Chapter 10

Multi-Frequency and Multi-Protocol RFID Card Reader Device: Hardware and Application Design

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Abstract

In this study, a dual frequency supported Radio Frequency Identification (RFID) card reader device that can operate at both 125 kHz and 13.56 MHz is developed for use in access control systems. Most of the existing systems operate at a single frequency band and therefore offer limited card compatibility. But, the proposed design supports multiple RFID standards and offers a more flexible and user-friendly solution. The reader functioning at 125 kHz can successfully detect cards based on the EM4100 protocol, whereas at 13.56 MHz, it effectively communicates with MIFARE Classic, MIFARE Ultralight, and Near Field Communication (NFC)-compatible cards. In the hardware design, two RFID modules have been optimized and integrated under the control of a single microcontroller. The system is capable of automatically detecting the card's frequency, switching to the appropriate protocol, and performing secure identity verification processes. Additionally, the device has been designed to be resistant to electromagnetic interference and capable of operating inside a metal enclosure, taking into account harsh environmental conditions. Thus, it can also exhibit reliable performance in areas such as industrial facilities, parking systems and dense

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metal environments. Thanks to this innovative approach, not only has compatibility with existing card infrastructures been achieved, but also an important step has been taken for long-lasting and secure access control systems.

INTRODUCTION

Radio Frequency Identification (RFID) is a technology and system that uses radio waves (wireless) to remotely identify and track objects. RFID systems consist of tag, reader, and back-end database components. Data transmission is carried out via electromagnetic fields (Piramuthu, 2007). The tag contains object identification (ID) data, the reader reads this data, and the back-end database is used to store product information (Khan et al., 2024). In the early days, RFID was only used to basically identify an object (for example, to understand who a product is) or to track its location. However, later, chip RFID went far beyond optical barcode technology. Thanks to radio waves, out-of-sight communication was provided. Therefore, the object could be read even when it was in the box. In addition, unlike barcodes, RFID chips could store more information, such as production date, manufacturer, temperature history, and transportation information. In addition, RFID systems can automatically identify an object when it enters the reading area without the need for human intervention (Lasantha et al., 2023).

Today, RFID technology is widely and effectively used in different sectors. RFID has gained application in many sectors such as manufacturing (e.g. inventory tracking), logistics (Wanhua, 2020), healthcare (Cheng et al., 2021), retail (e.g. stock tracking), construction, transportation systems (Casella et al., 2022). It offers a contactless, fast, and reliable solution, especially in security-oriented applications such as access control. Its main advantages include automation capability, multiple tag recognition, and reliable performance even in harsh environmental conditions. For example, it can identify many RFID tags simultaneously in fast-flowing production lines or at points with busy passages. In addition, RFID tags that are resistant to harsh environmental conditions such as high temperature, humidity, dust, and impact offer suitable solutions for industrial environments (Zhao et al., 2022).

RFID systems are divided into three basic groups according to their operating frequencies: Low Frequency (LF, 125–134 kHz), High Frequency (HF, 13.56 MHz), and Ultra High Frequency (UHF, 860–930 MHz). Generally, a certain type of passive RFID tag can only be read by a reader of the same type. LF RFID systems have a short reading range but work more stably in challenging environments such as metal and liquid. HF systems have a short reading range of about 12 cm and are widely used in contactless smart cards and access systems. UHF RFID systems provide a reading range of up to 3 meters (Ashour et al., 2023).

In RFID systems, readers are generally designed to operate only at a certain frequency, which leads to significant limitations in system integration. Most RFID readers operate either with only LF, only HF or only UHF protocols. This requires users to install multiple systems and increases hardware costs and system complexity. Because multiple readers or complex access systems must be installed to read RFID tags operating at different frequencies. This poses a significant problem in terms of traceability and flexibility, especially in industrial applications. In addition, due to frequency dependency, systems may need to be adapted separately to legal frequency restrictions in different geographical regions. In this context, the demand for hybrid systems is increasing today, because installation, maintenance and user management become more efficient thanks to devices that can support both HF cards such as MIFARE and LF cards such as EM4100. In addition, the importance of such systems for Internet of Things (IoT) integrations, multi-device compatibility and comprehensive security systems is rapidly increasing (Hirvonen et al., 2008).

