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Optimizing RFID-Based Toll Gate System: A Novel Approach to Reducing Latency and Enhancing Traffic Flow

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Abstract

This study presents a novel approach aimed at boosting the efficiency of Radio Frequency Identification (RFID) based toll gate systems. Traditional RFID-based toll gates function by reading the RFID data from the vehicle, fetching the corresponding user information from a centralized server, and subsequently deducting the toll amount from the user's account. This process, while effective, inherently introduces a latency period. This latency, particularly during peak hours, can result in significant traffic congestion at the toll gates. The proposed method tackles this issue by markedly reducing the latency involved in the toll collection process. This is achieved by optimizing the data retrieval and balance deduction processes. The optimization involves pre-fetching user data and implementing faster transaction protocols, thereby diminishing the time taken for each vehicle at the toll gate. By minimizing the time each vehicle spends at the toll gate, the proposed method not only boosts the efficiency of the toll collection process but also facilitates smoother traffic flow. This decrease in traffic congestion at toll gates can lead to enhanced fuel efficiency and reduced travel time for commuters. Moreover, the proposed method improves the user experience by offering a more seamless and efficient toll payment process.

Keywords: Radio frequency identification (RFID), toll gate systems, faster transaction protocols, seamless toll payment process, gate function, WORM

INTRODUCTION

Radio Frequency Identification (RFID) technology has revolutionized toll collection systems, offering a convenient and efficient means of processing payments without the need for physical contact. However, traditional RFID-based toll gate systems encounter challenges. One significant issue is the latency inherent in the toll collection process, particularly during peak hours, leading to traffic congestion and delays. This study presents a novel approach aimed at addressing these challenges and enhancing the efficiency of RFID-based toll gate systems. The traditional process involves reading RFID data from vehicles, retrieving user information from a centralized server, and deducting toll amounts accordingly. While effective, this process introduces a latency period that can exacerbate congestion at toll gates, impacting both commuters and toll operators. The proposed method focuses on reducing this latency by optimizing data retrieval and transaction protocols. By pre-fetching user data and implementing faster transaction protocols, the proposed approach aims to minimize the time each vehicle spends at the toll gate. This optimization not only improves toll collection efficiency but also facilitates smoother traffic flow, leading to

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enhanced fuel efficiency and reduced travel times for commuters. Beyond its implications for traffic flow improvement. By addressing these challenges, the proposed approach sets the stage for a more efficient and user-friendly RFID-based toll collection system. In this study, we will delve into the details of the proposed approach, discussing its key features, implementation strategies, and potential benefits. We will also explore the practical implications and challenges associated with its implementation, paving the way for future research in this field.

LITERATURE REVIEW

RFID systems consist of readers and tags. The reader, with a transmitter and receiver, interacts with the tag, which includes a responder and antenna. The reader emits radio signals, activating the tag to send back data. There are two types of tags: passive ones, which rely on the reader’s energy, and active ones, which have their own power source. These systems are widely used for unique identification wirelessly [1]. RFID tags operate in different modes, each serving specific functions. Read-only tags are designed for data retrieval, prohibiting any modification to the stored information. Read/write tags facilitate both data reading and writing capabilities. WORM (Write Once Read Many) tags allow data to be written onto them only once. RFID systems utilize various frequency bands tailored to specific environments and applications. Low-frequency RFID operates within the range of 125 to 134.2 kHz. High-frequency RFID operates at 135.6 MHz. Ultra-high frequency RFID operates within the range of 860 to 930 MHz. Microwave frequency operates at 2.45 GHz [2].

Currently, RFID technology is experiencing significant advancements. Efforts towards standardization are underway to establish global standards. There have been notable improvements in RFID systems, including extended read ranges, enhanced data transfer rates, and increased reliability [3]. Additionally, the integration of RFID with Internet of Things (IoT) and cloud computing technologies is on the rise. RFID autonomously captures data and archives it on the computer system. It facilitates computers to comprehend real-world events and processes independently, without human intervention. RFID technology streamlines data collection processes, minimizing human involvement and potential errors [4].

