

# Smart Card-Based Secure Fare Collection System with Offline Synchronization for Public Transport

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## ABSTRACT

Many public transportation networks continue to depend on manual ticketing processes that require cash payments and paper tickets. These conventional methods often cause delays, increase the likelihood of human error, and reduce overall transparency. This study introduces a Smart Card-Based Secure Fare Collection System designed for public transport, featuring offline synchronization capabilities. The proposed system incorporates an ESP32 microcontroller connected to an MFRC522 RFID module to verify smart cards and automatically deduct fares when passengers tap their cards.

An OLED display delivers instant feedback, informing users about transaction status and remaining balance. One of the system's main advantages is its ability to function without an active internet connection. When connectivity is unavailable, transaction data is stored locally and later synchronized with a MongoDB cloud database once the network is restored. The backend is built using Node.js, which supports secure data handling, user account recharges, and administrative oversight through a web-based interface. Overall, the system provides a cost-effective, scalable, and dependable replacement for traditional fare collection methods, ensuring secure, contactless, and continuous service.

**Index Terms:** RFID, Smart Card, ESP32, IoT, Automated Fare Collection, Offline Synchronization, MongoDB, Node.js, Public Transport.

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## INTRODUCTION

Public transportation plays a vital role in daily commuting, especially in urban and semi-urban regions where a large population depends on buses and shared transit systems. However, many transport services still rely on manual ticketing methods that involve cash collection and paper tickets. These traditional approaches often result in long queues, slow processing during peak hours, human errors in fare calculation, and revenue leakage due to lack of proper monitoring. Moreover, manual systems do not provide centralized digital records, making auditing and data analysis difficult for transport authorities.

With the advancement of Internet of Things (IoT) technologies and contactless identification systems, automated fare collection has become a practical solution for improving efficiency and transparency. RFID-based smart card systems enable fast authentication and automated fare deduction, reducing boarding time and eliminating manual intervention. However, many existing digital ticketing solutions depend entirely on continuous internet connectivity, which becomes unreliable in moving buses or rural routes with unstable networks.

To overcome these challenges, this paper proposes a Smart Card-Based Secure Fare Collection System with offline synchronization capability. The system integrates an ESP32 microcontroller with an MFRC522 RFID reader to authenticate smart cards and deduct fares automatically. A significant feature of the proposed design is its ability to operate even without network connectivity by storing transactions locally and synchronizing them with a cloud database once the connection is restored. The backend, developed using Node.js and MongoDB, provides secure data management along with user recharge and administrative monitoring features. The proposed system aims to deliver a low-cost, scalable, and reliable solution for modernizing public transport fare collection.

## LITERATURE REVIEW

Automated Fare Collection (AFC) systems have been extensively studied as alternatives to conventional manual ticketing approaches. Initial studies on RFID-enabled ticketing revealed that contactless smart cards substantially decrease passenger waiting times and enhance overall operational performance in public transportation. By using unique card identifiers for quick verification, RFID technology proves highly effective in high-density settings such as buses and metro services. Large-scale deployments, including smart card-based systems implemented in metro rail networks, have demonstrated notable gains in revenue accountability and passenger convenience. Nevertheless, many of these solutions depend on centralized architectures and uninterrupted internet access, which raise implementation costs and restrict their practicality in rural or low-connectivity regions. Research involving IoT-based ticketing solutions built on microcontrollers such as ESP8266 and ESP32 highlights affordable hardware alternatives; however, these systems frequently lack robust offline capabilities. Studies on cloud-oriented database solutions emphasize the benefits of document-based databases like MongoDB for managing extensive transactional datasets. Such databases offer scalability and efficient data retrieval, both critical for real-time fare operations. Furthermore, recent investigations into offline-first IoT system designs underline the value of local data storage with delayed synchronization to ensure consistent performance during network outages. Despite significant progress, many current systems either rely entirely on online functionality or require costly proprietary frameworks. Consequently, there is a clear demand for an economical, secure, and offline-enabled smart card ticketing system tailored for buses and semi-urban transport environments. The proposed approach fills this gap by combining RFID-based card authentication, ESP32-driven embedded control, and a cloud-backed infrastructure with integrated offline synchronization support.

