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LoRaLife: Seamless Traffic Clearance System for Emergency Response

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Abstract— This paper presents LoRaLife, a LoRa-based emergency vehicle priority system designed to eliminate traffic signal delays for ambulances navigating urban intersections. The system enables emergency vehicle operators to broadcast a priority clearance command that autonomously overrides conventional traffic signal cycles, ensuring unobstructed passage during time-critical medical emergencies such as cardiac arrests, trauma cases, and accident responses—where the first sixty minutes, widely recognized as the Golden Hour, are decisive for patient survival. A two-component architecture forms the core of the system: an Ambulance Unit acting as the transmitter and a Traffic Signal Unit acting as the receiver. The ambulance unit integrates an ESP32 microcontroller, a Neo-6M GPS module for real-time location and speed tracking, and an SX1278 LoRa transceiver operating at 433 MHz, while the traffic signal unit processes incoming priority packets and executes signal preemption autonomously. The system combines deterministic signal control logic with low-power, long-range LoRa communication to deliver reliable performance independent of cellular networks, internet infrastructure, or centralized coordination. The proposed solution demonstrates how embedded wireless technologies and microcontroller-based automation can be integrated to create a resilient, infrastructure-independent emergency response pipeline without reliance on GSM, 4G, or cloud-dependent communication frameworks.

Keywords— Emergency Vehicle Preemption, LoRa Communication, Traffic Signal Control, ESP32 Microcontroller, SX1278 Transceiver, GPS Tracking, Golden Hour, Urban Traffic Management, IoT-Based Systems, Infrastructure-Independent Communication

I. INTRODUCTION

With the rapid expansion of urban populations and the continuous rise in vehicle density, traffic congestion has become a persistent challenge in modern cities, significantly impacting mobility and emergency response efficiency. Emergency vehicles such as ambulances are frequently delayed at traffic intersections due to conventional signal systems that operate on fixed cycles and lack the ability to dynamically prioritize time-critical situations..

To address this challenge, vehicle-to-infrastructure (V2I) communication approaches have emerged, enabling emergency vehicles to interact directly with traffic control systems. However, many existing solutions depend on GSM, Wi-Fi, or internet-based networks, which introduce vulnerabilities such as communication delays, network congestion, and infrastructure dependency. This work introduces LoRaLife, a decentralized emergency traffic clearance system that establishes a direct, infrastructure-independent communication link between ambulances and traffic signal controllers using LoRa radio frequency technology.

The proposed system enables ambulance operators to transmit an emergency clearance command via LoRa, upon which the traffic signal unit automatically overrides the existing signal cycle to create an unobstructed green corridor for the approaching vehicle. Once the emergency vehicle clears the intersection, normal signal operation is restored without manual intervention. Additionally, the system integrates GPS-based location tracking to enhance situational awareness and ensure reliable, low-power communication suitable for deployment across diverse urban environments.

II. LITERATURE REVIEW

1) M. A. Al Breiki et al., "LoRaWAN Based Traffic Clearance System for Emergency Vehicles," International Journal of Intelligent Transportation Systems Research, 2022.

Deployment of a LoRaWAN communication framework to establish connectivity between emergency vehicles and traffic signal controllers.Automatic overriding of traffic signals upon reception of priority signals to create a green corridor for approaching ambulances.Experimental validation demonstrating reliable long-range communication with minimal power consumption in smart city environments.

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2) J. Silva et al., "Crash Response System Using LoRa-Based V2X Communication," IEEE Transactions on Vehicular Technology, 2021.

Design of a vehicle-to-everything (V2X) communication framework enabling accident-involved vehicles to autonomously transmit emergency signals to nearby infrastructure.Evaluation of LoRa communication performance in non-line-of-sight environments with physical obstructions such as buildings and urban structures.Demonstration of LoRa's suitability for supporting emergency response operations without dependence on centralized network infrastructure.

3) F. J. Ferrero et al., "LoRa-Based Traffic Flow Detection for Smart Roads," IEEE Sensors Journal, vol. 20, no. 16, pp. 9354–9362, 2020, doi: 10.1109/JSEN.2020.2981739.

