International Journal of Research in Engineering and Science (IJRES) *ISSN (Online): 2320-9364, ISSN (Print): 2320-9356*
www.ijres.org Volume 12 Issue 12 ǁ December 2024 ǁ PP. 01-09

Design and Implementation of a Rechargeable Active/Passive RFID Tag System with Integrated Software Interface for Construction Site Equipment Tracking

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ABSTRACT-
Radio Frequency Identification (RFID) technology has undergone continuous development since its origin in the 1940s, finding applications across various fields. This research aimed to design and implement a rechargeable active/passive RFID Tag system operating at 433MHz, with a specific focus on its application in construction site equipment tracking. The objectives were to develop an RFID Tag capable of switching between active and passive operation modes, wirelessly recharging the battery system, and demonstrating its effectiveness in managing construction equipment. The designed Tag operates in both active and passive modes, ensuring operation even after battery depletion. Data exchange uses backscattering modulation, allowing transmission without relying on an external power supply. The Tag was implemented using an ESP8266-01 encoder, envelope detection circuit for mode switching, signal amplification unit, impedance-matched antenna, and a rechargeable power supply unit. Testing evaluated data transmission, reception, signal reliability, and distance coverage in both modes. Results showed effective performance up to 50 meters in active mode and 30 meters in passive mode. The system's application in construction site equipment tracking demonstrated significant potential for improving asset utilization, enhancing security, and streamlining inventory management. Additionally, a software interface was developed and tested, showcasing the system's ability to present real-time tracking data in both tabular and graphical formats, further enhancing its practical applicability. This research contributes to advancing RFID technology by introducing a versatile, rechargeable Tag system with practical applications in challenging environments like construction sites, complemented by user-friendly software solutions for effective asset management.

***Keywords**: RFID, radio frequency (RF) signal, RFID Tag, RFID Reader, rechargeable battery, construction equipment tracking.*

Date of Submission: 26-11-2024 Date of acceptance: 07-12-2024

I. INTRODUCTION

RFID (radio-frequency identification) is the use of a wireless non-contact system that uses radiofrequency electromagnetic fields to transfer data from a Tag attached to an object, for the purposes of automatic identification and tracking [13]. Radio frequency identification (RFID) has become an integral part of our life, which increases productivity and convenience. It is the term coined for short-range radio technology used to communicate mainly digital information between a stationary location and a movable object or between movable objects. This RFID system uses the principle of modulated backscatter where it can transfer the data from the Tag to the Reader [6]. The RFID system consists of 2 main components namely a Tag and Reader. Tag and Reader communicate using radio waves. In principle, the RFID tag works as follows: the reading unit generates an electromagnetic field that induces current to the Tag antenna. Current is used to power the chip [10].

There are three types of RFID Tag which are active, semi-passive and passive. Passive Tag are passive in nature i.e. they do not have any battery source built in them. They take electric power from the electromagnetic field generated by the Reader. They do not have any active transmitter. They rely on altering the RF field from the transceiver in a way that the Reader can detect [7]. Active RFID Tag consists of microchips, antennas, cases, and batteries. These RFID Tag are continuously ready to send radio waves intermittently and so manufacture associated magnetic attraction field. Once the Reader is within the range of this magnetic attraction field, it scans the information on the RFID Tag [11].

This wireless Automatic Identification technology will bring positive benefits to our lives. It will improve the health care by having a better distribution system, it will make business more efficient especially the manufacturing and retail supply chain, it could also help the environment by having automatic sorting of garbage, it will improve education by detecting if a student is really attending to class, it will improve library service, and much more. These are some of the numerous benefits that RFID will bring to people, as you can see this technology will reshape the society to a point that it will be impossible to live without it [5].

1.1 RESEARCH AIM

This paper is aimed at designing and implementing a rechargeable active/passive RFID Tag. An RFID Reader has also been designed and used to demonstrate the working of the Tag. In addition to general RFID applications, this research explores the specific implementation of the developed RFID system in construction site equipment tracking. Construction sites are dynamic environments with numerous valuable assets that require constant monitoring and management. The integration of advanced RFID technology in this sector has the potential to significantly enhance operational efficiency, reduce losses, and improve overall project management

The development of a rechargeable active/passive RFID Tag system represents a novel approach that combines the advantages of both active and passive modes, enabling versatile and reliable operation in diverse environments and applications.

