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LOW-COST SDR SOLUTION WITH SWEEPING FOR ELECTROMAGNETIC SPECTRUM MONITORING

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Abstract: *The following article presents the design, implementation, and evaluation of a compact, inexpensive, and portable SDR-based sensor for monitoring the electromagnetic spectrum. Using SDR technology and a sweep-based measurement approach, the system enables configurable broadband scanning and optional IQ data acquisition for detailed signal analysis. The Raspberry Pi board serves as the processing unit, creating a lightweight platform suitable for integration with drones and remote operations. The study proposes an enhanced scanning algorithm that optimizes the balance between scanning speed, resolution, and the hardware constraints of affordable SDR devices. The experimental testing conducted in the laboratory and in real environments quantified the accuracy of frequency estimation, resolution, sensitivity, and scanning performance by demonstrating the usability and efficiency of the system in spectrum management, interference detection, and SIGINT-related applications.*
Keywords: *SDR, sweep spectrum monitoring, GNU Radio, drone-mounted system, SIGINT, low-cost sensor, spectrum management.*

1. INTRODUCTION

The electromagnetic spectrum is a valuable and limited resource that requires consistent regulation and monitoring to ensure its efficient and sustainable use. National spectrum management authorities use specialized reception equipment and services to analyze radio emissions, create usage databases, and inform regulatory and enforcement processes. Modern spectrum monitoring has evolved from manual instruments to flexible, autonomous RF sensor networks using software-defined architectures [1]. These systems enable large-scale, real-time data collection using COTS hardware [2-3].

SDR (Software-Defined Radio) technology has emerged as a transformative solution in the field of RF engineering [4]. Unlike conventional hardware-based radio systems, SDR uses affordable and flexible hardware and software to implement radio signal processing functions [5-6]. Affordable SDR devices, such as RTL-SDR or HackRF One, have democratized access to RF technology [7-8], allowing a wider community of users to research, experiment, and implement various applications specific to the field of radio communications [9].

Effective management of the electromagnetic spectrum is also vital for modern military operations, where rapid signal detection and analysis can determine mission success [10-11]. SDR systems, which combine real-time narrowband monitoring and wideband sweep scanning, offer a versatile solution to this challenge [12]. Real-time narrowband monitoring with high time resolution enables accurate, low-latency characterization of high-priority emitters to support Signals Intelligence (SIGINT) operations, detect and counter jamming, and enhance battlefield situational awareness. Complementing this, wideband scanning with good frequency resolution provides comprehensive spectrum monitoring, identifying unknown signals and assessing spectrum usage in complex environments.

Integrating these capabilities into SDR systems provides flexibility and rapid response,

allowing military operators to adapt to dynamic scenarios. Portable, cost-effective, and customizable, these systems support a variety of applications, from electronic warfare (electronic support) to spectrum management [13-14]. By leveraging SDR technology, armed forces are able to secure communications networks, counter emerging threats and maintain operational superiority in the electromagnetic domain [15-16].

Real-time spectrum monitoring is essential for rapidly detecting signals of interest, transient emissions and interference. However, real-time spectrum analyzers are often too expensive and require substantial data throughput and processing, which limits their use in many practical applications [17]. A cost-effective alternative is an SDR-based swept spectrum analyzer, which can sequentially tune and measure across frequency ranges that exceed the instantaneous bandwidth of low-cost SDR hardware. This approach facilitates wideband spectrum surveillance, congestion assessment and long-term frequency occupancy characterization, while preserving the flexibility and reconfigurability of software-defined implementations.

The main objective of the research is to implement a compact, low-cost, and portable sensor based on SDR technology for monitoring the electromagnetic spectrum. Designed for high adaptability and operational flexibility, the sensor provides wideband scanning and monitoring and can also capture and store raw in-phase and quadrature (IQ) data based on mission needs for subsequent, detailed SIGINT analysis. The SDR platform facilitates dynamic signal acquisition, while the Raspberry Pi development board serves as the processing unit, providing a lightweight, portable, and cost-effective solution. The minimalist design in terms of size and weight ensures seamless integration with drones without affecting flight performance or battery efficiency.

2. MATERIALS AND METHODS

The proposed spectrum analyzer concept is based on the use of SDR technology and spectrum scanning techniques to enable the monitoring of broadband waveforms, but with platforms limited to the acquisition of narrowband signals. To ensure flexibility, scalability, and accuracy in signal reception and processing, the architecture integrates hardware and software modules shown in the block diagram (Figure 1).