Deployment of wireless LoRa sensors for real-time traffic density monitoring across road networks.Transmission of collected traffic data to a central monitoring station leveraging LoRa's long communication range and energy efficiency.Validation of LoRa networks as a scalable solution for large-scale intelligent transportation monitoring systems.

4) R. Patel and S. Kumar, "IoT Traffic Control for Emergency Vehicles," International Journal of Advanced Computer Science and Applications, vol. 12, no. 4, pp. 210–218, 2021, doi: 10.14569/IJACSA.2021.0120425.

Integration of IoT sensors, wireless communication modules, and signal controllers to dynamically adjust signal timings upon detection of approaching emergency vehicles.Implementation of automated priority assignment logic that reduces intersection waiting time for ambulances and rescue vehicles.Experimental results demonstrating a statistically significant reduction in emergency vehicle delays compared to conventional fixed-cycle signal systems.

5) A. Kumar and P. Sharma, "Intelligent Traffic Signal Pre-Emption System for Emergency Vehicles," Journal of Transportation Engineering, vol. 147, no. 3, pp. 1–10, 2021, doi: 10.1061/JTEPBS.0000512.

Architecture comprising an in-vehicle transmitter unit and an intersection-mounted receiver unit to enable automated signal pre-emption.Override of normal traffic signal cycles upon signal reception, allowing emergency vehicles to pass through intersections without manual intervention.Comparative analysis highlighting the limitations of GSM and Wi-Fi dependent systems in terms of latency and infrastructure dependency, positioning LoRa as a more resilient alternative.

III. METHODOLOGY

The LoRaLife Emergency Traffic Clearance System was developed using the Evolutionary Prototyping Model, which emphasizes gradual enhancement through continuous hardware testing and iterative refinement. This approach enabled progressive improvements in communication reliability, signal processing accuracy, and system response time across multiple development cycles. Each iteration introduced refinements in LoRa packet transmission, authentication logic, traffic signal control, and GPS integration, ensuring optimal performance and deployment readiness in real-world urban environments.

The system architecture is structured into four major components — Emergency Signal Transmission, Authentication and Signal Validation, Traffic Signal Control Engine, and Embedded Hardware Interface — each playing a crucial role in delivering automated and reliable emergency traffic clearance.

1) *Emergency Signal Transmission:*

This phase focuses on transforming a driver-initiated trigger input into a structured wireless data packet suitable for long-range transmission. The ambulance unit accepts input through a push button emergency trigger connected to the ESP32 microcontroller. Once activated, the system generates a data packet containing the vehicle identification code and a traffic clearance command. Additionally, real-time GPS coordinates and vehicle speed data are captured using the Neo-6M GPS module and embedded within the packet. The LoRa RA-02 module operating at 433 MHz then transmits this packet wirelessly to the traffic signal unit. This phase ensures that emergency signals are generated promptly, structured correctly, and transmitted over long distances with minimal power consumption.

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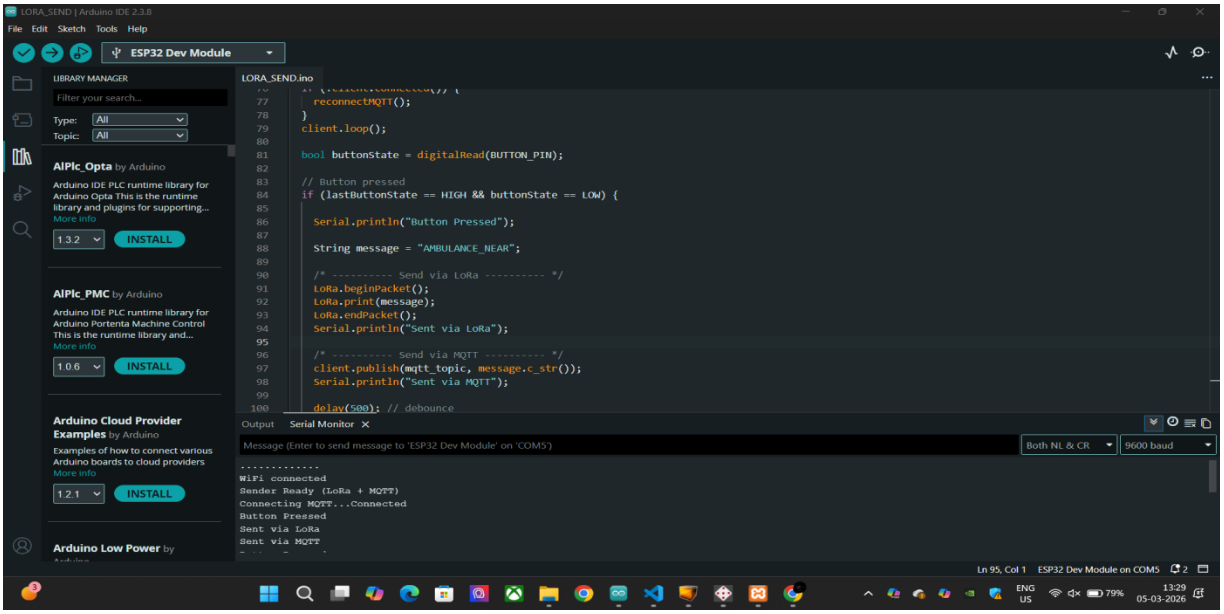

