On the impact of inter-UAV communications interference in the 2.4 GHz band

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***Abstract*—As the use of Unmanned Aerial Vehicles (UAVs) increases, protocols to avoid collisions between them and to achieve collaboration through swarm configurations are receiving more attention by the research community. In this work we study the performance of communication links between drones in the 2.4 GHz wireless band, where a high interference from the radio control unit is expected. We performed a large set of experimental tests, and the results demonstrate that the use of the WiFi 2.4 GHz band for any application is not compatible with overwhelming majority of remote controls working in the same frequency band. Moreover, the distance between drones, the data packet size, and the engines speed affect the communications link quality.**

I. Introduction

The use of Unmanned Aerial Vehicles (UAV) is spreading rapidly due to their wide scope of application, especially in critical areas including border surveillance, target tracking and filming [1], disaster response [2], fire fighting [3], and transportation of medicines or first aid [4], among others.

As time goes by, the number of UAVs on air increases, and so does the risk of collision between these devices [5]. Moreover, solutions where swarms of multicopters are used to solve more complex problems through cooperation are being proposed [6]. Both cases require UAVs to communicate among them to coordinate their flight, something that is only being done at an experimental level at this moment. Thus, more studies are required to determine which would be the most appropriate communication technology, and which are the factors affecting performance.

In this scope, the work by Andre et al. [7] concludes that WiFi is a good candidate. The 2.4GHz band is specially interesting because it is free, offers high bandwidth, and achieves long distances under free-space propagation conditions. Nevertheless, the remote control of the UAVs used for the experiments also use this band, which will generate interferences during experiments.

The main aim of this work is to study the communications performance between UAVs in the 2.4 GHz band, taking into account existing interferences. The fact that the remote controls use the same frequency band thereby becomes a serious issue, as the packet loss ratio could become too high to get a stable communications link.

In general, the results show that, for a greater distance between UAVs or larger sized data packets, the packet loss ratio is bigger, which means lower communication link quality and throughput. On the other hand, the distance between an UAV and its remote control only has effect at a very short distance, a situation that cannot occur during regular operation of the UAV. The greater is the power applied to the engines, the greater the degree of vibration generated and, therefore, the interference with the link signal. Finally, the impact of signal reflection due to ground proximity were masked by the interference of the remote control, which is several degrees of magnitude higher. So, the goal of this work is to properly assess the performance of WiFi communications in the 2.4 GHz band in the presence of interference in different situations.

The rest of the paper is organized as follows: in the next section we provide an overview of related works in the field of inter-UAV communications. Section III presents an overview of Dronning, an application we have developed in order to partially simplify field experiments and automate channel testing and result recollection. Details about the different field experiments are then provided in section IV. In section V,we present our experimental results, with appropriate discussion. Finally, section VI concludes the paper and refers to future works.

II. Related works

Andre et al. [7] studied the throughput and the delay provided by several wireless technologies that could be used for UAV-to-UAV communications. They concluded that XBee-PRO [8] and IEEE 802.11 are good candidates.

Regarding the use of IEEE 802.11 technology, Asadpour et al. [9] detected really low throughput. The current bandwidth adaptation mechanism used in the standard is too slow when reacting to the high mobility of UAVs. Moreover, they found that the relative antenna orientation and position strongly influences the communications link quality. In a later study [10], the same authors did comprehensive measurement campaigns to analyze the characteristics and influence of different factors, i.e.: physical, MAC and routing layers, antenna type, and data relaying strategies. Yanmaz et al. [11] analyzed the performance on one-hop communication between UAVs and a ground station, and two-hop communication between two UAVs through a ground station. Furthermore, their study includes both infrastructure and mesh modes, and the obtained results exhibit a high throughput variance, which disturbs the behavior of dynamic multi-hop networking.

