Dynamic Channel Hopping over Diverse Wireless Link for Semi-Autonomous UAVs

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***Abstract*—The communication link quality between a drone and its ground base station is a critical point-of-failure for drone operations. Excessive packet loss between the ground station and the drone can result in an interruption of the mission or even the loss of the drone. It has been shown in the literature that simple telecommunication techniques such as radio diversity and channel hopping can drastically improve the quality of a wireless link. This work presents a microcontroller-based prototype system, developed to test a communication link using radio diversity and channel hopping, to reduce packet loss in drone-base communication. The system consisted of a ground base station system connected to a laptop, and a receiver system, attached to a drone. After testing the system functionality in laboratory, validation field tests were conducted. These experiments on the field revealed that even using unsophisticated hardware modules, both telecommunication techniques can improve the wireless link for drone operations, particularly when used together.**

***Index Terms*—Drones Communication, Radio Diversity, Link Channel Abstraction, Communication protocol, Redundancy, Channel Hopping, Wireless Communication Link.**

I. Introduction

The worldwide usage of drone systems saw a huge increase over the last decade, both in professional sectors (like the military and agricultural markets [11]) as well as in the hobby and consumer market [20]. No Unmanned Aerial Vehicle (UAV) system operates without a communication link to a ground base station. Even fully autonomous UAVs need to communicate with a control base for diagnostics, mission updates, and telemetry. A reliable, quality communication channel is essential for any UAV system, whether it is for a professional purpose or just for entertainment [3][7][9]. In addition to unfavorable weather conditions, obstacles, and reflections, a wireless communication channel can suffer interference from other radios operating nearby and on the same frequency. This interference can even be deliberate, as a way of attacking the communication channel and disabling the UAV. There are several ways to strengthen a wireless communication channel [19], both in hardware and software. Some hardware possibilities would be to relocate the antennas, increase the transmission power, or change the channel frequency [21]. When it comes to software, it is possible to implement error correction techniques [18] and to create any communication protocol aimed at diagnosing the quality of the channel and sorting messages [10]. As the frequency possibilities are generally limited, and the transceiver's power cannot be increased indefinitely, more practical alternatives must be studied.

In telecommunications, a diversity scheme refers to a method for improving the reliability of a message signal by using two or more communication channels with different characteristics [8]. It is a method of applying redundancy to communication in order to make it more reliable and robust against noise, interference, or concurrency. Many diversity techniques can be applied to a communication channel, such as: Time diversity, where multiple versions of the same signal are transmitted at different time instants; Frequency diversity, where the signal is transmitted using several frequency channels or spread over a wide spectrum; and Antenna diversity, where multiple transmitter antennas and/or multiple receiving antennas are used.

A hardware method that can be applied to strengthen a wireless communication channel that does not require a physical change in the antenna or the power applied is spread spectrum communication [21]. Spread spectrum is a wireless communication technique whereby a wireless channel has its transmission deliberately spread out in the frequency domain over a wider frequency band, so that if the frequency chosen for transmission is already occupied by another radio or has a very high noise level, a better frequency band can be chosen for communication. There are several methods of spread spectrum communication, such as Frequency Hopping Spread Spectrum (FHSS), direct-sequence spread spectrum (DSSS), time-hopping spread spectrum (THSS), and chirp spread spectrum (CSS). All methods consist of dividing the available frequency band into several narrow-band channels. The transmitter then rapidly switches between these channels, following a logical, pseudo-random, or dynamic sequence.

Software efforts can also dramatically increase the quality of the communication channel. Detection and correction of message errors can easily be implemented in both hardware and software to ensure that only unadulterated messages are exchanged by wireless systems [18]. A simple message control protocol, akin to TCP/IP [12] can be implemented in software to ensure order and certainty in the wireless link.

As the radio spectrum worldwide is regulated, most commercially available drones utilize the ISM bands [22]. ISM stands for Industrial, Science, and Medical. These are free radio bands that can be utilized by any radio transmitter, with regulated power and time usage, but without the necessity of registering and licensing.

The proposal for the article is to study the implementation of a diverse wireless link to be used between a controller and a

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semi-autonomous UAV, utilizing dynamic frequency hopping between different sub-bands in different ISM frequency bands, with error correction and a basic communication protocol to ensure that only valid messages are exchanged between a drone and the ground control station. The main ISM bands utilized in Brazil are the 902-928MHz and the 2.400-2.500MHz ISM bands. The communication link is established over both bands, using different radios. The different bands are dynamically tested for transmission quality. A simple protocol is implemented to ensure the messages are exchanged successfully and in order. The communication link is as transparent as possible to the system utilizing it, having only control over what frequencies can be used and diagnostic information of the communication being executed. Telemetry and commands can be exchanged between the UAV and the controller to test how effective is the communication link, with and without the diversity, to analyze if there are any improvements over a simple fixed frequency transmission. The basic protocol is not, at least for now, designed to support more than one UAV and one controller over the same communication link.

The remainder of the paper is organized as follows: Section II presents the literature review. Section III describes the proposed communication systems, while Section IV presents the implementation details. Section V describes the designed experiments and Section VI discusses the acquired results. Finally, Section VII concludes the paper presenting directions for future work.

II. Related Works

Radio diversity is an old technique in the field of communications, but it is still very relevant not only for the telecommunications industry but also as a research subject, for it can be applied to every new technology in order to make it more reliable. There are studies on implementing link diversity on many radio frequencies and modulations.

Although this study is focused on generic radio links, explicitly avoiding using proprietary technologies, working on more complex infrastructures and systems like telephone networks, wi-fi, and even satellite networks could offer valuable insight into the matter of diversity, frequency hopping, and UAV networks. As mobile phone networks cover a good portion of the urban areas, are already proven technology, and offer a ready-to-work infrastructure, many works on reliable networks for UAVs use cellular network systems such as 5G as their communication medium. These works differ significantly from this study's context but still have interesting insights on the subject.