The hardware and software concept of the system are detailed below.

- Hardware subsystem design

The hardware system will use an SDR receiver connected to a receiving antenna. The RF signal captured over-the-air is transposed to the baseband and converted into complex I/Q digital samples. These samples are then transmitted to a processing station, where they serve as input for further digital processing and spectral analysis.

- Software subsystem design

A. Command and control software:

The SDR equipment will be managed through a specialized software application that controls essential parameters such as frequency tuning, gain, initial filtering and bandwidth. The software must be configured to facilitate real-time reception of IQ data and to execute automatic frequency sweeping. By controlled adjustment of the SDR's center frequency, this scanning process allows the system to cover a wider frequency range and process the spectrum in successive band segments.

B. Data processing and analysis software:

To process the collected data, IQ data will be transferred in parallel for each frequency scan, allowing simultaneous processing across multiple frequency bands. Each segment undergoes Fast Fourier Transform (FFT) calculations to extract spectral components. Spectrum calculated from all bands are then combined into a single spectrum, representing the entire frequency range covered during the scan.

This modular approach allows the system to efficiently handle large frequency ranges while maintaining good frequency resolution.

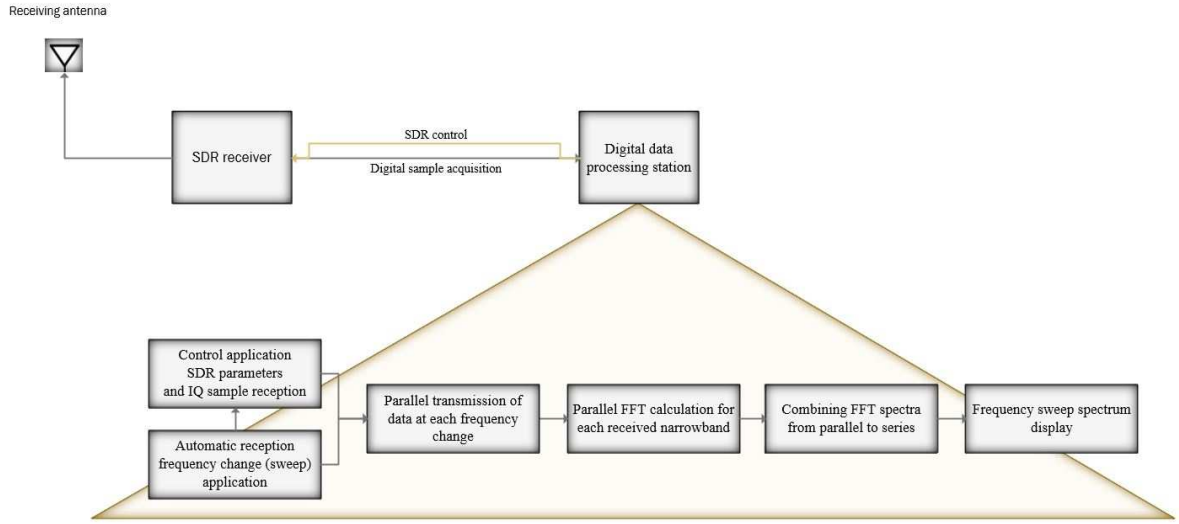


Fig. 1. Architecture of the implementation workflow for the SDR receiver system with sweep mode.

After establishing the design and architecture, the system was implemented and configured in practice under laboratory conditions. The following materials and tools were used for this purpose:

- Hardware implementation of the reception system

The hardware system comprises an ADALM-Pluto SDR platform, a Raspberry Pi Model 4 mini-computer, a BicoLOG30100X biconical antenna, and auxiliary devices, developing a portable spectrum monitoring platform for frequency scanning applications (Figure 2).

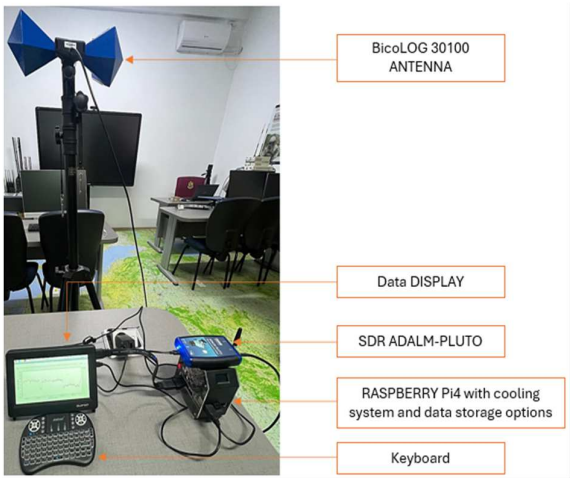


Fig. 2. Reception system hardware configuration.

