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Cloud-Based Wi-Fi Network Using Immediate ACK in Uplink Data Transmissions

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ABSTRACT In a cloud-based network architecture, the central unit (CU) at the cloud coordinates wireless nodes such as the remote access units (RAUs) at the edges of the network and manages most functions for providing wireless connectivity services to clients. The CU facilitates efficient communication resource management such as radio frequency or transmission power of RAUs by global resource coordination. In this paper, we propose a cloud-based Wi-Fi network architecture consisting of a CU and RAUs as an improvement on the conventional Wi-Fi architecture with traditional access points (APs). We then propose a method for uplink data transmission in a cloud-based Wi-Fi network. In a conventional Wi-Fi network with independently operating APs, APs close to each other may not be able to utilize the same frequency band efficiently because of significant amounts of interference. However, in a cloud-based Wi-Fi network, the CU coordinates RAUs so that they can operate in the same frequency band by transmitting or receiving signals through the shared wireless medium to improve spectral efficiency. For each frequency band, the proposed system utilizes a diversity combining that combines multiple signals and introduces a single improved signal with high signal-to-noise ratio for uplink transmission in the cloud-based Wi-Fi network. In our proposed uplink transmission method for a cloud-based Wi-Fi network, we utilize diversity combining with the immediate acknowledgement (ACK) transmission method that transmits the ACK frame to the client immediately before decoding. The proposed uplink data transmission method mitigates the performance degradation caused by the fronthaul propagation delay between the CU and RAUs, without significant modification of the IEEE 802.11 standard. Using an IEEE 802.11n standard-compliant simulation and experiments with software-defined radio equipment, we verify the goodput performance of the proposed method for a cloud-based Wi-Fi network architecture.

INDEX TERMS Cloud-based Wi-Fi networks, cooperative diversity combining, MAC protocol.

I. INTRODUCTION

A centralized wireless network architecture, in which remote radio heads (RRHs) equipped with radio-frequency (RF) modules located at the ends of the network and a central unit (CU) in the cloud coordinates network traffic, manages network resources, and performs signal processing has recently attracted research attention. The central processing at the CU facilitates efficient communication resource management to improve wireless connectivity performance by globally controlling communication resources of RRHs such as RF or transmission power allocation. Moreover, because most operations for providing data services including baseband signal processing or wireless medium access control (MAC) are performed at the CU in the cloud, service maintenance and updating new communication protocols of a cloud-based network are easier than those of the conventional decentralized network. Because of these advantages, much recent research has focused on centralized or cloud-based radio access network (CRAN) architecture and related methods for resource management in cellular networks [1], [2].

Although this cloud-based network architecture has many advantages and much potential, applying central network architecture to the Wi-Fi networks has not been much focused. That is, a Wi-Fi network is a public network that can be established by anyone who connects the legitimate access points (APs) to the Internet, and thus, backward-compatibility of protocols for a cloud-based Wi-Fi network is highly necessary. Moreover, short communication range of a Wi-Fi service requires tighter time-out bound of message transmissions compared to the cellular network with large coverage. However, as many APs for a Wi-Fi network are deployed densely to support high traffic demand, coordination and resource management of the APs become an important way to improve wireless service performance [3]. APs in conventional Wi-Fi networks provide wireless connectivity services independently of each other using the same industrial, scientific, and medical (ISM) radio bands. Hence, in a Wi-Fi network with densely deployed APs, interference from other APs or clients connected to them can significantly degrade the signal-to-noise ratio (SNR). The transmitted data is unlikely to be decoded successfully with a degraded SNR. Therefore, in a large area with densely deployed APs, the central processing that controls the communication resources of APs such as RF or power allocation in order to mitigate interference is important [4].

In this paper, we propose a cloud-based Wi-Fi network architecture consisting of CU at the cloud and remote access units (RAUs) with RF modules at the edges of the network. We then propose a method for uplink data transmission in a cloud-based Wi-Fi network. In the proposed centralized Wi-Fi network, most operations for providing the wireless connectivity services are processed at the CU, and the CU coordinates multiple RAUs located close to each other to receive signals cooperatively within a single channel to improve uplink throughput performance. The CU can utilize multiple RAUs as receivers for serving same client so that data received at multiple RAUs can be constructively combined to improve SNR and throughput performance. With diversity combining for constructive signal aggregation, highly reliable connectivity services with high data rates can be achieved in the proposed cloud-based Wi-Fi networks. The proposed method for uplink data transmission also solves the problem of long propagation delay between RAUs and the CU to adopt cloud-based network architecture in Wi-Fi networks. Because the CU is not located at the edge of the network like conventional APs, which are connected to clients directly through a wireless medium, the additional propagation delay caused by the links between the RAUs and the CU renders the conventional IEEE 802.11 standard inappropriate for direct application to a cloud-based Wi-Fi network architecture. In the IEEE 802.11 protocol, a receiver notifies a transmitter of successful signal reception by transmitting an acknowledgement (ACK) frame. Although the CU tries to transmit an ACK frame after decoding received data, the ACK frame might not be transmitted to the client in the given time-out duration because of a long propagation delay between the CU and RAU. To overcome this problem, many studies have focused on modifying the time parameters of the IEEE 802.11 protocol such as slot time or time-out duration. Nevertheless, increasing the slot time or time-out duration to accommodate the propagation delay in a cloud-based network will fundamentally degrade throughput performance owing to the time overhead. Unlike the previous work, the proposed method does not increase time overhead, but transmits an ACK frame before decoding the received data if successful decoding is expected. Thereby, the proposed method mitigates the performance degradation caused by a long propagation delay while maintaining backward-compatibility with the IEEE 802.11 protocol in terms of time.

The main contributions of this work are as follows:

- In this paper, we propose a cloud-based Wi-Fi network architecture consisting of CU and RAUs. Unlike the conventional Wi-Fi network with independently operating APs, in the proposed cloud-based Wi-Fi network, the CU globally controls communication resources and coordinates multiple RAUs to improve throughput performance.
- A diversity combining-based uplink method is proposed to increase the probability of successful signal decoding in a cloud-based Wi-Fi network. Unlike the conventional Wi-Fi networks, in which APs perform baseband signal processing independently, the proposed method performs baseband-signal-level cooperative diversity combining using multiple RAUs and provides highly reliable connectivity services.
- The proposed method mitigates the problem of propagation delay between CU and RAUs by allowing the CU to preemptively transmit an ACK frame before all client data have been decoded.
- We verify the improved goodput performance of our proposed method using IEEE 802.11 standard-compliant simulations and software-defined radio (SDR) equipment-based experiment.