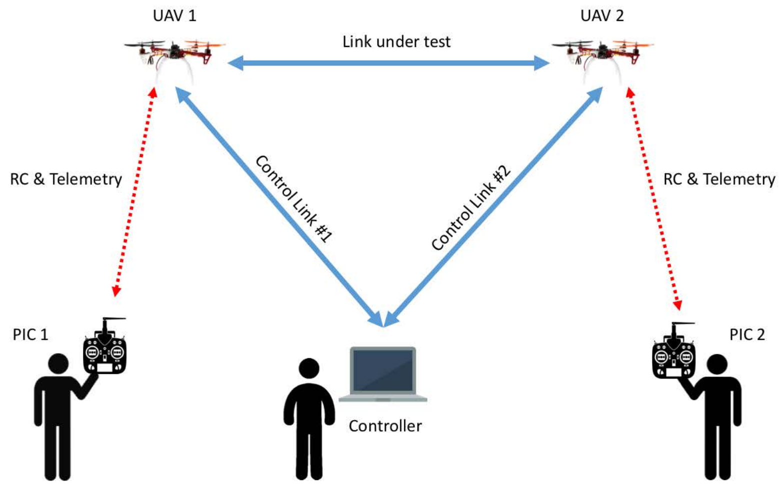

Figure 1. Wireless communication links diagram.

Concerning the use of other technologies apart from IEEE 802.11, Van Der Berg et al. [12] proposed the use of UAVs as eNodeB or User Equipment (UE) in the scope of LTE. The main conclusion related to this document is the extensive and important changes required in LTE networks for proper communication among UAVs with this technology. Ahmed et al. [13] asserts that the antenna orientation, environmental factors, and the multi-path fading effect due to the ground reflection degrade Zigbee communication links.

Other conclusions not related with an specific technology were obtained by Zeng et al. [14]. Firstly, the link communication is centered in the LoS component. Secondly, the ground reflection of the signal has a minimum effect on the link quality. Finally, the Doppler effect is significantly aggravated by the relative speed among UAVs.

In general, the authors agree that there is still room for a wider and deeper analysis of available technologies to establish the most appropriate one for UAV communications, taking into account their special needs.

This paper differs from previous studies by specifically focusing on WiFi communications in the 2.4 GHz band, studying the impact of UAV radio controllers also working this band, among other factors (distance, engine speed, presence of wind, etc.).

III. Overview of the Dronning tool

The impact of interferences on performance is directly related with the packet loss that happens during transmission. The Dronning tool [15] allows to measure the communication link quality between two UAVs. Our tool consists of two components: a test tool and a data analysis component. The test tool allows automating communications performance tests, controlling the conditions under which these tests are undertaken. Concerning the data analysis component, it consists of a set of scripts able to automatically analyze the gathered data and generate appropriate charts.

The test tool has been developed using the Java language, thus embracing compatibility across platforms. It is able to run on a Raspberry Pi and on a standard PC with different roles, and it supports noisy environments, with very high packet loss ratios.

Figure 1 shows the communication links stablished among the different devices involved in a test. Both UAVs and the computer with the “controller” role are connected through an Ad-Hoc WiFi network in the 2.4 GHz band. All of them were assigned static IP addresses. Additional links are stablished between drones and remote control units for telemetry and flight control purposes also work in the 2.4GHz band, which generates strong interferences, as documented later on this document.

Data packets are broadcasted via UDP, a protocol that avoids retransmission and data rate adaptation, thereby allowing to detect packet loss.

To perform a test, two Pilots in Command (PICs) with the appropriate flight authorization are needed to handle the UAVs. Another person is needed to input the test parameters into the standard PC and start the test.

The test tool is a distributed application. Firstly, it establishes communication links between the UAVs and among the UAVs and the computer with the controller role, being such links represented in the figure with blue arrows. The computer takes the controller role, one of the UAVs the client role, and the other UAV the server role. Secondly, the test parameters are introduced into the computer and the experiment is started. The UAV adopting the server role sends data packets to the other UAV respecting the test parameters initially defined. Finally, when the test ends, data are stored in the UAV with the client role for a later analysis with the data analysis component.