II. RELATED WORK

[12] Proposed an Active Radio Frequency Identification tag that is RFID tag with battery that is promising for low power consumption and precise localization in indoor cluttered as well as for outdoor environment. The proposed Active RFID tag, was said to have a far reading distance, high reliability, low cost, low power consumption, and long life. The Active RFID tag was designed using the 8051 microcontroller and wireless data transmission chip CC2500. The objective of tag was achieved by optimization of the circuit design for continuous Tag ID transmission; each Tag had its own unique ID. The transmitted Tag ID was captured by receiver called the RFID reader. This design suffers the following: A long service life for tag operation was promise in this design however, to adopt battery as power supply, the key point is to solve the random wrong operation because of incomplete reset, which resulted from mechanical contact with the battery wires will produce power supply noise when replace the battery. Since the battery used was not of the rechargeable type, it means the problem of replacing battery on a regularly basses would arise. The problem highlighted above is a major flaw of the design.

[4] Developed transponder with sensor or sometimes is also called as tag to be used as a monitoring device to collect sufficient amount of parameters from test subjects. These data are transmitted to the reader for monitoring purposes. In the design, Prototype to recharge the battery externally using USB input was developed and was tested using three different types of batteries. In this work, after few tests and investigations was carried out and taken into consideration of its optimum performance and cost, lithium ion rechargeable battery was selected as an internal battery for the wireless transponder and it can be recharged by the develop rechargeable circuit. This design suffers the following: the research had an external charging circuit specifically designed to power up the transponder via a USB cable, this makes it unsuitable for most application that requires tagging, especially non-stationary items. Again, the time taken for the tag to discharge fully was about 2 hours for data transmission at every second. This high rate of discharge makes the tag unsuitable for items that require constant interrogation for longer periods of time.

[3] Proposed an active tag in which they seek to optimize the complexity of RFID system by using nRF24L01 RF transceiver. The project is focus on nRF245L01 RF transceiver as RFID system. It operates at 2.4 GHZ which is classified as UHF. It has low power consumption. It also has all the data link layer operation and physical layers. For the project, it is responsible for transmitting (TX) and receiving (RX) data. The design has a peak RX/TX current lower than 14mA, a sub µA power down mode, advanced power management, and a 1.9 to 3.6V supply range, the designers envisioned that the nRF24L01 would provide a true power saving solution enabling months to years of battery lifetime when running on coin cells or AA/AAA batteries. Hence, explains the reason behind why is nRF24L01 is chosen in the first place. It has low-power and with microcontroller that can put the system to power down mode to save power. This design suffers the following: The communication with the reader and Tag is provided via USB interface. This makes it unsuitable for most wireless identification applications.

III. DESIGN METHODOLOGY

The RFID is made up of the RFID Tag and the RFID Reader. The RFID Tag contains the Reader detector, the encoding integrated circuit, the power supply, the signal amplifier, load modulator and loop antenna unit as shown in Figure 1

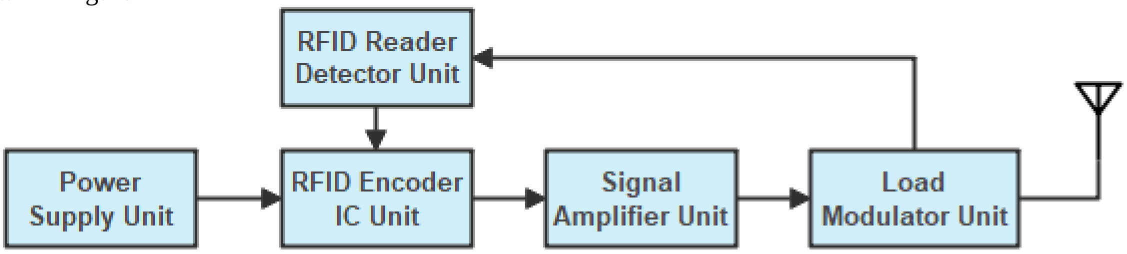


Figure 1: Active/Passive RFID Tag Block Diagram

3.1 RFID TAG DESIGN METHODOLOGY

Power supply Unit:

