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Enhancing monitoring systems with interference-handling radio frequency direction finding: BMKG C-Band weather radar in West Kalimantan Indonesia case study

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ABSTRACT

This study investigates the effectiveness of the interference-handling radio frequency direction finding (RFDF) monitoring system in detecting and localizing interference sources near the BMKG C-Band weather radar in West Kalimantan, Indonesia. We conducted field tests varying interference transmitter power levels (0-30 dBm) and distances (100, 500, and 1,000 m) from the radar. Results indicate the RFDF system's robust performance, consistently detecting interference within 5-20 minutes and accurately localizing sources with minimal deviation from actual positions. The findings confirm the system's superiority over traditional manual methods, offering a reliable solution for interference management in weather radar operations. However, limitations include controlled test conditions and a need for further exploration of the system's efficacy in diverse environmental settings. This research contributes to improving radar reliability and lays the groundwork for future studies to refine RFDF technology for broader meteorological applications.

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1. INTRODUCTION

Weather radar systems are indispensable tools in modern meteorology, facilitating the observation and prediction of atmospheric conditions crucial for various societal and economic activities [1], [2]. In regions characterized by dynamic weather patterns and susceptibility to severe weather events, such as West Kalimantan, Indonesia, the effective operation of weather radar is paramount. However, the reliability and accuracy of weather radar data can be compromised by interference originating from a myriad of sources, including radio local area networks (RLANs) and other electronic devices operating within the radar's frequency bands [3], [4]. Interference distorts radar signals and undermines the integrity of weather data, posing significant challenges for meteorological agencies such as the Badan Meteorologi, Klimatologi, dan Geofisika (BMKG).

Traditionally, interference mitigation in radar systems has relied on manual inspection and periodic checks by trained technicians. While these methods may suffice in specific scenarios, they are often time-consuming, labor-intensive, and may not effectively address complex interference scenarios [5], [6]. Recent advancements have seen a growing interest in developing and implementing advanced radio frequency (RF) monitoring systems for proactive interference management [7]–[12]. These systems leverage technology to precisely localize and identify interference sources in real-time, enabling rapid response and targeted mitigation measures. However, there is a notable gap in research focusing on the implementation and effectiveness of these RF direction-finding (RFDF) monitoring systems. This research seeks to address this gap by investigating the implementation of an RFDF monitoring system tailored explicitly for the BMKG C-Band weather radar in West Kalimantan. The primary objective of this study is to evaluate the performance of the RFDF monitoring system in detecting and mitigating interference at the BMKG C-Band weather radar facility. By comprehensively assessing the system's effectiveness in real-world operational conditions, this study aims to contribute valuable insights into developing robust interference management strategies for weather radar operations in challenging environments.

Our research will explore areas previously underexplored by focusing on the practical application and efficacy of RFDF technology in West Kalimantan, Indonesia. This study's findings are expected to evaluate the implementation of RFDF in assisting the tasks of the frequency spectrum monitoring center class 2 Pontianak in addressing interference issues. Previously, traditional methods were used, which required a long time to handle interference or disruptions. By integrating RFDF technology, we aim to accelerate the interference handling process, enhancing the reliability, accuracy, and operational efficiency of weather radar systems in West Kalimantan and similar regions worldwide. The monitoring system's design is built upon three central components: the main control unit (MCU), station slave (SS), and mobile direct finding (MDF). The MCU oversees and coordinates all SS units, which are strategically positioned across the BMKG Radar area. Each SS unit comprises a Raspberry Pi 4, a software defined radio (SDR), an antenna rotator, and a direction finder antenna, functioning as dedicated stations that can identify 2.4 and 5 GHz WLAN transmitters. The MDF acts as the ultimate locator, offering precise coordinates to pinpoint the exact locations of interference sources within the radar's operational domain. Subsequent sections will detail the system's design, implementation, performance evaluation, and the broader implications of our findings.

2. LITERATURE REVIEW

Interference mitigation in radar systems, especially in weather monitoring, has been a focus of recent research. Effective radar operation is crucial for accurate weather forecasting, but interference, such as from radio local area networks (RLANs), can degrade performance and reliability. This review explores research on interference handling techniques and implementing RFDF systems to address these challenges in radar facilities.

