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Analysis of RF Signal Characteristics for Passive UAV Detection Development

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Abstract: The importance of effective counter-unmanned aircraft systems (C-UAS) is growing due to increasing security risks from drones. This study explores RF spectrum monitoring as a method for detecting commercial drones, specifically the DJI Mini 3, SJR/C F11 Pro, and E88 Pro, operating at 2.4 GHz. The findings show that the DJI Mini 3 has the strongest signals and uses channels more flexibly, while the other drones have weaker signals and mainly use the upper part of the Wi-Fi spectrum. These results highlight the potential of passive RF monitoring systems as a reliable and effective method for drone detection in C-UAS applications.

***Keywords*— Unmanned aerial vehicles (UAVs), Counter-unmanned aircraft system (C-UAS), Passive RF detection systems**

I. INTRODUCTION

Unmanned aerial vehicles (UAVs), or drones, are becoming more widely used in various fields due to their advanced technology and flexibility. They are utilized in activities such as recreation, surveying, and agriculture. As their use increases, so do the security risks associated with unauthorized drone operations, making it essential to develop counter-unmanned aircraft systems (C-UAS) [1]. The main challenge for C-UAS technology is to detect, track, and neutralize drones in both urban and rural areas, where interference and environmental factors can make detection difficult. Several methods have been proposed for C-UAS, each with its own advantages drawbacks, and limitations.

Imaging and radar systems are commonly used and are especially effective in line-of-sight (LoS) conditions. These methods can detect drones in urban settings. However, buildings and other obstacles might block signals and reduce accuracy. Moreover, radar systems can produce false positives, such as mistaking birds or other flying objects for drones [2], [3]. Acoustic detection systems use the unique sound profiles created by drones, such as noises from motors, rotors, and propellers, to detect their presence. Despite their promise, these systems face challenges like limited detection range and susceptibility to background noise, particularly in complex urban environments [4].

Among detection methods, radio frequency (RF) spectrum monitoring has emerged as a strong alternative. RF-based detection systems do not need LoS and can track drones by detecting the communications between the drone and its controller within the electromagnetic spectrum. This method is particularly effective in areas where visual and radar detection may fail, such as locations with obstructions or low visibility. RF-based detection can identify drones by analyzing their control, telemetry, and video transmission signals, providing early warnings of unauthorized operations [5].

This paper focuses on passive RF-based detection, which does not use an active transmitter in the detection system. Instead, it relies solely on a receiver, like a spectrum analyzer, to listen to RF signals emitted by drones, rather than actively probing or sending signals. However, challenges arise when drone signals overlap with other RF sources, such as Wi-Fi or Bluetooth, particularly in dense urban environments. The paper contributes by observing the RF signal characteristics of three commercial drones—E88 Pro, SJR/C F11 Pro, and DJI Mini 3—using passive RF monitoring. The experimental campaign aims to analyze key parameters such as signal strength, channel allocation, and signal-to-noise ratio (SNR) under both controlled and real-world conditions. The findings offer valuable insights into the unique RF behaviors of these drones, contributing to the

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*Correspondence: Tanatsan Khantha, Space Technology Research Center (S-TREC), Geo-Informatics and Space Technology Development Agency (Public Organization) (GISTDA), Chonburi 20230, Thailand, (E-mail: tanatsan.kha@gistda.or.th) development of more efficient and cost-effective C-UAS technologies. The paper is structured as follows: Section II describes drone communications and their spectrum allocation. Section III details the experimental campaign conducted to observe RF signals from drones. Section IV discusses the experimental results, and Section V concludes the study and suggests future work.

II. DRONE COMMUNICATIONS

The wireless transceiver sets up communication links within the UAV system, which includes both the drone and its controller. Most commercial drones use bi-directional communication, meaning they send and receive signals (uplink and downlink). This bi-directional communication is essential to maintain continuous control and feedback between the drone and its controller [5]. The over-the-air signals in the UAV system are shown in Fig. 1.

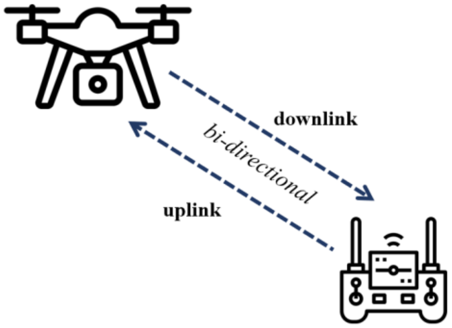


Fig. 1. Over-the-air signals between the drone and its controller.