The article [6] analyzes reliable cellular UAV communication via a simulation. Simulations are very important when studying UAV swarms, for it can be increasingly challenging to study swarms, depending on what technologies are used, the environment of the study, and mainly the number of drones involved. Although simulating a cellular UAV network system, it is clear that a multi-channel link from a drone to the control center or server will improve communication, making it more reliable and less susceptible to geographical outage zones and failures due to network capacity.

In [1], a more practical approach takes place. A communication link between a server and a drone is established via two different LTE cellular network ports. Several UAV flights were executed over the city of Aarhus, in Denmark, to test the performance and quality of the communication link. This is much closer to what this study proposes, although the prototype described used UDP. UDP differs from the proposal of this study because the main idea of a reliable communication channel is to be able to order and check the messages exchanged between the two peers in the network, which is actually how the TCP protocol is implemented, the main inspiration for the basic protocol proposed in this study. The results showed in [1] are promising, showing improvements in latency and reliability without a need of more investments in the infrastructure.

The work proposed by [17] involves radio diversity between UAVs, ground bases, and high-altitude platforms, such as satellites and high-altitude balloons. The work is more focused on network characteristics and metrics, such as line-of-sight communication and data-rate variation, to analyze the characteristics of diverse networks. Although it involves many different communication topologies, this work sheds some light on the main challenges of diverse radio communication when there is not an established and validated infrastructure as used by cellular communication.

In [16], a similar system is developed, although with a different hardware topology, but with a communication protocol and general working more similar to the prototype proposed in this study. This paper establishes a radio-diversity communication channel between a ground station and an actual plane, with a radio communication system inside, alongside the researchers. The paper focuses more on the telecommunication aspect of diverse radios than this study. Still, the fundamental working principles are the same: A communication link between a ground base and an aerial vehicle via a diverse radio.

The work done in [5] actually implements a dual radio system for drones very similar to the proposed one in this study, although aimed at drone flocks, with a short-range radio and a long-range radio. This is possibly the closest in topology to what is proposed in this study. The idea is to make one of the drones use the long-range radio to communicate with the ground base while the rest form a mesh network using the short-range radio. Even though diversity is used to switch a flock drone to the role of flock leader instead of strengthening the link to the ground base, the system used with two radios on a single drone is the same. Not only does the hardware follow the same principle, but the logic of the network protocol implemented shows the same level of flexibility between radios as well, switching between the long-range and the short-range on demand in order to keep a viable link to the ground base.

Lastly, it is possible to mentioned the works reported in [13] and [14], which highlight the importance of the subject handled in this current paper. While these two works deal in more advanced subjects in the telecommunication field, both address problems that are being tackled in this paper. The work presented in [13] shows the importance of a dynamic channel selection in urban environments when using a robust wireless communication link. The work reported in [14] highlights the importance of radio diversity in the communication of aerial manned and unmanned vehicles.

Even though the works described in [6] and [1] mainly deal with cellular networks, they still describe many challenges and solutions regarding the diversity and reliability of communication links. [17] deals with the diversity of radios for UAVs in many different scenarios, like communicating with high-altitude balloons and different ground bases. It is much more complex than what is proposed in this study, but it has a lot of invaluable information regarding many different aspects of diverse link communications. The work [16] goes in depth about the many challenges regarding the electromagnetism aspects of telecommunications. The team responsible for that study developed a complete radio system to be boarded on a plane in order to be as thorough as possible in the analysis of the communication between ground bases and UAVs in general. Even though it had a diverse radio with many similar frequencies, this work helped develop the system proposed in this study. The article that is more closely related to this study is the [5], with UAVs utilizing two radios for communication, with the selection of which radio to be used being dynamic, throughout the entire mission. It utilized the radios for different communication channels instead of using both for the same link, as the main proposal of this current paper.

In the many diverse telecommunication systems and topologies revised in this study, different aspects and characteristics were developed and analyzed. From cellular networks to drone swarms, they all implemented important radio diversity techniques. This study proposes a generic link between two peers in a network, with the main quirk of using different radio bands for the diversity scheme, in order to garner the best characteristics and reception in a given scenario. On top of that, frequency hopping and a basic identity and acknowledgment protocol should be implemented in order to boost the links' resistance to noise, interference, and jamming. A summary of the revised articles for this work can be seen in Table 1, with the following comparisons:

- (Type of work) If the article is about a simulation, numerical study, or a real prototype deployed for field tests;
- (Proprietary) If the work relies on proprietary infrastructure or modulation;
- (Different Frequencies) If the proposed solution involved different frequency ranges for the radio diversity setup.

TABLE I
SUMMARY OF THE MAIN REVISED WORKS FOUND IN THE LITERATURE.

Article	Type of work	Proprietary	Different frequencies
[6]	simulation	yes	no
[1]	real deployment	yes	no
[17]	numerical study	yes	no
[16]	real deployment	no	yes
[5]	real deployment	no	yes
[13]	simulation	no	no
[14]	simulation	yes	no
This paper	real deployment	no	yes

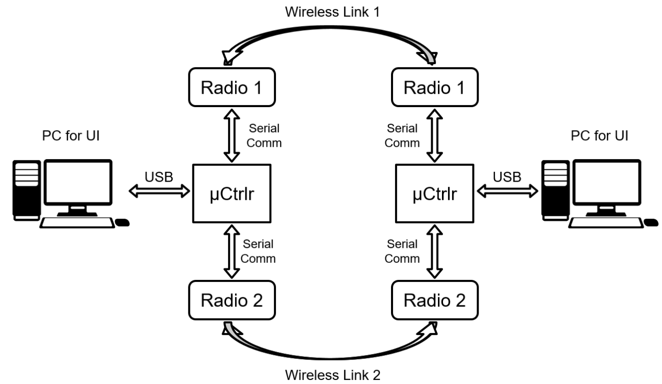

Fig. 1. The basic hardware topology proposed in this article

III. Proposed Solution

A. Design Overview

The proposed solution for a reliable wireless communication link is, in essence, very simple, for the only devices that are needed to implement a communication link are the transceivers and some type of controller that, in firmware, runs the protocol's state machine. As this article aims to just analyze point-to-point communication, only two systems were tested together. Each system has two different transceivers, both working on different ISM bands. With a hardware that simple, more of the work relied on building the different firmware functionalities. Laptops were used to communicate with the controllers in order to implement an easy way of setting the test values, reading test results, and, ideally, powering the system. Figure 1 shows a general idea of a generic test setup.

