Review of Computer Engineering Research
2025 Vol. 12, No. 3, pp. 120-138
ISSN(e): 2410-9142
ISSN(p): 2412-4281
DOI: 10.18488/76.v12i3.4333

UHF-RFID technology for smart tire presence detection: Performance evaluation and IoT integration

Mahfud Rozaki Rahman[1]
Giva Andriana Mutiara[2+]
Muhammad Rizqy Alfarisi[3]

[1,2,3]*Faculty of Applied Science, Telkom University, Jl. Telekomunikasi No. 1, Bandung, West Java, Indonesia.*
[1]*Email: rozakirahman@student.telkomuniversity.ac.id*
[2]*Email: givamz@telkomuniversity.ac.id*
[3]*Email: mrizkyalfarisi@telkomuniversity.ac.id*

(+ Corresponding author)

Article History
Received: 17 March 2025
Revised: 23 June 2025
Accepted: 15 July 2025
Published: 1 August 2025

Keywords
Internet of things
Prototype
Tire presence detection
UHF RFID
Vehicle safety.

ABSTRACT

This study aims to develop a smart tire presence detection system using UHF-RFID technology and the ESP32 microcontroller to prevent vehicle tire theft and unauthorized replacement. A prototype-based methodology was used, employing iterative testing and development cycles. Two UHF RFID readers—EL-UHF-RF014 and BR-20—were compared to determine optimal performance in detection range and response time. The selected reader was integrated into a system that transmits real-time data to an IoT-based web interface. The EL-UHF-RF014 outperformed the BR-20 in all scenarios, achieving a maximum detection range of 12 meters and faster response times. Real-time monitoring results showed a detection accuracy of 87.5%. The best antenna position for consistent detection was on the side of the vehicle, with average response times of 1.4 seconds. The proposed system reliably detects tire presence and improves vehicle safety. The EL-UHF-RF014 reader, combined with tire-integrated RFID tags and IoT connectivity, enables effective monitoring of tire conditions and prevents unnoticed tire swaps. The system is applicable in automotive workshops and fleet management, improving security and operational efficiency. It serves as a foundation for future IoT-based vehicle safety innovations.

Contribution/Originality: This study presents an innovative tire presence detection system by integrating UHF-RFID with IoT-based monitoring. Unlike previous works, it compares reader performance and evaluates real-time detection on actual vehicles, offering a practical solution for enhancing automotive safety through RFID-based anti-theft mechanisms.

1. INTRODUCTION

The increasing rate of vehicle and component theft particularly tire theft has become a major concern in many regions worldwide. Reports from security agencies highlight a significant rise in tire theft cases in recent years, resulting in substantial financial losses for both vehicle owners and insurance companies [1]. This trend not only impacts individuals but also undermines trust in the automotive sector's ability to ensure vehicle safety.

For vehicle owners and fleet operators, the unauthorized replacement or theft of tires poses serious consequences, including unexpected financial burdens and safety risks due to the use of counterfeit or inferior tires. Traditional security approaches such as physical locks and manual inspections are often inadequate, offering limited protection and lacking real-time oversight. Tire theft can also occur in workshops during maintenance processes like balancing or spooring, where tires must be temporarily removed from the vehicle. In such cases, owners may remain unaware that their original tires have been replaced with those in worse condition, potentially compromising road safety [2, 3].

To address these issues, this study proposes the development of a tire presence detection system capable of providing early alerts to vehicle owners. The goal is to prevent theft or unauthorized tire swaps by deploying an efficient and reliable monitoring solution. This system integrates Ultra High Frequency-Radio Frequency Identification (UHF-RFID) technology directly into the tire, functioning both as a monitoring and preventive tool [1]. The system is built on an ESP32 microcontroller platform, which processes tag data and communicates with a web-based interface. This setup allows real-time notifications to be sent to users, enabling timely preventive action [2, 3]. Rapid detection and immediate response can significantly reduce the likelihood of successful theft.

Throughout the development, this study explores techniques to improve detection accuracy and system reliability. By leveraging UHF-RFID and IoT integration, the research aims to enhance vehicle safety, streamline monitoring processes, and support broader adoption of intelligent transportation security technologies [4]. Furthermore, a comparative evaluation is conducted between two UHF RFID readers, EL-UHF-RF014 and BR-20, to determine the optimal hardware configuration. This comparison establishes technical benchmarks for performance in terms of detection range and response time, aiding the development of robust applications in real-world settings [4, 5].

This work contributes to the advancement of automotive security systems by increasing public awareness of tire theft prevention and reinforcing the protection of critical vehicle components. The proposed system benefits not only individual users but also fleet managers and service providers by offering transparent, real-time tire monitoring [6].

Ultimately, it supports the ongoing innovation of secure automotive solutions and highlights the value of integrating UHF-RFID and IoT in modern vehicle safety frameworks. The following chapters will describe the system design, evaluation process, and results derived from real-world testing.

The next chapter will detail the study and methods employed in this system. The third chapter showcases the findings and delves deeper into their analysis. The fourth chapter serves as the final discussion, articulated as a conclusion.

2. RESEARCH AND METHODOLOGY

This chapter presents an overview of the study and the methods utilized. This study focuses on the creation of a prototype, supported by a detailed guide for gathering findings through multiple methodologies, which include a thorough literature review and the meticulous design and construction of the prototype. Effectively implement a scenario testing strategy, execute tests based on the established scenario, and conduct a thorough analysis of the results obtained. The results obtained lead to a conclusion.

2.1. Literature Review

Radio Frequency Identification (RFID) technology utilizes radio waves for the automatic identification and tracking of objects. RFID consists of two main components: RFID readers and RFID tags. RFID tags, usually attached to the monitored item, contain specific information that can be accessed by the RFID reader. A radio frequency signal is emitted by the reader to activate the tag, which subsequently transmits the stored information back to the reader. RFID markedly improves the reliability of security systems [7, 8].

A study by Panganiban and Cruz [9] utilized RFID to demonstrate the progress of a vehicle management system [9]. The system is designed to tackle the challenges associated with vehicle monitoring, especially in areas with high vehicle density. This study aims to develop a system that improves security and efficiency in vehicle management. The system functions at a frequency of 13.56 MHz, identifying both registered and unregistered vehicles, and then sends an SMS notification to the database.

However, the High Frequency (HF) signal in the RFID system demonstrates a significant degree of weakness. In developing a vehicle tire detection system, it is crucial to integrate RFID readers and tags while considering radio frequencies to improve the system's performance and reliability [10].

UHF (Ultra High Frequency) refers to a radio frequency band that spans from 300 MHz to 3 GHz. The UHF RFID technology offers an impressive range for long-distance communication, particularly in settings that are either unobstructed or only slightly hindered by structures or obstacles [11]. UHF offers superior signal quality when compared to lower frequencies like HF and VHF, which makes it particularly suitable for data transmission. Therefore, choosing UHF RFID is the appropriate choice [12]. Figure 1 illustrates a comparison of HF, VHF, and UHF signals.

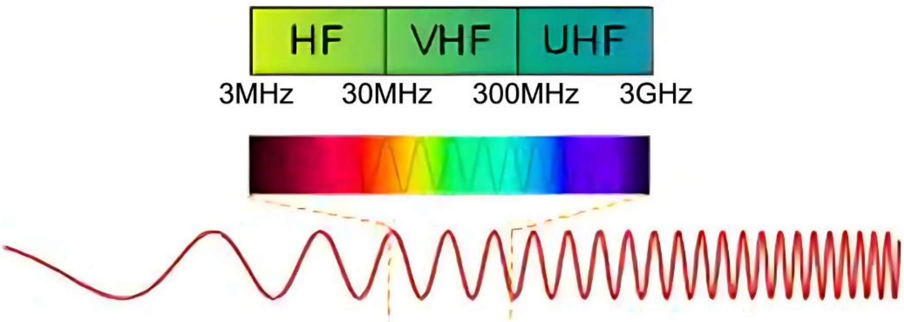

Figure 1. Difference in radio frequency signals.

The features of the UHF signal generated by a partial discharge in a transformer reveal several significant elements pertinent to detection. As illustrated in Figure 2, this signal exhibits a waveform defined by double exponential decay, demonstrating a swift reduction in amplitude over time, particularly at high frequencies, such as 600 MHz.

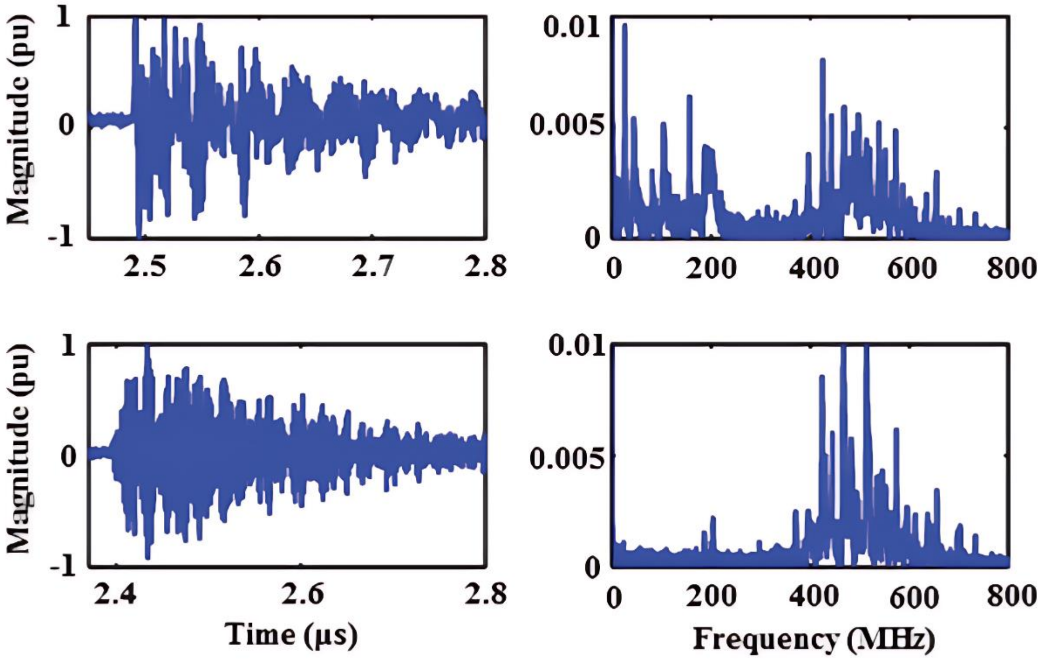

Figure 2. Characteristics of UHF signals.