METHODOLOGY

Our approach to optimizing the RFID-based toll gate system targets reducing latency, improving traffic flow, and enhancing efficiency. Key components include dual RFID scanners for faster processing, prefetching tag data to expedite transactions, real-time toll deduction, and synchronized database updates for accuracy. Advanced data prefetching techniques and a pre-fetching algorithm minimize server retrieval time. These elements collectively aim to streamline operations and enhance system performance [5].

Our primary focus is on implementing a dual RFID scanner system, a crucial step in substantially improving the efficiency of toll gate operations. Through the integration of this dual scanner setup, our aim is to transform the speed and accuracy of vehicle processing at toll gates. Additionally, we introduce a novel approach to further streamline toll gate operations: prefetching tag data [6] This advanced technique ensures that the relevant information required for each transaction is retrieved in advance, effectively eliminating any possible slowdowns caused by data retrieval delays. By proactively fetching tag data, we aim to expedite the toll payment process and enhance the overall user experience. Real-time toll deduction, triggered by RFID tag data, is a pivotal feature of our system. By leveraging real-time data processing capabilities, toll deductions are initiated instantaneously upon tag detection, eliminating delays and enhancing the overall transaction speed [7].

Additionally, we ensure the accuracy of transaction records through synchronized deduction and database update mechanisms, ensuring that each transaction is meticulously recorded for auditing and management purposes. Our system incorporates advanced data prefetching techniques, optimizing efficiency not only for daily but also weekly vehicle arrivals. By anticipating and retrieving necessary data ahead of time, it ensures seamless operations during peak traffic periods. Moreover, we introduce a pre-fetching protocol aimed at minimizing server data retrieval time, further enhancing the responsiveness of our system. Ultimately, our goal is to optimize the transaction experience for users through a streamlined toll deduction process [8]. By combining innovative RFID implementation, real-time processing, and advanced prefetching techniques, we strive to deliver a seamless and efficient toll processing system that enhances traffic flow and user satisfaction.

PROPOSED ALGORITHM

As a vehicle nears the first scanner station, its RFID tag is identified, and the system extracts the unique identifier (UID). This UID is then sent to a centralized control system equipped with sophisticated algorithms. The control system initiates a series of validations for the UID and associated data. It first checks its local database for relevant information like vehicle owner details, UID, registration number, and account balance. If this data is not locally available, it connects in real-time with the central server to obtain it. This information is then stored locally to speed up future transactions and improve system efficiency [9].

The controller assesses the vehicle's account balance using advanced algorithms. If funds are insufficient, an immediate notification occurs prompting necessary actions; if adequate, it prepares for the vehicle's arrival at the next scanner station. At this point, local data availability is reconfirmed to ensure redundancy and uninterrupted toll processing in case of scanner or communication failures [10].

After confirming local data accessibility and performing a final balance check that confirms sufficient funds for toll payment, the gate opens for the vehicle to pass through. Concurrently, a transaction request deducts the toll amount from the vehicle's account via communication with central server, exemplifying seamless coordination and efficiency of this advanced toll processing technology. This system, by integrating local and server data retrieval and rigorous balance checks, ensures smooth traffic flow while maintaining security and reliability. It demonstrates the power and effectiveness of using advanced technology to streamline toll processing and prevent potential issues. Flow chart for the proposed algorithm is shown in Figure 1.

Algorithm Scenarios Discussion

Toll processing systems encounter a variety of situations, each demonstrating the system's adaptability and reliability:

Initial Vehicle Scanning

As vehicles approach the toll gate, they are scanned by the first scanner. This process registers each vehicle into the toll system, detects the RFID tag on the vehicle, and initiates the toll transaction. The toll fee, calculated based on the vehicle's classification, is then deducted from the associated account.

Detection of Multiple Tags

The toll system may sometimes detect multiple RFID tags at once due to closely spaced vehicles or other factors. To handle this, the system uses algorithms to distinguish between tags and accurately process each transaction, ensuring correct toll fees for each vehicle [11].

