REAL-TIME TRAFFIC SIGNAL OPTIMIZATION USING QUANTUM COMPUTING AND IOT

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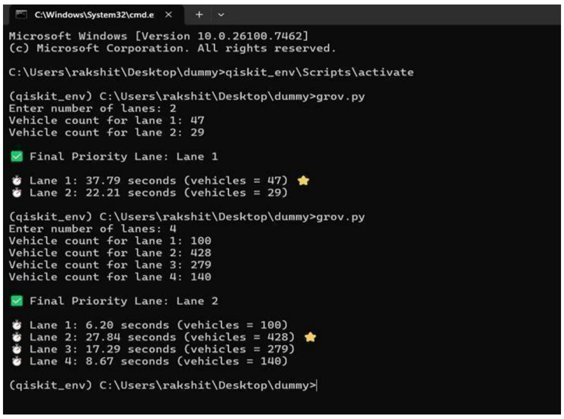
Quantum Computing, Internet of Things (IoT), Traffic Signal Optimization, Real-Time Traffic Control, QUBO (Quadratic Unconstrained Binary Optimization), Grover's Algorithm, Quantum Annealing, PyGame Simulation, Smart Cities, Intelligent Transportation Systems, YOLOv4-tiny, Raspberry Pi.

Introduction:

1. Rapid urbanization across the world has led to a significant increase in vehicular traffic, resulting in frequent congestion, longer waiting times at intersections, and increased fuel consumption and air pollution. Indian cities like Bengaluru are among the most traffic-congested urban centres globally, making intelligent traffic management an urgent necessity.
2. Traditional traffic signal systems operate on fixed or semi-adaptive timing cycles that fail to respond dynamically to real-time traffic conditions. These static systems lead to unnecessary idling of vehicles, wastage of fuel, and higher emissions. As cities grow, the limitations of conventional systems become increasingly severe.
3. The Internet of Things (IoT) has revolutionized traffic sensing by enabling continuous, real-time data collection from intersections through cameras, ultrasonic sensors, and RFID readers. When combined with advanced computing, this data can be used to make intelligent, adaptive traffic control decisions that minimize congestion.
4. Quantum Computing introduces a transformative capability: solving complex combinatorial optimization problems at speeds unattainable by classical computers. Concepts such as superposition and entanglement allow quantum systems to evaluate multiple signal timing configurations simultaneously. Specifically, Grover's Algorithm provides a quadratic speedup over classical search methods, making it highly suitable for real-time decision-making in traffic management.

5. This project proposes a hybrid system that integrates IoT sensing with quantum-inspired optimization to dynamically control traffic signals. The system collects real-time lane-wise vehicle count data, formulates the signal timing problem as a Quadratic Unconstrained Binary Optimization (QUBO) problem, and solves it using Grover's Algorithm implemented via the Qiskit optimization library. A custom Pygame-based simulation validates the system's effectiveness under various traffic conditions, demonstrating significant improvements over fixed-timer and IoT-only approaches.



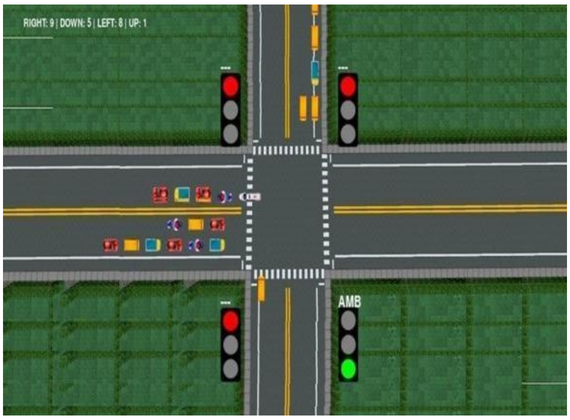


Fig.1 Groover's and Pygame's Output

Objectives:

- To develop an intelligent, adaptive traffic signal control system integrating IoT sensing and quantum-inspired optimization.
- To deploy IoT sensors (Raspberry Pi camera, ultrasonic sensors, RFID) at intersections for continuous real-time traffic data collection.
- To formulate the traffic signal timing problem as a Quadratic Unconstrained Binary Optimization (QUBO) problem solvable by quantum algorithms.
- To implement Grover's Algorithm using Qiskit Optimization for fast and deterministic lane-priority selection.
- To dynamically allocate green-light durations proportional to real-time traffic density, reducing average vehicle waiting time.
- To validate system performance through a custom PyGame simulation under balanced, biased, and congestion-peak traffic scenarios.
- To demonstrate scalability of the proposed architecture to multi-intersection deployments within smart city frameworks.