The UHF signal in the study Dukanac [13] is often affected by white Gaussian noise with a power of -15 dBW and an average signal-to-noise ratio (SNR) of around 22.27 dB, indicating that despite the noise, the signal can still be detected well. The attenuation of the UHF signal is affected by the distance between the source and the sensor, with an average attenuation of around 2.0 dB/m. Proper sensor placement can improve the accuracy in determining the location of partial discharge sources, although the internal structure of the transformer is not fully taken into account.

Multivariate wavelet denoising techniques are employed to minimize noise and preserve crucial information [14-16] while calculating the arrival times of signals at various sensors to ascertain the time difference of arrival (TDOA) [17]. The initial method for detecting peaks is utilized to determine the arrival time of signals, which may be influenced by frequency resonance. In summary, the properties of UHF signals indicate promise for efficient detection, even with obstacles concerning noise and attenuation. Employing suitable signal processing methods can enhance the precision in identifying the origin of release [18-20].

Additionally, a study conducted by Maria Cristina et al presented a method for implementing a wireless and automated tire inventory system utilizing UHF RFID technology within the tire handling process on a conveyor line [21]. This system employs an RFID integrator to gather data from RFID tags affixed to tires. The information contained within the tags is crucial and significant. The objective is to recognize and distinctly classify tires as they progress along a conveyor line [22] as illustrated in Figure 3. This system enables precise monitoring of the tire sequence on the conveyor, facilitating the selective execution of specific manufacturing processes on particular tires according to the data, thereby minimizing logistical errors [23].

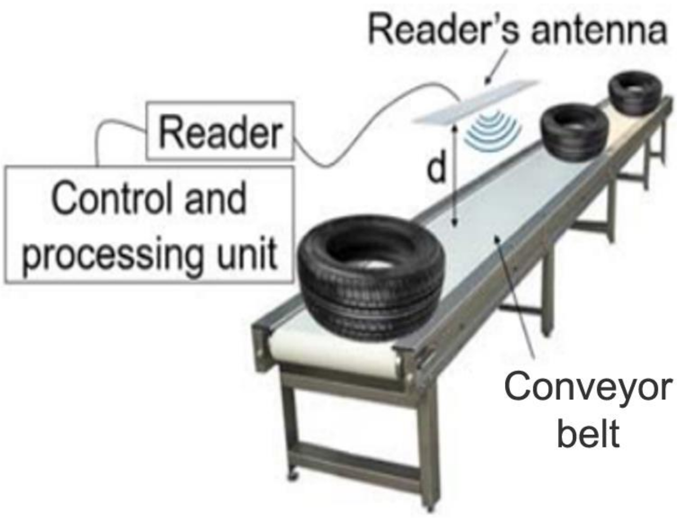

Figure 3. RFID reading gate installed along the path of a conveyor belt to manage and monitor conveyed tires.

However, the primary limitation of this technology lies in the substantial expenses associated with its installation and integration process. This solution is particularly well-suited for larger organizations that are capable of managing significant upfront investments and necessitate precise monitoring within their supply chain.

The implementation of UHF RFID across different industrial and commercial sectors presents several notable benefits. A key benefit is the extended read range when compared to alternative RFID technologies [24]. UHF RFID can read tags from distances of several meters, proving highly effective for applications involving tracking in expansive areas, both indoors and outdoors. Moreover, UHF RFID boasts a rapid read speed, enabling the simultaneous reading of numerous tags in a brief period. This capability is crucial, especially since the system can detect all four vehicle tires at once [25, 26]. Fitted with serial communication, this setup is highly appropriate for constructing a contemporary and functional Internet of Things (IoT) system [27].

A number of studies have advanced the application of RFID technology in the automotive sector, particularly in areas such as motorcycle tracking and vehicle security [28]. Subsequently, systems that verify vehicles are referenced in Samuel and Sebastian [29]. However, a system specifically designed to detect theft or illegal tire swaps has yet to be developed.

2.2. Tire Presence Detection System Design

The first step in creating a tire presence detection system involves understanding the layer structure of a vehicle tire, which is essential for determining the correct position for tire tag installation, as demonstrated by Saini et al. The structure of the tire consists of multiple layers, as shown in Figure 4. The tag position is situated on the Inner Liner.

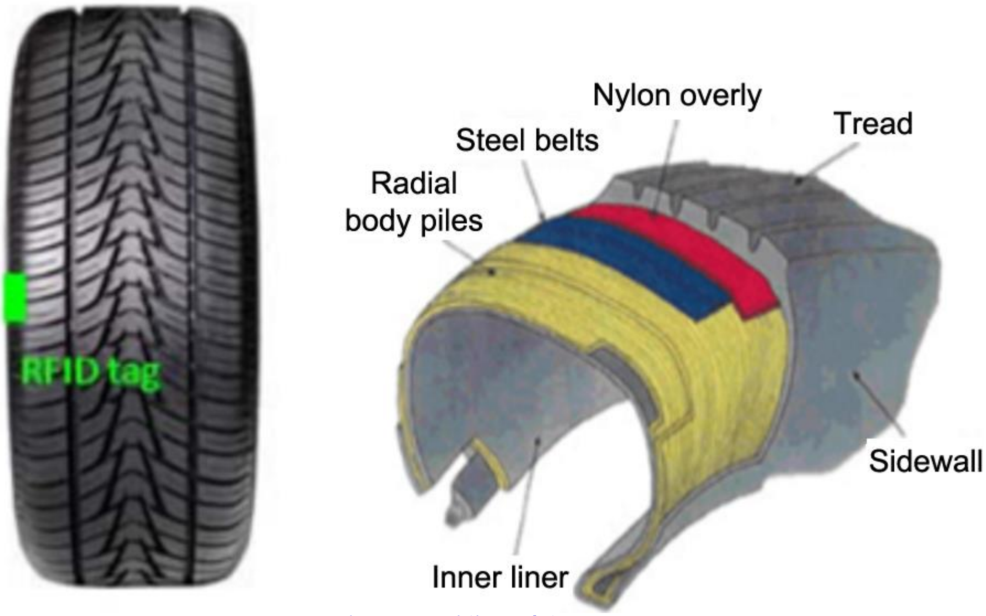

Figure 4. Multilayered tire system.

A study by Saini et al. involved the placement of RFID tags within the tire wall layer, specifically situated in the rubber layer that lies between the outer and inner layers of the tire [30]. This placement is intended to ensure that the tag operates efficiently under the extreme conditions found within the tire, including high pressure and fluctuating temperatures.

The RFID tag is strategically positioned to enable real-time monitoring of tire conditions, encompassing factors such as pressure and temperature. Incorporating it within the tire wall layer allows for the collection of pertinent data while maintaining the tire's structural integrity. This study highlights the significance of tag design and placement for achieving optimal performance in tire monitoring applications [31].

Figure 5 presents the block diagram of the proposed tire presence detection system. The reading system is transmitted using ESP-32 and an API. The data will be visible to the user on the display.

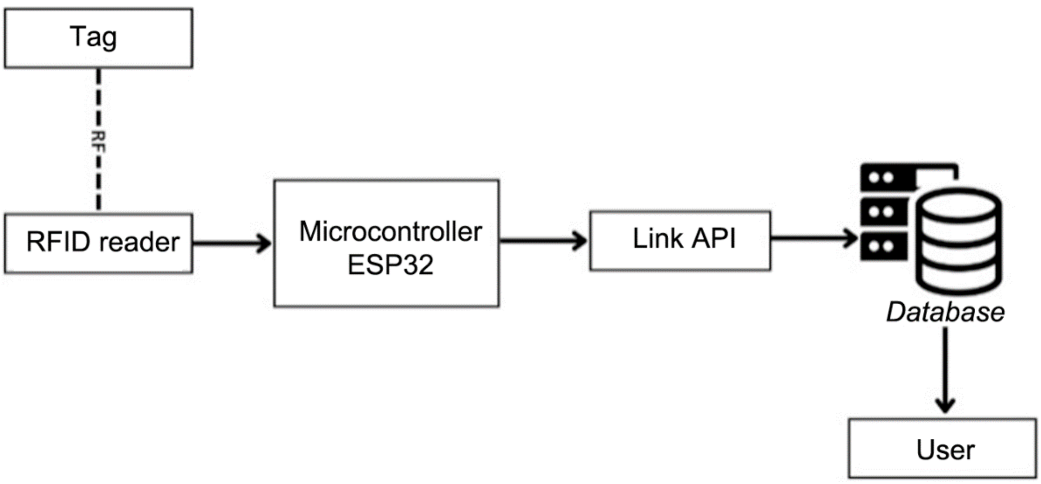

Figure 5. Diagram block of the tire presence detection system.