Numerous studies have demonstrated the negative impact of interference on radar systems and emphasized the need for effective mitigation strategies. For example, Umehira [13] developed a multi-channel adaptive filter to suppress sea clutter in passive radar sensors while preserving target signals, overcoming the limitations of single-channel high-pass filters [14], [15]. Alland *et al.* [16] analyzed interference in automotive radar systems, highlighting the importance of the interference-to-noise ratio (INR) and reviewing existing mitigation techniques. Lofù *et al.* [17] proposed URANUS, a framework using RF-based data and neural networks for real-time unmanned air vehicles (UAV) detection in restricted airspaces, achieving high accuracy in identification and tracking tasks. Other studies, such as [18], have advanced the modernization of radio direction finders (RDFs) for navigation and surveillance, building on earlier work in radio source identification and bearing determination [19]–[22].

Additionally, Wang *et al.* [23] introduced a novel single-channel blind source separation (SBSS) algorithm for radar systems, improving interference suppression by integrating variational mode decomposition (VMD) and sparse component analysis (SCA). Authors in [24]–[26] proposed a computationally efficient compressive sensing framework for automotive radar interference mitigation, and Rock *et al.* [27] explored quantization techniques to address resource constraints in CNN-based radar signal processing, considering the limitations of radar sensor hardware [28], [29]. Further, Guo *et al.* [30] developed an interference suppression method for SAR using short-time fractional Fourier transform (STFrFT), focusing on the adaptive gain coefficient for interference suppression. Despite these advancements, there remains a gap in implementing RFDF systems specifically for weather radar facilities in interference-prone regions like Kalimantan Barat, Indonesia. This study aims to fill this gap by evaluating the effectiveness of an RFDF system tailored for the BMKG C-Band weather radar in Kalimantan Barat, contributing to best practices for enhancing radar reliability in challenging environments.

3. METHOD

3.1. Manual direction-finding monitoring system

In the manual operation of a direction-finding antenna system as shown in Figure 1(a), the user takes direct control to search for the signal's direction. The process involves physically adjusting the antenna's position and orientation to locate the strongest signal. Typically, the operator employs additional tools such as a compass and a map to ascertain the signal source's location. This hands-on approach requires the user to be proficient in maneuvering the antenna and interpreting the received signal strength to pinpoint the source accurately.

Manual operation presents challenges primarily due to the operator's skill and experience. The accuracy of signal detection depends on the user's ability to interpret data and adjust the antenna, making human error a significant factor in potential inaccuracies. This method is time-consuming, requiring continuous manual adjustments and checks, which slows down the process and reduces reliability compared to automated systems. In contrast, the MCU-controlled direction-finding antenna system, as shown in Figure 1(b), operates automatically, minimizing human intervention. The MCU autonomously processes data, adjusts the antenna, and utilizes algorithms and sensors to accurately determine the signal's direction. This automation enhances speed and precision, reducing human error and improving reliability. The system can integrate additional sensors like global positioning system (GPS) for even greater accuracy. Automation through an MCU significantly increases efficiency, enabling continuous scanning, faster identification, and real-time adjustments. Additionally, an MCU can manage multiple antennas simultaneously, allowing for comprehensive monitoring and control over larger areas.