In addition to link quality information, the data stored includes navigation information from both UAVs in order to be able to analyze their impact on performance: GPS position, speed, yaw, roll, and pitch, among others. This information is retrieved from the Pixhawk flight controller [16] embedded in

Figure 2. Quadcopter model used for testing: maximum width: 560 mm; maximum height: 160 mm

Table I
HARDWARE CHARACTERIZATION OF QUADCOPTERS USED.

Model	Quaternium GRCQuad
Frame	DJI F330
Flight controller	3DR Pixhawk
Weight	1200 g
Engines	SunnySky X2212-980Kv
Propellers	GenFan 8”/4.5”
Telemetry	3DR Radio Telemetry Kit
Battery	GensAce LiPo 4S1P 3300 mAh
RC	FrSky Taranis X9D/X8R

the UAVs.

IV. Definition of field experiments

For out tests, we relied on two radio-controlled quadcopters, as illustrated in figure 2. Each one is endowed with a Pixhawk flight controller, as well as a Raspberry Pi version 2 for high-level management and communication support. Table I shows the most relevant technical details of the quadcopters used. The FrSky Taranis remote control establishes a radio-control link in the 2.4 GHz band, as well as a telemetry radio link that operates in the 433 MHz band. The first one interferes with the wireless network created among the UAVs and the standard PC since it uses the same frequency band. This interference significantly affected all the experiments done while the remote control devices were turned on.

An Ad-Hoc WiFi network was stablished between two UAVs to perform the experiments, as shown in figure 1.

Each experiment had a duration of 60 seconds, and a transmission packet ratio of 50 packets per second. If not stated otherwise, the packet size was 1500 bytes (maximum Ethernet MTU).

The analyzed factors and experiment parameters were the following:

- *Engine power on (electromagnetic interferences).*
  The running engines of the UAV produce electromagnetic interferences that affect the link signal. For this experiment the UAVs were initially leaning on the floor. Then, the data packet loss ratio at different distances between UAVs was measured in two situations: with the engines off and on, but at a very low power. The remote controls were turned on during both tests series.
- *Engine speed (structural vibrations).*
  If the engine power increases, the UAV starts to vibrate. Furthermore, the engines emit more electromagnetic radiation, which could increase the effect already studied in the previous experiment. Both UAVs where anchored to the ground at a distance of 20 meters between them. The engine power was increased from 0 to 100% in intervals of 25%.
- *Separation between UAVs (signal attenuation) and remote control activation (electromagnetic interferences).*
  The transmitted signal decreases with the distance. In addition, significant interferences are expected as the remote control link uses the same frequency band as the UAVs communication link, as discussed above. The packet loss ratio was measured for different distances between UAVs, with the remote controls off and on.
- *Separation between UAV and remote control (electromagnetic interferences).*
  Since the control signal can produce interferences, the distance between the remote and the UAV could significantly influence the communications link quality. As in previous experiments, the UAVs rested on the ground at a distance of 20 meters between them. The link quality was measured when separating the remote control from the UAV at short range distances.
- *Data packet size (media noise).*
  The longer the packet being sent, the longer the wireless media is busy, and the probability of noise transmission errors increases. Both UAVs were 20 m apart and measurements were made with 300, 1000 and 1500 bytes packet sizes.
- *Ground elevation (multi-path fading and Fresnel zone occupancy).*
  The transmitted signal reflects on the ground, which could produce multi-path fading. Furthermore, the Fresnel zone around the LoS could be intercepted by the ground, lowering the strength of the received signal. During the tests, both UAVs were 20 meters apart, and measurements were made at different elevations above the ground.
- *Relative antennas orientation*
  Real antennas are not isotropic, so the relative orientation between transmitting and receiving antennas affects the link strength. The Dronning tool provides charts with the evolution of relative antenna orientation and bursts of packets lost over the test time. The comparison of these charts allows to detect the correlation between the relative antenna orientation and the link quality.