In the past literature, it has been frequently emphasized that RFID systems mostly operate at only a single frequency, which creates serious limitations on system flexibility and hardware costs. In this context, Cui et al. (2019) discussed the place of RFID technology in IoT systems in terms of energy efficiency, data transmission and sensor integration in a review study. In the study, they detailed the working principles of both HF and UHF RFID systems. They analyzed the impact of different antenna designs and RF energy harvesting methods on RFID sensor performance. The authors emphasized that RFID-based sensors are generally optimized only for HF or UHF systems, and multi-frequency systems are not yet widespread, which limits interoperability in applications. Similarly, Bajaj et al. (2024) detailed the limitations of modern RFID reader antenna technologies in a review article. They also presented research trends in the development of multi-frequency systems. The authors noted that LF, HF, and UHF bands each serve different application requirements, but unfortunately most current readers are optimized for only a single frequency band. Based on this, the authors clearly emphasized the need for multiple readers, especially in environments where a wide variety of cards may be used, such as logistics, supply chain, and healthcare systems. In a separate study, Fischer et al. (2019) developed a multi-frequency (868 MHz and 915 MHz) RFID reader system in the

UHF band. The system was configured on a software-defined radio (SDR) platform in accordance with international standards. With this system, the authors aimed to increase the reading success in multipath environments. Experimental results showed that successful reading was achieved from the same tag at both frequencies. Thanks to frequency diversity, blind spots known as "dead zones" were significantly reduced. This study technically demonstrated the advantages of multi-frequency systems in terms of reliability, especially in harsh industrial environments. Similarly, Bournine et al. (2015) developed a multi-frequency RFID reader prototype operating at HF and UHF frequencies. They also integrated this device into a cloud-based traceability system. In the designed system, they combined Adafruit PN532 HF module and HYM730 UHF module using Arduino Due platform. They managed the frequencies sequentially with microcontroller software. For a secure access model, after user authentication with HF tag, transactions were allowed via UHF. This study presented a multi-frequency RFID that supports different RFID protocols on the same device and can be integrated into traceability processes.

This study aims to develop a multi-frequency and multi-protocol RFID reader system that can operate at both LF (125 kHz) and HF (13.56 MHz) frequencies on a single device. The developed system can successfully identify EM4100 based low-frequency cards and MIFARE Classic, MIFARE Ultralight and NFC compatible high-frequency cards. Thus, this application aims to provide a flexible and multi-purpose solution in response to the limited frequency compatibility of traditional RFID readers, similar to previous studies. The reader side of the RFID allows two different RFID modules to be automatically controlled by a single microcontroller. In this way, users can perform access transactions without thinking about which card they use in the system. In addition, the device's electromagnetic interference-resistant structure and its ability to operate even in metal enclosures make it suitable for use in harsh industrial conditions.

MATERIAL AND METHODS

Hardware Components

In the proposed system, a dual-frequency RFID card reader architecture is developed to enable the detection of both low-frequency (125 kHz) and high-frequency (13.56 MHz) RFID cards. At the core of the system is the NUC131 1L series microcontroller based on the Advanced RISC Machine (ARM) Cortex-M0 core. It also manages the communication with the peripheral components via Serial Peripheral Interface (SPI), Inter-

Integrated Circuit (I^2C) and Universal Asynchronous Receiver/Transmitter (UART) protocols.

