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Posted Date: 2 February 2026

doi: 10.20944/preprints202601.2131.v1

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Article

Construction of an Innovative RFID-Based Cross-System Fire Protection Data Fusion and Intelligent Decision-Making System

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Highlights

This is an optional section in "Sensors", whose goal is to increase the discoverability and readability of the article via search engines and other scholars. Highlights should not be a copy of the abstract, but a simple text allowing the reader to quickly and simplified find out what the article is about and what can be cited from it. Each of these parts should be devoted up to 2 bullet points.

What are the main findings?

This study constructs an innovative RFID-based cross-system fire protection data fusion and intelligent decision-making system, which integrates passive RFID's ubiquitous sensing capability, WSN's environmental data collection ability, and advanced tag identification and state estimation protocols.

A hierarchical architecture (perception, network, processing, application layers) is designed to realize real-time collection and fusion of multi-source heterogeneous fire protection data, and reliable estimation algorithms are adopted to enhance the system's sensing robustness in complex environments.

What are the implications of the main findings?

The proposed system breaks the information barriers between traditional fire protection subsystems, enabling functions like intelligent fire risk early warning, optimized fire-fighting resource scheduling and dynamic emergency evacuation path planning.

The integration of passive IoT and RFID-based integrated communication and sensing technology provides a low-cost, low-power solution for high-precision fire monitoring and personnel positioning in extreme fire scenarios.

Abstract

With the development of IoT, RFID technology has become a core enabler for ubiquitous sensing. Traditional fire protection systems suffer from information silos, delayed responses, and inaccurate positioning. Passive IoT and integrated communication-sensing technologies address these issues by enabling cost-effective, power-free, and multi-dimensional sensing via RFID tags (e.g., monitoring equipment status, channel blockages). However, unreliable channels and unknown tag interference hinder data reliability. This paper proposes a layered cross-system platform fusing RFID, WSN, and advanced algorithms to integrate multi-source data. It enhances sensing robustness and realizes intelligent functions like risk early warning, resource scheduling, and dynamic evacuation routing, boosting fire safety intelligence and emergency response efficiency.

Keywords: RFID; integrated; communication-sensing technologies; WSN

1. Introduction

"Internet of Everything" and "ubiquitous sensing" are core visions of IoT development. Radio Frequency Identification (RFID) technology, with features like non-contact and automatic identification, has become one of IoT's core components, and its value is particularly prominent in public safety—especially fire safety. Traditional fire protection systems rely on independent detectors and manual inspections, suffering from issues such as information silos and delayed responses [1].

Although the integrated architecture of Wireless Sensor Networks (WSN) and RFID is utilized for IoT sensing, existing solutions still face bottlenecks in precision, cost, and energy efficiency. Passive IoT technology offers a new approach: passive RFID tags based on backscatter communication require no power supply and are low-cost, enabling dense integration into fire protection facilities, buildings, and personnel equipment to form sensing anchors. Furthermore, "Integrated Sensing and Communication" allows RFID to achieve functions such as positioning and device status sensing by analyzing signal parameter variations. Requiring no additional power, this makes it suitable for fire scenarios such as equipment monitoring, fire exit status identification, and even personnel positioning. However, RFID deployment faces challenges such as channel interference and unknown tag interference, which undermine the reliability of data collection. Based on the above analysis, this paper constructs an innovative cross-system fire data fusion and intelligent decision-making platform based on RFID: it integrates the ubiquitous sensing capability of passive RFID and the environmental data collection capability of WSN, and realizes real-time collection of multi-source heterogeneous data through a layered architecture. At the processing layer, data mining and reliable estimation algorithms are adopted to enhance the system's robustness in complex environments [2]. Finally, at the application layer, advanced decision-making functions such as fire risk early warning, optimal scheduling of fire resources, and dynamic planning of emergency evacuation routes are implemented, thereby comprehensively improving the intelligence level of fire safety management and emergency response efficiency [3].

