An IOT-Enabled Radius-Based Traffic Signal Preemption Framework for Ambulance Priority in Smart Cities

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Abstract

Emergency Medical Services (EMS) response times are influenced by urban traffic congestion and specifically at signalized intersections in densely populated cities. EMS delays caused by fixed time traffic signals, may have a negative effect on the quality of care provided and ultimately patient survival rates. In this paper, an Internet of Things (IoT)-based radius-based traffic signal preemption framework is proposed to support priority traffic signal control for ambulances operating in urban traf- fic environments. The proposed system utilizes GPS enabled ambulance units, Roadside Units (RSUs), Edge Traffic Controllers (ETCs) and a Cloud-Based Monitoring Platform (CBMP) to provide real-time identification and communication of emergency vehicles to traffic infrastructure. The radius-based detection algorithm is used to detect the presence of an ambulance within a predefined 100 meter radius of an intersection to allow the ETC to dynamically override the current traffic signal phase and display a green light for the ambulance's desired route. The performance of the proposed system was tested using SUMO simulation software to simulate a network of multiple signalized intersections under moderate traffic conditions. Metrics such as ambulance travel time, intersection delay, and total response time were used to evaluate the performance of the proposed system relative to traditional traffic signal sys- tems. Results from experimental testing demonstrated the proposed system resulted in approximately a 42 percent reduction in ambulance delay and improved travel efficiency for emergency vehicles relative to traditional traffic signal systems. The proposed system is a low-cost, scalable solution to integrate priority traffic control for emergency vehicles into Smart City Intelligent Transportation Systems (ITS).

Keywords: Internet of Things, Emergency Vehicle Priority, Traffic Signal Preemption, Smart Cities, Intelligent Transportation Systems

1. Introduction

Rapid urbanization and increasing vehicle density have significantly intensified traffic congestion in major cities. One of the most critical consequences of this congestion is the delay experienced by emergency vehicles, particularly ambulances, at signalized intersections. Since conventional traffic signal systems typically operate on fixed-time cycles, they are unable to dynamically prioritize emergency vehicles. These delays can negatively affect emergency medical response and patient survival rates.

Recent developments in Intelligent Transportation Systems (ITS) and Internet of Things (IoT) technologies have enabled the development of smart traffic management solutions capable of real-time communication between vehicles and infrastructure. IoT-based systems allow ambulances equipped with GPS and communication modules to transmit their location to nearby roadside units (RSUs) and traffic signal controllers. This enables adaptive traffic signal control that can provide priority to emergency vehicles. However, many existing approaches rely on centralized control architectures, computationally intensive algorithms, or complex sensing infrastructure, which may limit scalability and increase deployment costs. Therefore, there is a need for a lightweight and scalable framework that can efficiently detect emergency vehicles and dynamically adjust traffic signals in real time.

To address these challenges, this study proposes an IoT-enabled radius-based traffic signal preemption framework for prioritizing ambulance movement at urban intersections.

Main Contributions

The main contributions of this work are summarized as follows:

- A lightweight IoT-based radius detection model for identifying ambulances within a predefined in- tersection zone using GPS data.

- A distributed traffic signal control architecture integrating ambulance units, roadside units (RSUs), and edge controllers for real-time communication and decision-making.

- Mathematical modeling of traffic dynamics, including signal switching latency, queue length estimation, and emergency vehicle delay.

- Simulation-based evaluation using the SUMO traffic simulator, demonstrating approximately 42% reduction in ambulance delay compared with conventional traffic signal systems.

2. Related Work

In the domain of Intelligent Transportation Systems (ITS), emergency vehicle prioritization has been widely studied to improve the responsiveness of emergency services and reduce delays at urban intersections. Various approaches have been proposed, including routing optimization, IoT-enabled communication frameworks, machine learning–based traffic control, and edge computing architectures. Kamble and Kounte proposed routing and scheduling models for emergency vehicle preemption, focusing on optimizing the movement of emergency vehicles through traffic networks by minimizing travel time and congestion.[1] Qin and Khan introduced an IoT-based emergency vehicle service framework that utilizes distributed sensing technologies and communication infrastructure to facilitate intelligent traffic management and real-time traffic monitoring.[2] Su et al. developed EMVLight, a reinforcement learning-based traffic signal control system designed to dynamically adjust signal timings in response to the presence of emergency vehicles, thereby improving intersection efficiency and reducing emergency vehicle delay.[3] Similarly, several studies have explored IoT-based smart traffic monitoring systems and edge computing architectures for real-time emergency vehicle detection and prioritization.[4, 5, 7] Recent research has also investigated the use of vehicle-to-infrastructure (V2I) communication, deep learning-based vehicle

