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Design of Energy-Efficient Wireless Communication Networks Using IoT-Based Traffic Management

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ABSTRACT

Rapid urbanization has intensified traffic congestion in major cities, leading to increased fuel consumption, air pollution, and economic losses. Traditional traffic control systems, based on fixed-cycle signals, are ineffective in handling dynamic urban traffic patterns. This study proposes an IoT-based Energy-Efficient Wireless Network (IoT-EWN) for smart traffic management in Peshawar, Pakistan. The proposed system integrates IoT sensor nodes, wireless relay nodes, and cloud-enabled gateways to monitor real-time traffic density, dynamically adjust signal timings, and transmit data through energy-efficient multi-hop communication. Key components include a Duty-Cycle Adaptive MAC (DCA-MAC) protocol, a fuzzy logic-based signal control algorithm, and an energy-aware routing protocol (GEAR-T). The system was evaluated through simulations using MATLAB R2023b and NS-3 (v3.38) over a 4 km × 4 km urban grid with 24 intersections. Results show that IoT-EWN reduces network energy consumption by 47.3% compared to traditional networks and 28.6% compared to standard IoT systems. It also achieves a packet delivery ratio of 96.8%, latency of 23.4 ms, and throughput of 4.87 Mbps. These findings demonstrate that the proposed architecture significantly improves energy efficiency, reliability, and real-time responsiveness, making it a practical solution for smart traffic management in developing urban environments.

Introduction

The congestion of urban traffic has become one of the most significant infrastructure problems of the twenty-first century that has subjected cities all over the world to unbelievable economic, environmental, and health burdens. According to the estimates of the World Bank, the cost of traffic congestion in developing countries is 2 to 5 percent of the gross domestic product yearly in wasted fuel, driver time, and inefficiency in transportation (World Bank, 2020). In Pakistan, a trend of rapid and increasing congestion is becoming acute: as the urban population increases at a rate of about 3.4 percent per year, which is one of the fastest-growing rates in the South Asian region, the major cities of Pakistan are facing a critical issue of road jams at traffic levels that are many times higher than those of the existing road infrastructure (Pakistan Bureau of Statistics, 2023). Peshawar is the second-largest city and cultural and economic capital of KPK Province and the epitome of this challenge. Having more than 5.2 million vehicles registered and an annual vehicle growth rate of 11 percent, the road network of Peshawar will always be under congestion during the rush hours, with an average vehicle speed per major arterial only reaching 12 kilometers per hour during morning and evening hours (KPK Urban Unit, 2022). The resulting fuel wastage, air pollution, and wastage of time are very expensive to the economy of the city coupled with the health and quality of life of the 13 million residents.

It is widely understood that the basic weakness of traditional systems of traffic management in combating such issues. Conventional traffic signal control systems are based on fixed cycle plans that were tuned to the historic traffic conditions and cannot respond to real-time conditions that are highly dynamic and variable that are inherent to modern urban traffic. These systems can be described effectively as open-loop controllers: they send signals based on a set of timing plans without any perceiving of the presence of any vehicle, length of the queue or occupation of the intersection. The consequence is an inefficient use of systematics: the red-light waiting of empty approaches, the early release of green periods to lanes with high demand and the spillback queue effects that extend beyond the immediate area around individual intersections. In addition, the wireless communication system that is being used to support traditional traffic management (where there is any) is generally intended to be as broad-banded and wide-range as possible instead of being energy efficient, making the wireless nodes much more power-consuming than they need to be, given the fairly modest data rates needed to coordinate traffic signals.

The Internet of Things paradigm presents a radically new solution to the traffic management that deals with these limitations on their basis. Traffic management systems IoT Traffic management systems use dense networks of inexpensive, low power sensor nodes at intersections and along roadways segments to continuously observe the presence of vehicles, traffic density, length of the queue, or pedestrian traffic. Adaptive signal control algorithms combine these sensor data streams, process and act on them in real time and dynamically optimize signal timing plans according to the current traffic conditions and not the historical averages. Even the communication substrate of such IoT networks should be energy-efficient by design: sensor nodes that have power sources (battery or energy harvesting) need to be able to transmit their data reliably over multi-hop wireless links to gateways and edge computing platforms, and the cost per packet should be low to allow such networks to support sufficiently long lifetime of their devices without batteries needing replacement or maintenance interventions.