The firmware state machine is the most important part of the prototype, for all the proposed solutions depend on the correct functioning of the state machine, detecting good communication channels on different bands and utilizing them in order to spread the communication all over the spectrum. The firmware ideally implements:

- Error detection, if not already implemented in hardware;
- Channel testing concurrent with communication;
- Wait period for ACK messages with a time limit;
- Numerical message identification.

With these features implemented in firmware, channel diagnostics are possible, and with the individual diagnostics information available, the state machine can control with which channels it will establish a communication link. In the end, it was not necessary to implement error detection in firmware because the used radios already implemented it in hardware. More details are presented in the following.

B. The Hardware

A hardware topology is defined before any work can be done on the firmware level. The goal of this work is the implementation of a complete radio diversity: Not only different antennas or frequencies but two completely different radios connected to a microcontroller, each operating on different frequencies and using different antennas, for complete redundancy. Ideally, the radios should not implement any proprietary modulation or link, in order to do the analysis solely on the radio diversity and obtain results as agnostic to the radios as possible. The modulation methods of the radios are not important for the proposed analysis as long as they are well-known, off-the-shelf, similar solutions. The majority of all generic, off-the-shelf transceivers found in the consumer market implemented some variation of Frequency Shift Keying (FSK), which is a method of digital modulation and consists of the transmitter switching the output frequency between two predetermined values [4], which differ from the central carrier frequency by a value called ”frequency deviation”. The receiver will then detect and decode the many changes between carrier frequencies into bits. The used radios are able to use many different channels in their respective ISM band. This is necessary to implement channel hopping. Fixed frequency transmitters are of no use for this work.

After valid communication is established between the microcontroller and the radio and valid configurations are set on the transceivers, data transmission is validated between the two systems. After a basic link is established, some kind of error detection/correction method should be implemented, if not already a hardware feature present on the radios. Although an error correction feature is not always available in hardware, at least error detection must be implemented, to make sure the messages have valid content. The most common method of error detection (with no correction) implemented in hardware on off-the-shelf ISM band transceivers is Cyclic Redundancy Check (CRC). The CRC logic consists of generating a unique checksum for each block of data that is transmitted. This checksum, called a CRC value, is calculated based on the data contents and appended to the data before transmission [15]. The receiver then performs the same calculation and compares the result with the received CRC value. The transmitted data contains no error/alteration if the CRC values match. With these steps concluded, the hardware can reliably transmit data, using different channels on an ISM radio band, with error detection (at least). This work was done with two different radios, to implement radio frequency diversity.

C. Firmware State Machine

After the hardware topology is defined and the hardware features are validated, a basic state machine is developed in firmware to enforce a communication protocol to ensure that the messages that are exchanged are being transmitted correctly and in order. A basic protocol constantly monitors if the message is received or lost. This was easily implemented using answer messages, known in the telecommunication field as ”ack”, short for ”acknowledgement message”. Every time the receiver has a message with a valid CRC value, it sends a message back to the transmitter acknowledging that the message was received. Not only that, but it can even confirm which message was received. For example, if the receiver has message number 3 in the receiving buffer but the next message is message number 5, it can report back that message 4 did not arrive. A simple message counter can make diagnostics possible by tracking which messages were lost and how many. To know if a message is lost, the sender waits for some time for the message to arrive, which the user configures. This configurable time is a ”communication timeout”. If the sender gets no messages until the timeout, this can indicate that the link to the receiver was lost. Finally, with channel diagnostics implemented, dynamic channel hopping can be achieved. Dynamic channel hopping consists on the constant test of every channel available on the selected radio band, all while already transmitting data. This allows channels that are suddenly the target of noise or unknown transmissions to be avoided. Just as some channels can be marked as unsuitable for transmission, they will still be tested over time, in case the event of noise or transmission is over, to maximize the usage of the radio band, and spread the transmission as much as possible over the spectrum. A diagnostics subroutine is implemented in firmware to test if every received message has a valid ID number and and was received within tolerated timing. This subroutine will flag valid and invalid channels to keep a list of good-quality links for the transmissions. The state machine is shown in Figure 2.