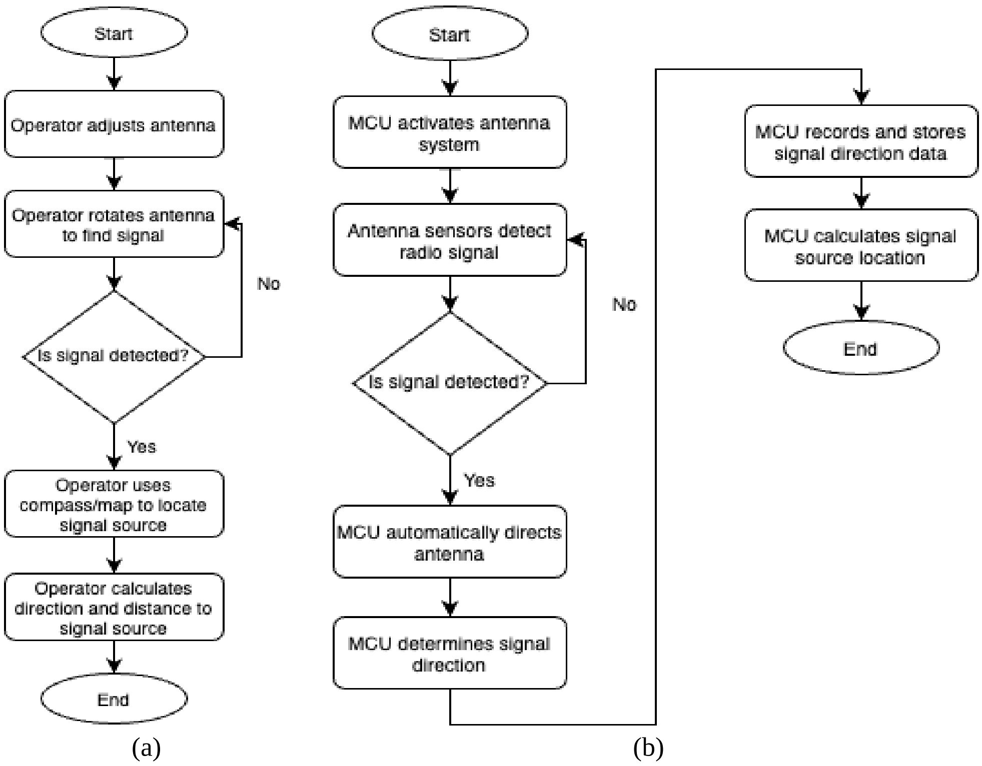


Figure 1. Comparison of monitoring systems: (a) manual direction-finding monitoring system and (b) proposed enhanced monitoring system design

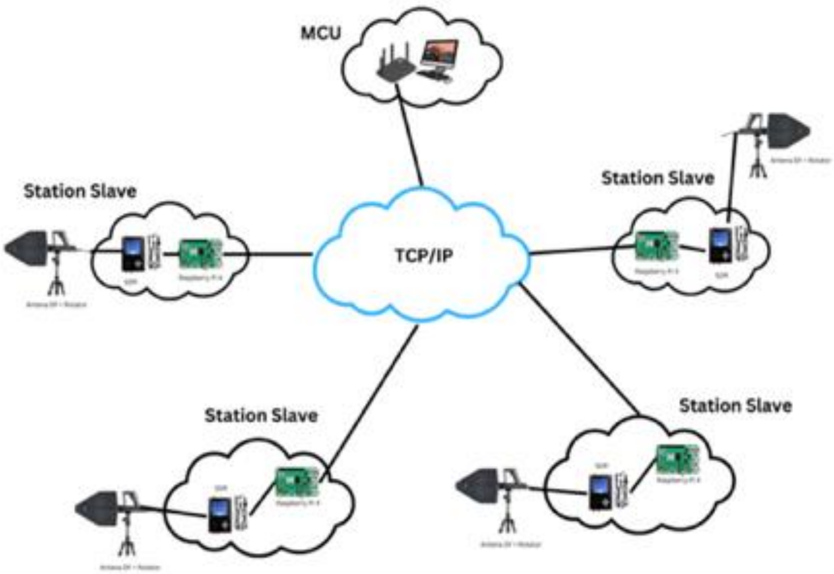
3.2. Proposed enhanced monitoring system design

This monitoring system is designed to identify users operating at both 2.4 and 5 GHz frequencies. The device provides a more comprehensive graphical user interface (GUI) for presenting information derived from received signals. Monitoring results from the system include data such as radio frequency, channel number, signal strength (level signal), SSID, and MAC ADDRESS. This identification data facilitates field analysis. In its application, the system is divided into three core components: the main control unit (MCU), SS, and mobile handling unit (MHU). The illustration of each unit of the system is depicted in Figure 2(a).

The proposed system architecture is presented in Figure 2(b). It consists of MCU and SS as the remote station. The MCU is positioned at the central control center within the BMKG Pontianak facility. This central hub is the command center responsible for supervising and coordinating all SS units dispersed across the region. The MCU comprises a powerful personal computer (PC) equipped to monitor and remotely control each SS unit, ensuring efficient and centralized management of the entire monitoring system. Its primary features include the ability to conduct monitoring through remote control operations and investigate potential interference issues. The connection between MCU and SS is established using TCP/IP as an intranet or virtual private network (VPN), which easily maintains security and transmission speed.