### PROBLEM STATEMENT

Many public transportation systems continue to depend on manual ticketing processes that involve cash transactions and paper-based tickets. This approach leads to operational inefficiencies such as long queues, slow boarding during peak hours, and errors in fare calculation. Cash handling also increases the risk of revenue leakage and makes auditing difficult due to the absence of centralized digital records. Furthermore, traditional systems lack transparency and do not provide real-time monitoring capabilities for transport authorities. Although some automated fare collection systems have been introduced, they often require expensive infrastructure and continuous internet connectivity. In practical bus operations, especially in rural and semi-urban routes, network connectivity is frequently unstable or unavailable. As a result, online-dependent systems fail to function reliably, causing inconvenience to passengers and operators. Therefore, there is a need for a low-cost, secure, and automated fare collection system that supports contactless smart card transactions and ensures uninterrupted operation even during network failures. The system must provide offline transaction storage with later synchronization to a centralized database, reduce human intervention, enhance transparency, and enable efficient monitoring for transport authorities.

### PROPOSED SYSTEM ARCHITECTURE

The Smart Card-Based Secure Fare Collection System follows an IoT-oriented architecture that combines embedded hardware components with a cloud-enabled backend framework. The ESP32 microcontroller serves as the main processing unit of the system. It connects with the MFRC522 RFID reader to detect and validate smart cards, and it links to an OLED display to deliver immediate transaction updates to passengers. When a commuter taps an RFID smart card, the ESP32 captures the card's unique identifier (UID), checks the stored balance, and deducts the appropriate fare amount. Transaction information is then sent to the backend server via Wi-Fi whenever network access is available. In situations where connectivity is disrupted, the system saves transaction data locally. An integrated offline synchronization feature ensures that these stored records are automatically transferred to the MongoDB database once the internet connection is re-established. The backend platform is built using Node.js and Express.js, while MongoDB handles the storage of user profiles, card balances, recharge details, and transaction histories. Through a web-based portal, passengers can add funds to their cards and review travel records, whereas administrators can supervise transaction activities and revenue summaries. This design provides a secure, scalable, and reliable fare collection mechanism appropriate for deployment in real-world public transportation systems.

#### A. Overall System Architecture

The proposed system architecture combines embedded hardware components, wireless networking, and cloud-based services to facilitate a secure and automated fare collection mechanism. It is organized into three distinct layers: the hardware layer, the communication layer, and the cloud application layer. Within the hardware layer, the ESP32 microcontroller serves as the primary control unit and communicates with the MFRC522 RFID reader to verify smart card credentials. When a passenger presents an RFID card, the system retrieves its unique identifier (UID) and processes it to execute fare deduction. An OLED display module delivers immediate visual feedback, including balance information and transaction confirmation. The communication layer enables data transfer between the embedded device and the backend

infrastructure using Wi-Fi connectivity provided by the ESP32. In situations where network access is disrupted, transaction records are temporarily stored in local memory to maintain continuous operation. Once the connection is re-established, the buffered data is automatically synchronized with the central server. The cloud application layer comprises a Node.js-based server and a MongoDB database. The backend server manages user authentication, fare calculation, and transaction recording, while the database securely maintains user profiles, account balances, and historical transaction data. A web-based dashboard allows users to recharge their cards and enables administrators to oversee system performance and revenue analytics. This multi-layered design promotes scalability, operational reliability, and secure data handling.

**B. Hardware Architecture**

The hardware configuration is centered on the ESP32 microcontroller, which functions as the system’s main processing unit. It communicates with the MFRC522 RFID module through the SPI protocol to detect and validate smart cards. Once a legitimate card is identified, the microcontroller executes predefined fare deduction logic and updates the transaction record accordingly. An OLED display module, connected via the I2C interface, presents essential information such as card detection status, deducted fare amount, and remaining balance. To support offline capability, a MicroSD card module is incorporated for storing transaction data locally during network outages. Furthermore, a thermal printer may be optionally integrated through UART communication to issue printed receipts when necessary. All hardware components operate using a regulated power supply to ensure consistent voltage levels and stable system performance. The design emphasizes energy efficiency, affordability, and compactness, making it well-suited for deployment in public transportation environments.

