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EXPERIMENTAL ANALYSIS OF VIDEO LINK RESILIENCE FOR DIGITAL FPV SYSTEMS UNDER CONTROLLED ELECTROMAGNETIC INTERFERENCE BASED ON SDR

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Abstract: *Technological developments in the field of UAS are constantly evolving, with the use of the electromagnetic spectrum becoming essential for reserving operating space. This article investigates the robustness and signal integrity of high-definition First-Person View (FPV) digital systems operating in congested electromagnetic spectra. Using the DJI O3 Air Unit as the primary system under test, the research evaluates video link degradation—measured by bit rate fluctuations and latency—in controlled interference scenarios. Using the ADALM-PLUTO Software Defined Radio (SDR) platform to generate precise interference profiles, including Additive White Gaussian Noise (AWGN) and adjacent channel interference, demonstrated the acquisition of essential data for understanding the effects of interference on these 5.8 GHz video transmission systems. The experimental results provide a quantitative correlation between interference density and packet loss, offering practical insights for optimizing signal reliability in professional UAV operations in high-density environments.*

Keywords: *Digital FPV, Signal Integrity, Software Defined Radio (SDR), Electromagnetic Interference (EMI), DJI O3, ADALM-PLUTO,SATSAGEN.*

1. INTRODUCTION

The rapid development of unmanned aerial vehicles (UAVs) in both urban and industrial environments has led to significant congestion in the 2.4 GHz and 5.8 GHz ISM (Industrial, Scientific, and Medical) bands. Although First-Person View (FPV) digital systems, such as DJI O3 or CaddxWalksnail Avatar HD, offer low latency, superior video quality, and range, they are abruptly interrupted when electromagnetic interference reaches a certain threshold.

The main issue addressed in this article is the lack of standardized experimental data on the impact of various sources of electromagnetic interference on these high-bandwidth digital links.

Existing studies generally address Wi-Fi interference at a generic level without providing a detailed analysis of the cumulative impact of disturbances generated by Software Defined Radio (SDR) systems and internal electromagnetic interference (EMI) produced by electronic speed controllers (ESCs).

This study presents an experimental analysis conducted in a controlled environment, utilizing the ADALM-PLUTO SDR platform to inject precisely defined electromagnetic interference (EMI) profiles, specifically Additive White Gaussian Noise (AWGN), into the communication path of a DJI O3 Air Unit. This digital video system represents the primary transmission standard for high-performance FPV (First-Person View) drones [1]. The experimental setup allowed for a rigorous evaluation of signal integrity under specific spectral stress conditions.

The novelty of this research lies in the integration of SDR-based external interference with internal EMI analysis generated by drones. Our contribution consists of a quantitative dataset that correlates packet error rate (PER) and bit rate stability with specific hardware configurations and interference densities. This

provides a practical framework for drone operators to evaluate link reliability in high-density electromagnetic environments.

2. APPLICATION FIELD AND RESEARCH STAGES

Digital video transmission systems used in the drone manufacturing industry, such as the DJI O3 air unit produced by DJI, are superior to analog systems, offering significant image quality and transmission stability. They use advanced compression and error correction mechanisms, thus maintaining a clear and coherent video stream in the presence of interference and signal variations.

Digital video systems operate on the basis of correct reception of data packets, resulting in an almost perfect image as long as the minimum video signal reception threshold is maintained, in analog transmission, signal degradation manifests itself progressively through the appearance of background noise (static), electromagnetic interference and the gradual loss of video detail. However, this approach introduces a specific vulnerability, known as the "cliff effect", which manifests itself in the abrupt degradation or complete interruption of digital transmission, without an intermediate visual warning phase, due to the system's inability to correct errors.[2]

The research focuses on analyzing the transmission of high-bandwidth digital video systems used in critical UAV applications, such as search, surveillance, and rescue operations in industrial areas and urban environments. In these scenarios, the 5.8 GHz spectrum is often saturated with high-power Wi-Fi routers and other industrial transmitters, making video signal integrity a critical factor for the safety of the activities undertaken.

The research was conducted in four distinct stages:

- Measurement of DJI O3 performance in an "electromagnetically quiet" environment to establish baseline transfer rate and latency.
- External interference injection: ADALM-PLUTO SDR was used to generate controlled interference profiles (AWGN and OFDM) with variable power levels. The standard antennas of this SDR were used for the established configuration, which work well in the 5.8 GHz range for short distances in laboratory conditions.
- Data correlation: Aggregating telemetry logs to define the "Digital Cliff" threshold.

