Energy-Efficient Full-Duplex MAC Protocol Design for Air–Terrestrial Communication

Tae-Yoon Kim, Jin-Ki Kim, Won-Jae Lee, Soyi Jung, and Jae-Hyun Kim

***Abstract*—Wireless communication using unmanned aerial vehicles (UAVs), such as drones, is expected to be a promising solution for improving spectral efficiency in 5G wireless networks. Moreover, full-duplex (FD) has been in the spotlight as a key technology for improving network performance. In this work, we design an energy-efficient medium access control (MAC) protocol for a UAV base-station (UAV–BS) aided FD wireless communication network and demonstrate a comprehensive analytical model considering the FD pair probability. In the proposed FD MAC protocol, the FD UAV-BS focuses on energy efficiency when establishing the FD pair. Throughput is also enhanced by transmitting downlink data without decreasing the uplink data rate. We consider the FD pair probability to improve the accuracy of the analytical model. Although the FD pair probability is an important parameter for performance analysis, it has rarely been addressed in most previous works. We analyze FD pair probability according to the altitude of the FD UAV-BS and the node transmission power. The analytical model can reflect an actual network better than prior works by considering the FD pair probability. Through extensive simulations using MATLAB and the Riverbed Modeler, we verified the superiority of the proposed FD MAC protocol and the accuracy of the analytical model.**

***Index Terms*—Full-duplex, full-duplex pair probability, MAC protocol, unmanned aerial vehicle base station.**

I. INTRODUCTION

GLOBAL mobile traffic grown exponentially over the last decade. The overall mobile traffic is expected to continue to grow exponentially and will exceed 5 ZB per month by 2030 [1]. Moreover, the spectral efficiency required to support the explosively growing mobile traffic has always been an important issue in wireless communication. Full-duplex (FD) has the potential to improve spectral efficiency because it supports simultaneous transmission and reception at the same frequency. However, it causes additional interference, such as self-interference and inter-node interference. Several studies have already been conducted to eliminate self-interference. Self-interference cancellation (SIC) technology has achieved 150 dB of cancellation [2]–[5]. Further, inter-node interference can be resolved by establishing an FD pair with the appropriate node.

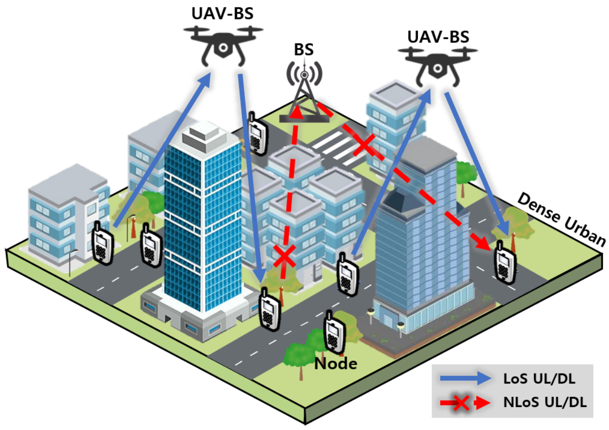

Fig. 1. UAV-BS and terrestrial infrastructure in dense urban scenario.

Although FD has the abovementioned advantages, FD wireless communication in situations involving terrestrial infrastructure, has limitations of deployment and nonline-of-sight (NLOS) caused by the obstructions, as shown in Fig. 1. Particularly in a dense urban scenario, there are plenty of users to service, and severe inter-node interference and channels fluctuation can occur [6]. To solve this problem, using UAV-BSs that have fast, flexible, and cost-effective deployment is essential. The use of FD-enabled UAV-BSs will enable more efficient communication than half-duplex (HD) or terrestrial communication. However, the major problem of UAV-BS is that the UAV platforms are extremely power-hungry. Because of battery limitation, the operation time is limited to a few hours. Therefore, energy-efficient communication is essential in UAV-BS wireless communication networks [7].

Because the UAV wireless communication network has features distinct from those of existing networks, a new medium access control (MAC) protocol to support the UAV wireless communication network is required. In this paper, we propose an FD MAC protocol for UAV BS-aided FD wireless communication networks focused on energy efficiency based on carrier-sense multiple access with carrier avoidance (CSMA/CA) with binary exponential backoff. The proposed FD MAC protocol also improves network throughput by establishing an FD pair without decreasing the uplink (UL) data rate. Establishment of the FD pair is a key challenge in a

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UAV BS-aided FD wireless communication network; however, it has rarely been addressed in recently published literature. Accordingly, we propose an FD pair establishment algorithm to maximize energy efficiency. The UAV-BS classifies FD pair candidates and builds a table that includes this information. Most prior works have established FD pairs based on channel capacity. However, even considering the saturation traffic model, fully utilizing the channel capacity is challenging owing to the MAC protocol overhead. Moreover, the data rate is lower than the channel capacity because the modulation and coding scheme (MCS) is already defined in the actual network. In the proposed algorithm, the FD pair is established based on the MCS. Therefore, the state of the actual UAV BS-aided FD wireless communication network can be better reflected compared with the existing research.

Further, we provide an analytical model to evaluate the UAV BS-aided FD wireless communication network. In the analytical model, we consider the FD pair probability that has not been addressed previously. The FD pair probability refers to the probability of establishing the FD pair. The accuracy of our analytical model is verified through extensive numerical simulations. A summary of the main contributions of this work is as follows:

- **UAV BS-aided FD wireless communication network**: We propose a UAV BS-aided FD wireless communication network to service nodes more efficiently. By using UAV-BS instead of a terrestrial infrastructure, more efficient communication is possible by increasing the LOS probability and deploying the UAV for energy-efficient FD.
- **Energy-efficient FD MAC protocol**: We propose an energy-efficient FD MAC protocol, in which the UAV-BS builds a table related to the FD pair candidates. Then, the UAV-BS establishes the FD pair based on this table. The proposed FD MAC protocol improves energy efficiency and network throughput.
- **FD pair probability**: We formulate the FD pair probability according to parameters such as UAV-BS and node locations, transmission power,and SIC. To the best of our knowledge, this is the first work that investigates FD pair probability in the FD UAV-BS wireless communication network.
- **FD UAV-BS analytical model**: We provide an analytical model for the UAV BS-aided FD wireless communication network considering FD pair probability. The effect of FD pair probability on throughput is analyzed. Moreover, the accuracy of the analytical model is demonstrated through comparison with simulation results.

