

Preliminary Evaluation of SDR-Based Jamming of Drone FHSS Uplinks [†]

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Abstract

This article presents a preliminary laboratory evaluation of an SDR-based jammer designed for controlled interaction with a drone’s FHSS uplink. The study examines the effects of instantaneous bandwidth, sweep duration, and spectral matching on time–frequency overlap with uplink hops. Both wideband and narrowband sweep configurations were analyzed. The results demonstrate that the effectiveness of interference improves when the sweep bandwidth matches the hop bandwidth more closely and when the total sweep duration is shorter than the uplink hop duration. A narrower sweep also enhances energy efficiency by concentrating transmitted energy within a smaller bandwidth, enabling effective coverage at moderate transmission power.

Keywords: software-defined radio; FHSS uplink; drone communications; sweep interference; time–frequency overlap; spectral power density; laboratory evaluation; ISM band

1. Introduction

The rapid advancement of UAV (Unmanned Aerial Vehicle) technology has led to its widespread use in civilian, industrial and military applications. However, the increasing availability, flexibility, and payload capacity of UAVs also introduce significant security risks, particularly when unauthorized operations occur in restricted airspace or in proximity to critical infrastructure. In order to address the threats posed by UAVs, a range of counter-UAV systems has been developed and tested. These systems employ electronic countermeasure techniques such as jamming, spoofing, cyber intrusion, and high-power electromagnetic energy emission [1].

A UAV RF architecture generally comprises four primary links: command-and-control (C2) uplink, video downlink, navigation, and telemetry. Most UAV attacks target navigation or control functions and are commonly classified as GPS spoofing, GPS replay, or GPS jamming attacks [2]. Given the reliance of numerous UAVs on GNSS for positioning and navigation, they are particularly susceptible to such threats. Furthermore, the use of RF C2 links by commercial UAVs can be interfered with by detecting and jamming their transmissions. The UAV navigation link relies on GNSS constellations such as GPS, GLONASS, Galileo, BeiDou, and NavIC [3,4]. These systems transmit L-band signals with ranging codes and navigation data used for positioning, timing, and safety functions such as return-to-home [5]. In Europe, GPS and Galileo are especially relevant due to



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their interoperability and multi-frequency operation [6]. UAV–remote control RF links can use standard Wi-Fi, enhanced Wi-Fi-based links, or proprietary protocols such as DJI Lightbridge and OcuSync [7–9].

The drone’s range, video transmission quality, latency, available control frequencies, and other related parameters depend heavily on the communication protocol used. Communications between UAVs and ground stations typically rely on Wi-Fi for short-range connections [10] and on mobile networks, such as 4G/5G [11]. RF links for UAV command and control, telemetry, and video use different channel access techniques. Orthogonal Frequency Division Multiplexing (OFDM) is typically used for high-data-rate links, such as video transmission [12]. Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS) are preferred for control and telemetry [13], as these techniques offer greater resistance to interference, jamming, and eavesdropping. The downlink channel uses OFDM with a bandwidth of up to 40 MHz (e.g., the DJI Matrice 30T) [14]. In contrast, the uplink channel uses narrowband channels of up to 2 MHz combined with FHSS modulation and rapid frequency hopping.

Commercial UAVs typically operate within the unlicensed 2.4 GHz and 5.8 GHz Industrial, Scientific and Medical (ISM) bands, alongside Wi-Fi and other wireless systems [15]. This shared spectrum makes identifying UAV links and deploying countermeasures challenging. Conventional broadband jamming can affect non-target systems in the same or adjacent bands, and typically demands high transmission power. Therefore, recent studies have focused on more selective, interference-aware mitigation techniques that reduce collateral effects while remaining effective against UAV links [16–18]. In this context, this paper proposes an SDR-based intelligent jamming technique that targets FHSS uplink channels. This adaptive interference with active frequencies in the hopping sequence improves energy efficiency compared with conventional wideband jamming.

