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Real-time traffic signal control using radio frequency identification and IQRF in distributed urban measurement systems

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ABSTRACT

The growing complexity of urban traffic networks demands adaptive control systems capable of responding to rapidly changing road conditions. In this work, a real-time traffic signal control system is proposed and implemented. The system integrates radio frequency identification (RFID) and IQRF wireless mesh technology as part of a distributed urban measurement platform. The system leverages passive RFID transponders embedded in the road infrastructure to detect and classify vehicles approaching intersections, transmitting event data to a supervisory controller. This controller dynamically adjusts signal phases according to current traffic demand, improving flow efficiency and reducing waiting times. Special attention was given to communication reliability and transponder read accuracy. The strategic placement of infrastructure transponders ensured unambiguous vehicle and direction detection. IQRF communication modules enable reliable low-power coordination between traffic signal units. The timing was referenced to the central microcomputer's system clock, and the integrity of the data was verified by synchronising RFID read events, signal activations, and vehicle motion logs. The approach was validated in a smart city mock-up that replicates real-world traffic scenarios using eight model vehicles with RFID readers on board that circulate along predefined routes. Comparative tests of the static algorithm and the dynamic algorithm based on RFID technology showed a significant improvement in average travel time and intersection capacity in favour of the dynamic algorithm.

Keywords: RFID, IQRF, Smart City, traffic management.

INTRODUCTION

Object identification is a fundamental component of modern technological ecosystems, influencing sectors ranging from manufacturing and logistics to healthcare and transportation. In industrial applications, for example, identification systems enable precise tracking of tools and components, supporting automation and predictive maintenance in Industry 4.0 environments [1]. In healthcare, identification technologies are used to both monitor patients and ensure safe handling of medical supplies, diagnostics, and pharmaceuticals [2]. The transportation sector relies on object identification not only for tracking freight and managing passenger flow, but also for optimising vehicle routing and infrastructure use [3].

The growing complexity of urban life presents new challenges that go beyond sector-specific needs. As cities continue to expand, urban management systems are under increased pressure from increasing traffic congestion, pollution, and infrastructure limitations [4]. These issues have led to the Smart City concept, in which integrated technologies and data-driven solutions enhance efficiency, safety, and sustainability. Within this framework, traffic management remains one of the most critical and technically demanding areas, requiring real-time decision-making, accurate vehicle detection, and seamless communication between vehicles and infrastructure [5].

Traditional sensing methods, such as computer vision and LiDAR, are limited by occlusion, lighting, and weather conditions. This has motivated a shift toward vehicle-to-infrastructure (V2I) and vehicle-to-everything (V2X) communication models, which offer improved reliability and responsiveness, particularly when supported by high-bandwidth technologies like 5G and C-V2X. In such systems, object identification serves as the basis for situational awareness, enabling the infrastructure to react dynamically to traffic conditions [6].

This article presents the development of a proof-of-concept adaptive traffic control system designed to improve intersection performance through event-driven, real-time signal control. The idea was verified on a modular six-by-five meters mock-up including intersections, pedestrian crossings, and a roundabout.

The originality of this work lies in the use of RFID-based vehicle detection combined with distributed communication provided by IQRF technology. Arrays of RFID transponders were placed in specific surface zones to increase detection reliability and ensure continuous data capture as vehicles passed through the reading area. This solution eliminates the need for powered sensors while maintaining high accuracy and durability. Data from RFID readers are transmitted through the IQRF mesh network to the control unit, where signal phases are adjusted in real time. The proposed structure is scalable and allows straightforward expansion to multi-intersection coordination while maintaining stable communication across the network.

The decision to adopt RFID technology followed a comparative analysis of existing detection methods. Inductive loops remain widespread but require invasive installation and costly maintenance, while offering only basic vehicle detection. Magnetic and piezoelectric sensors provide higher precision yet share similar drawbacks, as their placement within the pavement makes them prone to wear and degradation. Vision-based systems, though capable of delivering detailed traffic data, are sensitive to weather, lighting, and occlusion. Radar and ultrasonic sensors are less intrusive, but their accuracy depends on frequent calibration, and they remain vulnerable to environmental interference. In contrast, RFID offers not only reliable identification and data exchange but also the possibility of extending functionality in the future. The full scope of its capabilities is still not completely explored. This gives the technology a strong developmental perspective in intelligent transportation systems.

In the prototype model, identifiers were affixed directly onto the road surface of the mock-up. However, in real-world applications such a solution would be impractical. Instead, identifiers could be embedded in traffic signs, roadside poles, or other roadside infrastructure elements, ensuring durability, ease of maintenance, and integration with existing systems.

Comparative tests were carried out to evaluate the proposed idea. Eight model vehicles equipped with RFID readers moved along predefined routes for one hour under static and dynamic control modes. In the static case, signals operated on fixed cycles, while in the dynamic mode, phase switching was based on real-time RFID detections transmitted through the IQRF network. Three indicators were measured: average waiting time, traversal time, and queue length.

The experiment, conducted on a small-scale model under light traffic conditions, served as a proof of concept ensuring repeatable measurements. The results confirmed improved flow efficiency with dynamic control, demonstrating the feasibility of the proposed solution and its potential for future large-scale validation.

Related work

Identification technologies have become essential for urban traffic management systems, particularly in the context of Smart Cities as shown in Figure 1. According to recent reviews, RFID provides significant advantages over traditional detection methods due to its ability to operate without line-of-sight and under diverse environmental conditions [7].

One of the first large-scale deployments of RFID in transportation is in electronic toll collection (ETC) systems. Projects such as E-ZPass in the United States, Telepass in Italy, and implementations in China demonstrated that RFID-based tolling reduces congestion in plazas by allowing vehicles to pass without stopping [8]. Similarly, Singapore’s electronic road pricing (ERP) system, based on RFID units in-vehicles and overhead readers, successfully reduced peak-hour traffic volumes and stabilised average road speeds [9].

