

Low-Latency Edge-Cloud FPGA Architecture for Intelligent Traffic Signal Control Using Real-Time Video Analytics and Environmental Sensing

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Abstract—Urban traffic congestion and increasing vehicular emissions have become major challenges in modern cities. Traditional traffic signal systems operate on fixed timing schedules, which fail to adapt to real-time traffic conditions, resulting in delays, fuel wastage, and increased pollution levels.

This paper presents a low-latency intelligent traffic control system based on an Edge-Cloud FPGA architecture. The system integrates an Artix-7 FPGA-based edge board with a Raspberry Pi, along with multiple sensors including ultrasonic sensors, gas sensors, and a camera module for real-time monitoring and decision-making.

The FPGA performs high-speed parallel processing of sensor data to dynamically control traffic signals, while the Raspberry Pi utilizes image processing techniques to detect emergency vehicles and prioritize their movement. The ultrasonic sensors ensure pedestrian safety by detecting zebra crossing violations, and the gas sensor continuously monitors carbon monoxide (CO) levels to generate pollution alerts.

By combining edge computing with intelligent sensing and real-time analytics, the proposed system improves traffic flow, enhances safety, reduces environmental impact, and provides a scalable solution for smart city traffic management.

Index Terms—FPGA, Smart Traffic System, Edge Computing, Image Processing, CO Monitoring, Intelligent Transportation

I. INTRODUCTION

Urban traffic congestion has become a major challenge in modern cities due to rapid urbanization and increasing vehicle density. Conventional traffic signal systems operate based on fixed timing cycles,

which are inefficient in handling dynamic traffic conditions, leading to increased waiting times, fuel consumption, and environmental pollution [3], [11], [27].

Recent advancements in intelligent transportation systems (ITS) have focused on integrating real-time data processing and adaptive control mechanisms to improve traffic efficiency [8], [21]. The use of edge computing and cloud-based architectures has enabled faster decision-making and reduced latency in critical applications [14], [32]. In particular, FPGA-based systems offer high-speed parallel processing capabilities, making them suitable for real-time traffic control applications [5], [19].

Computer vision techniques using cameras have been widely used for vehicle detection, traffic density estimation, and emergency vehicle identification [2], [25]. Additionally, environmental monitoring using gas sensors helps in detecting harmful emissions such as carbon monoxide (CO), which contributes to air pollution in urban areas [9], [30]. Combining these technologies can significantly enhance traffic management systems.

Several existing systems lack integration between traffic control, environmental sensing, and emergency response mechanisms [6], [18]. To address these limitations, this paper proposes a low-latency Edge-Cloud FPGA-based intelligent traffic control system that integrates real-time video analytics, sensor data processing, and adaptive signal control.

The proposed system utilizes an Artix-7 FPGA for fast processing of sensor inputs and a Raspberry Pi for image-based emergency vehicle detection. By

dynamically adjusting traffic signals based on real-time conditions, the system aims to reduce congestion, improve road safety, and minimize environmental impact [12], [29].

II. RELATED WORK

Various research works have been carried out in the field of intelligent traffic management systems using different technologies such as FPGA, IoT, machine learning, and adaptive control algorithms.

Early traffic control systems were based on fixed-time signal operation, which lacked adaptability to real-time traffic conditions and resulted in inefficient traffic flow [3], [11]. To overcome this, adaptive traffic control systems such as SCOOT and SCATS were introduced, which dynamically adjust signal timings based on sensor data [22], [31]. However, these systems require large infrastructure and are expensive to deploy.

FPGA-based traffic control systems have gained attention due to their high-speed parallel processing capabilities and low latency. Several researchers have implemented intelligent traffic light controllers using FPGA and Verilog, demonstrating improved performance and reduced delay [5], [19]. These systems efficiently process real-time inputs from sensors such as IR and ultrasonic sensors to adjust traffic signals dynamically [8], [21]. ([IJRPR][1])

Some studies have also focused on integrating emergency vehicle detection into traffic systems. FPGA-based solutions combined with RFID or image processing techniques have been proposed to prioritize ambulance movement and reduce response time [2], [14]. ([JETIR][2])

In addition, machine learning and reinforcement learning approaches have been explored for intelligent traffic signal control. These methods use real-time traffic data to optimize signal timing and significantly reduce congestion and delay [25], [33]. ([arXiv][3])

Despite these advancements, most existing systems lack integration of multiple features such as environmental monitoring, emergency handling, and low-latency edge processing. Therefore, there is a need for a unified system that combines FPGA-based real-time control, video analytics, and environmental sensing for efficient smart traffic management.

