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# Identification of New EMC Factors of UAV FHSS Datalink in the Pre-Compliance Test Phase

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***Abstract***

This document presents a cost-effective methodology to diagnose the various parameters that influence the electromagnetic susceptibility (EMS) of a datalink using the frequency hopping transmission technique in drone applications. The innovative method is applied during the electromagnetic compatibility (EMC) pre-compliance test of a drone datalink. The paper outlines essential guidelines for establishing a reliable and affordable EMC test bench setup. It focuses on modifying specific parameters of the frequency hopping datalink that are typically not considered in conventional EMC testing. The results obtained reveal important new parameters of the datalink that utilizes hopping spread spectrum transmission techniques, including the communication protocol, datalink frequency bandwidth, and the number of transmission channels. By manipulating these key parameters, the electromagnetic immunity of the datalink used in experiments significantly improves.

*Keywords:* Datalink, Drone, Electromagnetic Compatibility (EMC), Electromagnetic Interference, Electromagnetic Susceptibility (EMS).

## 1. Introduction

Electromagnetic compatibility (EMC) refers to the ability of an electrical or electronic device/system to operate effectively within its environment without causing interference to other equipment in the same surroundings. Prior to being introduced into the market, electrical equipment must undergo EMC tests conducted in specialized laboratories to adhere to specific standards based on the nature of the Equipment Under Test (EUT). Notably, the EMC standards are primarily derived from the following sources:

- Europe: International Electrotechnical Committee (IEC), International Special Committee on Radio Interference (CISPR)
- USA: Federal Communications Commission (FCC) (e.g., FCC CFR 47 Part 15C), USA military standard (e.g., MIL-STD 461G)
- Civil aviation (e.g., RTCA-DO160-G)
- China: Guojia Biaozhun Tuijian GB/T

Generally, compliance with an EMC standard is sufficient for most "normal" use cases of the EUT. However, some certification tests fail to consider certain implicit factors that can significantly impact the EMC of the EUT, particularly for equipment that may pose safety risks. Let's consider the example of drone datalinks: an EMC issue with the datalink on a drone can potentially cause substantial harm to humans or property. Therefore, it is crucial to anticipate the various factors that influence the datalink's immunity on the drone, particularly the radiated datalink over antennas.

Therefore, antenna design usually takes an important place in the drone design process as it is outlined by Marques [1] and Prabhu [2]. The EMC of drone datalinks is a very critical component from a safety point of view for the entire Unmanned Aerial Vehicle (UAV) system. It represents a recent active topic research as it was highlighted in the survey work done by Wang [3] and Kim [4]. The prediction of the electromagnetic susceptibility (EMS) threshold of the drone datalink represents most of the recent work concerning the EMC of a UAV datalink, and it is therefore widely discussed. For instance, Xie [5] presented a simulation model of interference of the datalink that use frequency hopping technique using SIMULINK/MATLAB. The signal to interference ratio approach was used in this paper. The prediction of the EMC for dynamic datalink of UAV is discussed by Zhang [6]. The decrease of the amplitude of the control signal during the flight of the UAV exposes it to electromagnetic vulnerability. In the same context of dynamic datalink, Zhang [7] uses the machine learning in order to determine the EMS threshold accurately based on the frequency and amplitude of the signal. For Chen [8], the datalink EMS is proved to be susceptible to some special frequencies of the EMI signal. Xu [9] proposed a dual-channel convolutional neural network optimized by a sparrow search algorithm to predict the EMS of the UAV datalink. The input parameters for this method are the interference to signal ratio, hence amplitude and frequency. The Gray Prediction Model of Zhang [10] is also based on the amplitude and frequency of the EMI signal. All these papers discuss EMS prediction using classical parameters namely the frequency and amplitude of the EMI signal. Only the prediction method changes from simulation, statistics, and experiments. Hence, the results are obtained by modifying two main parameters of the interference signal: frequency and amplitude.

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This paper introduces a low-cost EMC test method aimed at identifying additional factors essential for evaluating the EMC of a drone's datalink. These tests were conducted during the pre-compliance test phase. The standard focused on in this paper is the MIL-STD-461G, which outlines the US military requirements for controlling electromagnetic interference characteristics of subsystems and equipment.

To achieve this goal, the paper is organized as follows: Section 2 provides an overview of the various types of datalinks commonly used in drones, along with the environmental conditions they may encounter. Section 3 presents a novel approach for conducting low-cost experimental tests on the telemetry datalink of a drone. Section 4 identifies the factors influencing the EMC of the datalink, as revealed by this technique. Finally, we will draw necessary conclusions that will lay the foundation for further research.