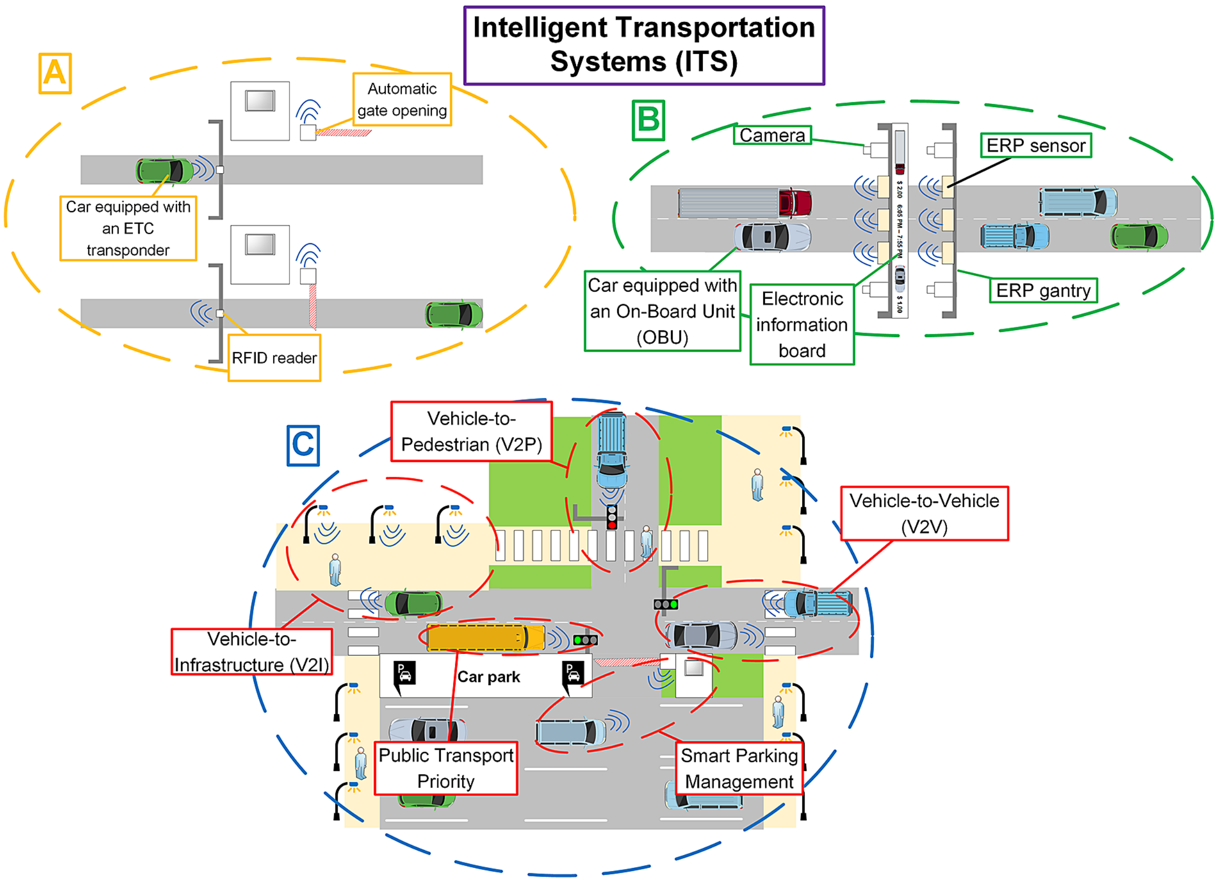

Figure 1. RFID in intelligent transportation systems: (a) electronic toll collection, (b) electronic road pricing, (c) vehicle-to-everything

Beyond tolling, RFID has been applied in prioritisation of public transport. Experiments in Barcelona and South Korea used RFID-equipped buses that interact with roadside readers to grant dynamic signal priority at intersections. The results indicated measurable reductions in delays and improved punctuality of the public transport fleets [10].

RFID also supports urban parking systems, enabling automated vehicle access, payment, and real-time occupancy monitoring. Pilot studies in Germany and the UAE confirmed that RFID-equipped vehicles simplified facility entry while providing accurate utilisation data to operators [11].

Another important research direction is vehicle-to-infrastructure communication using RFID. Studies in China and India embedded passive RFID transponders on the surface of the road to monitor traffic density and detect incidents in real time. These implementations confirmed the feasibility of RFID for distributed sensing, even with simple unique transponders, while maintaining low deployment costs [12].

Current trends emphasise three main strategies for the use of RFID in urban traffic as shown in Figure 2. The first is the installation of transponders on road infrastructure such as signs or traffic lights. This solution is easy to maintain and accessible but offers limited detection opportunities. The second strategy equips vehicles with transponders that interact with readers placed in the infrastructure. It is well suited for parking and access control, although it requires powered roadside readers. The third approach embeds transponders directly into the road surface. While effective once deployed, they are difficult to access or replace [13].

Each approach has trade-offs, but the growing trend is toward hybrid architectures combining RFID with IoT, big data, and 5G-based V2X communication to enhance scalability, resilience, and adaptability of traffic management systems [14]. In parallel with RFID research, IQRF technology has gained attention as an efficient wireless communication platform tailored for distributed IoT and Smart City applications as shown in Figure 3. Unlike conventional short-range solutions such as ZigBee or Bluetooth Low Energy, IQRF was designed with a strong emphasis on ultra-low energy

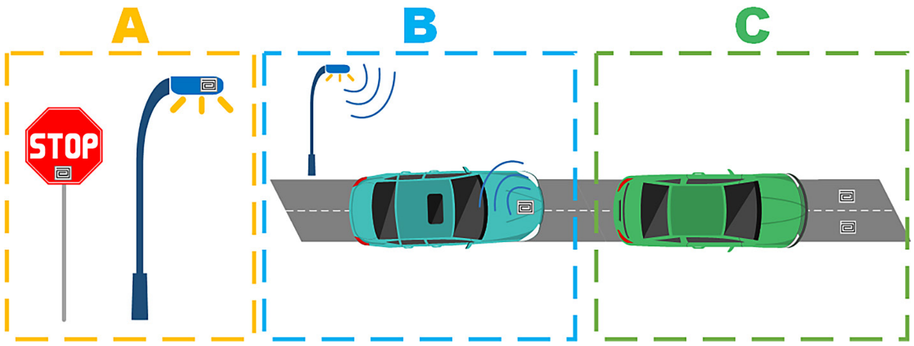

Figure 2. Strategies for the deployment of RFID technology in urban traffic management: (a) transponders on road infrastructure, (b) transponders on vehicles, (c) transponders embedded in the road surface

consumption, high security, and reliable mesh networking. These features make it particularly suitable for long-term deployments in urban environments where thousands of devices must interconnect and operate autonomously without frequent maintenance [15]. IQRF networks operate on sub-GHz frequencies, which provide better propagation and penetration in dense urban landscapes compared to higher-frequency wireless standards. This allows stable communication even in challenging conditions with buildings, traffic, and interference sources [16]. Simulation studies have shown that IQRF can deliver robust data transfer with packet delivery ratios exceeding 99% under heavy network load, while maintaining minimal energy requirements [17].