The remainder of this paper is organized as follows. Section II overviews related work about cloud-based Wi-Fi networks. In Section III, we present a system model of the proposed uplink transmission system in a cloud-based Wi-Fi network. Then, in Section IV, we explain the proposed uplink transmission protocol that uses immediate ACK frame and diversity combining. In Section V, results of the IEEE 802.11n standard-compliant simulations are presented, and SDR-based experimental results are presented in Section VI. Section VII concludes the paper.

II. RELATED WORK

Deronne *et al.* [5] investigated IEEE 802.11g performance in a network in which the central AP (or CU) responsible for Wi-Fi service is connected to RAUs through optical links, and RAUs establish the wireless connections with clients. They found that the propagation delay caused by wired links between the RAUs and the AP (or CU) may lead to significant performance degradation, if ACK messages arrive at nodes after the predefined time-out duration. This is because the propagation delay of the wired links was not considered when the time-out value was designed for the IEEE 802.11g standard. Deronne *et al.* have proposed increasing the slot time in the IEEE 802.11g standard and have numerically analyzed the throughput performance with respect to various fiber lengths. However, increasing the time-related parameters defined in the IEEE 802.11 standard may fundamentally increase time overhead and degrade the throughput performance of the Wi-Fi network.

Zhang and Franklin [6] mathematically analyzed the feasibility of using the IEEE 802.11 standard for cloud-based Wi-Fi networks. They modeled the throughput performance of the block ACK mechanism based on Markov chain. To model the latency in the cloud-based Wi-Fi network architecture, they adopted the shifted gamma distribution. Their results show that the conventional distributed coordination function (DCF) mechanism is not suitable for a cloud-based Wi-Fi network with long latency. They also found that the block ACK mechanism defined in the IEEE 802.11 standards mitigates performance degradation caused by these long latencies. Deronne *et al.* [7] also studied the frame-aggregation mechanism specified by IEEE 802.11n for use in a centralized Wi-Fi network. Unlike previous WLAN standards such as the IEEE 802.11 a/b/g, IEEE 802.11n includes frame aggregation that integrates multiple data frames into a single data frame and then transmits the aggregated frame to enhance transmission efficiency. After the aggregated data block is received, the receiver transmits a block ACK. The transmitter waits for this block ACK from the receiver for the block ACK time-out period designated when the frame aggregation scheme is set up. In [7], Deronne *et al.* set the block ACK time-out to 300 μs and numerically analyzed the performance of the IEEE 802.11n frame aggregation mechanism. They found that frame aggregation mitigates the performance degradation caused by propagation delays in a centralized Wi-Fi network architecture. However, frame aggregation can only be used when the client has large amount of uplink data to transmit consecutively.

Nishio *et al.* [8] investigated the problem of unexpected frame collisions caused by long propagation delay, and proposed an increase in the network allocation vector (NAV) of Wi-Fi nodes to avoid frame collisions in a centralized Wi-Fi network. In a conventional Wi-Fi network without centralized processing, when transmission from another node is detected, nodes in the network wait as long as the NAV to avoid frame collisions. However, because RAUs and clients in the centralized network have the additional delay caused by propagation in the wired network, the NAV defined in the standard cannot avoid collisions between nodes. Hence, the Nishio *et al.* suggested increasing the NAV of decentralized Wi-Fi nodes to be as much as twice the propagation delay in a wired fronthaul network, and they analyzed the performance of that NAV-increasing approach. Funabiki *et al.* [9] also studied the issue of coexistence of a conventional Wi-Fi network and the centralized Wi-Fi network and proposed a system called advanced transmission for radio over fiber-based WLAN (ATRAS). Instead, of increasing the NAV of conventional nodes in a decentralized Wi-Fi network, the proposed ATRAS method decreases the NAV of centralized Wi-Fi nodes by as much as two times the propagation delay. After waiting this short NAV, the RAU in the centralized Wi-Fi network transmits data with probability α. By adjusting the transmission probability α, the ATRAS method efficiently balances the amount of traffic handled by the conventional and centralized Wi-Fi networks.

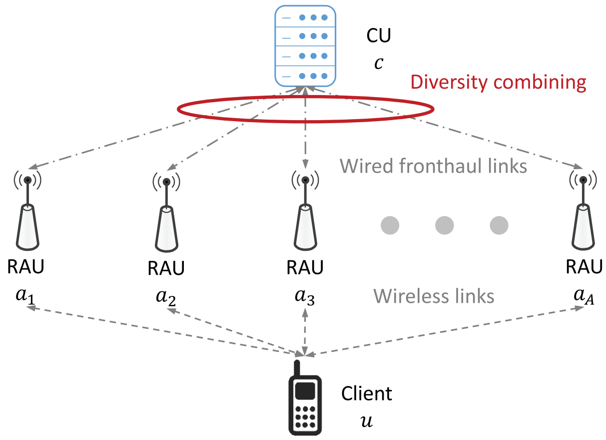


FIGURE 1. **A cloud-based Wi-Fi network system for a single channel.**

In cloud-based Wi-Fi networks, both throughput performance and performance degradation due to propagation delay are key research issues [5]–[9]. However, the frame aggregation approach may not be applicable in various scenarios, the approach of increasing slot time also increases time overhead, and adjusting the NAV is inappropriate in scenarios that involve highly time-variant propagation delays. In this paper, we propose an uplink data transmission method for cloud-based networks that implements a signal-level diversity combining and a preemptive ACK frame to improve the wireless connectivity service performance.