The remainder of this paper is organized as follows. In Section II presents previous research results. In Section III, we introduce the system model. In Section IV, we describe the detailed procedure of the proposed FD MAC protocol. Section V presents an analytical model for the FD UAV-BS wireless communication network. In Section VI, we evaluate the proposed FD MAC protocol through extensive numerical simulation. Finally, we conclude the paper in Section VII.

II. RELATED WORK

A. *Integration of UAVs into Wireless Communication*

UAVs can also provide wireless communication services at low cost and help overcome the spectrum shortage. Many researchers have conducted studies on the integration of UAVs into wireless communication. One suggestion is to use the UAV as a relay node [8]–[12]. In [8], the authors proposed a secondary UAV relay network in UAVs-assisted cognitive relay systems. The proposed scheme maximizes the average worst-case secrecy rate of the secondary network. In [9], a method to optimize radio resources based on the time-division long-term evolution advanced (TD-LTE-A) frame structure was proposed. The proposed scheme realizes efficient relay communication through a flexible frame configuration. In [10], an efficient relay concept, called time mirroring CSMA/CA was proposed, which provides better performance than the conventional CSMA/CA by guaranteeing that a relay always wins the channel competition. In [11], a UAV relay system using a laser transmitter for URLLC-enabled over-the-air charging was proposed. The authors formulated a jointly optimized problem with resource allocation, trajectory of UAVs and the energy-harvesting problem. In [12], by utilizing a UAV-aided virtual antenna array, the authors proposed a UAV relay system based on collaborative beamforming. They optimized the hovering positions of UAVs to schedule communication between the UAVs and remote ground users.

B. *UAV-Assisted Full-Duplex System*

Unlike the works presented above, FD was adopted in UAVs in [13]–[15] and the UAVs were also used as relays and FD BS [16]–[19]. Furthermore, the FD UAV was employed to increase the communication capacity of millimeter-wave networks in [13], where the authors investigated the joint optimization of positioning, beamforming, and power control to maximize the achievable rate. Similarly, in [14], the authors investigated an FD relay system with the joint design of beamforming and power allocation to maximize the instantaneous data rate. In [15], an energy-efficient FD relay network was proposed, and the optimal flight speed to maximize energy efficiency could be obtained. In [16], the authors investigated FD UAV-aided small-cell wireless systems, where the UAV serves as the BS. The UAV trajectory, downlink/uplink (DL/UL) user scheduling, and UL user transmit power were optimized alternately to maximize the total system capacity. In [17]–[19], the UAV-BS placement problem was addressed to achieve better performance. In [17], the authors proposed two heuristic algorithms based on UAV-BS placement strategies to determine the optimal UAV-BS location. The joint bandwidth and power allocation were also optimized according to the location of the UAV-BS. Moreover, the algorithm proposed in [18] aimed to minimize the required number of UAV-BSs in providing wireless communication service to user equipment. In [19], the authors focused on improving total network throughput. They considered both access links and backhaul links of UAV-BSs, which were not considered previously, to maximize throughput.

TABLE I
COMPARISON OF PREVIOUSLY PROPOSED FD MAC PROTOCOLS.

Paper (Ref. No.)	FD link type	Traffic model	FD pair probability	Consider performance metrics
[20]	Symmetric/ Asymmetric	Saturation	Not consider	Throughput
[21]	Asymmetric	Saturation	Partially consider	Throughput, fairness
[22]	Symmetric/ Asymmetric	Saturation	Not consider	Throughput, energy consumption
[23]	Asymmetric	Saturation	Not consider	Throughput
[24]	Symmetric/ Asymmetric	Saturation	Not consider	Throughput
[25]	Symmetric/ Asymmetric	Saturation, non saturation	Not consider	Throughput, energy consumption,
[26]	Asymmetric	Non saturation	Not consider	Throughput
Proposed FD MAC	Asymmetric	Saturation	Consider	Throughput, energy consumption

C. Full-duplex MAC Protocol Design

Numerous researchers have conducted studies on the design of FD MAC protocols. In [20], the authors proposed the FD-MAC protocol based on CSMA/CA concepts, which can identify users who are not considered ”blind” when transmitting. In [21], the authors proposed a new MAC protocol called A-duplex to enable efficient coexistence between FD and HD communications in wireless networks. A-duplex uses the signal-to-interference ratio (SIR) map to select the FD node pairs and employs a virtual deficit round-robin algorithm to ensure fairness in the MAC protocol. In [22], the authors proposed an energy-efficient MAC protocol for distributed FD wireless networks, which reduces the transmission power of data and acknowledgement packets to achieve energy efficiency. In [23], the authors proposed a novel FD MAC protocol that requires the IEEE 802.11 standard and establishes a link map based on the signal-to-interference-plus-noise ratio (SINR) of each link. In [24], the authors proposed the FD enhanced carrier-sensing (FECS) MAC protocol to solve the hidden-node problem. The FECS MAC protocol utilizes channel sensing before FD secondary transmission to mitigate this issue. In [25], the authors proposed the synchronized mode FD (SM-FD) MAC protocol to modify the IEEE 802.11 standard, which can establish both symmetric and asymmetric links with both FD and HD-capable nodes. Finally, in [26], the authors proposed an RTS/CTS-based FD MAC and throughput analysis model for wireless multi-hop networks, along with airtime expressions to handle RTS/CTS operations under FD MAC.

The researchers should consider establishing FD pairs and their corresponding probabilities, as the decision to use FD for transmission depends on the likelihood of successful transmission between the pairs. Furthermore, when dealing with UAV-BS scenarios, energy consumption should also be taken into account due to the limited battery capacity of UAV-BS. However, most previous works have overlooked the importance of considering these FD pair probabilities and energy consumption, particularly in the context of UAV-BS, and have not proposed any suitable solutions. Although the authors of [22] and [25] have considered energy consumption, they focused solely on nodes and did not address the issue in the context of UAV-BS. In [21], the FD pair probability was partially considered, but a fixed value was assumed despite its dependence on the number of nodes. Therefore, it is essential to treat the FD pair probability as a flexible value that can vary based on the number of nodes present. Consequently, we propose an energy-efficient FD MAC protocol for UAV-BS and an FD analytical model that considers the variable FD pair probability.

