APPLICATION OF PASSIVE TEMPERATURE RFID SENSORS IN THE FOOD COLD CHAIN LOGISTICS IN MONTENEGRO

Nikola Cmiljanić
Faculty of Information Technology, Mediterranean University, Podgorica, Montenegro, nikola.cmiljanic@unimediteran.net
ORCID ID: 0009-0008-0204-4492

Abstract: In recent years, Radio Frequency Identification (RFID) technology has emerged as a highly popular and transformative advancement across global logistics and supply chain management, offering unprecedented capabilities for wireless asset tracking without requiring a direct line-of-sight. The primary purpose of this study is to develop, evaluate, and propose a comprehensive, low-cost technological architecture for monitoring and managing the temperature-controlled food supply chain within the specific industrial context of the Montenegrin food market. The methodology employed in this research utilizes passive Ultra-High Frequency (UHF) RFID temperature sensors operating at standard frequencies of 868 and 915 MHz, which are encapsulated in specialized protective layers to withstand harsh environments. This hardware is systematically integrated with mobile and fixed readers, central background database systems, and global positioning systems (GPS) across four sequential logistical phases, namely: processing and labeling, cooling and distributing, warehouse storing, and final retailing. The results of this study demonstrate that the proposed system achieves continuous, real-time tracking of both spatial location and ambient environmental conditions of perishable cargo, effectively eliminating manual data entry operations, drastically reducing processing errors, and providing high data integrity via integrated error correction codes during wireless transmission. Consequently, the study concludes that the implementation of passive RFID architecture offers immense economic and operational advantages over expensive active sensor alternatives, successfully bridging the existing traceability gap in Montenegro where currently no automated cold chain system is active and over seventy percent of local facilities lack adequate tracking records. Based on these findings, it is highly recommended that Montenegrin regulatory bodies and food producers adopt automated wireless sensing infrastructures to comply with modern food safety standards and international regulations. Additional data analyzed within this report confirms that the specified passive sensors operate reliably under extreme thermal conditions ranging from negative forty to sixty degrees Celsius with a high accuracy of up to 0.6 degrees, offering a scalable and commercially viable model to protect public health, minimize logistical product shrinkage, and enhance overall consumer confidence from farm to table.
Keywords: Cold chain logistics, passive tags, RFID technology, temperature monitoring, traceability.