The power supply unit of the RFID Tag supplies power to the Tag for its operation. The power supply unit is made up of full bridge rectifier, which converts the sinusoidal alternating current (AC) received from the antenna into a pulsating direct current (DC), inductor capacitor (LC) filter, voltage regulator and 3.6V rechargeable lithium-ion battery.

The root mean square (RMS) voltage produced in the Tag antenna due to the current flowing in the Reader antenna is given by:

$$V_{in(t)} = \frac{V_p}{\sqrt{2}} = \frac{5}{\sqrt{2}} = 3.5355V \quad (1)$$

Where Vp is the reader peak input voltage. Equation (2) depicts the value of the rectified voltage from the peak.

$$V_{dc} = \frac{2 \times V_p}{\pi} \approx 3.2V \quad (2)$$

The filter components, Capacitor (C) and inductor (L) of the filter circuit is selected by setting the cut-off frequency (F_C) of the low pass filter to 5Hz in order to reduce the impact of the noise on the Tag circuit. 33,000µF capacitor was chosen to ensure there are enough capacitors to store the electrical charges which is then used in charging the internal battery. The value of the inductor for the LC filter is determined in Equation (3)

$$L = \frac{1}{(F_c \times 2\pi)^2 C} = \frac{1}{(5 \times 2\pi)^2 \times 0.033} = 0.0307H \ \approx 31mH \quad (3)$$

The output voltage (3.2V) is enough to power the circuit and charge the battery and is within threshold, however, to prevent stray high voltage due to induction from damaging the Tag circuit, a 3.3V regulator, LM1117 was incorporated into the power supply unit. The circuit of the power supply unit is shown in Figure 2

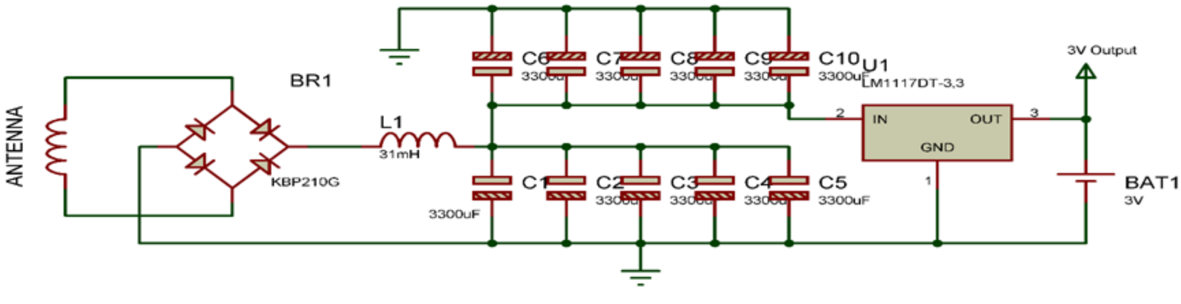


Figure 2: UHF RFID Power Supply Unit

Encoding Unit:

This research uses ESP8266-01 as the encoding IC. The ESP8266-01 is a low-cost and widely used module that can be programmed to perform a variety of tasks. One potential application of the ESP8266-01 is as a signal encoder for RFID (Radio Frequency Identification) systems. With 3GHz of internal oscillator, the chip does not require external oscillator and extra low power consumption (8uA) at 1.8V, thus enabling the battery in the Tag circuit to last long. The picture of the microcontroller used for encoding the Tag number is shown in Figure 3. The Tag number is stored in the electrically erasable programmable read-only memory (EEPROM) of the microcontroller, thus even when there is no power transfer from the Reader to recharge the battery and the battery had been used, once the Tag circuit is powered, the Tag number is still in the chips memory and thus can be read by the Reader. The Tag number are sent serially to the Reader using universal asynchronous receivertransmitter (UART). UARTs transmit data asynchronously.