For the LF section, an analog front end (AFE) circuit was designed according to the EM4100 protocol. The circuit consists of a resonant inductance-capacitance (LC) network operating at 125 kHz driven by a 50% duty cycle pulse-width modulation (PWM) signal generated by the microcontroller. A specially designed air core coil antenna optimized for high quality (Q) factor and mechanical stability was used. The multi-turn antenna design is shown in Figure 1. The inductance and resonant frequency were verified using an inductance-capacitance-resistance (LCR) meter and the antenna was tuned with a series capacitor. The magnetic signal induced in the LC circuit is passed through a low noise differential preamplifier, followed by an envelope detector and a comparator circuit to convert the signal to a digital format suitable for further processing. The digitized data is transferred to the digital input pin of the microcontroller and made available for timing analysis in the software layer.

For the HF section, a Texas Instruments TRF7970A RFID transceiver was used. This module supports International Organization for Standardization / International Electrotechnical Commission (ISO/IEC) 14443 and ISO/IEC 15693 standards, enabling communication with MIFARE Classic, MIFARE Ultralight, and near field communication (NFC) compatible cards. A planar spiral printed-circuit-board (PCB) antenna, designed according to calculation tools and radio frequency (RF) design guidelines, was directly interfaced with the TRF7970A module. The PCB antenna design is shown in Figure 2. Critical parameters such as trace width, spacing, and impedance matching were carefully considered to minimize signal loss and maximize read range. SPI communication was established between the TRF7970A and the microcontroller, and an interrupt request (IRQ) line was configured to trigger card detection events.

Figure 1. Multi-turn coil antenna (125kHz)

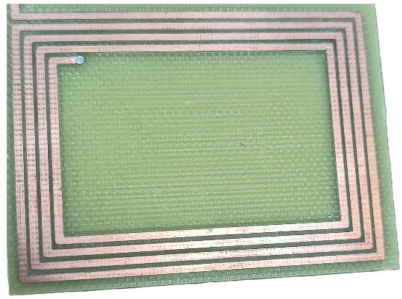

Figure 2. PCB antenna design (13.56Mhz)

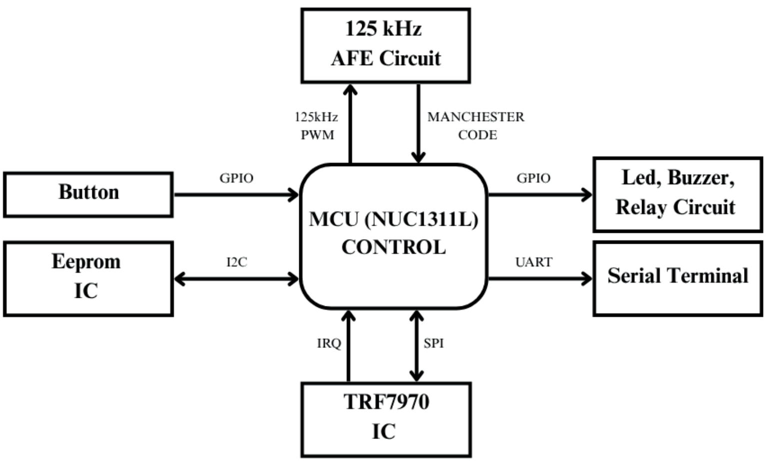

Figure 3. General Block Diagram of the Hardware

In addition to the main RFID modules, the system is equipped with light-emitting diode (LED) indicators, a buzzer circuit, and a relay module for access control feedback. Card registration and deletion are performed via a push-button interface, and card identification numbers (ID) are stored in an external electrically erasable programmable read-only memory (EEPROM) chip. The system compares each scanned card with the EEPROM database to verify authorization status. All relevant information, including the scanned card ID and authorization status, is transmitted via UART to a connected terminal for real-time monitoring. Figure 3 shows the overall block diagram of the design.

Software Components

RFID cards operating at 125 kHz typically use data encoding methods such as Manchester or Non-Return-to-Zero (NRZ). Manchester decoding is used in this study due to its reliability in detecting bit transitions. The microcontroller monitors the rising and falling edges of the input signal to determine each bit: a rising edge is interpreted as a logical '1', a falling edge as a logical '0'. This method allows the transmitted data stream to be accurately reconstructed. After the 64-bit Manchester encoded data stream is decoded, cyclic redundancy check (CRC) verification is performed to ensure data integrity. After successful verification, the 64-bit stream is processed to extract a 32-bit unique identifier (UID) used for access control logic.