This communication link sends precise control inputs, such as throttle, pitch, yaw, and roll, to ensure accurate navigation of the drone. Moreover, the system provides the pilot with critical information, including the drone's location, remaining flight time, distance from the pilot, payload data, speed, altitude, and video feed. Additionally, it allows for the transmission of flight missions, acknowledgments, and other protocol-specific data, thus extending the range of control commands beyond basic ones.

A. Drone communication spectrum allocation

Drone transmission systems typically operate in the industrial, scientific, and medical (ISM) bands, with frequency selection based on the drone's geographic location. In Thailand, the National Broadcasting and Telecommunications Commission (NBTC) has allocated specific radio frequencies within the ISM bands for drones [6]. Table 1 shows the frequency bands available for ISM applications, as defined by ITU-R [7], and their use in Thailand for drone communications.

As shown in Table 1, the frequency bands used for drone communications—2.4-2.5 GHz and 5.725-5.852 GHz—are the same as those allocated for Wi-Fi communication protocols. These bands provide an efficient and cost-effective control solution for many drone manufacturers. Additionally, other communication protocols, such as enhanced Wi-Fi, Lightbridge, and proprietary OcuSync [5], are also used to establish the RF link between the drone and its controller, alongside the Wi-Fi communication protocols. The choice of communication protocol significantly impacts the drone's range, video transmission quality, latency, available control frequencies, and other relevant factors.

TABLE I
FREQUENCY BANDS AVAILABLE FOR ISM APPLICATIONS
AND THEIR ALLOCATION FOR DRONE COMMUNICATION IN THAILAND.

Range	Bandwidth	Drones in Thailand
6.765-6.795 MHz	30 kHz	-
13.553-13.567 MHz	14 kHz	-
26.957-27.283 MHz	326 kHz	-
40.66-407 MHz	40 kHz	-
433.05-434.79 MHz	1.74 MHz	✓
902-928 MHz	26 MHz	-
2.4-2.5 GHz	100 MHz	✓
5.725-5.850 GHz	150 MHz	✓
24-24.25 GHz	250 MHz	✓
61-61.5 GHz	500 MHz	-
122-123 GHz	1 GHz	-
244-246 GHz	2 GHz	-

B. Wi-Fi communication protocol

The communication protocol varies among drone manufacturers. For simplicity, this paper focuses on drones that use the Wi-Fi standard for communications. The conventional IEEE Wi-Fi 802.11 network [8], commonly referred to as the 2.4 GHz and 5 GHz bands, is used to connect the drone and its controller. The drone creates a private Wi-Fi network that is only accessible between the drone and its controller, such as a remote controller, tablet, or mobile phone.

Most commercial drones support both frequency bands and can intelligently switch between them for optimal performance. The study of the standard usage of the 2.4 GHz band is crucial for RF-based detection. It is primarily used for connectivity, especially in more affordable and accessible drones. This band is divided into 14 channels, each 5 MHz apart, as shown in Fig. 2. Consequently, when the drone and controller are connected, their signal can be detected by RF-detecting devices operating in this band.

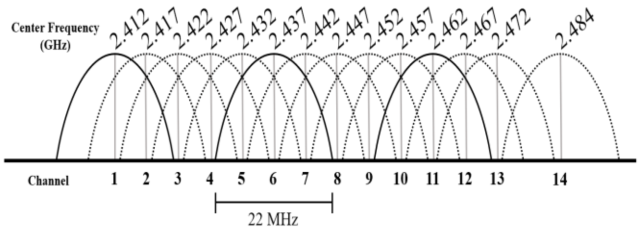


Fig. 2. Wi-Fi channels in the 2.4 GHz band.

C. *RF-based detection*

RF-based detection is a widely recognized technique for identifying and tracking drones through the electromagnetic signals transferred between drones and their controllers. The process begins with capturing the RF signals emitted during communication, including uplink signals from the controller to the drone and downlink signals from the drone back to the controller. These signals often carry vital information such as control commands, telemetry data, and video feeds, making them a reliable source for detection and identification.