Meanwhile, a design intended to enhance a diagram block of tire detection and notification, highlighting the thoughtful arrangement of components, can be seen in Figure 6. The system is engineered to improve the identification of vehicle tires through the application of UID to each tire tag. Tire tags are positioned with precision on the inner wall of the vehicle tire, particularly in locations that are expected to be detected by the UHF RFID reader. This design enables the activation of suitable tire detection alerts based on the vehicle tire presence readings during checks at locations like workshops or pools. Upon reading the tire tag and the reader, the resulting data is transmitted and recorded in real time to the ESP32 microcontroller for further analysis. The data is subsequently presented on a monitoring website, allowing users to easily track it [32].

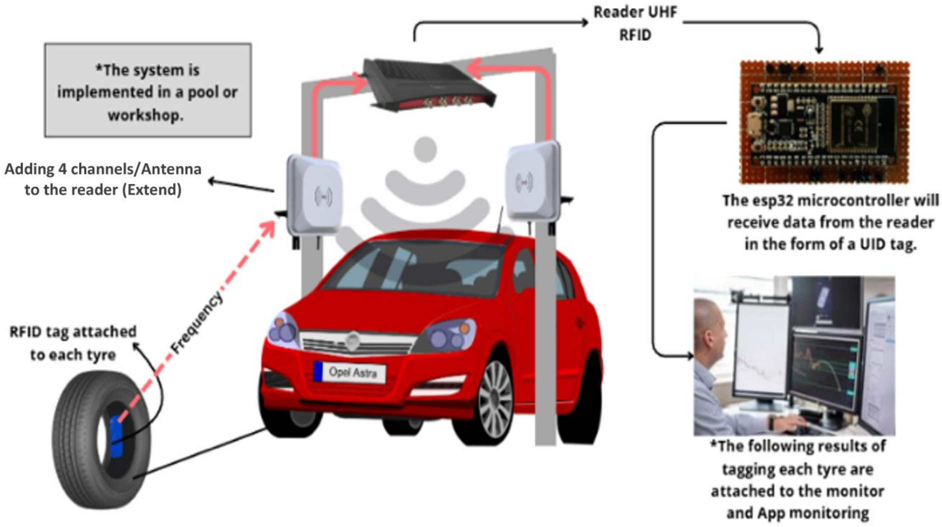

Figure 6. Tire presence detection structure.

Choosing the appropriate UHF RFID reader is a vital element in creating an efficient monitoring system, as it can significantly influence the system's overall performance. RFID readers act as the primary element tasked with recognizing and gathering information from the connected RFID tags. Consequently, conducting a comparative analysis of the different types of RFID readers available in the market is essential. This study will compare two distinct models of RFID readers, focusing on factors such as reading range, data processing speed, and their performance in diverse environments. Figure 7 displays both readers, and this comparison aims to determine the most appropriate RFID reader to enhance the monitoring system under development.

Figure 7. (a) BR-20 UHF RFID; (b) EL-UHF-RF014.

There are certain differences that exist between the two readers. Table 1 can be presented to illustrate the comparison of characteristics between the BR-20 UHF RFID and EL-UHF-RF014 readers.

Table 1. Comparison between EL-UHF-RF014 and BR-20 UHF RFID.

Specifications	EL-UHF-RF014	BR-20 UHF RFID
Reading range	1-12meters	1-7meters
Radio frequency power	33 dBm (Adjustable)	8 dBi (Non-adjustable)
Antenna	External (4 TNC Antenna Port)	Internal
Interface	RS232, RJ45, TCP/IP, USB	RS232, RS485, Wiegand, Trigger, TCP/IP, WiFi, and PoE
Durability	Non mentioned	IP54
Signal type	Omnidirectional	Line of Sight
Buzzer	Sound mode options	On/Off only
Applications	Large areas, indoor, outdoors	Limited area, more suitable indoor
RSSI	Support	Not supported
Dimensions	270x180x27mm	235x235x57mm
Price	USD. 450	USD.90

2.3. Flow Chart System

The functionality of tire presence detection is illustrated in the workflow outlined in Figure 8. As illustrated, the process of inspecting and validating the vehicle's unique tire code in the workshop commences with the activation of the sensor designed to identify the unique tire code through RFID technology or comparable sensors [33]. Upon the vehicle's arrival at the workshop, the first action involves verifying the unique tire code to confirm that the information aligns with the database.

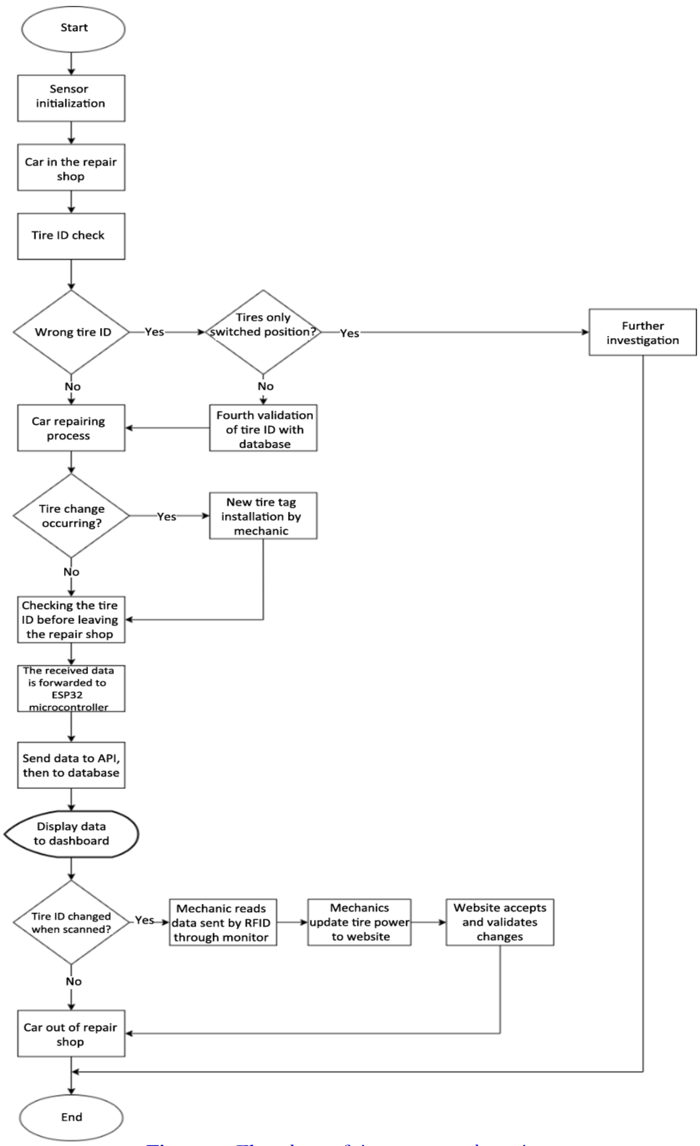

Figure 8. Flowchart of tire presence detection.

In the event that a unique code discrepancy is identified, additional analysis is conducted to ascertain if the discrepancy results from the tire position swap. When the tires are merely exchanged, the technician verifies the four tires by cross-referencing the identified unique code with the information stored in the database. However, if the reason for the discrepancy is not linked to the position, additional investigation is conducted to determine the cause of the issue. Upon completion of the validation, the vehicle may proceed to the repair process if deemed necessary. When a tire is replaced, the mechanic will fit a new tire accompanied by a randomly generated tire tag. Prior to the vehicle departing from the workshop, the distinct tire code undergoes a final verification to confirm that all unique codes align with the database.

The data collected during the inspection process is relayed to the ESP32 microcontroller for further processing and then transmitted to the server via an API. The information is stored in a database and displayed in real-time on a dashboard available to both mechanics and users [34]. Upon detection of a modification in the specific tire code during the final validation phase, the technician analyzes the information relayed by the RFID system via the display [35]. The mechanic updates the tire information via a web-based platform or application integrated with the system. Upon implementation of the update, the platform processes and verifies the changes in the submitted data. This process ensures that the information in the database is accurate and represents the actual condition of the vehicle. Upon completing all stages, the vehicle is prepared to leave the workshop, indicating the end of the inspection and validation process for the specific tire code. This system seeks to improve accuracy and efficiency in the management of information related to vehicle tires while minimizing the potential for data errors [36].

2.4. Testing Scenario

The test scenario for the tire presence detection prototype aimed to evaluate the effectiveness of RFID reading between the reader and the tire tag under various environmental conditions. The experiment consisted of four main phases, each involving the placement of the RFID reader in a different position: front, side, and rear.

The first scenario involved assessing the RFID reader and tire tag within an indoor environment, as depicted in Figure 9. The reader and tire tag were situated in a confined space to simulate controlled conditions. The data obtained from this test confirmed the system's accuracy under controlled conditions.