ADALM-Pluto performs as an analog-to-digital signal reception and conversion unit, capable of receiving RF signals over a wide frequency range from 325 MHz to 3.8 GHz (extendable to 70 MHz with firmware modifications). It is linked to the Raspberry Pi, which serves as the processing unit, featuring a high-performance quad-core processor and GPIO interfaces for additional hardware integration. The antenna allows signal reception in the 30-1000 MHz frequency range, while the cooling system, consisting of heat sinks and fans, ensures stable operation of the Raspberry Pi under overload conditions. An external power supply and shielded USB cables ensure stable, interference-free connections. In addition, external storage options allow large data sets to be recorded for extended monitoring tasks.

- Software implementation of the reception system

For the software subsystem, the GNU Radio programming environment was selected as the primary tool due to its numerous advantages. It offers a library of pre-built, open-source signal processing blocks and programming flexibility, making it the ideal choice for developing complex systems based on SDR technology. GNU Radio uses a modular, graph-based approach to signal processing that simplifies the creation of prototypes and custom digital processing workflows.

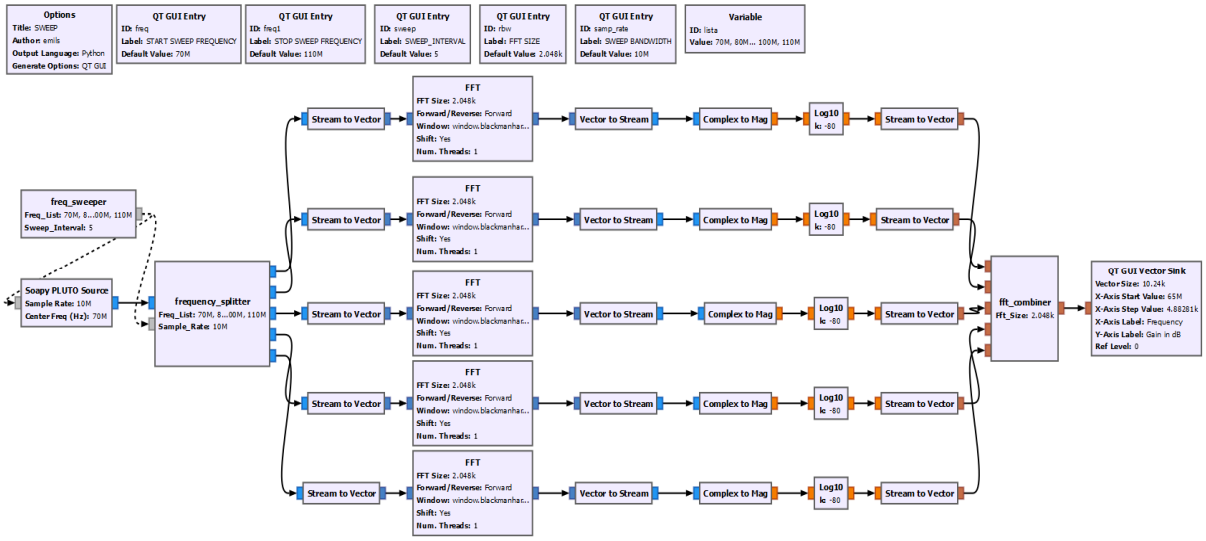


Fig. 3. Application developed for spectrum monitoring with sweeping.

The software flowgraph is initiated by the "Soapy Pluto" source, which acts as an interface for the hardware. At this stage, key parameters such as frequency, sampling rate, and gain are configured for the SDR device to operate within the specified range and conditions. A custom Python block called "frequency_sweeper" was developed to extend the frequency range beyond the instantaneous acquisition bandwidth of the SDR. This block, developed specifically for this application, is not part of the default GNU Radio library. The block systematically adjusts the SDR tuning over a specified frequency range in incremental time steps. The sweeping process is controlled by parameters such as start frequency, stop frequency, and sweep interval, thus allowing data acquisition over a wide spectral range that exceeds the platform's default bandwidth (20 MHz in real time). This custom block enables dynamic control of the frequency sweep process, which is essential for broadband spectrum analysis.