III. SYSTEM MODEL

In this paper, we consider an uplink transmission scenario in which a CU in the cloud performs most signal processing, including decoding. The CU controls RAUs that are connected through wired fronthaul links, as shown in Fig. 1. Let u be a client that tries to transmit uplink data, $\mathcal{A} = \{a_1, a_2, \cdots, a_A\}$ be the RAUs within the communication range of the client, and c be the CU that controls the RAUs in the Wi-Fi network. The signal received at each AP a_i, $i \in \{1, 2, \cdots, A\}$, can be represented as

$$y_{a_i} = h_{u,a_i}\sqrt{p_u}x_u + z_{a_i}, \tag{1}$$

where h_{u,a_i} is the channel coefficient from client u to RAU a_i, p_u is the transmission power of client u, x_u is the transmitted symbol, and z_{a_i} is additive white Gaussian noise with variance σ^2 at the RAU a_i. Using (1), the SNR γ_{a_i} at RAU a_i is given by

$$\gamma_{a_i} = \frac{p_u|h_{u,a_i}|^2}{\sigma^2}. \tag{2}$$

The RAUs in the network transmit received data to the CU through wired fronthaul links for diversity combining, and we denote the propagation delay of the wired fronthaul link

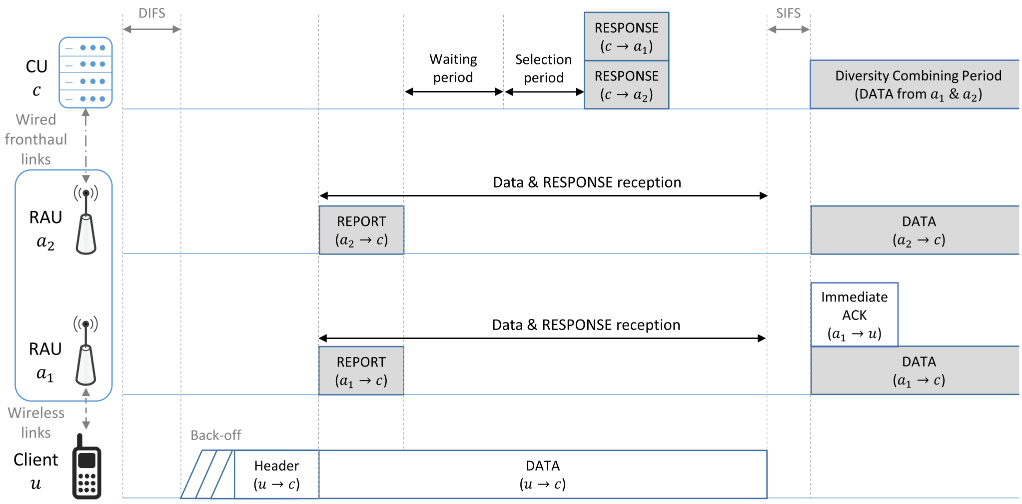


FIGURE 2. **The proposed cloud-based Wi-Fi MAC protocol using immediate ACK for uplink data transmissions in a network with two RAUs.**

between RAU a_i and CU c as $\tau_{a_i,c}^{PRO}$. After the RAUs deliver the received data to the CU, the CU applies diversity combining. The proposed system uses maximal-ratio combining (MRC) to exploit multiple RAUs as receivers for signal-level cooperation. Under the MRC, signals from multiple antennas are combined with different weights according to their SNR level [10].

Let $\mathcal{S}$ be the RAU set for MRC among all RAUs, i.e., $\mathcal{S} \subseteq \mathcal{A}$. The instantaneous SNR per bit at the output of the MRC diversity receiver is as follows [11]:

$$\gamma_{\mathcal{S}} = \sum_{a_i \in \mathcal{S}} \gamma_{a_i}. \tag{3}$$

By combining multiple signals from the RAUs in $\mathcal{S}$ using MRC, the CU yields a single improved signal, which increases the probability of successfully decoding the uplink data.

IV. IMMEDIATE ACK-AIDED UPLINK TRANSMISSION METHOD IN THE CLOUD-BASED Wi-Fi NETWORK

A. IMMEDIATE-ACK Wi-Fi MAC PROTOCOL

In a cloud-based Wi-Fi network, the throughput performance is significantly affected by the propagation delay between the RAUs and the CU. Although centralized baseband signal processing improves computational efficiency and makes coordination of multiple RAUs easy, long propagation delays between the RAUs and the CU degrade system performance. One solution is to increase the time parameters, such as slot time or ACK time-out defined in the IEEE 802.11 standards, but this also degrades throughput performance by increasing time overhead. Instead, the CU can immediately transmit an ACK frame before the received data is completely decoded to mitigate performance degradation caused by propagation delays. However, if the probability of successful decoding is low, this immediate-ACK transmission may significantly degrade the throughput performance. To improve the throughput performance, we propose to exploit multiple RAUs located near the client. The CU performs diversity combining so that data received from multiple RAUs near the client are combined into a single improved signal. If the MRC technique for diversity combining is applied, the SNR values at RAUs can be summed as shown in (3), and the CU can thereby improve the SNR. Because this makes it possible to achieve an improved SNR in a cloud-based Wi-Fi network, the average bit error ratio (BER) decreases and throughput performance will increase. However, because the central computation procedure is not applied in previous MAC protocols for Wi-Fi networks, a new Wi-Fi MAC protocol must be designed for cloud-based Wi-Fi networks. In this section, we propose an immediate-ACK MAC protocol for cloud-based Wi-Fi networks.

Figure 2 diagrams the operation of the proposed immediate-ACK MAC protocol for uplink transmission in a cloud-based Wi-Fi network with two RAUs. Note that wired and wireless transmissions are illustrated in gray and white boxes, respectively. Client u transmits uplink data to RAU a_1 through a wireless link, and RAUs a_1 and a_2 are connected to CU c through wired fronthaul links. The procedure of the immediate-ACK Wi-Fi MAC protocol is as follows:

(P1) The client that grabs the channel after backoff transmits a signal to the RAU. In the IEEE 802.11 standard, the transmitted signal consists of two parts: header and data. The header contains information about the signal, such as modulation and data length. When the RAUs receive the header of the transmitted signal from the client, they deliver the received I/Q samples to the CU. We denote this message transmitted from the RAUs to CU as a REPORT message. In Fig. 2, RAUs a_1 and a_2 transmit a REPORT message to the CU c after receiving the header of the signal from the client u.