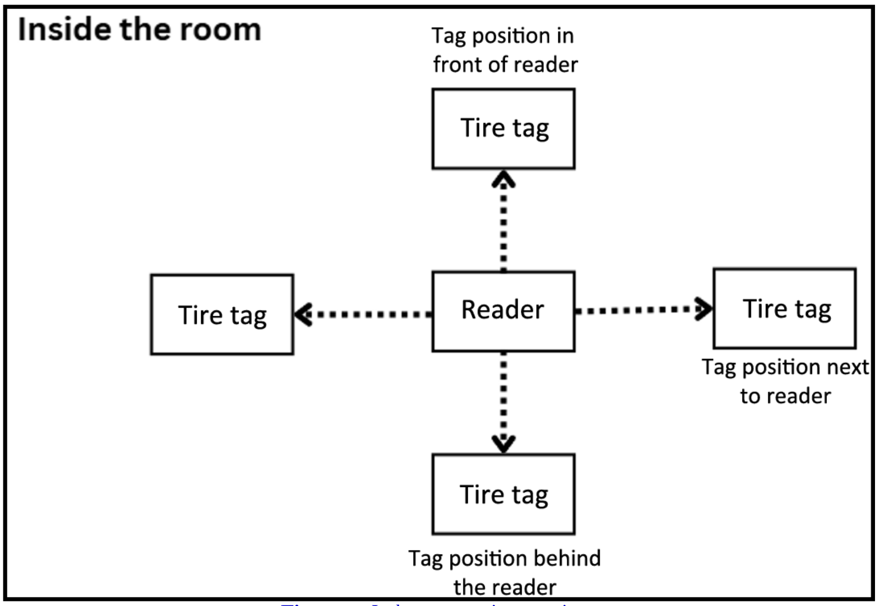

Figure 9. Indoor scenario overview.

The second scenario entails the relocation of the RFID reader and tire tag to an outdoor environment. This test aims to assess the system's performance in real-world conditions, taking into account the impact of environmental factors such as signal interference and weather conditions on measurement outcomes. Figure 10 illustrates this point. The data generated from this test is assessed in comparison to the reference value to ascertain the reliability of the system.

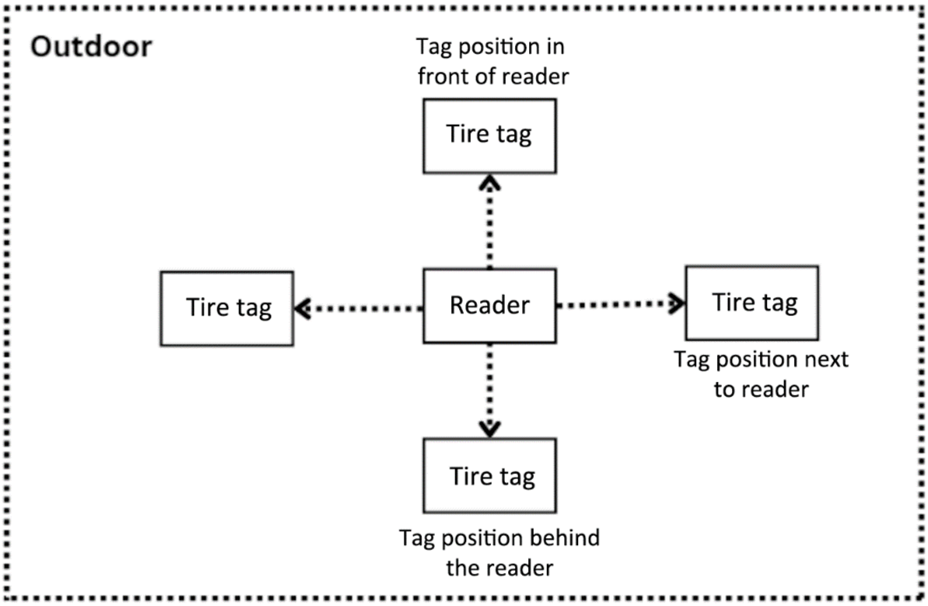

Figure 10. Outdoor scenario overview.

The third scenario involves an experiment where the RFID reader is located externally, and the tire tag is situated indoors, as seen in Figure 11. This scenario evaluates the data transmission capabilities between the reader and the tire tag under various conditions, identifying potential challenges arising from distance and physical obstacles.

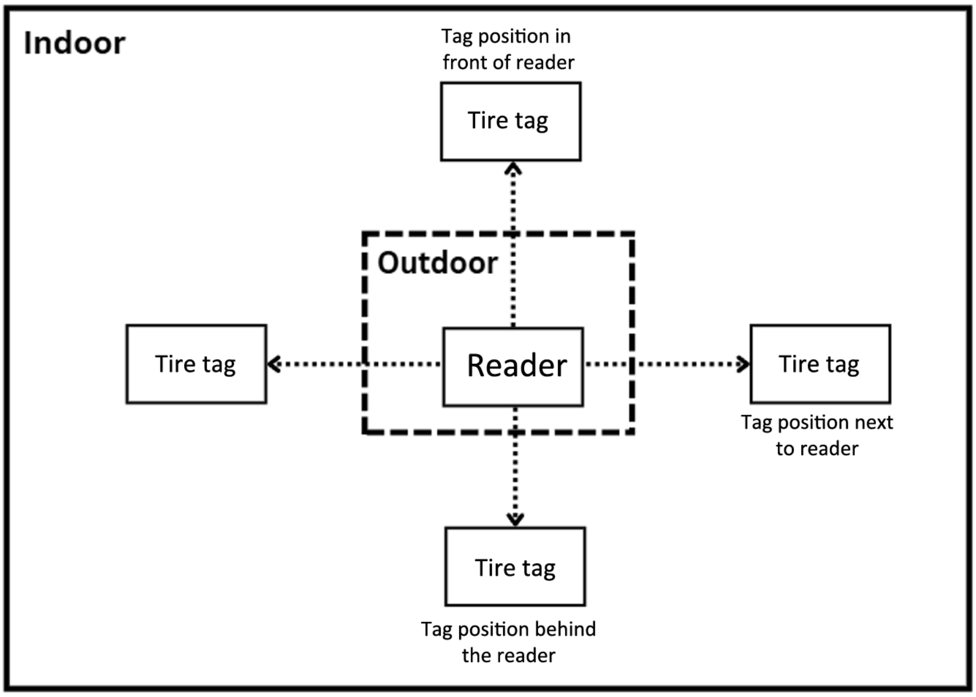

Figure 11. Indoor and outdoor scenario overview.

The fourth scenario involves a direct examination of the vehicle, with the tire tag affixed to the inner wall of each car tire. In the fourth stage, one of the two readers is selected based on the outcomes of the first, second, and third stage scenarios. In this scenario, the system operates to track the status of each tire in real time and guarantees the direct implementation of the system on the vehicle. This phase is depicted in Figure 6.

Once all testing phases are finalized, the results from each scenario are examined to pinpoint the challenges encountered, including signal transmission interference, range distance, and reading response time.

3. RESULT AND DISCUSSION

3.1. Result

This experimental setup includes various factors to improve the accuracy of the system's measurements. The elements are arranged according to the defined scenario. Figure 12 presents the results of the initial stage scenario test outlined in the previous chapter. This scenario establishes a foundation for evaluating the characteristics of the two RFID readers, namely the EL-UHF-RF014 and B-20 UHF RFID. This assessment is essential for identifying the limitations of the two readers by evaluating the range and response time metrics in indoor conditions. The results from the initial scenario test, EL-UHF-RF014, indicated enhanced performance in the front position, with a response time of 0.5 seconds at a distance of 3 meters, compared to BR-20, which exhibited a response time of 1 second at the same distance. At a distance of 7 meters, the EL-UHF-RF014 recorded a duration of 1.5 seconds, while the BR-20 recorded a duration of 4 seconds. In the side position, the EL-UHF-RF014 recorded 4 seconds at a distance of 3 meters, while the BR-20 recorded 3 seconds at a distance of 1 meter. The EL-UHF-RF014 recorded 1.5 seconds at 1 meter in the rear position, while the BR-20 recorded 5 seconds.

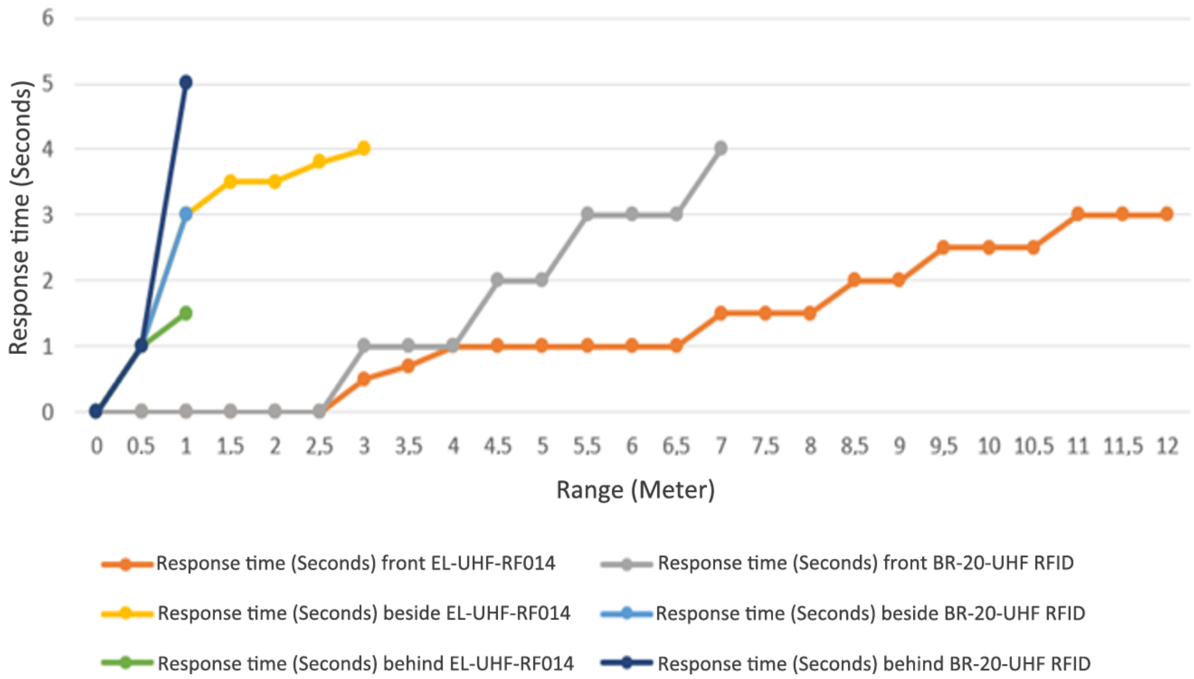

Figure 12. First test scenario result graph.