Handling Insufficient Balance

If a vehicle's associated account lacks sufficient funds for the toll fee, the system alerts the driver through visual or auditory signals. The driver is then given clear instructions on how to resolve the issue, such as recharging their account or arranging alternative payment methods.

First Scanner Failure

In case of a first scanner malfunction, the toll system implements contingency plans to keep toll processing uninterrupted. These may include manual toll collection or the use of backup scanners. Technicians are also promptly alerted to fix the issue and restore normal operations [12].

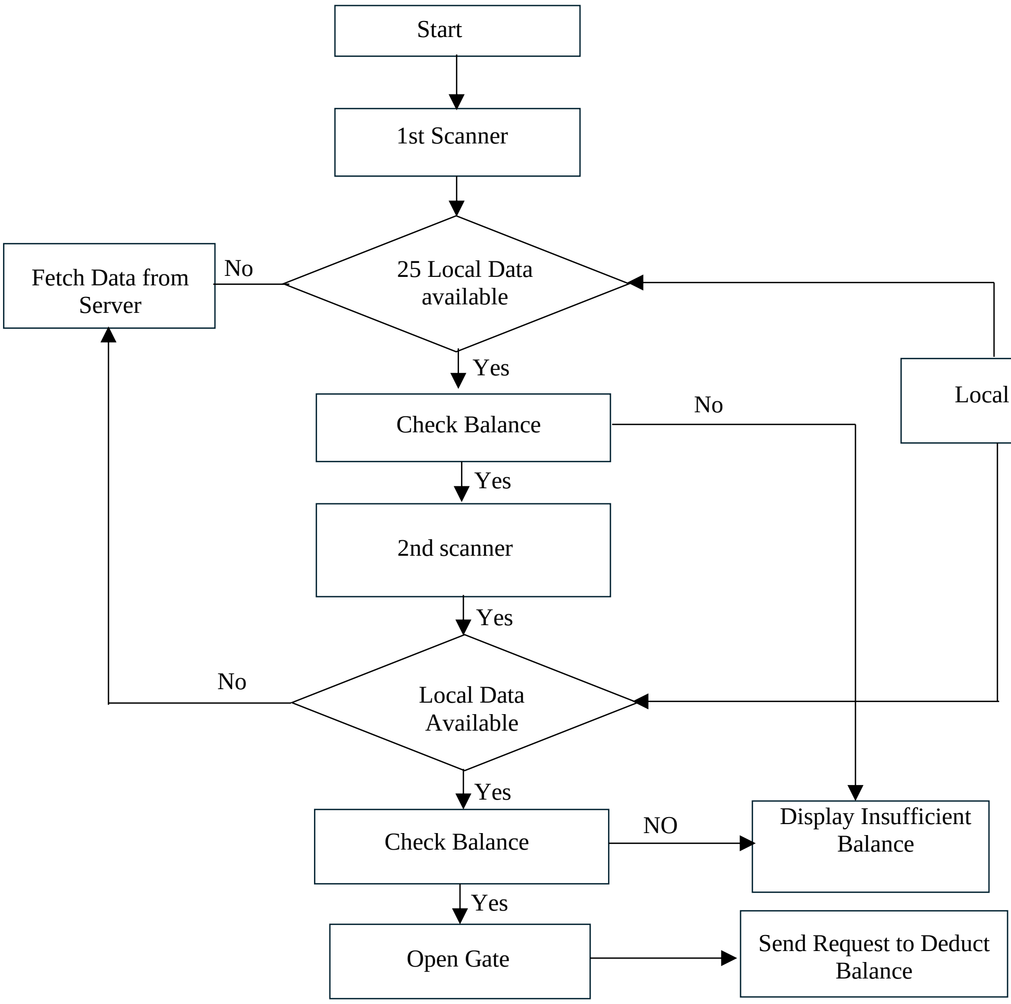

Figure 1. Flow Chart for the proposed algorithm.