detection, and UAV-assisted traffic monitoring to enhance emergency vehicle prioritization in complex urban traffic environments.[8, 9, 11, 12] These approaches demonstrate the potential of intelligent traffic management systems to improve emergency vehicle mobility and reduce intersection delays. However, many existing approaches rely on centralized control architectures, computationally intensive algorithms, or complex sensing infrastructures, which may increase deployment costs and limit scalability in large urban transportation networks. Additionally, several solutions focus on traffic optimization without providing a lightweight detection mechanism capable of operating efficiently in distributed IoT environments. Therefore, there remains a need for a lightweight, scalable, and real-time emergency vehicle detection framework that can dynamically adjust traffic signals with minimal computational overhead. To address this gap, this study proposes an IoT-enabled radius-based traffic signal preemption framework that detects ambulances within a predefined intersection zone and dynamically activates a green signal phase to facilitate faster emergency vehicle passage. The proposed system consists of four primary components that work together to enable real-time emergency vehicle prioritization in urban traffic environments. The first component is the ambulance unit, which is equipped with a GPS module and wireless communication interface to continuously transmit real-time location information. The second component is the roadside unit (RSU), which receives signals from nearby vehicles and performs edge-level processing to detect the presence of an ambulance approaching the intersection. The third component is the traffic signal controller, which dynamically adjusts the traffic signal phases by overriding the current signal cycle and activating a green light for the ambulance route when detection occurs. Finally, the system includes a cloud monitoring server that supports centralized monitoring, data storage, and analytics, enabling city authorities to track emergency vehicle movement and traffic system performance in real time.

Table 1: Summary of Existing Emergency Vehicle Traffic Management Systems

Ref	Authors	Method	Environment	Key Results
[1]	Kamble and Kounte (2022)	Routing and scheduling model	Traffic simulation environment	Improved emergency vehicle routing efficiency
[2]	Qin and Khan (2023)	IoT-based traffic management	IoT-enabled traffic infrastructure	Real-time monitoring of emergency vehicles
[3]	Su et al. (2021)	Reinforcement learning (EMV-Light)	Traffic signal simulation	Dynamic signal timing for emergency vehicles
[4]	Kumar et al. (2022)	IoT traffic monitoring	Smart city traffic sensors	Adaptive traffic signal control
[5]	Nguyen et al. (2023)	Edge computing framework	Edge-assisted IoT traffic network	Reduced latency in emergency response
[6]	Rosayyan et al. (2023)	Optimal control strategy	Urban traffic signal network	Improved emergency vehicle priority control

[7]	Bairi et al. (2025)	VANET communi-cation	Vehicular ad hoc network	Real-time vehicle–infrastructure com-munication
[8]	Ambeth Kumar et al. (2025)	UAV-based moni-toring	Aerial traffic moni-toring system	Improved emergency vehicle detection accuracy
[9]	Chen and Wang (2024)	Queue-aware sig-nal control	Signalized inter-section network	Reduced congestion during emergency events

3. Detection Radius Model

The ambulance detection zone is defined as a 100 m radius around the intersection.
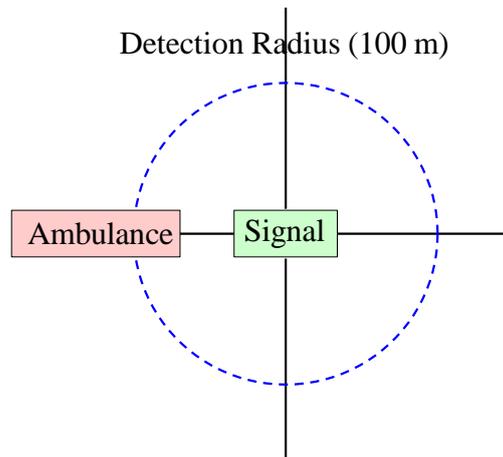

Figure 1: Detection radius model

4. Green Corridor Creation

The term" green corridor" has been used in the past to describe a coordinated method of traffic management whereby an emergency vehicle may be allowed to pass through one or more intersections without having to stop at the intersection as long as all traffic has come to a complete stop and the emergency vehicle has received permission from law enforcement to enter the corridor. Traffic flow control systems that provide real-time synchronization of traffic signals allow emergency vehicles to traverse multiple intersections with green signals. While emergency vehicles can normally only receive priority when they are traveling down highways, traffic signal control systems can assist emergency personnel in navigating busy urban areas. A green corridor will remain operational until the emergency vehicle has completed its passage and then it will automatically resume normal operation.
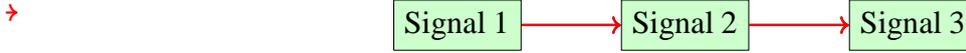
Figure 2: Green corridor formation for emergency vehicle priority