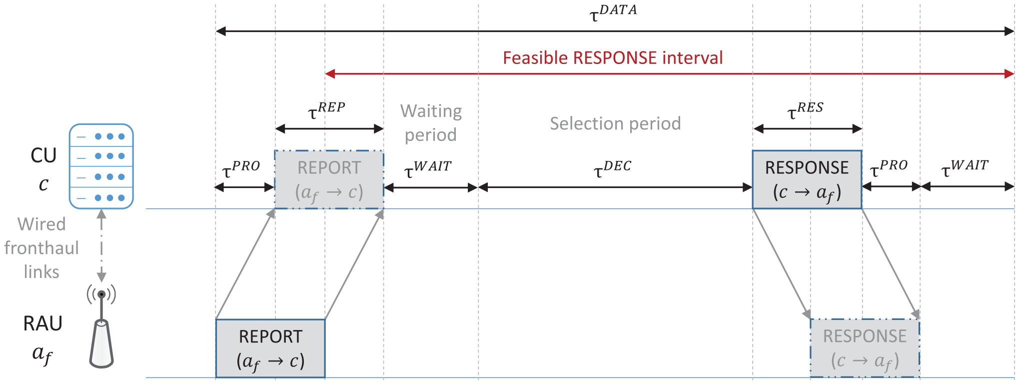


FIGURE 3. Selection of RAU set for diversity combining in uplink transmission.

(P2) The CU gathers the REPORT messages from the RAUs during a waiting period. Using the aggregated information of REPORT messages, during the selection period, the CU decides which RAUs ($\mathcal{S}$) will transmit received data to the CU for diversity combining if diversity combining is required for the uplink signal from client u. Then, the CU notifies the RAUs of its decision by transmitting RESPONSE messages. Note that among the RAUs available for diversity combining, the CU designates one RAU as a node for transmitting the ACK message to the client and includes the ACK information in the RESPONSE message to that RAU (for example, a_1 in Fig. 2). If unsuccessful decoding is expected due to low SNR, RESPONSE does not include ACK information. The details of the procedures for the waiting and selection periods are described in Sections IV-B and IV-C, respectively.

(P3) After RAU a_1 receives the RESPONSE message from CU c, RAU a_1 immediately transmits an ACK message (immediate ACK) to client u, although data decoding in the CU has not yet been completed. At the same time, the RAUs designated for diversity combining begin to transmit received data to the CU. At the CU, data from multiple RAUs are aggregated and combined into a single improved signal through diversity combining. Note that if SNR level is too low to decode data, the CU does not select any RAUs for diversity combining and no RAUs transmit data to the CU.

The propagation delay between an edge node like an RAU and the CU significantly decreases throughput performance. The proposed MAC protocol utilizes diversity combining with an immediate ACK scheme to improve the throughput performance and prevent the performance degradation caused by propagation delay between the RAU and the CU. When uplink transmission begins, the CU gathers REPORT messages, and with this collected information, the CU determines the set of RAUs to be used for diversity combining and delivers results to the RAUs before the data transmission from the client has ended. Then, an ACK is transmitted immediately after data transmission from the clients has been completed. Therefore, no additional time is required before the ACK is transmitted. In the following Sections IV-B and IV-C, we discuss the detailed processes in the CU.

B. SELECTION OF FEASIBLE RAUs FOR DIVERSITY COMBINING

In this section, we describe the details of the decision process to select a set of feasible RAUs. In the proposed method, the CU performs diversity combining with multiple RAUs located at the ends of the network by exchanging REPORT and RESPONSE messages. To guarantee effective diversity combining using multiple RAUs in a cloud-based Wi-Fi network, the CU needs to identify the set of RAUs that can transmit and receive REPORT and RESPONSE messages, respectively, before data transmission from the client ends.

Let the RAU from which the CU receives the first message be a_f. When the CU first receives the message from RAU a_f, the CU begins to gather information from the other RAUs. To gather information from other RAUs, the CU must wait for a period owing to the various propagation delays between RAUs and the CU; we call this period the waiting period, τ^{WAIT}. We denote the transmitted and received times of REPORT message for the RAU a_f as $t^{REP,tx}_{a_f,c}$ and $t^{REP,rx}_{a_f,c}$, respectively. Then the propagation delay between RAU a_f and CU c is given by $\tau^{PRO}_{a_f} = t^{REP,rx}_{a_f,c} - t^{REP,tx}_{a_f,c}$. We also denote the durations of the REPORT message, RESPONSE message, and selection period as τ^{REP}, τ^{RES}, and τ^{DEC}, respectively, as shown in Fig. 3. Let the uplink data length and rate from the client be l^{DATA}_c and r^{DATA}_c, respectively. Then, the duration τ^{DATA} of the data transmitted from the client is simply calculated as $\tau^{DATA} = l^{DATA}_c / r^{DATA}_c$. If we assume that the propagation delay from a RAU to the CU and the delay from the CU to the RAU are symmetric, then the total communication delay between the RAU and the CU satisfies the following condition:

$$2\tau^{PRO}_{a_f} + \tau^{REP} + 2\tau^{WAIT} + \tau^{DEC} + \tau^{RES} \leq \tau^{DATA}. \quad (4)$$

On the basis of the message from RAU a_f, the maximum waiting period to gather information from other RAUs is as follows,

$$\begin{aligned}\tau_{max}^{WAIT} &= \max\{\tau^{WAIT}\} \\ &= (\tau^{DATA} - 2\tau_{a_f}^{PRO} - \tau^{REP} - \tau^{DEC} - \tau^{RES})/2. \end{aligned} \tag{5}$$

If $\tau_{max}^{WAIT} < 0$ or the waiting period is longer than τ_{max}^{WAIT}, the RESPONSE message does not arrive at the RAU before the transmission from the client ends. Consequently, the uplink data transmission is likely to fail because the SNR level will not be high enough for successful decoding. From RAUs $a_i \in \mathcal{A}$ that are in the communication range of client u, the CU gathers the REPORT messages that arrive within $\tau_{max}^{WAIT} \geq 0$, which satisfies

$$\tau_{a_i}^{PRO} + \tau^{REP} \leq \tau_{a_f}^{PRO} + \tau^{REP} + \tau_{max}^{WAIT}. \tag{6}$$

Note that, in the uplink transmission scenario, only the terms for the transmitted data length l_c^{DATA} and rate r_c^{DATA} are adjustable by the client, and the rest of the terms depend on the network environment. We denote the feasibility indicator function for RAU $a_i \in \mathcal{A}$ as $I_{a_i}(l_c^{DATA}, r_c^{DATA}) = \tau_{a_f}^{PRO} + \tau_{max}^{WAIT} - \tau_{a_i}^{PRO}$. Then, the inequality in (6) can be rewritten as follows:

$$I_{a_i}(l_c^{DATA}, r_c^{DATA}) \geq 0. \tag{7}$$

Let $\mathcal{A}^{DC}$ be the set of RAUs that satisfies the propagation delay constraints in (7), i.e.,

$$\mathcal{A}^{DC} = \{\{a_i\} \mid I_{a_i}(l_c^{DATA}, r_c^{DATA}) \geq 0, \ \forall a_i \in \mathcal{A}\}. \tag{8}$$

Among the RAUs in $\mathcal{A}^{DC}$, the CU selects RAUs to participate in uplink transmission and deliver the received data from client u to CU c while ensuring that the fronthaul traffic overhead for delivering uplink data does not exceed the fronthaul capacity.