2. Materials and Methods

2.1. Hardware Implementation

The hardware platform was configured to operate in the 2.4 GHz and 5.8 GHz ISM bands, using a laboratory architecture that combines a reconfigurable SDR front-end with a reference RF analyzer. The setup consisted of an antenna, an RF splitter, the USRP N310 platform (Ettus Research, a National Instruments brand, Austin, TX, USA), the Rohde & Schwarz FSW analyzer (Rohde & Schwarz GmbH & Co. KG, Munich, Germany), and a computer station for software control and DSP. The signal of interest was captured by the antenna and distributed to two branches: one to the FSW analyzer, for reference spectral observation, and one to the USRP N310, for digital acquisition and processing. This topology allowed for a direct comparison between the SDR chain and the measurement instrumentation under controlled laboratory conditions.

The choice of this equipment was determined by its direct compatibility with the 2.4 GHz and 5.8 GHz bands. The USRP N310 operates over a frequency range of 10 MHz to 6 GHz, which fully covers both targeted ISM bands, while the FSW, depending on the variant, has a frequency range starting at 2 Hz and extending up to 8/13.6/26.5/43.5/50/67/85 GHz, so it can analyze signals in these bands without significant restrictions. In addition, the two instruments are complementary: the N310 offers flexibility, software control, and direct integration with the DSP chain, while the FSW provides reference-grade spectral visibility, high sensitivity, and a wide analysis bandwidth.

2.1.1. USRP N310

The USRP N310 platform was used as the central component of the SDR chain, particularly for the controlled transmission portion and for direct integration with the software

application developed for the experiment. The equipment is suitable for the 2.4 GHz and 5.8 GHz ISM bands, offers 4 RX channels and 4 TX channels, and can support up to 100 MHz instantaneous bandwidth per channel. This allows the use of the same platform in both bands without structural modifications to the RF front-end.

In this article, the primary focus for the N310 was on its transmission capabilities. The platform allows software control of the center frequency, sampling rate, and transmit gain via UHD, making it suitable for generating test waveforms in the laboratory. Its architecture, based on two AD9371 transceivers, along with high-speed connectivity via 10 Gigabit Ethernet, supports direct integration with a high-performance computer and control software. Table 1 briefly presents the most important features of the USRP N310 platform.

Table 1. Main features of the SDR USRP N310.

Feature	Relevant Value
RF Frequency Range	10 MHz–6 GHz
Channels	4 RX/4 TX
Instantaneous Bandwidth	Up to 100 MHz per channel
RF Architecture	2 × AD9371
Data Interface	2 × 10 Gigabit Ethernet
Internal Platform	Xilinx Zynq-7100 SoC

2.1.2. R&S FSW

The R&S FSW analyzer was used as the reference RF instrument for spectral analysis, signal parameter verification, and SDR chain validation. It was used to verify the center frequency, power distribution, spectral occupancy, and stability of the observed signals. Its capabilities are particularly relevant in the laboratory due to its internal bandwidth of up to 8.312 GHz, real-time bandwidth of up to 800 MHz, high sensitivity, and low phase noise—features that support robust and detailed measurements in both investigated bands. The key features of the analyzer are presented in Table 2.

Table 2. Key features of the FSW spectrum analyzer.

Feature	Relevant Value
Frequency Range	2 Hz–8/13.6/26.5/43.5/50/67/85 GHz
Internal Analysis Bandwidth	Up to 8.312 GHz
Real-Time Analysis Bandwidth	Up to 800 MHz
Phase Noise	<−136 dBc/Hz at 1 GHz, 10 kHz offset
DANL	<−166 dBm/Hz at 1 GHz, with preamplifier enabled

From a practical perspective, the USRP N310 and R&S FSW setup enabled both flexible experimentation and reliable measurement validation. The N310 enabled software-controlled signal processing and digital signal processing (DSP) integration, while the FSW independently verified the observed parameters. This configuration was ideal for testing the 2.4 GHz and 5.8 GHz ISM bands because both devices support these frequencies inherently and offer the necessary bandwidth and analysis capabilities.