Once the IQ data has been generated by the sweep mechanism, another custom python implementation named "frequency_splitter" block divides the received data into several parallel streams, each stream corresponding to a specific sub-band within the received frequency range. The parallelization process significantly improves system efficiency and allows simultaneous analysis of multiple sub-bands without compromising resolution.

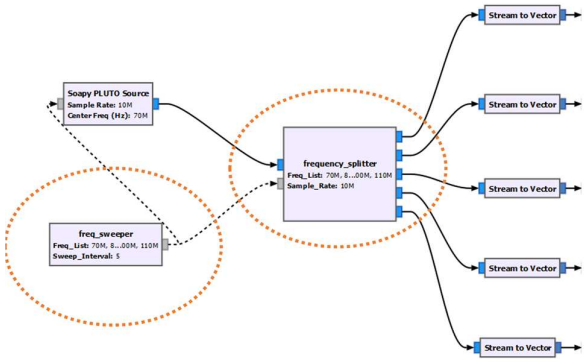


Fig. 4. Initial phase of the application: development of the two custom blocks.

Each split stream undergoes the same signal processing steps to extract spectral characteristics. The process begins with the "Stream to Vector" block, which converts the continuous IQ stream into discrete vectors (Figure 4). These vectors are then processed by the "FFT" blocks, which transform the IQ samples from the time domain to the frequency domain. Once the frequency domain data is obtained, it is converted back into a continuous stream using the "Vector to Stream" block. The stream is then passed through the "Complex to Mag" block, which calculates the magnitude of the spectral components. Finally, the magnitudes are converted to dB using the "Log10" block, facilitating the interpretation of spectral data (Figure 5).

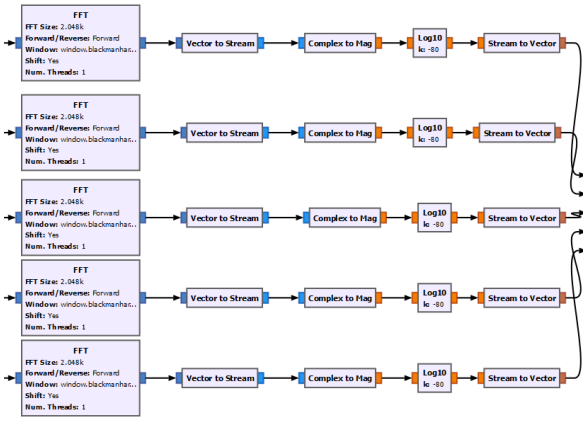


Fig. 5. Second phase of parallel processing of IQ streams.

The data resulting from all simultaneous processes is fed into the third custom Python block called "fft_combiner," which is also not included in the GNU Radio library. This element integrates the spectral data from individual sub-bands into a single spectrum, presenting a complete spectrum of the scanned frequency range. Proper handling of the overlapping regions between sub-bands ensures the continuity and accuracy of the final spectrum, making this step essential for combining the results of parallel processing into a coherent result. The final spectrum is then displayed using the "QT GUI Vector Sink" block, whose representation is similar to that of a sweep spectrum analyzer: the horizontal axis represents the frequency, and the vertical axis represents the power levels in dBm, providing an intuitive visualization of the spectral characteristics of the signal.

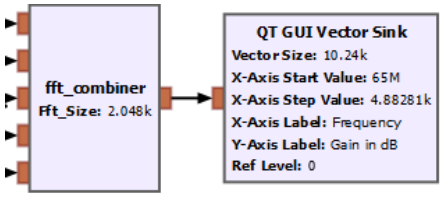


Fig. 6. The final stage of integrating parallel flows into a single spectrum.

3. RESULTS AND DISCUSSIONS

The process of designing and implementing the system involves evaluating the functionality of the application, assessing its performance under real conditions, and determining the minimum scanning interval for which monitoring occurs without errors. The following section details these system evaluations:

➢ Initial testing and visualization of application functionality

According to Figure 7, the graphical interface represents the initial phase of testing and validating the functionality of the GNU Radio-based spectral analysis application. The interface displays the results of spectrum scanning and spectral analysis over an extended frequency range. Key parameters, such as the scan range, scan bandwidth, FFT size, and the start and stop frequencies, are shown at the bottom of the interface.