C. OPTIMIZATION PROBLEM FORMULATION

Performing diversity combining for uplink transmission, as the number of RAUs participating in the uplink data frame transmission increases, the probability of successful decoding also increases. However, the increased number of RAUs participating in diversity combining introduces considerable traffic overhead in the fronthaul networks, because I/Q samples of large size are transmitted instead of the smaller bit streams that are obtained after baseband signal processing. Therefore, an appropriate subset of RAUs must be selected to transmit uplink data frames to the CU for diversity combining, rather than using all the RAUs in $\mathcal{A}^{DC}$. In the proposed method, the CU calculates the probability of decoding the received data based on SNR levels and the modulation and coding scheme (MCS) denoted in the header. Then, the CU selects the RAUs most appropriate for diversity combining while satisfying the fronthaul capacity constraint.

Let $f(\gamma_{\mathcal{S}})$ and m be the probability density function (PDF) of a Nakagami-m fading channel and its shape parameter. Then, $f(\gamma_{\mathcal{S}})$ is given by

$$f_P(\gamma_{\mathcal{S}}) = \left(\frac{m}{\bar{\gamma}}\right)^{mA} \frac{{\gamma_{\mathcal{S}}}^{mA-1}}{\Gamma(mA)} \exp\left(-\frac{m\gamma_{\mathcal{S}}}{\bar{\gamma}}\right), \quad m \geq 0.5, \tag{9}$$

where $\bar{\gamma}$ is the average SNR per bit for one channel and $\Gamma(\cdot)$ is the gamma function. For the Nakagami-m fading channel, Sharma derived the average bit error probability (BEP) for M-PSK modulation as follows [12]:

$$\begin{aligned}\bar{P}_{\mathcal{S}}^{out,PSK}(\gamma_{\mathcal{S}}, M) &\approx \alpha_1 \left(\frac{m}{\bar{\gamma}}\right)^{mA} \frac{1}{\Gamma(mA)} \frac{(mA-1)!}{\alpha_3^{mA}} \\ &= \alpha_1 \left(\frac{m}{m+\alpha_2\bar{\gamma}}\right)^{mA}, \end{aligned} \tag{10}$$

where $\alpha_1 = \frac{1}{\log_2 M}$, $\alpha_2 = (\log_2 M)\sin^2\left(\frac{\pi}{M}\right)$, $\alpha_3 = \alpha_2 + \frac{m}{\bar{\gamma}}$. For M-QAM modulation, Patterh *et al.* [11] derived the average BEP as follows:

$$\begin{aligned}\bar{P}_{\mathcal{S}}^{out,QAM}(\gamma_{\mathcal{S}}, M) &\approx f_1(M) \sum_{k=1}^{\log_2 \sqrt{M}} \sum_{j=0}^{f_2(M)} \Bigg\{ f_3(j, M) \\ &\quad \times \int_0^{\frac{\pi}{2}} \left[\frac{\bar{\gamma} f_4(j, g, \theta) A\rho\alpha}{\beta m} + 1\right]^{-m} \\ &\quad \times \left[\frac{f_4(j, g, \theta)}{\alpha} + 1\right]^{-m(A-1)} \mathrm{d}\theta \Bigg\}, \end{aligned} \tag{11}$$

where ρ is the correlation coefficient between any two divers RAUs, $\alpha = \frac{m}{\bar{\gamma}(1-\rho)}$, $\beta = \frac{A\rho\alpha}{1-\rho+A\rho}$, $k = \log_2 \sqrt{M}$, $g = \frac{3\log_2 M}{2(M-1)}$, $f_1(M) = \frac{2}{\sqrt{M}\log_2 \sqrt{M}}$, $f_2(M) = (1 - 2^{-k})\sqrt{M} - 1$, $f_3(j, M) = (-1)^{\lfloor \frac{j2^{k-1}}{\sqrt{M}} \rfloor} \left[2^{k-1} - \lfloor \frac{j2^{k-1}}{\sqrt{M}} + \frac{1}{2} \rfloor\right]$, and $f_4(j, g, \theta) = \frac{(2j+1)^2 g}{\sin^2\theta}$.

Let δ be the modulation indicator for one uplink data frame transmission. When the data frame follows M-PSK modulation, $\delta = 1$. Otherwise, for M-QAM modulation, $\delta = 0$. We define the BEP of the uplink transmission in a cloud-based Wi-Fi network, $\bar{P}_{\mathcal{S}}^{out}$, as follows:

$$\bar{P}_{\mathcal{S}}^{out}(\gamma_{\mathcal{S}}, M) = \delta \bar{P}_{\mathcal{S}}^{out,PSK}(\gamma_{\mathcal{S}}, M) + (1-\delta)\bar{P}_{\mathcal{S}}^{out,QAM}(\gamma_{\mathcal{S}}, M). \tag{12}$$