Figure 3 illustrates a scenario of passive RF-based drone detection, where a remote pilot controls the drone while hovering or flying near a detection site. The RF-based drone detection must be positioned in the area being protected. In the first phase of the study, this system must be capable of detecting both uplink and downlink signals at the physical layer, such as signal strength, bandwidth, and signal-to-noise ratio (SNR). Passive drone detection is a key focus of this paper, as it eavesdrops on RF signals emitted by the drone using a receiver, without the need for an active transmitter.

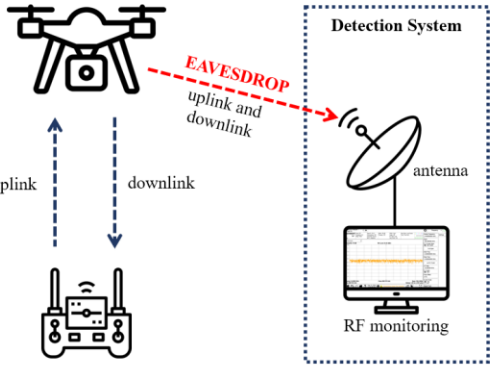


Fig. 3. Operation of the passive RF-based drone detection system.

III. EXPERIMENTAL CAMPAIGN

The experimental campaign aimed to observe the RF communication signals emitted by each drone. The goal was to investigate characteristics such as signal strength, which helps determine the threshold level for detecting the drone's RF signal. The campaign also examined the channels used during drone operations.

The campaign included two experiments: the first was indoors inside a shielded tent with a benchtop spectrum analyzer as the receiver, and the second was in an open field with a portable receiver. Both experiments used a spectrum analyzer as the RF receiver, focusing on RF signals at the physical layer. The results from this campaign will inform the design of the detection system in future development stages.

The experimental setup is shown in Fig. 3. The drone-under-test (DUT), shown in Fig. 4, were the E88 Pro and SJR/C F11 pro, which use the Wi-Fi protocol at 2.4 GHz, and the DJI Mini 3, which uses the proprietary OcuSync protocol. During measurement, the receiver scanned frequencies from 2.4 GHz to 2.5 GHz to detect uplink and downlink signals between the drone and its controller.

The experiments observed the drones in three different operation modes: "on" (drone powered on), "connected" (controller connected to the drone, but blades not spinning), and "flying" (blades spinning).

(a) E88 Pro (b) SJR/C F11 Pro (c) DJI Mini 3

Fig. 4. Drones used in the experiments.

The first experiment took place in a shielded tent, shown in Fig. 5, to create an interference-free. The measurement system consisted of 1) Keysight N9030B PXA signal analyzer and 2) ETS-Lindgren 3115 double-ridged guide horn antenna, shown in Fig. 6 (a) and (b). In this controlled environment, the distance between the drone and the measurement system was kept at 1.5 meters to accurately measure RF signals, identify channel allocation, and measure signal strength without external interference.

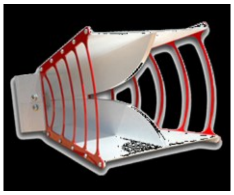
(a) outside

(b) inside

Fig. 5. A shielded tent to create an interference-free environment.

The second experiment was conducted in an open-field environment to simulate real-world conditions. For this experiment, the Keysight N9916B FieldFox, shown in Fig. 6 (c), replaced the benchtop receiver while the antenna stayed the same. Given the outdoor setting, a higher ambient noise floor was expected—approximately -80 dBm—compared to the shielded tent environment. The distance between the drone and the measurement system was also kept at 1.5 meters for consistency between the two experimental setups.

(a) Keysight N9030B PXA signal analyzer



(b) ETS-Lindgren 3115 double-ridged guide horn antenna

(c) Keysight N9916B FieldFox handheld microwave analyzer

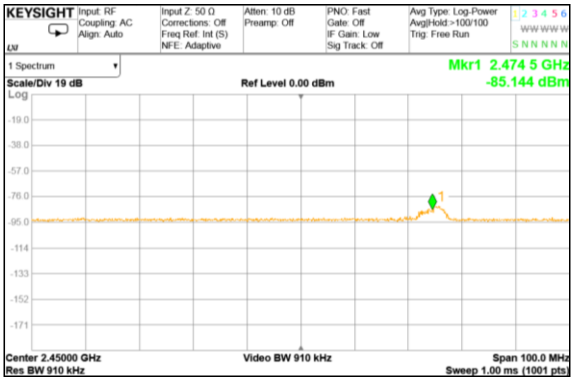
Fig. 6. Equipment and antenna utilized in the experiments.