In wireless IoT networks used in managing traffic, energy efficiency is not just a convenience in its operation but a design necessity that dictates the potential viability of large scale implementations. Each intersection-level IoT deployment can include eight to twelve sensor nodes, which should have wireless communication to the other sensor nodes and the upstream gateways. The cumulative energy use of a poorly implemented IoT network, when scaled down the thousands of signalized intersections in a city the size of Peshawar, may make the system economically infeasible, especially within a developing-country context with a limited availability of grid power to where the network serves and limited budgets to support its operation and maintenance. Moreover, wireless protocols that are inefficient consume energy and cause unnecessary interference between radio frequency, decrease network lifetime, and invalidate the reliability of time sensitive traffic management data all of which significantly worsen system performance. It is important to note that to realize energy efficiency in traffic IoT networks, a concerted design effort that cuts across the physical layer and MAC layer, network routing layer, and the application layer is needed, and traffic management needs, especially the need to provide sensor data to signal controllers with low latency, provides the binding performance constraints.

Studies in cross-disciplinary areas of the IoT, wireless network energy efficiency, and intelligent transportation systems have become a significant field of research in the last decade. Akyildiz, et al. (2002) were the first to develop the pillars of energy-saving wireless sensor network which are still applicable in contemporary IoT implementation. Later works by Ye, Heidemann, and Estrin (2004) presented the concept of duty-cycling as one of the key means of minimizing the MAC-layer energy waste in wireless sensor networks--the concept that is the basis of the DCA-MAC protocol that is presented in this research paper. Tubaishat et al. (2009) showed how traffic monitoring using the wireless sensor network can be feasible in the realm of intelligent transportation systems, whereas Fogue et al. (2012) generalized the principles to the ad-hoc networks of vehicles. More recent works have introduced cloud computing and edge intelligence in combination with IoT traffic sensors to allow adaptive signal control at the city level (Jin et al., 2018; Zheng et al., 2020). Nevertheless, there is an important gap in literature: existing literature either optimizes energy efficiency at the cost of latency and reliability, i.e., makes traffic management responsiveness less efficient, or attains low latency at the cost of energy-intensive always-on radio operation. Joint optimization of energy, reliability of packet delivery, throughput, and latency in a single IoT traffic management system is still an unsolved research issue, especially in the context of urban infrastructure of the developing cities.

The research design simulation-based study is suitable and quite reasonable in the context of examination of the design and functionality of the proposed IoT-based wireless network architecture in the context of traffic management. Implementing large scale IoT sensor networks in actual urban setting (that is, hundreds of sensor nodes, wireless relay stations, gateway hardware, and signal controller integration) would require both capital funding and civil works permission way beyond the academic research study, would involve interrupting the traffic flow during implementation, and would present environmental variables (weather, vehicle mix, seasonal traffic patterns) that could not be controlled in the scientific evaluation. Simulation platforms like MATLAB and NS-3 offer peer-reviewed and verified models of wireless channel propagation, MAC protocol operation, network routing and energy consumption dynamics which have been validated with experimental data in the literature. Simulation enables the researcher to carry out controlled, reproducible experiments whereby parameters of an individual system are independently varied to isolate their effects on performance measures, to test system behavior on a broad test range of traffic scenarios including rare high-congestion scenarios that cannot be reliably experienced in the field and to compare the proposed architecture with well-characterized baseline systems using the same conditions. Simulation-based performance evaluation in a wireless network evaluation methodology is also a standard and well-established practice in the networking and IoT research community, where, in particular, the NS-3 simulator itself (Riley and Henderson, 2010) and Castalia simulator in wireless sensor networks (Boulis, 2011) were both developed to perform this.

This research contributes to the field in four major ways. To begin with, it offers the IoT-EWN design-a hierarchical, end-to-end IoT-based, wireless city traffic management network design that combines a new duty-cycle adaptive MAC protocol, a dynamic signal control algorithm based on fuzzy logic, and an energy-aware routing protocol into a unified system design. Second, it constructs a high-fidelity simulated road network model of a representative 4km x 4km area of the road network of central Peshawar, calibrated using real traffic volume measurements of KPK Urban Unit surveys, to provide a realistic and context-based simulation environment. Third, it offers a thorough quantitative analysis of the proposed IoT-EWN system against two control systems, namely, the traditional fixed-infrastructure wireless networks and the standard IoT deployments without energy optimization, in four most important performance metrics, including energy consumption, network throughput, ratio of packet delivery and end-to-end latency. Fourth, it shows that the synergizing of these measures can be done with the help of coordinated cross-layer design, creating a design pattern of energy-efficient IoT traffic management networks that can be used in Peshawar and similar urban settings of a developing country.