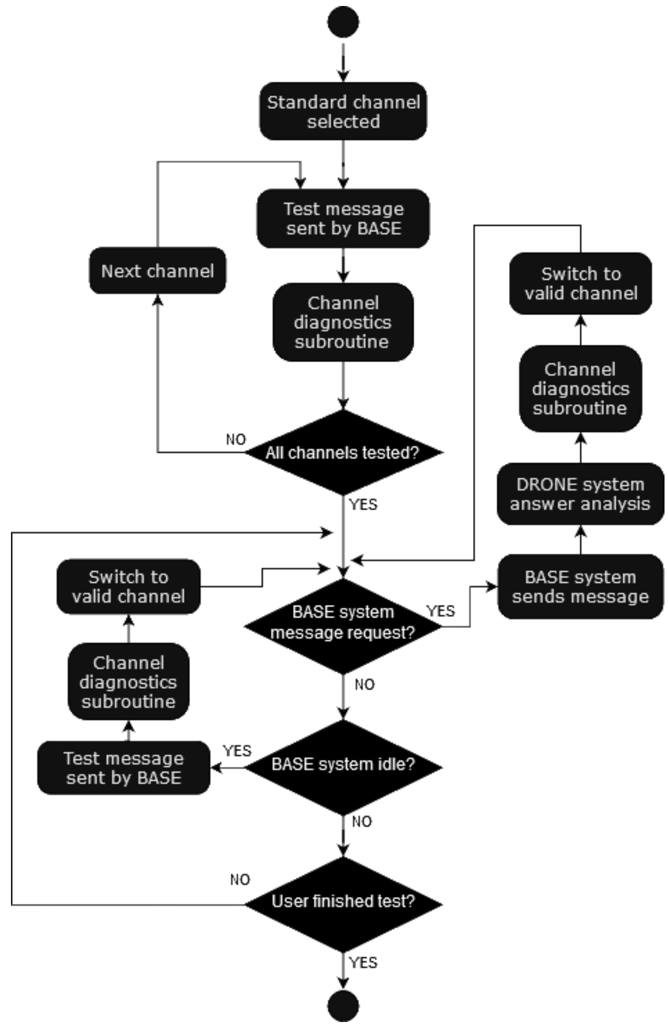

Fig. 2. The basic state machine proposed for the firmware

With both hardware and firmware solutions in place, it is time to test the performance of the transceivers. Most importantly, if the channel hopping over diverse radios brings any advantages to the system when it comes to link quality, compared to systems that do not use radio diversity or channel hopping. The quality of the link can be measured by how many messages are lost or received with errors. The main parameter of the communication link to be controlled by the test program is the hopping configuration. The test will not include variations on antennas, transmission power, or data rate, as the only parameters being tested are the configuration of the channel hopping and radio diversity. As the systems are linked by two, hopping enabled radios simultaneously, there are four possibilities for communication between two transceiver systems:

- No hopping and no diversity;
- Channel hopping within only one radio band;
- Channel hopping between two fixed channels on different radios to only test the radio diversity;
- Complete channel hopping, implemented seamlessly between radio links.

The first method was used in each band to obtain a reference for the tests. The third method was used to test radio diversity without channel hopping. The second method was compared with the first to determine if channel hopping used in a single radio band offers any advantage. After testing channel hopping in the two bands separately, the fourth method of transmission was tested to compare channel hopping in a single band versus channel hopping using radio diversity.

IV. Implementation

For simplicity purposes, the communication protocol is based on a master-slave scheme. The test system consists of two subsystems: One of the systems is denominated ”Base”, while the other is called ”Drone”. The Base system is the one initiating communication, and a Drone has to answer back, with a valid message, in time, to signify that the communication link is active and working. All four methods mentioned in the previous section were tested. To test each method of transmission against interference and attenuation, the systems were either physically moved apart, or the antennas were partially blocked.

The main objective of this work is the proposal of a system where the loss of messages on a radio link due to corruption or insufficient signal strength is reduced. Therefore, the main metric of the tests was the amount of loss that occurred in the radio links using the different test methods. The ability to switch between channels with less loss is the main difference between this design and more traditional radio links. As packet loss is the main focus, packets with empty messages will be exchanged, to only test the link. Therefore, the data in the payload will consist of the packet header, including all the metadata related to the protocol implemented, but no significant message data.

Regarding specific radio configurations, a few important concepts are vital for the best operation of the radio. Both radios allow the microcontroller to change their carrier frequency and data rate. Radio 2 has even more options (which will be addressed later). As the carrier frequency should not impact the signal quality as much, data rate becomes the most important parameter for signal reception. According to Nyquist’s bandwidth formula: In a noise-free environment, the limitation on data rate is simply the bandwidth of the signal [19]. For the impact of noise on a communication link, Shannon’s formula of channel capacity [19] tells that for a given noise level, the higher the data rate, the higher the error rate. So, to have a trustworthy communication link with the least number of errors, the system should aim to operate with larger bandwidth and lower data rates to avoid losing a packet due to excessive noise. As lower data rates allow for lower error rates, lower data rates allow for longer transmission ranges, as the signal’s intensity decays with distance and the impact of noise becomes more prevalent.

A. Hardware setup

Both subsystems, Base and Drone, consist of a prototyping board, each with one microcontroller, one 2.4GHz radio, and one 915MHz radio. Drone systems also have a LiPo battery and a voltage regulator so they can be moved away from the base system to test the quality of the link in many different signal strengths. The used Microcontroller was an ESP32-S3, the used 2.4GHz radio module was a Nordic nRF24-based module, and the 915MHz radio module was a Semtech SX1276-based module.

Many modulations and protocols could be used for both radios. However, as this work aims to avoid proprietary protocols and modulations, FSK modulation was used, and many extra configurations were ignored. The drone system was mounted externally on the drone, so the link could be tested at varying distances. The final test setup can be seen in Figure 3.

1) Antennas: Both transceivers used on both systems will employ simple antennas that came with the chip. The 2.4GHz radio used a dipole antenna and the 915MHz used a helical antenna. This is important because the radiation pattern of these types of antenna are not uniform [19], so the orientation of the antennas is important throughout the communication between the two systems. Dipole antennas transmit better in the direction perpendicular to the antenna, 360 degrees, almost like as radiation propagated from the antenna as a torus. The closer to parallel the direction to the other antenna is, the less power it transmits [2]. Helical antennas transmit much more power in the direction they are pointing. This is very important to drone communication links: If both drone and base station have vertical dipole antennas, and the drone flies over the base station, too close to the position exactly above the station, the drone’s antenna will fly over the base’s antenna’s dead zone, and communication will be lost. The higher the drone is flying, the farther from the base station it should be to have a better angle of transmission between the two antennas. If the transmitter and receiver have helical antennas, both antennas should be pointed at each other, otherwise the link is lost.