## 2. Electromagnetic test environment for drone's datalink

### 2.1 Datalink categories

The datalink is the channel through which communication passes between a drone system component. On the majority of drones, civil or military, there are 4 types of datalinks following Nichols [11]:

- UAV Base System: provides bi-directional command communication for drone control
- UAV Sensor System: allows the control of the payload (camera, radar, etc.)
- UAV Avionic System: this type of datalink is located within the drone and allows control data to be transmitted to on-board equipment (rudders, fins, stabilizer, etc.). This datalink is preferred wired over the radio one
- UAV Telemetry: Transmits the status of the drone (altitude, range, speed, signal strength, etc.) to the ground station

Communication by datalink can be established directly by line of sight in radio communication (our case study) or indirectly by satellite or by cloud-based multi-UAV networks for advanced systems. The design of these datalinks is done taking into consideration the environment in which it will be operated. As a result, the EMC of datalink components should be checked against the severe environment in which it could be deployed. Indeed, these drones sometimes find themselves victims of an intentionally (jamming) or unintentionally (noise) disturbed environment, strongly impacting their electromagnetic immunity as underlined by Bennageh [12].

### 2.2 Test environment

In order to evaluate the electromagnetic susceptibility (EMS) of a drone's datalink, specialized laboratories employ various devices to manipulate the environment of the Equipment Under Test (EUT). This includes the use of facilities such as anechoic or semi-anechoic chambers, transverse electromagnetic cells, specific antennas, amplifiers, signal generators, and more. It is important to bear in mind that EMS is closely tied to Electromagnetic Interference (EMI), particularly in relation to the Continuous-Wave (CW) electromagnetic environment, as highlighted by Xu [13]. Hence the importance of these experimental devices to create electromagnetic interference in the environment and to the EUT. The cost and maintenance of this special equipment are extremely expensive, so that almost all manufacturers outsource this certification task. Before sending equipment to a certified test house for expensive compliance testing, many manufacturers set up a low-cost laboratory to perform in-house pre-compliance testing. It allows the verification of the different EMC system-levels for the EUT as described by Su [14]: Intra-system EMC, Intersystem EMC and EMC issue between the system and the environment. This has the advantage of making significant savings to correct flaws on the EUT before sending it to final certification. Pre-compliance test methods must be more stringent to ensure both final certification and a more resilient product in hostile environments. Electromagnetic environment control involves injecting an electromagnetic wave from a signal source through a specific antenna to generate a field pattern on the radiated EUT. Also, it is already known that the main coupling path of the electromagnetic perturbation is through the "Front Door", i.e. the set: antenna, duplexer and transceiver as it has been confirmed by Bennageh [12] and Kay [15]. Among the 4 types of datalinks mentioned above, we choose to perform the tests on the telemetry datalink for the following reasons:

- Availability in several ranges on the market
- Robustness against interference as stated by Dixon [16]
- Telemetry datalink implements Frequency Hopping Spread Spectrum (FHSS) technology
- The communication frequency ranges can be customized
- The communication protocol can be customized (standard Mavlink, low latency Mavlink or Rawdata)
- The radios have telemetry logging built in to diagnose the interference levels

## 3. Low-cost method for pre-compliance testing

### 3.1 Standard EMC test protocol and assumptions

Normally, to perform a transmission system datalink electromagnetic susceptibility pre-compliance test, we try to approach as best as possible the test bench indicated by the certification standard target. In our case, the radiated immunity test bench MIL-STD-461G of electrical equipment according to the MIL-STD-461G [17] standard, is illustrated in Fig. 1.

In addition to the guidelines for size and value tolerances, the specified antenna type for testing purposes depends on the frequency range required. However, in the laboratory experiment described below, an omnidirectional antenna is used instead. This choice is made to cover both the drone and Ground Control Unit (GCU) by radiating a uniform field in all directions within the plane. Further justification for using the omnidirectional antenna over the traditional log-periodic antenna is provided later in this paper.

Furthermore, it is important to highlight the differences between the test bench employed in the laboratory experiment and the one outlined in the military standard:

- The tests were carried out in the basement laboratory of the electrical department of the Mohammadia

School of Engineers, where the rf signals are strongly attenuated

- The Line Impedance Stabilization Network (LISN) mentioned in Fig. 1 is no longer required in our case since the drone is powered by its own battery
- The omnidirectional antenna is fixed in one position since it got the same radiation pattern for both datalink terminals

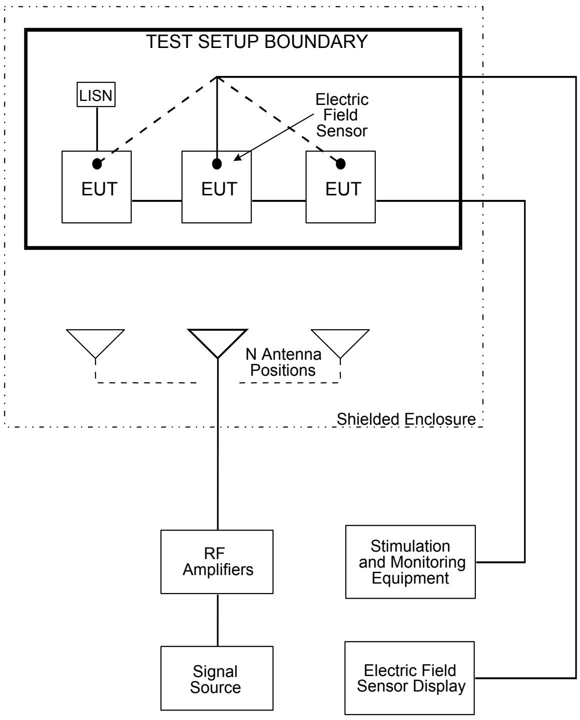


**Fig. 1.** Test bench specified in MIL-STD 461G for radiated EMS certification.

### 3.2 Test bench considerations

The test bench consists of 3 main blocks:

- Pixhawk Drone with aerial telemetry hardware
- Ground Control Station (GCS): PC and base telemetry hardware
- Jammer system: signal generator sources, amplifier, dual coupler, spectrum analyzer

The test bench is shown schematically in Fig. 2.

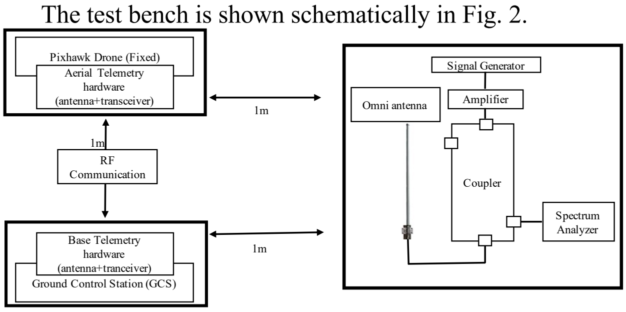


**Fig. 2.** Test bench performed in the laboratory.

First, drone's blades are removed for safety. GCS, drone, and interference systems are placed on 3 wooden tables. Each table is 1 m apart from the other two. The telemetry system is put into transmission/reception test mode by its software: the Received Signal Strength Indication (RSSI) of data and noise are obtained. In this work, the omnidirectional antenna of 12 dBi gain is used. The signal generator generates waves of narrow frequencies at variable powers. The spectrum analyzer measures the power of the signal reflected by the antenna.

This allows us to deduce the exact power transmitted by the antenna.

The equipment used in the experiments are as follow:

- Spectrum Analyzer: Anritsu MS2711E, 9 kHz to 3 GHz (up-to-date calibration)
- Pixhawk 2.4.8 autopilot-based drone (Length: 75 cm, wingspan: 1 m, height: 10 cm)
- 12 dBi omnidirectional antenna (up-to-date calibration)
- 6 dBi log periodic antenna, reference: LP-02-NARDA (up-to-date calibration)
- Keysight 778D Dual Directional Coupler (up-to-date calibration)
- Keysight 8648D Synthesized RF Signal Generator, 9 kHz to 4 GHz (up-to-date calibration)
- 3Dr Sik Telemetry Radio, 433 MHz, 3 dBi antennas
- !SiK Radio Config: Telemetry system monitoring software

The EM susceptibility threshold represents the minimum level of EMI interference felt at a telemetry datalink terminal to interfere with communication. It is important to remember that tests will not be performed in some kind of anechoic chamber nor in a certified Open Area Test Site (OATS). Instead, the tests are held in a basement laboratory room. Hence, to obtain reliable results, the marginal noise sources present in the test lab must be the lowest possible to have the lowest impact on the field strength generated by the antenna.

### 3.3 Noise reduction means

The anechoic chamber is the ultimate interference and noise cancellation solution for obtaining reliable results in terms of EMC. However, this is obviously the major obstacle in all development process for the certification of equipment locally, mainly because of the investment budget. In the absence of an anechoic (or semi-anechoic) chamber, the tests are carried out in an Open Area Test Site (OATS). Again, not just any open environment will solve the problem. Indeed, this environment do have some requirements according to the standard targeted (for MIL-STD-461-G, OATS should comply with the standard ANSI C63.4).

Generally, the OATS must be free of any obstructions and far from sources of electromagnetic noise and broadcast waves to avoid interference with other radio communications. In our case, the tests are carried out in a laboratory room of the university in the basement so as to approximate the OATS conditions. The choice was motivated by the following reasons:

- The basement room is free from any obstructions. There are only three wooden tables
- The RF signals, or noise that could interfere with antennas, are weak in that basement. The level of noise present in the basement was analyzed by the spectrum analyzer coupled to the omni antenna for 2 hours within [414 MHz; 460 MHz] band. The maximum level of noise sensed was –119 dBm which is insignificant and close to the lowest receive sensitivity (–121 dBm) of the EUT
- The lab basement is isolated from other placements of interest so as the tests of EMS would not interfere with other radio communications

- The room is enough big (10 m × 5 m × 4 m) to ensure the transmission in free space or in the first Fresnel ellipsoid