Numerous station slave units (SS) have been strategically deployed around BMKG Pontianak to ensure comprehensive coverage within the radar's operational radius. These SS units are equipped with essential components like the Raspberry Pi 4 Model B, software defined radio (SDR), antenna direction finder (ADF), and an antenna rotator. The Raspberry Pi runs RF scanning applications, while the SDR monitors the 2.4 and 5 GHz frequency bands for potential interference, providing a continuous, real-time overview of the RF spectrum. The ADF determines the direction of radio signals, enabling precise tracking and identification of signal sources. The antenna rotator allows the antenna to be oriented towards different signal sources, enhancing the accuracy of signal tracking. Together, the ADF and antenna rotator enable efficient real-time monitoring and identification of radio signal sources, ensuring smooth and precise frequency monitoring operations.

(a)



(b)

Figure 2. Layout and architecture of the monitoring system: (a) location of each system's part around BMKG Pontianak and (b) architecture of the monitoring system

3.2. Implementation of proposed enhanced monitoring system

In the implementation scenario, the transmitter will be configured to transmit frequencies that may or may not comply with the class licenses in Indonesia. Subsequently, the monitoring system will receive and identify these transmissions. The illustration is shown in Figure 3.

The flowchart illustrating the monitoring system implementation is depicted in Figure 4. The initial step involves utilizing remote desktop access to connect to the station slave. At the station slave, we employ the Raspberry Pi 4 Model B as a central component to run the application for scanning RF within a predetermined location. The Raspberry Pi 4 Model B plays a crucial role in operating our frequency monitoring system.