IV. RESULTS

For the indoor experiment, Fig. 7 (a)-(b) show that the E88 Pro emitted a signal at 2.4745 GHz, which falls between Wi-Fi channels 12 and 13. The SJR/C F11 Pro emitted signals at 2.4528 GHz and 2.4763 GHz, corresponding to channels 8 and 9, and channels 12 and 13, respectively. The RF signals from the E88 Pro and SJR/C F11 Pro were mainly transmitted in the upper part of the Wi-Fi channel spectrum, with signal levels around -80 dBm. In contrast, the DJI Mini 3 could transmit across any part of the channel spectrum, as shown in Fig. 7 (c)-(d). It transmitted an RF signal with a fixed bandwidth of 20 MHz, and its signal strength was approximately -64.86 dBm, which is significantly higher than the other two drones.

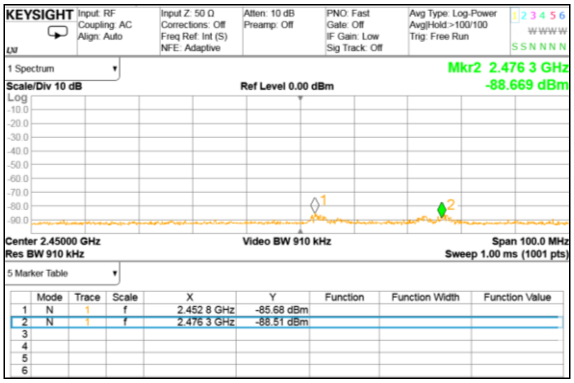
There was no observation in “flying” mode during this indoor experiment due to safety concerns and a technical issue with the SJR/C F11 Pro. The GPS could not be acquired inside the building, preventing the SJR/C F11 Pro from enabling the "flying" mode. However, it was expected that channel allocation would be similar to the "on" and "connected" modes. Additionally, when the drone is in "flying" mode, the signal strength is likely to be higher due to active communication between the drone and its controller, which requires more data transmission.

In the field experiment, the results from the “flying” mode are shown in Fig. 8-10. In Fig. 8 (a) and 9 (a), signals from the E88 Pro and the SJR/C F11 Pro were buried in ambient noise when measured in the normal trace mode of the spectrum analyzer.



Input: RF
Coupling: AC
Align: Auto
Input Z: 50 Ω
Corrections: Off
Freq Ref: Int (S)
NFE: Adaptive
Atten: 10 dB
Preamp: Off
PNO: Fast
Gate: Off
IF Gain: Low
Sig Track: Off
Avg Type: Log-Power
Avg|Hold:>100/100
Trig: Free Run
Mkr1 2.474 5 GHz
-85.144 dBm
Scale/Div 19 dB
Ref Level 0.00 dBm
Center 2.45000 GHz
Res BW 910 kHz
Video BW 910 kHz
Span 100.0 MHz
Sweep 1.00 ms (1001 pts)

(a) E88 Pro

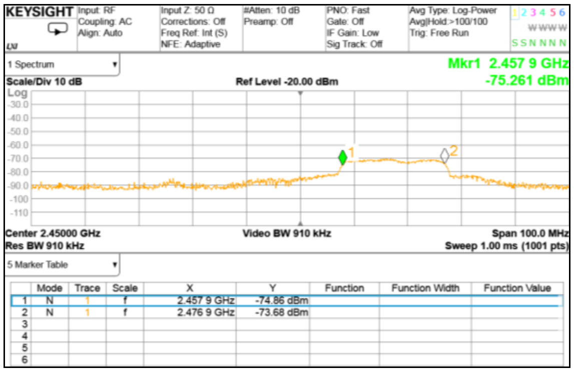


Input: RF
Coupling: AC
Align: Auto
Input Z: 50 Ω
Corrections: Off
Freq Ref: Int (S)
NFE: Adaptive
Atten: 10 dB
Preamp: Off
PNO: Fast
Gate: Off
IF Gain: Low
Sig Track: Off
Avg Type: Log-Power
Avg|Hold:>100/100
Trig: Free Run
Mkr2 2.476 3 GHz
-88.669 dBm
Scale/Div 10 dB
Ref Level 0.00 dBm
Center 2.45000 GHz
Res BW 910 kHz
Video BW 910 kHz
Span 100.0 MHz
Sweep 1.00 ms (1001 pts)

