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RFID and IoT-Enabled Public Transport Fare Systems: A Comparative Survey of Technologies and Security Challenges

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Abstract: This paper presents a comprehensive study and practical implementation of an IoT-based public transport fare collection system utilizing RFID technology. The system integrates an ESP32 microcontroller, MFRC522 RFID reader, OLED display, keypad, and thermal printer, all connected to a Node.js server with MongoDB as the backend database. A key feature of the system is its ability to handle offline fare management, where fare data is written directly to the RFID card, enabling seamless fare deduction even when network connectivity is unavailable.

Additionally, the system provides a web-based recharge portal, allowing users to remotely add balance to their cards. The backend server validates and synchronizes these transactions, ensuring that updated balances are reflected on the RFID card when scanned. To prevent unauthorized access and fraudulent recharge, a hardware-based authentication mechanism is implemented, ensuring that only authorized devices can issue or recharge cards.

Comparative analysis with traditional fare collection systems highlights improvements in operational efficiency, reliability, security, and user convenience. The proposed system demonstrates the practical feasibility of integrating RFID, IoT, and web technologies to create a modern, secure, and user-friendly fare collection solution for public transportation networks.

Keywords: RFID, ESP32, IoT, Public Transport, Fare Collection, MongoDB, Node.js, Hardware Security.

I. INTRODUCTION

Efficient public transportation is essential for urban mobility, economic growth, and environmental sustainability. However, conventional fare collection systems—such as cash payments, paper tickets, or magnetic cards—are often inefficient, error-prone, and vulnerable to fraud. These limitations lead to longer boarding times, operational delays, and increased administrative workload, impacting both transit authorities and passengers. The integration of RFID (Radio Frequency Identification) and IoT (Internet of Things) technologies provides a modern solution to these challenges. RFID allows contactless communication between cards and readers, enabling fast and accurate reading and updating of card balances. IoT-enabled devices like the ESP32 microcontroller can connect to cloud-based databases, such as MongoDB, through a Node.js backend, enabling centralized transaction monitoring, real-time analytics, and remote management of multiple devices. This combination ensures improved operational control, transparency, and scalability in public transport systems. Despite these advancements, many existing systems remain heavily dependent on continuous network connectivity, which can lead to disruptions in fare deduction and inconvenience for passengers. To address this, the proposed system implements offline balance management, where fare data is securely written and stored directly on MIFARE Classic RFID cards. This ensures uninterrupted fare deduction even when Wi-Fi or server connectivity is unavailable. A novel addition to this system is the web-based recharge portal, which allows passengers to add balance to their RFID cards remotely. The portal communicates with the backend server, updates the balance in the MongoDB database, and ensures that the updated balance is reflected on the card when scanned, even if the card was previously used offline. This integration of hardware and web technologies significantly enhances user convenience and reduces reliance on physical recharge points. Security is a major concern in fare collection systems. Unauthorized devices or card cloning can lead to substantial revenue loss. The system implements a hardware-based authentication mechanism, ensuring that only authorized ESP32 devices can issue or recharge cards, mitigating the risk of fraud. In summary, this system addresses critical challenges in conventional fare collection, including network dependency, security vulnerabilities, and operational inefficiency. By integrating RFID technology, IoT connectivity, offline balance management, hardware security, and a web-based recharge portal, the proposed solution provides a robust, scalable, and user-friendly fare collection system, suitable for modern public transport networks.

II. SYSTEM OVERVIEW AND COMPONENTS

The proposed IoT-enabled public transport fare system is a comprehensive, secure, and user-friendly solution designed to modernize fare collection by integrating RFID technology, IoT connectivity, offline balance management, and web-based recharge capabilities. The system architecture combines multiple hardware and software components to ensure reliability, efficiency, and scalability.

A. Hardware Components

1) ESP32 Microcontroller: The ESP32 serves as the central processing unit, orchestrating communication between the RFID reader, keypad, OLED display, thermal printer, and the backend server. It supports Wi-Fi connectivity to synchronize transactions with the MongoDB database while also managing offline operations independently.
2) MFRC522 RFID Reader: This contactless reader communicates with MIFARE Classic cards, enabling fast and secure reading and writing of card balances. It is capable of storing data directly on the card to support offline fare transactions.
3) OLED Display (128×64): The display provides clear visual feedback to users, showing card UID, current balance, fare deduction status, error messages, and recharge confirmations, enhancing user interaction and transparency.
4) Keypad: A 4×4 keypad allows passengers and operators to input fare amounts, PIN codes, and recharge amounts directly into the system, facilitating offline operations without requiring network connectivity.
5) Thermal Printer: Prints transaction receipts, including card UID, fare deducted, remaining balance, and timestamp, which acts as a proof of transaction and enhances accountability.