5. Proposed Algorithm

Algorithm 1 Radius-Based Signal Preemption **Require:** Ambulance GPS coordinates (x_a, y_a) **Ensure:** Dynamic traffic signal control

1: Receive ambulance GPS coordinates

2: Compute distance D between ambulance and traffic signal

3: **if** $D \leq 100\,m$ **then**

4:      Activate green signal for ambulance lane

5: **end if**

6: Monitor ambulance movement

7: **if** ambulance exits the intersection zone **then**

8:      Restore normal signal cycle

9: **end if**

6. Mathematical Model

Distance between ambulance and signal:

$$D(t) = \sqrt{(x_a - x_s)^2 + (y_a - y_s)^2} \quad (1)$$

Signal switching latency:

Queue length model:

Emergency vehicle delay:

$$T_{switch} = T_{detect} + T_{comm} + T_{process} \qquad (2)$$

$$Q = \lambda \times T_{red} \qquad (3)$$

$$D = T_{signal} + T_{queue} \qquad (4)$$

7. Traffic Flow Model

Urban traffic flow around signalized intersections can be modeled using fundamental traffic flow relationships. Let λ represent the vehicle arrival rate at an intersection (vehicles per second), and μ represent the service rate determined by the traffic signal.

The average traffic density is defined as:

$$\rho = \frac{N}{L} \qquad (5)$$

where N represents the number of vehicles within the road segment and L represents the road length. The traffic flow rate can be expressed as:

$$q = \rho \times v \qquad (6)$$

where v represents the average vehicle speed.

During emergency vehicle prioritization, the signal controller temporarily adjusts the service rate μ by activating a green signal phase for the ambulance route. This reduces queue buildup and allows faster emergency vehicle passage through the intersection.

The expected queue length at a signalized intersection is modeled as:

$$Q = \lambda \times T_{red} \qquad (7)$$

where T_{red} represents the red signal duration.

By dynamically reducing T_{red} during ambulance detection, the proposed system significantly minimizes queue length and improves traffic flow for emergency vehicles.

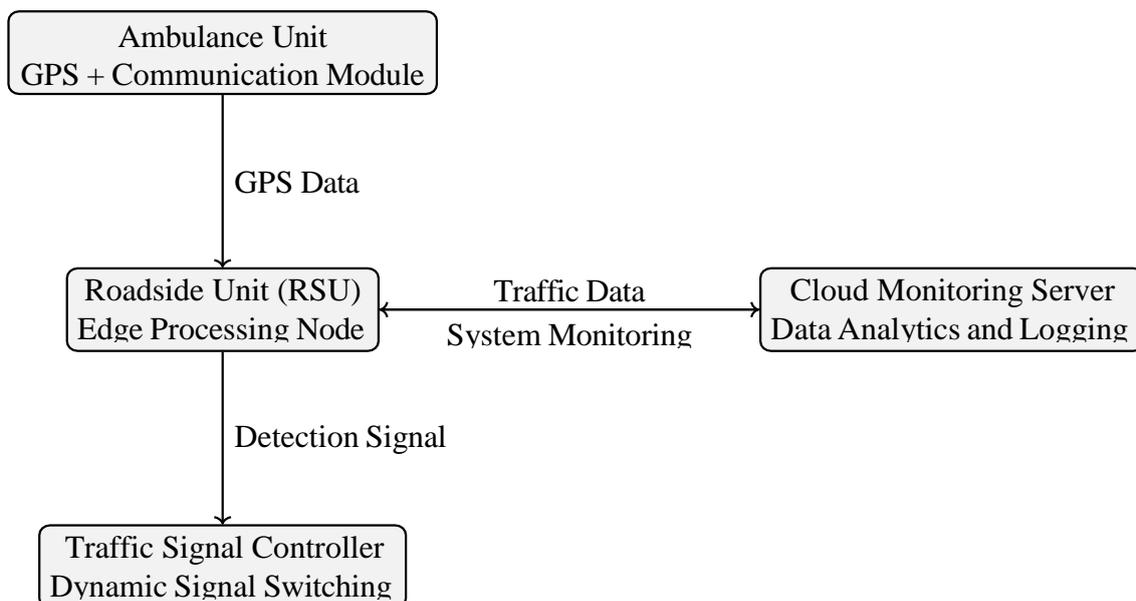## 8. System Implementation Architecture

Figure 3: System Implementation Architecture of IoT-Based Ambulance Traffic Signal Preemption

The implementation architecture of the proposed framework integrates multiple components within an IoT-enabled intelligent transportation environment.

