An Experimental Evaluation of Air-to-Air MIMO Transmission in Wireless LAN Relay Systems Using Drones

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***Abstract*—A wireless communication system employing drones is investigated. The drones, which are equipped with wireless LAN relay nodes, are used to overcome the terrain height and maintain the line-of-sight wireless communication. To improve the throughput performance of this system, we employ the multiple-input multiple-output (MIMO) in the air-to-air communication between drones. Then, we verify the performance improvement achieved using the MIMO by conducting experiments. The results show that by placing two antennas, which are orthogonal to each other on each drone, the throughput performance of the proposed MIMO transmission system can be improved. This improvement is achieved when the drones operate at an altitude of 30 m or lower. Also, the degradation ratio of the overall throughput performance in the multihop transmission system is about 1/5 compared to the expected value of 1/3 between the drones.**

***Index Terms*—UAV, wireless LAN, MIMO, multihop**

I. Introduction

It is considered that connecting base stations with wired facilities to work sites in mountainous areas, where the line-of-sight wireless communication is blocked and a wired connection cannot be used [1]. A wireless LAN relay communication system employing drones proposed to realize this idea is shown in Fig. 1. In this system, drones equipped with wireless LAN relay nodes are used to overcome the terrain and maintain the line-of-sight wireless communication. The following order of nodes is used during the communication process: a terrestrial node at the work site, a drone node above the work site, a drone node above the gateway, a terrestrial node in the gateway, and a node in the remote office. To perform the communication process in the opposite direction, the order of nodes is reversed. The benefit of using a wireless LAN is that no licensing is required.

To improve the throughput performance of the proposed system, we employ the multiple-input multiple-output (MIMO) in the air-to-air communication between drones. The MIMO has been used in ground-to-air communications, but not in air-to-air communications in [1]. This is because the IEEE 802.11s standard, which defines how wireless devices can interconnect to create a wireless LAN mesh network, does not support MIMO communication after the IEEE 802.11n standard. This study focuses employing the MIMO in air-to-air communication between drones, which has not yet been investigated.

Various studies on the air-to-air communication between drones or between aircrafts have been conducted. The effect of the altitude and terrain on the channel impulse response in air-to-air communications in the 250 MHz frequency band was reported in [2]. Takizawa et al. [3] investigated the effect of the radio waves produced by reflection in sea water and buildings in urban areas on the channel impulse response in air-to-air communications in the 2.3 GHz frequency band. The channel characteristics of air-to-air communications in the 6 GHz frequency band were reported in [4]. The effect of the multipath variation with altitude on air-to-air communications was reported in [5]. The distance characteristic of the communication performance for air-to-air communications according to the IEEE 802.11b/g standards was presented in [1]. Although the channel characteristics in air-to-air communications were investigated in the above studies, the performance of a MIMO air-to-air communication system has not been investigated.

In multipath-rich environments, multistream signals can be transmitted by employing the MIMO. As a result, the throughput performance can be improved. In terrestrial communications, in addition to the direct wave, there are also strong waves generated by reflection on the ground. In this case, the MIMO can improve the throughput performance. However, in air-to-air communications, the waves generated by reflection on the ground are weak due to the high altitude of the drones used. In this case, the ability of the MIMO in improving the throughput performance has not been clarified.

In this study, we investigate the ability of the MIMO in

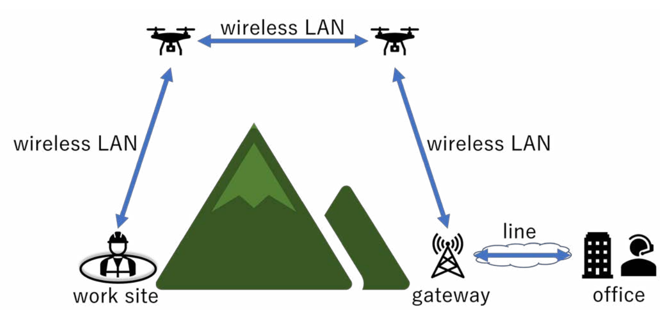


Fig. 1: Wireless LAN relay communication system employing drones.

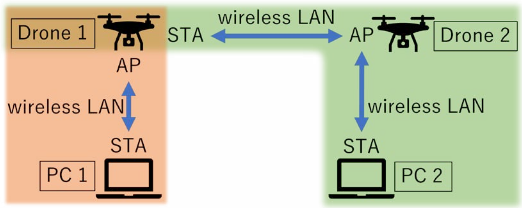


Fig. 2: Experimental system.