2) Microcontroller: The chosen microcontroller for the prototype was the Espressif ESP32-S3, for the performance capabilities and the framework used to program it (ESP-IDF). The microcontroller has two Xtensa LX7 cores running at 240MHz, 512kB of SRAM, and 45 GPIO’s, including SPI, the

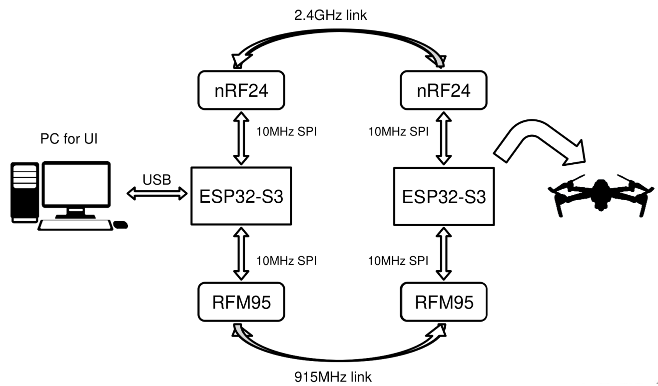

Fig. 3. Proposed test system.

main type of serial communication standard radio transceivers use. The microcontroller was used in a breakout board called ESP32-S3 Devkit C-1, and it was programmed in C utilizing Espressif's framework, ESP-IDF, which consists of a layer of hardware abstraction on top of an RTOS, which in IDF's case is Free-RTOS.

3) 2.4GHz radio: The radio module chosen for the 2.4GHz radio band (designated Radio 1) was an EBYTE E01-ML01DP5, which consists of a Nordic Semiconductor nRF24L01+ radio transceiver connected to a PA+LNA circuit. The PA+LNA circuit consists of two parts: PA stands for Power Amplifier as it amplifies the signal to be transmitted by the radio; LNA stands for the Low Noise Amplifier on the input part of the circuit, that amplifies incoming signals from other radios. The maximum configuration of Power Amplifier is +20dBm and the sensitivity of the LNA is -96dBm. Radio 1 can have data rates of 2Mbps, 1Mbps, and 250kbps over 127 discrete channels. Radio 1 can operate on a proprietary method of communication or just simply FSK.

4) 915MHz radio: The radio module chosen for the 915MHz radio band (designated Radio 2) was a HOP-ERF RFM95W, which consists of a Semtech SX1276 radio transceiver. The standard configuration of the radio transceiver can send signals at +20dBm and has a sensitivity of -148dBm. The main difference between Radio 2 and Radio 1 is that Radio 2 does not have discrete data rates or channel values. Instead, the system can be configured to transmit and receive at any rate up to 300kbps. Radio 2 can communicate through LoRa mode, FSK, or OOK (on-off keying, a method of transmission that consists of turning the carrier frequency on and off). Radio 2 operates in FSK to be comparable to Radio 1. In the FSK configuration, the radio can operate with frequency deviation values from 600Hz to 200kHz. The frequency deviation is the change in frequency when it shifts from the central frequency to the frequencies it uses to symbolize 0's and 1's.

5) Common radio configurations: As specified earlier, both radios offer many proprietary modes of operation. These modes were avoided, to keep this project as agnostic to the used radios as possible. This section only addresses configurations related to the FSK modulation used in both radios. When it comes to the hardware front-end of the radios, both radios were configured similarly:

- No individual addressing, as this work aims to test a single link only. In case of necessary addressing for radio operation, a standard address was used;
- Automatic CRC computation in hardware;
- Maximum transmission power (TXpower) of +20dBm;
- Both radios had the receiving power set to the maximum value (RXpower).
- Fixed-length payload, containing only protocol metadata;
- No interrupts used;
- Both radios stay in Receiver mode, waiting for a packet unless turned to stand-by via SPI (Happens when the other radio is in use).

Similarly, every configuration that would conflict with the proposed firmware machine state was turned off, as those functions were implemented in the microcontroller's firmware:

- No automatic ACK messaging;
- No automatic re-transmission in case of timeout;
- No automatic re-transmission in case of CRC error.

6) Radio 1 setup: As mentioned before for Radio 1, the only RF-related configurations that can be changed were:

- The RF discrete channel selection;
- Discrete data rate selection.

The radio chip handles the channel selection. So when one channel is selected from the 127 possible channels via SPI, the radio determines the FSK frequency deviation. This is done automatically every time a new channel is chosen. With bandwidth being handled automatically, the data rate is the only other RF configuration that can be handled. The nRF24 radio offers three options: 2Mbps, 1Mbps and 250kbps. As lower data rates allow for more reliability and distance, 250kbps is the fixed data rate for radio 1.

7) Radio 2 setup: For Radio 2, there are more RF-related configurations that can be changed:

- Carrier frequency selection;
- Frequency deviation;
- Arbitrary data rate selection;
- Shape of data packet;
- AGC and AFC.

With Radio 2, in order to choose a channel to exchange packets, the microcontroller firmware should directly choose values for carrier frequency and deviation. The frequency deviation value determines the bandwidth of the signal, and also how many channels fit in the 915MHz band (902MHz to 928MHz), and can vary from 600Hz to 200kHz. The data rate is also arbitrary. Values between 0 and 300kbps can be chosen. Lastly, the form of the data packet can also be vastly changed. In fixed length mode, apart from addressing, the radio can be configured with preamble and sync bytes. Preamble bytes indicate to the receiver that a transmission is starting and also help with frequency synchronization. Sync bytes actually flag when the payload actually starts, by having a different pattern than the preamble bytes. The more bytes are used for preamble and sync functions, the better the chances the receiver will successfully demodulate the packet. Lastly, there are AGC and AFC configurations. AGC stands for automatic gain control, for the input LNA. AFC stands for automatic frequency control, for adjusting the carrier frequency filter on the receiving side, in case of a difference in calibration or thermal drift. Both configurations are turned off for simplicity of operations.

Although these configurations can have arbitrary values, the radio's datasheet specifies some limits to each parameter to ensure reliable communication. The datasheet gives two clear limits for the frequency deviation (Fdev) and bit rate (BR) values:

1) $M \leq 250kHz$ with $M = Fdev + {}^{BR}/_{2}$;
2) $0.5 \leq \beta \leq 10$ with $\beta = 2 * {}^{Fdev}/_{BR}$
3) $BR < 2 * RxBw$

The first one (M value) specifies that the sum of frequency deviation and bit rate should not exceed certain limit, so the radio cannot simultaneously operate with both bit rate and deviation at very high levels. The second one specifies a range of values for the modulation index, so frequency deviation should be at least one-fourth of the bit rate but not higher than 5 times the bit rate. The third specifies that the bit rate should respect the sampling criterion, with RxBw being the filter at the radio's input. This filter was used at its maximum possible value of 250kHz to allow for great frequency deviation values.