The average BEP of a cloud-based Wi-Fi network is determined by the SNR values of uplink data transmission at the RAUs participating in diversity combining ($\mathcal{S} \subseteq \mathcal{A}^{DC}$). As the number of RAUs in $\mathcal{S}$ increases, the average BEP decreases. However, an increase in the number of RAUs for diversity combining also increases the fronthaul network overhead between the RAUs and CU. The proposed procedure determines the $\mathcal{S} \subseteq \mathcal{A}^{DC}$ that minimizes $\bar{P}_{\mathcal{S}}^{out}(\gamma_{\mathcal{S}}, M)$ without considerably increasing the overhead in the fronthaul network caused by uplink data transmission from the client. The problem is formulated as follows:

$$\begin{aligned} &\underset{\mathcal{S}\subseteq\mathcal{A}^{DC}}{\text{minimize}}\ \bar{P}_{\mathcal{S}}^{out}(\gamma_{\mathcal{S}}, M) \\ &\text{subject to}\ \sum_{a_i\in\mathcal{S}} r_{a_i}^{DATA} \leq R^{max}, \end{aligned} \tag{13}$$

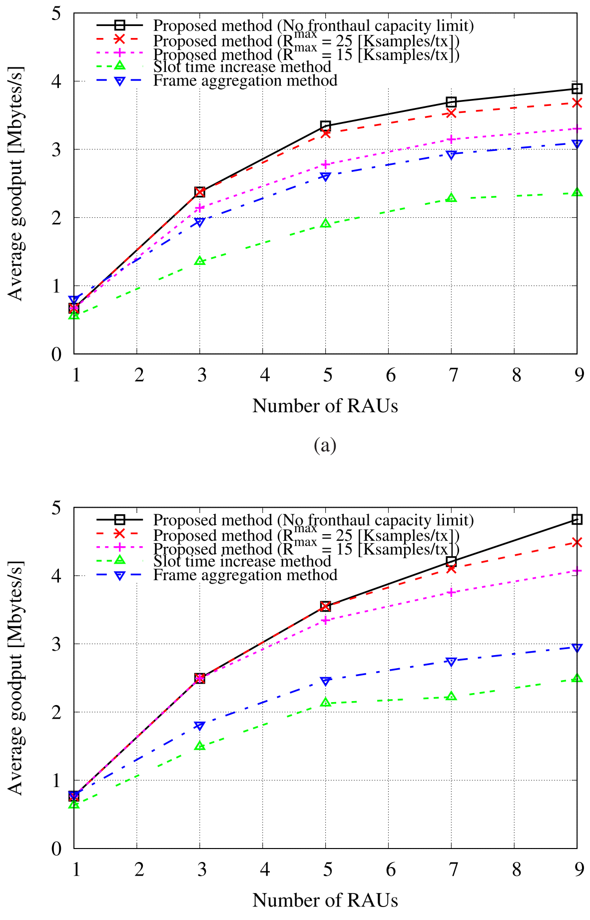
where $r_{a_i}^{DATA}$ and R^{max} are the uplink data rate of RAU a_i in the fronthaul network and the maximum network capacity of the fronthaul network, respectively. Note that $\bar{P}_{\mathcal{S}}^{out}(\gamma_{\mathcal{S}}, M)$ decreases as the number of RAUs participating in diversity combining increases [11], [12]. In other words, for a specific modulation M, $\bar{P}_{\mathcal{S}}^{out}(\gamma_{\mathcal{S}}, M)$ is a submodular function with regard to the SNR $\gamma_{\mathcal{S}}$, and the problem denoted in (13) can be solved by a greedy approach with a lower performance bound of $(1 - e^{-1})$ times the optimum [13]. Moreover, because all the RAUs receive the same signal from the client, the sizes of the I/Q samples transmitted from the RAUs to the CU for uplink transmission are the same, i.e., $r_{a_i}^{DATA} = r_{a_j}^{DATA}$, for $\forall i, j \in \mathcal{S}$. Therefore, the problem formulated in (13) can be solved easily by selecting RAUs with relatively high SNR values as long as the data transmission overhead does not exceed the fronthaul capacity.

V. PERFORMANCE EVALUATION

In this section, we present the results of a simulation designed to evaluate the performance of the proposed immediate-ACK aided uplink method in a cloud-based Wi-Fi network. We compare the proposed method with the method of increasing slot time by increasing the ACK time-out [5], and with the frame-aggregation method that uses block ACK frames [6]. The simulation was implemented in MATLAB and the WLAN system toolbox. The WLAN system toolbox provides standard-compliant IEEE 802.11 functions, and we constructed an IEEE 802.11n-based Wi-Fi network from them. The simulation parameters are listed in Table 1. In the simulation, A RAUs are randomly distributed in a square area 50 m on side, and the client u located at the center of the square area initiates uplink transmission. The propagation delay in the fronthaul network follows the gamma distribution with shape parameter d_k and scale parameter d_θ. We fix d_θ to 1 and perform simulations for various shape parameters d_k. Note that the mean value and variance of the gamma distribution are calculated as $d_k d_\theta$ and $d_k d_\theta^2$, respectively. The delay constraint in the proposed method is determined by the data length and transmission rate, whereas the delay constraints in the comparable methods is determined by the expected propagation delay in the fronthaul network, i.e., $d_k d_\theta$.

TABLE 1. 802.11n-based simulation parameters.

Parameter	Value
Carrier frequency	5.25 GHz
Channel bandwidth	20 MHz
Pathloss exponent	3.5
Small-scale fading	Rayleigh fading
Channel coding	Binary convolutional coding
The number of tx/rx antennas	Tx antennas: 2, rx antennas: 2
Guard interval	800 ns
Transmit power	23 dBm



(a)

(b)

FIGURE 4. Performance comparison for the methods (average delay, 5 μs; MCS, 12). (a) Average goodput when data length is 1024 bytes. (b) Average goodput when data length is 2048 bytes.