V. Experimental results

In this section we discuss the experimental results obtained in our experimental testbed. The first experiment (see figure 3) studies if the electromagnetic interferences generated be the engines have influence on the communication link quality. We find that the packet loss ratio is very high, increasing with the distance between UAVs. Nevertheless, there is no significant

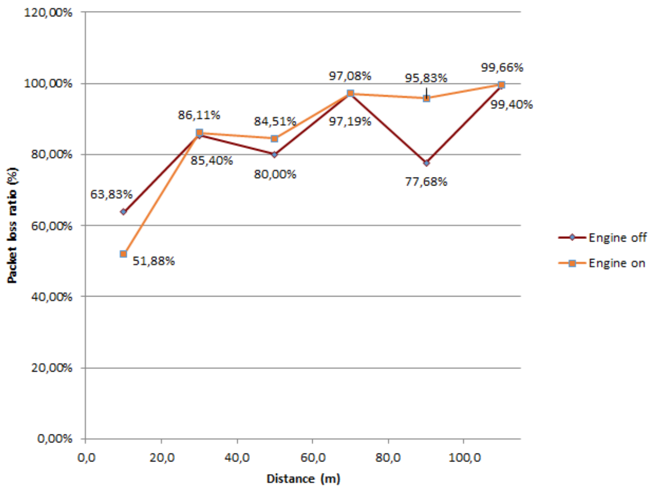

Figure 3. Packet loss versus distance. Effect of turning on the drones engines (25% power).

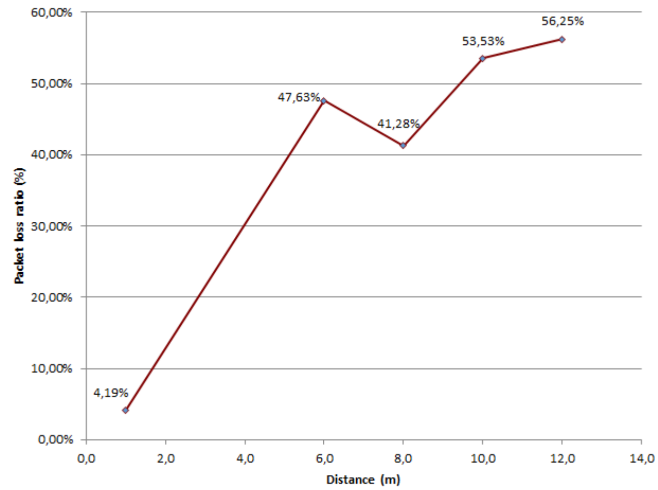

Figure 5. Packet loss versus distance. Effect of distance at low range when locating both UAVs near the ground, in static mode.

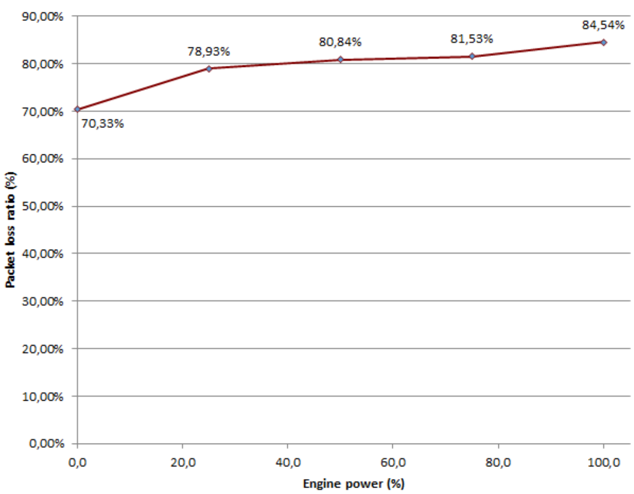

Figure 4. Packet loss versus engine power. Effect of vibration due to engine lift power.