Methodology:

1. The proposed system follows a layered architecture integrating IoT sensing with quantum-inspired optimization.
2. Initially, IoT devices such as Raspberry Pi with camera modules, ultrasonic sensors, and RFID readers are deployed at intersections to collect real-time

traffic data including vehicle count, queue length, and priority vehicle detection. This data is transmitted using lightweight communication protocols like MQTT or HTTP.

3. At the edge level, preprocessing is performed to reduce computational load. The YOLOv4-tiny model is used for vehicle detection and classification, processing 4–6 frames per second. The extracted features include lane-wise vehicle count and occupancy ratio.
4. The traffic signal problem is formulated as a Quadratic Unconstrained Binary Optimization (QUBO) model, where each lane is represented as a binary variable. The objective is to minimize waiting time by prioritizing lanes with higher traffic density, while ensuring only one lane receives priority per cycle.
5. Grover's Algorithm is implemented using Qiskit Optimization to solve the QUBO problem. The algorithm identifies the optimal lane configuration by amplifying the probability of the best solution, enabling faster decision-making compared to classical approaches.
6. Based on the optimized result, adaptive signal timing is assigned. A fixed cycle time is divided proportionally according to traffic density, with an additional priority bonus given to the most congested lane.
7. A custom simulation environment using Pygame is developed to validate the system under different traffic scenarios such as balanced, biased, and peak congestion conditions.
8. Finally, a continuous feedback loop updates the system dynamically. Real-time data is repeatedly collected, processed, optimized, and applied, ensuring adaptive and responsive traffic signal control.

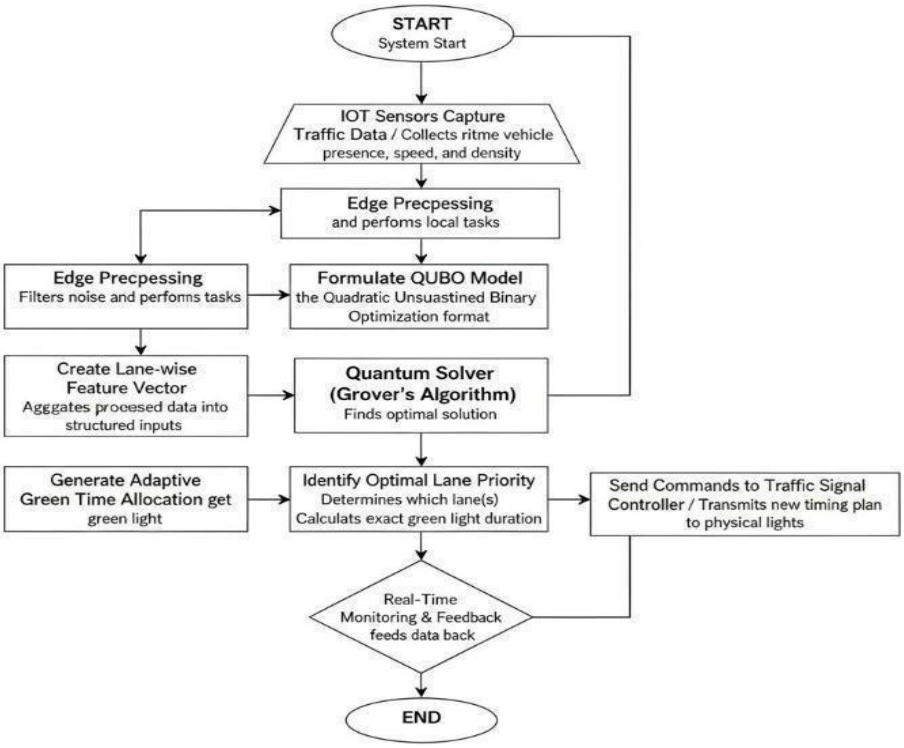


Figure 2: Proposed block diagram of the project

Result and Conclusion:

1. The system was evaluated across three key dimensions: vehicle detection accuracy, quantum optimization correctness, and simulated traffic flow improvement.
2. Vehicle Detection: The YOLOv4-tiny model running on Raspberry Pi successfully detected motorcycles, cars, buses, and trucks at 4–6 FPS under normal lighting; minor accuracy degradation occurred in dim environments, suggesting infrared illumination as a future improvement.
3. Quantum Optimization: The GroverOptimizer correctly identified the priority lane across all test cases. In a 2-lane scenario with 47 and 29 vehicles, Lane 1 was prioritized with green times of 37.79s and 22.21s respectively. In a 4-lane scenario, proportional timings with a 5% congestion bonus were computed accurately for each case.
4. Simulation Performance: The Pygame simulation confirmed that quantum-optimized timings cleared high-density lanes significantly faster than fixed-cycle controllers, with fewer idle cycles on low-density lanes. A comparative analysis showed average waiting times of approximately 65s for Fixed Timer, 45s for IoT+ML, and 28s for the Quantum Optimized system — a 57% reduction over traditional methods.
5. Overall Conclusion: The hybrid IoT-Quantum architecture demonstrated reliable and adaptive performance across all traffic patterns tested — balanced, biased, and peak congestion — confirming its feasibility as a practical smart city traffic management solution.