5 Marker Table

	Mode	Trace	Scale	X	Y	Function	Function Width	Function Value
1	N	1	f	2.452 8 GHz	-85.68 dBm			
2	N	1	f	2.476 3 GHz	-88.51 dBm			
3								
4								
5								
6								

(b) SJR/C F11 Pro



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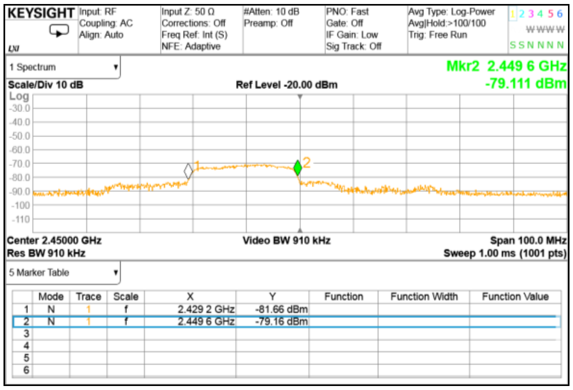
Coupling: AC
Align: Auto
Input Z: 50 Ω
Corrections: Off
Freq Ref: Int (S)
NFE: Adaptive
#Atten: 10 dB
Preamp: Off
PNO: Fast
Gate: Off
IF Gain: Low
Sig Track: Off
Avg Type: Log-Power
Avg|Hold:>100/100
Trig: Free Run
Mkr1 2.457 9 GHz
-75.261 dBm
Scale/Div 10 dB
Ref Level -20.00 dBm
Center 2.45000 GHz
Res BW 910 kHz
Video BW 910 kHz
Span 100.0 MHz
Sweep 1.00 ms (1001 pts)

5 Marker Table

	Mode	Trace	Scale	X	Y	Function	Function Width	Function Value
1	N	1	f	2.457 9 GHz	-74.86 dBm			
2	N	1	f	2.476 9 GHz	-73.68 dBm			
3								
4								
5								
6								

(c) DJI Mini 3 selects a center frequency at 2.4674 GHz.

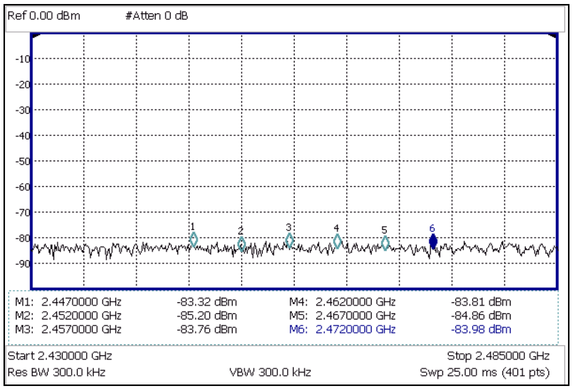

KEYSIGHT
Input: RF
Coupling: AC
Align: Auto
Input Z: 50 Ω
Corrections: Off
Freq Ref: Int (S)
NFE: Adaptive
#Atten: 10 dB
Preamp: Off
PNO: Fast
Gate: Off
IF Gain: Low
Sig Track: Off
Avg Type: Log-Power
Avg|Hold:>100/100
Trig: Free Run
1 Spectrum
Mkr2 2.449 6 GHz
-79.111 dBm
Scale/Div 10 dB
Ref Level -20.00 dBm
Center 2.45000 GHz
Res BW 910 kHz
Video BW 910 kHz
Span 100.0 MHz
Sweep 1.00 ms (1001 pts)
5 Marker Table

	Mode	Trace	Scale	X	Y	Function	Function Width	Function Value
1	N	1	f	2.429 2 GHz	-81.66 dBm			
2	N	1	f	2.449 6 GHz	-79.16 dBm			
3								
4								
5								
6								

(d) DJI Mini 3 selects a center frequency at 2.4394 GHz.