3. MATERIALS AND METHODS USED

The SDR system used in this experimental setup consists of an ADALM-PLUTO (PlutoSDR) software-defined radio device based on the Analog Devices AD9363 integrated transceiver. Although factory specifications limit the frequency range, the device has been software reconfigured to operate in an extended spectrum from 325 MHz to 6 GHz, thus covering the 5.8 GHz band required for DJI O3 system analysis. ADALM-PLUTO is a versatile learning and development platform that allows complete control over transmission and reception parameters through open-source libraries, making it ideal for testing the resilience of digital data links in controlled environments.



Fig. 1. Experimental setup for testing spectrum monitoring systems

Fig. 1 shows a scenario of digital video signal transmission and interference on a 5-inch FPV drone. The video connection is made via a digital video stream in the 5.8 GHz band, with a data transmission rate of approximately 7 Mbps, to a pair of DJI Goggles 2, acting as a video receiver.

To perform the experimental measurements, the equipment used was positioned as follows:

DJI Goggles 2 were positioned 1 m away from the SDR system, and the DJI O3 module installed on the drone was positioned 3 m away from the same SDR system (see Fig.1.).

The spectral data was then captured using SATSAGEN with a resolution bandwidth (RBW) optimized for detecting wideband digital signals. [3]

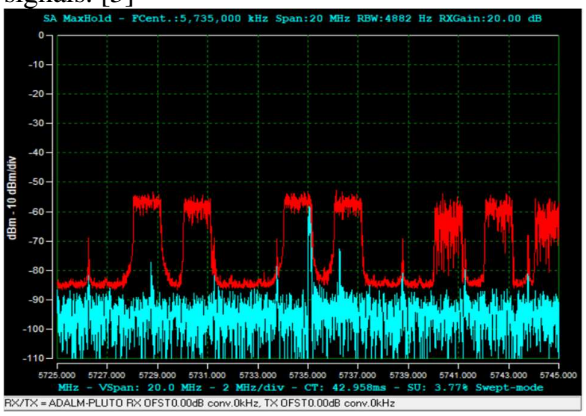


Fig. 2. View the spectrum in the frequency domain for DJI O3 systems.

Figure 2 illustrates the characteristic rectangular spectral profile of the Orthogonal Frequency Division Multiplexing (OFDM) signal, which is the underlying technology employed by DJI O3 systems for digital FPV drone transmissions.The spectrogram is made under controlled conditions without other emission sources in the 5.8 GHz range, using an SDR receiver (ADALM-Pluto) configured as a spectrum analyzer, in max hold mode, and illustrates both the useful signal and the associated electromagnetic noise. Thus, the video transmission worked without interruptions at a speed of 7Mbps, obtaining a continuous HD image in the DJI goggles 2 (Fig. 3.).



Fig. 3. Live transmission at 7 Mbps with the DJI O3 system in a controlled environment without interference.

The horizontal axis also shows the frequency, centred around approximately 5.735 GHz, with a span of 20 MHz, while the vertical axis indicates the spectral power level expressed in dBm. The cyan line corresponds to background noise and random components of the spectrum, characteristic of the receiver's noise floor and weak interference in the band. The red line, materialized using the max hold mode, highlights the maxima of the signals detected over time and represents relatively wideband emissions with steep edges, typical of OFDM digital transmissions used by modern FPV systems, such as the DJI O3 system tested in this case.

Active video transmission channels are indicated by high spectral plateaus located around −60 dBm, while irregular structures and increased energy levels between channels suggest contributions from adjacent electromagnetic noise, possibly originating from rapid ESC switching and high currents absorbed by motors. The difference between the useful signal level and the background noise provides an estimate of the signal-to-noise ratio (SNR), a critical parameter for digital link stability. A reduction in this ratio, through increased noise or a decrease in the received signal level, can lead to rapid performance degradation and, in extreme cases, to the cliff effect, which is characteristic of digital systems.

The values presented in Table 1 in Chapter 4 RESULTS AND DISCUSSIONS, were obtained through a real-time monitoring process, using the following experimental procedure:

- Bitrate Monitoring (OSD): The bitrate values were extracted directly from the On-Screen Display (OSD) of the DJI Goggles 2. The DJI O3 system displays the bandwidth used for the video stream in real time, reflecting the adaptive capacity of the link depending on the channel conditions.
- The 0 dB Gain value corresponds to the maximum output power of the SDR, and the -30 dB value was set to simulate a moderately noisy environment.
- For each interference threshold, the system was allowed to stabilize for 30 seconds. The

value recorded in the table represents the average of constant readings during this interval. In the case of the "Armed" state, where the bitrate fluctuates (12-25 Mbps), the variation range observed during the Forward Error Correction (FEC) process was recorded.