Advanced Data Prefetching

The system enhances the toll processing experience by prefetching data for regular commuters. By analyzing commuter patterns and transaction history, the system can predict upcoming transactions and prefetch relevant data, such as account balances and transaction history, reducing processing time and improving user experience.

Prefetching Data for the Next Week

The system further optimizes efficiency by prefetching and caching data for anticipated transactions in the upcoming week. By predicting future toll transactions based on historical data and user preferences, the system ensures seamless toll transactions for users.

In summary, these scenarios highlight the toll processing system's ability to adapt to various situations while maintaining efficient operations.

IMPLEMENTATION

Hardware Infrastructure Overview

Our toll gate system, based on RFID technology, is built upon a sophisticated hardware setup designed for efficient toll collection and traffic management. The key components of this infrastructure include RFID readers for vehicle identification, microcontrollers for data processing, a communication protocol for seamless data exchange, and reliable power supplies for continuous operation. This hardware setup is carefully orchestrated to ensure smooth toll gate operations, minimize processing latency, and optimize traffic flow. The initial step in our system setup involves initiating the MQTT broker, a crucial component that facilitates communication between the controller and the server.

Server Setup and Configuration

After setting up the MQTT broker and programming our server in Python, we have developed a robust system for efficient vehicle information management. The server initially retrieves relevant data from a designated text file containing comprehensive vehicle details, including the car owner's name, unique identifier (UID), vehicle number, and corresponding toll amounts. This information is then stored in a list data structure in the server's memory. Upon execution, the program displays the contents of the text file for validation. The server then establishes a connection with the MQTT broker, ready to receive incoming communications from the controller. When the UID transmitted by the controller is received, the server promptly initiates a series of processing procedures. These procedures include retrieving associated vehicle details from the stored database, verifying the UID against existing records, and calculating the applicable toll amount. After the processing phase, the server updates the toll amount within the list data structure. This iterative process ensures that the database consistently reflects the latest transactional information, facilitating seamless data synchronization and retrieval. By persisting the updated database back to the designated text file, our system ensures data integrity and consistency, even in the event of server restarts. This robust approach underscores our commitment to efficient toll transaction management, enhancing the overall reliability and robustness of our system.

In conclusion, our hardware implementation and system demonstration highlight our commitment to using advanced technology to optimize toll gate operations, streamline traffic management, and ensure a seamless user experience.

MFRC522 and ESP32 Pin Configuration

The Table 1 provides the pin configuration for the MFRC522 and ESP32 setup in our system.

Communication and Data Management between Controller and Server

Our system incorporates two MFRC522 RFID readers interfaced with an ESP32 microcontroller, programmed using MicroPython. The ESP32 acts as the control unit, overseeing RFID tag detection and liaising with the MQTT broker. Upon startup, the ESP32 initiates a connection with the MQTT broker, enabling smooth communication between the controller and the server. When an RFID reader scans a tag, it transmits the corresponding UID (Unique Identifier) to the ESP32 microcontroller via the SPI (Serial Peripheral Interface) protocol.

The ESP32 then publishes the received UID to the MQTT broker using the MQTT protocol, allowing the server to receive real-time updates about the scanned RFID tag. This process ensures synchronization between the controller, server, and RFID scanner units. This integrated system promotes efficient coordination and synchronization, guaranteeing precise and prompt processing of RFID tag data. The synergy between the controller, RFID scanners, and server boosts the overall functionality and reliability of our RFID-based toll gate system.

RESULTS AND DISCUSSION

Our algorithm is specifically designed to handle various scenarios in RFID-based toll gate systems, with five distinct cases.

Case 1: Initial Scan and Data Transmission

As a vehicle approaches Scanner 1, the system triggers the scanning process, capturing the RFID tag's Unique Identifier (UID). This UID is then extracted and stored within the ESP32 microcontroller for subsequent processing.

Table 1. Pin Configuration for MFRC522 and ESP32.