Fig. 7. The spectrum trace of the RF signal when the drone is in the "on" and "connected" modes.

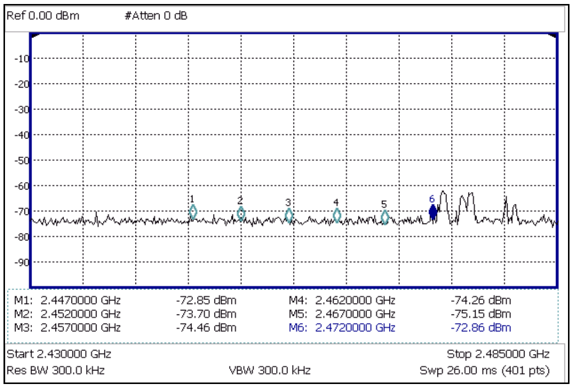
Both signals became clearly visible when traced with the max hold condition, occupying channels similarly to the earlier experiment, as shown in Fig. 8 (b) and 9 (b). In contrast, Fig. 10 shows that the signal strength of the DJI Mini 3 drone increased significantly during flight, reaching a maximum of -45.69 dBm and achieving a signal-to-noise ratio (SNR) of up to 40 dB. Table 2 summarizes all measurement results obtained from the experimental campaign.


Ref 0.00 dBm #Atten 0 dB

M1: 2.4470000 GHz -83.32 dBm
M2: 2.4520000 GHz -85.20 dBm
M3: 2.4570000 GHz -83.76 dBm
M4: 2.4620000 GHz -83.81 dBm
M5: 2.4670000 GHz -84.86 dBm
M6: 2.4720000 GHz -83.98 dBm

Start 2.430000 GHz
Stop 2.485000 GHz
Res BW 300.0 kHz
VBW 300.0 kHz
Swp 25.00 ms (401 pts)

(a) trace: CLK


Ref 0.00 dBm #Atten 0 dB

M1: 2.4470000 GHz -72.85 dBm
M2: 2.4520000 GHz -73.70 dBm
M3: 2.4570000 GHz -74.46 dBm
M4: 2.4620000 GHz -74.26 dBm
M5: 2.4670000 GHz -75.15 dBm
M6: 2.4720000 GHz -72.86 dBm

Start 2.430000 GHz
Stop 2.485000 GHz
Res BW 300.0 kHz
VBW 300.0 kHz
Swp 26.00 ms (401 pts)

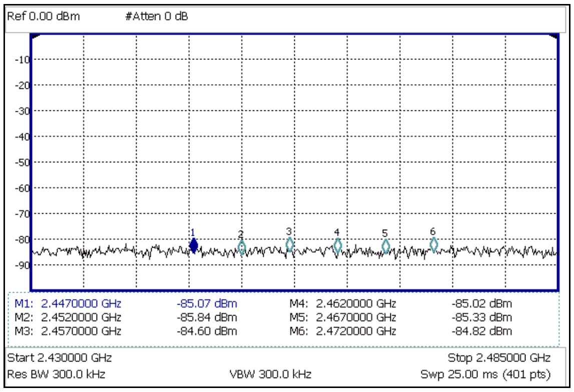
(b) trace: max hold

Fig. 8 The spectrum trace of the RF signal when the E88 drone was in flight.

V. CONCLUSIONS AND FUTURE WORK

In this study, the RF signal characteristics of three commercial drones —E88 pro, SJR/C F11 pro, and DJI Mini 3— were examined under both controlled conditions, such as in a shielded tent, and in outdoor settings. The measurement system, using signal analyzers as the receiver, captured and measured the drone signals in terms of channel allocation and signal strength.