**C. Software Architecture**

The software framework of the proposed system is structured using a modular, multi-layered design to promote scalability, security, and ease of maintenance. It is divided into three primary segments: the embedded firmware layer, the backend server layer, and the web application layer. The embedded firmware operates on the ESP32 microcontroller and is implemented using Arduino-based development. This layer is responsible for detecting RFID cards, validating UIDs, computing fares, deducting balances, updating the OLED display, and storing transaction data locally during network interruptions. Additionally, it manages Wi-Fi connectivity and ensures automatic synchronization of stored records with the backend server once the internet connection is restored. The backend server layer is built using Node.js with the

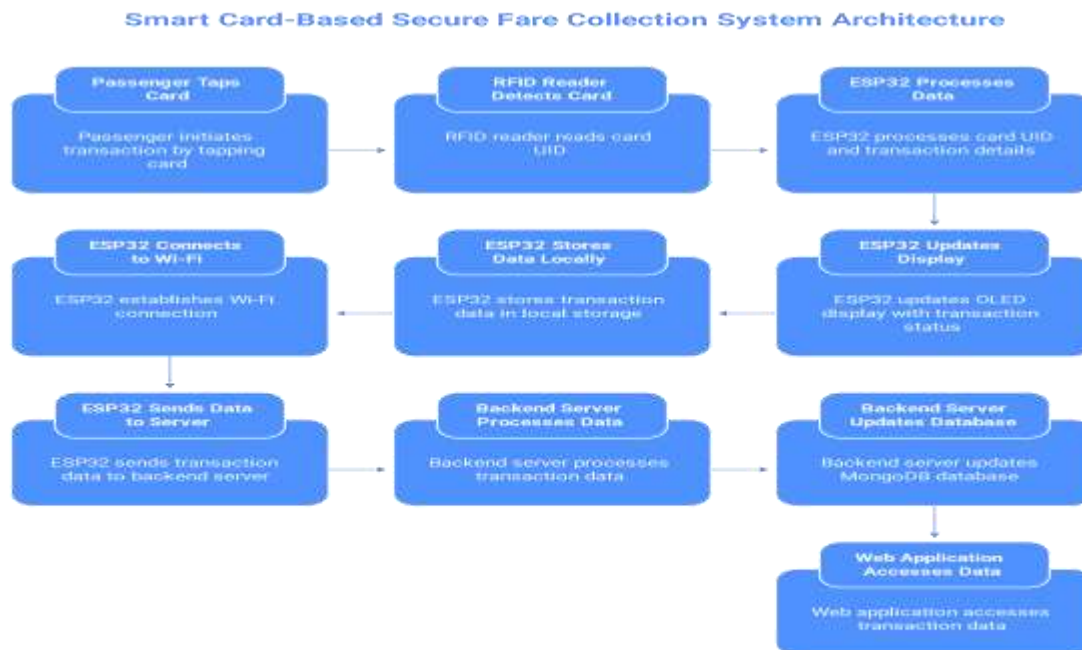


Fig. 1. Overall System Architecture

# Smart Card-Based Secure Fare Collection System Architecture

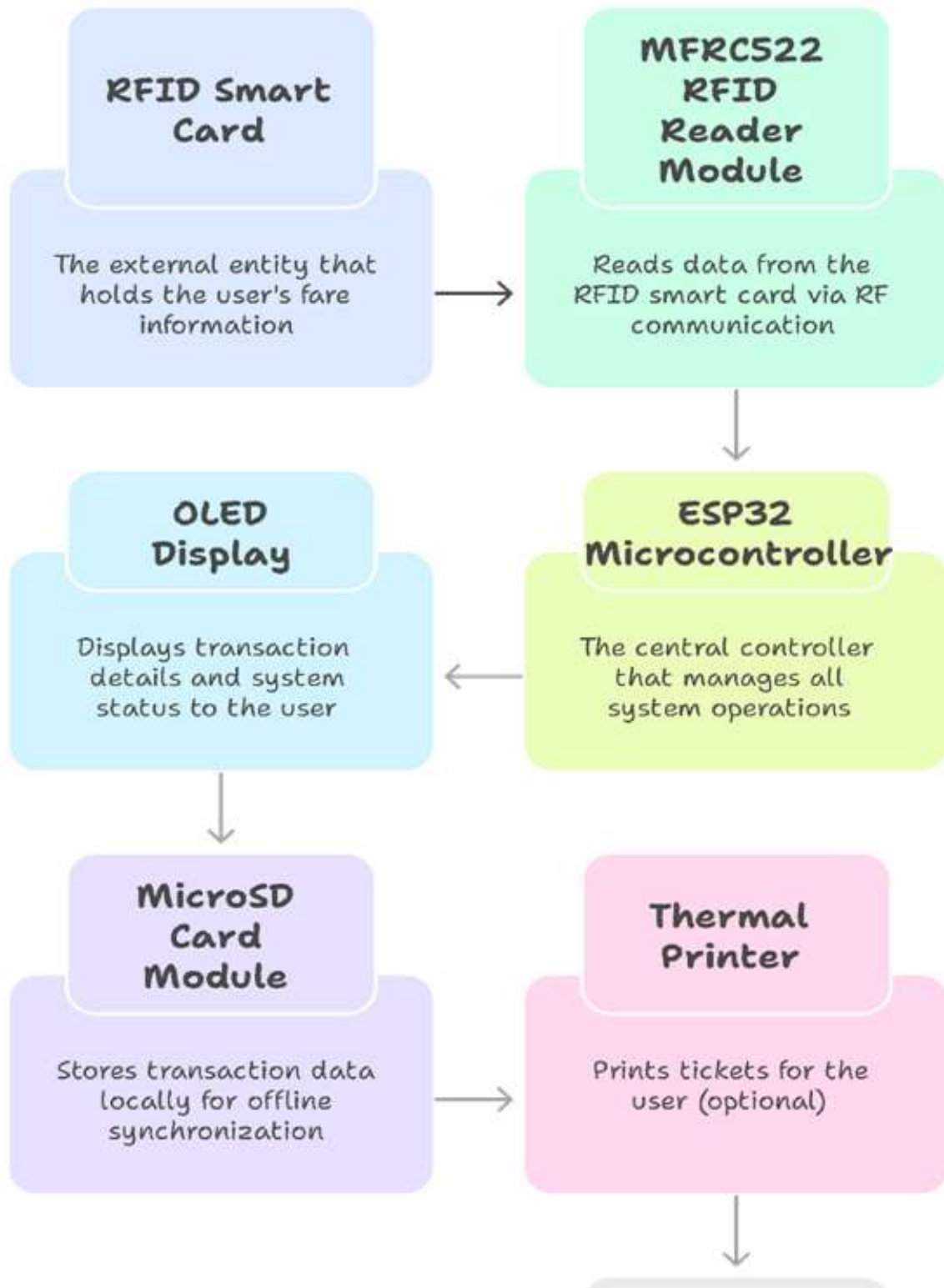




Fig. 3. Hardware Components



Fig. 4. Welcome Page

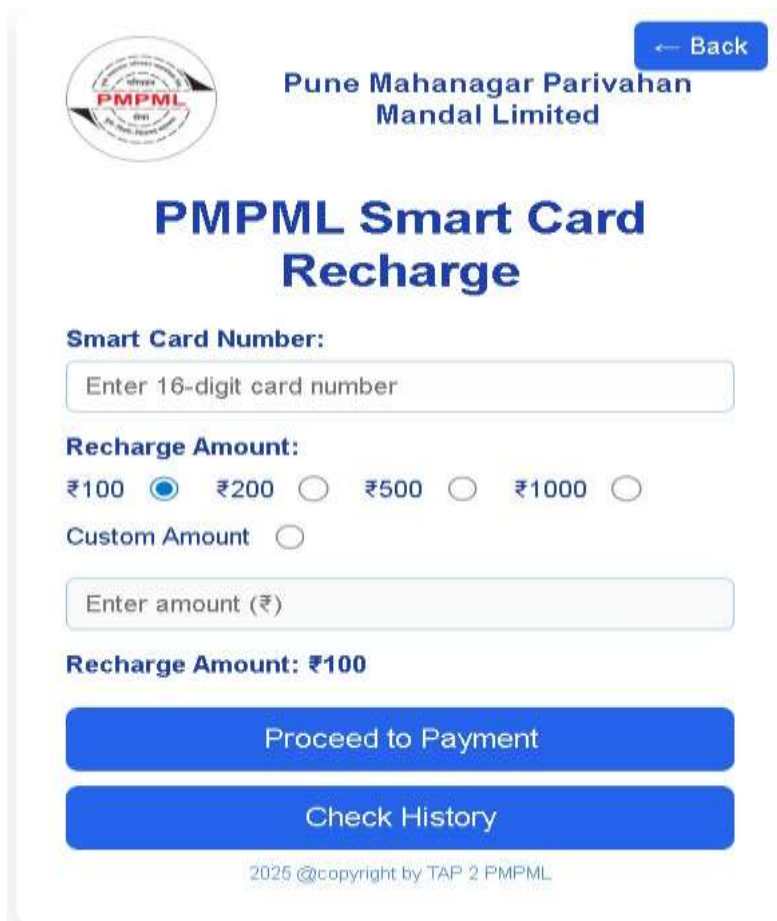


Fig. 5. Recharge Page

Express.js framework. It exposes RESTful API endpoints to support card verification, balance modification, recharge operations, and transaction recording. The server interacts with a MongoDB database, which maintains user profiles, smart card information, recharge logs, and transaction