1-1-2023

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Recommended Citation

APA Citation
Shaheen, M. Amer, H. & Ali, N. (2023). Robust Air-to-Air Channel Model for Swarms of Drones in Search and Rescue Missions. *IEEE Access,* 10.1109/access.2023.3292517
https://fount.aucegypt.edu/faculty_journal_articles/5510

MLA Citation
Shaheen, Marwa Mohamed Zaki, et al. "Robust Air-to-Air Channel Model for Swarms of Drones in Search and Rescue Missions." *IEEE Access,* 2023,
https://fount.aucegypt.edu/faculty_journal_articles/5510

This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and
content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2023.3292517

XXXDate of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.Doi Number

Robust Air-to-Air Channel Model for Swarms of Drones in Search and Rescue Missions

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ABSTRACT Drones have greatly enhanced search and rescue missions. They help improve the response time of the rescue team. They can cover vast challenging terrains quickly. Drones used in rescue missions are expensive. Because of the challenging terrains, if any drone crashes, it cannot be retrieved. This paper presents two contributions. The first contribution is a cruising scheme for a swarm of drones heading to a dangerous area to rescue victims. The proposed scheme guarantees the safety of the drones during the mission. It guarantees that no drone is lost; whenever a drone's controller fails, another drone will guide it home. Basically, each pair of drones should monitor the control system of one another. In case no watchdog signal is sent, an error is perceived and the operational drone begins to control the malfunctioning one (the drone with a failed controller). Every drone sends all its sensor data to the other drone every 1msec. When a fault occurs, the operational drone sends back the control signals to the malfunctioning one to control its actuators. A robust air-to-air communication channel between pairs of drones, is needed in order to realize the proposed navigation scheme and to achieve a safe cruise and a successful mission to every single drone in the whole swarm. Therefore, the second contribution is a channel model for the air-to-air links between pairs of drones. It is assumed that drones' transceivers use the 802.11n protocol. Simulations are conducted to test the proposed channel model in two scenarios. The first one is fault- free and the other one is when one of the controllers in a pair of drones, fails. The separating distance between every two drones in each pair and their relative velocity with respect to one another, differ in both scenarios. The proposed channel is robust as it achieves approximately zero BER in both scenarios.

INDEX TERMS Unmanned Aerial Vehicle (UAV), Air to air channels (A2A), Bit error rate (BER), Signal to noise ratio (SNR), Line of sight (LOS), Orthogonal frequency division multiplexing (OFDM).

I. INTRODUCTION

Internet of Things (IoT) is a modern technology which comprises many things connected to the Internet [1]. In IoT technology, 'things' mean all kind of devices including drones. Drones contain many electronic modules such as sensors, actuators and controllers [2]. Drones need to communicate with each other and also communicate with the central node to exchange the necessary information. This communication is wireless and is achieved using wireless technology which connects the drones to the Internet; therefore, Internet of Drones (IoD) fits under the umbrella of IoT and uses the same network and communication protocols.

Drones have a crucial role in search and rescue missions. Drones are used to fly over abrupt, inaccessible, distant or dangerous areas. Drone technology is used to decrease the response time of the rescue teams in finding and saving perished people in challenging terrains. They could be used on various terrains and with different search patterns and over different altitudes [3-5].

Yan et. al. [6] present a drone classification according to their size and structure. Drones used in search and rescue in this work are medium size drones. Their speed is 120km/hr. Each drone can carry a payload of around 60kg. Drones used in search and rescue are expensive. They carry necessary supplies and equipment to rescue the victims. Since the ground areas are dangerous, it will be very difficult to salvage a drone if its controller fails. Therefore, it is important to find a technique to prevent a drone from crashing after the failure of its controller.

Assuming the drones are flying in groups, it is possible for them to communicate; an operational drone would then be able to control a failed controller and guide it back to home base. A similar approach was used in [7] to rescue Autonomous Underwater Vehicles (AUVs) whenever a fault takes place, after their deployment in investigation missions.

