MAC protocol achieves higher throughput than the BRU MAC protocol by reducing the number of control frame transmissions and waiting time. Therefore, compared with the

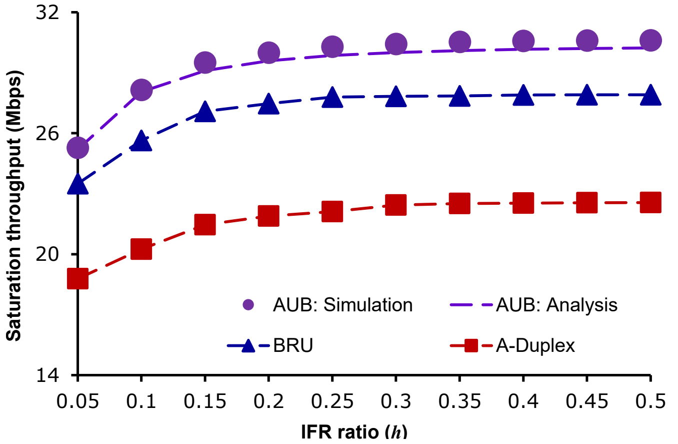

Fig. 7. Saturation throughput results of three MAC protocols according to various IFR ratios (n = 26 and k = 10).

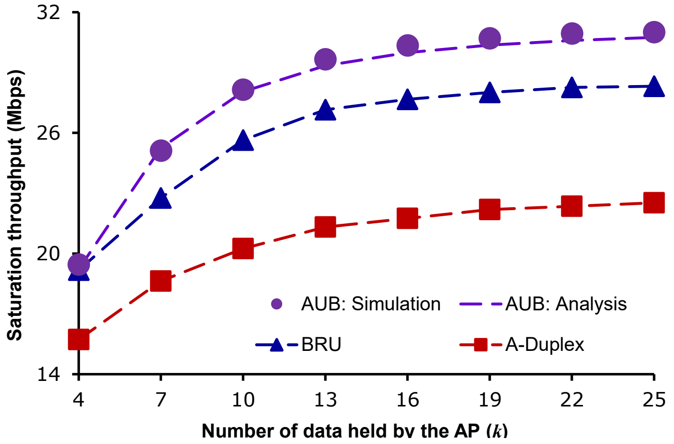

Fig. 8. Saturation throughput results of three MAC protocols according to the number of data frames held by the AP (n = 26 and h = 0.1).

BRU and A-duplex MAC protocols, the AUB MAC protocol achieved throughput improvements of up to 9.8% and 43.6% and of 9.2% and 38.3% on average. The relative error in the saturation throughput between the performance analysis and simulation results was 0.5% on average. The main causes of the relative errors are the random generations of IFR among nodes and k data frames held by the AP. Therefore, the simulations validated our performance analysis.

B. Saturation Throughput vs. IFR Ratio (h)

Fig. 7 shows the simulation results for the saturation throughput of three MAC protocols as the IFR ratio was changed from 0.05 to 0.5 when n was 26 and k was 10. When h is set to 0.05, the probability of establishing asymmetric full-duplex links is low because most nodes are in each other's interference zones. In addition, symmetric full-duplex links can only be established if the AP and a node have data to send to each other. Therefore, the opportunity to establish full-duplex links is quite limited and many data transfers are performed on half-duplex links, resulting in low throughput for all protocols. As h increases, the possibility of establishing full-duplex links of the three MAC protocols increases. Consequently, the saturation throughputs of the three MAC protocols increase. When h is set to 0.25 or higher in the AUB MAC protocol, the change in saturation throughput is small because most of the data transfer is performed on full-duplex links and the number of continuously established full-duplex links using the Delayed ACK method gradually converges to k. Compared with the BRU and A-duplex MAC protocols, the AUB MAC protocol achieved throughput improvements of up to 9.8% and 38.5% and of 9.3% and 34.8% on average. The relative error of saturation throughput between the performance analysis and simulation results is 1.2% on average.

C. Saturation Throughput vs. Number of Data Frames Held by the AP (k)

Fig. 8 shows the simulation results for the saturation throughput of the three MAC protocols as the number of data frames held by the AP was changed from 4 to 25 when n was 26 and h was 0.1. When the channel access competition begins, k non-overlapping nodes are randomly selected, and k data frames are generated from the AP's buffer and correspond one-to-one with the selected nodes. Accordingly, if k is set to 19, the AP has 19 data frames to send to randomly selected nodes when the channel access competition begins. When k is set to 4, the AP only has 4 data frames to send to 4 randomly selected nodes. Because k is small, the probability of establishing a full-duplex link is also low. Therefore, many data frames are sent on half-duplex links, resulting in low saturation throughput for all protocols. In particular, the saturation throughput of the BRU and AUB MAC protocols is almost the same. Even if a first full-duplex link is established, the probability of a second full-duplex link being established continuously is low due to the small value of k. Additionally, the BRU MAC protocol also has a low collision overhead because it uses a one-to-one collision resolution method between one AP and one non-AP node. As k increases, the saturation throughputs of the three MAC protocols increase because the possibility of establishing full-duplex links increases. In addition, the AUB and BRU MAC protocols increase the number of full-duplex links established without competition. Compared with the BRU and A-duplex MAC protocols, the AUB MAC protocol achieved throughput improvements of up to 10.3% and 39.6% and of 8.6% and 36.4% on average. The relative error in the saturation throughput between the performance analysis and simulation results is 0.9% on average. Overall, as h and k increase, more full-duplex links are established by the Delayed ACK method, which increases the throughput of the AUB MAC protocol.