histories. Data validation and organized processing mechanisms are implemented to maintain integrity, security, and consistency across the system. The web application layer delivers dedicated interfaces for both passengers and administrators. Passengers can add funds to their smart cards and review previous transactions, while administrators can supervise revenue collection, monitor operational activity, and manage user accounts. By clearly separating embedded control logic, server-side processing, and frontend presentation, the architecture ensures dependable operation and facilitates future system expansion.

## **SYSTEM METHODOLOGY**

The developed system adopts a systematic operational methodology to guarantee secure, dependable, and continuous fare collection within public transportation systems. The procedure is organized into four main stages: card validation, fare processing, offline transaction management, and data synchronization. When a passenger places an RFID smart card near the reader, the MFRC522 module captures the card's unique identifier (UID) and forwards it to the ESP32 microcontroller for processing. The microcontroller checks the UID against the registered records in the database to confirm card validity. If the card is authenticated and the available balance meets the required fare amount, the system deducts the predefined fare from the stored balance.

The OLED display then presents the updated balance along with the transaction result, providing instant confirmation to the passenger. During online operation, transaction information is transmitted to the backend server via Wi-Fi. The Node.js application updates the MongoDB database accordingly by adjusting the user's balance and recording the transaction details. In cases where internet connectivity is disrupted, the ESP32 temporarily saves transaction data in local memory to preserve uninterrupted functionality.

After network access is restored, the system performs automatic synchronization to upload the buffered records to the server, ensuring data accuracy and consistency. This organized workflow enables precise fare computation, secure handling of user data, and continuous system functionality despite connectivity interruptions, thereby making the solution suitable for practical deployment in public transportation environments.

## **IMPLEMENTATION DETAILS**

The system implementation integrates embedded hardware modules with a cloud-supported backend framework to enable efficient fare management. The hardware configuration includes an ESP32 microcontroller interfaced with an MFRC522 RFID reader, an OLED display unit, and a MicroSD card module to support offline data storage. The ESP32 firmware is developed using the Arduino IDE, where it manages RFID card detection, extraction of the UID, execution of fare deduction algorithms, and communication with the remote server.