B. Software Components

1) Node.js Backend Server: Manages all API endpoints for card issuance, fare deduction, and web-based recharge. It ensures secure communication with the MongoDB database and validates hardware devices using a device ID lock to prevent unauthorized recharges.
2) MongoDB Database: The database stores detailed transaction records in a collection named fare_logs. Each log contains the card UID, transaction timestamp, fare amount, remaining balance, and device ID, supporting auditing, reporting, and data analytics.
3) Web-Based Recharge Portal: A responsive web interface allows passengers to recharge their cards remotely. The portal securely communicates with the backend, updates the database, and ensures the new balance is synchronized with the RFID card upon its next scan. This reduces the reliance on physical recharge points and enhances user convenience.

C. System Operations

The system supports two primary operations:

1) Card Issuance and Recharge:
   - Authorized personnel or passengers can issue or recharge a card using the hardware keypad or the web-based portal.
   - In web-based recharge, the backend verifies the transaction and updates the MongoDB fare_logs collection. The card balance is updated on the RFID card during the next scan.
   - A hardware ID authentication mechanism ensures that only approved devices can write balances, preventing fraudulent card recharges.
2) Fare Deduction:
   - Upon boarding, passengers scan their RFID cards. The system reads the balance directly from the card.
   - If the balance is sufficient, the fare is deducted, the remaining balance is updated on the card, and a receipt is printed.
   - Simultaneously, the transaction is logged in the MongoDB database with details such as card UID, fare deducted, remaining balance, timestamp, and the device ID.
   - If the balance is insufficient, the OLED displays a warning: “Insufficient Balance. Please Recharge Your Card.”

D. Offline Handling and Synchronization

1) The system implements an offline-first design, where fare deduction can be performed directly on the card without network connectivity.
2) During network outages, all transactions are stored locally on the card. Once connectivity is restored, the system automatically synchronizes transaction data with the MongoDB database, ensuring consistency and data integrity.

3) This design guarantees uninterrupted service for passengers and allows the system to function reliably in areas with poor network coverage.

E. Security Features

1) Device ID Lock: Each ESP32 device has a unique ID. Only authorized devices can write or recharge cards, preventing unauthorized recharges or fraudulent cloning.
2) Transaction Logging: Every fare deduction or recharge is securely logged in the database with device ID verification, enabling real-time monitoring and auditing.
3) Offline-First with Sync: Even offline transactions are secure, as the system ensures accurate synchronization with the central database once connectivity is restored.

F. System Benefits

1) Efficiency: Reduced boarding times due to contactless RFID transactions.
2) Security: Hardware-level authentication prevents fraud.
3) Reliability: Offline balance handling ensures uninterrupted service.
4) Convenience: Web portal allows remote recharge, complementing hardware-based operations.
5) Transparency: Real-time logging and printed receipts improve accountability and passenger trust.

III. METHODOLOGY

The proposed RFID and IoT-enabled public transport fare system is designed to provide a secure, reliable, and convenient solution for fare collection in public transport. It integrates hardware-based fare machines, RFID cards, IoT connectivity, web-based recharge, and database synchronization, enabling seamless operations even in areas with intermittent network connectivity. The methodology can be divided into web-based card recharge, card scanning and balance synchronization in buses, fare deduction, offline handling, and security measures, as described below.