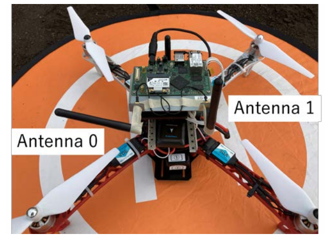


Fig. 3: Drone.

Table I: Configuration of drone.

Drone		
	Drone 1	Drone 2
Name	Hquad [8]	LAB445 [9]
Type	Quad	Quad
Size	62 cm×53 cm×12 cm	45 cm×70 cm×9 cm
Flight controller	Cube Orange [10]	PixHauk mini [11]
GPS receiver Barometer	Here 3 [12]	Micro M8N GPS [13]
Microcomputer		
Name	Armadillo-X1 [14]	
Size	10 cm×6.4 cm	
Wireless LAN protocol	IEEE 802.11a/b/g/n	
Frequency band	2.4 GHz	
Antenna		
Name	WAND2DBI-SMA-2NB [15]	
Radiation	Omnidirectionally in the horizontal direction	
Polarization	Vertical	
Length	10.9 cm	
Gain	2 dBi	

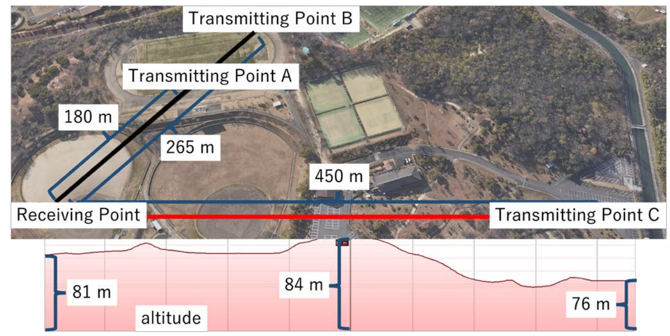


Fig. 4: Site of the experiment.

improving the throughput performance in air-to-air communications between drones. Specifically, we conduct experiments using drones equipped with wireless LAN interfaces and two antennas. By varying the distance between the drones and the drone altitude, we measure the throughput with and without employing the MIMO. In this way, we can verify whether the MIMO improves the throughput.

II. Description of the Experiments

The improvement in throughput that can be achieved by employing the MIMO depends on the correlation among simultaneously transmitted signals. If the correlation is low, the throughput will be improved. The configuration of the antennas changes the polarization, which in turn, changes the correlation among signals. In Experiment 1, we investigate the configuration of the installed antennas that results in the best improvement in throughput using the MIMO.

If the distance between the drones is very long, the received power will be low. In this case, the MIMO cannot improve the throughput performance. In Experiment 2, we evaluate the maximum transmission distance at which the MIMO can improve the throughput performance by investigating the effect of the transmission distance on the communication performance.

As mentioned in Section I, at a high drone altitude, the waves generated by reflection on the ground become weak. In Experiment 3, we examine how the throughput performance improvement achieved using the MIMO varies with the drone altitude by investigating the effect of the altitude on the communication performance.

From a practical point of view, it is necessary to investigate the degradation in the throughput performance in a multihop transmission between terrestrial nodes. For this purpose, we investigate the end-to-end throughput performance between terrestrial nodes in Experiment 4.

III. Experimental Measurements

A. Experimental Configuration

To conduct measurements, we implemented an experimental system consisting of two drones and two PCs. This system is shown in Fig. 2. Each drone was equipped with a microcomputer, which enables the drone to communicate and make measurements in the air. The PCs were placed on the ground and used to remotely send instructions to the drone microcomputers. Multihop communication measurements between terrestrial nodes were conducted using the PCs. As shown in Fig. 2, the PCs are connected with the microcomputers via a wireless LAN. The drones operate as access points (APs) and accommodate the PCs, which operate as stations (STAs). In [1], air-to-air communication was achieved using a mesh network, where the drones acted as mesh points (MPs) in addition to the APs by employing a virtual interface function. However, the IEEE 802.11n standard, which includes the MIMO, does not support MPs. Therefore, we added an STA to Drone 1 by employing the virtual interface function so that the AP of Drone 2 can accommodate the STA of Drone 1. The orange and green areas in Fig. 2 illustrate the communication networks. By employing the virtual interface function, Drone 1 belongs to both networks.

The drone configuration is shown in Table I and a drone photograph is shown in Fig. 3. Each drone was equipped with a flight controller, a GPS receiver, a barometer, and

Table II: Parameters used in Experiment 1.

