



Development of an Intelligent Traffic Management System Using Wireless Sensor Networks

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Peer Review Information

Submission: 12 Jan 2021

Revision: 08 Feb 2021

Acceptance: 16 March 2021

Keywords

*Wireless Sensor Networks,
Intelligent Transportation
Systems, Adaptive Traffic
Signal Control, Traffic
Congestion, Smart City*

Abstract

Urban intersections are frequently controlled by fixed signal plans that cannot respond effectively to short-term variations in vehicle demand. This methodology paper develops a wireless sensor network (WSN)-based intelligent traffic management framework in which low-power roadside sensor nodes measure vehicle presence and queue conditions, forward observations through clustered wireless links, and support a controller that adjusts signal green time according to current traffic pressure. The proposed study uses a design-science and simulation methodology rather than claiming field deployment. Its architecture combines sensing, data aggregation, congestion estimation, adaptive phase selection, emergency-priority logic, and performance logging. A one-hour microscopic time-step simulation is repeated thirty times for light, medium, and heavy traffic conditions and is compared with a conventional equal-split fixed-time controller. Under the stated assumptions, the adaptive controller reduces mean waiting time from 12.39 to 7.77 s in light demand, from 15.30 to 11.18 s in medium demand, and from 82.59 to 61.67 s in heavy demand, while also reducing average queue size and improving heavy-load throughput. The results support the methodological feasibility of using WSN measurements for responsive traffic signal control, while emphasizing that communication loss, sensor error, multi-intersection coordination, security, and real-world calibration must be addressed before field implementation.

Introduction

Rapid urbanization and growth in private and commercial vehicle use have increased congestion, travel delay, fuel consumption, emissions, and intersection safety problems. Conventional fixed-time traffic signals are typically configured from historical averages and therefore provide the same or similar phase duration even when traffic is highly unbalanced. Intelligent Transportation Systems (ITS) address this limitation by combining sensing, communication, computing, and control. Within this context, WSNs are attractive because small sensor nodes can be distributed along road

approaches and can communicate observations without extensive cabling. Tubaishat et al. (2009) identified WSNs as a flexible means of improving transportation sensing and management, while Dimitrakopoulos and Demestichas (2010) described broader ITS architectures in which distributed sensing and knowledge exchange support traffic and safety functions.

For traffic management, the central methodological requirement is to transform raw vehicle detections into decisions quickly enough to change the signal state before congestion propagates. WSN-based ITS research has therefore examined sensor placement, vehicle

detection, data delivery, network topology, and adaptive control. Losilla et al. (2011) emphasized that WSNs can reduce installation cost and can operate as components of heterogeneous ITS platforms. Pascale et al. (2012) further showed that denser spatial sampling can improve traffic-state estimation and short-term prediction. These findings motivate a closed-loop architecture in which sensing and signal control continuously influence each other rather than operating as separate subsystems.

The objective of this paper is to define and evaluate a reproducible methodology for developing an intelligent traffic management system using WSNs. The paper focuses on a signalized four-arm urban intersection and asks whether real-time queue information collected through a WSN can improve signal timing relative to an equal-split fixed-time plan. The contribution is methodological: it specifies the system components, data flow, control logic, simulation design, evaluation measures, and limitations so that the approach can later be implemented using physical sensor nodes or extended to a corridor of connected intersections.

Literature Review

Early research established the suitability of WSNs for transportation sensing. Tubaishat et al. (2009) reviewed their use in ITS and highlighted wireless deployment as an alternative to conventional wired sensing. Losilla et al. (2011) provided a comprehensive survey covering vehicle detection, classification, architecture, topology, communication protocols, and design constraints. Their work is particularly relevant to the present methodology because it treats WSNs not as isolated sensing devices but as collaborative components in larger transportation systems. Pascale et al. (2012) examined traffic management and road safety and reported that higher sensor density can

improve the spatial resolution of traffic observations, which can strengthen traffic modeling and prediction.