As can be seen in Figure 7, the frequency spectrum is divided into five distinct segments, labeled from "Sweep 1" to "Sweep 5," representing the successive band scans performed by the application. Each band covers a specific portion of the sweep range, defined by the "START FREQUENCY" (70 MHz), the bandwidth allocated to each sweep (10 MHz), and the "STOP FREQUENCY" (110 MHz). The color-coded segments: blue, red, green, etc. indicate the results of the spectral analysis for each scan, ensuring a clear distinction between adjacent frequency ranges. The sweep bandwidth is 10 MHz, while the FFT size is set to 2048. These parameters determine the bandwidth over which the sweep is performed and, respectively, the frequency resolution after FFT processing. These settings provide a balance between detailed spectral analysis and processing efficiency.

This initial visualization confirms that the application is functioning as intended, accurately performing frequency scanning and spectral analysis within the defined range. The spectrum segmentation illustrates the functionality of custom blocks, including the frequency scanner and sub-band integrator, in capturing and integrating data from multiple frequency bands into a unified visualization. Future efforts will center on refining parameters and enhancing transitions between adjacent sweeps to optimize performance.

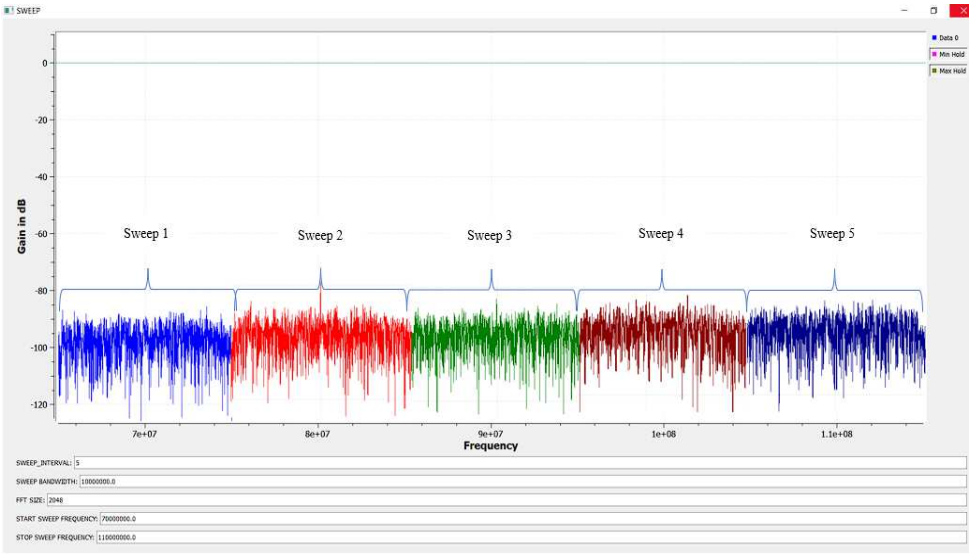


Fig. 7. The result of running the developed application.

➢ Testing the system under real conditions

The graphical interface in Figure 8 illustrates the results of a real test performed with the reception system operating in "sweep" mode. The spectrum analysis covers the frequency range from 65 MHz to 115 MHz, divided into 10 MHz sub-bands. To ensure complete coverage, the system performs a 1 second scan for each sub-band. During this interval, all data from the segments is displayed continuously until the sweep cycle returns to the sub-band and refresh it. The FFT size of 8192 ensures high spectral resolution, facilitating detailed visualization of the acquired signals. During the test, notable signals are identified in the 87.5 MHz – 108 MHz range, which indicates the presence of signals from FM radio stations active in the VHF band.

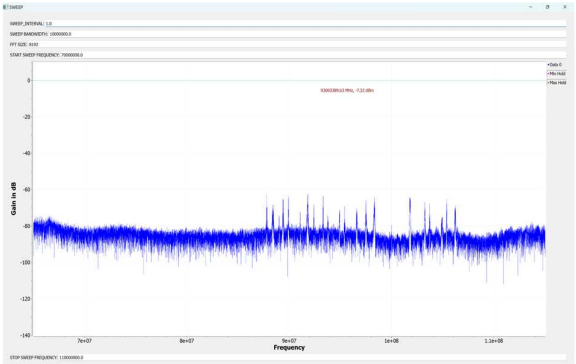


Fig. 8. Graphical interface resulting from spectrum scanning under real conditions.

Therefore, the scanning mechanism divides the 50 MHz frequency range into 5 segments, allocating 1 second for each 10 MHz portion, and for a signal to be detected 100%, it must remain active for at least 5 seconds. Consequently, short-duration signals may not be detected if they do not coincide with the sub-band scanned at that moment. While this configuration is effective at detecting continuous or long-duration signals, it may fail to detect short-duration signals, such as frequency-hopping signals.