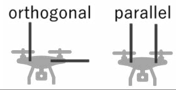
Measurement flow	Between drones (Drone 1 → Drone 2)
Transmission rate	Auto rate of 11n
Measurement time, s	10
Configuration of antenna	
Distance, m	265
Altitude, m	15

Table III: Parameters used in Experiments 2 and 3.

Measurement flow	Between drones (Drone 1 → Drone 2)
Transmission rate	Fixed rates shown in Table IV Auto rates of 11b/g and 11n
Measurement time, s	10
Measurement samples	One at 450 m, two at 180 m and 265 m
Distance, m	180, 265, 450
Altitude, m	15, 30

a microcomputer with its battery. Each microcomputer was equipped with a wireless LAN interface, which supports the IEEE 802.11b/g/n standards. The IEEE 802.11b (11b) and IEEE 802.11g (11g) standards do not use MIMO, whereas the IEEE 802.11n (11n) standard does. The antennas installed on the drones radiate omnidirectionally in their horizontal direction and enable the wireless LAN interfaces to achieve a 2-stream MIMO communication.

The iperf tool [6] was employed to send packets between the microcomputers and between the PCs to enable the throughput measurement. The tcpdump tool [7] was employed at the receiving microcomputer to acquire the received packets and enable the measurement of the received signal strength indicator (RSSI) of the two antennas and the combined RSSI of each packet.

B. Experimental Environment

The site where the experiments were conducted was a sports field (Fig. 4). PC 2 was placed at the Receiving Point and Drone 2 flew over it. PC 1 was placed at Transmitting Points A, B, and C, which were located at different distances from the Receiving Point, and Drone 1 flew over it.

The graph at the bottom of Fig. 4 shows the altitude variation (defined by the red line) between the Receiving Point and Transmitting Point C. The path between the Receiving Point and Transmitting Point C is a non-line-of-sight communication path at ground level, but it is a line-of-sight of communication path at a 15 m altitude. Similarly, the paths between the Receiving Point and Transmitting Points A and B are line-of-sight communication paths at a 15 m altitude.

C. Experiments

Experiment 1: effect of the configuration of antennas: This experiment was conducted to determine the configuration of the installed antennas at which the MIMO achieves the best throughput performance improvement. The parameters used in this experiment are shown in Table II. The throughput and RSSI were measured be employing the MIMO for both the orthogonal and parallel antenna configurations.

Table IV: Fixed transmission rates used in Experiments 2 and 3.

Modulation scheme			BPSK	QPSK
Coding rate			1/2	1/2
Transmission rate, Mbps	11g		6	12
	11n	1-stream	6.5	13
		2-stream	13	26

Table V: Parameters used in Experiment 4.

Mesurement flow	Between PC (PC 1 → Drone 1 → Drone 2 → PC 2)
Transmission rate	Auto rate of 11n
Measurement time, s	30
Distance, m	265
Altitude, m	15

Experiment 2: effect of transmission distance: This experiment was conducted to investigate the effect of the transmission distance on the communication performance. The parameters used in this experiment are shown in Tables III and IV. We used two sets of three fixed rates with the same modulation scheme and coding rate to compare non-MIMO, 1-stream MIMO, and 2-stream MIMO transmissions, as shown in Table IV. In addition, we used the 11b/g auto rates without MIMO transmission and the 11n auto rate with MIMO transmission. The throughputs and RSSIs, with and without MIMO transmissions, were measured for different transmission distances.

Experiment 3: effect of altitude: This experiment was conducted to obtain the effect of altitude on the transmission performance. The parameters used in this experiment were those used in Experiment 2. The throughputs and RSSIs, with and without MIMO, were measured at different altitudes.

Experiment 4: multihop transmission: This experiment was conducted to evaluate the end-to-end throughput performance of a multihop transmission. The parameters used in this experiment are shown in Table V. We measured the throughput at the auto rate of 11n, which employs the MIMO.

IV. Experimental Results

A. Experimental Conditions

The experiments were conducted on November 28, 2022 and December 12, 2022. The weather was cloudy on November 28, 2022 and sunny on December 12, 2022 with a weak wind of a 3.0 m/s peak speed.

B. Experiment 1: Effect of the Configuration of Antennas

The measured throughput and RSSI results obtained by conducting Experiment 1 are shown in Table VI. The RSSI and the correlation coefficient between the RSSIs of the two antennas were smaller in the orthogonal configuration of the antennas than those in the parallel configuration. This is due to the difference in polarization. The throughput was higher in the orthogonal configuration of the antennas than that in the parallel configuration. This is because when the correlation coefficient among the signals is small, the use of the MIMO improves the throughput performance.