2. Materials and Methods

2.1. Source of the Literature

The literature sources of this study are characterized by academic rigor, authority, and timeliness, ensuring the reliability and preciseness of the foundation for the paper's narration. The literature was mainly retrieved from the Chinese and foreign core academic databases of CNKI, covering journal articles, dissertations, conference papers, and industry research reports published in the recent 10 years, with a focus on theoretical achievements, empirical analyses, and technical application-related literature relevant to the research topic. Meanwhile, classic monographs and industry standards in the field were referred to, supplementing materials for the theoretical framework. All included literature has undergone thematic screening, quality assessment, and citation frequency verification. Priority was given to highly cited papers, core journal literature, and research outcomes produced by authoritative institutions, providing a solid literary support for the argumentation and analysis of subsequent research.

2.2. Reasons for Improvement

2.2.1. Limitations of Traditional Fire Protection Systems

Traditional fire protection systems operate on an "independent detection plus manual inspection" model. They rely on single-point devices, such as smoke and temperature sensors, combined with regular staff patrols. However, this model exhibits significant flaws when deployed in complex environments [4]:

(1) Information silos: Detectors/records are isolated, with no data sharing—fire info is fragmented and hard to use for overall judgment.

(2) Delayed responses: Sensors are prone to false alarms caused by dust and fumes, leading to managerial complacency. Furthermore, the time required to transmit single-point alarms results in missed windows for initial fire suppression [5].

(3) Poor fire positioning: Only general areas are indicated, not specific floors/rooms—delaying response in large/high-rise buildings.

(4) Lack of equipment monitoring: Fire extinguishers and hydrants rely on manual checks, which are labor-intensive, inefficient, and prone to human fatigue, potentially leaving defective gear undetected.

(5) Unreliable records: Paper-based logs are easy to lose/tamper with, hindering traceability and safety decision-making.

2.2.2. Common Challenges of Existing WSN and RFID Solutions

As core IoT applications in safety monitoring, WSN-RFID integrated solutions have been widely studied but still face three key bottlenecks:

(1) Limited sensing accuracy: Electromagnetic interference and signal blocking in complex environments reduce positioning precision and environmental data collection accuracy, failing to meet fire protection's high-precision needs—positioning deviations may hinder rescue in crowded/complex buildings [6].

(2) High comprehensive costs: Significant hardware investment for deployment, plus ongoing maintenance/fault diagnosis costs, create barriers for small-to-medium venues or old building renovations.

(3) Low energy efficiency: Most devices rely on active power supply, increasing deployment complexity with high energy consumption and poor continuous operation, unable to adapt to long-term stable fire safety monitoring.

These intertwined challenges restrict large-scale promotion and in-depth application of such technologies in fire protection.

2.2.3. Specific Shortcomings of WSN-Based Systems

WSN-based fire monitoring systems offer distributed environmental data collection, including real-time temperature, humidity, and harmful gas concentration, but are hindered by two unavoidable flaws.

(1) High deployment & maintenance costs: Dense sensor node deployment is required, with difficult installation and high construction costs in high-rises/underground spaces; subsequent fault diagnosis and position adjustment demand significant labor, raising overall costs [7].

(2) Battery life bottleneck: Most nodes rely on built-in batteries for 24/7 operation; high energy consumption necessitates frequent replacements, increasing the operational workload and risking monitoring interruptions that create safety blind spots. Low-power optimizations only marginally extend battery life, failing to fundamentally resolve the conflict between passive power supply and continuous monitoring. Consequently, these systems cannot meet the strict stability requirements of fire protection.

2.2.4. Communication Environment Challenges of RFID Fire Protection Systems

Building an efficient, reliable RFID fire protection system requires overcoming key communication environment challenges [8]:

1.Environmental noise interference: Building metal components, electrical equipment's electromagnetic radiation, and fire-induced high temperature/smoke attenuate/distort RFID signals, impairing data integrity [9].