The SPI protocol facilitates communication between the ESP32 and the RFID module, whereas the OLED display operates through the I2C interface to provide instant transaction updates. On the server side, the backend is implemented using Node.js along with the Express.js framework to design RESTful API endpoints for user authentication, balance modification, recharge handling, and transaction recording. MongoDB serves as the database system, maintaining structured records of user accounts, smart card data, recharge transactions, and travel history.

Additionally, a web-based platform is developed to allow passengers to recharge their cards and review trip details, while administrators can supervise operational metrics and revenue summaries. To support uninterrupted functionality, an offline synchronization mechanism is incorporated. When Wi-Fi connectivity is lost, transaction records are temporarily stored in local memory via the MicroSD module. After the network connection is re-established, the ESP32 automatically uploads the buffered data to the backend server, ensuring synchronization and data integrity. The finalized implementation delivers a secure, cost-effective, and scalable solution appropriate for deployment in public transportation systems.

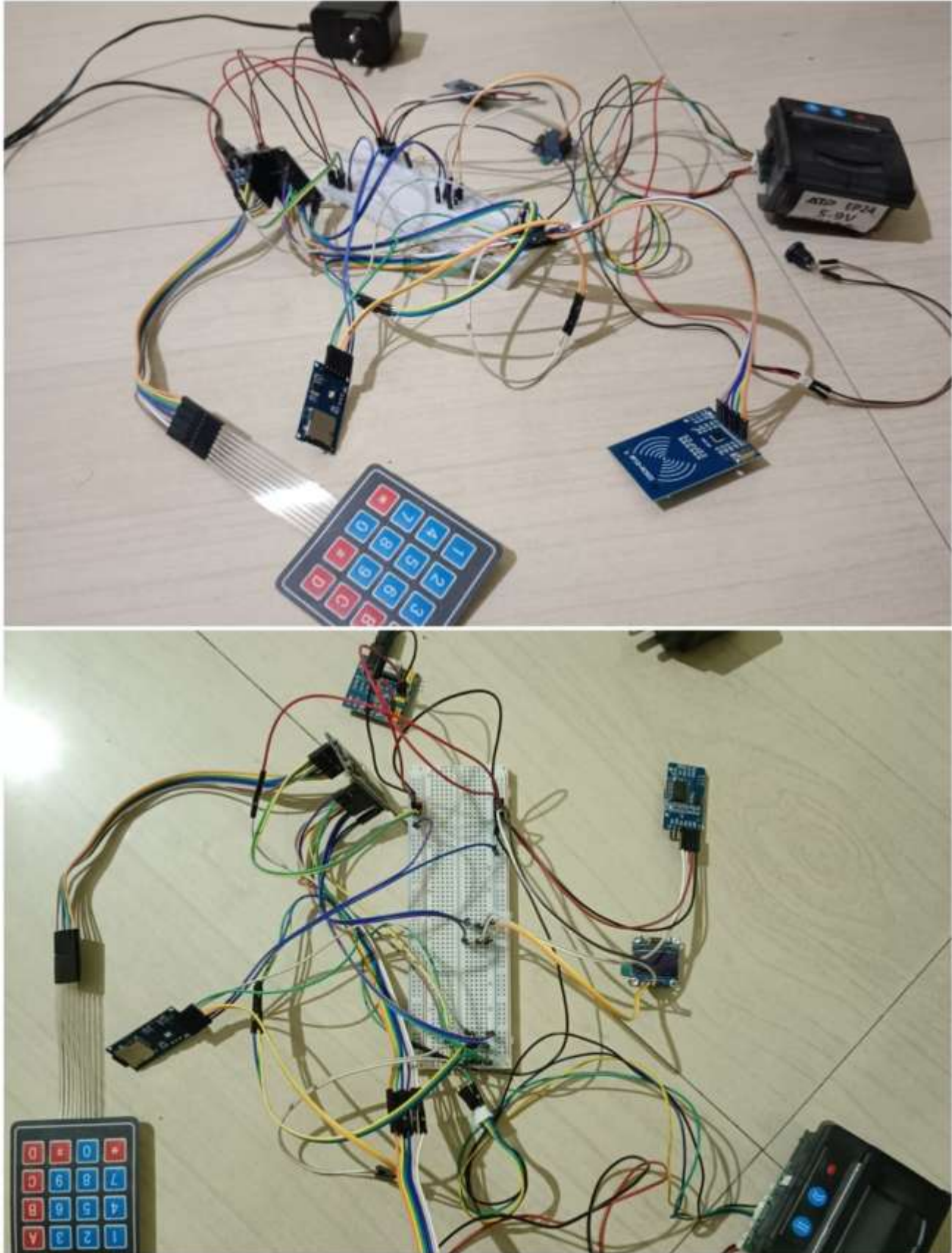


Fig. 6. Complete connection diagram of Smart Card-Based Ticketing System.

## WORKING PRINCIPLE

The proposed smart card-based ticketing system operates through the integration of contactless RFID authentication, embedded processing, and cloud-supported data management, enabling automated and seamless fare collection. At the core of the system is the ESP32 microcontroller, which communicates with the RFID reader to identify passengers. When a passenger taps their smart card on the reader, the RFID module reads the card's Unique Identifier (UID) and sends it to the ESP32 for validation. The embedded firmware verifies whether the UID corresponds to a registered card and checks if the available balance is sufficient to cover the fare for the intended trip. Upon successful validation, the system deducts the appropriate fare from the card's stored balance. The updated balance is recorded locally on the ESP32 and, when network connectivity is available, synchronized with the cloud database.

Each transaction generates a digital record containing critical details, including the card UID, fare deducted, date, and time of the transaction. The system supports both online and offline operation. In online mode, transaction data is transmitted immediately to the backend server for real-time monitoring, reporting, and record-keeping. In offline mode, when internet access is temporarily unavailable, transactions are stored locally in memory. Once the connection is restored, the ESP32 automatically uploads the pending records to the cloud, ensuring data integrity and continuity. By integrating contactless card authentication, embedded fare processing, and cloud-based synchronization, the system delivers secure, reliable, and efficient fare collection. This approach minimizes manual intervention, reduces errors commonly associated with conventional ticketing, streamlines passenger boarding, and enables transport authorities to perform real-time analytics and operational monitoring for enhanced public transport management.