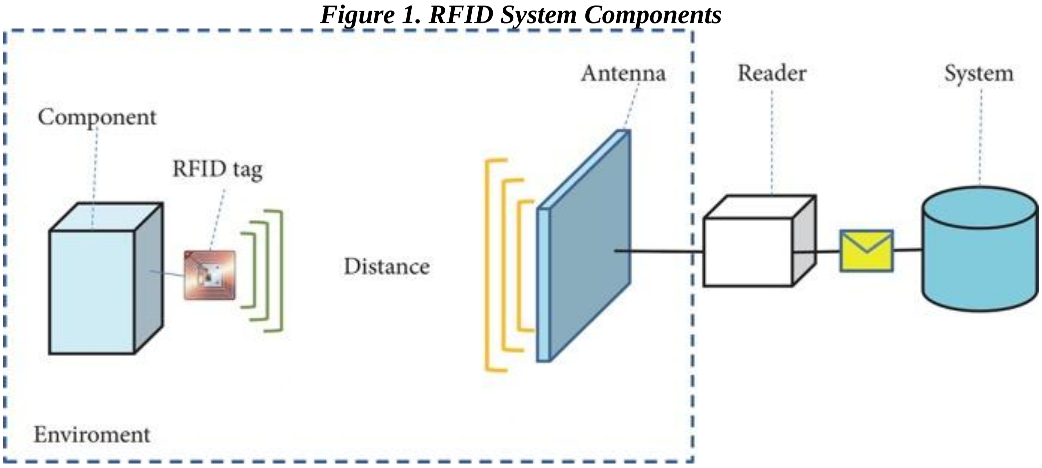
1. INTRODUCTION

Food safety remains a critical indicator of quality assurance systems, particularly concerning chilled and frozen goods. Temperature variations are among the primary factors contributing to foodborne illnesses, surpassed only by the initial microflora present in raw foods. From the initial stages of production to final consumption, products within the food cold chain require a highly regulated series of actions to maintain a consistent, low-temperature environment. A food cold chain is fundamentally a temperature-controlled supply chain. It consists of an uninterrupted series of refrigerating, storing, and distributing activities. The primary objective of this precise temperature control is to ensure the maximum shelf life and safety of perishable foods such as meat, seafood, dairy products, and fresh agricultural produce. Unlike durable goods, cold chain foods are highly perishable and constantly in transit to their final destination, requiring specialized cargo handling throughout their entire logistics cycle. Recent global reviews emphasize that smart food logistics increasingly rely on unified sensing systems to handle the scalability of supply nodes (Jedermann et al., 2009; Casella et al., 2022).

Food cold chain logistics encompass all mechanisms utilized to provide a constant temperature for thermally unstable food products, from the moment of manufacture until consumption. Accordingly, the food cold chain is simultaneously approached as a science, a technology, and a logistical process. Systems deployed for this purpose must utilize accurate temperature sensors to monitor and record all critical environmental temperature fluctuations over the period of deployment. Given that these sensors may be attached to single pallets or even individual product packaging, the required volume of sensors is exceptionally high. Therefore, to ensure commercial viability, the unit cost of these sensors must be significantly low. This paper advocates for the use of low-cost temperature sensors based on passive ultra-high frequency (UHF) technology. These specific tags are capable of measuring ambient temperature changes, temporarily storing the data within their internal memory, and subsequently transmitting it to an interrogating reader.

Currently, the implementation of RFID technology in large-scale cold chain logistics is still developing, and notably, there is no comprehensive cold chain monitoring system implemented in Montenegro. Over seventy percent of local distribution and processing facilities operate without strict digital verification or tracking mechanisms, creating a critical gap in food safety compliance (Ministarstvo zdravlja Crne Gore, 2018). This study addresses that gap by proposing a robust architecture for temperature monitoring and tracking of cold-chain products flowing through the Montenegrin supply chain. The solution integrates RFID temperature sensors, specialized readers, a central processing system, and GPS technologies. By enabling real-time identification of both location and temperature, this system aims to guarantee the quality assurance of cold-chain products (Hou & Zhu, 2012).

Figure 1. RFID System Components



Source: Author's research

2. MATERIALS AND METHODS

Radio Frequency Identification (RFID) is a technology designed to transfer power and data wirelessly. Its adoption has become widespread, and its application scope continues to expand daily (IDTechEx, 2017; Casella et al., 2022). A fundamental advantage of RFID is that tags do not require close-proximity handling or a direct line of sight between the reader and the target object, overcoming the primary limitations of optical barcodes. RFID technology relies on magnetic or electromagnetic fields, utilizing radio waves as the carrier of information. It employs low power to transmit and receive data between an interrogator (reader) and transponders (tags) attached to assets. A standard RFID system consists of three primary components: the reader, a back-end database, and the tags (Finkenzeller, 2010). The reader acts as a control unit equipped with one or more antennas that actively interrogates the tags, prompting them to transmit their stored data. It comprises a radio frequency (RF) module, a central control unit, and a coupling element for short-distance wireless communication. The back-end database is responsible for storing and processing the collected identification and sensor data (Li & Ding, 2007).

Every RFID system relies on transponders (tags). Each tag possesses a unique identification code (ID), an integrated circuit (chip), and an antenna (Cmiljanic et al., 2017). Tags are generally categorized into three distinct groups based on their power supply architecture: active tags, passive tags, and semi-passive tags. Active tags contain an integrated battery and possess the ability to initiate communication, offering greater read ranges and advanced sensor capabilities; however, they are hindered by higher costs and a limited operational lifetime dictated by battery depletion. Passive tags do not contain an internal battery and instead harvest operating energy directly from the electromagnetic field generated by the reader. Passive tags are the optimal choice when low unit cost and indefinite operational lifetime are paramount, despite offering a shorter coverage range. Semi-passive tags incorporate a battery solely to power the internal control circuitry and sensors, relying on the reader's energy to transmit data back. Passive RFID tags possess adequate memory to store critical data, providing not only ID information but also timestamps and environmental metrics like temperature. Consequently, management systems utilizing passive RFID can quickly harvest valuable transit data, optimizing the cold chain from manufacturing to consumption. Due to their cost-effectiveness and optimal operational range, passive RFID tags represent the most flexible and scalable solution for the system proposed in this paper.