Adaptive traffic control is the second foundation of the proposed design. Bhuvaneswari et al. (2012) proposed a WSN-based adaptive traffic signal flow-control method and reported simulation advantages over fixed-time control. This supports the use of measured traffic demand as the input to phase timing. Sensor placement is also important because poorly located nodes increase blind areas or redundant communication. Gu et al. (2015) formulated WSN layout and density optimization for traffic information collection, showing that coverage, connectivity, and deployment cost must be considered jointly. Fernández-Lozano et al. (2015) demonstrated a WSN platform for urban traffic characterization using Bluetooth, ultrasound, and laser sensing and showed that flexible nodes can support real-time traffic monitoring in real conditions.

Nellore and Hancke (2016) surveyed WSN-based urban traffic-management systems and organized the field around traffic sensing, intelligent signal control, emergency-vehicle priority, congestion management, and waiting-time reduction. Their survey also noted practical concerns such as node energy consumption, communication reliability, and heterogeneous sensing. More recent work by Hilmani et al. (2020) proposed an automated real-time traffic-control system for smart cities using clustered WSN nodes, congestion estimation, and dynamic traffic-light control. At the wider ITS level, Guerrero-Ibañez et al. (2021) reviewed data-driven and deep-learning support for traffic prediction, automated signal management, lane detection, and object recognition. Although the present methodology uses a transparent queue-pressure rule rather than deep learning, the 2021 review indicates a clear trajectory toward increasingly data-driven traffic control.

Table 1. Selected literature supporting the proposed methodology (all publications ≤ 2021)

Study	Focus	Key point	Use in this paper
Tubaishat et al. (2009)	WSN use in ITS	Low-cost wireless sensing can support transportation monitoring and management.	Foundation for WSN sensing layer.
Losilla et al. (2011)	WSN-based ITS survey	Architecture, detection, topology, and communication must be jointly designed.	Guides layered architecture.
Pascale et al. (2012)	Traffic monitoring / safety	Dense WSN measurements improve spatial sampling and traffic-state estimation.	Supports distributed roadside nodes.
Bhuvaneswari et al. (2012)	Adaptive signal control	Traffic-responsive signal timing can outperform fixed-time control in simulation.	Basis for adaptive green allocation.

Gu et al. (2015)	Node layout optimization	Coverage and connectivity depend on suitable WSN node placement.	Informs deployment strategy.
Fernández-Lozano et al. (2015)	Urban traffic characterization	Flexible multi-sensor WSN nodes can collect traffic data in real conditions.	Supports multi-sensor detection.
Nellore & Hancke (2016)	Urban traffic management survey	WSN systems support sensing, congestion control, priority, and waiting-time reduction.	Defines functional requirements.
Hilmani et al. (2020)	Real-time WSN traffic control	Clustered sensor data can drive dynamic traffic-light control in smart-city settings.	Closest architectural precedent.
Guerrero-Ibañez et al. (2021)	Data-driven ITS review	Modern ITS increasingly uses real-time data for prediction and automated control.	Supports future intelligence layer.

Methodology

A design-science methodology is used to specify the WSN-enabled traffic system and a controlled simulation is used to evaluate its behavior. The study unit is a four-arm signalized intersection with north, south, east, and west approaches. Sensors are assumed to detect vehicle arrivals and queue occupancy near each stop line. Data are aggregated by a local WSN gateway and

converted into a traffic-pressure estimate. The controller then extends or terminates a green phase subject to minimum and maximum green constraints. This structure follows the traffic-sensing and adaptive-control principles identified in earlier WSN-ITS research (Losilla et al., 2011; Nellore & Hancke, 2016; Hilmani et al., 2020).

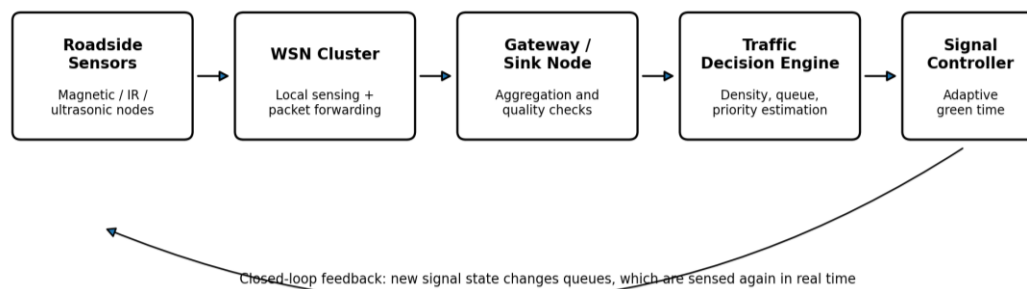


Figure 1. Proposed closed-loop WSN architecture for intelligent traffic management

Step 1: Define system requirements. The system must detect approaching vehicles, estimate lane or approach demand, transmit observations with low delay, adjust signal timing, preserve a minimum green interval for safety and fairness, and record performance measures. The primary performance objectives are lower average waiting time and queue length without reducing completed vehicle throughput.