Also, the distance between the antenna and the EUT is small enough to reduce the reflections of the walls rebars. It is recalled that the Fresnel ellipsoid is a volume around the line of sight between two RF antennas which most of the energy will flow if there are no obstructions or reflections. This volume is defined by the positions occupied by the point M according to Eq.1:

$$MA + MB = AB + n \times \frac{\lambda}{2} \quad (1)$$

Taking A and B the respective positions of the antennas and the foci of the ellipsoid, n is the rank of the ellipsoid (n = 1 in our case) and λ is the wavelength (For F = 433 MHz ⇒ λ ≈ 69 cm). We therefore ensure the absence of any foreign body on the volume defined by the first Fresnel ellipsoid (except antennas) to apply the Friis formula for the electromagnetic wave in free space:

$$D = 20 \log \frac{4\pi d}{\lambda} \quad (2)$$

Where *D* is the logarithmic power loss due to the propagation in open area at a distance *d*. Note that the Friis formula Eq.2 is only valid in far field which is our case. Indeed, we know that the far field region of an antenna, that is physically larger than a half wavelength, should be distant by R that verify Eq.3:

$$R > \frac{2L^2}{\lambda} \quad (3)$$

where *L* is the antenna's length (0.5 m) and *λ* the wavelength (0.693 m). Thus, the distance between the system drone under test and the antenna of more than 1 m verify the far field condition. The more this distance increase the weaker the signal gets, and the more the perturbations of the environment (Walls rebars reflections) will impact the results.

### 3.4 Test configuration

To highlight the different factors influencing the EMS threshold, we will act on different parameters:

- Frequency of operation of the telemetry datalink
- Interference frequency
- Radio transmission technique: bandwidth of Frequency Hopping Spread Spectrum (FHSS)
- Antenna polarization
- Communication Protocol (Mavlink standard, etc.)
- Data processing speed: Baud rate

For each parameter, the corresponding EMS threshold will be noted, and a final summary will be presented.

### 3.5 EMS threshold calculation

The EMS threshold indicates the minimum strength of electromagnetic interference (EMI) that can disrupt communication as observed from the perspective of the Equipment Under Test (EUT). It is important to note that the criteria for communication interference in electromagnetic compatibility (EMC) vary among different devices. Currently, there is no specific indicator for evaluating the EMC of a system, although there are some initial findings regarding EMC conditions at the system level Su [14]. However, several indicative parameters are available for quantifying EMC data according to the system studied: Signal to Noise Ratio (SNR), Received Signal Strength Indication (RSSI), Signal to Interference Rate (SIR), Bit Error Rate (BER), etc. The telemetry system software has an RSSI measurement tool. It will be used to detect any radio interference, hence, the EMS threshold. The power of the interference field is therefore calculated using the generalized transmission formula of FRIIS:

$$\frac{P_r}{P_t} = G_t(\theta_t, \phi_t) G_r(\theta_r, \phi_r) P_\theta (1 - |\Gamma_t|^2)(1 - |\Gamma_r|^2) \left(\frac{\lambda}{4\pi R}\right)^2 \quad (4)$$

In logarithmic form Eq.5:

$$P_{r,dB} - P_{t,dB} = G_{t,dB}(\theta_t, \phi_t) + G_{r,dB}(\theta_r, \phi_r) + P_{\theta,dB} + 10\log_{10}(1 - |\Gamma_t|^2) + 10\log_{10}(1 - |\Gamma_r|^2) + 20\log_{10}\left(\frac{\lambda}{4\pi R}\right) \quad (5)$$

Where $P_r$: Power received, $P_t$ : Power transmitted, $G_{t,dB}(\theta_t, \phi_t) = G_T D(\theta_t, \phi_t)$: Gain of the transmission antenna in $D(\theta_t, \phi_t)$ direction, $G_r(\theta_r, \phi_r) = G_R D(\theta_r, \phi_r)$: Gain of the receiving antenna in $D(\theta_r, \phi_r)$ direction, $(1 - |\Gamma_t|^2)$: Transmitter mismatch impedance factor, $(1 - |\Gamma_r|^2)$ : Receiver mismatch impedance factor; $P_\theta$ : polarization mismatch between the two antennas.
In our case, we ensure the impedance of the entire system at 50 Ω to reduce as much as possible the terms $\Gamma_t$ and $\Gamma_r$ relating to the impedance mismatch. Also, the three antennas have a vertical polarization and have been arranged parallel to each other to cancel the losses related to the polarization shift $\log_{10}(P_\theta)$. Although making these approximations, we must specify ξ as the residual tiny losses for polarization misalignment, impedance mismatch, losses in connectors and coupler. We obtain the new equation Eq.6:

$$P_{r,dB} - P_{t,dB} = G_{T,dB} + G_{R,dB} + D_{t,dB}(\theta_t, \phi_t) + D_{r,dB}(\theta_r, \phi_r) + 20\log_{10}\left(\frac{\lambda}{4\pi R}\right) + \xi \quad (6)$$

Terms relating to the directivity of omnidirectional antennas $D_{t,dB}(\theta_t, \phi_t)$ and $D_{r,dB}(\theta_r, \phi_r)$ can be approximated by the formula proposed by Schrank [18]:

$$D_{dB}(\theta_r, \phi_r) = 10\log_{10}\left(191\sqrt{0.818 + \frac{1}{\alpha}} - 172.4\right) \quad (7)$$

α, also known as Half Power Bandwidth, is the angle in degrees where more than half of the power is radiated from the antenna. Using Eq.7 means a perfect knowledge of the omnidirectional antenna which is not the object of our study. The directivity is deduced through the experiments since the different components of the test bench will keep the same positions.