Fig. 1: Arduino IDE Implementation for Emergency Signal Transmission

2) Authentication and Signal Validation:

The core of the system involves a whitelist-based authentication mechanism that verifies the legitimacy of incoming emergency signals before any traffic control action is executed. When the traffic signal unit receives a packet, the ESP32 receiver extracts the vehicle identification code and cross-references it against a pre-configured list of authorized emergency vehicles. Packets originating from unrecognized sources are discarded to prevent unauthorized traffic signal manipulation. The system also includes fallback logic to ensure that normal traffic signal operation continues uninterrupted if a received packet fails validation. This hybrid approach combines deterministic rule-based authentication with real-time signal verification, significantly enhancing system security and operational integrity.

3) Traffic Signal Control Engine:

This module acts as the decision-making and execution core of the system. Upon successful authentication, the ESP32 at the receiver unit sends control signals to a relay module that interfaces directly with the physical traffic signal lights. The engine temporarily overrides the active signal cycle, activating a green signal for the ambulance lane and maintaining it for a predefined duration. A blue emergency beacon is simultaneously triggered to alert surrounding vehicles. Once the timer elapses, the engine automatically restores the normal traffic signal cycle without requiring any manual intervention. The control engine ensures accurate, low-latency, and reliable signal switching that supports uninterrupted emergency vehicle passage through intersections.

4) Embedded Hardware Interface:

The hardware layer of the system is developed around ESP32 microcontrollers and SX1278 LoRa transceiver modules, providing a compact, low-cost, and easily deployable embedded platform. The ambulance unit integrates a push button trigger, LED status indicator, GPS module, and LoRa transmitter into a unified circuit. The traffic signal unit integrates a LoRa receiver, relay module for signal switching, and an LED beacon. Both units communicate over the SPI protocol between the ESP32 and LoRa modules. The modular design of the hardware allows future expansion to support multiple intersections and simultaneous emergency vehicle coordination across larger urban networks.

5) Tools and Technologies:

Programming Language: Embedded C/C++
Development Platforms: Arduino IDE, Visual Studio Code
Microcontroller: ESP32 (Dual-core, Wi-Fi and Bluetooth enabled)
Communication Module: SX1278 LoRa RA-02 (433 MHz, SPI interface)

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GPS Module: Neo-6M (NMEA protocol for location and speed data)
Communication Protocol: LoRa peer-to-peer (P2P), SPI
Monitoring and Testing Tools: MQTT Box, Grafana
Database and Server: MySQL, XAMPP (Apache)
Libraries: LoRa.h, TinyGPS++, Wire.h, SPI.h