- Each gain change in the Python script was visually correlated with the telemetry displayed in the goggles. The 0 Mbps moment was defined as the point at which the video decoder could no longer reconstruct any frames (image freeze), followed by the system warning message.

4. RESULTS AND DISCUSSIONS

To achieve the experimental objectives, controlled electromagnetic interference was introduced into the transmission channel, simulating an intentional jamming scenario. This process directly impacts the signal-to-interference-plus-noise ratio (SINR) of the radio link, allowing for a quantitative evaluation of the communication system's robustness. The sources of this interference, modelled as Additive White Gaussian Noise (AWGN), are generated and controlled by the ADALM-Pluto SDR system, connected to a laptop running spectral analysis and generation software (SATSAGEN). The diagram thus highlights how a digital video transmission system is subject to RF interference and suggests the experimental context for evaluating the robustness of the digital link, including observing its characteristic behaviour near the reception threshold, where phenomena such as sudden degradation or complete signal loss occur.

The DJI O3 video system saves hardware resources and avoids overheating when the drone is in disarmed mode. This behavior is called "Power Management & Bandwidth Allocation Strategy." Thus:

- in disarmed mode, the system enters "Low Power Mode" because the drone is not flying and does not need minimum latency or maximum detail, so it limits the stream to 7 Mbps.
- in armed mode, when the engines start, the system estimates that take-off is imminent and the transmitter switches to maximum power and unlocks the 50 Mbps bitrate to ensure the best visibility and minimum latency (below 28 ms, see Fig. 4.). [4]



Fig. 4. Live transmission at 50 Mbps with the DJI O3 system in armed mode.

The automation of the broadband electromagnetic interference injection process for testing the resistance of the video link was implemented in Python. This allowed us to transform the ADALM-PLUTO device into a controlled interference generator to determine the point at which the digital signal degrades(see Fig. 5.).

The Python code was created to generate an AWGN (Additive White Gaussian Noise) signal covering the 20 MHz spectrum of the video channel [5]. The main purpose was to measure the impact of increased interference power on the video bitrate, thus identifying the "Digital Cliff" threshold (0 Mbps). [6]

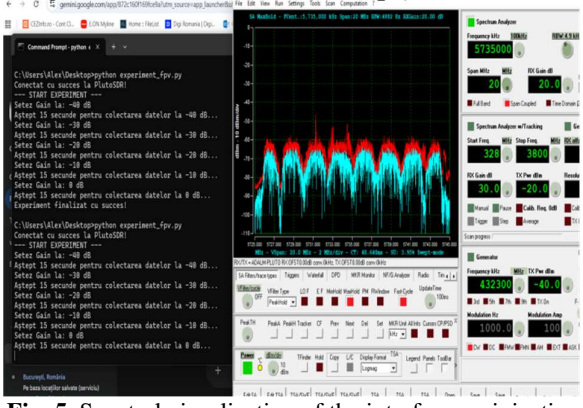


Fig. 5. Spectral visualization of the interference injection process.

The blue trace represents the SDR-generated AWGN floor rising to meet the red DJI O3 OFDM carriers.

Knowing that the DJI O3 system menu allows manual selection of one of three

available 20 MHz channels or the default 40 MHz automatic channel, experimental analyses were performed on CH 01, which was manually selected because the ADALM SDR system can generate AWGN signals up to a bandwidth of 20 MHz in the baseband. Thus, the DJI O3 system was manually configured on channel 1 (CH01), corresponding to the frequency of 5735 MHz.The execution of the Python script demonstrated that, under AWGN noise conditions and a fixed bandwidth of 20 MHz, the data rate dropped to zero, resulting in complete video signal failure (see Fig. 6.).