2.2. Control and Monitoring Software Interface

To operate the experimental platform, a dedicated GUI (Figure 1) was developed with the purpose of integrating, within a single environment, the functions for SDR parameter configuration, test-signal generation, near-real-time spectral monitoring, and execution logging. The interface was designed as a higher-level layer built on top of the GNU Radio (v3.10.12.0) infrastructure and UHD drivers, allowing the operator to coherently control

both the baseband processing parameters and the RF front-end parameters of the USRP N310 platform.

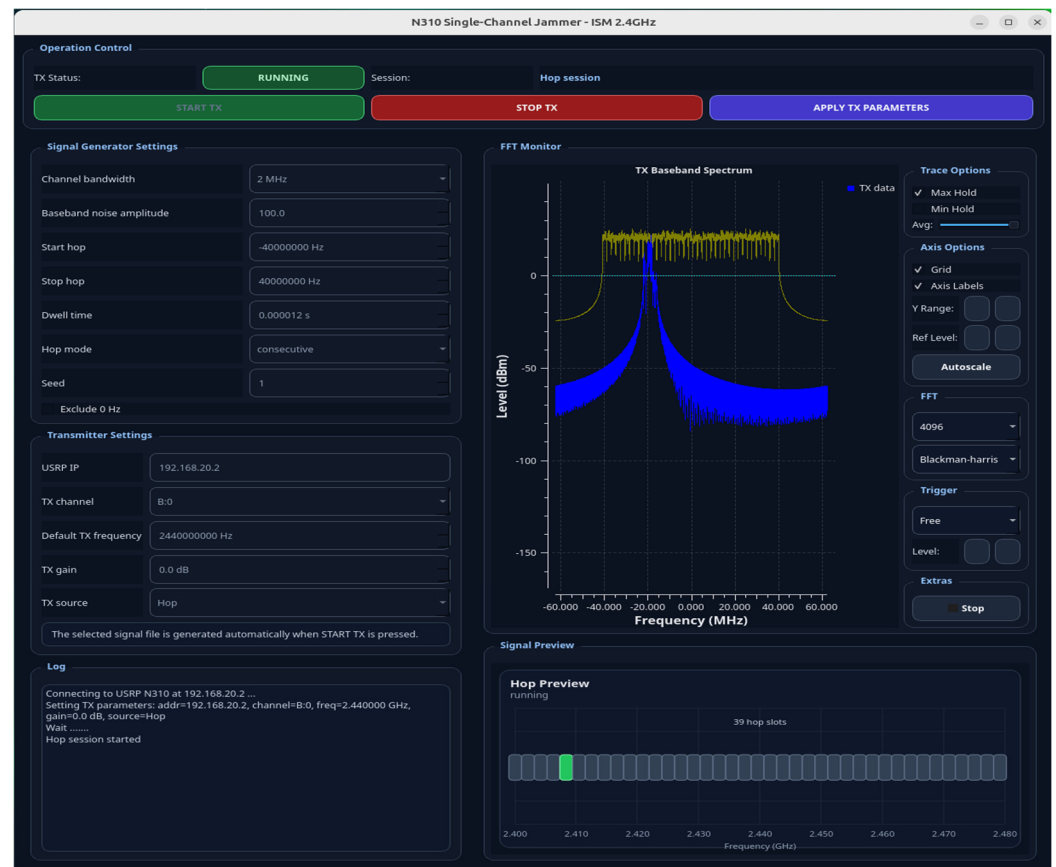


Figure 1. Control and monitoring GUI.

From a methodological perspective, this approach reduced configuration time between experiments, improved reproducibility, and ensured an explicit correspondence between the software configuration and the actual state of the hardware. The application architecture was organized in a modular way and consisted of the following components: the operational control module, the signal generator configuration module, the SDR transmitter configuration module, the FFT monitoring module, the spectral sequence preview module, and the logging module. From a functional perspective, the software workflow is illustrated in Figure 2.