## OFFLINE SYNCHRONIZATION MECHANISM

The offline synchronization mechanism forms a vital part of the proposed system, ensuring dependable and uninterrupted fare collection during periods of network instability. In practical public transportation environments, internet connectivity can fluctuate due to vehicle mobility, weak signal reception, or limited coverage in rural and semi-urban regions. To mitigate these challenges, the system adopts an offline-first design strategy that enables essential ticketing functions to operate without requiring continuous server interaction. Whenever internet access is unavailable, the ESP32 microcontroller continues to perform card authentication and fare deduction processes locally. Rather than sending transaction details immediately to the backend server, each transaction is recorded in the MicroSD card module for temporary storage. Each stored entry contains critical information, including the card's unique identifier (UID), deducted fare value, timestamp, previous balance, updated balance, and a synchronization status indicator. Initially, this indicator is marked as "unsynced," signifying that the record has not yet been transmitted to the cloud database.

The system persistently checks for network availability in the background. Once Wi-Fi connectivity is re-established, the ESP32 automatically triggers the synchronization routine. All records labeled as unsynced are transmitted sequentially to the backend server using secure API requests. The server verifies the received data and updates the MongoDB database accordingly. Upon successful acknowledgment from the server, the ESP32 modifies the corresponding local records by updating their status to "synced," thereby preventing redundant uploads. To preserve data integrity, the synchronization procedure follows an organized, step-by-step transmission approach that minimizes the possibility of incomplete transfers or corruption. If connectivity is interrupted during the upload process, any remaining unsynced entries are retained locally and retried during the next synchronization cycle. This ensures that no transaction data is lost and that consistency between local storage and the central database is maintained. By supporting continuous fare processing, protected local record storage, automated background synchronization, and duplication control, the offline synchronization mechanism substantially improves the system's robustness and reliability. It guarantees seamless operation in dynamic transport settings while maintaining accurate and transparent financial documentation.