The ambulance unit is equipped with a GPS module and wireless communication interface that continuously transmit its location to nearby roadside units (RSUs). These RSUs act as edge computing nodes capable of processing ambulance detection events in real time.

When an ambulance enters the predefined detection radius of an intersection, the RSU forwards the detection signal to the traffic signal controller. The controller then overrides the current signal cycle and activates a green phase along the ambulance route.

Communication between system components can be implemented using lightweight IoT protocols such as MQTT or vehicle-to-infrastructure (V2I) communication networks. The system also connects to a cloud monitoring server that logs traffic events and supports centralized monitoring and analytics.

This distributed architecture ensures low latency response, scalable deployment across multiple intersections, and reliable operation in large urban transportation networks.

9. Simulation Setup

Simulation experiments were conducted using the Simulation of Urban Mobility (SUMO) platform, which is widely used for evaluating intelligent transportation systems. The simulated environment consisted of four signalized intersections separated by 300 meters. Traffic flow and ambulance movement parameters were configured to represent moderate urban traffic conditions.

Table 2: Simulation Parameters

Parameter	Value
Intersections	4
Intersection Distance	300 m
Traffic Flow	600 vehicles/hour
Ambulance Speed	40–60 km/h
Detection Radius	100 m

10. Experimental Results

The proposed system was evaluated by comparing ambulance travel time and intersection delay under conventional traffic signals and the proposed IoT-based preemption framework.

Table 3: Performance Comparison

Metric	Conventional System	Proposed System
Travel Time	120 s	70 s
Intersection Delay	35 s	10 s
Delay Reduction	–	42%

The results demonstrate that the proposed system significantly reduces ambulance travel time and intersection delay. The implementation of radius-based detection and dynamic signal switching enables faster ambulance movement across intersections. Overall, the proposed framework achieved approximately **42% reduction in delay** compared with conventional traffic signal systems.
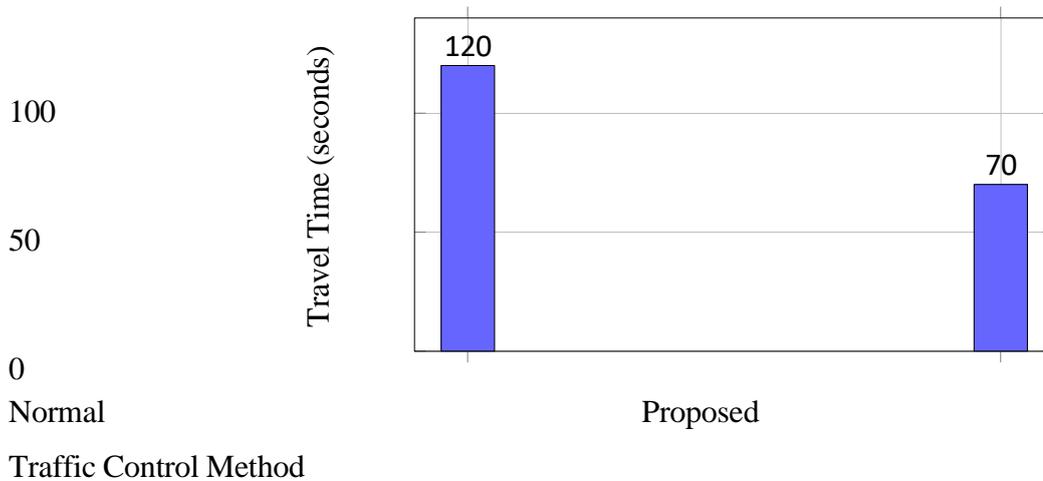
Performance Analysis

Figure 4: Comparison of ambulance travel time under conventional and proposed traffic signal systems

11. Computational Complexity Analysis

The proposed algorithm primarily involves distance computation and signal switching operations. Distance calculation requires constant time complexity:

$O(1)$

Therefore, the algorithm is suitable for real-time deployment.

12. Scalability Analysis

The proposed architecture is scalable because each intersection independently processes ambulance detection and signal switching operations. This distributed architecture prevents central server overload.

13. Conclusion

This paper presented an IoT-enabled radius-based traffic signal preemption framework for ambulance priority. Simulation results demonstrate that the system significantly reduces ambulance delay while maintaining stable traffic conditions. Future work will focus on real-world deployment using V2X communication technologies and integration with city-wide intelligent transportation infrastructure.

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