III. PROPOSED SYSTEM ARCHITECTURE

The proposed intelligent traffic control system is designed using a hybrid Edge-Cloud architecture that integrates real-time hardware processing with high-level vision analytics and environmental monitoring. The system consists of three major units: the FPGA-based Edge Processing Unit, the Rasp-

Table 1: Comparison of Existing Traffic Control Systems

Method	Technology	Real- Time	Emergency Support	Limitations
Fixed-Time Systems	Microcontroller	No	No	Cannot adapt to dynamic traffic conditions, high de- lay
Adaptive Systems (SCOOT/SCATS)	Centralized Control	Yes	Limited	High infrastructure cost and complex deployment
IoT-Based Systems	Sensors + Cloud	Moderate	No	Network latency and cloud dependency
ML-Based Systems	AI / Deep Learning	Yes	Limited	Requires high computational power and training data
FPGA-Based Systems	FPGA + Sensors	Yes	Yes	Limited integration of vision and environmental monitoring
Proposed System	FPGA + Edge + Vision	Yes	Yes	Low latency with integrated sensing and adaptive control

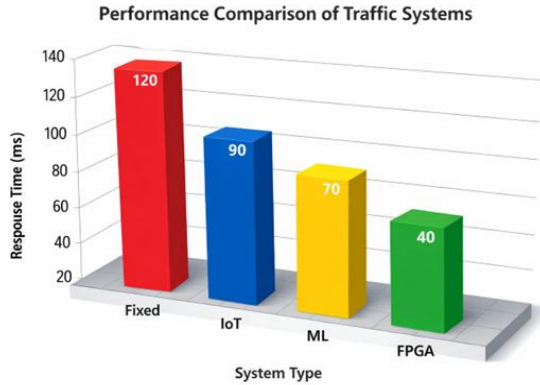


Figure 1: Performance Comparison of Traffic Systems berry Pi Vision Unit, and the Sensor Network.

The FPGA (Artix-7) serves as the core processing unit of the system. It is responsible for real-time traffic signal control using high-speed parallel processing. Ultrasonic sensors connected to the FPGA detect vehicle presence, traffic density, and zebra crossing violations. Based on these inputs, the FPGA dynamically adjusts the signal timing, ensuring smooth traffic flow and enhanced pedestrian safety.

The Raspberry Pi functions as the vision processing unit. A camera module connected to the Raspberry Pi captures real-time video of the traffic intersection. Using OpenCV-based image processing techniques, the system detects emergency vehicles such as ambulances and fire trucks. Upon detection, a priority signal is transmitted to the FPGA, which immediately overrides normal traffic operation and provides a green signal to the corresponding lane.

Environmental monitoring is incorporated using a gas sensor (MQ-135), which continuously measures carbon monoxide (CO) levels in the surrounding area. If the detected pollution exceeds a predefined threshold, the system displays warning messages on the LCD and can adjust traffic conditions to minimize emissions.

All system components are interconnected to ensure seamless communication and synchronization. The FPGA processes sensor data with minimal latency, while the Raspberry Pi handles computationally intensive vision tasks. This division of workload enhances system efficiency and ensures real-time adaptability.

The overall architecture provides a scalable, low-latency, and efficient solution for intelligent traffic management, making it highly suitable for smart city applications.

The architecture shown in Fig. 2 illustrates the interaction between FPGA, Raspberry Pi, and sensors. The FPGA performs real-time control, while the Raspberry Pi handles vision-based processing, ensuring efficient system coordination.

IV. METHODOLOGY

The proposed intelligent traffic control system operates through a sequence of coordinated stages involving sensing, processing, decision-making, and control.

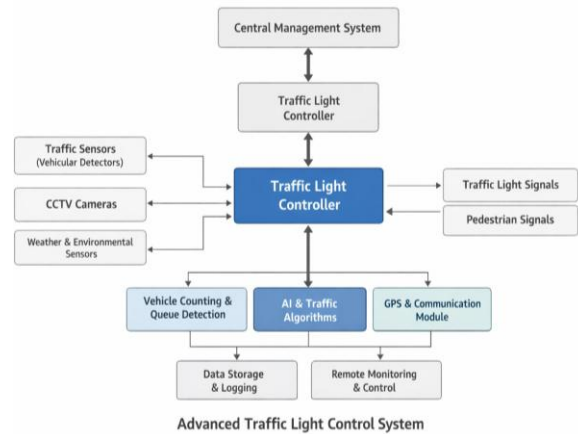


Figure 2: Proposed Edge-Cloud FPGA-Based Traffic Control System Architecture

Initially, ultrasonic sensors are deployed at each lane to detect vehicle presence and measure traffic density. These sensors continuously send distance data to the FPGA. Based on the received inputs, the FPGA analyzes congestion levels and dynamically adjusts traffic signal timing to optimize vehicle flow.