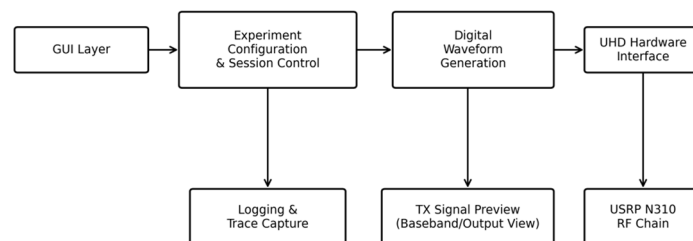


Figure 2. Software block diagram implementation.

In this chain, the graphical user interface acts as a single point of control and observation for the entire experimental setup. The operational control module manages the transitions between the main application states, including session initialization, parameter application, flow start, and flow stop.

In the case of a predefined sequence of spectral positions, the set of operating frequencies can be written as:

$$f = \{f_1, f_2, \dots, f_K\}, f_k \in [f_{\min}, f_{\max}] \quad (1)$$

where $f_{\min}$ and $f_{\max}$ define the operating interval, and K is the total number of spectral positions used during one experimental session. If the positions are uniformly distributed across the interval, the theoretical spacing between two consecutive positions is:

$$\Delta f = \frac{f_{\max} - f_{\min}}{K - 1} \quad (2)$$

The dwell time at each position is controlled by the parameter T_d , so that the total duration of one complete sequence becomes

$$T_{\text{seq}} = K \cdot T_d \quad (3)$$

In addition, the inclusion of a seed parameter makes it possible to regenerate the exact same sequence in repeated experiments, which is essential for measurement reproducibility.

Spectral monitoring is performed through an FFT module integrated into the interface, which provides a near-real-time representation of the signal in the frequency domain. This function plays an essential role in the immediate validation of the selected parameters and in observing the spectral behavior of the generated signal.

The interface also includes a spectral sequence preview module, through which the user can verify how the operating positions are distributed over the configured frequency band. This discrete representation is useful for checking the consistency between the defined parameters and the internally planned sequence.

In pseudo-random traversal modes, the order of the elements in the frequency vector f is determined by a permutation controlled by the seed parameter. This preview function allows configuration errors to be detected before launching the experiment and helps correlate the planned sequence with the behavior observed in the spectral monitor.

The application also includes a logging module that records key events during the experiment, such as the connection of the USRP, the application of parameters, the initialization of the flow, and shutdown and communication errors. This ensures experiment traceability and enables the configuration used for each measurement to be reconstructed, which is important in RF testing, where even minor changes can impact the results. By combining these functions in one interface, the software became an essential tool for operating the experimental platform. It provides centralized control, reduces complexity, synchronises hardware and DSP parameters, and improves reproducibility during 2.4 GHz laboratory testing.

3. Results and Discussion

3.1. Frequency Behavior of the Uplink of a DJI Mini 3 Drone

In this stage, the frequency behavior of the uplink of a DJI Mini 3 drone was analyzed by observing the signal in a spectrogram in the 2.4 GHz band. The primary focus was on identifying frequency hopping and determining its main parameters, such as hop duration, interval between successive hops, and temporal transmission distribution. Such an analysis is important for understanding how the command link operates, as well as for characterizing the temporal and spectral behavior of the signal transmitted from the control station to the drone.

Figure 3 shows that the relevant value is estimated as $D2 \approx 576 \mu\text{s}$, or approximately 0.576 ms, which corresponds to approximately 1736 hops per second, assuming a constant rate. In terms of the spectrogram, this means that the signal remains at a certain frequency

for about 576 microseconds before shifting to another. In other words, this is the dwell time on the channel for that measured event.

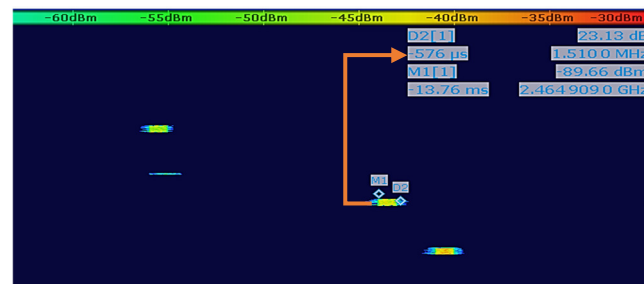


Figure 3. Estimation of the dwell time of the frequency-hopping drone waveform.