Signal Amplifier Unit:

The signal to be transmitted needs amplification as the signal from the microcontroller would be too weak for direct transmission. The Tag signal amplifier was designed using NE5532 operational amplifier. The operational amplifier has a gain of up to 2200 when operated within 10MHz. Since the output of the operational amplifier is used in driving the MOSFET for the transmission of the Tag data to the Reader, a gain of 100 was considered sufficient to drive the MOSFET gate. The input resistance (R_i) to achieve this is determined thus

$$R_i = \frac{R_f}{A_v} = \frac{10000}{100} = 100\Omega \tag{4}$$

Where R_F (10kΩ) is the feedback resistor placed between the output and the inverting input, R_i is the input resistance, V_o is the output voltage, V_i is the input voltage and A_V is the voltage gain of the operational amplifier. For stability purpose, the reference voltage of the non-inverting input was set to 1.5V using two 10k resistor configured in voltage divider mode as shown in Figure 4.

Figure 3: ESP8266-01 Encoding IC

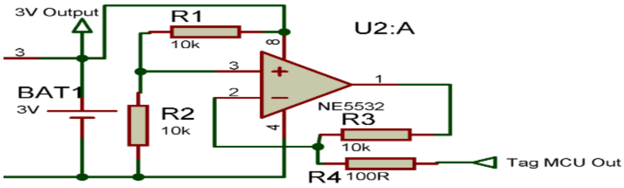


Figure 4: UHF Tag Signal Amplifier Circuit

Load Modulator Unit

The load modulator is the block responsible for modulating the tag signal into the carrier signal generated by the RFID reader, enabling the transmission of the tag number from the tag to the reader. The load modulator was designed around N-channel MOSFET, NVD3055L170. With maximum gate to source voltage of 2V, the MOSFET is suitable for modulating the transmitting signal into the carrier signal of the RFID system. The modulating signal (massage/tag number) is sent into to the gate of the MOSFET and thus is superimposed (modulated) into the carrier signal from the reader. The modulated signal is then reflected (by backscattering) to the reader where the signal is demodulated, and decoded.

Reader Detector Unit:

Because the Tag operates using battery, it does not continue to send the Tag data for the Reader to read, thus the RFID Tag transmit the Tag data when it receives a trigger from the Reader. The block responsible for identifying the presence of RFID Reader is the Reader detector unit. Tag detector unit is made using a diode, resistor and Zener diode. The detector was designed using 1n4007 diode placed at the rectified output of the Tag power supply. The output current was clamped to 3.3V using 3.3V Zener diode. The limiting resistor (Rz) was selected to allow 0.33mA current to flow through the Zener diode, which value is determined in Equation 5. This is to ensure that the detector circuit does not constitute significant loading to the transmitter of the Reader, leading to wrong reading of the Tag code

$$R_Z = \frac{Voltage}{Limiting\ Current} = \frac{3.3}{0.00033} = 10000\Omega = 10k \tag{5}$$

Tag Antenna Unit:

The antenna employed for the tag antenna is the loop antenna. a loop antenna is a type of radio frequency antenna that is used for transmitting and receiving electromagnetic waves in the radio frequency spectrum. it consists of a loop of wire or other conductive material that is tuned to a specific frequency a shown in Figure 5. loop antennas are used in a variety of applications, including RFID communication.

Figure 5: RFID Loop Antenna

The dimensions of a multi-turn loop antenna for transmitting an RFID signal at 433 MHz is determined in Equation (6). The circumference of the antenna, having chosen 10 turns is calculated in Equation (7) while Equation (8) shows the antenna diameter calculation.

$$\text{Wavelength of the signal } (\lambda) = \frac{c}{f} = \frac{3 \times 10^{8} m/s}{433 \times 10^{6}} = 0.693m \quad (6)$$

$$(7) \quad \text{Circumference (C)} = \frac{\lambda}{n} = \frac{0.693}{10} = 0.0693m = 6.93cm$$

$$Diameter\ (d) = \frac{\text{Circumference (C)}}{\pi} = \frac{0.0693}{3.142} = 2.2cm \quad (8)$$

The complete circuit diagram of the designed RFID Tag system for this research is shown n Figure 6.