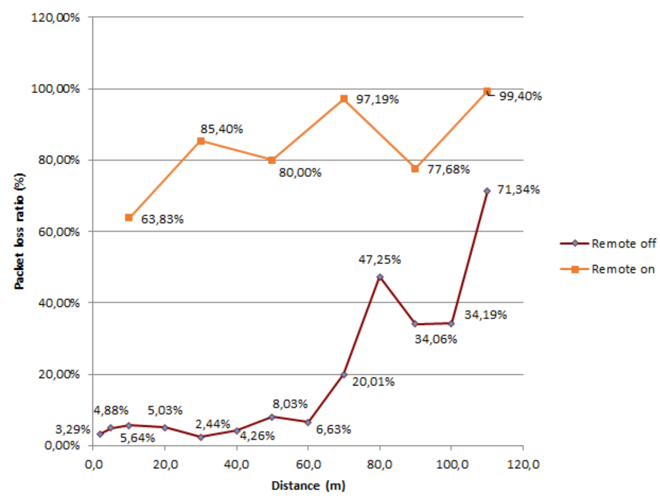

Figure 6. Packet loss versus distance. Effect of remote control interference and distance when locating both UAVs near the ground, in static mode.

difference in terms of loss magnitude, as both series overlap, which means that the simple fact of turning on the engines does not significantly affect the communication link quality.

The mean size of bursts of lost packets was also analyzed for a confidence interval of 95%. These intervals also overlap, which means that the difference in the size of bursts is again not significant.

The second experiment (see figure 4) shows that the packet loss ratio increases with the engine power from about 70% to about 84.5%. This is mostly due to the vibration of the structure of the quadcopter, causing antennas to tilt, thereby affecting the signals sent and received.

The following experiment analyzed the influence of the distance between UAVs. Figure 5 shows very low packet loss ratio when the UAVs are very close. We find that this ratio, initially quite low (<5%) increases quickly as UAVs moves away (>40%). The high packet loss ratio is due to the aforementioned sharing of the 2.4 GHz wireless band between the radio remote controllers and the WiFi communications link.

To have further insight onto the interference caused by remote controllers under more realistic conditions, we repeated the previous experiment with larger distances while having the remote controllers turned on or off, as shown in figure 6. We can see that, despite there is an overall trend whereby packet loss increases with the distance, turning on the remotes has a drastic impact of communications, causing the communications link to become mostly useless, no matter what the actual distance is.

Arrived at this point, and considering that remote controls are also a source of interference in the 2.4 GHz band, we proceed to study how the distance between the remote controllers and the UAVs affect to the packet loss ratio. Figure 7 shows that indeed the proximity between the remote control and the UAV has a clear influence on link quality. However, the effect is only significant when the remote control is very

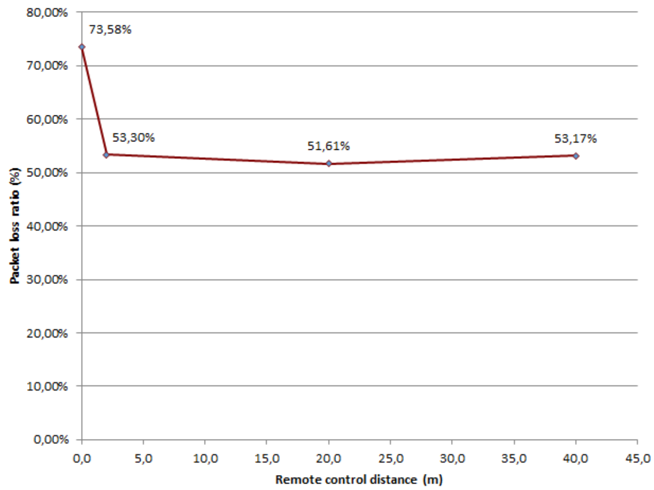

Figure 7. Packet loss versus remote control distance. Effect of remote control interference with radio controllers turned on and static UAVs..