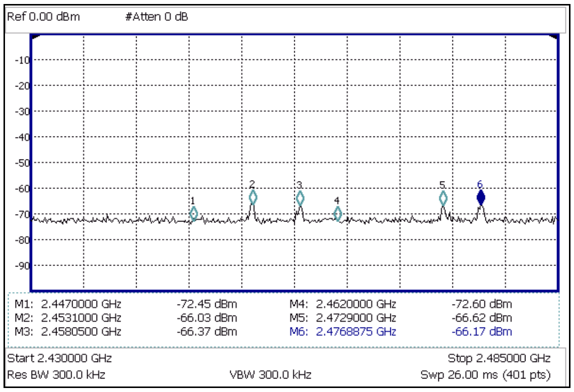
The E88 Pro and SJR/C F11 Pro drones primarily occupied the upper part of the Wi-Fi channel spectrum when emitting RF signals. Their weak signal strengths present challenges for detection in field environments, even with a high-precision signal analyzer. In contrast, the DJI Mini 3 showed significantly stronger signal strength, especially during flight, and used channels more flexibly.


Ref 0.00 dBm #Atten 0 dB

M1: 2.4470000 GHz -85.07 dBm
M2: 2.4520000 GHz -85.84 dBm
M3: 2.4570000 GHz -84.60 dBm
M4: 2.4620000 GHz -85.02 dBm
M5: 2.4670000 GHz -85.33 dBm
M6: 2.4720000 GHz -84.82 dBm

Start 2.430000 GHz
Stop 2.485000 GHz
Res BW 300.0 kHz
VBW 300.0 kHz
Swp 25.00 ms (401 pts)

(a) trace: CLK

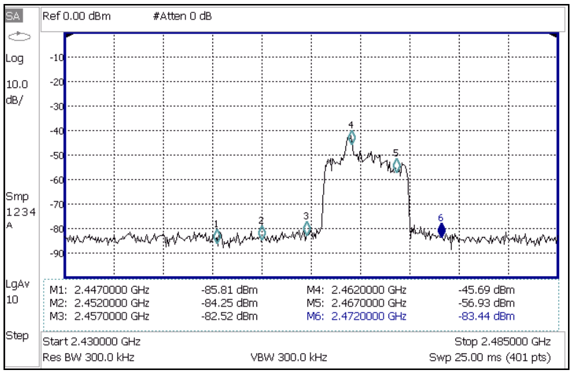

Ref 0.00 dBm #Atten 0 dB

M1: 2.4470000 GHz -72.45 dBm
M2: 2.4531000 GHz -66.03 dBm
M3: 2.4580500 GHz -66.37 dBm
M4: 2.4620000 GHz -72.60 dBm
M5: 2.4729000 GHz -66.62 dBm
M6: 2.4768875 GHz -66.17 dBm

Start 2.430000 GHz
Stop 2.485000 GHz
Res BW 300.0 kHz
VBW 300.0 kHz
Swp 26.00 ms (401 pts)

b) trace: max hold

Fig. 9 The spectrum trace of the RF signal when the SJR/C F11 drone was in flight.



```
Ref 0.00 dBm          #Atten 0 dB
M1:  2.4470000 GHz     -85.81 dBm     M4:  2.4620000 GHz     -45.69 dBm
M2:  2.4520000 GHz     -84.25 dBm     M5:  2.4670000 GHz     -56.93 dBm
M3:  2.4570000 GHz     -82.52 dBm     M6:  2.4720000 GHz     -83.44 dBm
Start 2.430000 GHz                                       Stop 2.485000 GHz
Res BW 300.0 kHz                VBW 300.0 kHz        Swp 25.00 ms (401 pts)
```

Fig. 10 The spectrum trace of the RF signal when the DJI Mini 3 drone was in flight.

TABLE II
RF SIGNAL CHARACTERISTICS OF THREE DRONES OBSERVED IN BOTH INDOOR AND OUTDOOR EXPERIMENTS.

Experiment	Parameter	E88 Pro	SJR/C F11 Pro	DJI Mini 3
Indoor experiment (“on” and “connected” modes)	Signal strength	-75.14 dBm	-75.68 dBm	-64.86 dBm
	SNR	< 10 dB	< 10 dB	20 dB
	Channel	upper part	upper part	switched on-the-fly
Outdoor experiment (“flying” mode)	Signal strength	-72.86 dBm	-66.17 dBm	-45.69 dBm
	SNR	< 2 dB	< 6 dB	40 dB
	Channel	upper part	upper part	switched on-the-fly

Future work will aim to use the results from this study to develop practical and affordable passive RF-based drone detection systems. This may involve using Software Defined Radio (SDR) technology or other portable devices.

ACKNOWLEDGMENT

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