### 3.6 Directivity calculation method

We set up the test bench proposed in Fig. 2, and we configure the telemetry system in test mode. This mode is used to perform a succession of transmission/reception between the transmitter and the receiver while measuring 4 RSSI parameters: transmitter (drone), receiver (GCS), noise felt at the transmitter and noise felt at the receiver.

The characteristics of the datalink have been configured using its software (Fig. 3).

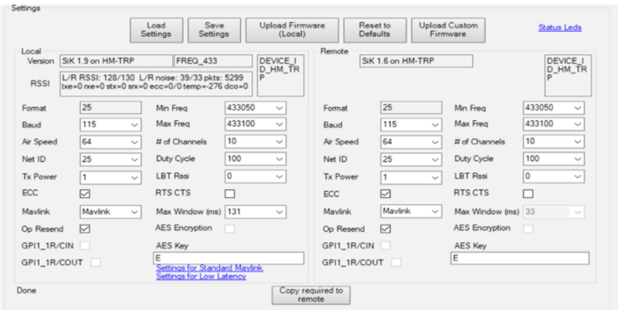

**Fig. 3.** Software interface for configuring telemetry datalink parameters.

The datalink was interfered by a continuous signal of 433.075 MHz (mid frequency of the UAV bandwidth signal) using a power generator output of $P_{t,dB} = 7.2$ dBm (Fig. 4). The RSSI green trace falling to zero denotes the failure at drone's datalink terminal.

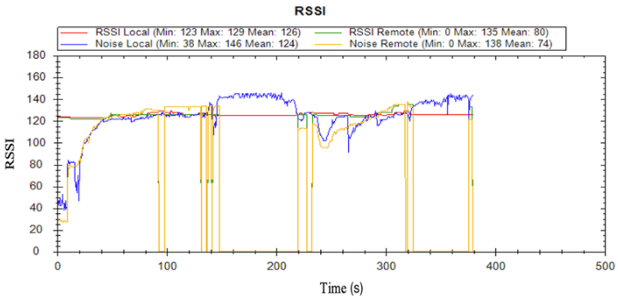

**Fig. 4.** Datalink interference for telemetry hardware (local = GCS and remote = Drone). The green and orange traces (Drone's datalink) fall at 90s, 130s, 148s, 230s and 318s.

The software maps the power measured $P_{\text{dBm}}$ into the quantity $i_{\text{RSSI}}$ (indicated in the software) following the formula Eq.8 specified by the software documentation:

$$P_{dBm} = \frac{i_{RSSI}}{1.9} - 127 \tag{8}$$

From Fig. 4, we get the following data:

- Interference power at drone's receiver telemetry antenna $i_{RSSI(\text{EMI})} = 132$, hence $P_{r,dB(\text{EMI})} = -57.5$ dBm
- Telemetry signal power $i_{RSSI(\text{SIG})} = 129$, hence $P_{r,dB(\text{SIG})} = -59.1\ dBm$

In this configuration, the EMS threshold is calculated as follows:

$$SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) = -1.6 \tag{9}$$

We conclude from Eq.6 that $D_{t,dB}(\theta_t, \phi_t) + D_{r,dB}(\theta_r, \phi_r) + \xi \approx -54.49$ dBm such that ξ represents the residual losses due to the impedance mismatch and the losses caused by the connectors and the assembly. In order to reuse these same values of the directivity and residual losses, the various electronic components are fixed, and the configuration changes are performed only by means of the software.

### 3.7 Datalink components vulnerability

According to Su [14], the system-level EMC is articulated around 3 levels: inter-system EMC issues, intra-system EMC issues and issues between the system and the environment which is the scope of this work.

The primary significance of a disturbance caused by an omnidirectional antenna lies in its ability to affect the entire data link system, including components that may be spatially separated such as the transmitter, receiver, and electromagnetic field.

It has been noticed that for all the experiments relating to radiated electromagnetic compatibility, the rf terminal on board the drone has the lowest electromagnetic immunity threshold, making it the most vulnerable of the telemetry system. This is illustrated in Fig. 4 by the green trace of the RSSI Remote (drone) which drops before that of the RSSI Local (GCS). However, during an electromagnetic attack, it is the drone that is most often targeted. We deduce that the EMC factor must be taken during the design to suit the electromagnetic environment for which the system is intended.