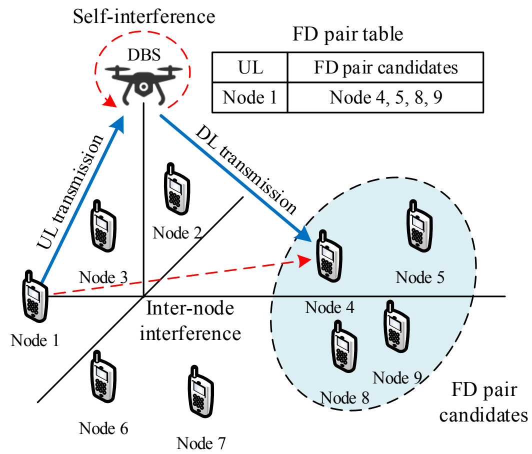

Fig. 2. UAV-BS aided FD wireless communication network.

III. SYSTEM MODEL

We consider a network comprising one UAV-BS and N nodes, as depicted in Fig. 2. We assume that the UAV-BS and nodes use a single-input and single-output system. The nodes are randomly distributed within the coverage area of the UAV-BS and communicate only with the UAV-BS. The UAV-BS establishes the FD pair with two nodes (UL and DL). The UL transmission interferes with the DL transmission because the UL and DL use the same frequency band in the FD pair. Therefore, the UAV-BS selects one node from the FD pair candidates as the DL node. If FD pair candidates do not exist, the UAV-BS operates in HD mode. The considered network adopts CSMA/CA, which is used by most UAVs [10], [27]–[29]. In the modern UAV-BS network, the

UAV-BS flying time is extremely short due to the battery limitation, and energy consumption owing to propulsion is high. Therefore, we consider a UAV-BS hovering in a fixed position. It is assumed that only the UAV-BS has FD capability, whereas the nodes operate in HD to support backward compatibility with existing devices. In addition, we assume that the considered network uses adaptive modulation. The MCS for each transmission is determined according to the SINR.

A. Channel Model

We consider only the LoS component of the air-to-ground (A2G) channel. Because the altitude of the UAV-BS is high, the A2G channel mostly contains a strong LoS link [14], [30], [31]. Thus, the A2G channel is dominated by the LoS component. The channel model follows Rayleigh fading. In this case, the received signal power follows an exponential distribution. The probability density function is given as follows:

$$f(P_r) = \frac{1}{P_0} \exp\left(-\frac{P_r}{P_0}\right), \quad P_r \geq 0, \tag{1}$$

where P_r is the received signal power, and P_0 is the average power of the received signal. Moreover, P_0 is expressed as follows:

$$P_0 = P_{tx} G_t G_r PL(d), \tag{2}$$

where P_{tx} is the transmission power, G_t and G_r are the antenna gains of the transmitter and receiver, d is the distance between the transmitter and receiver, and $PL(d)$ is the path-loss with distance d. We assume that the log-distance path loss model with a path loss exponent is 2 [32], [33]. Meanwhile, the long-term properties of the channel must be reflected to analyze the network performance. Therefore, we use the ergodic value in the analytical model, whereas we apply Rayleigh fading in the simulation. The ergodic SINR value of the UL, γ_u, can be calculated as follows:

$$\gamma_u = \frac{P_n G_t G_r}{\xi + N_0} \times \left(\frac{\lambda}{4\pi d_u}\right)^2, \tag{3}$$

where P_n is the transmission power of the node, λ is the wavelength, d_u is the distance between the UAV-BS and the UL node, ξ is the residual self-interference, and N_0 is the noise power. Similarly, the ergodic SINR value of the DL, γ_d, can be calculated as follows:

$$\gamma_d = \frac{P_d G_t G_r \times \left(\frac{\lambda}{4\pi d_d}\right)^2}{P_n G_t G_r \times \left(\frac{\lambda}{4\pi d_n}\right)^2 + N_0} \approx \frac{P_d d_n^2}{P_n d_d^2}, \tag{4}$$

where P_d is the transmission power of the UAV-BS, d_d is the distance between the UAV-BS and DL node, and d_n is the distance between the UL and DL nodes. The noise power is negligible because it is very low compared to the inter-node interference.

B. Energy Consumption Model

The UAV-BS energy consumption comprises three components: General propulsion energy, hovering energy, and communication-related energy. In this paper, two components, excluding the propulsion energy, are considered because we assume that the UAV-BS is hovering in a fixed position. The total energy consumption, E_{tot}, can be determined as follows [34]:

$$E_{\text{tot}} = (P_h + P_c)t, \tag{5}$$

where P_h is the hovering power, P_c is the communication-related power and t is the hovering time. The communication-related power considers the signal radiation power when transmitting packets. The hovering power can be expressed as follows [35]:

$$P_h = \underbrace{\frac{\beta}{8}\rho s A \Omega^3 R^3}_{\text{blade profile}} + \underbrace{(1+k)\frac{W^{3/2}}{\sqrt{2\rho A}}}_{\text{induced}}. \tag{6}$$

The blade profile is the product of the power required to turn the rotors and the torque at the rotation rate. The induced power is the power to produce lift and overcome gravity. The parameters related to the hovering power are presented in Table II [35].

TABLE II
NOTATION RELATED TO HOVERING POWER.