The TRF7970A module for high-frequency cards manages communication using ISO/IEC compliant protocols. When a card enters the detection range, the module generates an IRQ, which triggers the microcontroller to initiate SPI-based data reception. The incoming data stream is parsed according to the card's protocol structure and the UID is extracted. After verification and format conversion, the UID is reduced to a 32-bit card ID for uniformity in access processing.

In both frequency domains, the system ensures that only valid and correctly formatted card IDs advance to the access control evaluation phase. To support dual-frequency operation, the system alternates between LF and HF scan cycles. The microcontroller initiates a 200 ms LF scan window and actively checks 125 kHz cards. If no cards are detected within this window, the LF scanner is disabled and the HF scanner is enabled for the next 200 ms. This alternating cycle continues indefinitely. If a card is detected during any of the scan stages, the system temporarily stops scanning to process the card data. Once processing is complete, the alternating scan routine continues from the next cycle.

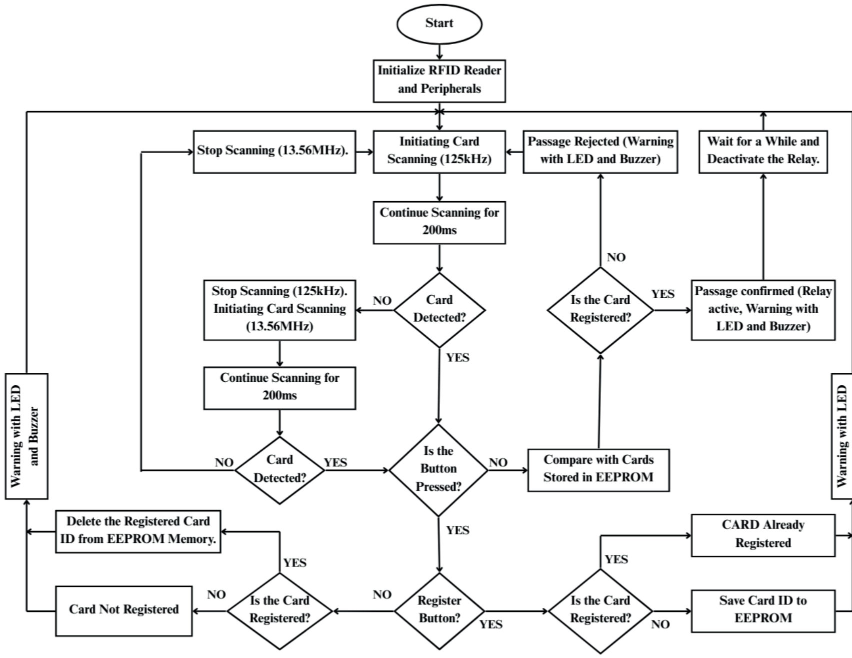

Figure 4. Algorithm Flowchart

The access logic of the system includes card registration, deletion and authorization control. A user can press a physical button to register a new card or delete an existing card. When a card is presented in this mode, the system checks its existence in the EEPROM database. If the card is not registered, it is added to the database. If it is already registered, a "duplicate" warning is given. If deletion is requested, the card is removed from the EEPROM or a "not found" message is returned if it is not stored at all. In normal operation, each card scanned is compared with the list stored in the EEPROM. If the card is recognized, the system authorizes access by triggering the relay, turning on the green LED and briefly sounding the beeper. For unrecognized cards, the system activates the red LED and emits a long beeper tone. All card events and system responses are recorded and transmitted to a serial terminal via UART for monitoring and debugging purposes. Figure 4 shows the general flowchart for the software algorithm.