A subsequent analysis, illustrated in Figure 4, demonstrates that the temporal interval between successive occurrences exhibits variation among the samples. This means that although each hop lasts about the same amount of time, the timing of the next hop is not exactly the same each time.

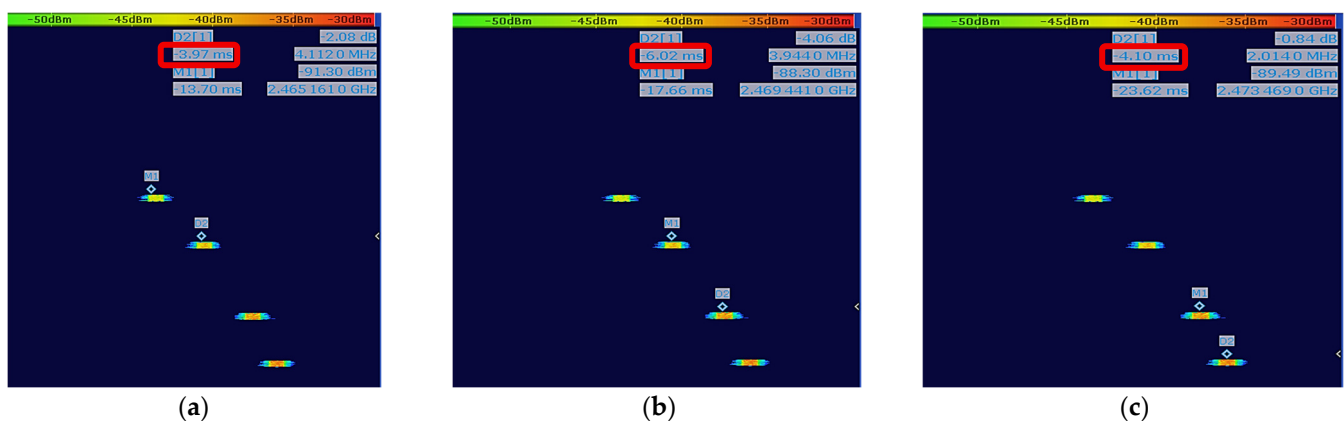


Figure 4. Spectrogram comparison of successive hops in the frequency-hopping signal: (a) first measured hop instance: 3.97 ms; (b) second measured hop instance: 6.02 ms, and (c) third measured hop instance: 4.10 ms.

This can be interpreted in analysis as follows:

- The signal does not have a strict periodic structure over time.
- There is a variation in the inter-hop interval.
- The system exhibits non-uniform or pseudo-random temporal behavior.
- Therefore, it is not sufficient to characterize the signal solely by the duration of the hops; rather, the temporal distribution of the hops must also be analyzed.

3.2. Comparative Analysis of Power Distribution and Implications for Uplink Jammer

After characterizing the uplink hops in the 2.4 GHz ISM band, a series of comparative measurements was conducted in a controlled laboratory environment using a USRP N310 connected directly to the measurement chain via an RF cable. The transmission power was kept low and constant throughout the tests. This stage was intended to evaluate the effect of signal bandwidth on the spectral level measured by the R&S FSW analyzer, the frequency-domain energy distribution, and the potential spectral overlap with the received uplink signals. Gaussian noise generated by software was used as the test waveform because it provides a controlled spectral profile and allows direct comparison of different bandwidth configurations under identical conditions.

For these measurements, the R&S FSW analyzer was configured in Real-Time Spectrum mode, with the center frequency set to 2.442 GHz, a span of 85 MHz, RBW = 106.25 kHz, sweep time = 64 μ s. Under these conditions, four emission modes were investigated, corresponding to bandwidths of 2 MHz, 6 MHz, 12 MHz, and, respectively, a full wideband mode, in which the energy was distributed over the entire 2.4 GHz ISM band (Figure 5).