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In order to realize this cruising model, an Air-to-Air (A2A) channel model must be developed for drones to communicate. Few papers address A2A channel models. However, Yan et. al. [6] present many papers that address aeronautical and UAV channels. Haas [8] presents channel models for aeronautical channels in different scenarios. Measurement campaigns are given in [9-11]. These measurement campaigns adopted the Rice distribution to model the channel between drones. They estimate the channel parameters in order to fit the measurement results. Ray trace simulations are conducted to model the A2A channel between drones in [12]. The peak RMS delay is estimated to be 25ns. Goddemeier et. al. [11] investigates the IEEE 802.11 A2A channel in altitudes below 50m. It investigates the effect of distance, antenna directivity and height on the channel. The Rice distribution is chosen to model the A2A channel below 50m. The Rice factor is assumed to be around 10dB.

This paper introduces a navigation scheme to ensure drone safety during the mission by rescuing the drones whose controllers fail (malfunctioning drones). In the proposed scenario, a swarm of drones is heading to a doomed area; the drones are carrying the necessary supplies. Every pair of drones in the swarm navigate together and has a full duplex communication link. In every pair of drones, the drones monitor the control system of one another. Drones regularly send all sensor data to one another. In case the controller in one of the drones fails, the second drone's controller takes over its tasks and controls the actuators of the malfunctioning one.

The data exchanged between the two drones is either a watchdog signal to make sure that the system is working properly, or sensors readings or control signals from the operational drone to control the actuators of the failed drone. Since the data is critical, the channel must be robust against noise and multipath fading. Therefore, it is essential to have zero Bit Error Rate (BER). The relative velocity of each drone with respect to each other makes the communication link time-varying. The channel link undergoes changes whenever a drone starts to fall, as the separating distance between the drones, changes. The paper mainly focuses on flying above cities or mountains at 100m altitude. This means that multipath components should be considered in the channel model. A channel model is proposed for the A2A link. The channel parameters are set based on the measurement campaigns in [9, 10, 12]. There are different methods for establishing communication between drones such as Bluetooth, cellular, and Wi-Fi. Bluetooth is suitable over only short communication distances [13]. Cellular systems provide good communication services over wide areas, but they are not efficient when only a few base stations are deployed in the desired area. Wi-Fi (IEEE 802.11) provides an efficient and low-cost network to be implemented where a network infrastructure is not available. The IEEE 802.11n is chosen as the communication protocol in this paper, since it is one of the IEEE 802.11 protocols which provides high data rates. In the context of search and rescue missions, the central station sends off a swarm of drones to the desired area and the drones are distributed in pairs. Each pair of drones communicate with each other and send any necessary information to the central station using the built-in Wi-Fi module. The 802.11n is the protocol between the two communicating drones. The proposed model is simulated in two scenarios. The first one is the fault-free scenario where the two drones are flying at their regular speed. The second scenario is when one drone begins to fall and the other one takes the lead and controls the actuators of the failed drone. A Rice distribution will be adopted to model the channel in this scenario. The proposed channel model and the proposed transceiver achieve zero BER in both scenarios.

The rest of the paper is organized as follows. Section II presents the related work. Section III presents the proposed channel model. Section IV discusses the simulations and results. Section V has the conclusion of this work. Finally, all symbols are defined in the appendix.

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II. RELATED WORK

In [10], a A2A channel is created by transmitting a signal at 2.4GHz. A channel response is calculated based on a snapshot of a received signal; power delay profiles are calculated from Channel Impulse Responses (CIRs). It is found that the largest relative delay is 32µs. It is stated that the number of multipath components ranges from 1 to 20; however, 75% of the channel impulse responses provide their direct path component only. It is stated that the channel over sea is a 2-ray model; however, over cities, it includes Line of Sight (LOS) and diffuse components.