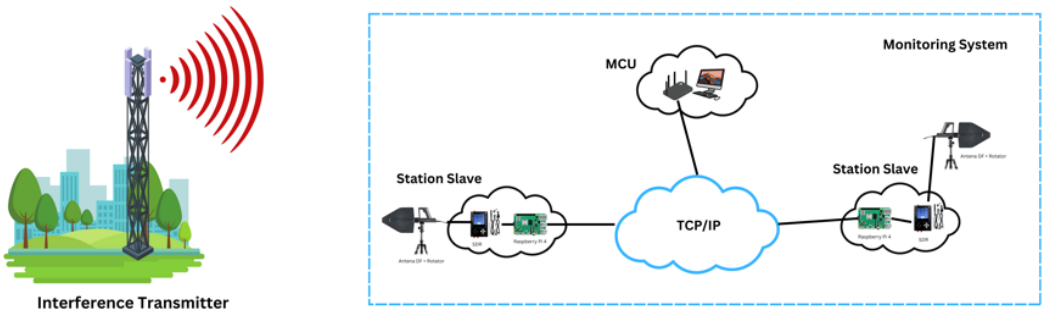


Figure 3. Implementation configuration

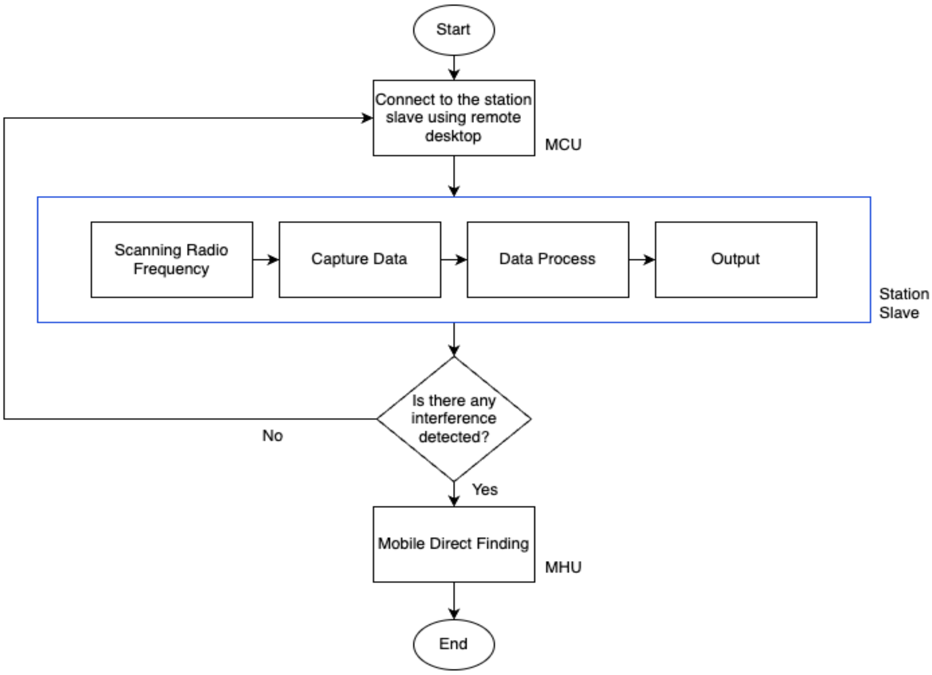
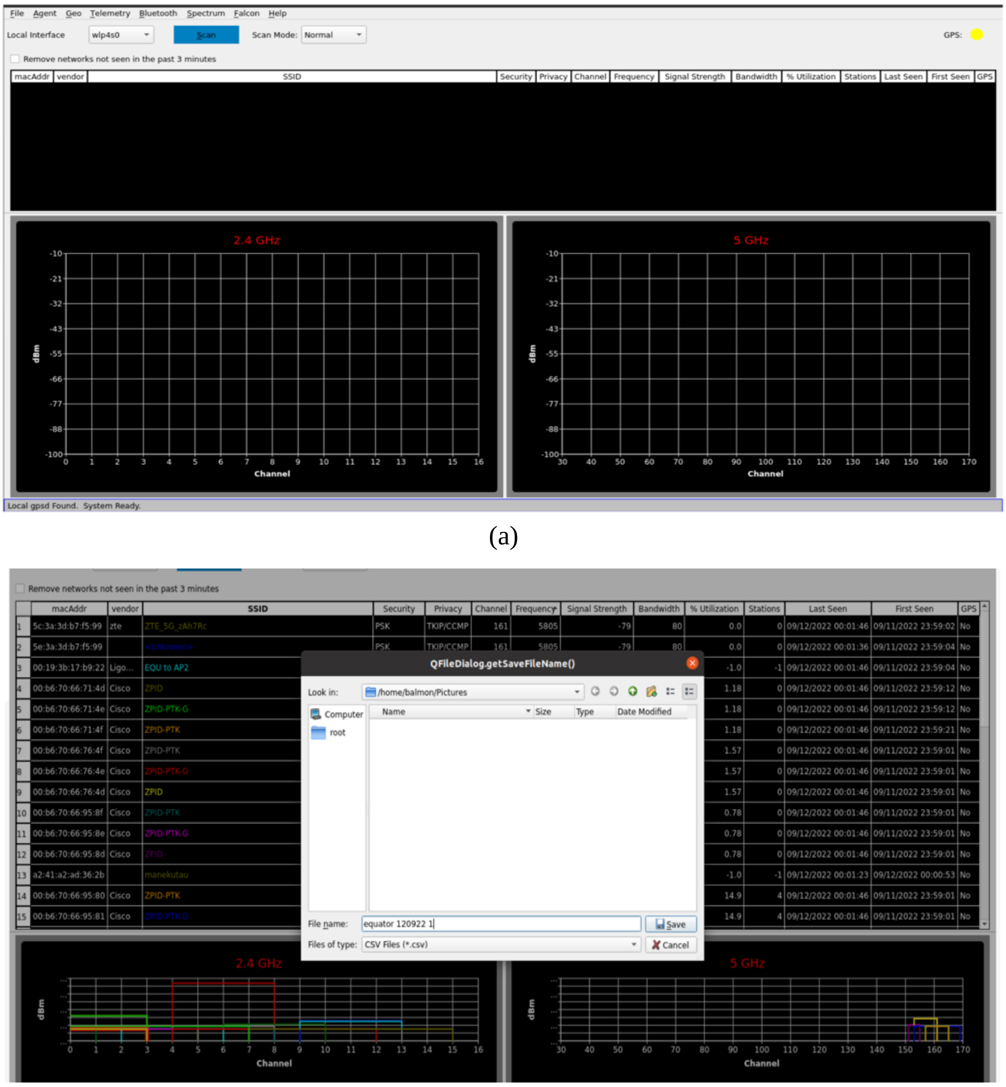