The second scenario is designed to evaluate the system's performance in conditions that replicate a real-world environment. This outdoor test considers multiple environmental factors, such as signal interference and conditions, that may affect the measurement results. The test data is graphically represented to provide a clear depiction of the system's accuracy and reliability, as demonstrated in Figure 13.

In the second scenario, the EL-UHF-RF014 reader exhibited notable performance, achieving a response time of 5 seconds at a distance of 11 meters in the front position, while the BR-20 reader recorded a response time of 22 seconds at a distance of 7 meters. In the side position, the EL-UHF-RF014 exhibited a response time of 4.5 seconds at a distance of 3 meters, while the BR-20 displayed a response time of 4 seconds at a distance of 1 meter. The EL-

UHF-RF014 exhibited a response time of 2 seconds at a distance of 1 meter in the rear position, while the BR-20 recorded a response time of 5 seconds.

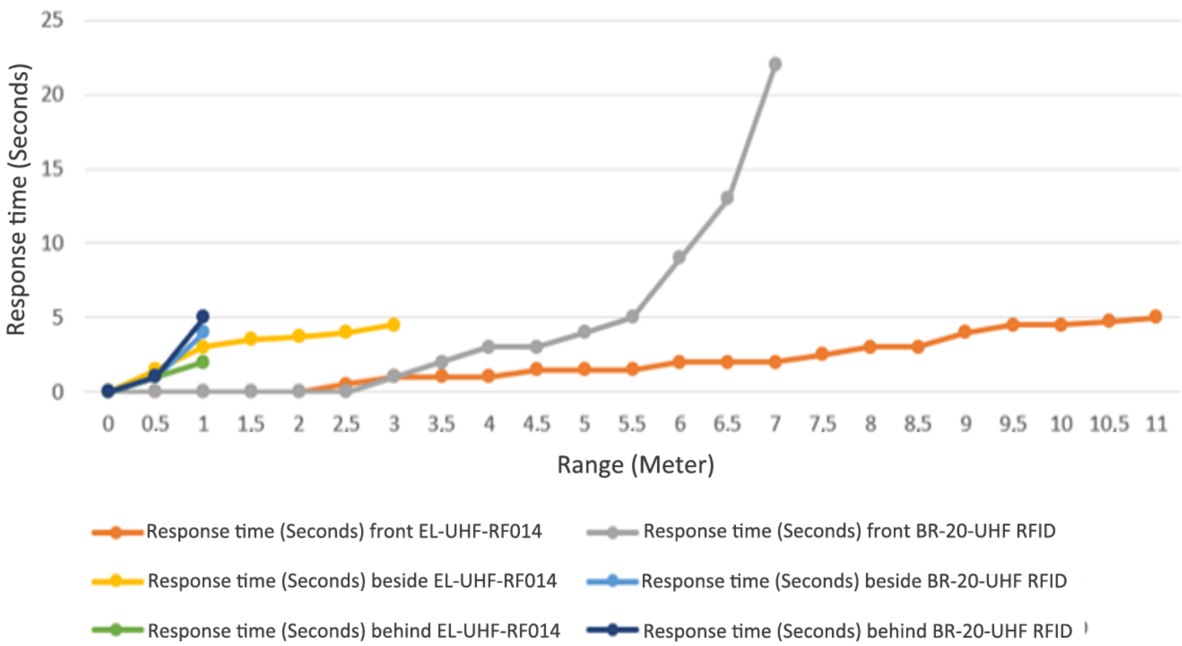

Figure 13. Second test scenario result graph.

The third stage scenario involved positioning the RFID reader externally, while the tire tag remained indoors. This scenario was designed to evaluate the data transmission capability between the reader and the tire tag under different conditions, while also identifying potential challenges arising from distance and physical obstacles. The test results are presented in graphs shown in Figure 14, providing a clearer understanding of the system's effectiveness in these scenarios. Figure 14 presents the response time test data for two UHF RFID readers, namely the EL-UHF-RF014 and BR-20 UHF RFID, at various detection distances.

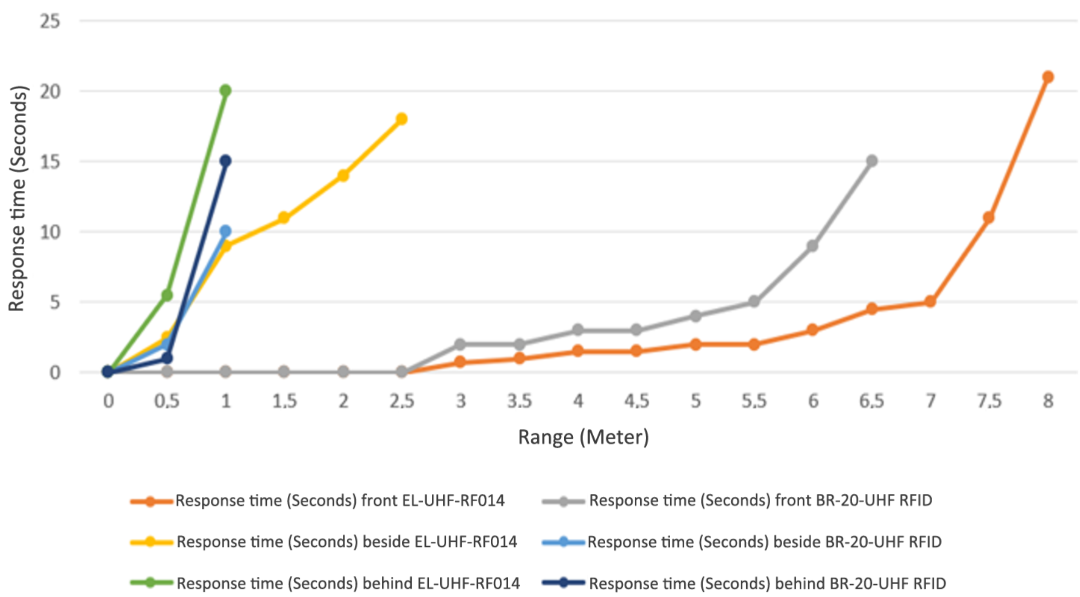

Figure 14. Third test scenario result graph.

The test results show that the EL-UHF-RF014 reader exhibits a significantly better response time than the BR-20 UHF RFID, especially at greater distances. The EL-UHF-RF014 demonstrated a response time of 21 seconds at a distance of 8 meters, while the BR-20 recorded a time of 9 seconds at a distance of 6 meters. In the lateral position, the EL-UHF-RF014 exhibited a response time of 9 seconds at a distance of 1 meter, while the BR-20 recorded a response time of 10 seconds.

At a distance of 2 meters, the EL-UHF-RF014 recorded a duration of 14 seconds, whereas the BR-20 was not detected. In the rear position, both devices demonstrated a response time of 0 seconds at a distance of 0 meters. At a distance of 1 meter, the BR-20 recorded a detection time of 20 seconds, while the EL-UHF-RF014 recorded 15 seconds, indicating the superior RFID detection capabilities of the EL-UHF-RF014 device.

An extensive evaluation of various test scenarios indicates a significant disparity in the performance outcomes of the EL-UHF-RF014 and BR-20 UHF RFID readers. Figure 15 presents a comparative analysis of the performance of the EL-UHF-RF014 and BR-20 UHF RFID in various scenarios, including positional accuracy and maximum range. The results demonstrate that the EL-UHF-RF014 consistently exceeds the performance of the BR-20 UHF RFID in all assessed scenarios.