Another strength of IQRF is its mesh topology, where each node can act as a router, extending the range of communication and improving overall resilience. This ensures that even if individual nodes fail or are temporarily unavailable, the network can self-heal and reroute data dynamically. Such properties are particularly important for Smart City scenarios such as distributed traffic management, where uninterrupted communication between controllers, sensors, and central units is essential [18]. The interoperability of IQRF devices is supported by the IQRF Alliance standard, which defines common communication protocols and device profiles [19]. This makes it possible to integrate heterogeneous devices – such as traffic light controllers, RFID readers, air

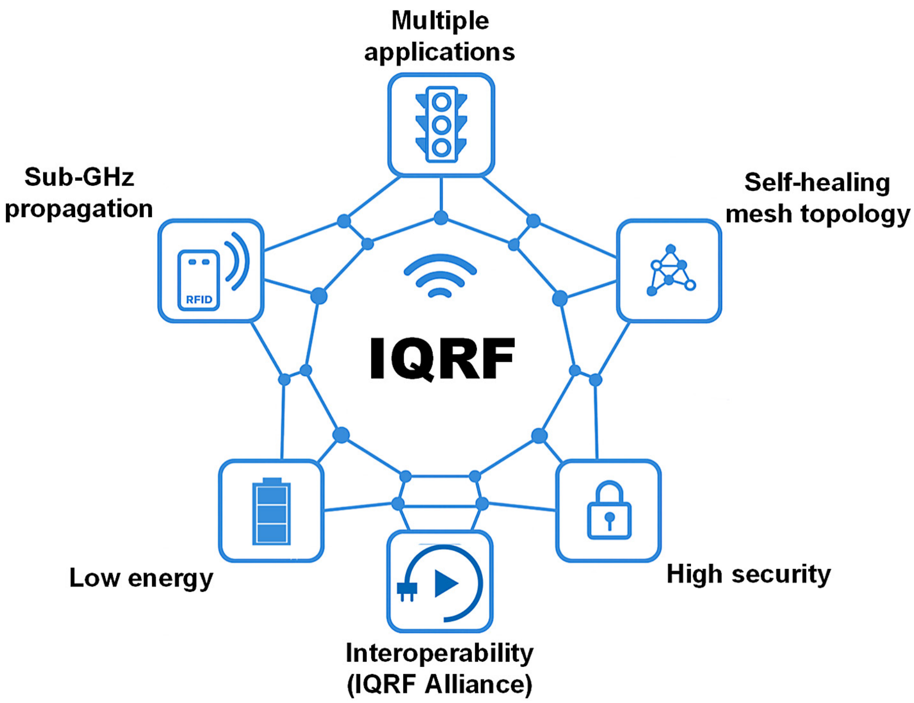

Figure 3. Key features of IQRF networks in Smart City applications

quality sensors, or parking monitors – into a unified system without requiring custom interfaces for each deployment [20].

Conceptual design

The conceptual design of the proposed traffic control system is based on a layered architecture that integrates passive RFID identification with a distributed wireless communication backbone provided by IQRF technology, as shown in Figure 4. The goal is to enable real-time, event-driven traffic signal control that adapts dynamically to vehicle flows in a smart city environment.

Similar large-scale implementations, such as SCOOT in London and Surtrac in Pittsburgh, have demonstrated that adaptive coordination can significantly reduce travel times in metropolitan areas, while V2X pilot projects in Singapore, Munich, and Beijing confirmed the effectiveness of vehicle–infrastructure integration for improving traffic efficiency and safety. The proposed RFID–IQRF concept follows this trend by offering a cost-effective and scalable alternative suitable for distributed smart-city deployments.

In the detection layer, passive RFID transponders are arranged in arrays at critical points such as intersections, pedestrian crossings, and restricted zones. Vehicles are equipped with onboard RFID readers that capture these transponders while in motion, allowing the system to determine both the presence and the direction of travel. The transponders require no external power supply, which ensures high durability, low maintenance, and easy integration with existing infrastructure.

Detected events are transmitted to the infrastructure layer, where they are processed by the supervisory unit based on a Raspberry Pi 5 equipped