The carrier frequency is determined by which section of the band the radio will operate. The quantity of channels is determined by the bandwidth, which is controlled by the frequency deviation. The bigger the frequency deviation, the better the reception of the signal when it comes to noise. The opposite is true for the bit rate. Lower values will result in better reception, as explained before. The practical limitations are the two conditions listed in the chip's documentation and the fact that an excessively slow data rate will result in an extremely slow communication channel. Some tests were performed for optimized configurations to have a comparable behavior and communication link quality to Radio 1.

Preliminary tests were executed as many configurations could be set in Radio 2. Starting with the preamble and sync bytes. Standard values returned good results when testing inside the laboratory, but reducing them significantly reduced the success rate of transmissions. Standard values were then kept for all subsequent testing. Bit rate and frequency deviation were incremented together, to keep the modulation index inside the specified range. Just to refresh the concepts: For better performance against noise and better communication distances, the system should operate with lower bit rates and higher frequency deviations. The bit rate should not be too low because communication would take too much time. Frequency deviation can not be just incremented indefinitely, for there is a filter in the transceiver's input and the frequency deviation must fit inside the filter's bandwidth. Frequency deviation was incremented to its upper limit, 200kHz, then lowered until the communication link presented no packet loss. For the lab preliminary tests, a frequency of 150kHz of frequency deviation showed no packet loss. As Radio 1 operated at 250kbps at 2.4GHz, the first attempt to configure the bit rate of Radio 2 aimed to maintain a proportion between the two. As Radio 2 is operating at approximately 37.3% of the frequency of Radio 1 (${}^{915MHz}/_{2.45GHz}$), a bit rate of 100kbps was tested at first. Packet loss was minimal but present, so the bit rate was lowered even further until the laboratory preliminary tests showed no packet loss. The final bit rate was 50kbps. With this bit rate and frequency deviation, the modulation index is 6, in the middle of the specified range. The M value equals 175000, much lower than the maximum of 250000. This configuration fits all the specifications detailed in the chip datasheet and the limits shown in this section.

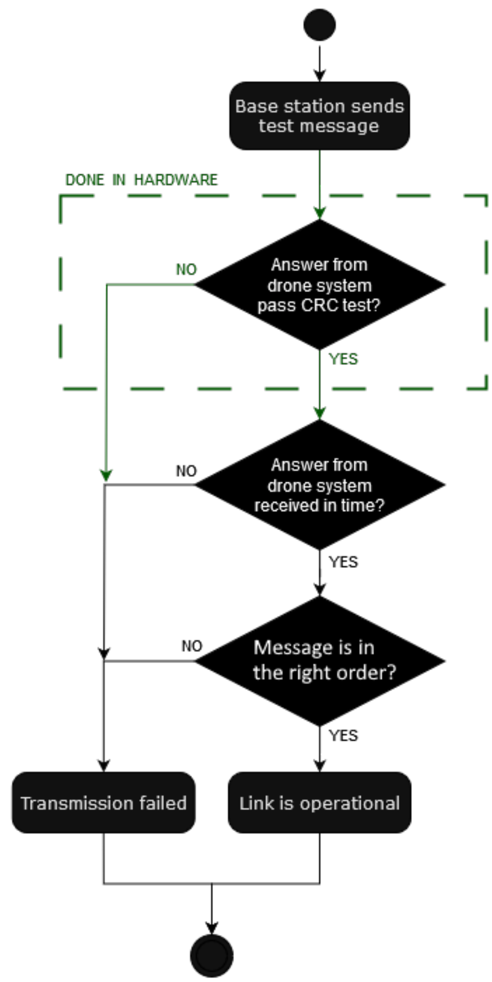

Fig. 4. Firmware state machine algorithm for a single test

B. Firmware state machine

With both radio links operational and stable (at least in the preliminary test at the laboratory), the only work left was to develop a state machine in firmware that would test the performance of the communication link between the Drone and Base systems. As previously mentioned, the firmware controls the enumeration of messages, the timing of the messages, and the channel used for the message exchanges. These processes involve having a header in the payload to control metadata and a state machine in firmware to control the message exchange process and to mark which channels are fit for communication. A flowchart of the state machine of a single message test is shown in Figure 4.

1) Radio payload: Apart from the message in itself, which will not be present in the packet loss tests, the payload in the radio packets contains a header introduced by the firmware, which contains the metadata for the type of message, the message counter, and the channel used in the next message, resulting on a header of 3 bytes. The first specifies which type of message is being transmitted. The second holds the information about which message is being transmitted. The third contains the next channel in the hopping sequence.

2) Packet order: The information about which message is being transmitted is inside the packet header. The state machine detects if messages arrive out of order and mark that channel as compromised. If the message ordering is correct, the message counter is simply incremented.

3) Packet timing: Message transactions also have timeouts. This controls if the other side of the message exchange is not responding. Excessive timeouts also flag the current channel as compromised. Time counting is done via hard real-time interrupts in the microcontroller. The current interrupt tick used is of 20µs. The Free-RTOS standard system tick is of 10ms.

C. Test loop

Different test loops were executed. As the radios were already tested and initialized, changing channels is a matter of calling for a function on the library and a small time overhead.

First, each radio band was tested to ensure the radios were operating normally. That test served as a benchmark for the upcoming results.

As a second test, two different channels on different radio bands were used together to test radio diversity performance and compare it to the simple link. For these tests, the radio channel was chosen by other devices near the laboratory to avoid busy channels. A spectrum analyzer was used to detect the least busy channels. Central frequencies seemed to be the busiest ones, so channels on the lower/upper limits of the radio bands were chosen.