A. Web-Based Card Recharge

1) Passenger Access: Passengers log into the web portal using secure credentials. The portal provides four key options:
   - Recharge Card – top up the existing balance based on personal usage.
   - Monthly Pass – purchase unlimited rides for a month.
   - Daily Pass – purchase unlimited rides for a day.
   - Check History – view detailed transaction history of all previous trips and recharges.
2) Card Identification: The passenger enters their RFID card's unique identifier (UID) or scans the card using a compatible reader to link the account with the physical card.
3) Recharge / Pass Selection: The passenger chooses the desired recharge amount or selects a monthly/daily pass option. The system calculates the new balance or updates the pass validity accordingly.
4) Server Validation and Database Update:
   - The Node.js backend validates the request to ensure correctness and authenticity.
   - The server updates the MongoDB database (fare_logs collection), storing the card UID, updated balance, transaction type, timestamp, and device ID of the last bus machine that performed an operation.
5) Confirmation and Notification: Once the transaction is recorded successfully, the portal confirms the recharge to the passenger via an on-screen message, ensuring transparency and trust.

B. Card Scanning and Balance Synchronization in Bus

1) Card Tap on Fare Machine: Upon boarding, the passenger taps their RFID card on the ESP32-based fare machine installed on the bus.
2) UID Reading: The MFRC522 RFID reader reads the unique identifier (UID) of the card, which the ESP32 uses to fetch the latest balance information.
3) Server Communication: The machine communicates with the backend server over Wi-Fi to retrieve the most up-to-date balance from the MongoDB database.

4) Balance Update on Card:
- The machine writes the retrieved balance onto the RFID card.
- This ensures that passengers who recharged their cards via the web portal have their updated balance available on the physical card immediately when boarding the bus.
- The system also verifies device authentication before writing to prevent unauthorized access.

C. Fare Deduction Process

1) Fare Determination: The fare for the passenger's journey is calculated automatically based on route or predefined fare slabs. Alternatively, the operator can input a specific fare using the machine keypad if necessary.

2) Balance Verification:
- The machine authenticates the card and reads the current balance from the RFID card.
- If the balance is sufficient, the fare is deducted.
- If the balance is insufficient, the OLED displays "Insufficient Balance. Please Recharge Your Card." and the transaction is aborted to prevent unauthorized travel.

3) Balance Update:
- The remaining balance is securely written back to the RFID card using the authorized key.
- Simultaneously, the fare transaction is logged in MongoDB, capturing the card UID, fare deducted, remaining balance, timestamp, and device ID.
- This dual-record approach ensures that both the physical card and database reflect the correct balance, maintaining consistency.

4) Receipt Printing: For transparency, the thermal printer generates a printed receipt with the UID, fare deducted, remaining balance, and transaction timestamp.

D. Offline Handling and Synchronization

1) The system supports offline-first operations. If network connectivity is unavailable:
- Fare deduction is performed directly from the balance stored on the card.
- Transactions conducted offline are temporarily recorded locally on the machine.

2) Once the network is restored, the machine synchronizes all offline transactions with the MongoDB database, updating the central fare_logs collection.

3) This ensures continuous service, no disruption for passengers, and data consistency between card and database even in areas with poor Wi-Fi connectivity.

E. Security Mechanisms

1) Device ID Authentication:
- Each ESP32 fare machine has a unique identifier (device ID).
- Only devices with registered IDs are authorized to write to or recharge cards, preventing unauthorized devices from performing fraudulent operations.

2) Key-Based RFID Authentication:
- The system uses a predefined key to authenticate access to the RFID card's balance block.
- Unauthorized access attempts are rejected to prevent cloning or tampering.

3) Transaction Logging:
- All operations, including web-based recharges, fare deductions, and offline transactions, are logged with UID, fare amount, remaining balance, timestamp, and device ID.
- This provides real-time monitoring, auditing, and accountability.

4) Fraud Prevention:
- Unauthorized devices or attempts to recharge cards without server validation are blocked.
- The combination of hardware and server-side authentication ensures secure fare management.