Table VI: Experiment 1: throughput and RSSI for two antenna configurations.

Configuration of antennas	Through-put, Mbps	Average combined RSSI dBm	Average RSSI of antenna 0, dBm	Average RSSI of antenna 1, dBm	Correla-tion coefficient of RSSIs
Orthogonal	13.7	−69.3	−72.1	−72.5	0.35
Parallel	11.3	−66.7	−69.4	−70.1	0.52

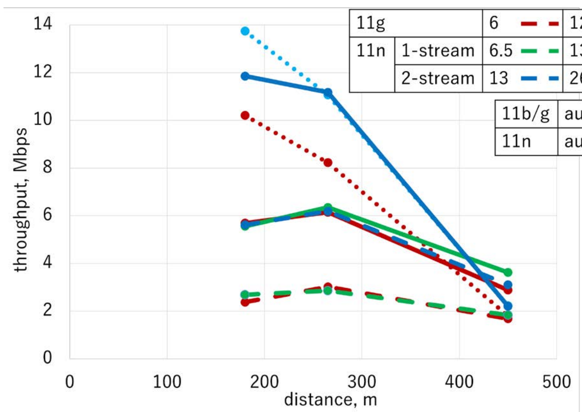


Fig. 5: Experiment 2: effect of transmission distance on throughput (altitude: 15 m).

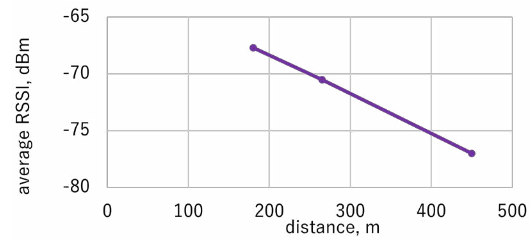


Fig. 6: Experiment 2: effect of transmission distance on RSSI (altitude: 15 m).

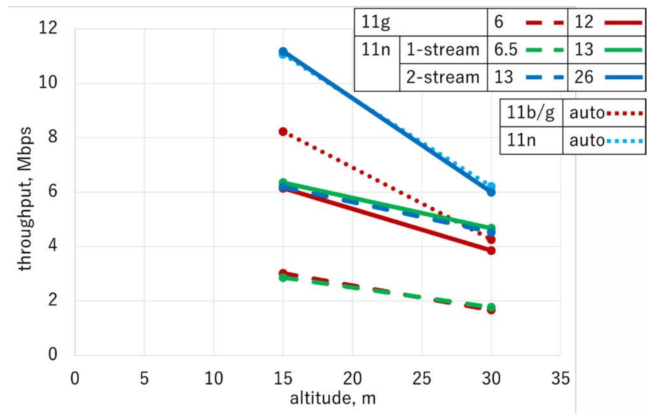


Fig. 7: Experiment 3: effect of altitude on throughput (transmission distance: 265 m).

In the other experiments, the orthogonal antenna configuration was used.

C. Experiment 2: Effect of the Transmission Distance

The average measured throughput results obtained by conducting Experiment 2 are shown in Fig. 5. For the same modulation scheme and coding rate, and for transmission distances of 180 m and 265 m, the throughput obtained using the 11n 2-stream MIMO transmission rate was higher than that using the 11n 1-stream MIMO transmission rate and the 11g non-MIMO transmission rate. Focusing on the auto rates, the throughput obtained when using the 11n MIMO transmission rate was higher than that using the 11b/g non-MIMO transmission rate. On the other hand, there was little difference in throughput with and without MIMO transmission for a 450 m transmission distance.

To further investigate this result, we plotted the average measured RSSI, as shown in Fig. 6. We observe that the RSSI decreases as the transmission distance increases. This is due to the propagation loss. The use of the MIMO improved the throughput at the 180 m and 265 m transmission distances. However, the throughput could not be improved at the 450 m transmission distance due to the very small RSSI value.

D. Experiment 3: Effect of Altitude

The measured throughput results obtained by conducting Experiment 3 are shown in Fig. 7. For the same modulation scheme and coding rate, the throughput of the 11n 2-stream MIMO transmission was higher than that of the 11n 1-stream MIMO transmission and the 11g non-MIMO transmission at 15 m and 30 m altitudes. In the case of the auto rates, the throughput of the 11n MIMO transmission was higher than that of the 11b/g non-MIMO transmission. Although the throughput at a 30 m altitude was lower than that at a 15 m altitude, the difference in throughput with and without MIMO transmissions was independent of the altitude. Therefore, we can assume that the MIMO improves the throughput, even if the drone altitude is high.