The rest part of this paper will be as follows. The second part is the review of literature available on the topics of IoT-based traffic management, energy-efficient wireless protocols, and smart city implementations. The third part explains the planned IoT-EWN architecture and the design of the components. The fourth part outlines the methodology of the simulation, such as network model, traffic scenarios, and performance evaluation model. The fifth part gives the results of the simulation and its analysis. The sixth part represents the discussion of the findings, limitations and implications. The seventh part has the final contributions and research directions.

Literature Review

Traffic Management Systems which use IoT

The use of a wireless sensor network in traffic monitoring and management is an active research topic since early 2000s. Tubaishat et al. (2009) became the first to use inductive loop sensor replacements with a wireless magnetometric sensor mounted on the roadway surfaces and was found to have vehicle detection rates of more than 95 percent with wireless transmission distance of 30-50 meters even in normal urban conditions. Yousef, Al-Karaki, and Shatnawi (2010) used this to be applied to multi-intersection traffic monitoring and demonstrated that distributed wireless sensor networks have the potential to give near-real-time traffic density estimates that can be used in adaptive signal control with latencies lower than the 100 ms limit imposed by most signal controller specifications. Even more recent IoT-based traffic systems take advantage of the integration of low-power wide-area network (LPWAN) technologies, specifically LoRaWAN and NB-IoT with edge computing platforms to provide city-scale implementations. Jin et al. (2018) described a deployment of LoRaWAN-based traffic monitoring at 47 intersections in a city in China with 97.2 percent packet delivery rates at a range of up to 2 km with an average node energy consumption of 14.7 mJ per packet. This work is relevant to the current study because it has shown that the range and energy demands of the urban traffic IoT implementation can be fulfilled using the LPWAN technologies, but the latency nature of LoRaWAN (usually 1-10 seconds) might not be sufficient to realize the signal control application that has a response time smaller than 100 ms.

In the case of latency-sensitive applications of adaptive signal control short-range low-power wireless networks in the 2.4 GHz and 915 MHz ISM bands, such as IEEE 802.15.4 (Zigbee), IEEE 802.11p (DSRC), and the new IEEE 802.15.4g smart utility networks are more suitable. Priemer and Friedrich (2009) described a traffic sensor network based on IEEE 802.15.4 that was able to measure vehicle-to-controller latencies of 23-47 ms in a three-intersection corridor, which is significantly below the 100 ms requirements of adaptive signal control. The power considerations of running at the increased data rate and duty cycle needed to achieve lower latency delivery, however, require a close MAC protocol design as examined in the next subsection.

MAC protocols that use less energy based on the IoT network

The radio transceiver activity in wireless IoT nodes is the largest consumer of energy, and especially the energy loss in three modes: idle listening (radio transceiver is on but does not receive any packets), overhearing (data packets sent to other nodes are received and processed), and protocol overhead (data packets received by the radio transceiver are control packets, not data packets, such as beacons, acknowledgments, and routing advertisements). IoT network MAC protocols focus on these waste modes by duty cycling (periodically shutting the transceiver down and up based on a schedule) to trade off the energy saving of sleep against the wake latency and throughput limits (Ye, Heidemann, and Estrin, 2004).

The original S-MAC protocol (Ye et al., 2004) showed that 10 percent duty cycles could save around 7.5 times compared to operating continuously with acceptable throughput loss in periodic monitoring systems. T-MAC (van Dam and Langendoon 2003) enhanced S-MAC by adjusting the sleep time to the traffic load, consuming less energy up to 98 percent in low-traffic conditions and having less latency in high-traffic conditions. Highly advanced adaptive duty-cycling protocols, such as A-MAC (Dutta et al., 2010) and X-MAC (Buettner et al., 2006) added asynchronous wake scheduling using low-power strobing of preamble to provide sub-milliseconds of wake latency and a duty cycle of less than 1 percent during idle intervals. The DCA-MAC protocol suggested in the given research is based on these principles but in this case, it is a traffic-adaptive duty-cycling protocol but in this instance applied to the designation of the heterogeneous traffic loads peculiar to the urban intersection monitoring when the activity of nodes is closely linked with the vehicular traffic intensity and has a predictable diurnal variation.