In [8], a channel model is presented for aeronautical links in different scenarios. The first scenario discusses the communication links in en-route scenarios when the airplane is airborne. The second scenario is the arrival and take-off scenario and the last one is the taxi scenario. This work assumes that drones face communication links close to the aeronautical links in arrival and take-off scenarios. This claim is based on the fact that the aircrafts, in arrival or take off scenarios, have low altitudes and low velocity. In the take-off scenario, the channel is modeled by scattered path components and a strong line of sight (Rician distribution with K_{RICE}=15dB). The maximum excess delay τ_{max} is up to 7µs. The excess delays are assumed to be exponentially decreasing as shown in Fig.1. The pdf of the one-sided power is given by equation 1.

$$\boldsymbol{\rho_{\tau}(\tau)} = \begin{cases} \dfrac{\mathbf{1}}{\boldsymbol{\tau_{slope}}\left(\mathbf{1} - \boldsymbol{e^{\frac{-\tau_{max}}{\tau_{slope}}}}\right)} \boldsymbol{e^{\frac{-\tau}{\tau_{slope}}}} & \boldsymbol{, if\, 0 < \tau < \tau_{max}} \\ \mathbf{0} & \boldsymbol{, otherwise} \end{cases} \qquad (1)$$

τ_{slope} is assumed to be 1µs in order to generate Rician-distributed samples. In [8], it is shown how to generate τ_n as in equation 2. $u(n)$ is a random uniformly distributed variable

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$u(n)\epsilon(0,1)$ and $g_\tau(u_n)$ is the inverse of the desired cumulative distribution function.

$$\boldsymbol{\tau_n = g_\tau(u_n) = -\tau_{slope}.\,log_e\left(1 - u_n\left(1 - e^{\frac{-\tau_{max}}{\tau_{slope}}}\right)\right)} \qquad (2)$$

$$\boldsymbol{\tau_n = -\tau_{slope}.\,log_e(1 - u_n)} \qquad (3)$$

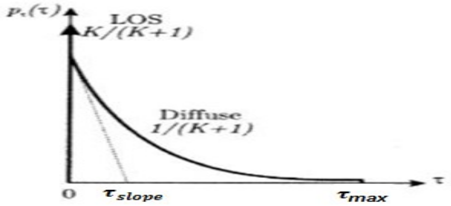

FIGURE 1. Delay Power Spectrum [8]

In [7], a rescue approach similar to the one presented in this paper, is used with Autonomous Underwater Vehicles (AUVs). If the controller of a single AUV fails, another AUV will be sent to rescue. The sensors and actuators of both the rescue and the failed AUVs are connected to the rescue AUV. This rescue scheme is similar to fault tolerance technique used in [14].

III. METHODOLOGY

This paper is concerned with the usage of drones in catastrophes. Drones can cover vast areas and challenging terrains. This work targets double rotor drones with speeds of around 120 km/hr. The drones are medium size drones that can carry a payload of around 60kg [15]. Similar to the architecture in [7], the drones' network architecture consists of sensors, actuators and a controller connected on top of Switched Ethernet. This is commonly known as a Networked Control System (NCS) [2]

The paper presents an approach to guarantee a safe flight for the whole swarm of drones. Every pair of drones are expected to make the whole flight together. Both drones monitor each other's control system to ensure that both processors are operating properly. This takes place by exchanging a watchdog signal from one drone to the other every 1ms. The drones use the 802.11n communication protocol. The shortest frame in the MAC layer is 46 Bytes [16], hence the payload of the watchdog signal is 46 Bytes in addition to 6 bytes for the header. The drone sends all the data read from its sensors regularly every 1ms, which is the sampling time of the sensors [17]. The data that is sent on the channel every 1ms is 100 Bytes. Sensors in one drone send this data to their own controller and to the controller of the other drone in the pair (as shown in Fig. 2). Sensors in the other drone behave similarly. Let drones A and B be paired together. Let us further divide the 1ms sampling period into four equal periods of 0.25ms each: T1, T2, T3 and T4 (as shown in Fig. 3). Focusing on the sensors of drone A and the beginning of T1, these sensors send 100 Bytes to their own controller and that of drone B. Drone B will process this data during T2; hence, T1 must be long enough for drone A to transmit the data and for the data to propagate from drone A to drone B.