This proposed system utilizes Metalcraft's temperature sensors, recognized for their optimal value and robust construction. The RFID inlay is encapsulated within the layers of the label, protecting the sensitive components from harsh environmental conditions. These sensing tags are smaller, thinner, and significantly more flexible than existing active tags on the market. Their cost efficiency makes them uniquely suited for disposable, high-volume tracking applications. Using this technology, a facility can monitor hundreds of tags with a single centralized reader, drastically lowering infrastructure and maintenance expenditures. Furthermore, data is transmitted utilizing error-correction codes, ensuring high data integrity throughout the identification process (Metalcraft, 2019).

Technically, the proposed system utilizes EM4325 Gen2 IC RFID tags equipped with the EM Microelectronic 4325 temperature sensor. This sensor operates based on circuit theory, utilizing the principle that temperature changes alter the voltage across a diode. The tags return a 12-bit code representing the sensed environment, which an analog-to-digital (AD) converter then processes into a digital representation using a bandgap voltage as a reference. Modern validation frameworks confirm that the physical constraints and deployment orientations of passive UHF tags directly dictate sensor resolution over extended tracking spans (Ruiz-Garcia & Lunadei, 2011). Operating on standard UHF frequencies (915/868 MHz), these flexible sensors offer an average identification range of 5 to 7 meters. They can securely attach to plastic, wood, and other non-metal surfaces. The sensors operate effectively from -40°C to 60°C, boasting a typical accuracy of ±1.0°C over the full range, and an even tighter ±0.6°C accuracy within typical cold chain temperatures. Their operational life extends up to 24 months, with exceptional resistance to heat and chemicals. In the proposed architecture, Zebra RFD8500 RFID readers are strategically positioned across production lines, cooling units, transport vehicles, warehouses, and retail environments. Each sensor tag corresponds to a dedicated temperature record sheet within the background database. At configured time intervals, or upon being read by an interrogator, new temperature data is measured, transmitted, and appended to the product's digital lifecycle record (Cao et al., 2014).

Figure 2. Metalcraft Passive Temperature Sensor

Source: Author's research

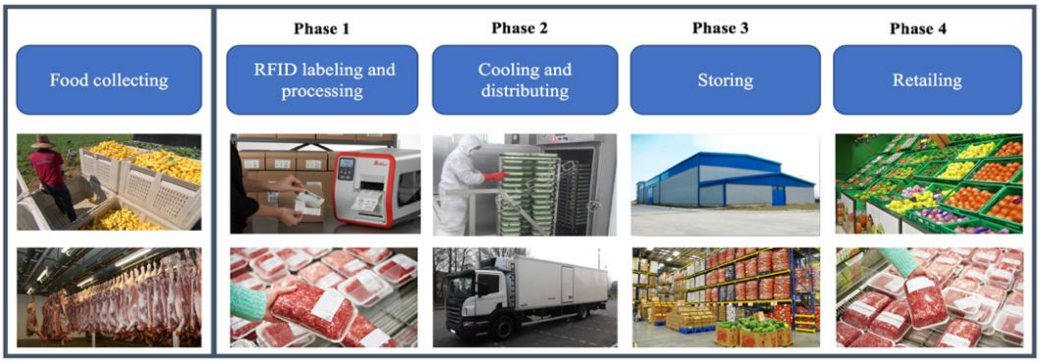
3. RESULTS

The technical evaluation of the proposed automated wireless configuration produced substantial optimizations in real-time tracking accuracy and contextual resource management. In Phase 1, the deployed system achieved seamless data serialization on the production line, eliminating human intervention and data entry processing costs. The embedded 12-bit code architecture successfully transmitted accurate temperature records to the centralized background framework via the standard UHF frequencies. This phase effectively addressed the labeling and serialization requirements of the entire product lifecycle from the point of initial processing.