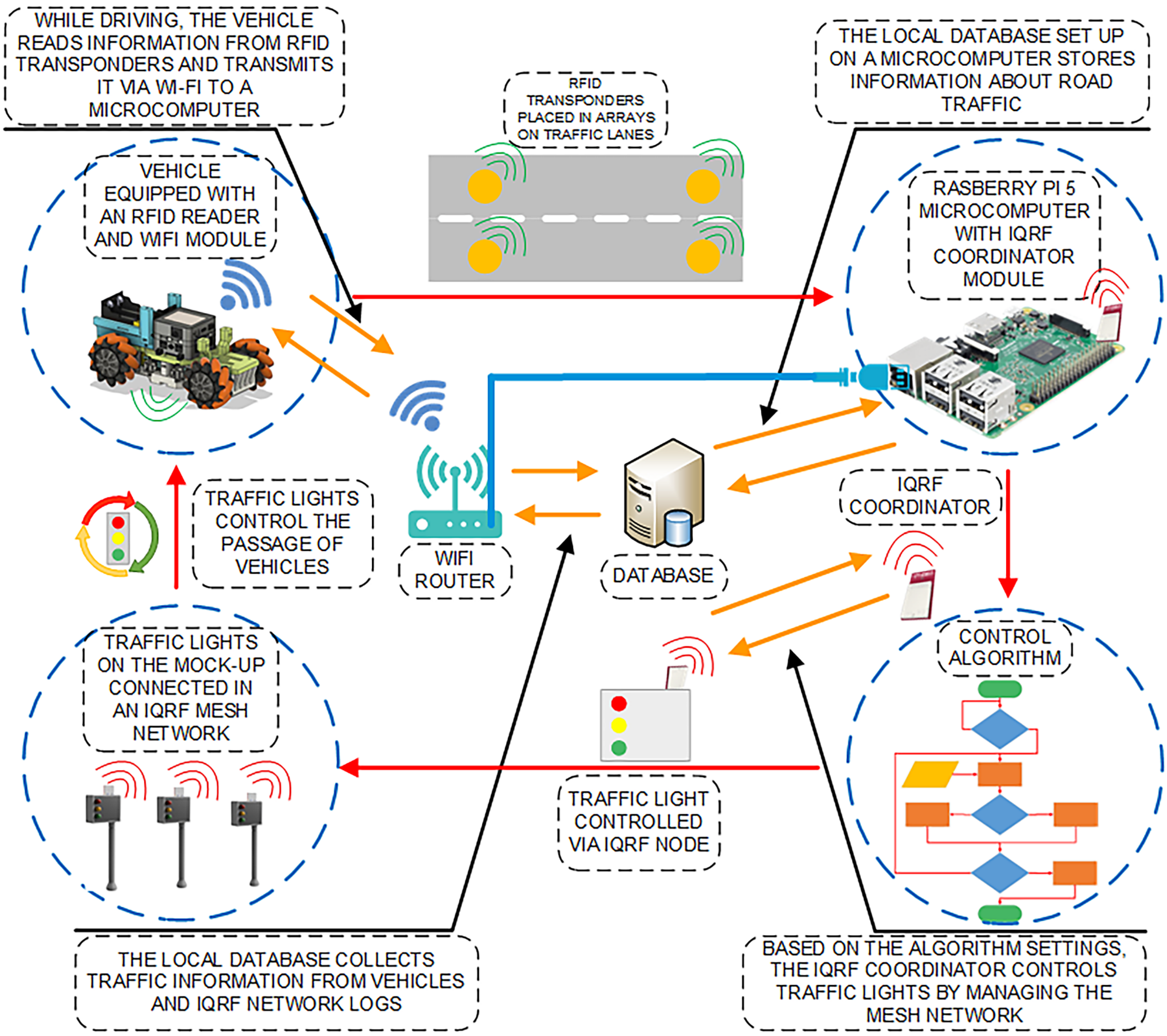

Figure 4. Architecture of the RFID- and IQRF-based traffic control system

with an IQRF Coordinator. The coordinator manages data exchange between distributed nodes and records all detection and communication events in a local database. The IQRF mesh operates in a self-healing topology in which every node can act as a router, providing reliable and low-latency communication even in dense network conditions.

Each traffic-light controller is built on an IQRF TR-72GA module programmed in C using the IQRF IDE environment and the DPA (Device Peripheral Access) framework. The application logic is implemented through the CustomDpaHandler procedure, which interprets incoming DPA commands and sets GPIO outputs corresponding to signal states (red, yellow, green). Nodes are addressed by their DPA handles and communicate with the coordinator through standard DPA peripherals for I/O and diagnostics. The Smart Bonding mechanism in IQRF IDE securely pairs each node with the coordinator by its unique Module ID and Bonding Key, forming a closed IQMESH network dedicated to local control. At the decision layer, the supervisory algorithm evaluates vehicle presence data from RFID transponders and dynamically determines optimal signal timings. Unlike traditional fixed-time control, the adaptive strategy allocates green phases according to actual demand. The calculated phase commands are transmitted through the IQRF mesh to individual nodes, which apply them and send confirmation frames back to the coordinator for logging. All RFID detections and IQRF logs are stored in a local database, providing full traceability of communication and system performance. This enables long-term analysis, verification of network stability, and refinement of the control algorithm. The integrated hardware–software design ensures deterministic response, low latency, and practical scalability, confirming the feasibility of the proposed real-time control architecture.

RFID-based vehicle detection

The model vehicles used in the experiments were equipped with compact RFID readers positioned on the front underside, ensuring close proximity to the road surface and consistent identification. The readers were configured to capture the ID of the detected transponders, which was then forwarded to the infrastructure layer via the IQRF communication network as shown in Figure 5. This method of vehicle detection offers several advantages over traditional traffic sensors such as inductive loops or video cameras. First, passive transponders do not require a power supply, making them maintenance-free and easy to deploy in large numbers. Second, the system is robust to environmental conditions such as poor lighting or adverse weather, which often degrade the performance of optical sensors. Finally, the low cost of passive transponders enables scalable deployment across extensive road networks, making this approach suitable for smart city applications. Using RFID-based detection as the foundation of the system, vehicles can be reliably tracked in real time, enabling the traffic control unit to dynamically adapt signal phases based on actual demand rather than fixed schedules.

IQRF communication framework

The communication layer of the proposed system is built on IQRF technology (Figure 6),

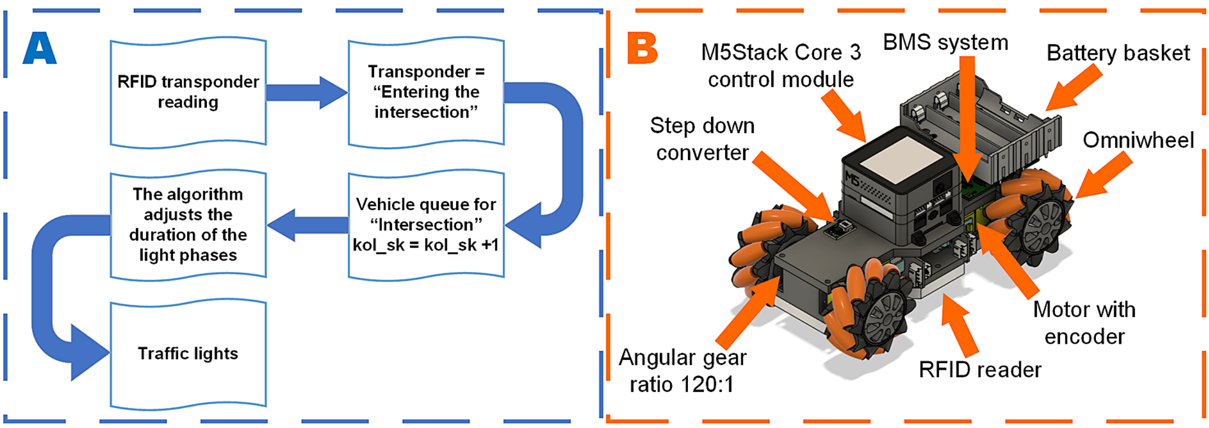

Figure 5. RFID-based adaptive traffic control model: (a) control algorithm workflow, (b) test vehicle architecture

which provides a lightweight and reliable wireless mesh framework for distributed traffic control. IQRF operates in the sub-GHz ISM band, offering longer range and better penetration in dense urban environments compared to higher frequency protocols. Its low-power design ensures that the nodes can operate for extended periods without frequent maintenance, which is a critical factor for large-scale smart city deployments.

In the mock-up implementation, the IQRF transceivers were integrated into local controllers positioned at intersections and connected to the central supervisory unit. The mesh topology allowed each node to function as both a transmitter and a router, ensuring that information about vehicle detections and control commands could propagate through the network even if direct communication paths were temporarily obstructed. This self-healing mechanism increased the robustness of the system and minimised latency. The framework thus supported bidirectional communication: upstream for real-time data collection and downstream for adaptive signal control commands. The modularity of the IQRF network also allowed seamless integration of additional nodes, making it possible to extend the system to new intersections or incorporate other smart city sensors without major reconfiguration.

By providing a reliable, energy-efficient, and scalable wireless backbone, the IQRF framework complements the RFID detection layer and enables real-time coordination across distributed components of the traffic control system.