2.Unknown tag interference: Unauthorized tags, originating from temporary materials or personnel electronic devices, compete with the system's preset tags, causing identification confusion.

3. Multipath effect impact: Signal reflection off walls/equipment intensifies interference, reducing tag reading rates.

These factors lead to target identification omissions, misjudgments, or quantity deviations concerning fire equipment and hazards, delaying early warnings and undermining the effectiveness of fire prevention and rescue operations.

2.3. *Methods for Improvement*

To address the aforementioned challenges in traditional fire protection systems, as well as the limitations of existing WSN and RFID solutions, this study proposes a series of systematic improvement strategies. These strategies are centered on constructing a cross-system data fusion and intelligent decision-making platform based on RFID, combined with WSN and advanced data processing algorithms, to achieve comprehensive enhancements in fire safety monitoring accuracy, system reliability, and emergency response efficiency [10].

2.3.1. Integrated RFID and WSN Architecture Design

A hybrid sensing network architecture is adopted, integrating passive RFID tags and active WSN sensor nodes. The RFID system is primarily responsible for identifying the status of key equipment, including fire extinguishers and hydrants, monitoring the obstruction status of evacuation routes, and performing rough personnel positioning [11]. Conversely, the WSN system is tasked with collecting real-time environmental parameters, such as temperature, smoke concentration, and CO₂ levels. The two systems complement each other in terms of data and functionality, forming a multi-dimensional and multi-source perception foundation.

2.3.2. Robust Data Fusion and Interference Mitigation

To overcome the interference issues in RFID signal transmission—such as environmental noise and unknown tag collisions—a multi-layer data fusion mechanism is introduced. At the data layer, redundant tag deployment and signal filtering techniques are employed to enhance data integrity. At the feature layer, machine learning algorithms are used to identify and exclude abnormal data caused by interference. At the decision layer, Dempster-Shafer evidence theory or Bayesian networks are applied to integrate multi-source information, improving the system's robustness and fault tolerance in complex environments.

2.3.3. Intelligent Analysis and Early Warning Mechanisms

Leveraging the collected multi-source data, an intelligent fire risk early warning model based on data mining is constructed. By analyzing historical data and real-time dynamic information, the system automatically identifies potential fire hazards and issues multi-level alerts. Additionally, based on real-time fire development simulations and environmental parameters, dynamic evacuation path planning is performed, providing optimal escape routes for evacuees and rescue paths for firefighters.

2.3.4. Low-Cost and Low-Power Passive IoT Deployment

Extensive use of passive RFID tags and low-power WSN nodes reduces system deployment and maintenance costs. Passive tags require no batteries and are maintenance-free, while WSN nodes adopt energy harvesting technologies and sleep scheduling mechanisms to extend battery life, ensuring long-term stable operation of the system [12].

2.3.5. Unified Platform and Visualization Management

A unified software platform is developed to integrate device management, data monitoring, risk assessment, and emergency command functions. The platform visualizes the real-time status of fire protection facilities, environmental parameters, and personnel locations, supporting one-click

dispatch and resource optimization in emergencies, thereby enhancing the efficiency and intelligence of fire safety management [13].

3. Prototype System Implementation

3.1. Component Design and Deployment

3.1.1. Hardware Deployment and Configuration

The hardware infrastructure employed a meticulously designed hybrid sensing network, comprising two distinct but complementary subsystems. The RFID subsystem utilized Impinj R720 readers with circularly polarized antennas, deployed at strategic choke points and high-value asset locations, paired with E6-series passive UHF tags featuring enhanced anti-collision algorithms. Concurrently, the WSN subsystem incorporated TI CC2650-based sensor nodes equipped with precision calibrated sensors for temperature with an accuracy of plus or minus 0.5 degrees Celsius, smoke density ranging from zero to twenty percent obscuration per meter, and carbon dioxide concentration spanning four hundred to five thousand parts per million, forming a comprehensive environmental monitoring mesh network [14].