The experimental test validates the system's ability to accurately detect, process, and display RF signals with high spectral resolution. The system demonstrates effectiveness in monitoring VHF signals and performing spectrum occupancy analysis. Application improvements could include reducing the sweep interval or narrowing the frequency bands to improve detection of short-duration signals. In addition, the system's performance for specific use cases can be further improved by expanding the frequency range or fine-tuning parameters.

A second test was performed to evaluate the system's ability to identify signals emitted under controlled laboratory conditions. (Figure 9). In addition to monitoring the FM channels present in the spectrum, a VHF transmitter was configured to emit a signal at a frequency of 70 MHz within the scanned range. This test aimed to validate the system's ability to detect and display the controlled transmission within the spectrum.

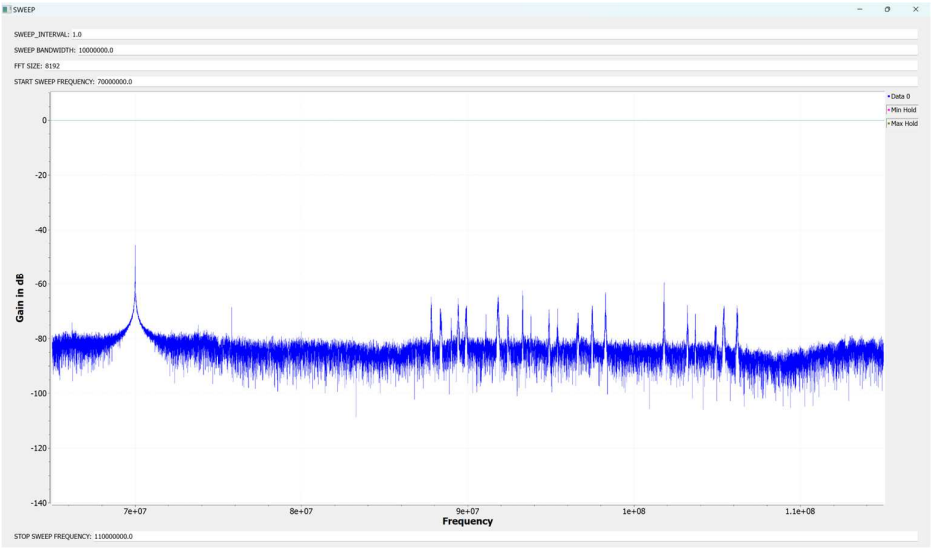


Fig. 9. Display of the sweep spectrum under real conditions.

The results confirmed that the system could successfully to identify VHF transmissions. However, depending on the sub-band monitored during the scan, transmissions active for less than five seconds were often undetected. This aligns with the system's inherent limitations, whereby signal detection depends on the sweep interval and the analyzed sub-band at the time of transmission.

➢ Testing the minimum sweep interval

The next experimental test was performed under laboratory conditions using a signal generator with sweeping capabilities to determine the minimum sweep time achievable without errors. The main objective was to evaluate the system's ability to handle fast frequency sweeps while maintaining accurate data processing and visualization. For consistency, the sweep range was set between 70 MHz and 110 MHz, as in previous tests.