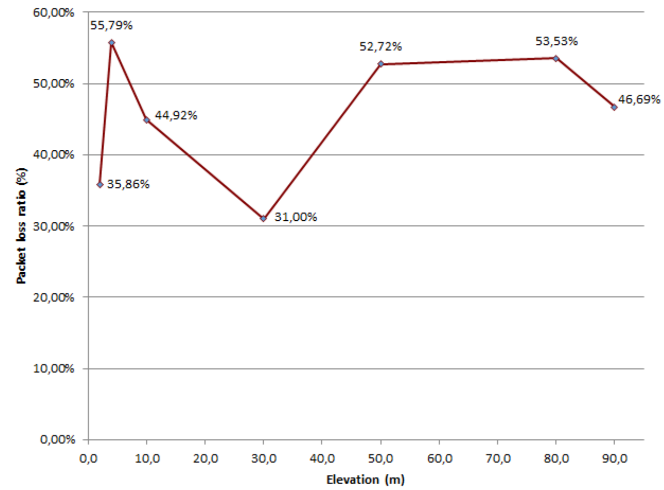

Figure 9. Packet loss versus elevation. Multi-path fading effect when UAVs are flying at different distances to the ground.

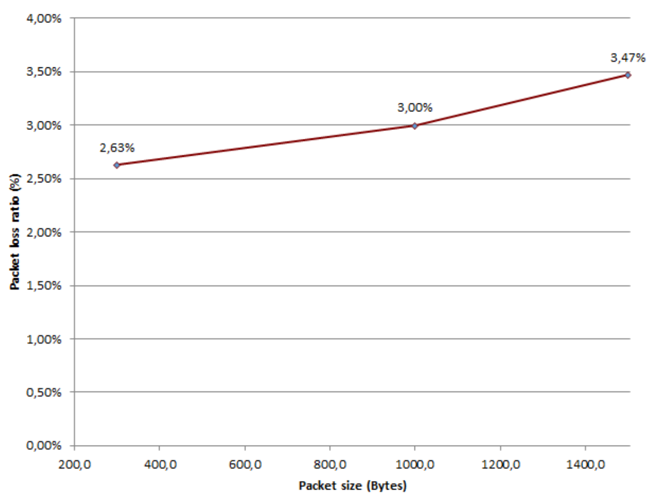

Figure 8. Packet loss versus packet size. Effect of increasing the packet size with radio controllers turned off and static UAVs.

close to the UAV (<1m). Since such distances never take place during normal UAV operation, we can discard this effect.

In general, the bigger is the data packet, the greater is the probability of transmission errors, as the physical media is busy for a longer period. Thus, the effect of the packet size has also been analyzed (see figure 8) by testing with packet sizes of 100, 300, and 1500 bytes. The initial hypothesis was verified, as the packet loss increases with the packet size. However, the overall packet loss ratio is quite low (<4%). This means that, compared to other factors affecting inter-UAV communications performance in the 2.4 GHz band, packet size is a parameter with little overall relevance.

Regarding the effects related to signal propagation, the WiFi signal is reflected by the ground and other surfaces like any wireless signal. Moreover, the ground can represent a significant part of the Fresnel zone when assuming free-space communications, thereby reducing the link quality. However, this experiment (see figure 9) failed to clearly confirm these effects, as the interferences produced by the remotes mask the results. We nevertheless consider that differences of up to 25% deserve more scrutiny.

Finally, we attempted to find a correlation between the relative antenna orientation and the packet loss. To achieve it we flew UAVs in *GPS hold* mode under windy conditions (~20 km/h), which caused UAVs to continuously adjust their position, thereby causing antennas to tilt. Simultaneously, we captured packet losses along with flight attitude parameters and GPS information, using this information to obtain the relative angle between UAVs.

Figure 10 shows the evolution of the relative orientation of the UAV antennas along one test, while figure 11 shows the burst sizes associated to lost packets. We find that, despite some peak angular values have a match in terms of packet loss bursts, no correlation can be found between both charts in the strict sense. Again, we consider that the interference from remote controllers contributes to masking this effect, preventing us from having a clear view of the results.