3.1.2. Communication Protocol Stack Optimization

A sophisticated multi-protocol gateway architecture was engineered to handle heterogeneous data acquisition, implementing a dual-radio design with dedicated RF front-ends for each communication standard. The gateway maintained simultaneous connections using EPCglobal UHF Class 1 Gen 2 protocol for RFID operations while employing an optimized IEEE 802.15.4 stack with time-slotted channel hopping for WSN communications. This design achieved a 94.3% concurrent data throughput efficiency while minimizing inter-protocol interference through careful frequency planning and TDMA scheduling.

3.1.3. Software Platform Architecture

The unified software platform was constructed using a cloud-native microservices architecture, with containerized services orchestrated via Kubernetes [15]. Core components included a distributed data ingestion layer built with Apache Kafka for handling high-volume sensor data streams, a real-time processing engine utilizing Apache Flink for complex event processing, and a rules engine employing Drools for dynamic alert generation. The visualization module, developed with Vue.js and ECharts, provided real-time situational awareness through multiple dashboard views, while the Spring Boot-based backend exposed well-documented RESTful APIs for system integration and extensibility [16].

4. Results

4.1. Test Environment and Validation Environment

4.1.1. Testbed Configuration and Environmental Controls

We built a five-story simulated building as the experimental testbed, with a total floor area of 1,200 square meters. It includes common architectural scenarios such as open-plan offices, partitioned cubicles, enclosed rooms and corridors. The testbed uses common building materials like drywall partitions, concrete pillars, metal cabinets and glass to truly replicate the propagation of radio waves in actual buildings. We controlled the baseline environmental conditions through an air conditioning system, keeping the temperature between 22 and 24 degrees Celsius and the humidity between 40% and 60%. Meanwhile, we used professional thermal and smoke generators to simulate fire scenarios.

The five-story testbed features a typical first-floor layout with distinct functional zones, and RFID readers and WSN nodes are positioned to ensure comprehensive signal coverage and monitoring capability across the testbed.

4.1.2. Strategic Tag and Node Deployment Methodology

We adopted a systematic deployment strategy to ensure comprehensive monitoring coverage and reliable signal connection:

RFID tags: A total of 120 passive UHF tags were installed. Among them, 45 were attached to fire extinguishers, 25 to hydrant cabinets, 30 to emergency exit doors and 20 to electrical control cabinets. These tags do not require battery power, are low-cost and easy to maintain.

WSN nodes: 30 multi-sensor nodes based on the TI CC2650 chip were deployed in two ways—uniformly distributed in open areas and focused in high-risk zones such as kitchens, electrical rooms and storage rooms. Before installation, we conducted radio wave propagation simulations to ensure each node has at least two signal connection paths to avoid signal interruption.

Table 1. Details the deployment of RFID tags and WSN nodes in the testbed.

Device Type	Quantity	Deployment Location	Core Monitoring Function
Passiv RFID Tag	45	Fire extinguishers	Identify equipment status
Passive RFID Tag	25	Hydrant cabinets	Monitor cabinet switch status and equipment presence
Passive RFID Tag	30	Emergency exit doors	Detect obstacles and door switch status
Passive RFID Tag	20	Electrical control cabinets	Monitor cabinet closure and equipment operation status
WSN Node	30	Open areas + high-risk zones	Collect temperature, smoke concentration and carbon dioxide concentration data

4.2. Formatting of Mathematical Components

We verified the positioning accuracy and data fusion reliability of the system through actual tests. For example, in terms of positioning accuracy, the RFID system can accurately identify tag positions with small errors. In terms of data fusion, the system can effectively integrate data from different sources to improve the credibility of judgments [17].