VI. Discussion

The throughput of the AUB MAC protocol increased with the number of full-duplex links configured with the Delayed ACK method. For simplicity, our performance analysis and simulation randomly selected a downlink node among the nodes that satisfied the conditions of the Delayed ACK method. Thus, the number of full-duplex links set using the

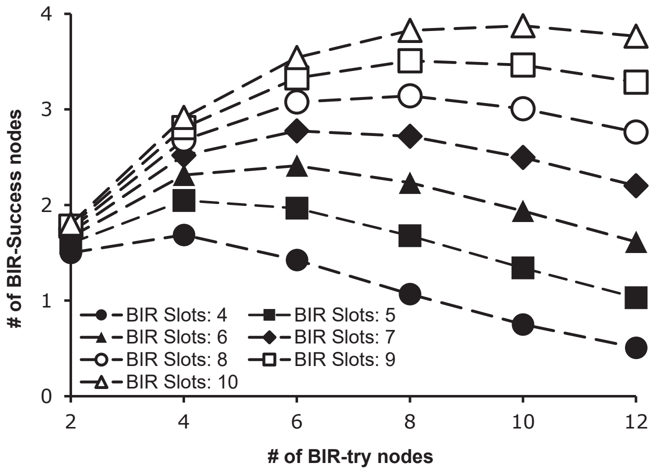

Fig. 9. The number of BIR-success nodes according to the numbers of BIR-try nodes and BIR slots.

Delayed ACK method is not the maximum. If an optimal downlink node selection algorithm that can maximize the number of full-duplex links configured with the Delayed ACK method is utilized, the throughput of the AUB MAC protocol would further increase.

The performance analysis and simulation assumed that the AP sufficiently knew the buffer information among the nodes. Let B_{suc} and B_{try} be the numbers of BIR-success nodes and BIR-try nodes, respectively, when the number of BIR slots is l. For a node to become a UC node, it must have data to transmit and an IFR with the current downlink node. Thus, B_{try} is $h(n-1)$. For a successful reporting of buffer information during an IUP, each BIR slot must be chosen by only one BIR-try node. B_{suc} is calculated as follows:

$$B_{suc} = B_{\text{try}}(1-\frac{1}{l})^{B_{\text{try}}-1}. \quad (14)$$

If B_{suc} is greater than one, on average, at least one node reports buffer information to the AP whenever a full-duplex link is established. Therefore, after a certain time, the AP can sufficiently know the buffer information of the node. Fig. 9 shows the estimated B_{suc} according to the change in B_{try} and l in (14). B_{suc} is greater than one in most cases, except when B_{try} is large and l is small. If B_{suc} is less than one, other BIR methods using ACK frames [21] or collisions [22] can be utilized. Therefore, we believe that the AP knows the buffer information among the nodes sufficiently. In addition, we will consider the advanced BIR attempt method in a future study. In the current BIR attempt method, all UC nodes attempt to report the buffer information to the AP. However, if the length of the IUP is considerably short or if too many UC nodes attempt to report buffer information, their BIR fails with a high probability. Therefore, an advanced BIR attempt method that operates stably in this situation should be considered in a future study.

In this study, we focused on solving the IUP problem on a WLAN with only a single BSS. However, in a WLAN, multiple BSSs exist and interfere with each other. In particular, due to the characteristics of full-duplex radio, the AP and a non-AP node transmit signals simultaneously, causing more interference to neighboring BSSs. Also, for simplicity, we did not consider residual self-interference signals. Therefore, we consider solving the IUP problem in the real WLAN with residual self-interference signals and multiple BSSs as another future study.

VII. CONCLUSION

A full-duplex radio can double the efficiency of a frequency band. However, to effectively exploit full-duplex radio, the IUP problem must be addressed. An IUP often occurs on a full-duplex link because of the nature of real WLAN traffic. When an IUP occurs, the uplink frequency band is wasted, which reduces the benefits of the full-duplex radio. However, during the IUP, UC nodes can transfer signals to the AP without interfering with the downlink node. Therefore, a method for reducing IUP is required to increase the efficiency of the uplink frequency band. We proposed an AUB MAC protocol that effectively reduces the IUP by sending an uplink ACK frame and the buffer information of the nodes. It exploits the Delayed ACK method and newly defined control frames to transmit ACK and BIR frames during the IUP. Consequently, the AUB MAC protocol achieved a throughput improvement of up to 43.6% compared with the existing protocol by reducing the number of control frame transmissions and the IUP. The AUB MAC protocol is more efficient in real WLANs than existing studies because it is designed to consider the request-response traffic pattern, which is the most common traffic pattern in real WLANs. In addition, most of the full-duplex MAC protocols proposed in the literature are designed based on IEEE 802.11 DCF, which is also the case in this study. Therefore, the Delayed ACK method, which improves the uplink frequency band of full-duplex links by sending an uplink ACK frame during an IUP, can be easily adapted to existing full-duplex MAC protocols.

APPENDIX A

TABLE II

ABBREVIATIONS AND ACRONYMS DEFINITIONS.

Abbreviation/Acronym	Description
ACK	acknowledgment
AFL	asymmetric full-duplex link
AID	association identifier
AP	access point
AUB	ACK, uplink data, and buffer information
BIR	buffer information reporting
BSSs	basic service sets
CTS	clear-to-send
DCF	distributed coordination function
DIFS	distributed inter-frame space
FACK	full-duplex ACK
FACTS	full-duplex ACK and CTS
FCTS	full-duplex CTS
IFR	interference-free relationship
IUP	idle uplink period
MAC	medium access control
OFDM	orthogonal frequency division multiplexing
PLCP	physical layer convergence procedure
RTS	request-to-send
RSSI	received signal strength indicator
SFL	symmetric full-duplex link
SIC	self-interference cancellation
SIFS	short inter-frame space
UC node	uplink transmission candidate node
WLANs	wireless local area networks

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