Smart-city mock-up design

The smart-city mock-up, measuring six-by-five meters, was constructed as a modular platform to evaluate the RFID- and IQRF-based traffic management system. It reproduces typical urban features such as intersections, pedestrian crossings, a roundabout, and parking areas. Its modular

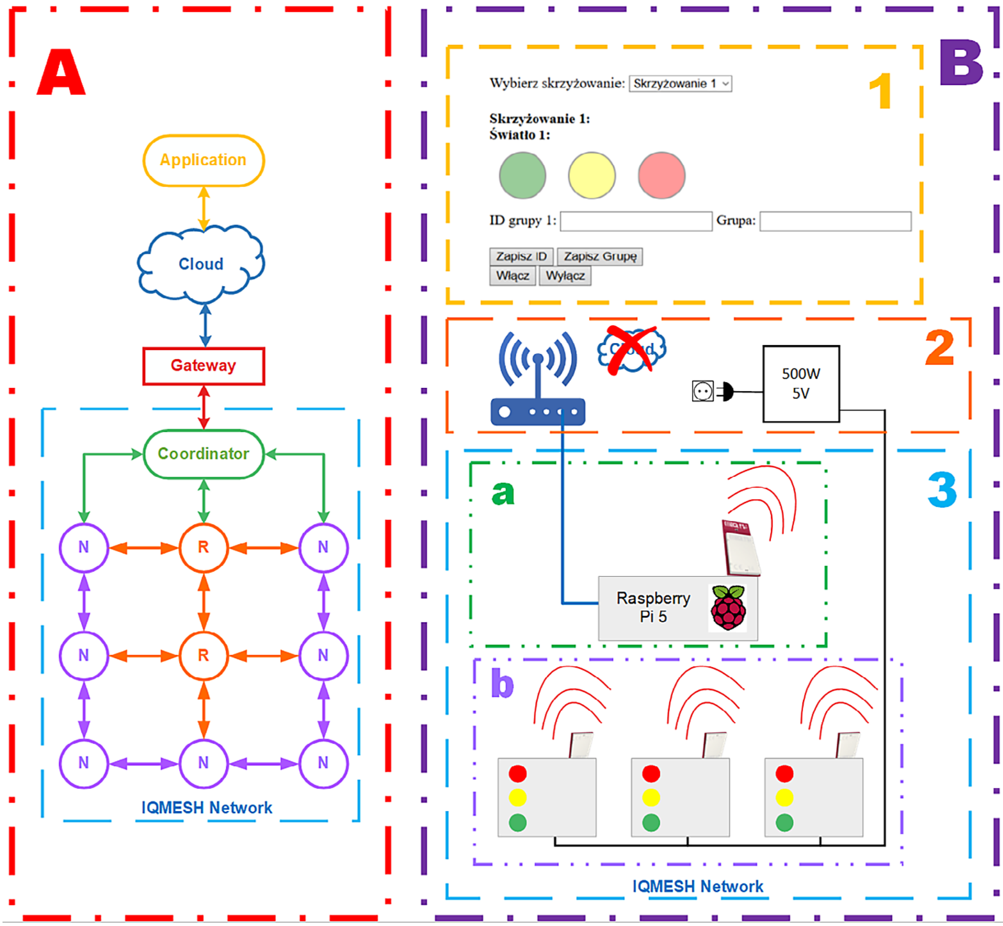

Figure 6. Comparison of IQRF network architectures: (A) typical IQRF network structure, (B) implemented mock-up environment: (1) user interface for traffic light control, (2) local access only (no cloud connection), (3) IQMESH network: (a) microcomputer with IQRF coordinator; (b) IQRF nodes integrated with traffic lights

design enables reconfiguration of layouts, allowing researchers to test different road geometries and traffic scenarios without rebuilding the entire setup. The road network was equipped with 167 passive RFID transponders embedded directly into the pavement at strategically selected locations (Figure 7). To ensure reliability, most event points employed three-transponder sequences: early warning, decision trigger, and confirmation, while parking areas were equipped with pairs of transponders. Each transponder ID corresponded to a specific category of traffic situation, as detailed in Table 1.

The correct placement and redundancy of the RFID components were crucial to ensure consistent detection. Arrays of two or three identical transponders minimised the probability of misreads caused by electromagnetic interference, vehicle misalignment, or rapid speed variation. The transponders were embedded flush with the road surface, avoiding mechanical interference with vehicles and guaranteeing a stable detection distance. Vehicles followed repeatable, predefined routes to simulate traffic interactions at controlled levels of congestion. Their maximum speed was calibrated to the real-world equivalent of 12 km/h, reflecting typical urban driving conditions. When a transponder was detected, its ID was processed, and predefined behaviours such as speed adjustment, lane change, manoeuvre execution, or stop commands were executed as shown in Figure 8.

Traffic light modules and IQRF network

The traffic light modules (Figure 9) in the mock-up were designed as compact units that integrate LED indicators with an embedded IQRF communication module. Each traffic light consisted of a three-colour LED assembly (red, yellow, green) mounted on a vertical pole, driven by a custom PCB.

The modular construction allowed direct integration of the traffic lights into the IQRF wireless mesh. Each light unit functioned as a network node capable of receiving commands from the central coordinator. The commands were

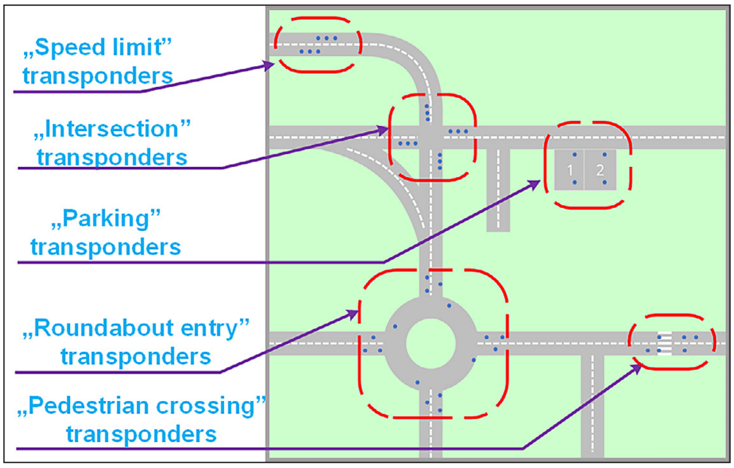

Figure 7. Fragment of smart city map with RFID transponders

Table 1. Classification of RFID transponders and their corresponding trigger events

Traffic situation category	Hex code	Quantity	Triggered action
General warning	0000	60	Activate vehicle alert mode
Straight road	0001	45	Maintain speed and direction
Curve	0002	11	Reduce speed, initiate cornering mode
Triple intersection	0003–0006	21	Path decision (left, right, straight)
Quadruple intersection	0007–000A	12	Adjust based on right-of-way logic
Parking spots (1–10)	000B–0014	10	Stop vehicle, log position
Triple roundabout	0015–0018	4	Initiate rotation logic, check exits
Quadruple roundabout	0019–001C	4	Loop management, path correction