## 4. Test results

### 4.1 Omnidirectional antenna in EMS testing

As mentioned before, the omnidirectional antenna is used for the EMS testing instead of the traditional log-periodic or horn antenna. In order to show the advantage of this solution, we perform the test bench in Fig. 2 with the following parameters:

- The distance between each antenna is 5 m
- The Omni antenna is replaced by the log-periodic antenna (Reference: LP-02-NARDA)
- The datalink hardware is configured to test mode in the frequency range 432 MHz to 434 MHz and the EMI frequency is set to 433 MHz
- The EMI antenna or Omni antenna directivity (position) is modified during the test in order to get the lowest EMS threshold

During the tests, it was observed that there are two primary antenna directions where the EMS threshold is at its lowest: towards the drone terminal and the GCU terminal. In Fig. 5, the measurement process consists of two phases:

- In the first phase (0 to 300 s), the log-periodic antenna is directed towards the Local or GCU terminal. The system's datalink is lost when the output power of the signal generator reaches 13.9 dB.
- In the second phase (300 s to 650 s), the log-periodic antenna is pointed towards the Remote or drone terminal. The system's datalink is lost at -5 dB of the output power of the signal generator

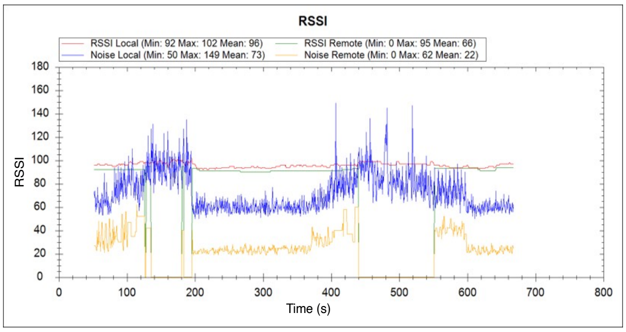

**Fig. 5.** Datalink interference by log-periodic antenna in different directions (green and orange traces falls depict datalink failure at 124s and at 440s)

In the case of omnidirectional antenna, for the same position we get the lowest EMS threshold of the system datalink interference at 1.5 dB of the output power of the signal generator. That is not the case with directional antenna where we should change the direction (and polarization) of the antenna in order to get the optimal position. Also, every position change induces a modification to the residual losses due to the impedance mismatch and the losses caused by the connectors and the assembly as described before. Moreover, the results investigated in this paper do not require a high radiation power that can be provided by a directional antenna. We choose then to use the omnidirectional antenna for a fluid EMI testing over the datalink system.

### 4.2 FHSS bandwidth effect on electromagnetic immunity

During the last decade, the use of spread spectrum techniques (FHSS, DSSS, CSS, etc.) on drone datalinks has become very common. Indeed, this transmission technique allows to spread the datalink signal over a wide band to mask it and make it more resilient to interference. As a reminder, the FHSS transmission technique is a signal transmission method by radio wave over several channels in a pseudorandom manner. A data packet can therefore be transmitted over several channels.

Radiated electromagnetic susceptibility certification tests for this kind of frequency hopping system do not use all the radiation frequencies used by the datalink. Some test-house prefer to radiate the EUT by 3 frequencies: The minimum frequency of use, maximum and the average frequency of the two extrema. Despite some strict EMC standards that specify special radiation methods for this type of frequency hopping equipment, some test houses keep using only the 3 frequencies aforementioned. For instance, on the military standard MIL-STD461G [17], the measurements must be carried out on frequency bands containing at least 30% of all possible frequencies of the datalink, and must be distributed over 3 segments: low, mid, and high end of the EUT operational frequency range.

The studied datalink uses the Frequency Hopping Spread Spectrum (FHSS) technique. The advantage with the telemetry component that we have is that the spread spectrum bandwidth can be set via its software. The spread spectrum width can be configured from 50 kHz to 46 MHz within [414 MHz; 460 MHz] band. In order to highlight the effect of the spread spectrum on the EM susceptibility of the datalink, the frequency of the interference signal is fixed at a value (137 MHz) and the spread band is varied. The configured band must have the interference frequency as the average frequency of these two extrema. The results are obtained in Tab. 1.

**Table 1.** Electromagnetic susceptibility (EMS) of FHSS datalink test under EMI of 137 MHz.

| Id | Freq min (MHz) | Freq max (MHz) | Signal power (RSSI/dBm) | EMI power (dBm) | SNR (dB) |
|---|---|---|---|---|---|
| 01 | 436.95 | 437.00 | 117/-65.4 | -66.5 | 1.1 |
| 02 | 436.95 | 437.05 | 116/-65.9 | -66.5 | 0.6 |
| 03 | 436.90 | 437.10 | 113/-67.5 | -67.2 | -0.3 |
| 04 | 436.85 | 437.15 | 112/-68.0 | -68.7 | 0.7 |
| 05 | 436.80 | 437.20 | 99/-74.9 | -74.5 | -0.4 |
| 06 | 436.75 | 437.25 | 121/-63.3 | -62.8 | -0.5 |
| 07 | 436.50 | 437.50 | 101/-73.8 | -65.5 | -8.3 |
| 08 | 436.00 | 438.00 | 138/-54.3 | -60 | 5.7 |
| 09 | 435.00 | 439.00 | 147/-49.6 | -58 | 8.4 |
| 10 | 430.00 | 444.00 | 133/-57 | -105 | 48 |