Figure 4. Implementation configuration

Various components are collaborating with the Raspberry Pi 4 Model B, including the SDR, antenna direction finder (DF), and rotator. SDR technology utilizes programmable hardware to build a software-based radio, serving as a critical element in scanning and monitoring RF frequencies. The Antenna DF acts as a directional indicator for the transmission source, while the rotator allows for flexible adjustment of the antenna's orientation to suit the scanning requirements. To access the station slave and control its operations, we rely on the remote desktop app Revance Therapeutics, Inc. Common Stock (RVNC), integrated with a virtual private network (VPN) connection. It ensures that each station slave can be accessed and operated remotely. The initial program interface shown in Figure 5(a).

Within each station slave, the DF Station utilizes a multi-triangulation method to determine the antenna direction for scanning the source of RF signals. This method enables us to precisely estimate the direction from which the radio signal originates, a key focus in our frequency monitoring. In the station slave, an RF scanning application is executed to commence the antenna orientation process. This application scans RF frequencies, particularly in the C Band range, from 5,600 to 5,650 MHz. RLAN devices connected to internet service providers (ISPs) or RT/RW Net networks primarily use this frequency range.

During the scanning process, the application collects data, including critical information such as MAC addresses, vendor details, frequency channels, SSIDs, and signal levels. This information is pivotal in the identification and monitoring of RF signal sources. Running this scanning application on the station slave ensures efficient data collection for radio frequency spectrum monitoring and RLAN user identification within ISP and RT/RW Net networks. The captured data shown in Figure 5(b). The data gathered from scanning is meticulously stored in a comma-separated values (CSV) file format to facilitate in-depth and structured analysis. The CSV file format shown in Figure 6 is chosen due to its tabular data organization, with clear columns separated by commas, allowing easy access and processing using standard data analysis software. Each entry in the CSV file encompasses all the collected information during the scanning, including MAC addresses, vendor details, frequency channels, SSIDs, and signal levels. This structured data storage supports compatibility with various devices and standard data analysis software, establishing a robust foundation for further analysis.



(a)

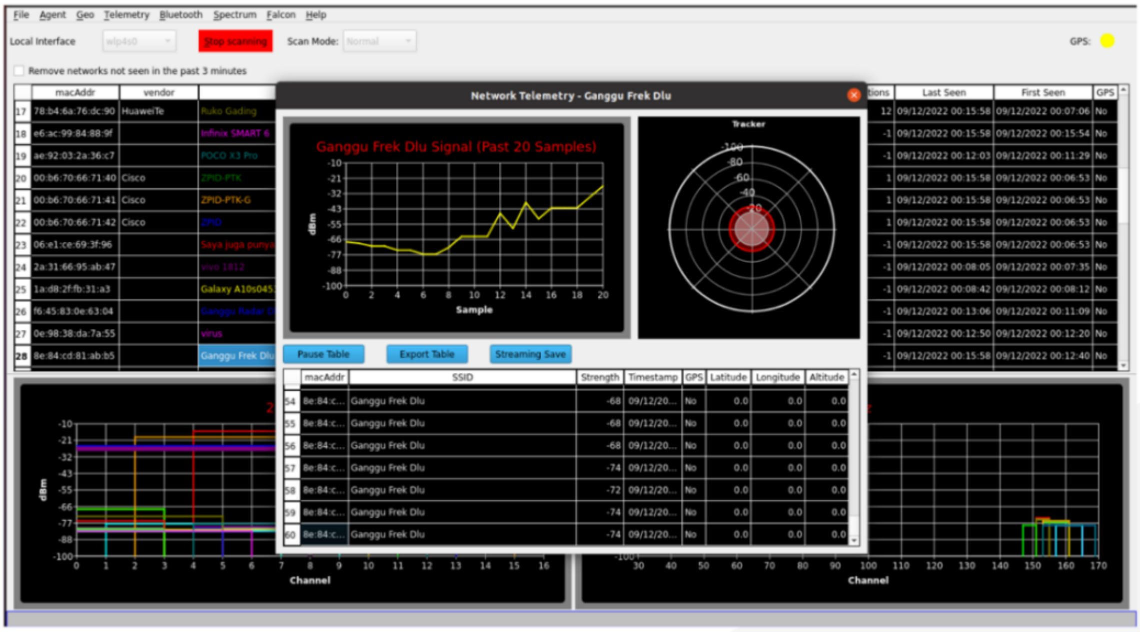
(b)