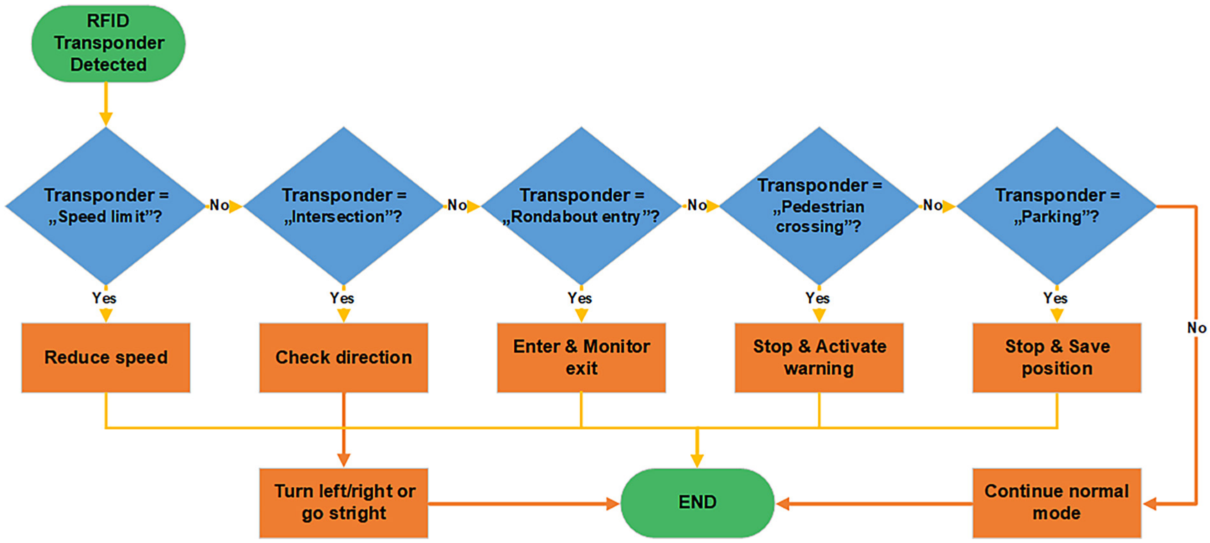

Figure 8. Event handling coroutine

processed by the controller and immediately translated into changes in the light state.

At the network level, IQRF nodes were installed at intersections, where they collected data from RFID-based vehicle detection and transmitted control commands to the respective traffic lights. Communication between nodes was managed in a low-latency mesh topology, ensuring reliable data dissemination across the mock-up even under interference.

Static ALGORITHM

The static scheduling approach represents the conventional method of traffic signal control, in which signal phases are predefined and repeated cyclically without considering real-time traffic demand, as shown in Figure 10. In the mock-up implementation, each cycle consisted of fixed green, yellow, and red intervals allocated to all intersection approaches in a round-robin

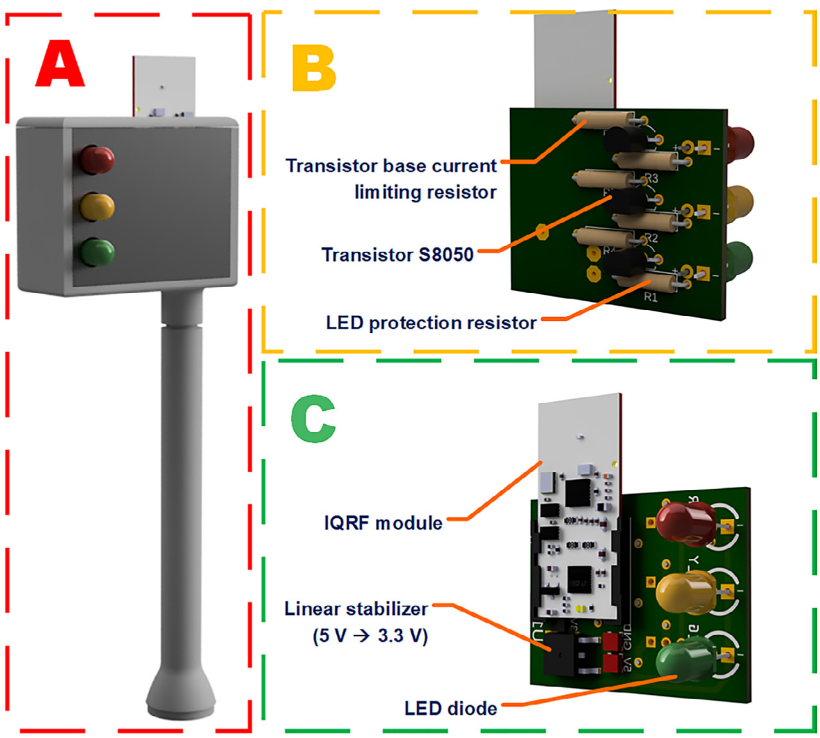

Figure 9. 3D model of the traffic light node: (a) complete traffic light unit, (b) reverse side of the PCB with control components, (c) front side of the PCB with IQRF module

sequence. The duration of these intervals was determined in advance based on average traffic expectations but remained constant throughout the experiment.

This approach ensured predictable and uniform operation of the traffic lights, which is one of its main advantages in practice. Drivers and pedestrians can anticipate signal patterns, and the system requires minimal computational resources. Furthermore, the absence of continuous monitoring and decision-making processes simplifies implementation and reduces system complexity. However, the limitations of static control become apparent under fluctuating or unbalanced traffic flows. When demand is low in one approach and high in another, fixed cycle allocation may result in unnecessary red phases for empty lanes and excessive waiting times for congested ones. These inefficiencies increase queue lengths, increase vehicle idle times, and contribute to fuel consumption and emissions. In the experimental evaluation, the static scheduling algorithm served as a baseline reference. Its consistent and repeatable behaviour allowed direct comparison with the dynamic RFID-IQRF strategy, providing clear insight into the benefits of adaptive signal control.

Dynamic RFID-based control algorithm

The dynamic control algorithm was designed to overcome the limitations of static scheduling by adapting signal phases to real-time traffic conditions. Its operation relies on continuous vehicle detection (Figure 11) through RFID readers installed on the model vehicles and passive transponders embedded in the road surface.