Notation	Definition	Value
W	Aircraft weight	1375 g
R	Rotor radius	0.4 m
A	Rotor disc area	0.503 m^2
b	Number of blades	4
c	Blade or aerofoil chord length	0.0157
s	Rotor solidity, $s = bc/\pi R$	0.05
Ω	Blade angular velocity	300 radians/s
U_{tip}	Tip speed of the rotor blade, $U_{\text{tip}} = \Omega R$	120 m/s
S_{FP}	Fuselage equivalent flat plate area	0.0151 m^2
d_0	Fuselage drag ratio, $d_0 = S_{FP}/sA$	0.6
ρ	Air density	1.225 kg/m^3
v_0	Mean rotor induced velocity, $v_0 = \sqrt{W/2\rho A}$	4.03
β	Profile drag coefficient	0.012
k	Incremental correction factor to induced power	0.1

IV. PROPOSED MAC PROTOCOL

In this section, we describe the proposed FD MAC protocol based on CSMA/CA. Firstly, the UAV-BS builds the FD pair table that contains information on FD pair candidates. The FD pair candidates are determined based on the SINR value. Then, the UAV-BS selects one of the FD pair candidates as the DL node, considering the energy efficiency. The detailed procedure is explained below.

A. Full-Duplex Pair Table

As mentioned earlier, the UL transmission signal interferes with the DL transmission in the FD pair. Thus, if the DL node is close to the UL node, the DL transmission rate decreases, or packet collisions occur, thereby degrading network performance. To prevent this problem, the UAV-BS builds an FD pair table that contains FD pair candidates for each node.

Algorithm 1 Energy efficient FD pair algorithm

Require: Node i that wins the channel competition
$k \leftarrow 0$
$EW_{DL} \leftarrow 0$
$T_{UL} \leftarrow T_i$
for $j = 1$ **to** N **do**
  if $j \in S_i$ **then**
    $T_{DL} \leftarrow T_j$
    if $T_{UL} > T_{DL}$ **then**
      $E_{\mathrm{tot}} = P_h \cdot T_{UL} + P_c \cdot T_{DL}$
      $EW_{i,j} = E_{\mathrm{tot}}/(L_i + L_j)$
      if $EW_{i,j} < EW_{DL}$ **then**
        $EW_{DL} \leftarrow EW_{i,j}$
        $k \leftarrow j$
      end if
    end if
  end if
end for
if $k = 0$ **then**
  UAV-BS operates on HD mode
else
  UAV-BS establishes FD pair with node k
end if

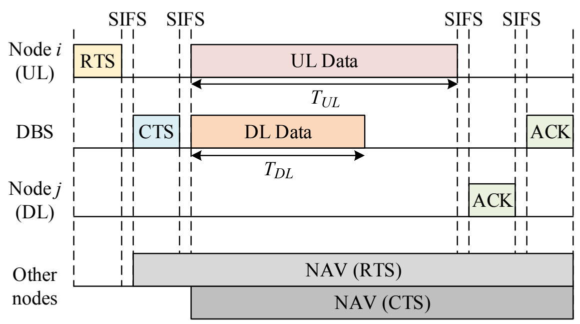

Fig. 3. FD transmission procedure.

The table is built according to the SINR value. However, the UAV-BS cannot measure a node's SINR value because it does not know the location of each node. Therefore, each node measures the SINR value and informs the UAV-BS through a RTS/CTS exchange procedure [21], [36].

The signal strength from the UAV-BS becomes the desired signal strength. Conversely, the signal strength from the UL node becomes the interference strength. When a node wins the channel competition, it transmits the RTS packet to the UAV-BS. Other nodes can measure the interference strength by overhearing the RTS packet. Similarly, the desired signal strength can also be measured by overhearing the CTS packet from the UAV-BS. Each node provides the SINR information to the UAV-BS via the RTS packet when it wins the channel competition. The UAV-BS compares the collected SINR value with an SINR threshold (δ). If the SINR value is higher than the SINR threshold, the UAV-BS adds the node to the FD pair candidates. However, the measured SINR value is not constant owing to fading. Therefore, the FD pair table must to be updated continuously. The set of FD pair candidates for node i, S_i, is given as follows:

$$S_i = \{j \in S_N | \mathrm{SINR}_{i,j} > \delta\}, \tag{7}$$

where, S_N is the set of nodes and $\mathrm{SINR}_{i,j}$ is the measured SINR of node j when node i is the UL node.

B. Energy-Efficient Full-Duplex Pair Algorithm

Because of battery limitations, the UAV-BS has difficulty in providing wireless communication services for a long period. Therefore, energy consumption in the UAV-BS network is essential. In this paper, we propose an algorithm to establish an FD pair, considering energy efficiency. The objective of the proposed algorithm is to minimize the energy consumed when transmitting data. Energy consumption depends on which node is selected to establish an FD pair. Thus, the proposed algorithm aims to establish an FD pair with a node that can reduce energy consumption. It also improves throughput by establishing an FD pair that does not affect the UL transmission.

The energy-efficient FD pair algorithm is summarized in Algorithm 1. The FD pair can only be established when nodes other than the UAV-BS win the channel competition. The node that wins the channel competition transmits the RTS packet to the UAV-BS. The UAV-BS can determine the time required for transmitting the UL data (T_{UL}) through the duration field of the RTS packet. The UAV-BS can also calculate the required time for transmitting the DL data (T_{DL}) to each FD pair candidate because it collects SINR information. If T_{DL} is longer than T_{UL}, the UL node must wait until the DL transmission is finished to receive the ACK packet. Therefore, the UAV-BS establishes the FD pair with a node that can finish DL transmission before the UL transmission is finished. When many such nodes exist, the UAV-BS calculates energy-efficiency weighting. In this paper, energy-efficiency weighting is defined as the amount of energy consumed to transmit a unit of data. Thus, a smaller value of energy-efficiency weighting results in better energy efficiency. The energy efficiency weighting of node j when node i is the UL node, $EW_{i,j}$ is as follows:

$$EW_{i,j} = \frac{E_{\mathrm{tot}}}{L_i + L_j}, \tag{8}$$

where L_i is the packet payload size of node i. The UAV-BS selects the node with the smallest EW as the DL node and notifies it through the CTS packet. Other nodes that overhear the RTS/CTS packet read the duration field and set their network allocation vector (NAV), as shown in Fig. 3. They keep silent until the NAV is zero, which helps avoid collision during the data transmission. If FD pair candidates do not exist, the UAV-BS operates in HD mode. To improve energy efficiency, the FD pair establishment criterion can be expressed as:

$$\mathrm{DL\ node} = \mathbf{argmin}\ (EW_{i,j}). \tag{9}$$

In practical scenarios, periodically determining energy-efficiency weights to select energy-efficient nodes may increase the overhead of the UAV-BS. However, as previously mentioned, the proposed MAC protocol can compute the energy-efficiency weight during the exchange of RTS/CTS packets without incurring extra overhead. This approach enhances energy efficiency and makes the protocol easily implementable in practical scenarios.