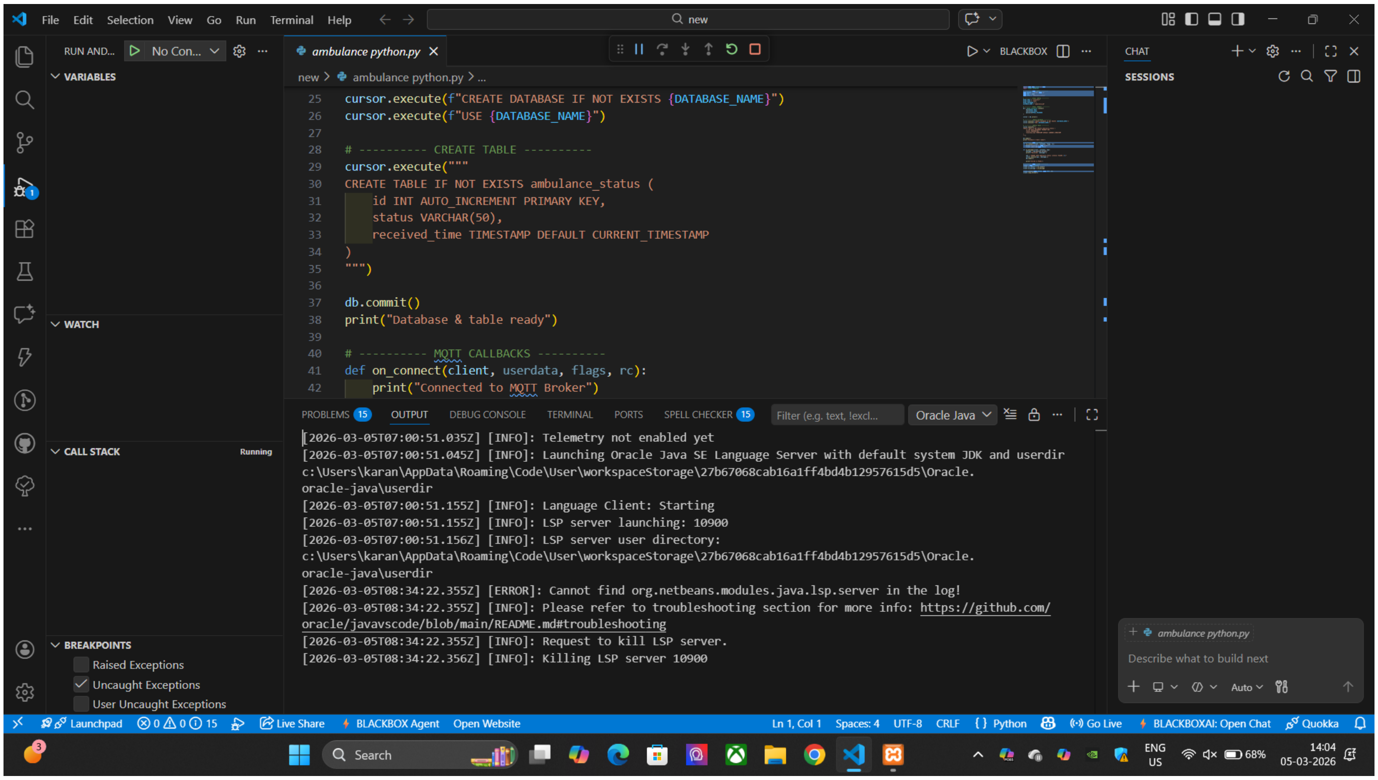

Fig. 2: Python-based MQTT Callback and Database Integration Logic

IV. MODELING AND ANALYSIS

The development of the LoRaLife Emergency Traffic Clearance System involved a structured process of system modeling and requirement analysis, ensuring that both functional and non-functional aspects were clearly defined prior to implementation. This phase was essential in transforming the conceptual idea of decentralized emergency vehicle prioritization into a practical and reliable framework capable of operating independently of internet infrastructure while delivering real-time traffic signal control.

Through detailed analysis, the system was designed to handle direct wireless communication between two embedded nodes — the Ambulance Unit and the Traffic Signal Unit — which must operate reliably in dynamic urban environments characterized by physical obstructions, variable traffic densities, and unpredictable emergency scenarios. The modeling phase focused on designing modular components for emergency signal transmission, whitelist-based authentication, traffic signal override control, and automated system restoration — each optimized for low latency, energy efficiency, and deployment scalability.

The overall system architecture ensures seamless integration between the ESP32-based embedded firmware, LoRa peer-to-peer communication layer, and relay-controlled traffic signal interface, enabling a smooth operational flow from emergency trigger activation to green corridor creation and automatic signal restoration.

A. System Analysis

1) Functional Requirements:

The functional requirements define the core operations that the system must perform to achieve its objectives.