At the supervisory level, the detection events were aggregated and assigned to specific intersection approaches. This enabled the system to estimate the demand by monitoring both the presence and the accumulation of vehicles in queues. The algorithm (Figure 12) then compared current demand levels across all approaches and adjusted the distribution of green times accordingly. Approaches with higher detected volumes received extended green phases, whereas those without

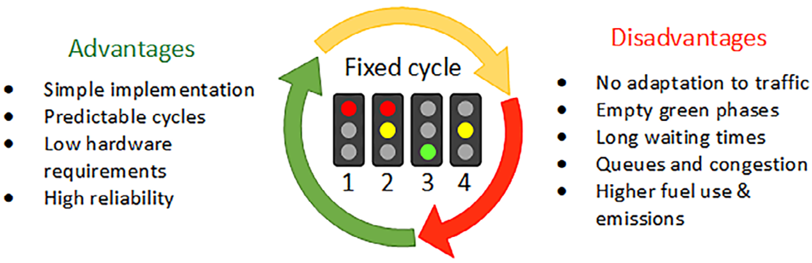

Figure 10. Static traffic light cycle

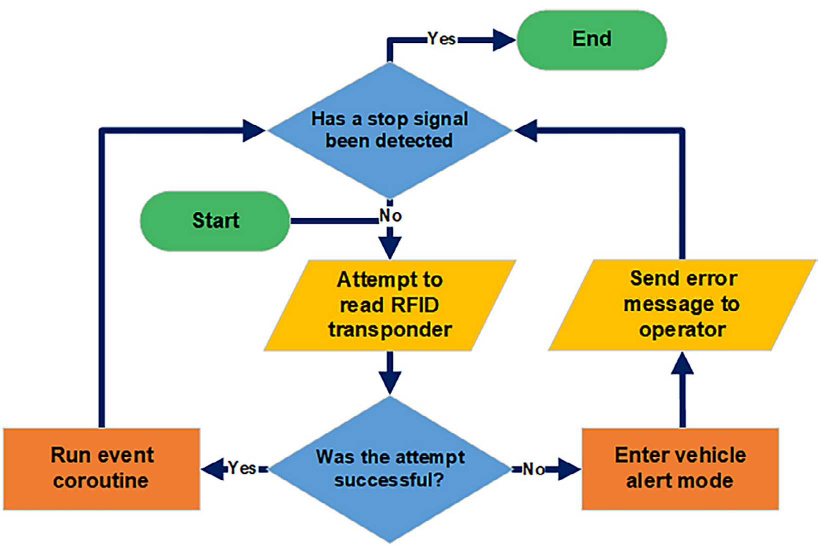

Figure 11. Car RFID handling flowchart

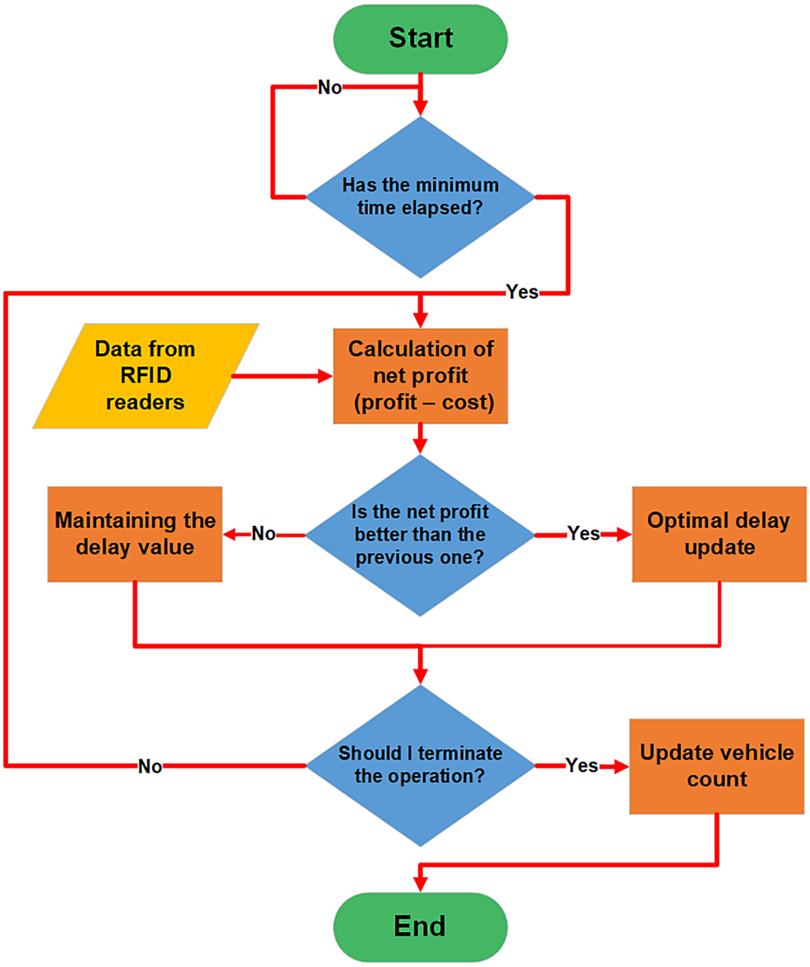

Figure 12. Dynamic algorithm operation diagram

active detections were assigned shorter or skipped cycles, subject to minimum safety constraints.

After the minimum green interval had elapsed, the algorithm evaluated extensions of the active phase. For each candidate delay, a net gain value was calculated as the difference between the estimated number of vehicles that could clear the intersection and the cost in terms of additional waiting time imposed on other approaches. If a higher net gain was identified, the corresponding extension was stored as the new optimal solution.

Once the evaluation cycle was completed, the algorithm verified the termination conditions. If further extension was justified, the current green phase was prolonged by the selected delay; otherwise, the system initiated a phase change. Transition commands were transmitted through the IQRF network to the relevant traffic light controllers, ensuring synchronised execution across the intersection. This real-time feedback mechanism allowed the system to dynamically balance traffic flows, reducing idle green phases, and minimising queue lengths. The algorithm also incorporated safeguards such as minimum green times and all-red intervals to prevent unsafe or abrupt transitions.

Organisation of the experiment

The experiment was conducted to evaluate the effectiveness of the proposed dynamic control algorithm compared with the traditional static scheduling method. The main objective was to verify whether real-time phase adaptation based on RFID detection can reduce vehicle waiting time and improve traffic flow efficiency.

Tests were carried out on a modular smart-city mock-up with dimensions of six-by-five meters. Eight model vehicles equipped with RFID readers circulated along predefined routes including intersections, pedestrian crossings, and a roundabout. Each vehicle communicated with the central control unit via the IQRF network, transmitting detection data in real time. Two independent test sessions were performed: one under static

control with fixed signal cycles and the other under dynamic control responding to actual traffic demand. Between sessions, all system components were reset to ensure identical initial conditions and full repeatability of measurements. During the trials, three primary performance indicators were recorded:
- average waiting time at the stop line before entering the intersection,
- traversal time from the point of entry to the point of exit across the intersection,
- queue length, defined as the maximum number of vehicles waiting simultaneously.