V. Full-Duplex UAV Base Station Network Analytical Model

A. Full-Duplex Pair Probability

The analytical model contribution considers the FD pair probability, which has not been noted in conventional studies. The FD pair probability is the probability of occurrence of FD transmission. Therefore, the FD UAV-BS network can be analyzed by considering the FD pair probability.

For the FD transmission, the two SINR values (γ_u and γ_d) must exceed the SINR threshold. The SINR threshold has values according to MCS. Therefore, the MCS of the UL transmission is determined according to the location of the UL node and residual self-interference. If the residual self-interference is small enough to be considered negligible, FD transmission is possible even if the UL node is far from the UAV-BS. The condition for d_u is given by as follows:

$$d_u^2 \leq \frac{P_n G_t G_r \lambda}{\delta\left(\xi + N_0\right)}. \quad (10)$$

The Cartesian coordinate system is considered in this paper. If the UL node and UAV-BS are respectively located at (x_u, 0, 0) and (0, 0, h), respectively, x_u is the two-dimensional projected distance between the UL node and UAV-BS. The condition of x_u for γ to exceed the SINR threshold is given as follows:

$$x_u \leq x_{u,max} = \sqrt{\frac{P_n G_t G_r \lambda}{\delta\left(\xi + N_0\right)} - h^2}. \quad (11)$$

In the considered system, nodes are randomly distributed within the coverage of the UAV-BS. Thus, the probability density function of x_u is given as follows [37]:

$$f\left(x_u\right) = \frac{2x_u}{r^2}, 0 < x_u < r, \quad (12)$$

where r is the radius of the UAV-BS coverage.

The UL transmission signal interferes with the DL transmission. Therefore, the DL node should be far from the UL node and close to the UAV-BS to establish the FD pair. Thus, γ_d is affected by d_d and d_n. The condition for γ_d to exceed the SINR threshold is as follows:

$$\frac{d_d^2}{d_n^2} \leq \frac{P_d}{\delta P_n}. \quad (13)$$

If the DL node is located at (x_d, y_d, 0), d_n and d_d are respectively given as follows:

$$d_d = \sqrt{x_d^2 + y_d^2 + h^2}, \quad (14)$$

$$d_n = \sqrt{\left(x_u - x_d\right)^2 + y_d^2}. \quad (15)$$

Substituting (14) and (15) into (13), the condition of y_d, $f\left(x_u, x_d, h\right)$, can be computed as follows:

$$y_d \leq f\left(x_u, x_d, h\right) = \sqrt{\frac{\frac{P_d}{\delta P_n}\left(x_u - x_d\right)^2 - \left(x_d^2 + h^2\right)}{1 - \frac{P_d}{\delta P_n}}}. \quad (16)$$

The DL node can be the FD pair candidate only when it satisfies (16). The conditional probability that the DL node cannot be the FD pair candidate, $P_{dl}(x_u, h)$, can be computed as follows:

$$P_{dl}(x_u, h) = 1 - \frac{1}{\pi r^2}\int_{-r}^{r} 2f(x_u, x_d, h)dx_d. \quad (17)$$

If no FD pair candidate (i.e., N-1 nodes) except for the UL node satisfies (16), the FD pair cannot be established. Therefore, the average probability that FD pair establishment is impossible, P_{NFD}, can be calculated as follows:

$$P_{NFD} = \int_0^r \frac{2x_u}{r^2} \times P_{dl}(x_u, h)^{N-1} dx_u, \quad (18)$$

where N is the number of nodes. Finally, the average FD pair probability, P_{FD}, is as follows:

$$P_{FD} = 1 - P_{NFD}. \quad (19)$$

B. Saturation Throughput

To analyze the proposed MAC protocol saturation throughput, we adopted the Markov model from [38], which does not considered FD communication. Therefore, we modified the Markov model by considering the FD pair probability to analyze the FD UAV-BS network.

All nodes, including the UAV-BS, attempt to transmit a packet when their backoff counter is zero. They select one random number as the backoff counter in the range (0, W_0-1), where W_0 is the minimum contention window size. If a node transmits a packet and a collision occurs, the contention window size doubles. When m is the maximum backoff stage, the contention window size increases up to $2^m W_0$. Thus, even if more than m collisions exist, the contention window size remains $2^m W_0$. The probability that each node attempts to transmit a packet, P_t, can be calculated as follows:

$$P_t = \frac{2}{1 + W_0 + pW_0 \sum_{i=0}^{m-1}\left(2p\right)^i}, \quad (20)$$

where p is the conditional collision probability. If two or more nodes transmit a packet, a collision occurs. Since $N+1$ nodes exist in the considered system, the conditional collision probability is given as follows:

$$p = 1 - \left(1 - P_t\right)^N. \quad (21)$$

A channel is in an idle state when all nodes do not attempt to transmit a packet. Thus, the probability of being idle, P_i, can be calculated as follows:

$$P_i = \left(1 - P_t\right)^{(N+1)}. \quad (22)$$

When a node attempts to transmit a packet, the channel is in a busy state. Only one node attempts to transmit a packet, while other nodes remain silent to ensure a successful transmission. The probability that the UAV-BS transmits successfully, P_D, is as follows:

$$P_D = P_t\left(1 - P_t\right)^N. \quad (23)$$

Similarly, the probability that a node transmits successfully, P_N, is as follows:

$$P_N = NP_t\left(1 - P_t\right)^N. \quad (24)$$

If the UAV-BS attempts to transmit, then only HD transmission is possible. Conversely, if a node, except for the UAV-BS attempts to transmit, FD transmission is also possible. The probability of FD transmission depends on the FD pair probability. Therefore, the probabilities of FD and HD transmission, P_F and P_H, are as follows:

$$P_F = P_N P_{FD}, \quad (25)$$

$$P_H = P_N P_{NFD} + P_D. \quad (26)$$

The collision probability, P_{co}, is as follows:

$$P_{co} = 1 - P_i - P_D - P_N. \quad (27)$$

According to [38], the saturation throughput is the average payload successfully transmitted per unit of time. The required times for FD and HD transmission, T_F and T_H, are as follows:

$$T_F = T_{RTS} + T_{CTS} + T_{UL} + 2T_{ACK} + 4T_{SIFS} + T_{DIFS}, \quad (28)$$

$$T_H = T_{RTS} + T_{CTS} + T_{UL \text{ or } DL} + T_{ACK} + 3T_{SIFS} + T_{DIFS}, \quad (29)$$

where T_{RTS} is the RTS time, T_{CTS} is the CTS time, T_{UL} and T_{DL} are the required times for transmitting the UL and DL data respectively, T_{ACK} is the ACK time, T_{SIFS} is the short inter-frame space (SIFS) time, and T_{DIFS} is the DCF inter-frame space (DIFS) time. When the UAV-BS establishes the FD pair, it selects a node that has a shorter T_{DL} than T_{UL} as the DL node. Thus, T_F is affected by only T_{UL}. The collision time, T_{co}, is as follows:

$$T_{co} = T_{RTS} + T_{CTS} + T_{SIFS} + T_s, \quad (30)$$

where T_s is one time slot. The saturation throughput of the FD UAV-BS network, S, can be calculated as follows:

$$S = \frac{P_H E[P] + P_F 2E[P]}{P_i T_s + P_H T_H + P_F T_F + P_{co} T_{co}}. \quad (31)$$

where $E[P]$ is the average payload.

C. Energy Efficiency

The energy efficiency of the UAV-BS can be represented as the ratio of the successfully transmitted payloads to the energy consumed by the UAV-BS. The hovering energy is continuously consumed, whereas the communication energy is consumed only during the signal radiation period. Four cases of the signal radiation period exist: 1) When the UAV-BS wins the channel competition (T_{D1}), 2) When the node without an FD pair candidate wins the channel competition (T_{D2}), 3) When the node with an FD pair candidate wins the channel competition (T_{D3}), and 4) When a collision occurs (T_{D4}). In each case, the period of signal radiation is as follows:

$$T_{D1} = T_{RTS} + T_{DL}, \quad (32)$$

$$T_{D2} = T_{CTS} + T_{ACK}, \quad (33)$$

$$T_{D3} = T_{CTS} + T_{DL} + T_{ACK}, \quad (34)$$

$$T_{D4} = T_{RTS}. \quad (35)$$

TABLE III
SIMULATION PARAMETERS.

Parameter	Value	Parameter	Value
PHY header	20 μs	PHY preamble	16 μs
PHY signal	4 μs	Frequency	5 GHz
Bandwidth	20 MHz	SIC	130 dB [5]
RTS size	20 bytes	CTS size	14 bytes
ACK size	14 bytes	Payload size	1500 bytes
SIFS	16 μs	DIFS	34 μs
Slot time	9 μs	r	500 m
CW min	15	CW max	1023
P_d	30 dBm [19]	P_n	15 – 20 dBm

TABLE IV
DATA RATE AND SINR RANGE ACCORDING TO MCS.

MCS	Data rate	SINR range (dB)
No Tx	0 Mbps	SINR $<$ 10 dB
BPSK	6 Mbps	10 $\leq$ SINR $<$ 13 dB
QPSK	12 Mbps	13 $\leq$ SINR $<$ 18 dB
16-QAM	24 Mbps	18 $\leq$ SINR $<$ 26 dB
64-QAM	54 Mbps	26 dB $\leq$ SINR

Finally, the energy efficiency of the UAV-BS, EE_D, can be calculated as follows:

$$EE_D = \frac{P_h + P_c\{P_D T_{D1} + (P_F - P_D)T_{D2} + P_F T_{D3} + P_{co} T_{D4}\}}{S}. \quad (36)$$

VI. Performance Evaluation

In this section, we demonstrate the superiority of the proposed FD MAC protocol and evaluate the accuracy of the analytical model. MATLAB and Riverbed Modeler were used to run the simulation. The average results were obtained by running 1,000 simulations per scenario.

A. Simulation Environment

Table III summarizes the simulation parameters used for the simulation, based on the IEEE 802.11 standard [40]. The radius of the UAV-BS coverage is assumed to be 500 m. All nodes are randomly distributed within the UAV-BS coverage. The number of nodes is set from 10 to 100. We assume that the UAV-BS and nodes use a single-input and single-output (SISO) communication scheme. To enhance frequency efficiency, multi-input and multi-output (MIMO) scheme can be taken into account [39]. Nevertheless, this paper primarily aims to propose and design a FD MAC protocol and validate its performance in a UAV-BS environment. Therefore, we only considered SISO in this study. Also assume that, the SIC technique can eliminate self-interference up to 130 dB. The altitude of the UAV-BS is set from a minimum of 100 m to a maximum of 500 m. The minimum and maximum contention window sizes are set to 15 and 1,023, respectively. Although we have considered the ergodic SINR value in the analytical

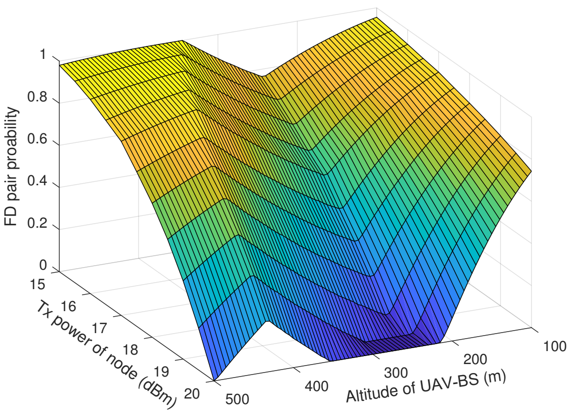

Fig. 4. FD pair probability versus altitude of UAV-BS with 100 nodes.