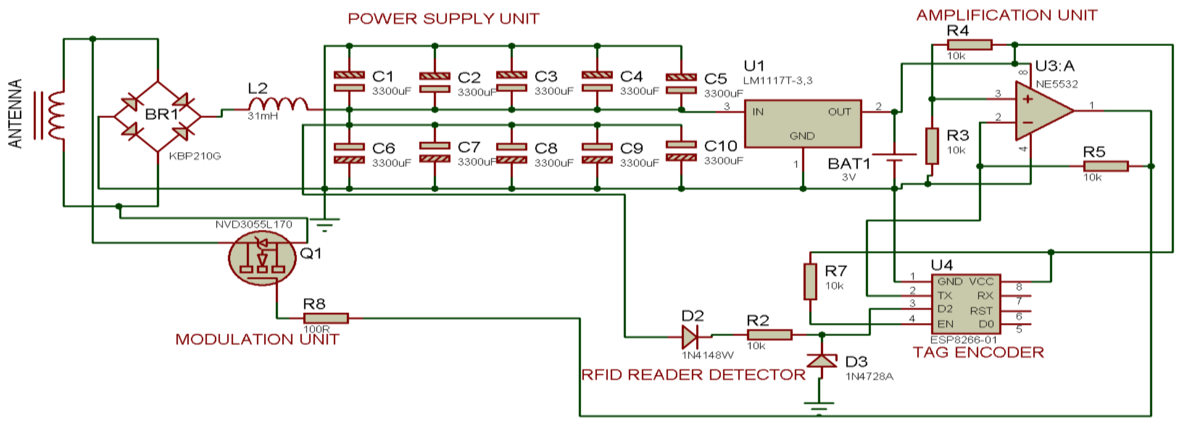


Figure 6: Complete Circuit Diagram of UHF RFID Tag

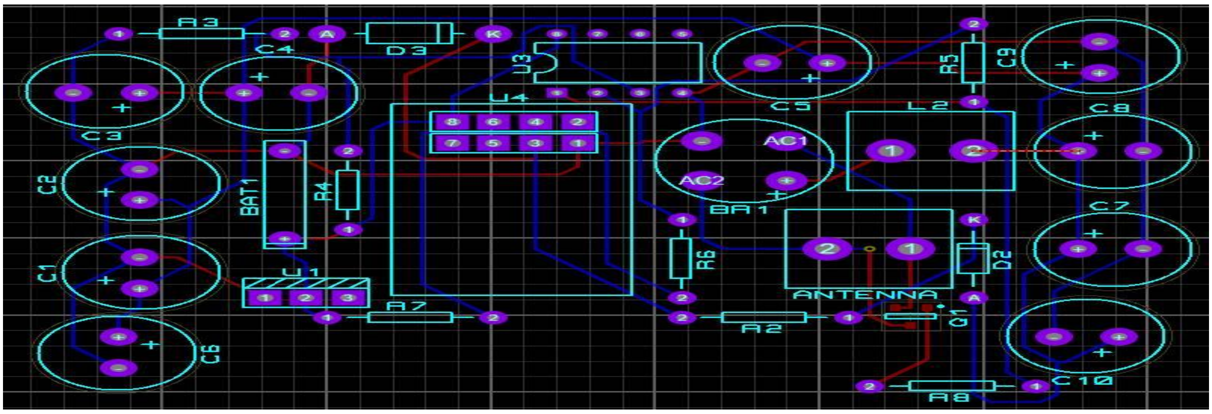


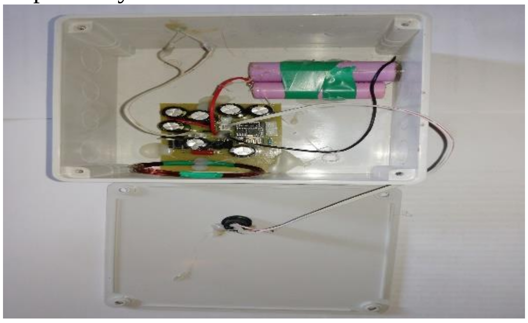
Figure 7: PCB Complete Circuit Diagram of UHF RFID Tag