The ambulance unit must transmit an emergency clearance signal upon activation of the driver-operated push button trigger. The signal packet must contain the vehicle identification code and a traffic clearance command. The system must support long-range wireless communication between the ambulance unit and the traffic signal unit over distances ranging from several hundred meters to more than one kilometer.

Upon receiving a valid emergency packet, the traffic signal unit must authenticate the vehicle ID against a pre-configured whitelist before executing any signal override. Once authentication is successful, the traffic signal controller must temporarily override the active signal cycle and activate a green signal for the ambulance lane. A visual emergency beacon must be triggered simultaneously to alert surrounding road users. After a predefined time interval, the system must automatically restore the normal traffic signal cycle without requiring manual intervention. The system must support real-time GPS-based location and speed monitoring through the Neo-6M module integrated into the ambulance unit. Communication status must be displayed on the OLED display installed in the ambulance unit to provide the driver with real-time feedback. System activity logs including signal transmissions, authentication results, and traffic signal activations must be stored in a MySQL database for performance analysis and auditing.

These functionalities make the system highly reliable, infrastructure-independent, and suitable for deployment in smart city environments, developing urban regions, and disaster-prone areas where network connectivity may be unavailable.

2) Non-Functional Requirements:

The non-functional requirements define the quality and performance characteristics of the system.

- Low Latency: Ensures that the time between emergency signal transmission and traffic signal activation is minimized to support real-time emergency response.
- Reliability: Provides consistent and accurate signal processing even in non-line-of-sight environments with physical obstructions such as buildings or dense traffic.
- Scalability: The decentralized peer-to-peer architecture allows the system to be extended to support multiple intersections and multiple emergency vehicles across a larger urban network.
- Security: Whitelist-based authentication prevents unauthorized vehicles from triggering traffic signal overrides, ensuring system integrity.
- Energy Efficiency: All embedded components, including the ESP32 microcontroller and LoRa modules, are selected for their low power consumption, ensuring long operational life.
- Ease of Deployment: The system is designed to integrate with existing traffic signal infrastructure with minimal modifications, reducing installation complexity and cost.
- Fault Tolerance: The system includes automatic signal restoration logic to ensure that normal traffic flow resumes even in the event of communication interruption or system timeout.
- Maintainability: The modular firmware architecture allows individual components such as authentication logic, signal control routines, and communication parameters to be updated independently.

B. Hardware and Software Requirements

1) Hardware Requirements:

ESP32 Dual-Core Microcontroller (240 MHz, for both transmitter and receiver units)
SX1278 LoRa RA-02 Transceiver Module (433 MHz, long-range low-power RF communication)
Neo-6M GPS Module (NMEA protocol, for real-time location and speed tracking)
Relay Module (for physical traffic signal switching)
OLED Display (for real-time system status feedback in the ambulance unit)
Push Button Switch (emergency trigger input)
LED Indicators and Blue Emergency Beacon (visual status and alert output)
Resistors: 10kΩ (pull-up) and 330Ω (current limiting)
Regulated DC Power Supply (for stable continuous operation of all components)

2) Software Requirements:

Programming Language: Embedded C/C++
Development Platforms: Arduino IDE, Visual Studio Code
Communication Protocol: LoRa peer-to-peer (P2P) via SPI interface
Monitoring and Testing Tools: MQTT Box, Grafana
Database and Local Server: MySQL, XAMPP (Apache)
Embedded Libraries: LoRa.h, TinyGPS++, Wire.h, SPI.h, Adafruit SSD1306 (OLED)

V. RESULTS AND DISCUSSION

The LoRaLife Emergency Traffic Clearance System was extensively tested across a range of operational scenarios simulating real-world urban traffic conditions, covering varying communication distances, physical obstructions, and emergency trigger response sequences. The evaluation focused on assessing the system's ability to reliably transmit emergency signals, authenticate vehicle identities, execute traffic signal overrides, and restore normal signal cycles with minimal latency and without dependence on internet infrastructure.

Prior to full system testing, both hardware units underwent individual component verification. This included confirmation of SPI communication between the ESP32 and SX1278 LoRa modules, validation of GPIO pin responses for the push button trigger and relay output, and accuracy testing of the Neo-6M GPS module for real-time location and speed data. These preliminary checks ensured that hardware-level inconsistencies were identified and resolved before integrated system testing commenced.