The two bands were tested individually for a third test but with channel hopping. The results were compared with the single-band/single-channel test to analyze the performance of channel hopping in a communication link.

Lastly, the system was tested with both radio diversity and channel hopping, so both bands and all channels were used. The hopping between the two different bands was done continuously, as both radios operated as one, from the microcontroller's point-of-view.

D. System modules

Two circuit boards were soldered to build the Drone and Base prototypes. Each board contains a microcontroller, a 915MHz radio and a 2.4GHz radio. The drone system also has a Li-Po battery, a voltage regulator, and a battery alarm; a drone carries the drone system to test the link's performance over a distance. Both were stored in small cases to protect modules from damage. Both boards are shown in Figure 5, where the left is the Drone board, and the right is for the Base system, to be plugged on a laptop.

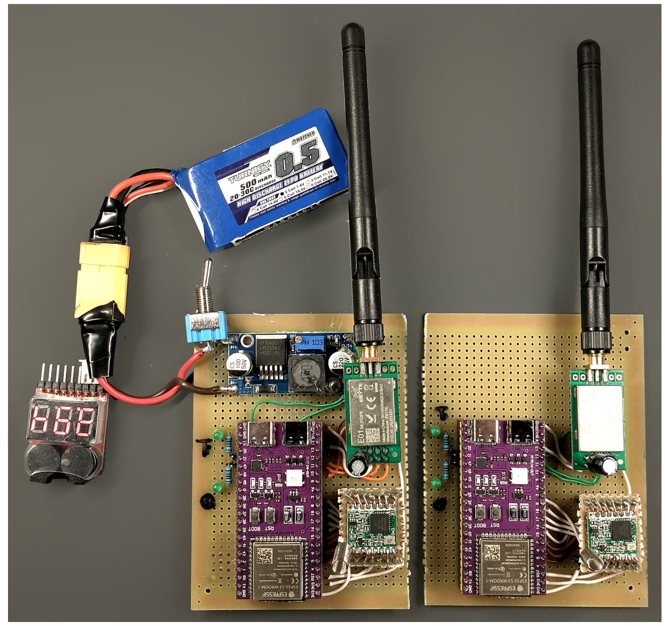

Fig. 5. Drone and Base system boards

V. Experiments

As explained above, two major factors affecting a wireless transmission link are the distance between the two radios and the presence of obstacles between them. The maximum range between two radios depends mostly on transmission power and antenna orientation. The region between two antennas, called Fresnel Zone [19], needs to be clear of obstacles, as more clutter will result in more loss of signal strength. This is the case considering that the two antennas are perfectly parallel between each other (for dipoles). To test the impact of obstacles in the transmission link, one antenna of the pair can be partially or totally blocked, to observe how radio diversity would make it possible for the system to ignore the blocked antenna and prioritize the functioning one. To test the impact of distance, the "Drone" system could be attached to an actual drone and flown away from the "Base" system until transmission was completely compromised. It's important to note that both radios' inputs have LNA's (Low Noise Amplifiers). These amplifiers are designed to amplify very attenuated signals, in order to boost the distance of communication. If the transceivers are positioned too close to each other, the amplifiers' inputs can be overloaded, resulting in distortion of the input signal, and consequently, packet loss.

A. Baseline

Before the actual tests, the system was tested in ideal conditions, inside the laboratory, with no obstacles, in order to get reference results (baseline) for the validation tests to be performed. Later, tests inside the lab utilizing metal obstacles as well as outdoor tests utilizing drones were executed, and the results were compared to the reference results.

B. Attenuation by obstacle

The first set of tests was done inside the laboratory, by testing the different communication setups with metal barriers between the radios to verify if the radio diversity was properly working. Using any Faraday cage, it is possible to induce partial or complete signal loss of one link. These tests were executed mainly to check the entire system's working in a controlled environment before doing the final validation field test.

C. Attenuation by distance

The plastic container with the Drone system's board was attached to the drone upside down, so the PCB and ground plane were closer to the drone and the antennas were more in line of sight with the Base board on the ground. The drone utilized is a 3DR Solo model drone. It is a fully stabilized drone. First, the signal reception was tested while the drone was landed on the ground, 1.5 meters away from the Base system's board and laptop. Then, the drone took off, stabilized at 5 meters of altitude from the ground, and traveled 10, 20, and 50 meters in a straight line, away from the Base system, while maintaining altitude.

VI. Results

For all tests, the results regarding the adaptive channel hopping include all packet losses, including the ones that occurred during the channel test phase. Once adaptive channel hopping was on for enough time, packet loss numbers drop, due to the fact that the algorithm is then avoiding noisy/lossy channels.

The tests inside the laboratory showed promising results. Communication between the two modules was good, in both frequency ranges. Without factors like the drone hull, winds varying the orientation of the antennas, and altitude, the results showed that :

1) A transmission link with radio diversity adds redundancy to the communication link, decreasing the packet loss;
2) A transmission link with channel hopping has better performance, after the link had time to exclude the bad channels from the transmission;
3) A transmission link with channel hopping and radio diversity is the best option of all tested.

The packet loss rate of the transmission tests can be seen in Figure 6. It is important to note that, as the Radio 2 had no losses in transmission at a distance of 1 meter, all transmission tests executed with radio diversity had no packet loss, even though Radio 1 had some packet loss.

The tests involving attenuation by obstacles showed the system successfully detected that one antenna was compromised, marked the respective channels as unsafe, and only utilized the working antenna. These tests showed that the system could successfully operate in a radio or antenna failure case without losing the communication link.