Figure 5. Overview of the monitoring system interface and data capture: (a) initial program interface of the monitoring system and (b) captured data

The data collected is analyzed against current regulations to ensure compliance with frequency usage and class permits set by regulatory bodies. This analysis identifies whether RLAN users are compliant or non-compliant with frequency regulations. Users are then categorized as either non-suspicious (compliant) or suspicious (non-compliant and potentially causing interference). After classification, a triangulation method is used to estimate the signal source's location based on the collected data. This precise location estimate is crucial for monitoring and tracking RF signals. Mapping then visualizes the triangulation results, representing the signal source's estimated location on a map or graph. This visualization aids in identifying areas requiring more focused monitoring and supports further actions like mobile direction finding (MDF). In MDF, the system uses the Homing method to accurately track mobile RF signal sources, with a setup similar to Stationary Stations but focused on mobile sources.

During this process, mobile direction finding as shown in Figure 6(a), optimizes components such as the software-defined radio (SDR), antenna direction finder (DF), and rotator, similar to the configuration in stationary stations. However, the Homing method allows the MDF to dynamically direct RF signals toward the moving signal source. Applying the Homing method is crucial in ensuring accurate tracking capability when RF signal sources can move or change location rapidly. The configuration, similar to stationary stations, allows us to integrate data from the MDF with data obtained from stationary stations, creating a holistic understanding of the radio frequency spectrum environment, including the movement of RF sources that may potentially cause interference or have specific interests. Thus, the system ensures reliable monitoring and tracking, even when signal sources are mobile. The result of homing method shown in Figure 6(b).

(a)



(b)

Figure 6. Overview of the mobile direction-finding process: (a) the mobile direction-finding process and (b) the result of the homing method

4. IMPLEMENTATION SCENARIO, RESULT, AND DISCUSSION

The testing scenario in this study aims to evaluate the effectiveness of the RFDF monitoring system in detecting and localizing interference sources near the BMKG weather radar. The testing scenario shown in Table 1. The scenarios involved varying levels of interference transmitter power (0-30 dBm) at 100 meters from the radar, with corresponding interference detection times and distances to the actual transmitter location shown in Table 2. The results demonstrate the system's capability to detect interference across various transmitter power levels. Despite the variation in power levels, the interference detection times remained constant at 5 minutes for all scenarios. This consistency suggests that the system's detection mechanism is robust and unaffected by changes in interference transmitter power, ensuring prompt identification of interference events. Furthermore, the observed distances to the actual transmitter location varied inversely with interference transmitter power levels. As the power level increased from 0 to 30 dBm, the distance to the actual location decreased from 102 to 80 meters. This trend indicates a strong correlation between interference transmitter power and the accuracy of interference localization. Higher power levels result in stronger and more detectable interference signals, leading to more precise localization of interference sources.

This test scenario aimed to evaluate the performance of the interference-handling RFDF monitoring system in detecting and localizing interference sources near the BMKG weather radar in Pontianak, West Kalimantan. The scenario involved varying interference transmitter power levels (0-30 dBm) at 500 meters from the radar, with recorded interference detection times and distances to the actual transmitter location. The results shown in Table 3 indicate that the system effectively detected interference across all tested power levels, with detection times ranging from 7 to 8 minutes. It suggests a consistent system response time in identifying interference events, which is critical for timely mitigation measures and uninterrupted radar operations. Furthermore, the distances between the detected interference locations and the actual transmitter location ranged from 190 to 195 meters. Although there are slight variations in distance, all detected locations were near the actual transmitter location.