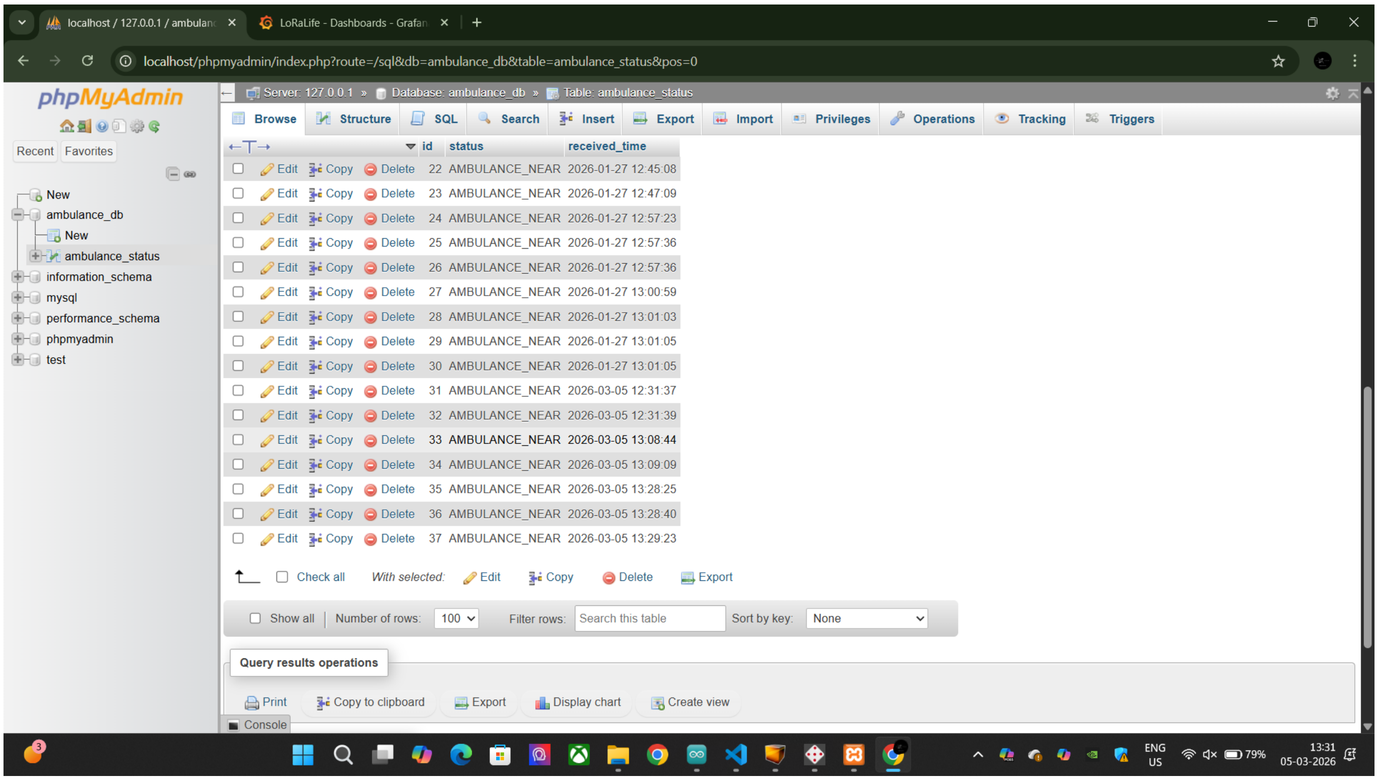

Fig. 3: Real-time Emergency Signal Logs in MySQL Database

The system leverages a hybrid approach combining deterministic embedded control logic with LoRa peer-to-peer wireless communication. The ambulance unit generates a structured data packet containing the vehicle identification code and clearance command upon trigger activation, while the traffic signal unit applies whitelist-based authentication before executing any signal override. This approach enhances security and operational reliability across different deployment environments, allowing the system to function consistently without manual configuration or network dependency.