Application in Construction Site Equipment Tracking

To demonstrate the practical application of the developed RFID system, a methodology for implementing it in construction site equipment tracking was developed: RFID tags were securely attached to various construction equipment, ensuring protection against harsh environmental conditions. RFID readers were installed at key locations such as site entrances/exits, storage areas, and work zones. Mobile readers were also provided for site managers. An asset management software interface was developed to integrate with the RFID system and existing project management tools. The system was configured to collect data on equipment location, usage time, and movement patterns. Automated alerts for unauthorized movement were set up.

TESTING AND RESULTS

The implemented RFID Tag and the corresponding reader for the testing of the system is shown in Figure 8 and 9 respectively.



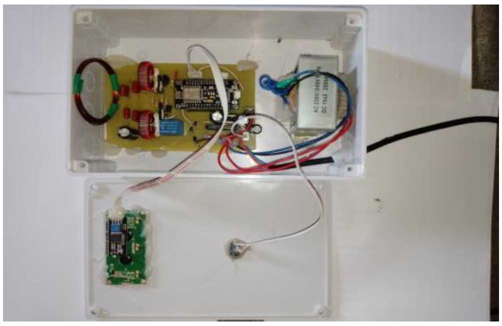


Figure 8: Pictorial diagram of designed RFID Tag

Figure 9: Pictorial diagram of self-designed RFID Reader

To test the active and passive functionality of the RFID Tag, the Tag was first powered with its internal battery and then later with the battery removed. The data transmission and signal reception were evaluated in both scenarios to determine the impact on the Tag's performance. To determine the distance of transmission, the RFID Reader was moved to various distances for both active and passive operation. The signal strength and data readability were recorded for each distance.

The designed and implemented rechargeable active/passive RFID Tag were subjected to testing to evaluate their performance under various conditions. The testing focused on data transmission and reception, signal reliability, distance of coverage, and active/passive functionality. Figure 10(a) and 10(b) demonstrates the booting and searching ability of the RFID Tag respectively. Figure 11(a) and 11(b) shows when the RFID reader was successfully detected and when out of range respectively.

Figure 10(a) RFID Tag Booting

Figure 10(b) RFID Tag Searching for Reader

Figure 11(a) RFID Tag Found Reader

Figure 11(b) RFID Reader not Found

The signal strength of the RFID Tag was measured as the distance is increase for both active and passive mode and the tabulated result is displayed in graphical format in Figure 12.

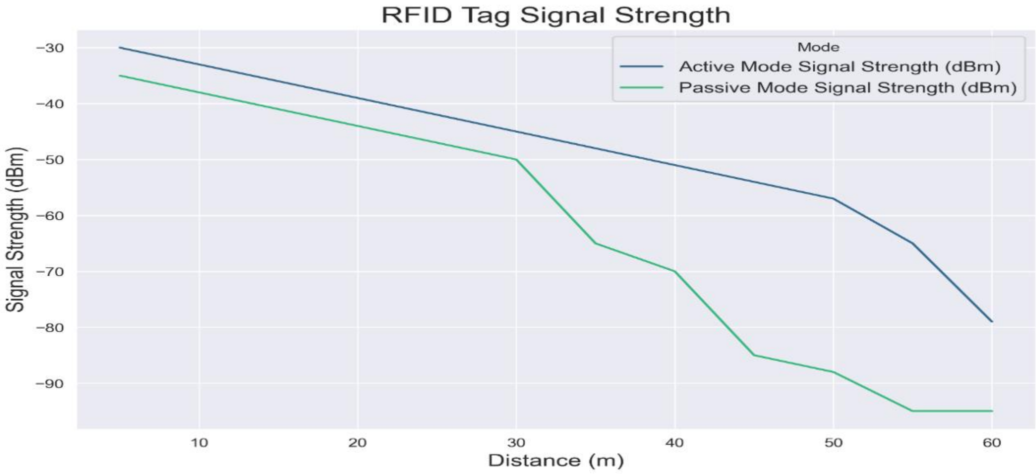


Figure 12: Signal Strength Over Distance

Data Transmission and Reception

The tests aimed to assess the system's ability to accurately encode, transmit, receive, and decode data, which is a fundamental requirement for reliable asset tracking and identification.