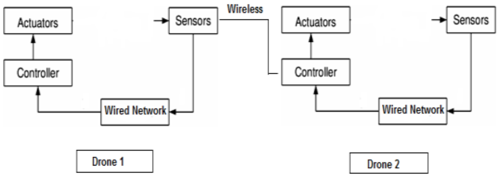

FIGURE 2. Network Architecture

According to the IEEE 802.11n communication protocol, the bit rate ranges from 54Mbit/sec to 600Mbit/s [16]; consequently, the bit duration will range from 18.5ns to 1.67ns. Therefore, the maximum time required for transmission of 100 Byte will be 14.8µs (using the maximum bit duration of 18.5ns) according to equation (4), which means that T1 is long enough to transmit this amount of data.

$$\boldsymbol{t_{tx} = N\,.\,T_b} \qquad (4)$$

$$\boldsymbol{t_{rx} = t_{tx} + t_p} \qquad (5)$$

where N is the number of transmitted bits, $\boldsymbol{t_p}$ is the propagation delay which equals 0.3µs (distance divided by the velocity of light) and T_b is the maximum bit duration which equals 18.5ns.

At the beginning of T3, the controller in drone A sends a watchdog signal to the controller in drone B. This is just an "I'm Alive" signal and does not contain any specific information. So, 52 Bytes are sent from drone A to drone B. The same equations above apply here, and it takes 7.996µs for the 52 Bytes to be received by drone B (7.696µs for the transmission in addition to 0.3µs for the propagation delay). If this signal is not received by drone B, this indicates that the processor of drone A has failed. But, since drone B has already calculated the control actions for the actuators in drone A during T2, it can send these control actions to the actuators of drone A during T4.

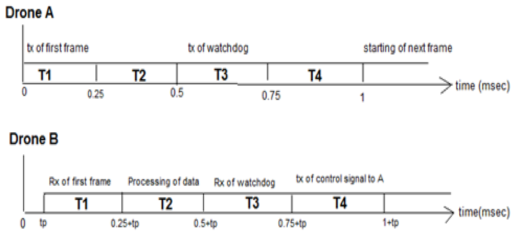

FIGURE 3. The proposed system Time slots

Taking into consideration the size of the drones and their speed in different scenarios, the maximum separating distance

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between the drones in each pair is assumed to be 100m. The drones are flying at an altitude of 100m.

Next is the channel model of the Air-to-Air (A2A) communication link between the two drones in each pair. The air-to-air link is characterized by the influences of Doppler and multipath fading. The two drones communicate at 2.4GHz. The Doppler spread problem is solved at 5GHz band by more sophisticated means. These solutions actually allow the system to benefit from the Doppler effect and to support higher rates. One possible solution is to use beamforming as mentioned in [18]; another solution is to use time diversity. However, 2.4GHz is more suitable for the proposed application, as the drones send a limited amount of data (around 100 Bytes every 1ms). After investigating several measuring campaigns in several crowded cities and over rural areas as well, it is found that the Rice distribution fits the measurements of the channel gains [11]. Since the two drones are flying close together, there is a line of sight path and several delayed paths resulting from the reflections with the surrounding buildings or trees. However, it is expected that there are no obstacles directly between the two drones. The Rice distribution considers the dominant LOS and the NLOS paths. However, for simplicity in the fault-free scenario, NLOS paths are neglected as LOS is strong and the channel is arbitrarily modeled as an AWGN channel. In the faulty scenario, the Rice distribution is adopted. The ratio between the LOS and the diffuse components is called the Rice factor. The Rice factor is given by equation (6) [8].

$$\boldsymbol{K_{RICE} = \frac{a^2}{c^2}} \tag{6}$$

where, a is the amplitude of the LOS path and c^2 is the variance of the diffuse process with zero mean quadrature components. Both a and c could be derived in terms of the Rice factor for normalized fixed mean throughput power as shown in equation (7) [8].

$$\boldsymbol{a = \sqrt{\frac{K_{RICE}}{K_{RICE}+1}} \quad and\ c = \sqrt{\frac{1}{K_{RICE}+1}}} \tag{7}$$

Using the parameters mentioned in the two previous equations, the Rice distribution is defined as shown in equation (8) [8], where $I_o(z)$ represents the modified Bessel function of the first kind with order zero.

$$\boldsymbol{p(\mathrm{x}) = \frac{2a^2}{c^2} e^{\frac{-x^2-a^2}{c^2}} I_0(\frac{2xa}{c^2})} \tag{8}$$