Figure 4 shows the average goodput against the number of RAUs in the network when the length of the uplink data is 1024 or 2048 bytes, the average propagation delay in the fronthaul network is 5 μs, and the MCS index is 12. As shown in Fig. 4(a), when the data are 1024 bytes long, the goodput performance of the proposed method increases as the number of RAUs in the network increases, and the proposed method shows higher goodput performance than the other methods. This is because the proposed method utilizes multiple RAUs located near the client for diversity combining, which yields improved signals with high SNR. Note that as the number of RAUs for diversity combining decreases because of limited fronthaul capacity, the average goodput performance of the proposed method decreases. The slot-time-increase and frame-aggregation methods improve performance because the client is connected to the closest RAU, and the statistical distance between the client and the RAU decreases as the number of RAUs increases in a

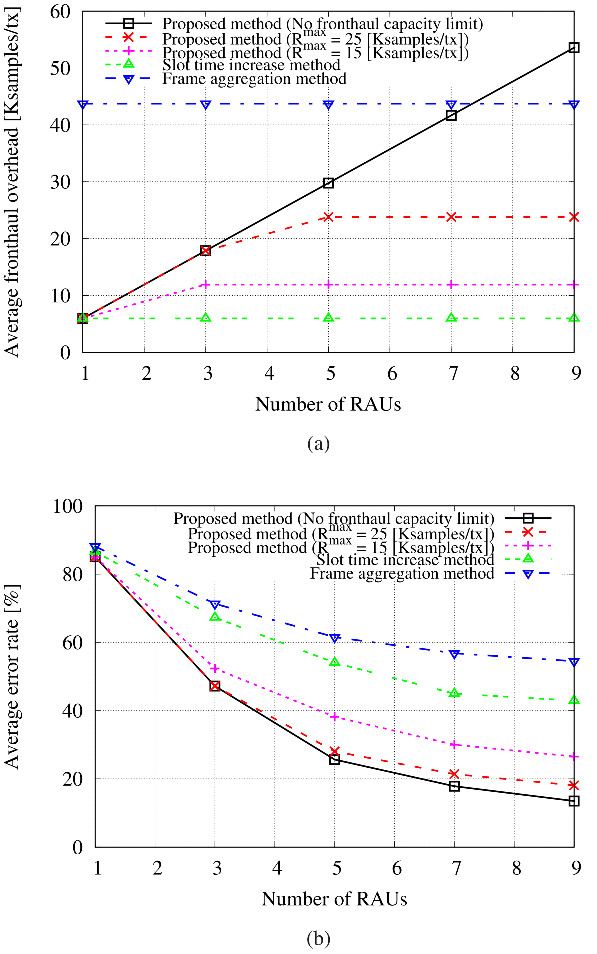
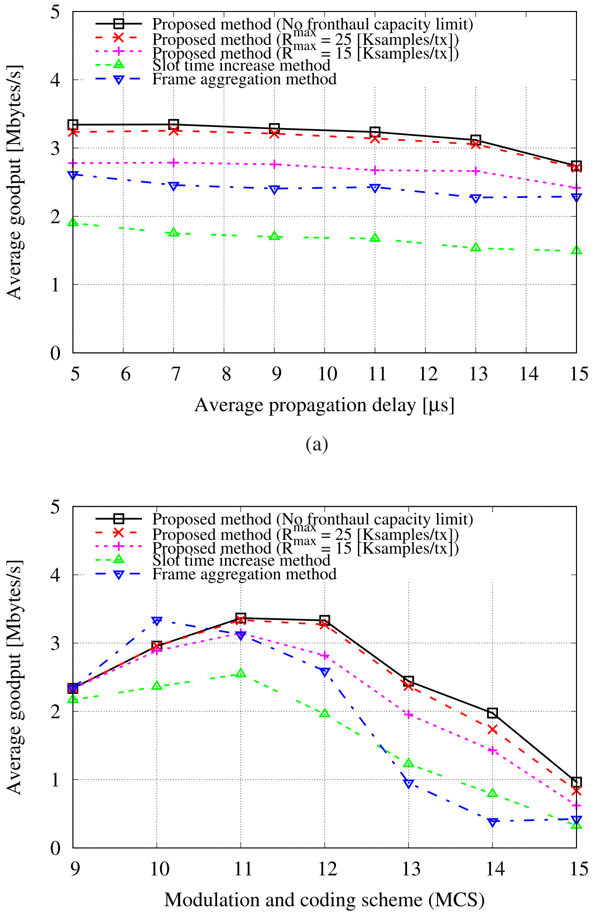


FIGURE 5. **Performance comparison of the methods (average delay, 5 μs; MCS, 12; data length, 1024 bytes). (a) Average fronthaul overhead. (b) Average packet error rate.**

given network area. Figure 4(b) shows the average goodput when the data are 2048 bytes long. Although this is double the data length, the goodput is unexpectedly not doubled, because the probability of successful decoding decreases as the data length increases. Nevertheless, the proposed method performs better than the other methods, because the proposed method can take more time to gather the information for diversity combining as the data length increases, following (5). Due to this relationship, the proposed method becomes more robust against performance degradation due to propagation delay in the fronthaul network as the data length increases.

Figure 5 plots the average fronthaul overhead and packet error rate with respect to the number of RAUs in the network for all three methods we simulated. As shown in Fig. 5(a), the average fronthaul overheads of the proposed methods increase as the number of RAUs used for diversity combining increases, while the fronthaul overheads of other methods are consistent regardless of the number of RAUs. In the proposed method, more I/Q samples are transmitted through the fronthaul network as the number of RAUs increases until the fronthaul capacity constraint is satisfied, though only one RAU at a time transmits signals to the CU in the other methods. Figure 5(b) shows that the packet error rate with the proposed method decreases as the fronthaul capacity increases. This is because the probability of successful decoding increases as more RAUs are selected for diversity combining. On the other hand, although the fronthaul network overheads of the slot-time-increase and frame-aggregation methods remain constant, the average error rate still decreases as the number of RAUs increases. With these methods, as RAUs are deployed more densely, the distance between the RAU and the client is likely to decrease. Note that the error rate of proposed method with no fronthaul capacity limit and the one with $R^{max} = 25$ show small differences, while the fronthaul overhead between the two variations differs greatly. This result implies that the proposed method returns sufficiently high goodput performance even if the fronthaul capacity is limited, and the fronthaul capacity of each link between the RAU and the CU may be adjusted to optimize the network architecture in response to environmental factors such as node density or traffic amount.