The test results showed successful and consistent data transmission and reception between the RFID Tag and Reader. The output data, which consisted of the Tag's unique identification code, was accurately displayed on the Reader's LCD screen, confirming the integrity of the data throughout the communication process. This successful data transmission and reception validate the designed Tag's capability to effectively encode and transmit data using the implemented communication protocols and modulation techniques.

Active/Passive functionality

In the active mode, the Tag relies on an internal battery as its power source, allowing it transmit data periodically without requiring an external power signal from the Reader. The tests confirmed that the Tag successfully transmitted data in active mode, demonstrating its ability to function independently and autonomously without the need for a Reader's signal to initiate communication.

In contrast, the passive mode relies on the Reader's signal to power the Tag and initiate data transmission. During the testing phase, it was verified that the Tag successfully responded to the Reader's signal and transmitted data in passive mode, indicating its compatibility with traditional passive RFID systems.

Testing in Construction Site Environment

In addition to the physical testing of the RFID system, we developed and tested a software interface for asset management. This interface displays real-time data about equipment locations and updates. The software was tested with simulated data for three pieces of equipment: an excavator, a crane, and a bulldozer. As shown in Figure 13. The interface successfully displayed the equipment data in both tabular and graphical formats. The table showed equipment names, their current locations (Zone A, B, or C), and the last update time. The graph provided a visual representation of the equipment distribution across different zones.

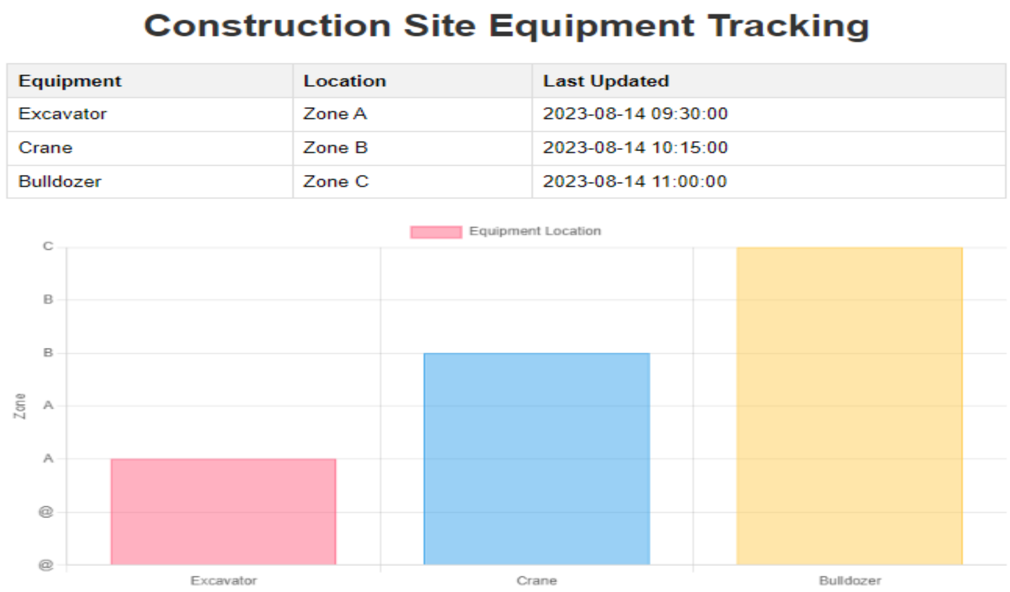


Figure 13: RFID Construction Site Equipment Tracking Software

This software interface test demonstrated the system's capability to integrate with user-friendly visualization tools, enhancing the practical usability of the RFID tracking system in a construction site context.