RESULTS

In this study, a dual-frequency RFID card reader system capable of operating at both 125 kHz and 13.56 MHz was successfully designed, implemented, and tested. All tests and experimental analyzes were carried out at BUTKON R&D center (BUTKON, 2025). The system demonstrated reliable performance in reading EM4100-compliant LF cards, including MIFARE Classic, MIFARE Ultralight, and NFC-enabled cards, as well as ISO/IEC 14443-compliant HF cards. Combining both frequency bands under the control of a single microcontroller enabled seamless protocol transition and real-time access control functionality. Figure 5 shows the designed circuit board, and Figure 6 shows the card ID information read as a result of the tests.

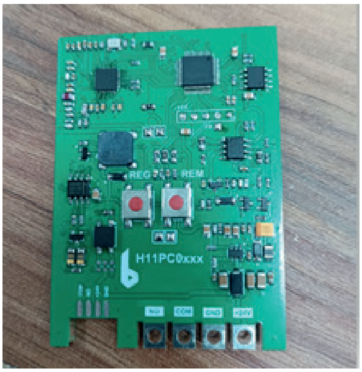

Figure 5. The prototype of the designed circuit

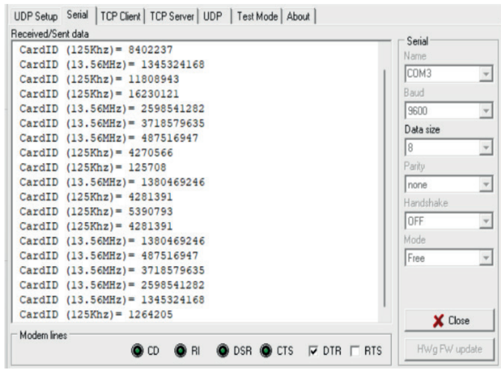

Figure 6. Serial Terminal Output

Considerable emphasis was placed on robust hardware design practices, including careful PCB layout with ground plane separation and controlled return paths to reduce electromagnetic interference. LC resonator and planar PCB antenna structures were optimized to target resonant frequencies and validated through experimental testing using LCR meters and functional range measurements. Terminated antenna designs provided stable performance and adequate read distances in both frequency domains.

Overall, the developed system provides a compact, scalable and cost-effective solution for modern access control applications. Its ability to support multiple card types, conduct secure authentication and withstand harsh environmental conditions makes it suitable for use in factories, smart building entry points and high-traffic areas. The dual-frequency design ensures long-term compatibility with a wide range of existing RFID infrastructures and simplifies system management by combining different card technologies on a unified reader platform.

CONCLUSION AND DISCUSSION

In this study, a multi-frequency and multi-protocol card reader prototype that can read both low-frequency (LF, 125 kHz) and high-frequency (HF, 13.56 MHz) RFID cards was developed. The developed system successfully identified EM4100-based LF cards and HF/NFC compatible cards such as MIFARE Classic and Ultralight; and automatically switched between frequencies. The tests showed that the cards could be read correctly and that the system could operate stably even in metal enclosures against electromagnetic interference. In this way, it offers a practical, flexible and reliable solution for security-oriented applications such as device access control.

While the current system successfully achieves multi-frequency RFID card detection and access control functionality, future studies could focus on extending its capabilities through integration with IoT platforms. Adding IoT support would enable real-time remote monitoring, centralized data logging, and improved traceability of access events. Secure communication protocols can be implemented to transmit card activity to cloud-based databases, allowing for advanced data analytics and audit capabilities. In addition, the development of a user-friendly web or mobile application interface could simplify user registration, card management, and remote authorization processes. Such improvements would enhance the system's scalability and usability in complex or distributed environments, such as smart buildings, campuses, or industrial facilities. Incorporating features like biometric verification or multi-factor authentication in future iterations may also further strengthen system security and versatility.

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Conflict of Interest

The authors have declared that there is no conflict of interest.

Author Contributions

Mustafa Talip Koyuncu: Methodology, investigation, visualization, writing.

Burak Demir: Methodology, investigation

Muhammet Fatih Aslan: Writing, supervision.

Akif Durdu: Supervision.