The applied configuration corresponded to low traffic density, representative of off-peak urban conditions. This ensured controlled testing and accurate comparison between algorithms while avoiding saturation of the mock-up network. It should be emphasised that the study represents a proof-of-concept validation performed on a reduced-scale model. The obtained results confirm the feasibility of adaptive control under light traffic, but further research is required for multi-intersection coordination and higher-density scenarios to fully assess scalability and robustness.

Additionally, statistical data from the Central Statistical Office (GUS) and the Polish Automotive Industry Association (PZPM) were analysed. These reports indicate a continuous increase in the number of vehicles in Polish cities and a corresponding rise in congestion and road incidents. The proposed adaptive control idea directly addresses these challenges by enabling real-time phase optimisation and, in future, may support predictive accident detection and prevention in large-scale smart city systems.

RESULTS

The experimental data allowed a direct comparison of the two signal control strategies.

The first indicator, illustrated in Figure 13, revealed a clear advantage of the dynamic algorithm over the static approach. In static mode, the average waiting time reached 25.1 seconds, while in dynamic mode this value dropped to 12.6 seconds, representing a reduction of 50%. Under static control, each cycle follows a fixed structure, which forces vehicles arriving "out of phase" to wait for the entire next cycle. This leads to frequent stops and queue formation, even under moderate traffic demand. Even small real-time adjustments of green time reduced the number of waiting cycles and improved traffic flow.

The second indicator analysed was the average traversal time across the intersection, measured from entry to exit. As shown in Figure 14, traversal time in static control averaged 4.5 seconds, while in dynamic control it decreased to 3.2 seconds. Although the difference of 1.3 seconds may appear modest, it reflects more efficient vehicle processing and queue clearance. Vehicles

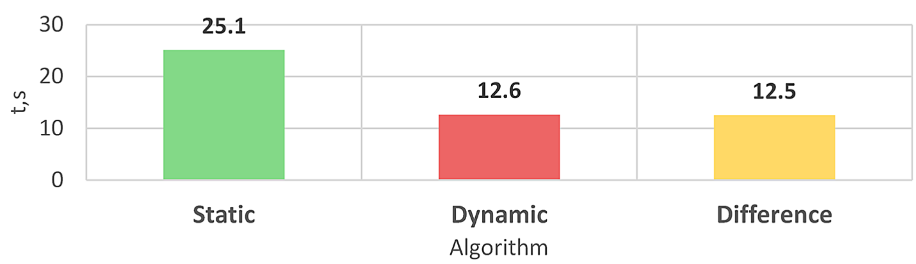

Figure 13. Comparison of the average waiting time at intersections

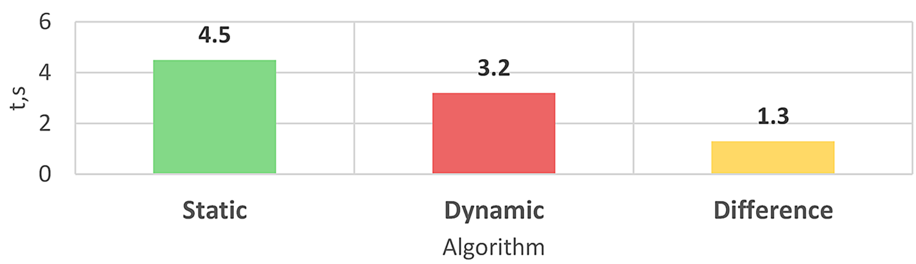

Figure 14. Comparison of the average travel time through an intersection

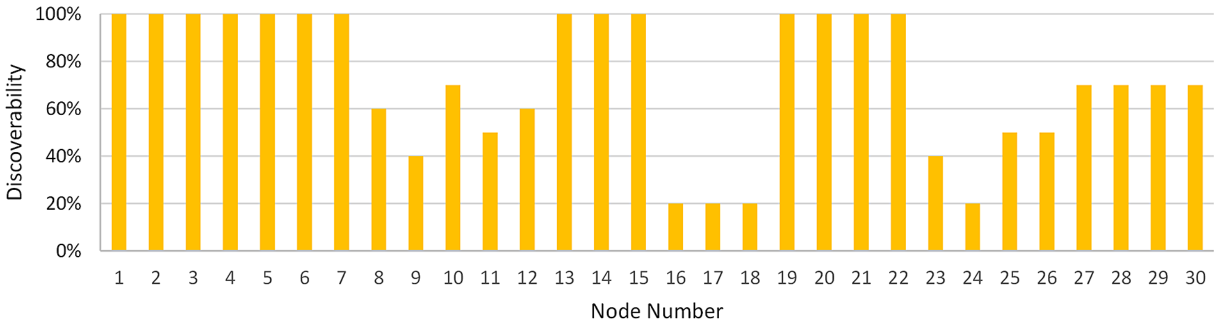

Figure 15. Single node detection

in dynamic mode experienced fewer stops near the stop line and smoother acceleration once the green phase was active. In cumulative terms, shorter traversal times translated directly into higher intersection throughput, reducing vehicle accumulation during successive signal cycles.

Figure 15 shows the discoverability of individual IQRF nodes during the network discovery phase. While several nodes were consistently detected with 100% reliability, others dropped below 40%, reflecting shadowed areas or unfavourable propagation. This variability applies only to the coordinator's ability to detect nodes during initialization, not to data transfer once connections are established.

CONCLUSIONS

This work presented the design and evaluation of a proof-of-concept adaptive traffic signal control system combining RFID-based vehicle identification with an IQRF wireless mesh network. A six-by-five-meter smart-city mock-up was used to verify the complete process chain—from detection to communication and control. Comparison with a static algorithm confirmed the effectiveness of the proposed approach, reducing the average waiting time by almost 50% and improving intersection throughput.

The experiments also confirmed the general stability of the system. Arrays of RFID transponders ensured reliable vehicle detection, while the IQRF mesh provided low-latency and self-healing communication between distributed nodes. Some variability was observed during the network discovery phase, where the coordinator detected certain nodes with lower reliability depending on placement and antenna orientation. Ongoing work focuses on improving this stage to achieve more uniform coverage and faster initialization. The study was conducted to verify the feasibility of the proposed idea in a controlled environment. Large-scale tests under real conditions, including weather variability, system robustness, and integration with existing smart city platforms, are planned for future research stages. Extended statistical validation, including significance testing of performance differences, will also be performed to strengthen the quantitative evaluation of results.

Building upon this concept, current research uses data collected from the RFID–IQRF platform as input for reinforcement learning models. This approach responds to the increasing complexity of urban traffic, where dynamic road conditions and vehicle diversity require adaptive, data-driven control. Preliminary simulations in SUMO using Transformer-based architectures and the PPO algorithm show promising improvements over classical strategies, confirming the potential of the proposed system as a foundation for AI-driven traffic management.

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