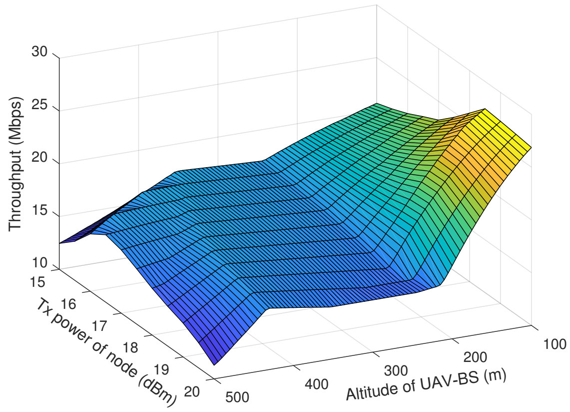

Fig. 5. Throughput versus altitude of UAV-BS with 100 nodes.

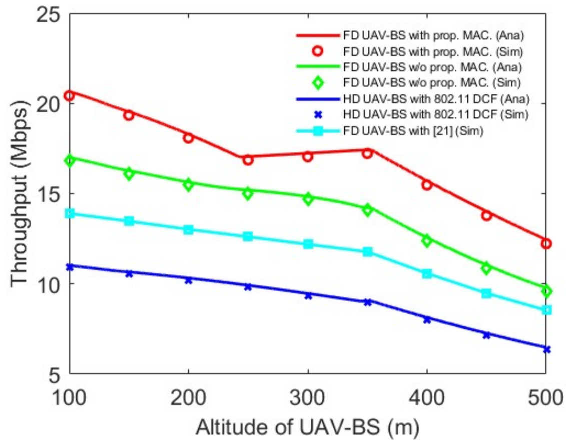

Fig. 6. Throughput versus altitude of UAV-BS under the MAC protocol.

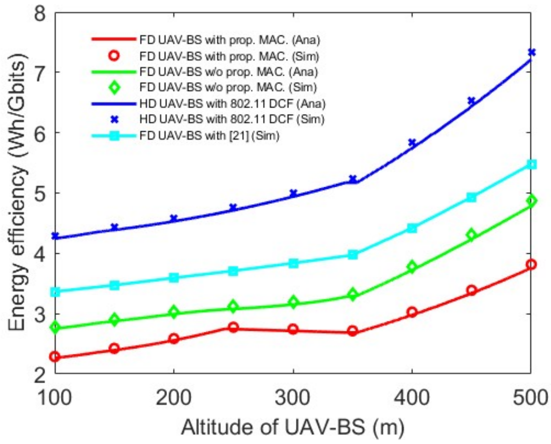

Fig. 7. Energy efficiency versus altitude of UAV-BS under the MAC protocol.

model, Rayleigh fading is applied in the simulation. We also consider adaptive modulation according to the SINR value. The MCS employed in the simulation has four types; BPSK, QPSK, 16-QAM, and 64-QAM. The UAV-BS and nodes select one MCS according to the SINR value. The data rate and SINR range of each MCS are described in Table IV [9], [40].

B. Simulation Results: Altitude of the UAV-BS

Fig. 4 illustrates the FD pair probability for the different altitudes of the UAV-BS when the number of nodes in the network is 100. The DL signal attenuation increases as the altitude of the UAV-BS increases. Based on a P_n of 15 dBm, the FD pair probability decreases as the UAV-BS altitude increases until around 250 m. However, the FD pair probability increases when the UAV-BS hovers at an altitude of more than 250 m. The MCS of UL is switched from high to low mode (e.g., switched from QPSK to BPSK) as the distance between the UAV-BS and UL node increases. Therefore, the FD pair probability increases because T_{UL} becomes longer. In addition, a higher FD pair probability is achieved when P_n is weak.

If P_n is very strong, the UL signal strength and inter-node interference increase, which leads to a lower FD pair probability. Fig. 5 illustrates the throughput for the different altitudes of the UAV-BS when the number of nodes in the network is 100. The throughput tends to decrease as the UAV-BS altitude increases regardless of P_n, similar to the FD pair probability. When the UAV-BS hovers over 250 m, the throughput is nearly constant, unlike the FD pair probability. Although the gain can be obtained due to the increased FD pair probability, loss due to the low MCS also occurs. If the altitude of the UAV-BS is over 400 m, the throughput decreases continuously. This result also demonstrates that the optimal P_n depends on the altitude of the UAV-BS.

To evaluate the performance of the FD UAV-BS network, we compared its throughput according to the proposed FD MAC protocol was applied. Additionally, to make a comparison with other existing studies, we included the FD MAC protocol proposed in [21]. Lastly, to compare the performance between FD and HD, we used the conventional 802.11 DCF. Fig. 6 illustrates the throughput for each MAC protocol when P_n is 15 dBm. If the proposed FD MAC protocol is applied, the UAV-BS selects a node as the DL node that does not require switching of the MCS of the UL transmission. However, if the proposed FD MAC protocol is not applied, the MCS of the UL transmission may be switched to a low mode. Thus, the proposed FD MAC protocol always achieves better

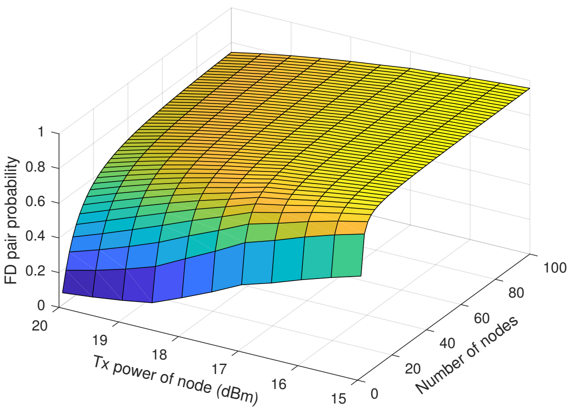

Fig. 8. FD pair probability versus number of nodes (h = 100 m).