Figure 6 shows average goodput performance with regard to the average propagation delay in the fronthaul network and the MCS index. Note that we set the delay distribution in the simulation to a gamma distribution with various shape parameters d_k and fixed the scale parameter $d_\theta = 1$, and both the mean propagation delay and variance were calculated in terms of d_k. Because the delay variance increases as the average propagation delay increases, the outage probability for dissatisfying the delay constraint increases, and the goodput performance decreases if the propagation delay is relatively long. The goodput performances of the proposed method decreases little more sharply than the other methods because the proposed method does not modify the time parameters in the IEEE 802.11n standard. The standard time parameters make gathering information from the RAUs difficult in an environment with long propagation delay. Nevertheless, the goodput performance of the proposed method is consistently higher than the other methods. Figure 6(b) shows the average goodput performance with respect to the MCS index. Note that different MCS indices support different data rates, and for transmissions with a high data rate, a high SNR is necessary. As shown in the results, the goodput performance increases at first, but decreases with higher MCS indices. The gooduput drops off because the high SNR level required for successful decoding becomes difficult to satisfy as the MCS index increases, even though transmission with a high MCS index is intended to support high data rates. The results also show that the proposed method always performs better than the slot-time-increase method, but when the MCS index is 10, the frame-aggregation method performs better than the proposed method. When the MCS index is 10, the outage probability for successful decoding is very low, and thus, transmitting a large amount of aggregated data in the frame-aggregation method yields higher goodput performance than the proposed method. However, for MCS indices greater



(a)

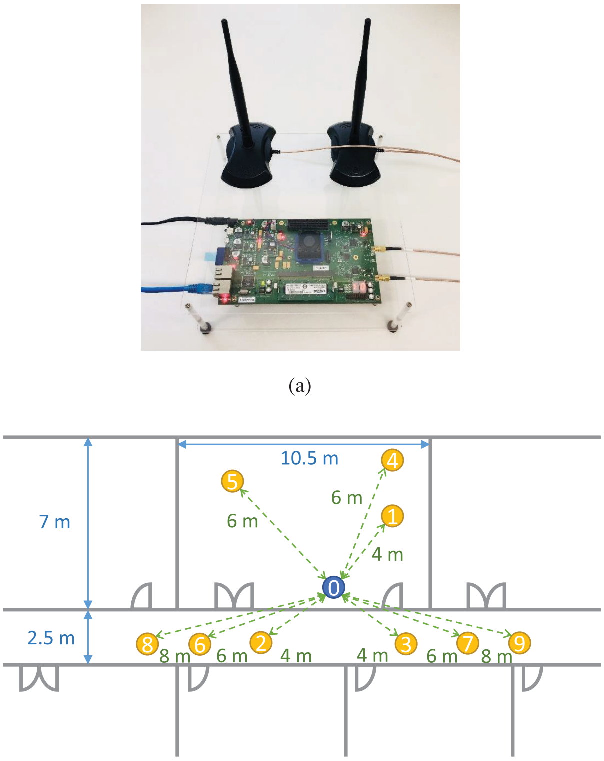
(b)

FIGURE 6. **Performance comparison of the methods (data length, 1024 bytes; number of RAUs, 5). (a) Average goodput versus average propagation delay. (b) Average goodput versus modulation and coding scheme index.**

than or equal to 11, the proposed method shows better performance. According to the results in Figs. 6(a) and 6(b), the proposed method shows generally better goodput performance than the other methods for dealing with propagation delay in cloud-based Wi-Fi network environments.

VI. EXPERIMENTAL RESULTS

In this section, we present the results of an experiment using SDR equipment. We implemented a client and RAUs on the Wireless Open Access Research Platform (WARP) hardware pictured in Fig. 7(a). Figure 7(b) shows the experimental network topology. We placed the client node at location 0, and the client transmitted data to RAUs located at points 1 to 9. In this test, the client transmits 1440 bytes of uplink data with 16-QAM modulation, and power of −16 dBm. When the RAUs receive this data from the client, they deliver the received data to the computer acting as a CU through Ethernet. Then, the computer combines data from multiple RAUs using MRC. The RAUs for diversity combining are added following the order of the locations presented in Fig. 7(b). For example, when the number of RAUs is three, RAUs located at points 1, 2, and 3 deliver the received data to the computer for diversity combining. In the experiment, we manually adjusted the propagation delays between the RAU and the computer so that they followed the gamma distribution as described in Section V.



(a)

(b)

FIGURE 7. **Experimental environment using SDR equipment. (a) SDR equipment: WARP v3 board. (b) Experimental network topology.**

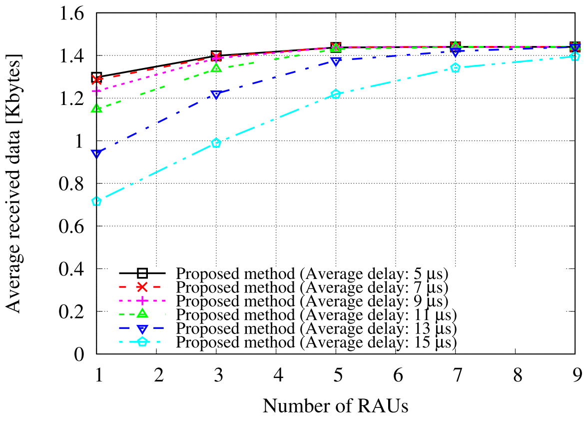


FIGURE 8. **Successfully received data using SDR-based testbed.**

Figure 8 plots the average amount of received data against the number of RAUs when the number of data transmissions is 1000. The performance of the proposed method degrades as the propagation delay between RAUs and the computer increases. Note that when relatively few RAUs are in the network, the probability that a sufficient number of RAUs satisfies the constraint in (7) is low. However, as the number of RAUs located close to the client increases, the delay constraint is more likely to be satisfied, and a greater number of RAUs can be used for diversity combining, so the performance improves. This experiment verifies the feasibility of the proposed method in a real indoor environment and shows that the proposed method is a good solution for improving goodput performance in a cloud-based Wi-Fi network.

VII. CONCLUSION

In this paper, we have proposed an uplink transmission method that implements immediate ACK frames in a cloud-based Wi-Fi network. The proposed method utilizes multiple RAUs located near the client as receivers for diversity combining. Since diversity combining is handled by the CU in the cloud with signals from multiple RAUs, a sufficiently high SNR to guarantee decoding of the received uplink data is achieved. The proposed method also mitigates the performance degradation caused by propagation delay between RAUs and the CU in a cloud-based Wi-Fi network using immediate-ACK strategy. Through extensive simulations with models of IEEE 802.11n-compliant network environment and SDR-based experiment, we showed that the goodput performance of a cloud-based Wi-Fi architecture is improved by the proposed method.

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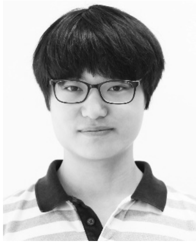

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