As illustrated in Section II, the pdf of the delay power spectrum is exponential as in equation (1). The excess delays are exponentially decreasing as the amplitudes of the delayed paths have a Raleigh distribution. The maximum excess delay is assumed to be 7μs and $\tau_{slope}\ is\ 1\mu s$ based on the take-off model in [9]. The Doppler shift is defined as in equation (9).

$$\boldsymbol{f_d = \frac{v}{\lambda} cos\theta} \tag{9}$$

where Θ is the angle between the moving transmitter and receiver, v is the relative velocity of one drone with respect to the second one and $\boldsymbol{\lambda}$ is the wavelength. The A2A link between the drones is characterized by slow fading. The maximum velocity of the drone is 120km/hr [15]. Basically, the channel is not affected by the Doppler spread in the fault-free scenario since the two drones are moving parallel to each other at the same speed and hence the relative velocity is negligible. The channel is affected by the Doppler spread when one drone starts to slow down or fall; this happens for 1ms before the second drone takes the lead and controls its actuators. This scenario is studied in detail in the next section. Basically, the Doppler power distribution follows the Jakes distribution [8]. This is because the antenna is omnidirectional and the received signal is the superposition of multiple waves at random directions.

The received power at the receiver is calculated using the free space model as in equation (10), where P_R is the received power, P_T is the transmitted power, G_T is the transmitter antenna gain, G_R is the receiver antenna gain and d is the distance separating the two drones.

$$\boldsymbol{P_R = P_T G_T G_R (\frac{\lambda}{4\pi d})^2} \tag{10}$$

By investigating the receivers' noise figure and their output signal to noise ratio, it is found that the output signal to noise ratio of the receivers is typically 10dB [8, 11]. The transceivers of the drones use the 802.11n protocol. The exchanged data between the pair of drones assures the safety of the drones and the success of the rescue missions. Hence, the retrieved data at each transceiver must be error-free. To tackle this problem, the transceivers use the error correcting codes available in the Wi-Fi transceiver chain.

IV. SIMULATION RESULTS

A. SIMULATION SETUP

In order to generate Rician distributed samples, there are two approaches to generate the channel gains. The first approach is to use the functional transformation [8] illustrated in Section II. The generated $u(n)$ represents the channel gains. The channel gains are normalized and scaled to obey the Rice factor where the total diffuse power should be equal to $1/(1+K_{Rice})$. The channel gains are used to generate the channel delays as illustrated in equation (3). The second approach uses the MATLAB Rice distribution to generate the amplitudes. The generated amplitudes are squared to generate the gains. The delays are generated using equation (3).

For both approaches, the generated channel delays and channel gains are fed to the MATLAB built in function (comm.RicianChannel) to generate the multipath Rician fading channel. Therefore, these two approaches are approximately the same and achieve the same results with very little difference.

B. FAULT-FREE SCENARIO

The transceiver of the drones uses the 802.11n protocol. In this scenario, it is assumed that the two drones are moving parallel to each other at the same speed with a direct line of sight; therefore, the channel can be modeled as an AWGN channel. Fig. 4 shows the BER of the main frame given that the output SNR is 10dB and the separating distance between the two drones is 100m. This simulation is conducted using BPSK modulation and no error correction codes. Each drone sends 100 Bytes every 1ms. These 100 Bytes represent the readings of the sensors of each drone. The measurement of BER is repeated for 33 simulation runs, so the x axis in the figure represents the number of simulation runs and the y axis represents the corresponding BER value for each run. The average BER over the number of runs is 3.575×10^{-6}. The same simulation is repeated for the watchdog signal as each drone sends 52 Bytes every 1ms. The BER for each simulation run is shown in Fig. 5. The average BER over the number of simulation runs is 3.376×10^{-6}. The 802.11n protocol has two encoders, Low Density Part Check (LDPC) and a convolutional encoder.