Overall we consider that, to gain more insight and awareness on the impact of the different parameters, this same analysis should be repeated in other frequency bands, or having remote controllers working in other bands.

VI. Conclusions and future work

Despite the emerging applications for UAVs, including those requiring inter-UAV coordination, the issue of UAV communications is a topic that remains mostly untackled in the literature.

This work addresses this issue by studying the performance of UAV communication links based on WiFi in the 2.4 GHz band. Performance was tested using our Dronning tool [15] in the presence of interferences caused by the wireless remote controllers used for UAV, that mostly operate in the 2.4 GHz band as well.

In general we find that a resilient WiFi transmission in the 2.4 GHz band is incompatible with the UAV remote controls widely available in the market. In fact, we find that the packet loss ratio is unacceptable for almost any application. Thus,

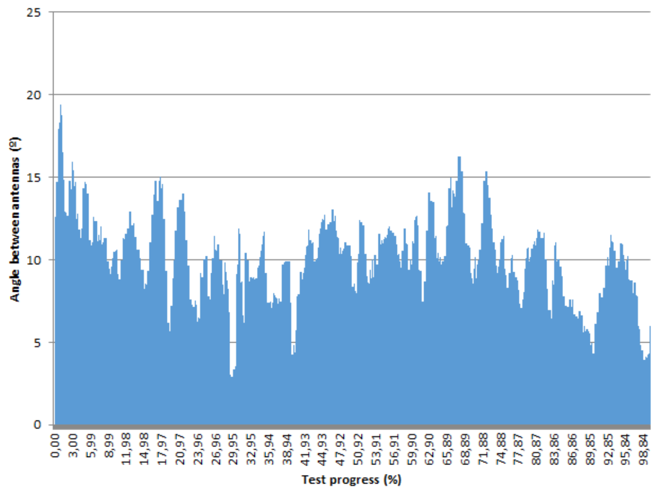

Figure 10. Angle between UAVs antennas vs test progress. The inter-UAVs distance was of 15 m, and the ground elevation was of 30 m.

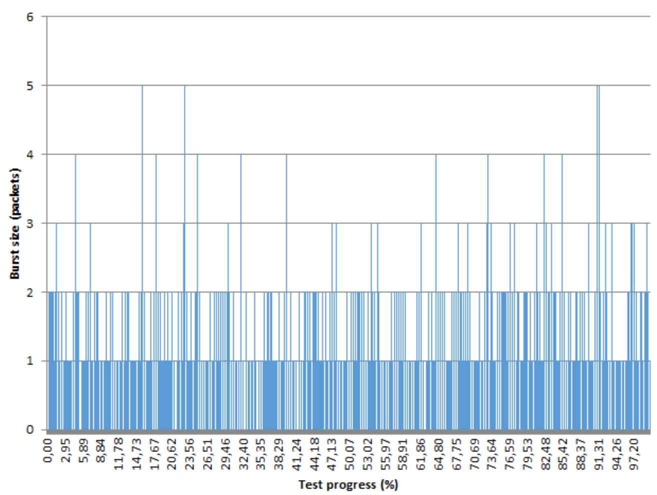

Figure 11. Size of bursts of lost packets versus test progress.

it would be convenient to use remote controls that work in other frequency band or shift the communications link to other frequency band.

Overall, it has been found that several factors influence the communications link quality, as the distance between UAVs, or between UAV and remote control, in addition to the data packet size and the structural vibration caused by UAV engines. In particular, the bigger is the distance between UAVs or the data packet size, the bigger is the packet loss ratio, which means that there will be a lower quality of the communications link. On the other hand, the remote control proximity only affects communications performance at very short distances that are unfeasible during normal UAV operation. Based on attitude parameters and GPS information, we have also measured the influence of ground reflection and relative antenna orientation in the link quality; however, the high interference levels caused by the remote control prevented reaching statistically representative differences.

As future work we plan to perform similar experiments in the 5 GHz band using IEEE 802.11a/n technology, assessing performance in this interference-free band where much better results are expected.

Acknowledgments

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