During experimentation, the system demonstrated strong performance in end-to-end emergency signal processing. The LoRa communication link maintained stable packet transmission across test distances, with signal reception confirmed in both open-field and partially obstructed environments representative of urban road layouts. Authentication processing at the receiver unit was completed within a short response interval, and the relay-controlled traffic signal switched to the green corridor state promptly upon validation. Compared to conventional GSM or Wi-Fi dependent systems, the LoRaLife system significantly reduced communication overhead and eliminated vulnerability to network congestion or connectivity failures.

The automatic signal restoration feature effectively returned traffic signal operation to its normal cycle after the predefined green corridor duration elapsed, ensuring that emergency prioritization did not cause prolonged disruption to general traffic flow. System activity logs recorded in the MySQL database confirmed consistent and accurate logging of signal transmissions, authentication outcomes, and traffic signal state changes, which were further visualized through Grafana dashboards for performance monitoring and analysis.

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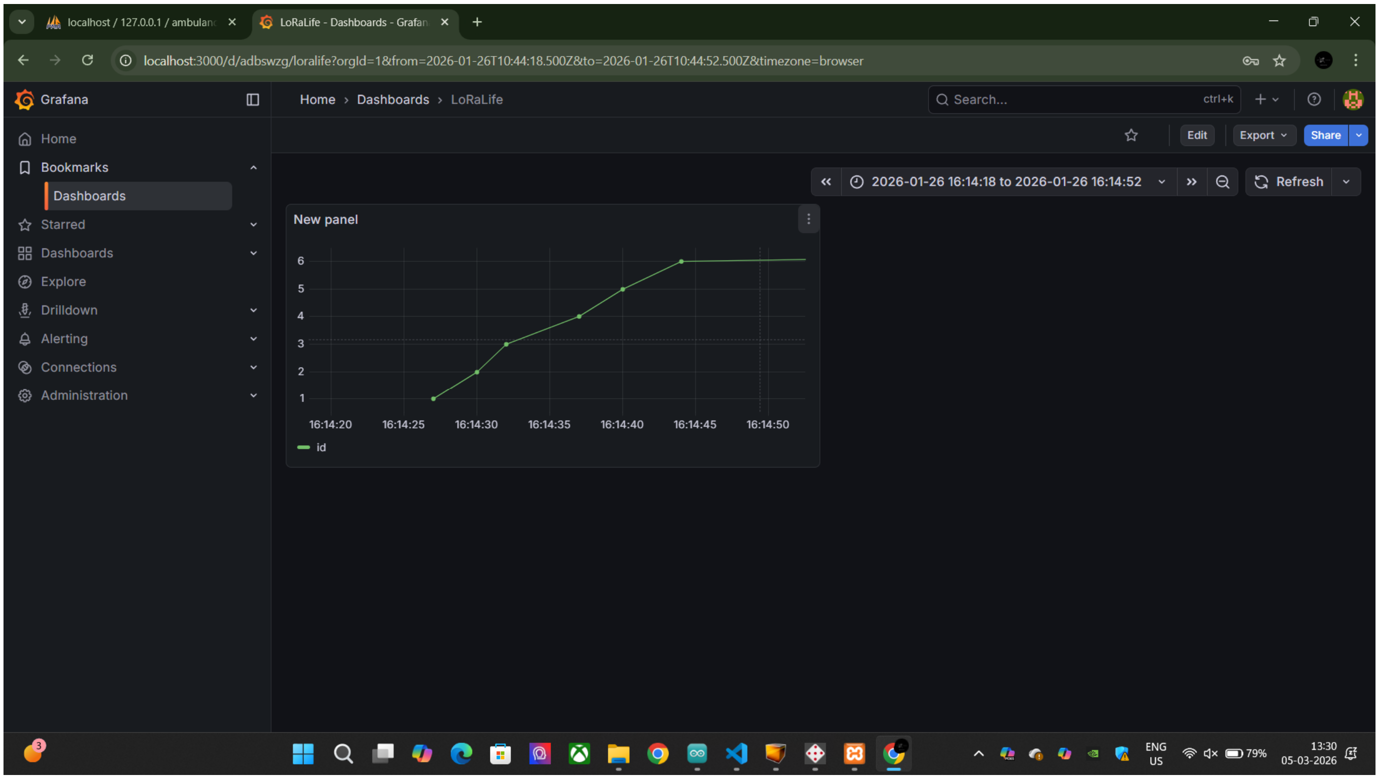

Fig. 4: Grafana Dashboard for Real-time Performance Monitoring

The FastAPI-based backend ensured efficient processing and smooth execution of the analysis pipeline, while the web-based frontend provided a simple and responsive user interface. Users were able to upload datasets, initiate analysis, and download comprehensive PDF reports with minimal latency. The seamless integration between frontend and backend contributed to a user-friendly and efficient experience.