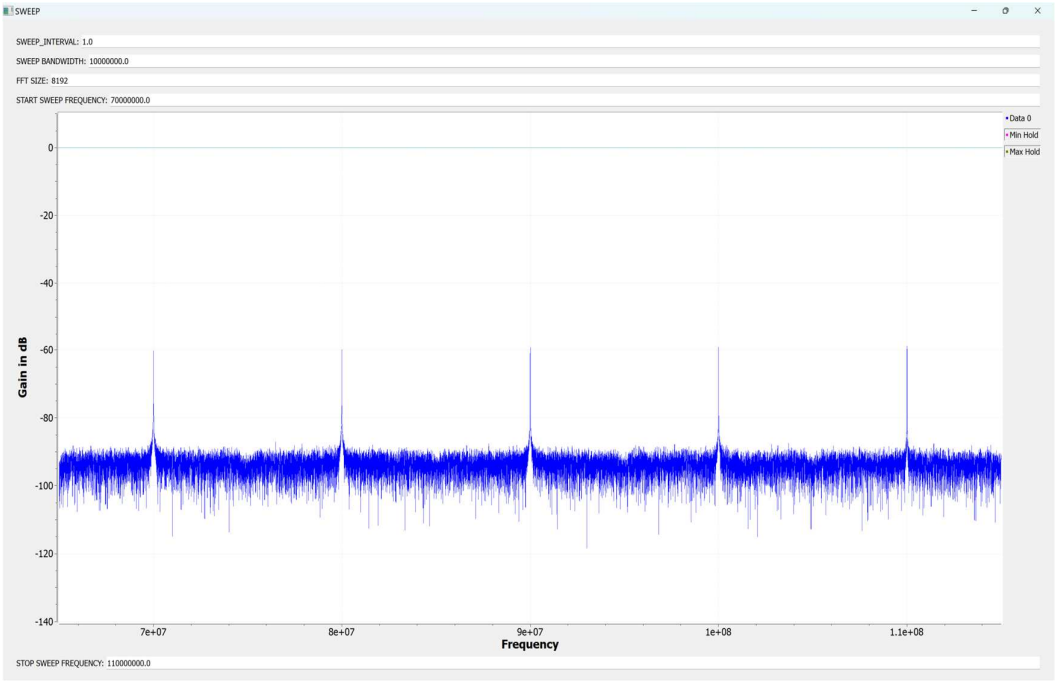


Fig. 10. Result of the application for a sweep time of 1s.

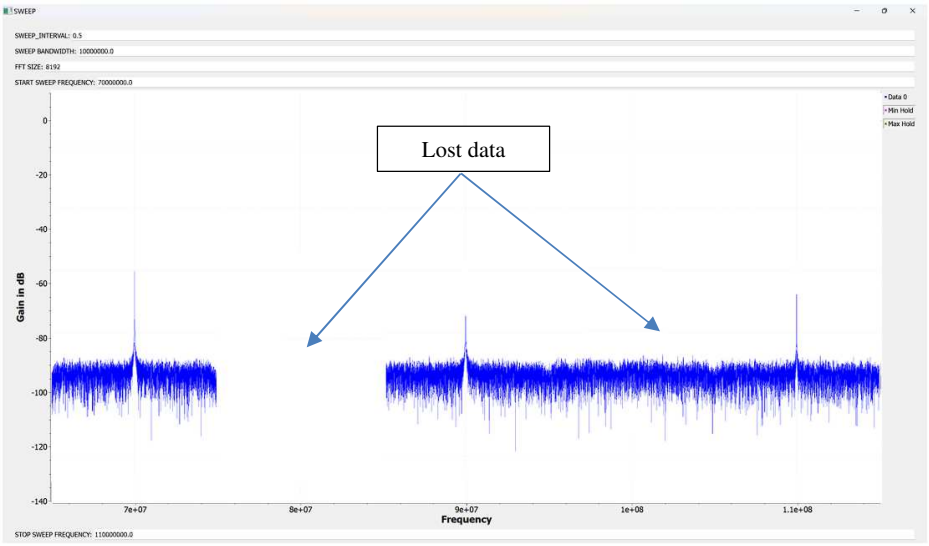


Fig. 11. Result of the application for a sweep time of 0.5 s.

As can be seen in Figure 10, the system only works correctly when the sweep interval is set to 1 second or more. Reducing the interval to less than 1 second leads to significant data loss, resulting in errors in spectral visualization (Figure 11). This limitation restricts the system's ability to accurately detect rapidly changing signals or transient spectral events that occur within short time intervals. Total data loss for sweep intervals of less than 0.5 seconds is due to timing differences introduced during each retuning step. It is important to note that, when the ADALM-Pluto LO is retuned, the RF chain requires significant settling time. This time is necessary to ensure the correct operation of the PLL lock and stabilize the analogue front end. During this period, the IQ stream may pause, resulting in the initial samples being invalidated and discarded. For short-term dwell times, this transient can consume the entire step. This results in zero valid FFT frames for that frequency segment. Consequently, there will be an empty section in the sweep plot.

Furthermore, frequent retunes trigger a buffer flush in the libiio/USB streaming path. This can result in entire IQ blocks being dropped if the subsequent retune command is not executed before the next buffer is filled. In conclusion, on the Raspberry Pi host, real-time FFT processing and GUI updates create backpressure. When the processing chain cannot sustain the required throughput, the sweep generator advances the frequency steps before sufficient IQ data has been processed. This results in complete gaps. These effects make the system's behavior clearer at intervals of at least one second, but result in some sweep segments being absent at intervals of less than 0.5 seconds.