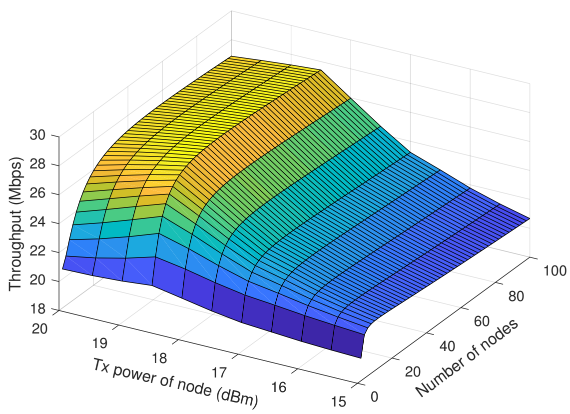

Fig. 9. Throughput versus number of nodes (h = 100 m).

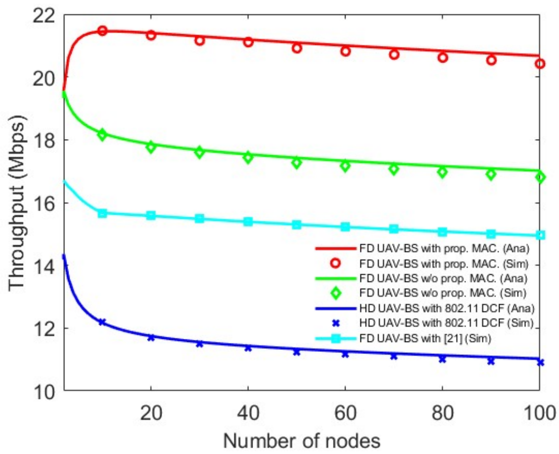

Fig. 10. Throughput versus number of nodes under the MAC protocol (h = 100 m).

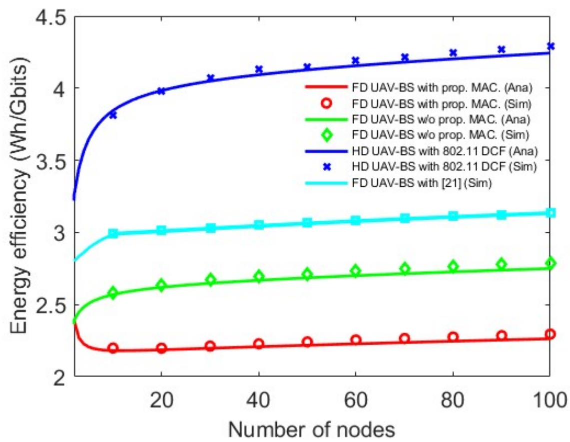

Fig. 11. Energy efficiency versus number of nodes under the MAC protocol (h = 100 m).

throughput. The FD-MAC protocol proposed in [21] used a fixed FD pair probability value of 0.4371 and employed a round-robin method for selecting the DL node. As a result, we observed that the performance of our proposed FD-MAC protocol was consistently superior to that of the FD-MAC protocol proposed in [21]. The FD UAV-BS always provides higher throughput than the HD UAV-BS regardless of whether the proposed FD MAC protocol is applied, as illustrated in Fig. 6.

Fig. 7 illustrates the EE_D for each MAC protocol. The EE_D represents the amount of energy consumed to transmit a 1 Gb payload. When applying the proposed FD MAC protocol, the UAV-BS can reduce EE_D by up to 22% compared to when it is not applied. Furthermore, our proposed protocol enables EE_D reductions of up to 31% and 48% when compared to the FD UAV-BS with [21] and HD UAV-BS, respectively.

C. Simulation Results: Number of Nodes

Fig. 8 illustrates the FD pair probability for the number of nodes when the UAV-BS hovers at an altitude of 100 m. The UAV-BS can establish the FD pair even if only one FD pair candidate exists. Therefore, as the number of nodes increases, the FD pair probability also increases and reaches saturation. The FD pair probability is highest when P_n is 15 dBm. In this case, the MCS of UL is a relatively low mode. Moreover, the inter-node interference is weak, which leads to a high FD pair probability. However, the throughput is the lowest, as depicted in Fig. 9. When P_n is 20 dBm, the throughput is high even though the FD pair probability is low. This result reveals that the FD transmission does not always guarantee an improvement in the network throughput. The numerous nodes in the FD UAV-BS network increases the collision probability. Thus, the throughput loss due to the collision probability with an increase in the number of nodes is larger than the gain due to the FD pair probability.

Fig. 10 illustrates the throughput for each MAC protocol when P_n is 15 dBm. The proposed FD MAC protocol has always improved throughput regardless of the number of nodes. The energy consumption of the UAV-BS is also the smallest when the proposed FD MAC protocol is applied, as displayed in Fig. 11. It reduces EE_D by 18% compared to when it is not applied, and by 27% and 47% when compared to the FD UAV-BS with [21] and HD UAV-BS, respectively. These results, reveal that the proposed FD MAC protocol can improve throughput while reducing energy consumption. Moreover, our analytical model is valid because the analytical results are close to the simulation results.

VII. CONCLUSION

An energy-efficient FD MAC protocol is proposed in this paper to support the UAV BS-aided FD wireless communication network. We also provide an analytical model considering the FD pair probability that has not been addressed previously. In the proposed FD MAC protocol, the UAV-BS builds the FD pair table that contains the information on the FD pair candidate. Then it establishes an FD pair with a node that has the smallest energy-efficiency weighting. Through extensive numerical simulations, we demonstrate that the proposed FD MAC protocol effectively improves the throughput and reduces the UAV-BS energy consumption. The analysis and simulation results for the FD pair probability and throughput are consistent. Based on these results, the analytical model estimates the UAV BS-aided FD wireless communication network accurately. Additionally, the analytical model can be easily applied to other networks by adjusting the SINR threshold. As a future direction, we plan to consider a multi-UAV scenario as a system model. Additionally, while we validated our proposed FD MAC protocol by comparing it to an analytical model, as demonstrated in [41], it is crucial to conduct real-world prototyping for algorithm validation. As such, we aim to establish a real-world UAV communication environment to verify the effectiveness of our proposed FD MAC protocol.

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