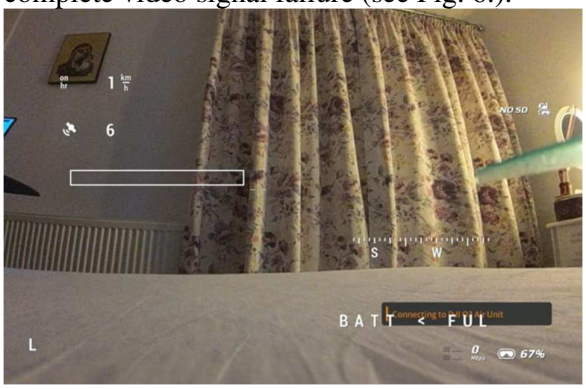


Fig. 6. Viewing the "Digital Cliff" in DJI Goggles.

The image in Fig. 7 represents the moment when the digital connection collapses, a phenomenon known as the "Digital Cliff." The DJI O3 system attempts to maintain a clear image through aggressive compression under the massive interference generated by PlutoSDR on the fixed channel CH01.

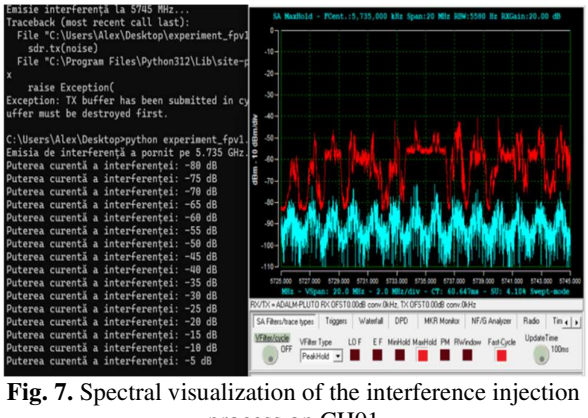


Fig. 7. Spectral visualization of the interference injection process on CH01

At the bottom of the screen in Fig. 7, the displayed bitrate value is 0 Mbps, confirming that the video data stream has been completely interrupted. Also, the central message "Connecting to DJI O3 Air Unit" indicates that the goggles have lost synchronization with the transmission unit. The background image is "frozen", representing the last valid information received before the signal-to-noise ratio (SNR) fell below the critical decoding threshold, resulting in a total absence of video signal.

Table 1

Table with the results obtained

Interference Level (SDR Gain Setting)	Disarmed State (Video Bitrate)	Armed State (Video Bitrate)	OSD Visual Status & Telemetry
No Interference (SDR OFF)	7 Mbps	50 Mbps	Signal Full / Stable
Moderate Interference (-30 dB)	7 Mbps	12 - 25 Mbps	Bitrate Fluctuating
Critical Interference (0 dB)	0 Mbps	0 Mbps	0 Mbps (Link Lost)

Table 1 details the behavior of the video stream under the influence of wideband electromagnetic interference (EMI), modeled as AWGN and generated by the ADALM-PLUTO SDR. The data highlights the nonlinear degradation characteristics of the DJI O3 system, as visualized in the spectral analysis in Fig. 7.

The transition from a nominal rate of 50 Mbps to a fluctuating range of 12-25 Mbps under a controlled interference gain of -30 dB demonstrates the resilience of the system through adaptive mechanisms. However, the convergence of both operational states to 0 Mbps at maximum hardware gain (0 dB) identifies the absolute reception threshold. This empirically validates the “digital cliff effect”, in which the signal-to-interference-plus-noise ratio (SINR) drops below the decodability limit, resulting in an instantaneous collapse of the high-definition video link.

Digital signal loss can be described mathematically by the Shannon-Hartley theorem, in which capacity (C) approaches zero as interference power (P_I) increases:

$$C = W * \log_2\left(1 + \frac{P_S}{P_N + P_I}\right) \quad (1)$$

C-Channel Capacity (bits/second), W-Bandwidth (Hertz), P_S-signal power, P_N- noise power, P_I- interference power (controlled via the Python script)

When the P_I interference power becomes equal to or greater than the P_S signal power, the ratio tends towards 0, resulting the channel capacity equal to 0. This is when the glasses display a transfer rate equal to 0 Mbps and the reconnection message.

In Fig. 8, you can see three 20 MHz channels: CH01 for drone 1, CH02 for drone 2, and CH03 is free.

A closer inspection of the graph reveals spacing between adjacent channels, known as “guard bands”. DJI systems maintain approximately 35 MHz between the center frequencies of 20 MHz channels.

Calculation:

5804.5 (CH02) - 5768.5 (CH01) = 36 MHz.

It is important to note that although the signal is only 20 MHz wide, the remaining 16 MHz are left free to prevent signal "leakage" (interference) from one drone to another.