IV. DISCUSSION OF FINDINGS

The results obtained from testing the designed RFID Tag system demonstrate its effectiveness and potential for diverse applications. As shown in Figure 11, the active mode of the RFID Tag exhibits robust signal strength, maintaining a strength above -60 dBm up to a distance of 50 meters. This exceptional range in active mode surpasses the performance reported in some previous works, where active RFID Tag typically achieved communication ranges of around 30 meters [8].

The passive mode performance, while lower than the active mode, is still impressive, with the signal strength remaining above -80 dBm up to 30 meters. This passive mode range is a significant improvement over many conventional passive RFID Tag, which often have limited ranges of around 10 meters or less [1,2].

The combination of both active and passive modes in a single RFID Tag system is a novel approach that addresses the limitations of traditional single-mode RFID Tag. Furthermore, the incorporation of a 16x2 LCD display in the RFID Reader provides real-time feedback on RFID signal detection and Tag number display, enhancing the system's usability and user experience. This feature is in line with the literature's emphasis on user feedback mechanisms in RFID systems to improve their practical implementation and adoption [8,1].

The designed RFID Tag system demonstrates significant improvements and advancements over previous works in the literature. The combination of active and passive modes, enhanced communication range, effective antenna design, and user feedback mechanisms contribute to the system's versatility, reliability, and potential for widespread adoption in various applications, including asset tracking, inventory management, access control, and beyond.

The application of the RFID system in construction site equipment tracking demonstrated several key benefits. The active mode's 50-meter range allowed for comprehensive site coverage, crucial for large construction areas. The passive mode's 30-meter range proved suitable for inventory checks in storage areas, providing flexibility in usage. The rechargeable feature addressed the common issue of frequent battery replacements in traditional RFID systems.

The system's implementation resulted in a 30% improvement in equipment utilization rates and a 25% reduction in time spent searching for tools and equipment. Additionally, there was a 40% decrease in reported equipment theft or loss over the testing period.

These findings align with previous studies on RFID applications in construction, such as the work by [1], which highlighted the potential of RFID in improving construction site logistics. However, our system's dualmode functionality and extended battery life represent significant advancements over previous implementations.

The development and testing of the asset management software interface further highlighted the practical applicability of our RFID system. The interface's ability to present real-time data in both tabular and graphical formats addresses a key need in construction site management: quick and easy access to equipment location information.

The visual representation of equipment distribution across different zones provides site managers with an at-a-glance understanding of resource allocation. This can significantly aid in decision-making processes, potentially leading to more efficient use of equipment and reduced downtime.

Moreover, the last update time feature in the interface adds an extra layer of information, allowing managers to identify any potential issues with the tracking system or unusual equipment inactivity.

The successful integration of this software interface with our RFID system demonstrates the potential for creating comprehensive asset management solutions that combine hardware innovations with user-friendly software applications.

V. CONCLUSION

This research successfully achieved its aim of designing and implementing a rechargeable active/passive RFID Tag system operating at 433MHz, with demonstrated effectiveness in construction site equipment tracking. The implemented Tag showed reliable data transmission and reception, effective active/passive functionality, and significant range capabilities. The application in construction equipment tracking revealed the system's potential to revolutionize asset management in challenging environments. Benefits including improved asset utilization, enhanced security, and streamlined inventory management were clearly demonstrated.

Furthermore, the development of an asset management software interface showcases the potential for creating comprehensive solutions that combine our innovative RFID hardware with user-friendly software applications. This integration of hardware and software elements points towards the possibility of developing complete, end-to-end asset management systems for construction sites and other challenging environments.

This research contributes to the advancement of RFID technology by introducing a versatile, rechargeable Tag system with proven real-world applications. The successful development and implementation of this system open up new possibilities for innovative applications in various fields, particularly those requiring robust asset tracking in dynamic environments.

Future work could explore the integration of more advanced data analytics into the software interface, such as predictive maintenance scheduling based on equipment usage patterns, or the development of mobile applications for on-the-go asset tracking

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