Project outcomes And Industry Relevance:

1. The project demonstrates that quantum-inspired computing, when combined with IoT sensing, can provide a practical and scalable solution to urban traffic congestion, a problem that costs billions of rupees annually in lost productivity, fuel, and emissions in cities like Bengaluru.
2. From an industry perspective, the system architecture aligns with ongoing smart city initiatives by BBMP, Smart Cities Mission, and national ITS (Intelligent Transportation Systems) programs. Traffic management authorities, smart city solution providers, and transportation departments can directly adopt this model for pilot deployments at congested intersections.
3. The modular design — with a standard IoT sensing layer, a classical preprocessing stage, and a quantum optimization engine — allows vendors to integrate the system with existing traffic control infrastructure without full replacement. The use of inexpensive Raspberry Pi hardware keeps deployment costs low, making it feasible for Tier-2 and Tier-3 cities as well.
4. As quantum hardware matures and becomes commercially accessible via cloud platforms (IBM Quantum, AWS Braket, Azure Quantum), the system can be upgraded from simulation-based quantum optimization to execution on real

quantum processors, delivering exponentially greater optimization power for city-scale deployments.

Working Model VS Simulation /Study:

Working Model / Hardware	Simulation / Software
Raspberry Pi 4 with Pi Camera Module Ultrasonic sensors (HC-SR04) for vehicle detection RFID readers for emergency vehicle detection MQTT/HTTP data communication protocol YOLOv4-tiny for real-time vehicle detection	Custom traffic simulator built with Pygame Qiskit Optimization — GroverOptimizer for QUBO Python backend for signal timing computation Multi-scenario testing: balanced, biased, peak congestion Performance comparison against fixed and IoT+ML methods

Project outcomes and learnings:

Outcomes:

- Successfully implemented a working prototype combining Raspberry Pi IoT sensing with quantum-optimized signal control.
- Achieved real-time vehicle detection at 4–6 FPS using YOLOv4-tiny on edge hardware.
- Demonstrated correct lane-priority selection and adaptive green time allocation through GroverOptimizer in all test scenarios.
- Showed measurable reduction in average vehicle waiting time (~28s quantum vs ~65s fixed timer) through simulation.
- Developed a modular system architecture scalable to multi-intersection, city-wide deployments.

Learnings:

- Gained practical experience in IoT hardware setup, sensor integration, and MQTT-based communication.
- Developed understanding of QUBO problem formulation and its role in combinatorial optimization.
- Learned quantum computing concepts — superposition, amplitude amplification, and Grover's Algorithm — and applied them using Qiskit.
- Understood the trade-offs between QAOA and Grover's Algorithm for real-time applications, and justified the choice of Grover's for low-latency requirements.

- Gained hands-on experience in Python simulation development with Pygame and debugging hardware-software integration challenges.

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Future Scope:

1. The system can be meaningfully extended in multiple directions. Reinforcement learning can be integrated alongside the quantum optimizer to provide predictive control based on historical traffic patterns, reducing response latency further. As cloud quantum platforms such as IBM Quantum, AWS Braket, and Azure Quantum become commercially accessible, the system can transition from Qiskit simulation to real quantum hardware, enabling true quantum speedup at scale.
2. The QUBO model can be extended to coordinate signals across multiple intersections simultaneously, enabling city-wide green wave optimization along arterial corridors. YOLOv4-tiny can be upgraded to YOLOv8-nano or deployed with dedicated AI accelerators such as Coral TPU or NVIDIA Jetson Nano to improve detection accuracy in adverse lighting and weather conditions.
3. Emergency vehicle pre-emption can be formally encoded as hard constraints within the QUBO problem. A centralized cloud dashboard can aggregate intersection data for real-time monitoring and remote override by traffic engineers. Vehicle-to-Infrastructure (V2I) communication can complement camera sensing with direct vehicle position reporting for improved data quality.
4. An emission tracking module can quantify CO_2 savings per intersection to support national Smart Cities and Green India sustainability targets. Finally, adversarial robustness testing and classical fallback mechanisms will ensure system reliability and safety in real-world production deployments at scale.