The system also demonstrated robustness through fallback mechanisms, ensuring that analysis could proceed even if the AI workflow component was unavailable. This increased reliability and made the system suitable for real-world usage scenarios.

Overall, the results confirm that integrating AI-assisted planning with traditional data processing techniques can significantly enhance automation, efficiency, and usability in dataset analysis systems. The proposed solution effectively bridges the gap between manual data analysis and fully automated pipelines, providing a scalable and practical tool for data-driven decision-making.

VI. CONCLUSION AND FUTURE WORKS

This project presents a robust IoT-based LoRaLife Emergency Traffic Clearance System designed to automate priority access for emergency vehicles at urban traffic intersections, from emergency trigger activation to green corridor creation and automatic signal restoration. By integrating long-range LoRa wireless communication with embedded microcontroller-based control logic, the system effectively eliminates the delays caused by conventional fixed-cycle traffic signals and makes reliable emergency vehicle prioritization accessible without dependence on internet infrastructure or centralized network systems.

The system leverages an ESP32-based embedded architecture for efficient signal processing and traffic control orchestration, combined with an SX1278 LoRa transceiver for seamless long-range peer-to-peer communication. The integration of a whitelist-based authentication mechanism enables secure and selective signal validation, ensuring that only authorized emergency vehicles can trigger traffic overrides. Additionally, the implementation of GPS-based location tracking, relay-controlled signal switching, OLED status feedback, and automated system restoration ensures a complete, reliable, and operationally independent emergency response pipeline.

The system demonstrates strong capability in handling real-world communication scenarios involving physical obstructions, variable distances, and dynamic urban environments. Compared to traditional GSM or Wi-Fi dependent traffic preemptionapproaches, it significantly reduces communication latency while improving deployment flexibility and fault tolerance.

Furthermore, the integration of MQTT-based monitoring and Grafana-based visualization provides a comprehensive platform for performance tracking and system diagnostics, making the solution suitable for smart city infrastructure, disaster-response environments, and developing urban regions with limited network coverage.

This work highlights the potential of combining low-cost embedded devices with decentralized wireless communication to build scalable and infrastructure-independent intelligent transportation solutions. It bridges the gap between complex traffic management requirements and accessible IoT-based implementations, enabling wider adoption of automated emergency response systems in modern urban networks.

Future Enhancements:

Multi-Intersection LoRa Mesh Network: Extend the current single-intersection architecture into a city-wide mesh network where multiple traffic signal units communicate collaboratively, enabling the creation of continuous green corridors across several intersections simultaneously for faster ambulance transit.

AI-Based Predictive Traffic Clearance: Integrate machine learning algorithms to analyze real-time GPS speed and location data from the ambulance unit, enabling the system to predict arrival times at upcoming intersections and pre-emptively trigger signal overrides before the vehicle reaches the junction.

Cloud-Based Fleet Monitoring and Analytics: Transition the local MySQL and Grafana setup to a cloud-based infrastructure such as AWS IoT or Google Cloud, enabling centralized monitoring of multiple emergency vehicles, remote system diagnostics, and large-scale performance analytics across an entire urban emergency response network.

Mobile Application Integration: Develop a companion mobile application for ambulance operators and traffic control centers that provides real-time visibility into vehicle location, signal override status, estimated route clearance, and system health, improving coordination between emergency response teams.

GPS-Based Automatic Route Pre-Clearance: Enhance the ambulance unit firmware to automatically detect upcoming intersections along a predefined route using GPS coordinates and trigger sequential signal overrides without requiring manual button activation by the driver, reducing cognitive load during emergencies.

Renewable Energy Power Supply: Incorporate solar-powered battery systems for the traffic signal units to improve energy sustainability, reduce operational costs, and ensure continuous system functionality in remote or power-unstable urban locations.

VII. ACKNOWLEDGMENT

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