ESP32	RFID 1	RFID 2
3.3 V	3.3 V	3.3 V
GPIO4 (D4)	RST	RST
GND	GND	GND
GPIO19 (MISO)	MISO	MISO
GPIO23 (MOSI)	MOSI	MOSI
GPIO18 (SCK)	SCK	SCK
GPIO15 (D15)	SDA	-
GPIO5 (D5)		SDA

Figure 2 illustrates this initial phase where Scanner 1 captures the vehicle's UID. After the capture, the UID is transmitted to the server as shown in Figure 3 for validation against a database. If the UID is not found, the server displays "UID not found". However, if the UID is validated, the server retrieves associated data such as the car owner's name, UID, vehicle number, and amount from the server database (Figure 4).

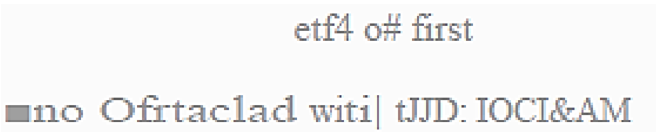

Figure 2. Vehicle UID by Scanner 1.

Figure 3. Transmitting UID to Server.

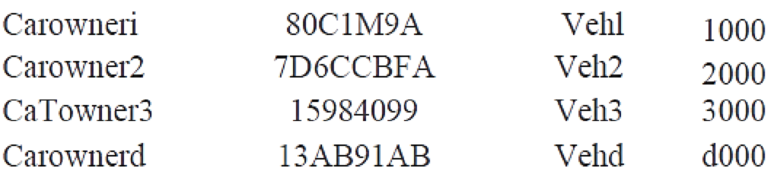

Figure 4. Server Database.

To optimize the usage of the MQTT protocol, this data is consolidated into a single string, separated by commas "Car_owner_name, UID, Vehicle_number, amount". This method negates the need for multiple topics for individual data points transmission over MQTT, thereby streamlining the messaging process, reducing overhead, and simplifying the overall communication structure between the server and the controller in the RFID-based toll gate system. The consolidated data is then sent to the controller via the MQTT protocol as shown in Figure 5.

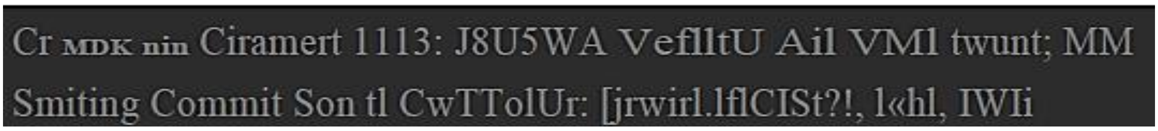

Figure 5. Server Retrieves Data from Database and Sends Response to Controller.

The controller receives data, separates it into four variables using the variable_name.split(",") method, and checks for adequate balance. If the balance is sufficient, the data is stored locally for future use (Figure 6).'

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Figure 6. Received and Stored Data in Local Memory.

When vehicle reaches the second scanner, the controller scans the RFID tag and checks if the UID data is stored locally. If the data is found, indicating that the vehicle has passed the first scanner and initiated the toll payment, the controller opens the gate and requests the server to deduct the toll from the associated account (Figure 7).

```
RFID lag Detected with UID: 80C15A5A from Scar.net: 2 Matching
string in Local Meioiy: Caromer1,80C15A8A,Vehl,1000 Caromed
80C15A9A Vehl 1000
The set toll balance after deduction :: 900
```

Figure 7. Deducted Amount Transmitted by Controller.

The server, upon receiving the UID and deducted amount, checks its database for the UID. It verifies the transaction and ensures the correct UID is associated with the deducted amount. Once the UID is found, the server updates the associated account balance by deducting the toll amount (Figure 8).

This process ensures an efficient toll collection system.