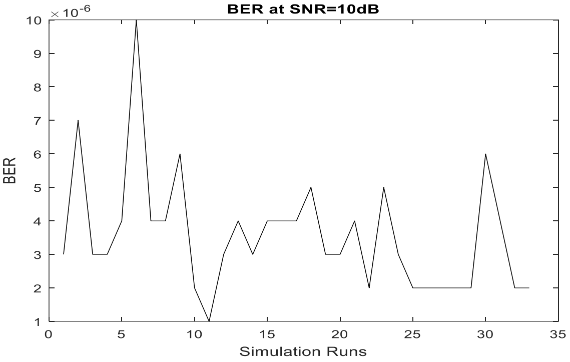

FIGURE 4. BER of the Main Frame at 100m

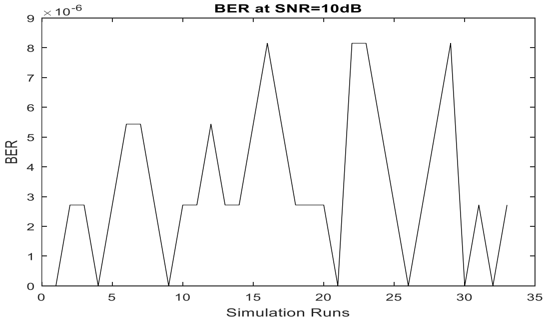

FIGURE 5. BER of the Watchdog Frame

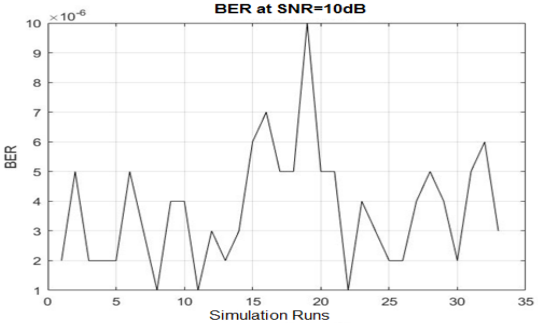

FIGURE 6. BER of the Main Frame at 50m

In this paper, the convolutional encoder is used. The minimum distance of the convolutional encoder used in the 802.11n protocol [16] is calculated. It is equal to 10; this makes the convolutional encoder powerful enough to guarantee zero BER transmissions. Four coding rates $1/2$, $3/4$, $5/6$ and $2/3$ are supported by the transceiver in 802.11n. As the coding rate increases, the correction capability decreases, however the information rate increases. After adding the convolutional encoder (using a code rate of 1/2 or a puncturing rate of 2/3), the BER falls to zero in all the simulation runs.

C. FAULTY SCENARIO

This scenario takes place when one drone starts to fall. The maximum separating distance between the two drones is assumed to be 100m. As the drone starts to fall, the separating distance between the drones, changes. The Rice distribution is adopted to model the channel in this scenario. Fig. 6 shows the BER of the main frame given that the separating distance between the two drones is 50m. Fig. 7 shows the BER of the main frame given that the separating distance between the two drones is 20m. As the distance between the two drones decreases, the line-of-sight component becomes stronger and K_{Rice} increases. Basically, the Doppler effect is supposed to affect the model in this scenario, as the two drones are supposed to move with different velocities. However, the sampling time is too short; therefore, the drone remains uncontrolled for only 1ms. The displacement during this 1ms is irrelevant and therefore, the initial velocity of the falling drone, which is the velocity during normal flight, is approximately equal to its final velocity. The final velocity is the drone's velocity after 1ms under free fall rules. Hence, the relative velocity has not changed. The Doppler effect does not have a relevant impact on the model thanks to the high frame rate between the two drones. The Convolutional encoder with code rate 1/3 is used with this model to obtain zero BER.