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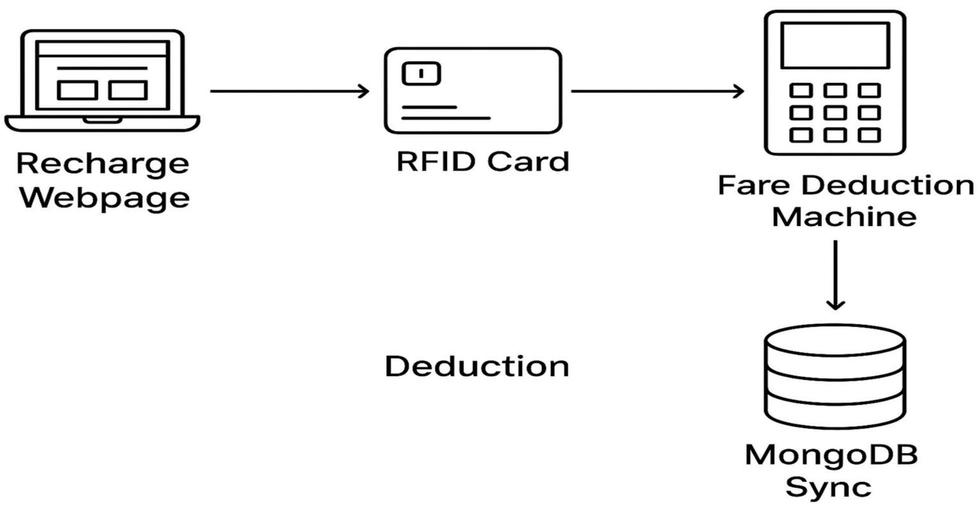
F. Advantages of the Proposed Methodology

1) User Convenience: Passengers can recharge cards online via the web portal at any time, reducing dependence on physical recharge points.
2) Seamless Integration: Web-based recharges are reflected automatically on the card during the next tap on a bus machine.
3) Reliability: Fare deduction continues uninterrupted even during network outages, thanks to offline-first design.
4) Security: Device ID authentication and key-based RFID writing prevent fraud and unauthorized access.
5) Transparency and Accountability: Printed receipts, OLED feedback, and database logging ensure clarity and trust.
6) Scalability: The system can handle multiple buses, devices, and passengers simultaneously with centralized monitoring via MongoDB.
7) Enhanced Passenger Experience: The system supports daily passes, monthly passes, and real-time balance checking, providing flexibility according to passenger needs.

IV. SYSTEM FLOW DIAGRAM



V. NOVELTY AND CONTRIBUTION

The proposed system introduces several innovative features and improvements over existing public transport fare systems. The key contributions are summarized as follows:

A. Web-Based Recharge Integration

- Unlike conventional fare systems that rely solely on physical recharge points, this system allows passengers to recharge their RFID cards via a web portal.
- The web portal provides flexible options including: Recharge Card, Monthly Pass, Daily Pass, and transaction history checks.
- Recharged balances are synchronized automatically with the RFID card during the next tap on the bus, providing seamless and real-time service.

B. Offline-First Fare Deduction

- The system is designed to operate even when the network connection is down.
- Fare deduction can occur directly from the balance stored on the RFID card, ensuring that service continuity is maintained even in remote or low-connectivity areas.
- Offline transactions are synchronized with the MongoDB database once connectivity is restored, preserving data integrity and consistency between the card and the server.

C. *Hardware-Level Security*

- Each ESP32 fare machine has a unique device ID, ensuring that only authorized devices can write or update balances on RFID cards.
- Unauthorized devices attempting to recharge or manipulate card balances are blocked automatically, mitigating the risk of fraud.
- Additionally, the RFID card's balance block is protected with a predefined key, preventing tampering or cloning.

D. *IoT-Enabled Real-Time Synchronization*

- The system leverages Wi-Fi connectivity and IoT communication to maintain real-time synchronization between the bus machines and the central MongoDB server.
- All fare transactions, recharges, and passes are logged with details including card UID, fare amount, remaining balance, timestamp, and device ID.
- This ensures full transparency, auditing capability, and centralized monitoring of the entire fare collection system.

E. *Multi-Mode Fare Management*

- The system supports various fare management modes including single-ride fares, daily passes, and monthly passes.
- This flexibility allows passengers to choose the plan that best suits their travel needs, improving convenience and adoption.

F. *Enhanced Passenger Experience*

- By combining hardware-based RFID fare machines, web-based recharge portals, and offline-first reliability, the system significantly improves passenger convenience, security, and reliability.
- Printed receipts via the thermal printer, OLED feedback, and detailed transaction logging provide passengers with trust and clarity regarding their fare usage.