Case 2: Multiple Tag Detection

Our algorithm incorporates a mechanism to manage situations where multiple vehicles are detected by the first scanner before they reach the second one. This is achieved by the controller efficiently receiving, organizing, and storing the data associated with each vehicle's RFID tag from the server as shown in Figure 9. The stored data includes unique identifiers (UIDs), transaction details, and other relevant toll collection information. This process ensures that the toll collection remains accurate and streamlined, even in high-traffic situations, by effectively handling concurrent vehicle arrivals. Furthermore, our system is designed to handle scenarios where the sequence of vehicle arrivals at the toll gate deviates from the order they were scanned at the first scanner. For example, if car 4 reaches the second scanner before car 3, despite being scanned later, the system ensures that the toll is deducted only for car 4, not car 3. This feature is crucial for maintaining accuracy in toll collection in dynamic traffic conditions.

Caronnerl	80C15A9A	Vehl	900
Carowner2	706CCBFA	Veb2	2600
Carowmeri	1S984D99	Vehl	3600
Carownera	13AB91AB	WM	4000

Figure 8. Updated Database on Server.

```
Printing Stored data in Local Memory
Carovneri, 80C15A5A,Vehl,500
Carovner2,7D6CCBFA,Veh2,2000
Carovner3,15584D55,Veh3,3000
Carowner4,13AB91A3,Veh4,4000
```

Figure 9. Multiple Stored Data.

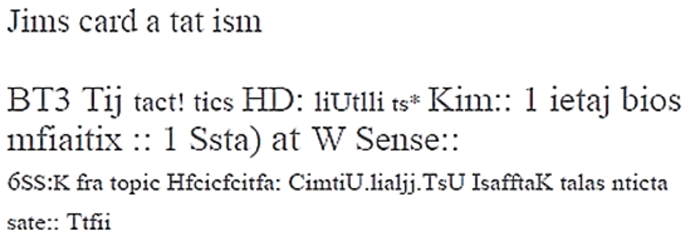
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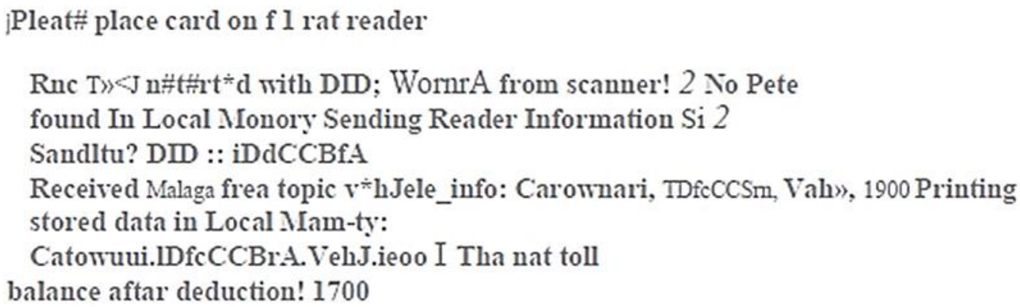
Figure 10. Insufficient Balance Alert by Reader 1.

Case 3: Insufficient Balance

Our algorithm is designed to manage situations where a vehicle lacks sufficient funds at the initial checkpoint. In such cases, the system proactively displays a "Insufficient Balance" message along with the vehicle's number. This alert allows the toll gate operator to identify vehicles with insufficient funds before they reach the gate. If a vehicle bypasses the initial scanner and proceeds directly to the second one without enough funds, our system promptly displays an "Insufficient Balance" alert as the vehicle approaches the gate as shown in Figure 10. This early warning system ensures immediate attention to payment issues, thereby maintaining smooth operations at the toll gate.

Case 4: First Scanner Failure:

In the RFID-based toll gate system, if the first scanner fails to read a vehicle's tag due to issues like over speeding or environmental factors, the standard protocol is activated. The secondary scanner steps in, quickly identifying the unique identifier (UID) linked to the vehicle's RFID tag. It then checks locally for the UID's associated information. As the first scanner's failure implies the data will not be locally available, the UID is sent to the central server. This server maintains a comprehensive database with crucial details for each registered RFID tag, including the owner's name, vehicle registration number, UID, and the required toll amount. Upon receiving the UID, the server swiftly fetches the relevant information, facilitating the toll transaction process's smooth continuation. If the controller verifies that the tag's associated balance is sufficient, the toll gate controller starts the gate opening process. Concurrently, a deduction request is sent to the server, authorizing it to deduct the appropriate toll amount from the vehicle's account as shown in Figure 11.