To examine the channel characteristics, we plotted the cumulative RSSI distribution, as shown in Fig. 8. Here, the horizontal axis represents the RSSI normalized by its mean value and the vertical axis represents the cumulative RSSI distribution. A steep slope curve indicates that the effect of the reflected waves is small. The effect of the reflected waves at 15 m and 30 m altitudes were approximately the same since the curve slopes were similar for both altitudes.

To investigate the cause of difference in throughputs at 15 m and 30 m altitudes, we plotted the RSSI, as shown in Fig. 9. We observe that the RSSI at a 30 m altitude is slightly higher than that at a 15 m altitude. Therefore, no factors deteriorating the throughput at a 30 m altitude were found.

Next, we investigated the interference from other wireless LANs not related to our experiments. Table VII shows the number of wireless LAN APs detected by Drone 1. The number of APs at a 30 m altitude was larger than that at a 15 m altitude. This suggests that more waves from other wireless LANs reached Drone 1 at a 30 m altitude. As a result, this interference degraded the throughput performance.

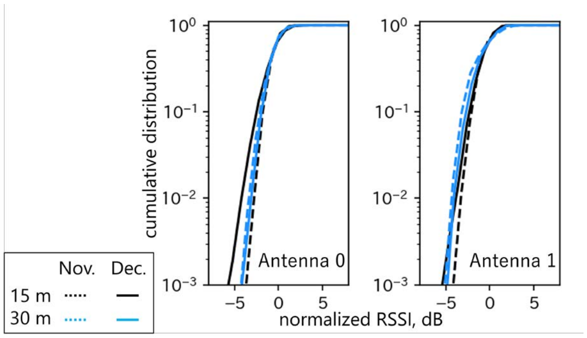


Fig. 8: Experiment 3: cumulative distribution of RSSI (transmission distance: 265 m).

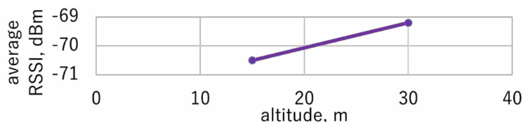


Fig. 9: Experiment 3: effect of altitude on RSSI (transmission distance: 265 m).

E. Experiment 4: Multihop Transmission

Table VIII shows the throughput results obtained by conducting Experiment 4. The degradation ratio is defined as a ratio of the throughput achieved between the PCs to the throughput achieved between the drones. The throughput achieved between the drones was 13.7 Mbps and the throughput achieved between the PCs was 2.63 Mbps, resulting in a degradation ratio of about 1/5. In multihop transmissions, while one node transmits, the other nodes wait for their turn to transmit. As the number of relay nodes increases, the end-to-end throughput performance decreases [16]. In our experimental system, while PC 1 and Drone 2 transmit, Drone 1 waits for its turn to transmit. In this case, the expected degradation rate is 1/3. The reason for obtaining a degradation ratio lower than 1/3 is that, when Drone 2 (for example) receives packets from Drone 1, the interference induced by PC 1 causes packet loss, making the auto rate to select a reduced transmission rate. As a result, the throughput is reduced.

V. Conclusions

In this study, aiming at improving the performance of wireless LAN relay systems using drones, we employed the MIMO and conducted experiments. Specifically, we investigated the configuration of the installed antennas that results in the best improvement in communication performance using the MIMO. We also investigated the effect of the distance and altitude on the communication performance. In addition, we investigated the communication performance in multihop transmissions.

The experimental results showed that the MIMO can achieve a better throughput performance in the orthogonal antenna configuration than that in the parallel configuration. Regarding the effect of distance, the MIMO improved the throughput performance in air-to-air communications, except for the 450 m distance. As the distance increased, the improvement in the throughput performance achieved by the MIMO was decreased. The effect of the reflected waves on the throughput improvement was almost the same at 15 m and 30 m altitudes. The degradation ratio of the end-to-end throughput performance in the multihop transmission system was about 1/5 compared to the expected value of 1/3 between the drones.

Consequently, the application of the MIMO in air-to-air communications using drones improves the communication performance when the drones fly at a height of 30 m or lower.

Table VII: Experiment 3: number of detected access points.

Altitude, m	Date	Average number of access points
15	November 28	12.875
	December 12	17.75
30	November 28	31.125
	December 12	46.375

Table VIII: Experiment 4: throughput in multihop communication.

Channel	Throughput, Mbps	Degradation ratio
Between drones	13.7	-
Between PCs	2.63	0.192

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