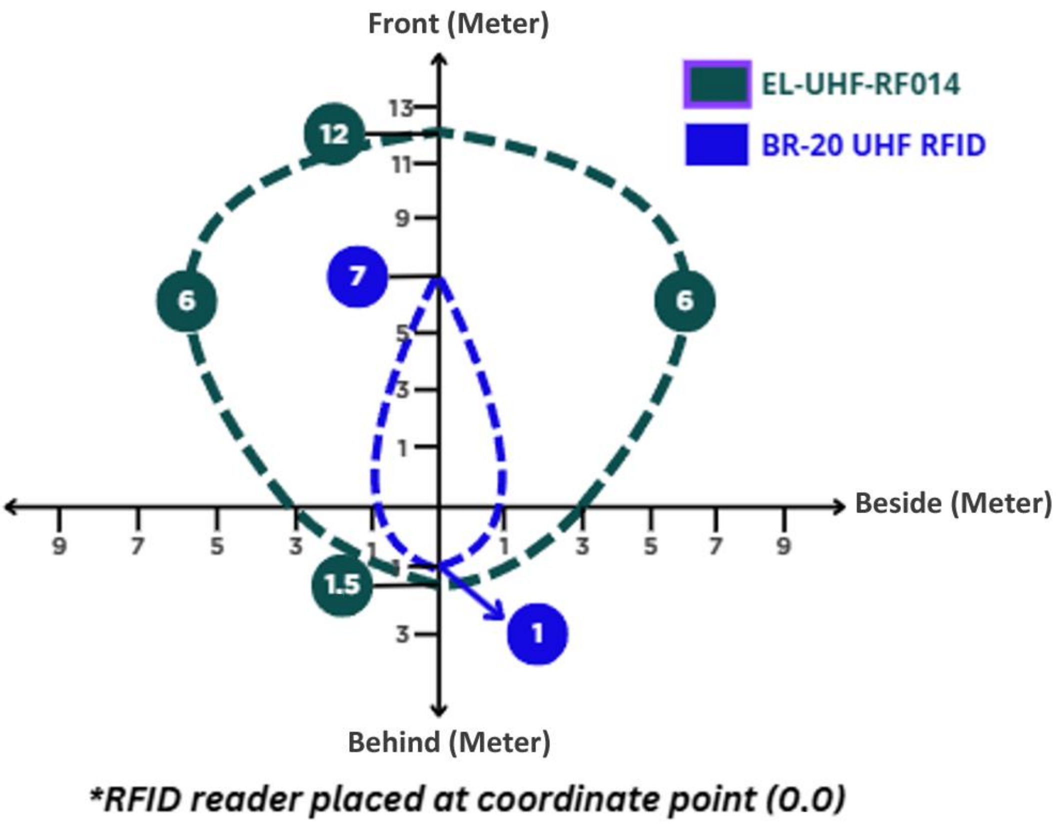

Figure 15. Signal power.

The test results indicate that within indoor settings, the EL-UHF-RF014 reader can detect tire tags from a distance of up to 12 meters in the front position, whereas the BR-20 has a maximum detection range of 7 meters. When positioned on the side, the EL-UHF-RF014 has a detection range of up to 3 meters, whereas the BR-20 is limited to just 1 meter. In outdoor settings, the EL-UHF-RF014 demonstrates a peak detection range of 11 meters when positioned at the front, while the BR-20 reaches a maximum of 7 meters. When the reader is outside and the tire tag is inside, the EL-UHF-RF014 outperforms with a maximum distance of 8 meters, whereas the BR-20 achieves 6.5 meters. The findings clearly indicate that the EL-UHF-RF014 outperforms the BR-20 in terms of detection range and effectiveness, whether in indoor or outdoor settings. Consequently, the EL-UHF-RF014 has been chosen for the fourth stage of testing, during which the tire tag will be placed inside the vehicle tire to enhance the efficiency of the detection system in real-world conditions.

During the fourth scenario, testing for tire presence detection is conducted directly on the vehicle, utilizing the tire tag affixed to the inner wall of the car tire, as illustrated in Figure 16. This placement safeguards the tire tag from outside influences and guarantees its performance during vehicle operation. The system continuously tracks the presence of tires in real-time through the EL-UHF-RF014 reader, chosen according to the outcomes of earlier evaluations. The objective of this testing is to validate the performance of the tire detection system in actual operational scenarios.

Figure 16. Installation of tire tags on vehicle tires.

The EL-UHF-RF014 reader necessitates the connection of an external UHF antenna, as this specific reader operates with an external antenna [37]. Prior to testing, the reader was set up through the app and subsequently linked to the ESP32 microcontroller using an RS232 Male to TTL MAX232 cable [38, 39]. Testing was conducted at a vehicle stop location (checkpoint), with antennas positioned at the front, side, and rear of the vehicle. Throughout the testing phase, performance data of the system were gathered for assessment across different conditions.

The results of the test are illustrated in a graphical format, as shown in Figure 17. Figure 17 illustrates the response time at the UHF RFID antenna location positioned in front of the vehicle. The parameters assessed encompass response time for tire positions FR, FL, BR, and BL, with data comprising timestamp, antenna distance to tire tag (meters), and response time (seconds).

At a distance of 0.5 meters, the recorded response times were 1 second for the front right and front left, 3 seconds for the back right, and 2 seconds for the back left. At a distance of 1 meter, the response time showed a slight increase to 1.5 seconds (FR), 1 second (FL), 3 seconds (BR), and 3 seconds (BL). At a distance of 1.5 meters, the response time for FR rose to 2 seconds, FL stayed at 2 seconds, BR increased to 6 seconds, and BL reached 5 seconds. At a distance of 2 meters, the response time notably rose for FR (5 seconds) and FL (7 seconds), whereas BR and BL went undetected, suggesting a restricted antenna range or interference with the RFID signal.

In the evaluation of the antenna placement adjacent to the vehicle depicted in Figure 18, the findings indicate that at a distance of 2 meters, the tire tags located in the Front Right (FR) and Right Back (RB) positions were undetected, as evidenced by the lack of a recorded response time, suggesting restricted reading capabilities at greater distances. The test data indicate that at a distance of 0.5 meters, the response time for FR is 0.7 seconds, FL is 1 second, and BL is 0 seconds. At a distance of 1.0 meters, the response time for the front right increases to 1.5 seconds, while the front left and back left are at 1 second, and the back right is at 2 seconds. At a distance of 1.5

meters, the front right is recorded at 3.5 seconds, the back right at 2.7 seconds, while both the front left and back left are each at 1 second. The findings highlight the necessity of modifying antenna positioning and enhancing system performance, particularly for tire detection at greater distances in the FR and BR locations.

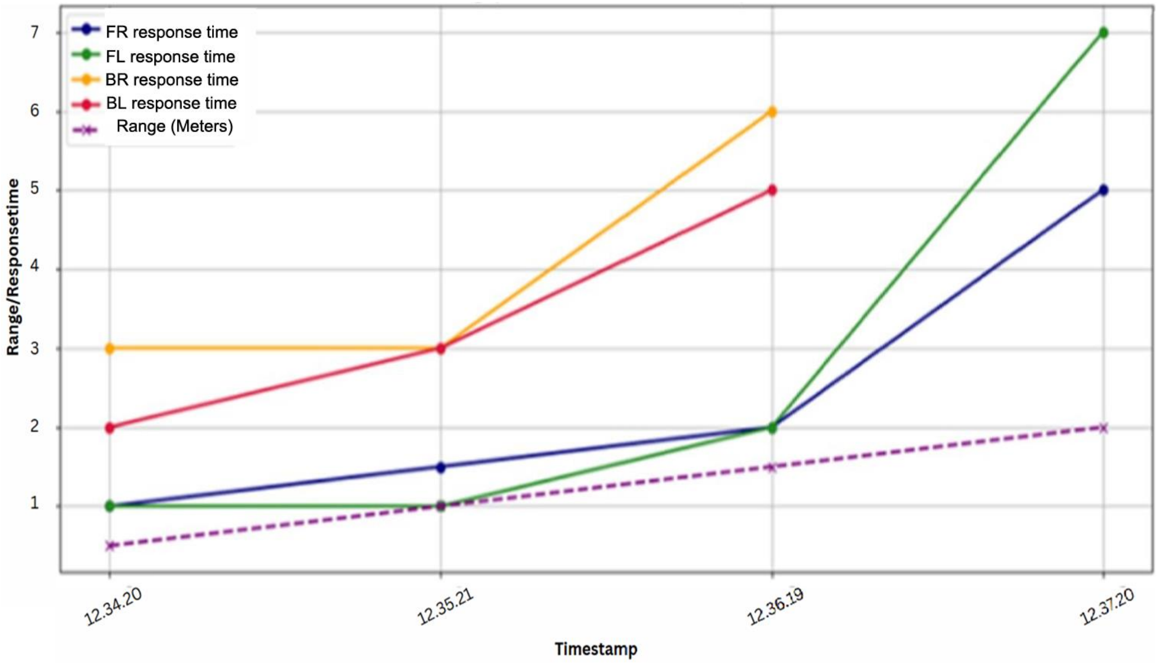

Figure 17. Result of antenna position in front of the vehicle.

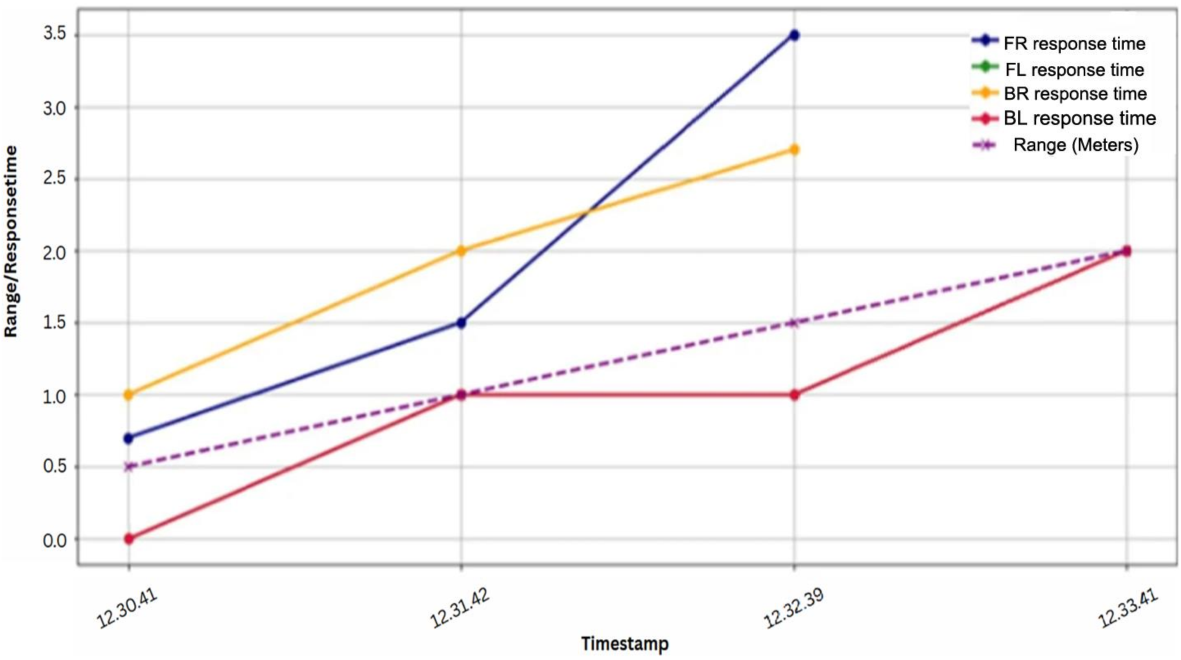

Figure 18. Result of antenna position on the left/right of the vehicle.