Based on the information provided in Tab. 1, it can be inferred that when the frequency bandwidth of the datalink is narrow (less than 1 MHz), the electromagnetic susceptibility threshold (SNR) follows a random pattern (identified as 1 to 7 in Tab. 1). This behavior can be attributed to the pseudorandom frequencies utilized by the telemetry hardware. The interference signal's frequency is fixed within the middle of the frequency range used, causing disruption in the signal when a transmitted data coincides with the frequency (137 MHz) multiple times, leading to temporary interruptions in the datalink.

As the frequency range expands (identified as 8 and 9 in Tab. 1), the electromagnetic susceptibility threshold decreases to the point where it becomes challenging to interfere with the signal using a single fixed frequency, even with high-power radiation. In experiment 10, the datalink remained uninterrupted (refer to Fig. 6). This can be attributed to the significant extension of the FHSS (Frequency-Hopping Spread Spectrum) signal bandwidth (14 MHz). Despite emitting a power of 34.4 dBm from the frequency generator, the telemetry terminal on the drone side received a greatly attenuated disturbance.

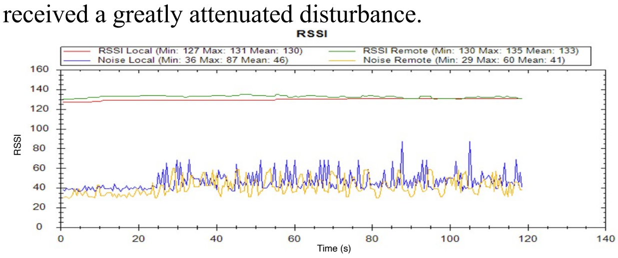


**Fig. 6.** FHSS datalink [430 MHz; 444 MHz] under high power EMI (F = 437 MHz, Generator Power = 34.4 dBm). No interference is reported.

In conclusion, to ensure the robustness of a datalink between a drone and its ground station when employing frequency hopping techniques, it is crucial to maximize the FHSS bandwidth. Furthermore, for electromagnetic susceptibility certification, the testing approach should be modified to target a frequency range nested within the spectrum used by the datalink, rather than focusing solely on a single frequency. As an example, military standards specify the inclusion of at least 30% of the spectrum for such testing.

### 4.3 Communication protocol effect on EMS

The test bench specified in Fig. 2 is reproduced. The frequency range is configured to [433.05 MHz; 433.10 MHz] and the perturbation frequency to 433.075 MHz. In this part, we evaluate the impact of the protocol or the type of data passing between the two terminals of the datalink. The hardware can be configured on 3 types of data/protocols:

- Mavlink: this is the classical lightweight messaging protocol for communications in UAV's systems
- Low Latency: This mode is suitable for controlling the drone by tablet. The data packet is transmitted at least once every 33 ms instead of the classic 131 ms of the Mavlink protocol
- Raw Data: consists of transmitting data packets in the raw format

The datalink interference results were recorded in Tab. 2. We deduce that the threshold of the EMS depends strongly on the type of protocol used. The Mavlink protocol is the most robust against the other two. For the "Low latency" mode, the shortened duration for packet transmission imposes a reduction in the available bandwidth, increasing the probability of using the central channel of the bandwidth under perturbation. As for the “Raw Data” mode, the error correction codes (ECC) are much less efficient than those used by the other protocols, so it is normal that this mode is the least protected against electromagnetic interference.

**Table 2.** Datalink EMS thresholds to protocols.

| Mode | Mavlink | Raw Data | Low Latency |
|---|---|---|---|
| Generator Power output (dBm) | 4.5 | 2 | 2.5 |

In all EMC test certification, an EUT is tested against all its operational modes and especially in its worst configuration. Similarly, certification tests should take into consideration these kinds of protocols and perform the susceptibility test on the most sensitive protocol. If it is unknown, all the radiated datalink protocols should be tested since the communication protocol influences the EMS threshold.

### 4.4 Data processing speed effect on EMS

The datalink is configured in accordance with Fig. 2 and with the following characteristics:

- Frequency: 433.05 MHz to 433.1 MHz
- Interference frequency: 433.075 MHz
- Protocol: Mavlink

We change the communication speed on the GCS port of the telemetry datalink. We obtain the results recorded in Tab. 3.