Based on testing, the ADALM-Pluto and Raspberry Pi 4-based sweep spectrum analyzer faces several technical limitations. The system scans a 50 MHz bandwidth in 5 steps of 10 MHz, with each step taking 1 second, meaning that a full scan takes 5 seconds. This approach results in the loss of short-duration signals (less than five seconds) if they occur while the receiver is scanning another frequency band. This results in delayed spectrum updates and challenges in identifying rapidly changing signals. Additionally, buffering issues and a lack of FFT overlap make capturing short-duration signals more difficult. While FFT optimizations can improve system performance, real-time monitoring requires an SDR with a faster connection and a more powerful processor, such as a Raspberry Pi 5, Jetson Nano, or x86 mini PC, to efficiently handle the high-speed data stream.

The SDR-based reception system can be used as a stationary sensor (Figure 2), but its compact design and small, lightweight antennas also make it ideal for integration with unmanned

aerial vehicles (Figure 12). When mounted on a drone, the sensor can use its mobility and altitude to extend line-of-sight coverage, improving access to remote, obstructed, or otherwise inaccessible environments. This enables rapid, on-demand spectrum observation. This capability supports various applications, including monitoring telecommunications signals, detecting and localizing interference, supporting search and rescue operations, managing radio-frequency spectrum, and conducting electronic warfare missions, such as electronic support measures and situational awareness.

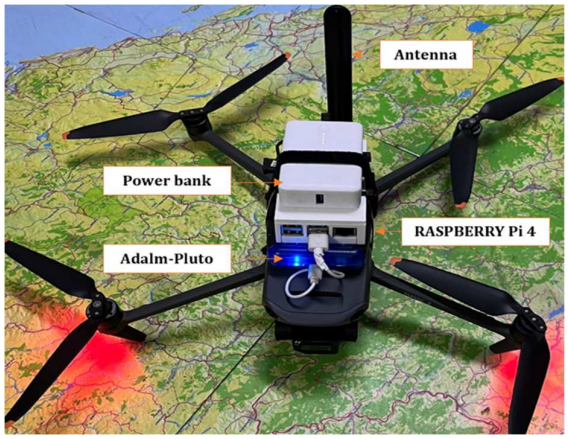


Fig. 12. Sweep monitoring system mounted on the DJI Mavic 3 drone.

4. CONCLUSIONS

The designed, implemented, and tested system proved to be stable and functional when operating with a sweep interval of 1 second or more, making it suitable for applications requiring moderate speed spectral sweeps. However, achieving shorter sweep intervals requires improvements such as upgrading the processing hardware, optimizing the software, or using an SDR with higher performance capabilities. These limitations should be considered when planning to use this configuration for high-speed spectral analysis tasks, particularly those requiring real-time signal detection.

Despite the above-mentioned limitations, this innovative approach enables low-cost spectral analysis. The entire system costs less than €500 (not including the antenna), though the cost may vary depending on the type of antenna used. The system can perform real-time narrowband analysis with a maximum bandwidth of 20 MHz, or it can operate in sweep mode across the equipment's entire frequency range, with sweep time directly proportional to the analyzed bandwidth. These capabilities bring the system's performance close to that of conventional scanning spectrum analyzers, which are significantly more expensive. This demonstrates the value and potential of the developed system in providing advanced spectral analysis at substantially reduced costs.

While there is considerable potential for enhancement in both software and hardware, the current implementation demonstrates the feasibility of achieving efficient and versatile spectral analysis using a low-cost configuration. This renders the system an attractive solution for educational, experimental, and budget-constrained applications where affordability and functionality are paramount.

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Soluție SDR de preț redus cu baleiere pentru monitorizarea Spectrului electromagnetic

Rezumat: Acest articol prezintă proiectarea, implementarea și evaluarea unui senzor compact, ieftin și portabil, bazat pe SDR, pentru monitorizarea spectrului electromagnetic. Folosind tehnologia SDR și o abordare de măsurare bazată pe baleiere, sistemul permite scanarea configurabilă de bandă largă și achiziția opțională de date IQ pentru analiza detaliată a semnalului. Placa Raspberry Pi servește drept unitate de procesare, creând o platformă ușoară, potrivită pentru integrarea cu drone și operațiuni la distanță. Studiul dezvoltă un algoritm optimizat de scanare care echilibrează viteza de scanare, rezoluția și limitările hardware ale dispozitivelor SDR accesibile. Campania experimentală desfășurată în laborator și în medii reale a cuantificat acuratețea estimării frecvenței, rezoluția, sensibilitatea și performanța de scanare, demonstrând utilitatea și eficiența sistemului în managementul spectrului, detectarea interferențelor și în aplicații asociate războiului electronic.

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