Step 2: Select sensing and node placement. Two or more detection points are conceptually placed on each approach: one close to the stop line to represent queued vehicles and one upstream to estimate arrivals. Magnetic, infrared, ultrasonic, or comparable low-power detectors can be used. Deployment should maintain communication coverage while avoiding unnecessary density, consistent with the coverage-connectivity trade-off discussed by Gu et al. (2015).

Step 3: Form the WSN communication layer. Roadside nodes are organized into local clusters. Each sensor transmits a compact message containing node ID, time stamp, vehicle-presence count, and battery/status information. A cluster head or sink node aggregates packets and forwards the latest demand state to the traffic controller. Sequence numbers and time stamps can be included so that duplicates and stale packets can be discarded. The design allows retransmission or fallback to the last valid state if a packet is lost.

Step 4: Estimate traffic state. For every approach i , the controller maintains an estimated queue q_i and recent arrival rate λ_i . The phase pressure for north-south is $P_{NS}=q_N+q_S$ and for east-west is $P_{EW}=q_E+q_W$. These variables are intentionally simple so that the controller is interpretable and can run on modest embedded hardware. More advanced classifiers or

predictive models could later be added, as suggested by the broader data-driven ITS literature (Guerrero-Ibañez et al., 2021).

Step 5: Apply adaptive signal logic. The currently green phase is held for at least 15 s. After the minimum green, the controller compares the competing phase pressure. A phase change is requested when the opposing pressure exceeds 1.25 times the current pressure, or when the current phase reaches a 45 s maximum. A 3 s lost-time interval represents amber/all-red clearance. This produces demand-responsive operation while limiting excessive switching and starvation.

Step 6: Provide fail-safe and priority behavior. If sensor data are unavailable beyond a configured timeout, the controller reverts to a fixed-time equal-split plan. For a future physical prototype, authenticated emergency-vehicle messages or dedicated priority sensors can override the ordinary pressure rule while still enforcing safe phase clearance. Security, node health, and watchdog functions should be logged because network failure can directly affect traffic safety.

Step 7: Construct the simulation experiment. A one-second time-step simulation is run for 3,600 s. Vehicle arrivals are generated from Poisson processes at each approach. Saturation discharge during green is modeled at 0.5 vehicle/s per approach. Both the fixed controller and the WSN-adaptive controller receive identical arrival streams within each replication. Thirty replications per scenario are used to reduce sensitivity to random arrivals. The fixed controller alternates 30 s north-south and 30 s east-west greens with the same 3 s clearance loss.

Step 8: Define traffic scenarios and metrics. Three demand levels represent increasing load and directional imbalance. Average waiting time is estimated by accumulating the number of queued vehicles at every second and dividing by the number of discharged vehicles. Average queue is the time-average number of waiting vehicles, and throughput is the number of discharged vehicles per simulated hour. The percentage waiting-time reduction is calculated relative to the fixed-time baseline.

Table 2. Simulation design and controller parameters

Parameter	Value / assumption
Simulation duration	3,600 s per replication
Replications	30 per traffic scenario and controller
Time step	1 s
Approaches	North, South, East, West
Service rate during green	0.5 vehicle/s per approach
Fixed-time green	30 s per phase
Adaptive minimum green	15 s
Adaptive maximum green	45 s
Adaptive switching threshold	Opposing pressure > 1.25 × current pressure
Clearance / lost time	3 s after a phase change
Light demand (veh/h)	N=300, S=250, E=200, W=150
Medium demand (veh/h)	N=600, S=500, E=400, W=300
Heavy demand (veh/h)	N=900, S=750, E=650, W=500