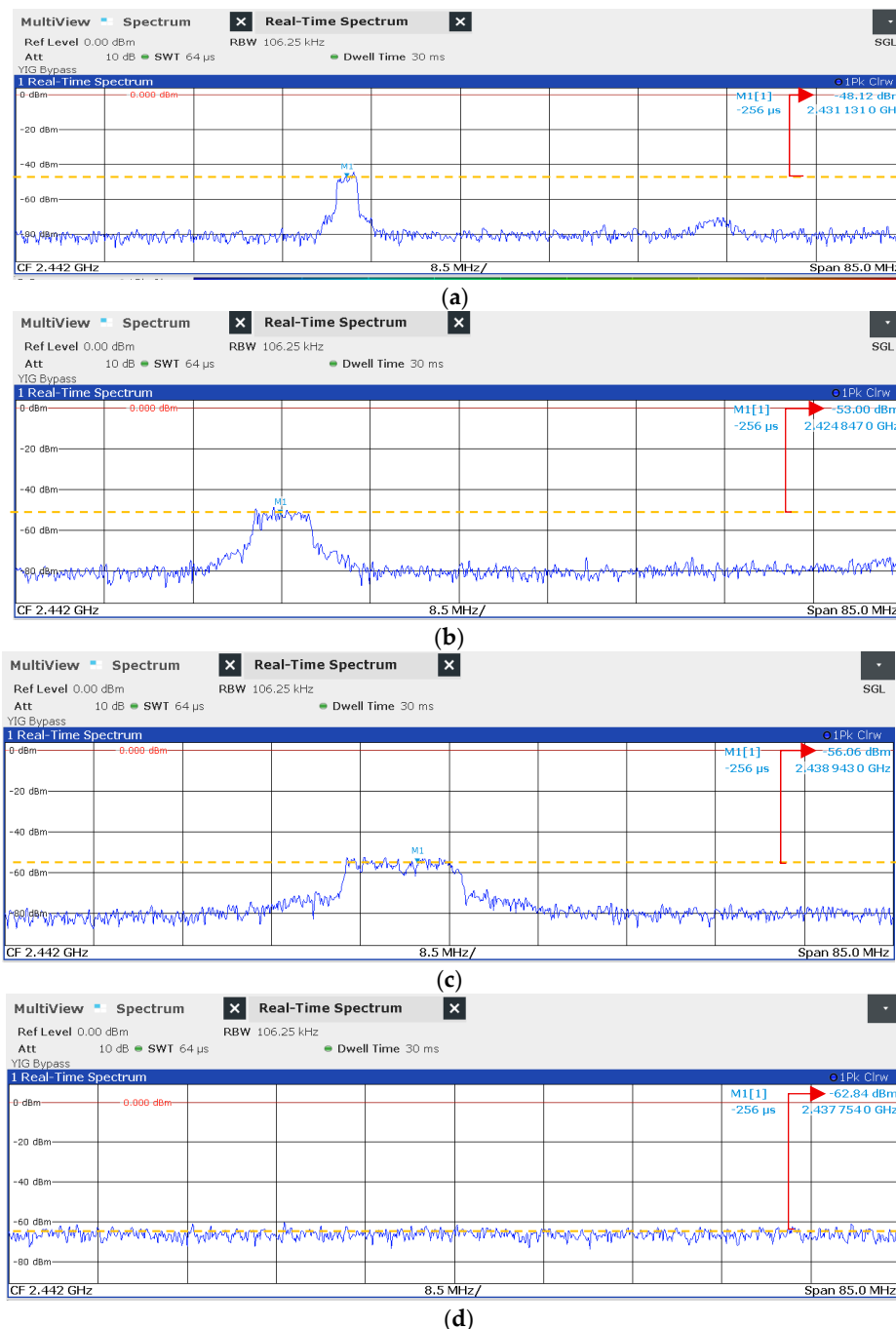


Figure 5. Real-time spectrum monitoring channels at 2 MHz (a); 6 MHz (b); 12 MHz (c) and 85 MHz (d) generated by N310 SDR.