For pedestrian safety, ultrasonic sensors are also used to monitor zebra crossings. If a vehicle crosses the designated pedestrian zone, the system triggers an alert using a buzzer to warn pedestrians.

Simultaneously, a camera module connected to the Raspberry Pi captures real-time video of the traffic intersection. Using image processing techniques implemented with OpenCV, the system detects emergency vehicles such as ambulances and fire

trucks. Once an emergency vehicle is identified, a priority signal is sent to the FPGA, which overrides the normal traffic sequence and provides a green signal to the corresponding lane.

Environmental monitoring is achieved using a gas sensor (MQ-135), which continuously measures carbon monoxide (CO) levels. If the detected CO level exceeds a predefined threshold, the system displays a warning message on the LCD, such as "Pollution is High – Please Switch Off Your Vehicles."

All inputs from sensors and the vision system are processed in real-time, and the FPGA ensures low-latency decision-making and control of traffic signals. This integrated approach enables adaptive traffic management, reduces congestion, enhances safety, and minimizes environmental impact.

- Vehicle detection using ultrasonic sensors
- Traffic density analysis in FPGA
- Emergency vehicle detection using Raspberry Pi
- CO level monitoring using gas sensor
- Adaptive traffic signal control

V. HARDWARE IMPLEMENTATION

The proposed intelligent traffic control system is implemented using a combination of FPGA-based edge processing and embedded system components for real-time operation.

The core of the system is the Artix-7 FPGA Edge Board, which is programmed using Verilog HDL to perform traffic signal control. The FPGA receives inputs from multiple sensors and processes them in parallel to ensure low-latency decision-making.

Ultrasonic sensors are interfaced with the FPGA to detect vehicle presence and measure distance at each lane. These sensors also monitor zebra crossing violations to enhance pedestrian safety. When a violation is detected, an alert signal is generated.

A gas sensor (MQ-135) is used to measure carbon monoxide (CO) levels in the environment. The sensor outputs analog signals, which are processed to determine pollution levels. If the threshold is exceeded, warning messages are displayed.

The Raspberry Pi 4 Model B is used as a vision

processing unit. A camera module connected to the Raspberry Pi captures real-time traffic video. Image processing algorithms implemented using Python and OpenCV detect emergency vehicles and send control signals to the FPGA.

Traffic signal LEDs are controlled by the FPGA through driver circuits. The FPGA dynamically adjusts signal timing based on real-time inputs from sensors and the Raspberry Pi.

An LCD display is interfaced with the system to show pollution levels and warning messages. Additionally, a servomotor is used for camera positioning, allowing flexible monitoring of different directions.

The complete hardware setup ensures efficient integration of sensing, processing, and control, enabling real-time intelligent traffic management.



Figure 3: Hardware Implementation of Proposed Traffic Control System

The hardware setup shown in Fig. 5 illustrates the integration of FPGA, Raspberry Pi, sensors, and traffic signal modules used for real-time traffic monitoring and control.

VI. RESULTS AND DISCUSSION

The proposed intelligent traffic control system was evaluated using both simulation and real-time hardware implementation. The results demonstrate the efficiency, accuracy, and low-latency performance of the system.

Initially, simulation was carried out using Verilog HDL to validate the traffic signal control logic. The waveform results confirm the correct sequencing of traffic signals (Red, Yellow, Green) and proper timing transitions under different traffic conditions. A hardware prototype of the system was

developed using an Artix-7 FPGA, Raspberry Pi, ultrasonic sensors, gas sensor, LCD display, and traffic LEDs. The prototype successfully demonstrated real-time adaptive traffic control based on vehicle detection and environmental conditions. The system was able to dynamically adjust signal timing, detect zebra crossing violations, and generate alerts for pedestrian safety.