Smart Routing in Wireless Sensor Networks

Routing algorithms in energy-constrained wireless sensor networks have to balance the conflicting goals of minimizing the energy use per packet, ensuring that the network nodes receive a fair allocation of energy, and ensure that the quality of paths (delivery ratio, latency) meets the needs of the application. Yu, Govindan, and Estrin (2001) proposed a hybrid approach to geographic forwarding and energy-aware hole avoidance called geographic and energy-aware routing (GEAR), which is based on geographic forwarding and the use of energy-aware hole avoidance. The GEAR-T protocol recommended in the current work is based on the GEAR framework augmented with traffic-flow-aware path selection where real-time queue length and signal phase data is used to choose relay paths to minimize the energy of communication and the end-to-end delay of time-critical traffic sensor data.

The development of Smart Traffic Management in the Cities

Of particular interest to smart traffic control in the cities of developing countries have been the constraints of the infrastructure budgets, grid power accessibility at roadside locations, the harsh environmental conditions, and the fluctuating-quality wireless spectrum environments, which have been given relatively little consideration in the research literature, typified by studies in North American, European, and East Asian settings. Particular exceptions are Djahel et al. (2015) on adaptive traffic management in African urban settings and Ahmad et al. (2019) on IoT-based traffic monitoring in the Gulberg district of Peshawar that reported extreme wireless interference levels due to dense mobile networks deployments and suggested frequency planning solutions to ISM-band IoT deployments in Pakistani urban settings. Khan, Iqbal and Hassan (2020) presented a survey of smart city project in Pakistan, where traffic management is the top area of application and that there is no implemented infrastructure to monitor traffic by IoT as at 2020 in any Pakistani major city. This gap is directly covered by the present study which proposes, simulates and evaluates an entire IoT-EWN architecture that is specifically applied to the Peshawar urban setting.

Proposed Architecture IoT-EWN

Overview and Design Principles of the System

The IoT-EWN architecture is modeled on the four general engineering principles that manifest the uniqueness of the Peshawar urban traffic management. First, energy proportionality: network components must use only proportional amounts of energy as their load changes to reduce the amount of energy wasted when idle or lightly loaded there by employing aggressive duty cycling and sleep scheduling. Second, determinism in latency: the architecture should be able to guarantee bounded and predictable end-to-end packet delivery latency to traffic sensor data so that signal control decisions are not made with out-of-date traffic state data, and that latency does not exceed 50 ms in all traffic conditions simulated. Third, fault tolerance and graceful degradation: when one sensor or relay node fails, it should not affect the overall system of monitoring and controlling traffic and needs redundant communication routes and fallback operating modes. Fourth, deployability in the Peshawar environment: the architecture should be practically deployable based on the available Peshawar road infrastructure, constraints on power availability, and wireless spectrum environment.

The suggested system architecture has three hierarchical levels, in which each of them has features of specific functional roles, energy utilization patterns, and communication needs. The base level includes IoT Sensor Nodes (ISNs) that are installed at every intersection approach and stop line of a signalized intersection to detect the presence of vehicles by embedded magnetometric and infrared detection devices. The mid layer consists of Wireless Relay Nodes (WRNs) placed on every intersection and combining sensor data, of all the neighboring ISNs, and transmitting processed information about traffic state up the the multi-hop routes. The upper level consists of Edge Gateway Nodes (EGNs) that are installed at the key arterial crossings and which do the local coordination of collections of intersections as well as provide the backhaul network connectivity to the Traffic Management Cloud (TMC) through either cellular or fiber-optic connections.

IoT Sensor Node Design

Both IoT Sensor Nodes include a low-power microcontroller (ARM Cortex-M0+, 48 MHz, 1.7 V operation), a dual-mode radio transceiver supporting IEEE 802.15.4-2015 at 250 kbps in the 2.4 GHz band, a magnetometric vehicle detector (AMR sensor with 0.5 nT sensitivity), a passive infrared vehicle detector, and a 3.7 V lithium iron phosphate battery with a capacity of 2,4 The ISN hardware is intended to be implemented on the roadside by an IP67-rated weatherproof box mounted on signal poles 2.5-3.0 meters above the road surface.