Results

Table 3 summarizes the mean outcomes across thirty replications. The simulated adaptive controller consistently lowered waiting time and queue size. Under light traffic, mean waiting time decreased from 12.39 s to 7.77 s, a reduction of 37.3%. In medium traffic it decreased from 15.30 s to 11.18 s, a reduction of 26.9%. The difference was largest in absolute terms under heavy,

directionally unbalanced demand: waiting time fell from 82.59 s to 61.67 s, or about 25.3%. The heavy scenario also shows the importance of capacity utilization because the adaptive controller increased mean throughput from approximately 2,695 to 2,734 vehicles/h by assigning more effective green time to the more heavily loaded north-south direction.

Table 3. Mean simulation results for fixed-time and WSN-adaptive control

Scenario	Average waiting time (s)		Delay reduction (%)	Average queue (veh)		Throughput (veh/h)	
	Fixed	Adaptive		Fixed	Adaptive	Fixed	Adaptive
Light	12.39	7.77	37.3	3.08	1.94	894.87	895.67
Medium	15.30	11.18	26.9	7.60	5.56	1,784.57	1,787.10
Heavy	82.59	61.67	25.3	61.86	46.93	2,695.07	2,733.57

The queue results follow the waiting-time pattern. Average queued vehicles fell from 3.08 to 1.94 in the light scenario and from 7.60 to 5.56 in the medium scenario. In the heavy scenario the reduction was from 61.86 to 46.93 vehicles. The fixed-time controller performs relatively well when demand is low because unused green time causes limited harm; however, when demand becomes both high and asymmetric, equal phase splits waste capacity on the less-demanded direction while the heavily loaded approaches continue accumulating vehicles. The adaptive method responds to this imbalance by reallocating green within the specified 15–45 s range.

These simulation outcomes are methodologically consistent with earlier WSN-based adaptive-control research rather than being direct replications. Bhuvaneshwari et al. (2012) similarly used traffic-responsive control to improve over a fixed-time reference, and Hilmani et al. (2020) linked WSN congestion information to dynamic signal timing. The present model differs by using a deliberately simple queue-pressure trigger and identical random traffic streams for paired comparisons. Therefore, the results should be interpreted as evidence that the proposed control logic is internally plausible under the stated assumptions, not as proof of field performance.

Conclusion and Discussion

This paper presented a step-by-step methodology for developing an intelligent traffic management system using wireless sensor networks. The proposed architecture places low-power sensors on intersection approaches, forms a WSN for real-time data transfer, estimates directional queue pressure at a gateway/controller, and dynamically adjusts signal phases within safety-oriented minimum and maximum green limits. The methodology is grounded in prior WSN and ITS literature through 2021 and combines design requirements, communication structure, adaptive control, fail-safe behavior, and simulation-based evaluation. The simulation indicates that real-time demand information can be valuable when traffic is uneven or approaches capacity. Across the selected scenarios, adaptive control reduced mean delay by about 25–37% and reduced average queues, while the largest throughput improvement appeared under heavy loading. This supports the central design assumption that a signal controller should react to measured demand instead of relying only on a historical fixed split. It also reflects the wider literature showing that WSNs can provide dense, flexible traffic observations (Pascale et al., 2012;

Fernández-Lozano et al., 2015) and that adaptive control is a natural application of those observations (Nellore & Hancke, 2016; Hilmani et al., 2020). Several limitations must be addressed before implementation. First, the simulation assumes accurate vehicle detection and omits packet loss, interference, sensor drift, and battery depletion. Second, it models only one intersection and therefore does not capture spillback or coordination between neighboring signals. Third, Poisson arrivals and a constant discharge rate simplify real driving behavior, lane changing, turning movements, pedestrian phases, buses, and incident conditions. Fourth, a real controller requires certified safety logic, secure communication, protected firmware, and a fallback timing plan. Future work should therefore integrate realistic radio models, measure packet delivery ratio and energy use, calibrate traffic using field counts, extend the controller to a multi-intersection corridor, and compare the pressure rule with fuzzy, optimization, or learning-based control. A small physical prototype using magnetic or ultrasonic nodes and a gateway can then be validated against manually counted traffic before any public-road deployment.

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