The field tests utilizing a drone in an open field demonstrated how challenging implementing a communication system can be. As explained before, the angle between the Base system's antenna and the Drone system's antenna is very important. As the drone took off vertically, the reception of the signal worsened for the dipole antenna of the 2.4GHz radio. Then, as the drone traveled away, signal reception got better

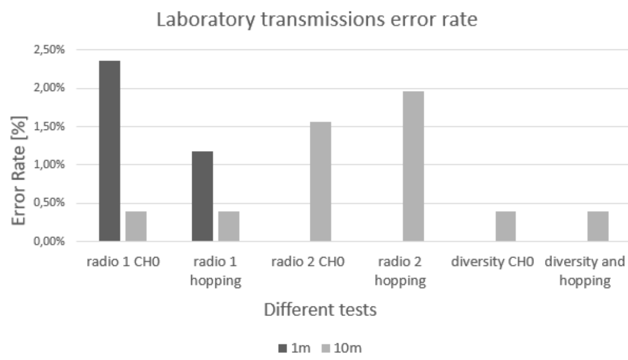

Fig. 6. Indoor tests with two different distances

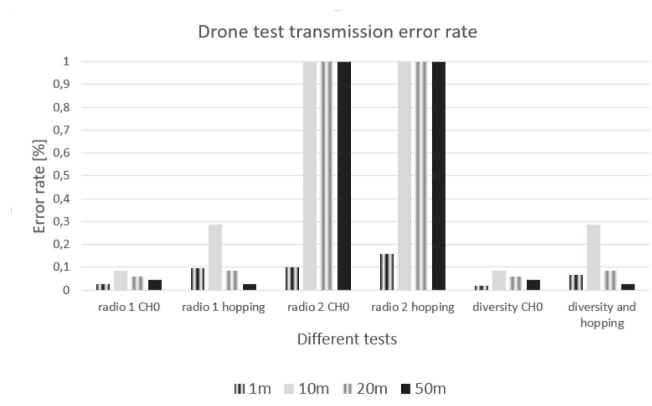

Fig. 7. Outdoor tests with four different distances

until the attenuation by the transmission distance exceeded the system's capabilities. Nonetheless, for the helical antenna of the 915MHz radio, as distance increased, it became harder and harder to keep both antennae pointing at each other, with factors like the wind and the ability of the pilot to point the drone correctly, which made the 915MHz radio link very weak at distances.

Not only did the geometry of the transmission drastically worsen the packet loss, but another possible source of interference was the 3DR drone, to which the Drone system was attached. Eventually, the transmission failed completely for the 915MHz radio, but the 2.4GHz link showed great results. It is important to note that the 915MHz radio configuration was not readjusted after the field test, and it would probably improve its performance.

The results, shown in Figure 7, show that the test with the drone landed next to the Base board performed similarly as when it was tested in the lab, with a loss of performance due to it being attached to the drone, in contrast to being tested in a laboratory controlled environment. As distance increases, Radio 1 shows a significant performance improvement, with the worst error rate being at 10m. Unfortunately, at 10m it became very hard to aim the 915MHz antennas, and this link failed, with an error rate of 100%.

With the 1-meter tests being the only one where Radio 2 could operate nominally, with an average of 255 message attempts, it can be observed that, on average:

Fig. 8. Quadcopter with DRONE system attached

1) Radio 1 + channel 0 suffered 7 packet losses;
2) Radio 2 + channel 0 suffered 25 packet losses;
3) Radio 1 + channel hopping had 24 packet losses;
4) Radio 2 + channel hopping had 40 packet losses;
5) Radio diversity + only channel 0 had 5 packet losses;
6) Radio diversity + channel hopping had 17 packet losses;

As adaptive channel hopping tests the entire frequency range, including the more populated middle frequencies, it can incur more packet losses in the first moment, as it is shown in the results. Radio diversity, on the other hand, shows a clear advantage compared to using only one transceiver/frequency range for a communication link, only having a packet loss when both radios cannot transmit/receive. Figure 8 shows the Drone system attached to the 3DR Solo drone. Figure 9 shows a picture of the drone flying during the 10-meter tests.

Fig. 9. Quadcopter in flight during tests.

VII. Conclusion

This work proposed the development of a radio diverse communication link using adaptive channel hopping, utilizing common transceivers and microcontrollers. Radio diversity adds a layer of redundancy to the communication link, and the different frequency ranges lower the possibility of interference affecting both radios equally. Adaptive channel hopping can enable the communication link to change it's channel dynamically, avoiding channels that are already in use by other radios or present a high level of noise. This is an important asset for the safety of drone operations, creating redundancy in communication. Two boards with microcontrollers were designed to operate as transceivers, with one called Drone responsible for answering messages and one called Base responsible for sending the test messages and evaluating the responses or the lack of them.

Both systems worked successfully with ideal antenna positioning in the lab test. Adaptive channel hopping showed more errors initially, because the middle frequencies of each radio were already in use by devices in the vicinity. The error rate would get lower after several minutes of the test, once the system marked all the non-ideal channels. Radio diversity showed good results, leveraging the advantage of needing only one radio to function in order to never lose a packet, thus displaying better results than both radios when tested separately.

The field tests showed that, using a directional antenna can severely diminish the advantages that the radio diversity or the channel hopping could offer. As discussed in the study, the used antennas were the ones that came with the transceiver modules. Even though Radio 2 did not worked without precise aim, the system did not lose packets unless Radio 1 also failed, which clearly shows the advantage of redundancy.

Even though adaptive channel hopping showed, on average, more packet losses, this happened only because channel 0 in both radios was not being used by devices in the vicinity of the test. In the case the system did not employ channel hopping and the channel 0 was compromised, no communication would be possible. After some time, packet loss count numbers dropped for the test using channel hopping. Radio diversity, on the other hand, clearly showed that, from the perspective of the communication link, it only offers advantages. It is true that a radio diverse system consumes more energy and reduces the space for payload, but it is a trade-off that needs to be considered in the system design.

Future work on the system would include a better antenna system for the 915MHz radio. A setup utilizing dipole antennas would be ideal, for the radiation pattern of said antenna being the best for transmissions where the orientation of the device under test cannot be guaranteed. This would ensure that both radio diversity and channel hopping could be tested in the field, from different distances, even with wind and an unskilled pilot. Another future work direction is the extension of the proposed system to support multiple drones systems.

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