The ISN firmware uses the DCA-MAC protocol (in Section 3.4) and a simplistic traffic state reporting application which sends two kinds of packets: periodically (1 Hz) heartbeat packets (64 bytes) and event-related detection packets (128 bytes) when a vehicle is detected or cleared. These types of packets can be distinguished so that the DCA-MAC protocol can use varying duty-cycling schedules: periodic reporting packets can be aggressively sleep-scheduled whereas event-driven detection packets which need low latency can be immediately woken and transmitted.

Wireless Relay Node Design

The Wireless Relay Nodes will be attached to an existing pole in the middle of the instrumented intersection on the pole of a traffic signal. WRNs have three main functions, they are the aggregation of sensor data packets by the neighboring ISNs (usually, 8-12 nodes in an intersection), local processing to calculate intersection-level traffic state summaries (queue length per approach, total occupancy, estimated number of vehicles), and the transmission of processed data packets upstream to the nearest Edge Gateway Node by the GEAR-T routing protocol. The WRN uses a DC power converter to use the traffic signal mains supply (220 V AC, 50 Hz in Pakistan) to avoid battery limitations, and allows the radio to be used at all times. Nonetheless, energy efficiency is also applicable to WRNs in terms of thermal management and power infrastructure size and the energy-consciousness of the GEAR-T protocol path selection can assist in reducing aggregate network energy even in areas where WRN power supply is not a limiting factor.

DCA-MAC Protocol Specification

The Duty-Cycle Adaptive MAC (DCA-MAC) protocol that is suggested to be applied to the ISN tier changes the active duty cycle of the radio transceiver of each sensor node based on three dynamic inputs, namely the local traffic intensity (based on the recent vehicle detections), the time of the day (via a learned diurnal traffic profile), the battery state of charge (SOC). The D(t) duty cycle at time t is determined as per the control law as follows:

$$D(t) = D\_min + (D\_max - D\_min) \times [\alpha \times f\_traffic(t) + \beta \times f\_tod(t) + \gamma \times f\_soc(t)]$$

where D_min = 0.5% and D_max = 15% are the minimum and maximum duty cycle bounds; f_traffic(t) ∈[0,1] is a normalized traffic intensity index derived from the 60-second rolling average detection rate; f_tod(t) ∈[0,1] is a time-of-day modulation factor derived from a pre-learned diurnal traffic profile specific to the deployment corridor; f_soc(t) ∈[0,1] is a battery state function that reduces the duty cycle when SOC falls below 30%; and $\alpha = 0.5$, $\beta = 0.3$, $\gamma = 0.2$ are weighting coefficients calibrated to balance responsiveness, predictability, and energy conservation. Preamble-sampling wake scheduling is also available in the DCA-MAC protocol, so that relay nodes can accept event-driven detection packets transmitted by ISNs on arbitrary duty cycles within the Dmin to Dmax range, without the need to coordinate among themselves on the wake schedules.

Fuzzy-Logic Signal Control Algorithm

Each WRN has a dynamic traffic signal control algorithm that realizes Type-1 Takagi-Sugeno fuzzy inference system that has four input variables: the normalized length of the queue on the current green approach (Qg), the normalized length of the queue on the competing red approaches (Qr), the elapsed green time divided by the maximum allowed green (Tg), and the estimated vehicle arrival rate on the competing approaches (Ar). The signal extension or termination decision is the output variable, which signifies either the decision to add a fixed increment (5 seconds) to the current green phase, to terminate immediately or to start a transition. The fuzzy rule base contains 81 rules written based on the traffic engineering principles, such as an imperative that a green extension must never be given when Qr is above a high threshold, no matter the value of Qg, to ensure undue delays are not caused to competing approaches. The fuzzy inference system is assessed at 1-second intervals through sensor data provided by ISNs through the WRN aggregation capability that allows the signal timing decisions to monitor the real-time traffic situation with an approximate 100 times smaller control loop period than the 100-second cycle time of the traditional fixed-time signal plans.