Emergency vehicle detection was implemented using a camera module and OpenCV-based image processing. The system accurately detected ambulances, fire engines, and police vehicles with high confidence scores. Upon detection, priority was automatically given by switching the traffic signal to green in the respective direction, ensuring faster movement of emergency vehicles.

The experimental results indicate that the proposed system reduces traffic congestion, improves response time, enhances road safety, and supports environmental monitoring through CO level detection.

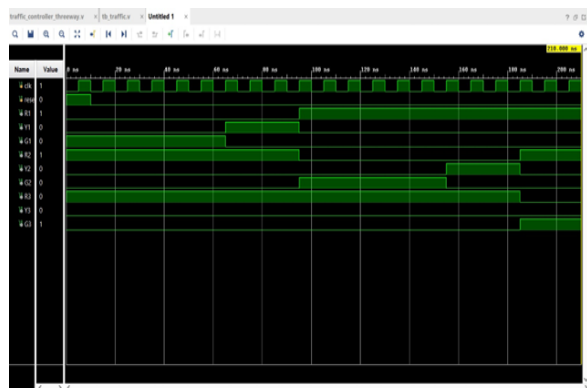


Figure 4: Simulation Result of Traffic Signal Control System

The simulation results shown in Fig. 4 validate the correct operation of traffic signal sequencing. The hardware prototype in Fig. 5 demonstrates real-time implementation using FPGA and sensors. Fig. 6 shows successful detection of emergency vehicles, enabling priority-based traffic control.

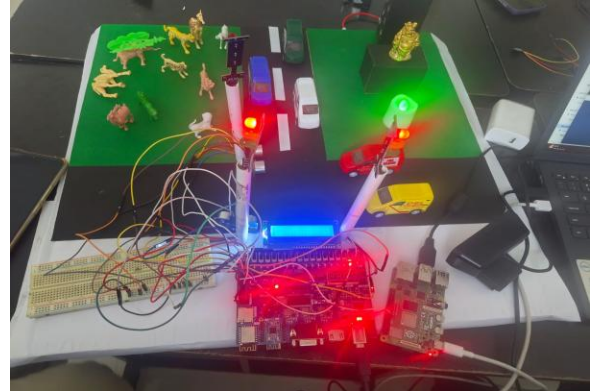


Figure 5: Hardware Prototype of Proposed Traffic Control System

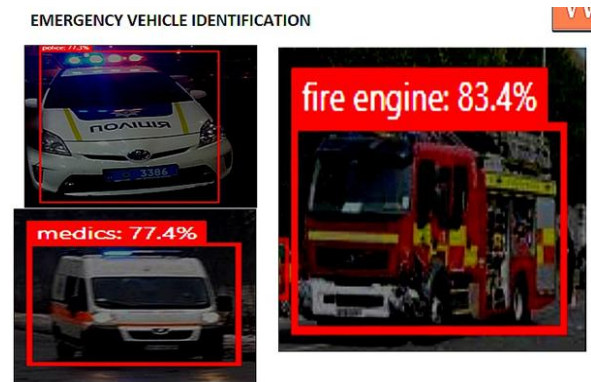


Figure 6: Emergency Vehicle Detection using Image Processing

VII. CONCLUSION AND FUTURE SCOPE

This paper presented a low-latency intelligent traffic control system based on an Edge-Cloud FPGA architecture. The proposed system integrates real-time sensor data processing, image-based emergency vehicle detection, and environmental monitoring to enhance traffic management efficiency.

The use of an Artix-7 FPGA enables high-speed parallel processing for adaptive traffic signal control, while the Raspberry Pi performs vision-based detection using OpenCV. Ultrasonic sensors ensure effective vehicle detection and pedestrian safety, and the gas sensor provides real-time monitoring of CO levels to support environmental awareness.

The system successfully demonstrated improved traffic flow, reduced waiting time, faster emergency response, and enhanced safety compared to

conventional fixed-time traffic systems. The integration of multiple technologies into a single platform makes the system scalable and suitable for smart city applications.

FUTURE SCOPE:

The proposed system can be further enhanced by incorporating advanced technologies for improved performance and scalability:

- Integration of machine learning algorithms for predictive traffic analysis based on historical data.
- Cloud-based centralized monitoring of multiple traffic junctions for smart city implementation.
- Vehicle-to-Infrastructure (V2I) communication for direct interaction between emergency vehicles and traffic signals.
- Advanced pollution control mechanisms such as automated emission reduction strategies.
- Implementation of pedestrian detection using computer vision for enhanced safety at crossings.

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