In the evaluation of the antenna placement at the back of the vehicle shown in Figure 19, the front right and front left positions were not identified at a distance of 2 meters. At a distance of 0.5 meters, the recorded response times were as follows: FR at 2.7 seconds, FL at 3 seconds, BR at 1 second, and BL at 0 seconds. At a distance of 1 meter, the front right and front left response times were measured at 1 second, while the back right and back left recorded times were 1.5 seconds and 1.7 seconds, respectively. At a distance of 1.5 meters, the response times for the front right and front left increased significantly to 7 seconds, while the back right and back left were recorded at

2.7 seconds and 3 seconds, respectively. A decline in detection performance was observed as the distance increased, particularly in the FR and FL areas. This reduction was attributed to multiple factors, one of which included signal strength. Consequently, additional assessment is required to enhance it.

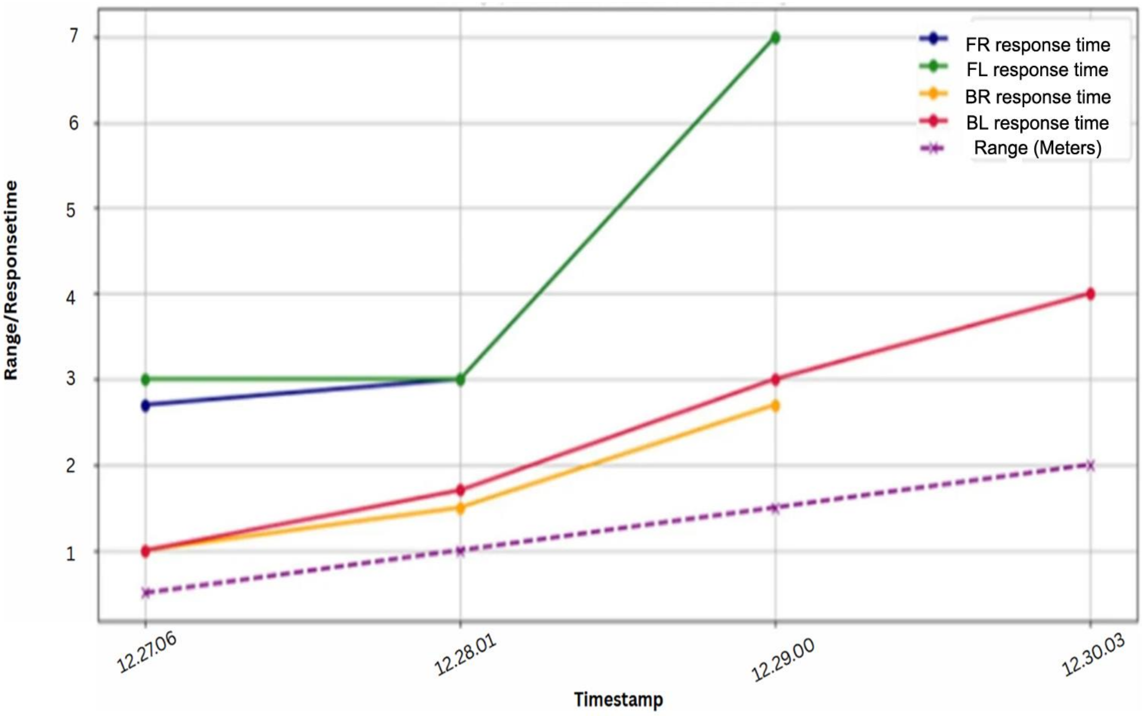

Figure 19. Graph of antenna position at the rear of the vehicle.

The data shown in Figure 19 reveals a decline in detection performance with increasing distance, particularly for FR and FL. This reduction is attributed to multiple factors, one of which is the strength of the signal. Consequently, additional assessment is required to enhance it. The outcomes of data retrieval from the vehicle tire presence detection system are accessible via the monitoring website.

Figure 20. Web monitoring.

Figure 20 illustrates the output on the web-based display screen, showcasing the four distinct RFID codes associated with the tires as they are presented on the monitor. The web display shows that there are no tires lost or exchanged.

3.2. Discussion

This study develops a system for detecting the presence of vehicle tires through the application of UHF RFID technology. The tire presence detection system was created as a solution aimed at reducing or minimizing theft or unauthorized tire replacement.

This study could serve as a foundation for future inquiries that may greatly enhance advancements in the automotive sector, particularly in the areas of driving safety and security. This system comprises three primary components, with the first being a UHF RFID reader that operates to read and identify tags functioning on UHF frequencies. Second, tire tags, which are RFID tags designed for application to vehicle tires, serve to provide unique identification to vehicle tire objects. Each tag contains a unique code that enables the system to recognize and differentiate between vehicle tires. Third, UHF antennas play a significant role in enhancing the tire tag reading range while also minimizing interference from various sources.

This study holds considerable practical relevance for enhancing vehicle security and is particularly applicable for organizations managing extensive vehicle inventories, such as those overseeing commercial vehicle fleets to mitigate tire theft. This system ensures that workshop customers have clear visibility into the status of their vehicle tires. Consequently, it has the potential to enhance efficiency in tire inventory management through the use of real-time data.

The choice of the EL-UHF-RF014 reader has demonstrated its effectiveness when compared to the BR-20 UHF RFID reader. The notable variation that arises is the signal strength generated by each reader. The EL-UHF-RF014 features an omnidirectional signal, whereas the BR-20 UHF RFID operates on a line-of-sight basis. Furthermore, it is essential to take into account the financial commitment that will be allocated to this system, as the BR-20 UHF RFID presents a more economical price point.

While the outcomes are encouraging, it is important to acknowledge certain limitations, particularly that the system was exclusively evaluated in a controlled setting (laboratory and workshop simulation). A broader field test is essential to evaluate performance in real-world conditions, including the impact of weather and environmental disturbances. Furthermore, this system exclusively assesses two categories of RFID readers that have been analyzed. Incorporating additional variants can offer a wider perspective on this technology. The monitoring system section lacks a fallback mechanism in the event of an IoT connection disruption. This may pose difficulties in situations where the internet connection is unreliable.

Based on these findings, there are several opportunities for further development, including integrating machine learning algorithms to predict potential tire damage based on historical data. Adding security features, such as user authentication or data encryption between RFID and IoT servers. Furthermore, developing mobile-based applications to provide easier access for users to monitor tire status.

4. CONCLUSION

This study concentrates on the automotive industry, particularly on vehicle parts, specifically tires. The primary aim of this study is to create a system for detecting the presence of vehicle tires, which will help mitigate the risks associated with theft or unauthorized tire replacement while also enhancing overall vehicle safety. The developed system effectively delivers real-time data by utilizing EL-UHF-RF014 readers and strategically positioned tire tags to accurately identify the location of vehicle tires. The test results indicated a reading accuracy of 87.5%, with response times fluctuating based on the antenna position.

The test results indicated that at a distance of 3 meters, the system was able to detect only two tire positions. The average response time for the front position was recorded at 3 seconds, while the side position had a response time of 1.4 seconds, and the rear position was noted at 3.2 seconds. Consequently, it was established that the best location for the antenna is on the side of the vehicle. This innovation is anticipated to serve as a crucial basis for enhancing vehicle safety, featuring a system capable of delivering information about the position of each tire via the tire tag affixed to the inner wall of the tire.

This study also pinpointed various weaknesses that present opportunities for additional growth. Future plans involve implementing the system on operating vehicles, enhancing the strength of the UHF signal, and creating a security system for tire tags to ensure they remain disconnected from other readers. The incorporation of anomaly detection capabilities via algorithm development will serve as a significant emphasis to enhance system precision. Therefore, this study plays a crucial role in enhancing vehicle safety and efficiency.

Funding: This research is supported by PPM of Telkom University, Bandung Technopark Telkom University, and PT. Transtrack, Indonesia (Grant number: KWR4.039/BTP01/BTP/2024).
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

REFERENCES

[1] M. Sathiyanarayanan, S. Mahendra, and R. B. Vasu, "Smart security system for vehicles using internet of things (IoT)," in *2018 Second International Conference on Green Computing and Internet of Things (ICGCIoT)*, 2018: IEEE, pp. 430-435.

[2] D. Mukhopadhyay, M. Gupta, T. Attar, P. Chavan, and V. Patel, "An attempt to develop an IOT based vehicle security system," in *2018 IEEE International Symposium on Smart Electronic Systems (iSES)(Formerly iNiS)*, 2018: IEEE, pp. 195-198.

[3] S. Mohanasundaram, V. Krishnan, and V. Madhubala, "Vehicle theft tracking, detecting and locking system using open CV," in *2019 5th International Conference on Advanced Computing & Communication Systems (ICACCS)*, 2019: IEEE, pp. 1075-1078.