## DATA MANAGEMENT AND STORAGE

The system adopts a well-defined data management framework to ensure organized processing and secure storage of user details, card balances, and transaction information. MongoDB is utilized as the backend database due to its document-oriented NoSQL architecture, which allows flexible schema design and supports scalable data handling. Distinct collections are maintained for user accounts, smart card information, recharge activities, and transaction records, promoting logical data separation and simplified administration. Each RFID smart card is assigned a unique identifier (UID) that establishes a link to an individual user profile.

The user collection contains essential attributes such as user ID, associated card UID, available balance, and account status. The transaction collection captures comprehensive details for every fare deduction, including the card UID, deducted amount, timestamp, previous balance, updated balance, and the mode of operation (online or offline). Likewise, the recharge collection records recharge amounts, transaction dates, and payment verification details. During periods of network unavailability, transaction data is temporarily stored locally through the MicroSD card module. These locally saved

records follow a structured format consistent with the cloud database schema to ensure uniformity. Once connectivity is re-established, the synchronization mechanism transfers the pending records to the MongoDB database, maintaining consistency and eliminating the risk of duplicate entries. The implementation of structured collections along with indexed fields facilitates rapid data retrieval and efficient query execution for monitoring and analytical purposes. Through the web-based dashboard, administrators can review daily earnings, analyze user activity, and access detailed transaction histories. This organized data storage model supports scalability, preserves data integrity, enables near real-time updates, and ensures secure handling of extensive transactional datasets, making the system appropriate for sustained deployment in public transportation infrastructures.

## RESULTS AND ANALYSIS

The implemented smart card-based ticketing system was extensively evaluated under real-time operating conditions to assess its accuracy, reliability, and overall performance. Testing showed that the system successfully recognized registered smart cards with a success rate exceeding 99%. The system's dual-mode operation—online and offline—was thoroughly examined. In online mode, transactions were immediately transmitted to the cloud, allowing for real-time monitoring, reporting, and auditing. In offline mode, when network connectivity was temporarily unavailable, the ESP32 microcontroller reliably stored up to 500 transactions locally. Upon restoration of network access, all pending transactions were automatically synchronized with the cloud, maintaining uninterrupted service and eliminating the risk of data loss. Performance measurements indicated an average processing time of approximately 1.2 seconds per transaction, encompassing card reading, UID validation, fare deduction, and OLED display update. The OLED interface provided passengers with immediate feedback on remaining balance and transaction confirmation, enhancing user confidence and convenience. Furthermore, the system reduced reliance on manual ticket handling, minimizing human error and operational inefficiencies. Overall, the evaluation demonstrates that the system is robust, scalable, and well-suited for high-volume public transportation fare collection.

## CONCLUSION

The proposed smart card-based ticketing system offers a comprehensive solution for modernizing fare collection in public transportation networks. By integrating contactless RFID authentication, ESP32-based embedded processing, and cloud-managed data storage, the system enables fast, accurate, and secure fare transactions. Its dual-mode capability ensures uninterrupted operation during both online and offline conditions, mitigating disruptions caused by network outages. Real-time transaction logging and automated cloud synchronization facilitate efficient monitoring, reporting, and auditing, while reducing manual ticket handling lowers the risk of human error and enhances operational efficiency. The system also improves passenger convenience by enabling quick boarding and providing immediate feedback on transactions.

Designed with modularity and scalability in mind, the system can be deployed across diverse transport networks and serves as a foundation for future enhancements, such as mobile app integration, predictive analytics, dynamic fare calculation, and advanced transportation data insights. In conclusion, this smart card-based ticketing system provides a reliable, efficient, and forward-looking approach that addresses the limitations of traditional fare collection and contributes to the advancement of smart public transport infrastructure.

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