VI. COMPARATIVE ANALYSIS

Compared to traditional systems, the proposed setup offers reduced dependency on central servers, enhanced data integrity, and improved fault tolerance. The table below summarizes the key comparisons:

Traditional System	Proposed System
Limited hardware security	Hardware ID lock enabled
Higher operational cost	Low-cost ESP32-based design
Requires constant network	Works offline with local card storage
Centralized transaction storage	Distributed MongoDB with local sync

VII. CONCLUSION

This paper presents an integrated RFID and IoT-based fare management system optimized for public transport applications. The combination of ESP32, MFRC522, and MongoDB ensures real-time and offline synchronization capabilities. Future work includes integrating GPS tracking for route-wise fare computation and expanding the system for multi-operator transport networks.

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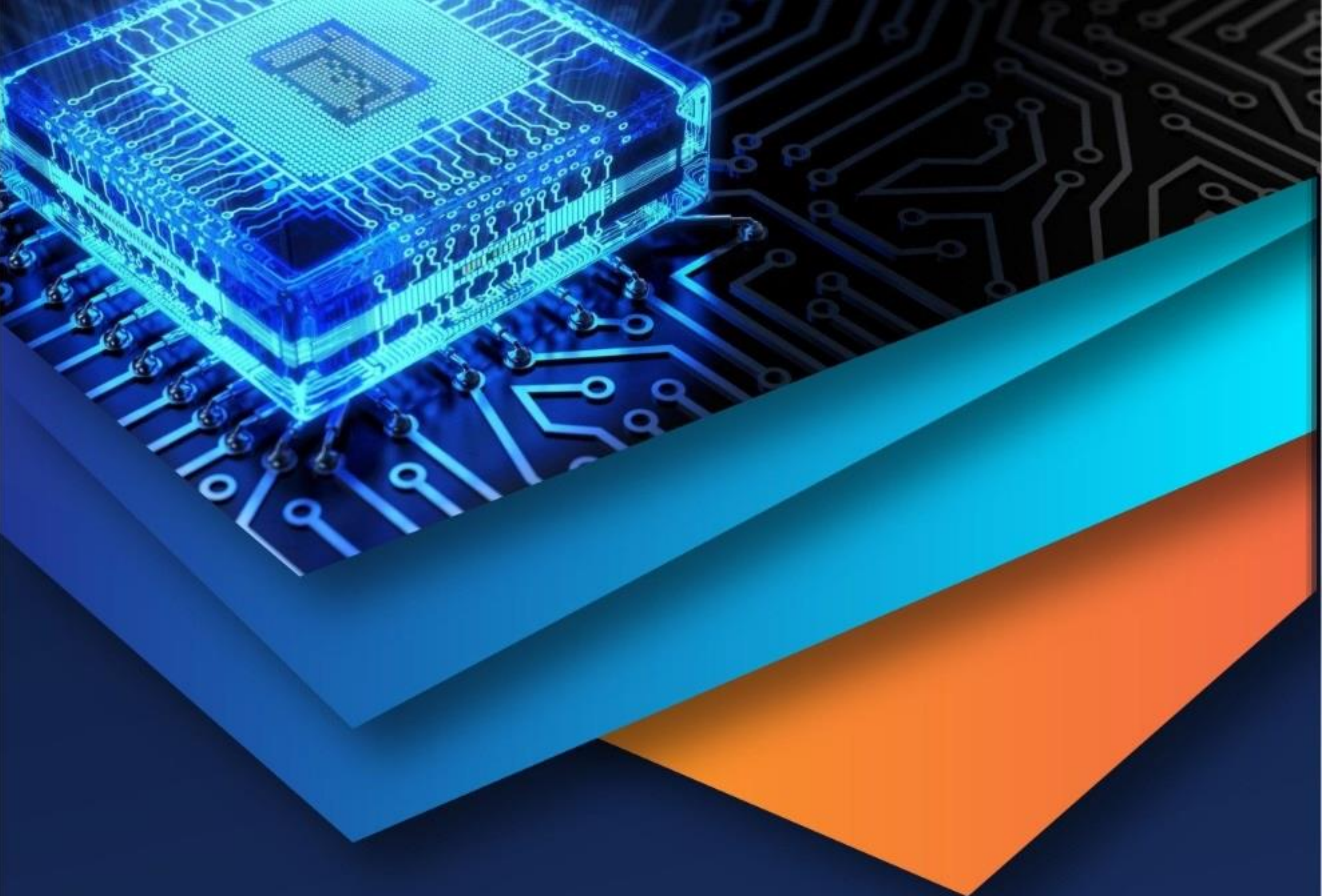

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