[4] A. A. Elkhail, R. U. D. Refat, R. Habre, A. Hafeez, A. Bacha, and H. Malik, "Vehicle security: A survey of security issues and vulnerabilities, malware attacks and defenses," *IEEE Access*, vol. 9, pp. 162401-162437, 2021. https://doi.org/10.1109/ACCESS.2021.3130495

[5] N. Kiruthiga and S. Thangasamy, "Real time biometrics based vehicle security system with GPS and GSM technology," *Procedia Computer Science*, vol. 47, pp. 471-479, 2015. https://doi.org/10.1016/j.procs.2015.03.231

[6] P. Singh, T. Sethi, B. K. Balabantaray, and B. B. Biswal, "Advanced vehicle security system," in *2015 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS)*, 2015: IEEE, pp. 1-6.

[7] R. Aggarwal and M. L. Das, "RFID security in the context of" internet of things"," in *Proceedings of the First International Conference on Security of Internet of Things*, 2012, pp. 51-56.

[8] N. Kannouf, Y. Douzi, M. Benabdellah, and A. Azizi, "Security on RFID technology," in *2015 International Conference on Cloud Technologies and Applications (CloudTech)*, 2015: IEEE, pp. 1-5.

[9] E. B. Panganiban and J. C. D. Cruz, "RFID-based vehicle monitoring system," in *2017IEEE 9th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM)*, 2017: IEEE, pp. 1-6.

[10] J. Sourice, G. Kaboré, N. Sauger, A. Hamdoun, and M. Latrach, "Energy-autonomous UHF RFID sensor for tire pressure monitoring system," *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, vol. 2, p. 100072, 2022. https://doi.org/10.1016/j.prime.2022.100072

[11] R. Chen, X. Huang, Y. Zhou, Y. Hui, and N. Cheng, "UHF-RFID-based real-time vehicle localization in GPS-less environments," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 7, pp. 9286-9293, 2021. https://doi.org/10.1109/TITS.2021.3085824

[12] P. V. Nikitin, K. Rao, and S. Lazar, "An overview of near field UHF RFID," in *2007 IEEE international conference on RFID*, 2007: IEEE, pp. 167-174.

[13] D. Dukanac, "Application of UHF method for partial discharge source location in power transformers," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 6, pp. 2266-2278, 2018. https://doi.org/10.1109/TDEI.2018.006996

[14] Ç. P. Dautov and M. S. Özerdem, "Wavelet transform and signal denoising using Wavelet method," in *2018 26th Signal Processing and Communications Applications Conference (SIU)*, 2018: Ieee, pp. 1-4.

[15] H. Sinaga, H. Sitorus, D. Permata, Y. Yuniati, and R. Vraja, "Denoising of partial discharge waveforms using multivariate wavelet method," in *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 857, no. 1: IOP Publishing, p. 012020.

[16] A. Phinyomark, C. Limsakul, and P. Phukpattaranont, "An optimal wavelet function based on wavelet denoising for multifunction myoelectric control," in *2009 6th international conference on electrical engineering/electronics, computer, telecommunications and information technology*, 2009, vol. 2: IEEE, pp. 1098-1101.

[17] B. Xu, G. Sun, R. Yu, and Z. Yang, "High-accuracy TDOA-based localization without time synchronization," *IEEE Transactions on Parallel and Distributed Systems*, vol. 24, no. 8, pp. 1567-1576, 2012. https://doi.org/10.1109/TPDS.2012.248

[18] M. Srivastava, C. L. Anderson, and J. H. Freed, "A new wavelet denoising method for selecting decomposition levels and noise thresholds," *IEEE access*, vol. 4, pp. 3862-3877, 2016. https://doi.org/10.1109/ACCESS.2016.2587581

[19] A. Halidou, Y. Mohamadou, A. A. A. Ari, and E. J. G. Zacko, "Review of wavelet denoising algorithms," *Multimedia Tools and Applications*, vol. 82, no. 27, pp. 41539-41569, 2023. https://doi.org/10.1007/s11042-023-15127-0

[20] G. Baldazzi *et al.*, "Systematic analysis of wavelet denoising methods for neural signal processing," *Journal of Neural Engineering*, vol. 17, no. 6, p. 066016, 2020. https://doi.org/10.1088/1741-2552/abc741

[21] M. C. Caccami, S. Amendola, and C. Occhiuzzi, "Method and system for reading RFID tags embedded into tires on conveyors," in *2019 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, 2019: IEEE, pp. 141-144.

[22] R. Amorim, N. Barbot, R. Siragusa, and E. Perret, "Chipless RFID tag imaging system based on conveyor-belt radio frequency scanning," in *2023 IEEE Conference on Antenna Measurements and Applications (CAMA)*, 2023: IEEE, pp. 636-639.

[23] G. Ezhilarasi, D. Dhyanesh, P. Ragavendiran, P. Rajkumar, E. Maheswari, and N. S. AS, "Conveyor belt breakdown detector," in *2024 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS)*, 2024: IEEE, pp. 1-7.

[24] Y. Houeix, A. Rivadeneyra, C. Moraila, N. Rodríguez, D. P. Morales, and J. F. Salmerón, "A fast method to design and characterize the performance of UHF RFID tags," in *2022 IEEE 12th International Conference on RFID Technology and Applications (RFID-TA)*, 2022: IEEE, pp. 33-36.

[25] Q. Zhihong and W. Xue, "An overview of anti-collision protocols for radio frequency identification devices," *China Communications*, vol. 11, no. 11, pp. 44-59, 2014. https://doi.org/10.1109/CC.2014.7004523

[26] K. Zheng, K. Zhang, L. Xia, X. Wang, Y. Chen, and H. Wang, "A Fast Anti-Collision Algorithm for RFID Tag Identification," in *2022 IEEE 6th Advanced Information Technology, Electronic and Automation Control Conference (IAEAC)*, 2022: IEEE, pp. 1392-1395.

[27] M. Maemunah and M. Riasetiawan, "The Architecture of Device Communication in Internet of Things using inter-integrated circuit and serial peripheral interface method," in *2018 4th International Conference on Science and Technology (ICST)*, 2018: IEEE, pp. 1-4.

[28] M. A. Afandi, S. I. Purnama, and G. Wibisono, "Low-cost vehicle security system using location change and vehicle status based on internet of things," *Elinvo (Electronics, Informatics, and Vocational Education)*, vol. 9, no. 1, pp. 38-51, 2024.

[29] A. J. Samuel and S. Sebastian, "An algorithm for IoT based vehicle verification system using RFID," *International Journal of Electrical & Computer Engineering (2088-8708)*, vol. 9, no. 5, 2019. https://doi.org/10.11591/ijece.v9i5.pp3751-3758

[30] N. S. Saini, S. Shao, A. Kiourti, R. J. Burkholder, and J. L. Volakis, "RFID tags for in-situ tire monitoring," in *2016 URSI International Symposium on Electromagnetic Theory (EMTS)*, 2016: IEEE, pp. 575-578.

[31] A. Badriev, I. Makarova, and P. Buyvol, "The RFID system for accounting and control of truck tires with two-step identification: A case study," in *2020 13th International Conference on Developments in eSystems Engineering (DeSE)*, 2020: IEEE, pp. 100-104.

[32] F. Costa, S. Genovesi, M. Borgese, A. Michel, F. A. Dicandia, and G. Manara, "A review of RFID sensors, the new frontier of internet of things," *Sensors*, vol. 21, no. 9, p. 3138, 2021. https://doi.org/10.3390/s21093138

[33] A. Boursianis, T. Samaras, A. C. Polycarpou, and J. N. Sahalos, "A UHF RFID reader antenna for searching tagged items," in *2014 IEEE RFID Technology and Applications Conference (RFID-TA)*, 2014: IEEE, pp. 193-198.

[34] G. Pradeepkumar, S. Sneha, A. Thilakshanaa, N. Vinoth, and S. Chandraprabha, "Real time automatic vehicle monitoring system using IoT," in *2022 8th International Conference on Smart Structures and Systems (ICSSS)*, 2022: IEEE, pp. 1-6.

[35] M. Sathish, R. Kanchana, and R. Pranesh, "A smart vehicle monitoring system using real-time data processing and advanced sensor integration," in *2024 5th International Conference on Electronics and Sustainable Communication Systems (ICESC)*, 2024: IEEE, pp. 817-822.

[36] L. Pan *et al.*, "Application of computer big data technology in the safety intelligent monitoring of high voltage charging of electric vehicles," in *2021 International Conference on Intelligent Computing, Automation and Systems (ICICAS)*, 2021: IEEE, pp. 366-370.

[37] J. S. Jung, J. N. Lee, J. M. Kim, and J. K. Park, "An UHF RFID reader antenna with multitag identification for extremely low-temperature medical systems," *International Journal of Antennas and Propagation*, vol. 2020, no. 1, p. 2482961, 2020. https://doi.org/10.1155/2020/2482961

[38] X. Han and X. Kong, "The designing of serial communication based on RS232," in *2010 First ACIS International Symposium on Cryptography, and Network Security, Data Mining and Knowledge Discovery, E-Commerce and Its Applications, and Embedded Systems*, 2010: IEEE, pp. 382-384.

[39] M. Babiuch, P. Foltýnek, and P. Smutný, "Using the ESP32 microcontroller for data processing," in *2019 20th International Carpathian Control Conference (ICCC)*, 2019: IEEE, pp. 1-6.