The results show that, while increasing the test-signal bandwidth improves spectral coverage, it reduces the local spectral level. In the 2 MHz case, the energy is concentrated in a narrow region, resulting in the highest peak spectral level. For 6 MHz and 12 MHz, the occupied bandwidth becomes progressively wider. However, the spectral power density decreases. This is because the same approximate total power is distributed over

a larger frequency range. This confirms the trade-off between power concentration and instantaneous spectral coverage. This compromise is particularly pertinent for FHSS uplinks in the 2.4 GHz band, where the signal occupies narrow frequencies that change rapidly over time. A larger part of the band can be covered by barrage-type jamming and less dependency on the hopping sequence is exhibited, but the available power is spread and efficiency per channel is reduced. Sweep-type jamming concentrates energy in a narrower spectral region, producing a stronger local effect; however, its effectiveness depends on the overlap between the sweep and hopping rates. If this overlap is unfavorable, some hops may remain unaffected.

3.3. Analysis of the Overlap Between the FHSS Uplink and the Sweep Signal Generated with the N310

Figure 6 shows an FHSS uplink, where narrowband emissions transition among discrete carrier frequencies according to the hopping sequence. The downlink, meanwhile, occupies a wider instantaneous bandwidth. The USRP N310 generated a consecutive sweep with a 6 MHz instantaneous bandwidth, which was superimposed on these signals and covered the full 85 MHz band in 4 ms. The resulting overlap depends on the relationship between the sweep rate and the uplink hop dynamics. Since the sweep occupies only a small portion of the band at any given moment, it takes too short a time to reliably intercept active uplink hops.

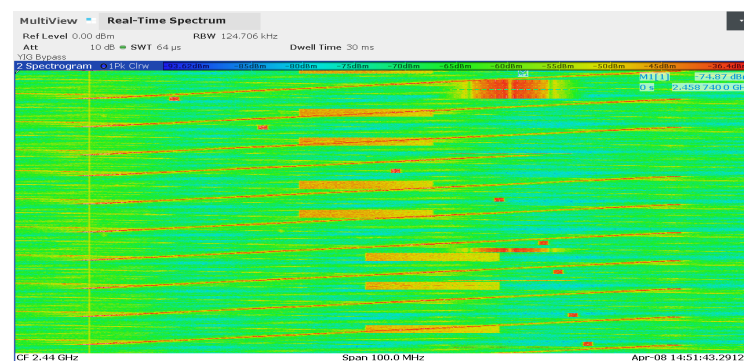


Figure 6. Monitoring of instantaneous bandwidth (6 MHz) sweeping across the entire 85 MHz band in 4 ms.

A 6 MHz sweep over 85 MHz in 4 ms does not result in sustained co-channel overlap with the uplink hops; rather, it produces sporadic time–frequency intersections. As the sweep is not synchronised with the hopping pattern, the probability of exact coincidence with the active uplink channel is low. Consequently, the N310 signal is mainly perceived as a transient disturbance distributed across the spectrum, producing only a limited increase in spectral occupancy rather than blocking the hopsets effectively. As shown in Figure 7, the USRP N310 also generates a 2 MHz instantaneous-bandwidth signal that sweeps through the entire band at 39 frequency positions, with 12 μ s per position and a total sweep time of approximately 0.468 ms. Since this is shorter than the uplink hop duration of 0.576 ms, the sweep can traverse the full band within a single hop interval. This significantly increases the probability of time–frequency overlap with the active channel.