¡Pleat# place card on f 1 rat reader

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found In Local Monory Sending Reader Information Si 2
Sandltu? DID :: iDdCCBfA
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stored data in Local Mam-ty:
Catowuui.lDfcCCBrA.VehJ.ieoo I Tha nat toll
balance aftar deduction! 1700

Figure 11. First scanner failure.

Case 5: Advanced Data Prefetch for Commuters

The algorithm has a unique feature designed for regular commuters. If a vehicle passes through the toll gate for three consecutive days, the controller records the data from these instances. On the fourth day, it analyzes the stored data to identify recurring Unique Identifiers (UIDs) and calculates the average arrival time, subtracting 30 min from this average. In anticipation of the vehicle's arrival on the fourth day, the corresponding UID is sent in advance to the server for balance verification. As a result, when the vehicle reaches the toll gate, the gate opens smoothly, speeding up the passage and simultaneously initiating a request for toll amount deduction. For instance, if a car passes through on Monday, Tuesday, and Wednesday, the system will analyze the stored data as shown in Figure 12 on Thursday to identify common UIDs and calculate the average arrival time, subtracting 30 min from this average. The corresponding UID is sent to the server ahead of time for balance verification, ensuring a seamless transaction when the vehicle arrives at the toll gate. The calculated average arrival time is 15:48. Therefore, at 15:18, the corresponding UID is sent to the server, and the associated data is collected, ensuring proactive balance verification as shown in Figure 13. As the vehicle nears the toll gate, it is promptly allowed access, resulting in a smooth opening of the gate. At the same time, a deduction request for the toll amount is initiated, guaranteeing a swift collection of the toll.

MC1U9A 15 W	15414099 11 49	15914099 15:51
15984099 15:48	TOKCIFA 15:49	1)489148 15:51

Figure 12. Data Stored on Monday, Tuesday and Wednesday.

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Figure 13. Advance data received.

Our algorithm's performance was thoroughly evaluated by comparing its execution time with two scanners equipped with a prefetch mechanism against a scenario using only one scanner. The results were striking, demonstrating that our optimized approach was approximately 6000 times faster than the existing algorithm, as evidenced by the comparative performance data in Table 2. This substantial speed enhancement highlights the effectiveness of our innovative approach in optimizing toll gate operations. By employing advanced techniques such as prefetching and optimizing scanner placement, we have successfully reduced latency and significantly increased the system's throughput. These results confirm our solution's potential to transform RFID-based toll gate systems, promising not only shorter wait times for drivers but also improved traffic flow efficiency.

Table 2. Results.

System	Time Taken
Existing System	1.5 sec
Proposed Algorithm	0.000233 sec

CONCLUSION AND FUTURE SCOPE

In conclusion, our research has successfully demonstrated a novel approach to optimizing RFID-based toll gate systems, significantly reducing latency and enhancing traffic flow. The implementation of dual RFID scanners and advanced data prefetching techniques has proven to be a game-changer in the realm of traffic management. Our system not only streamlines the toll collection process but also offers a blueprint for future advancements in transportation infrastructure.

The practical implications of our study are far-reaching, with the potential to revolutionize how toll gates operate, leading to smoother traffic, reduced congestion, and a better overall commuting experience. The integration of these technologies into existing infrastructure is a testament to the transformative power of innovation in addressing real-world challenges.

As we look ahead, the scope for further research is vast. We aim to refine our algorithm, explore additional optimizations, and seek collaboration for real-world application. The prospect of integrating GPS and satellite technology presents an exciting frontier for enhancing the precision and efficiency of toll gate operations.

Our work lays a solid foundation for the next steps in this journey, and we are optimistic about the positive impact our contributions will have on the future of RFID-based toll gate systems.

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