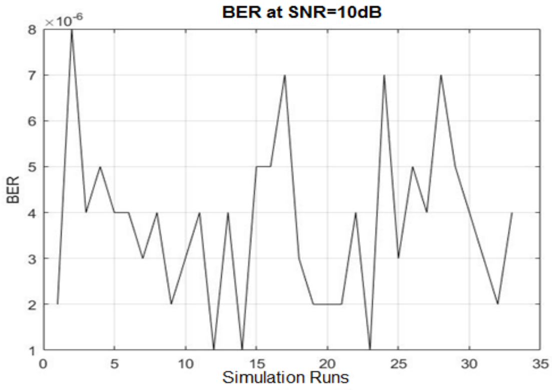

FIGURE 7. BER of the Main Frame at 20m

V. DISCUSSION

The 802.11n protocol uses OFDM modulation. In orthogonal frequency division multiplexing, the high-rate data stream is split into low-rate parallel data streams. Each individual data symbol is carried on a single carrier. By the use of the guard interval, the subcarriers are made to be orthogonal. However, the orthogonality of the subcarriers is destroyed when the channel is time variant. Consequently, the interference between the subcarriers creates an irreducible error floor.

Given that the velocity is 120km/hr and the frequency is 2.4GHz, the maximum Doppler frequency is 278Hz. In order to support the transmission with 1Mb/s and to support the highest coding scheme, this system uses a half-clocked OFDM system with 10MHz channel spacing. Hence, the subcarrier frequency is 0.15625MHz (10MHz/64). According to [8], in order to avoid the Inter-Carrier Interference ICI, $f_{d_{max}}$ should be less than 0.1 of the subcarrier frequency or the normalized Doppler frequency should be less than 0.02 as mentioned in [19]. The Normalized Doppler frequency is $f_d N T_s$. Since both conditions are satisfied, the channel is assumed to be constant during the duration T_s of the multicarrier symbol and no inter carrier interferences are taken into account. The power of ICI is negligible compared to the noise. The guard interval is chosen greater than or equal to the delay spread. The delay of each path is irrelevant if all echoes lie within the cyclic extension. This cyclic prefix eliminates the effect of the inter-symbol interference ISI.

VI. CONCLUSION

Drones have excellent capabilities to search vast areas, quickly making search and rescue operations more efficient. Necessary supplies are transported using drones regardless of the difficult ground conditions. Drones used in search and rescue are expensive. Whenever a drone falls, it cannot be retrieved because of the difficult terrains.

The cruising scheme proposed in this research ensures the safety of the drones during rescue missions. In this scheme, a group of drones are heading to a doomed area. Each drone carries a payload of supplies weighing about 60kg. For each pair of drones, they have to monitor each other's control system. This takes place by exchanging a watchdog signal every 1ms. Whenever the watchdog signal is not received, an error is perceived, and the operational drone controls the actuators of the falling drone. Since each drone periodically (every 1ms) sends all its sensors readings to the other drone in the pair, both controllers always have all sensor data.

A channel model is needed to realize this navigation scheme. This paper proposes a channel model for the communication link between the drones. The drones are communicating at a center frequency of 2.4GHz using the 802.11n protocol. The Convolutional encoder is used to obtain a zero-bit error rate. In order to ensure that the channel is robust, two scenarios are simulated. The first scenario is a fault-free scenario while the second scenario is when the controller of one drone fails. The Rice distribution is adopted to model the channel in the second scenario for different separation distances between the two drones and consequently different K_{Rice}. As the separating distance between the drones decreases, K_{Rice} increases. Multipath components are neglected in the first scenario and the channel is modeled as a AWGN channel for simplicity. In both scenarios, the data between the drones is successfully transmitted with zero-bit error rate. Finally, it is found that Doppler spread has no great impact on the channel model whether the channel uses single carrier or OFDM. This is because of the strong LOS between the two drones.

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This article has been accepted for publication in IEEE Access. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2023.3292517

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APPENDIX

Symbol	Quantity
$\boldsymbol{\tau_{max}}$	maximum excess delay
N	number of transmitted bits
t_p	propagation delay
t_{tx}	transmission time
T_b	maximum bit duration
K_{Rice}	Rice factor
a	amplitude of LOS component
c^2	variance of the diffuse component
$I_o(z)$	modified Bessel function of the first kind with order zero
f_d	Doppler shift
v	relative velocity of one drone with respect to the second one
Θ	angle between moving transmitter and receiver
$\boldsymbol{\lambda}$	the wavelength
P_T	transmit power
P_R	received power
G_T	transmit antenna gain
G_R	receive antenna gain
d	distance separating the two drones

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