Table 1. Implementation test scenario

Test scenario	Description
Interference transmitter setup	Position interference transmitter 100, 500, and 1,000 meters away from BMKG weather radar. Vary transmission power (0-30 dBm).
Interference detection testing	Monitor RFDF system output signals, record detection times for each interference signal. Test with low amplitude.
Interference localization testing	Use directional antennas to calculate spatial coordinates of interference signals. Compare with actual transmitter location.

Table 2. Test scenario result with interference transmitter setup 100 m from radar

Test Scenario	Interference transmitter power (dBm)	Interference detection time (minutes)	Distance to actual location (m)
100m from Radar, 0 dBm	0	5	102
100m from Radar, 10 dBm	10	5	100
100m from Radar, 20 dBm	20	5	97
100m from Radar, 30 dBm	30	5	80

Table 3. Test scenario result with interference transmitter setup 500m from radar

Test Scenario	Interference transmitter power (dBm)	Interference detection time (minutes)	Distance to actual location (m)
500 m from Radar, 0 dBm	0	8	195
500 m from Radar, 10 dBm	10	8	191
500 m from Radar, 20 dBm	20	7	193
500 m from Radar, 30 dBm	30	7	190

The conducted field tests aimed to assess the performance of the interference-handling RFDF monitoring system in detecting and localizing interference sources at a distance of 1,000 meters from the BMKG weather radar. Key parameters including interference transmitter power levels, interference detection times, and the distance to the actual transmitter location were analyzed to evaluate the system's effectiveness. The results shown in Table 4 indicate consistent interference detection across varying transmitter power levels. Despite the increasing power levels (0 to 30 dBm), the interference detection times remained relatively stable, ranging from 18 to 20 minutes. This suggests that the system's detection capabilities are robust and unaffected by changes in interference power levels within the tested range. Furthermore, the distances between the detected interference locations and the actual transmitter location were measured. The recorded distances ranged from 200 to 210 meters, indicating a close approximation to the actual transmitter location.

The comparative analysis of the three testing scenarios reveals consistent patterns in the system's response to variations in testing parameters. Specifically, there is a linear increase in the interference transmitter power levels (dBm) with increasing distance from the BMKG radar. However, the detection time of interference remains relatively stable at around 5-8 minutes for distances of 100 and 500 m from the radar, irrespective of the interference transmitter power levels. Yet, at 1,000 m, there is an increase in detection time with higher interference transmitter power levels. Conversely, the distance to the actual location exhibits a consistent decrease with increasing distance from the BMKG radar, indicating the system's ability to accurately identify and localize interference sources even at greater distances.

Despite these strengths, there are limitations to consider. The test scenarios were conducted under controlled conditions, which may not fully replicate the complexities of real-world environments. Additionally, while the system showed robust performance at tested distances, further research is needed to explore its efficacy beyond 1,000 meters and in varying weather conditions. This study aimed to enhance the reliability of weather radar operations by integrating RFDF technology, crucial for regions like West Kalimantan that experience high interference levels. Our findings confirm the system's effectiveness in detecting and localizing interference, contributing valuable insights for meteorological agencies and decision-makers. However, questions remain regarding the system's long-term performance and adaptability to different environmental conditions. Future research should investigate these aspects, possibly incorporating more extensive field tests and exploring the integration of RFDF systems with other interference mitigation technologies. By addressing these unanswered questions, future studies can further refine and optimize RFDF technology for broader applications in meteorology and beyond.

Table 4. Test scenario result with interference transmitter setup 1,000 m from radar

Test Scenario	Interference transmitter power (dBm)	Interference detection time (minutes)	Distance to actual location (m)
1,000 m from Radar, 0 dBm	0	18	210
1,000 m from Radar, 10 dBm	10	20	201
1,000 m from Radar, 20 dBm	20	19	205
1,000 m from Radar, 30 dBm	30	18	200

5. CONCLUSION

This study demonstrates that the interference-handling RFDF monitoring system effectively detects and localizes interference sources near the BMKG weather radar in West Kalimantan. The system showed consistent detection times and reliable localization accuracy across various power levels and distances, highlighting its practical application for weather radar environments. While our findings confirm the system's potential for improving interference management, further research is needed to assess its long-term performance and adaptability in different environmental conditions. This study contributes to enhancing radar reliability and offers a foundation for future work in refining RFDF technology for meteorological use.

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