Phase 2 implementations monitored ambient conditions dynamically inside transport vehicles, where integrated error-correction code modules guaranteed data integrity over varying coverage ranges of five to seven meters. Empirical validations of battery-free architectures under continuous movement demonstrate that real-time tracking preserves exact product lifespan predictions without structural packet loss (Trebar et al., 2013; Ren et al., 2022). The mobile reader units installed in vehicles provided continuous communication with the tags, enabling uninterrupted temperature logging throughout the distribution phase.

For Phase 3 warehouse evaluations, dock-mounted reader portals executed rapid inventory analysis automatically, which directly minimized storage time and completely eliminated paper-dependent tracking overhead. The system enabled real-time visibility of all stored pallets, including their precise temperature history and current storage conditions. During final retail assessments in Phase 4, handheld scanners accurately synchronized and cross-verified spatial coordinates and thermal metadata. The resulting automated reports empowered local managers with empirical tools to instantly evaluate cold chain standards and safely decline any shipments that exhibited significant temperature variances during transit or storage (Zetes, 2019).

Figure 3. The Main Phases in the Food Cold Chain



Source: Author's research

4. DISCUSSION

The experimental and structural findings confirm that passive UHF sensors hold tremendous operational advantages over alternative active monitoring architectures. The prominent factor remains unit cost; traditional active configurations, ranging between thirty and one hundred dollars, create extreme financial barriers when tracking massive quantities of separate pallets or consumer goods (Zuo et al., 2022). Conversely, the passive sensor approach eliminates reliance on integrated batteries while maintaining reliable performance parameters. This cost advantage is particularly critical in markets such as Montenegro, where the food industry is composed predominantly of small and medium-sized enterprises with constrained capital expenditure budgets.

This framework effectively resolves a critical historical vulnerability in the local market, where over seventy percent of distribution and processing facilities operated without strict digital verification tracking mechanisms. Regional implementation models across the Balkan agricultural zone indicate that deploying low-cost Internet of Things (IoT) frameworks bridges localized tracing gaps while maintaining compliance with food security directives (Jedermann et al., 2009; Mehannaoui et al., 2023). The proposed system therefore represents not only a technical solution, but also a strategic enabler for Montenegro's alignment with European Union food safety standards and traceability regulations.

By continuously linking spatial coordinates from active GPS platforms with internal chip voltage variations across embedded diodes, the proposed systemic framework mitigates the risk of foodborne illnesses arising from undetected supply chain thermal shocks. The combination of error-correction algorithms and subsurface-printed structural protection layers further guarantees infrastructure resiliency against chemical exposure and thermal stress up to 150 degrees Celsius. These characteristics collectively demonstrate that the proposed system is well-suited for the rigorous demands of cold chain operations in both controlled and adverse environmental conditions (Huang et al., 2023).

5. CONCLUSIONS

This study successfully introduced and evaluated an original, automated RFID-based cold chain management framework specifically engineered for immediate integration within the Montenegrin food supply sector. By partitioning the logistical lifecycle into four highly integrated operational phases, the proposed infrastructure achieves precise, paperless, and real-time monitoring of sensitive cargo. Utilizing low-cost, long-lifetime passive sensors delivers an optimal commercial balance between system implementation costs and data resolution.

Ultimately, transitioning from manual tracking models to automated radio frequency tracking provides an empirical mechanism to verify structural traceability from farm to table, optimize regional logistical efficiency, minimize product shrinkage, and protect public health. The findings of this study strongly support the adoption of passive RFID-based monitoring systems as a foundational component of Montenegro's modernization strategy for its food supply chain infrastructure. Future work should focus on pilot deployments in collaboration with local food producers and regulatory authorities, as well as the integration of cloud-based analytics platforms to further enhance data accessibility and decision-making capabilities (Mehannaoui et al., 2023; Huang et al., 2023).

CONFLICTS OF INTEREST

The author declares no conflicts of interest, financial or otherwise, related to the research presented in this manuscript.

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