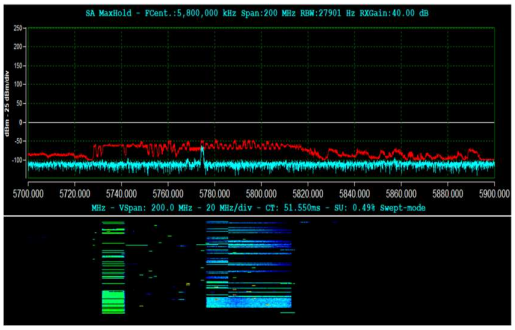


Fig. 8. Spectral visualization for two DJI O3 systems

Fig. 9 shows the evolution of the radio spectrum subject to interference generated by the SDR system, where two FPV drones with two DJI O3 video systems were started, manually switched to separate channels (CH01 and CH02), observing that the use of the 5.8 GHz band presents specific vulnerabilities in urban operating scenarios, where the density of parasitic signals is high. [7]

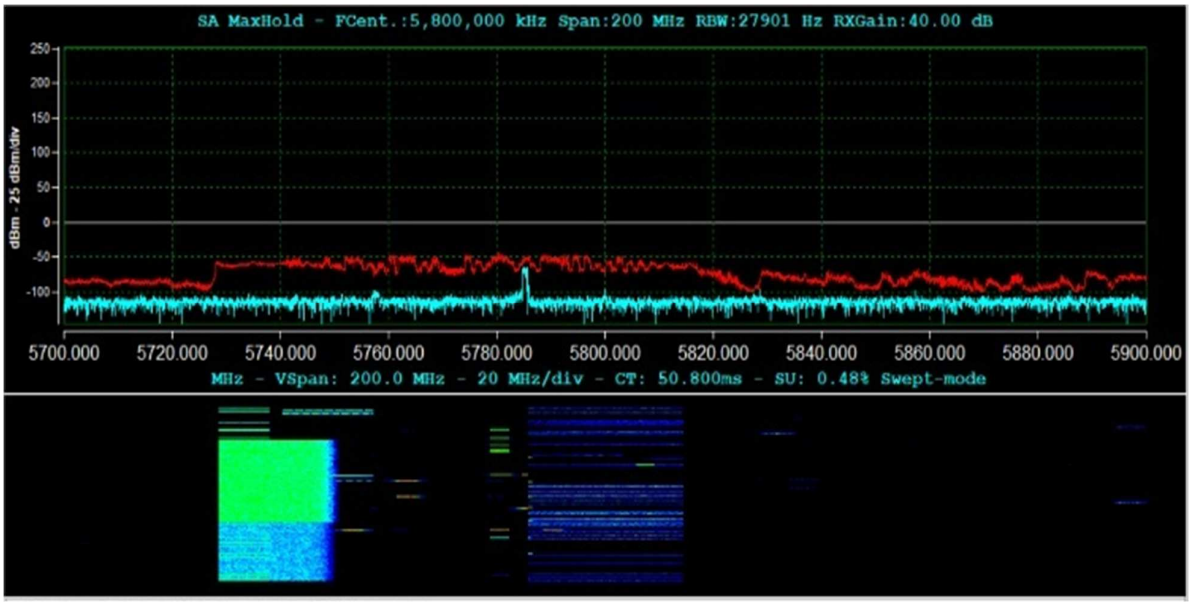


Fig. 9. Spectral visualization of the interference injection process on CH01 for both drones.

The Waterfall diagram in Fig. 9, visible at the bottom, highlights stable transmission and noise congestion in the center of the band, while the right portion remains an ideal free zone for interference-free flight.

In the configuration shown in Fig. 10, the DJI O3 system maximizes data flow by occupying an extended 40 MHz channel, which provides superior video clarity but limits the space available for other drones. On the SATSAGEN spectral analysis software, a massive and constant presence can be observed across the central frequencies.

5. CONCLUSION

The radio communication protocols used by modern drones (UAVs) in the 5.8 GHz range must cope with an increasingly crowded electromagnetic environment, especially in urban areas where interference is ubiquitous

due to the multitude of equipment using this band.

Although modern video systems, such as the DJI O3 system, use advanced transmission technologies, their performance remains dependent on the signal-to-noise ratio in the operating environment. In this paper, the collapse threshold of the video link was investigated using a testing methodology based on AWGN noise generation, a method validated in specialized studies for video resilience analysis.