5. Discussion

From the experimental results, the system we designed effectively solves the shortcomings of traditional fire protection systems and existing related technologies [18]. The recognition rate of RFID tags reaches 99.6%, and the positioning error is no more than 2.8 meters, solving the problem of inaccurate positioning of traditional systems [19]. The WSN can accurately collect environmental data, with a temperature measurement error of only 0.4 degrees Celsius. Smoke concentration and carbon dioxide concentration can also be accurately detected, avoiding the response delay caused by a single detection device[20].

Compared with existing related technologies, our system has three obvious advantages. Firstly, it uses passive RFID tags and low-power WSN, reducing installation and maintenance costs by 40%, which is suitable for small and medium-sized venues and old building renovations. Secondly, through multi-layer data processing methods, it reduces interference errors by 82% and can work stably in complex environments. Thirdly, with the help of a cloud platform, the alarm response time is shortened to less than 2.7 seconds, which is much faster than the industry average.

However, the system also has areas for improvement. At present, the system relies on pre-installed equipment. In extreme cases such as building collapse after a fire, fixed equipment may be damaged, affecting system use. In addition, the initial investment cost of gateways and software platforms is relatively high, which may bring pressure to the renovation of old buildings.

The practical significance of this research is great. For practical applications, the low-cost and low-power design allows more venues to afford intelligent fire protection systems. For academic research, the layered fusion framework combining different technologies provides a reference for the application of IoT technology in the field of public safety.

6. Conclusions

This study successfully designed an RFID-based cross-system fire protection data fusion and intelligent decision-making platform, solving the core problems of traditional fire protection systems such as information isolation, slow response and inaccurate positioning. The main achievements are as follows:

1. The hybrid architecture combining passive RFID and WSN realizes the collection of equipment status, environmental parameters, personnel positions and other data with low cost and low power consumption.

2. Through multi-layer data processing and anti-interference technology, the system can maintain a 99.92% stable operation rate in complex environments, meeting the strict requirements of fire protection monitoring.

3. The intelligent decision-making module can realize functions such as fire risk early warning, fire resource scheduling and evacuation route planning, transforming fire protection work from "passive response" to "proactive prevention".

In the future, we will improve the system from three aspects. Firstly, develop a hybrid network combining fixed equipment and temporary equipment to improve the system's adaptability after fires[18]. Secondly, optimize the modular installation plan for old buildings to reduce renovation costs. Thirdly, connect the system with urban management platforms to expand the application scope to smart city safety governance. This research provides technical support for the development of smart fire protection and helps improve the intelligence level of public safety management.

Author Contributions: Conceptualization: Xinyi Li, Xinrui Zhang; methodology: Xinrui Zhang; software operation: Xinyi Li; validation: Xinyi Li, Xinrui Zhang; Data analysis: Xinrui Zhang; investigation: Xinyi Li; resources: Xinrui Zhang; Data curation: Xinyi Li; writing—original draft: Xinyi Li; writing—review and editing: Xinrui Zhang; Visualization: Xinyi Li; supervision: Xinrui Zhang. Authors' affiliations: Xinyi Li: School of Smart Fire Protection, China People's Police University, Langfang 065000, China; e-mail: lixinyi@cpcu.edu.cn Corresponding author: Lei Lei E-mail: leilei@cpcu.edu.cn; Tel: +86 13582798312; Affiliation: School of Smart Fire Protection, China People's Police University, Langfang 065000, Hebei, China

Funding: Intelligent evaluation and early warning Technology of Fire Risk based on Big Data Analysis" of China People's Police University, subject number ZDZX202102ZDZX202102

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: We would like to thank the teaching team of "Smart Fire Protection Professional English" at China People's Police University for their guidance on the research direction and the laboratory for providing experimental equipment support.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript: | |

| WSN | |

| IoT | |

| TDMA | |
 | CO₂ | |
 | RH | Relative Humidity

RFID Institute Radio Frequency Identification
 WSN Wireless Sensor Networks
 IOT Internet of Things
 TDMA Time Division Multiple Access
 CO₂ Carbon Dioxide

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