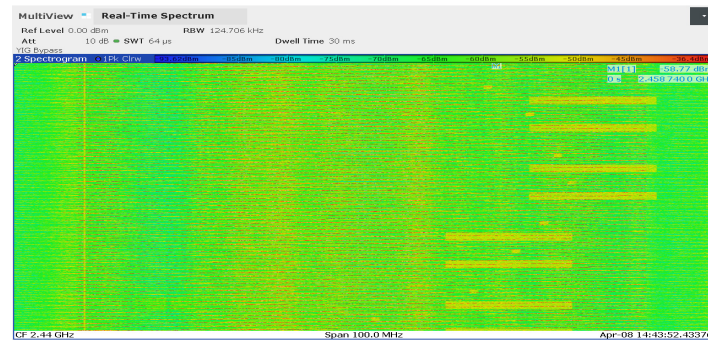


Figure 7. Monitoring of instantaneous bandwidth (2 MHz) sweeping across the entire 85 MHz band in 0.468 ms.

The 2 MHz sweep configuration is more power-efficient than the 6 MHz configuration because the same transmission power is concentrated into a bandwidth that is three times narrower. This increases the spectral power density at the frequency that is occupied at any given moment. Consequently, more useful energy is injected into the active portion of the band, rendering each overlap with an uplink hop more effective. This configuration provides two main advantages. The sweep is fast enough to cover the entire band within one uplink hop. The narrower bandwidth produces stronger power concentration. Therefore, in both temporal and power terms, the 2 MHz, 0.468 ms sweep is technically superior to the 6 MHz, 4 ms case, increasing the probability and effectiveness of interference during overlap. Figure 8 illustrates the remote-control display with the jammer stopped (Figure 8a) and started (Figure 8b).

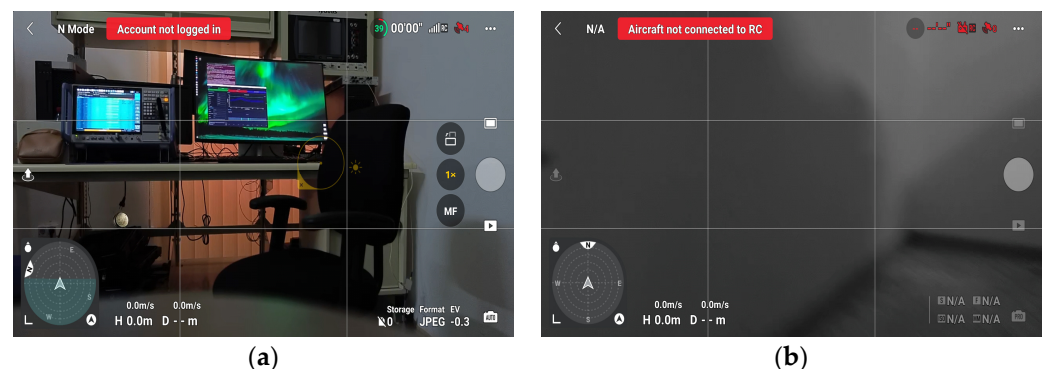


Figure 8. Remote control display when (a) the jammer is stopped and (b) the jammer is started.

Another advantage of this approach is that selecting a sweep bandwidth similar to the instantaneous bandwidth of the uplink hop enables the overlap effect to be achieved with transmission power at N310 that is slightly higher than the uplink transmitter's power. Since energy is concentrated in a spectral portion close to that occupied by the hop instead of being dispersed over a much wider band, the result is significantly higher energy efficiency. Under these conditions, a significant increase in total transmitted power is unnecessary to produce a relevant level of interference on the active hop. This makes the system more efficient in terms of power consumption and coverage. In practice, adapting the N310 signal band to the uplink hop's spectral scale achieves a good balance between power density, transmission efficiency, and radio coverage area.

4. Conclusions

The main result of this experimental work is that a narrower, faster N310 sweep is more effective at interacting with the FHSS uplink than a wider, slower sweep. The 6 MHz, 4 ms configuration produced limited overlap with active hops, whereas the 2 MHz,

0.468 ms sweep covered the full hopping band within a 0.576 ms hop interval, significantly increasing the probability of overlap. The narrower bandwidth also improved spectral power density and energy efficiency. Future work will extend the validation process to the 5.8 GHz ISM band through field measurements conducted at various distances and using different transmitters.

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