The DJI O3 system reaches a "digital cliff" when the interference generated by the SDR ADLM-PLUTO platform exceeds the safety margin, the bitrate no longer decreases linearly but instantly drops to 0 Mbps, forcing the transmitter into a reconnection state, despite robust error correction protocols (FEC).A remarkable observation of this study was the visual quality of the video stream at the critical threshold of 7 Mbps. Despite the massive injection of AWGN noise, the DJI O3 system avoided progressive degradation (pixelation), maintaining a clear image until the moment of total disconnection. This behavior demonstrates a superior implementation of adaptive bitrate algorithms, which prioritize visual integrity over latency or frame rate under conditions of extreme interference.

The use of SDR platforms such as ADALM-PLUTO with cyclic buffers has proven to be an effective method of simulating jamming attacks in the 5.8 GHz ISM band, but their effectiveness is directly influenced by the distance from the UAV.

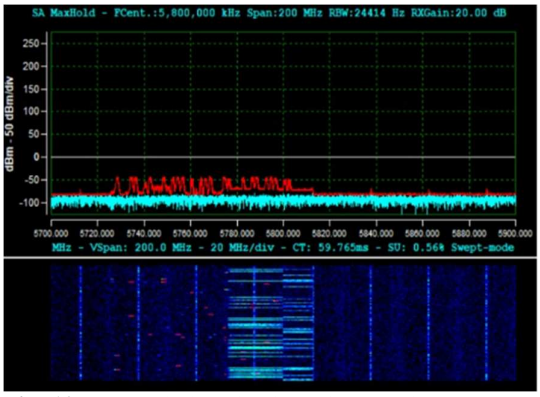


Fig. 10. Spectral visualization of channel CH01 at 40 MHz

6. FUTURE RESEARCH DIRECTIONS

In the current experiment, omnidirectional antennas from the standard SDR system package were used. A future direction is to test the impact of interference using Yagi or Patch antennas on PlutoSDR to simulate a long-range jamming attack. This allows us to measure the energy efficiency of jamming over long distances.

Future research directions will focus on implementing Cognitive Jamming Algorithms. Instead of emitting constant noise (AWGN), let's develop a Python script that is capable of spectrum sensing and emitting interference only on the active subcarriers of the DJI O3 video systems. This "reactive jamming" is much harder to detect and requires much lower transmit power.[8]

Implementing such a system on the ADALM-PLUTO platform would require real-time spectrum sensing capabilities to detect the DJI O3's bursts and trigger the interference instantaneously. This would significantly increase the energy efficiency of the attack and its stealthiness, providing a more sophisticated model for testing the resilience of modern digital UAV links."

Testing in real urban environments (Multi-path Fading) by extending the experiment from the lab to a real urban environment, where in addition to the interference generated by SDR systems, the signal is also affected by reflections (multi-path) and Wi-Fi 6 interference from the environment, to which I will gradually add one to three drones with the same video transmission system. This would provide a "worst-case scenario" model for signal integrity.

Future research directions will include correlating signal degradation with control latency (M2C - Motion to Photon) and how this affects the drone's autonomous navigation or obstacle avoidance algorithms during critical interference moments.

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Analiza experimentală a rezilienței legăturii video pentru sistemele digitale FPV sub acțiunea interferenței electromagnetice controlată bazată pe SDR

Rezumat: Evoluția tehnologiilor în domeniul UAS este în dezvoltare continuă unde utilizarea spectrului electromagnetic devine esențială pentru rezervarea unui spațiu de operare. Articolul de față investighează robustețea și integritatea semnalului sistemelor digitale de înaltă definiție First-PersonView (FPV) care funcționează în spectre electromagnetice aglomerate. Folosind DJI O3 Air Unit ca sistem principal testat, cercetarea evaluează degradarea legăturii video - măsurată prin fluctuațiile ratei de biți și latența - în scenarii de interferență controlate. Utilizarea platformei ADALM-PLUTO Software Defined Radio (SDR) pentru a genera profiluri precise de interferețe, inclusiv zgomot alb gaussian aditiv (AWGN) și interferențe ale canalelor adiacente, a demonstrat obținerea de date esențiale pentru înțelege efectele interferențelor pentru aceste sisteme de transmisie video în gama 5.8 Ghz. Rezultatele experimentale oferă o corelație cantitativă între densitatea interferențelor și pierderea de pachete, oferind informații practice pentru optimizarea fiabilității semnalului în operațiunile profesionale cu UAV în medii cu densitate ridicată.

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