**Table 3.** Datalink EMS threshold to processing baudrate.

| Baudrate | 4800 | 9600 | 38400 | 115200 |
|---|---|---|---|---|
| Generator Power output at perturbation (dBm) | 4.6 | 4.7 | 4.5 | 4.5 |

The experimental results prove that the electromagnetic susceptibility is not impacted by the data processing speed on the GCS. It confirms that the interference is felt mainly in the “Front Door”. This observation can be deduced for the datalink received by the drone. Therefore, it can be concluded that the datalink data processing speed by the autopilot does not impact the susceptibility of the datalink.

### 4.5 Effect of FHSS channels on EMS

By carrying out the test described in Fig. 2 with the following configurations:

- Frequency: 425 MHz to 435 MHz
- Interference frequency: 433 MHz
- Protocol: Mavlink
- Number of channels: Fig. 7-a: 5 channels and Fig. 7-b: 50 channels

We notice on the spectrum analyzer connected to the drone telemetry terminal (Fig. 7) that the FHSS signal with 5 channels is not spread out over all the available spectrum 425 MHz to 435 MHz, while it is the case with 50 channels. It is therefore normal to have the following results: with a wider spectrum (50 channels) the datalink immunity is much greater than that of a 5-channel transmission.

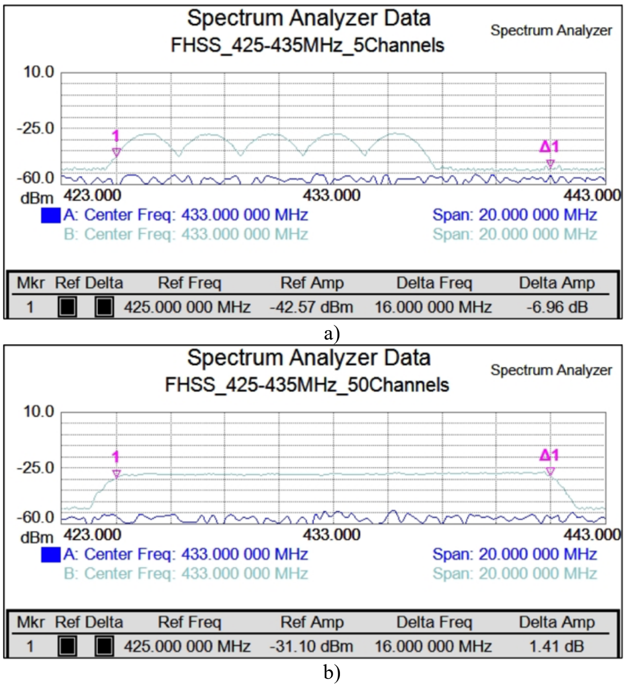


**Fig. 7.** Telemetry FHSS signal spectrum 425 MHz to 435 MHz: (a) FHSS signal over 5 channels and (b) FHSS signal over 50 channels

However, we can’t say that the EMS threshold varies linearly with the number of FHSS channels. Indeed, by analogy to the experience in Tab. 1, if we have few channels, the EMS threshold follows a random logic following the two major parameters: EMI frequency and number of transmission channels. If the EMI frequency is within a channel of transmission and there are few channels, the EMI will absolutely interfere the transmission. On the contrary, the more the transmission uses lot of channels, the EMI frequency would have lower impact and the EMS threshold gets bigger.

## 5. Conclusion

The protection of a datalink that uses FHSS technique on a drone begins above all with a successful passage of EMC tests according to a standard. Whether it is the manufacturer, or the customer seeking to enhance the datalink's reliability or ensure its robustness in specific electromagnetic environments, understanding the various factors that influence the equipment's immunity is crucial. In this article, a test bench was established within the university laboratory to approximate the conditions of EMC pre-compliance testing. This test bench incorporates various measures to ensure accurate results and minimize errors, aiming to replicate the conditions of an Open Area Test Site.

The tests were performed on the telemetry datalink of a drone equipped with a Pixhawk autopilot. This datalink employs the frequency hopping spread spectrum transmission technique, known for its resilience in highly disturbed environments. The electromagnetic susceptibility tests conducted in this study revealed new criteria that influence the EMS threshold, including the communication protocol, FHSS transmission signal width, and the number of transmission channels. Specifically, the tests demonstrated that the datalink utilizing the "Mavlink" protocol exhibited greater resilience compared to the "Low Latency" or "Raw Data" protocols. Additionally, the results indicated that a wider FHSS bandwidth increased the datalink's resistance to electromagnetic interference. Likewise, it was observed that the FHSS datalink showed greater resilience when the signal spread across a larger number of channels.

These newly identified parameters significantly impact the electromagnetic susceptibility threshold, surpassing the effects of classical methods that solely consider frequency and power variations of the interfering signal. Although this work did not discuss other factors that may influence the electromagnetic susceptibility threshold due to their lack of configurability in the utilized datalink (such as modulation type - QAM, QPSK, etc.), it is important to acknowledge their potential influence. Given the pseudo-random nature of frequency hopping transmission, applying artificial intelligence techniques to uncover hidden factors affecting the immunity of FHSS datalinks on drones would be a promising avenue for future research.



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