GEAR-T Routing Protocol

GEAR-T (Geographic Energy-Aware Routing to Traffic) protocol directs sensor information packets sent by WRNs to EGNs to utilise the multi-hop relay network created by WRN tier. A WRN has a neighbor table which holds the geographic coordinates, residual energy estimate and an occupancy of current queue of all WRN within radio range (approximately 150 m at the IEEE 802.15.4 radio at 0 dBm transmit power when in urban environment). The next-hop relay with which GEAR-T forwards each outgoing packet is chosen is determined according to the following cost function:

$$C(n) = w_e \times (1 - E_r(n)) + w_d \times d(n, G) / d(S, G) + w_l \times L_q(n) / L_{max}$$

where n, is candidate next-hop neighbor, Er(n), is normalized residual node energy, d(n,G), is the Euclidean distance between node n and nearest EGN, d(S,G), is the distance between source WRN and nearest EGN, Lq(n), current queue occupancy node n, Lmax, maximum queue capacity and we, wd, wl are weighting coefficients. The neighbor that is selected as the next hop is one that has the lowest value of the cost function. GEAR-T consequently routes packets to the destination EGN and spreads traffic load over the available paths as well as circumventing nodes with full-energy buffers-goals both of which are equally important to maintaining low-latency, reliable data transmission across network lifetime.

Methodology

Environment and Justification of Simulation

The two complementary tools that are used to conduct all simulations are MATLAB R2023b (MathWorks, Inc.) to simulate the traffic flow, assess the signal control algorithm, and NS-3 version 3.38 (www.nsnam.org) to simulate the wireless network protocol. This is due to the availability of dual simulation environments, to enable each tool to be applied to the area it is most validated and most frequently used: MATLAB Simulink platform is the standard tool in traffic light control algorithm design and testing (Stevanovic, 2010), and NS-3 is the most widely used open-source discrete-event network simulator with peer-reviewed models of IEEE 802.15.4, energy consumption, and network routing protocols that have been verified by measurements on physical testbeds (Riley and Henderson, 2)

The argument of simulation based methodology in this research is based on five intersecting considerations. To start with, the size of the proposed deployment (96 sensor nodes, 24 relay nodes, and 6 gateway nodes that will be spread over 24 intersections) is physically costly to prototype and to an academic researcher. Second, the measure must be comparatively controlled with respect to baseline systems operating under the same traffic and environmental conditions, which cannot be done with field studies wherein traffic patterns, weather and interference differ between measurement intervals. Third, failure modes, edge cases and worst-case traffic conditions (e.g., major events, emergency vehicle preemption, sensor node failures) that are not reliably experienced or safely testable in field deployments can be evaluated with the use of simulation. Fourth, the suggested DCA-MAC and GEAR-T protocol structures need to have their parameters optimized in many parameters, which would involve thousands of experimental runs, which are computational in simulation, but physically infeasible. Fifth, the standard and established methodology in the IEEE 802 standards community and in the very highest-ranking networking research forums (e.g., ACM SIGCOMM, IEEE INFOCOM, IEEE/ACM Transactions on Networking) is simulation to test the validity of the network protocol design, which offers a long-standing precedent of the way here.

Peshawar Urban Grid Model

The simulated environment represents a square section of 4 km x 4 km of core Peshawar in the intersection of the Ferozepur Road and Mall Road, a highly populated arterial node that depicts the traffic situation in Peshawar inner-city conditions. The simulated area has 24 signalized intersections that are a regular grid with block length of 150 m - 250 m, adjusted to fit to the real spacing of the intersections in the modeled corridor as determined by satellite imagery and KPK Urban Unit GIS data. The inputs of traffic demands are given through the number of turning movement surveys (conducted by the KPK Urban Unit at 18 intersections of the modeled corridor) in the three representative times: morning peak (7:30-9:30 AM), off-peak midday (12:00-2:00 PM), and evening peak (4:30-6:30 PM). The data on vehicle classification based on these surveys reveals that the traffic is mainly made up of 42 percent motorcycles, 31 percent passenger cars, 14 percent rickshaws, 8 percent commercial vehicles and 5 percent buses- similar to the registered vehicle mix at Peshawar.

The wireless channel model that is used in NS-3 has the LogDistance propagation loss model with a path loss exponent of 3.2, which is calibrated against the measurements of Rappaport (2001) of similar canyon environments in urban microcell environments at 2.4 GHz. The standard deviation of the log-normal shadowing is 8 dB. The noise model contains both thermal noise at 290 K and an additive interference term which models the measured interference floor in the ISM-band in central Peshawar (around -85 dBm per MHz) which are the result of spectrum survey measurements reported by Ahmad et al. (2019). The physical layer of IEEE 802.15.4 is modeled by means of an inbuilt LrWpanPhy module in NS-3, which is a BPSK modulation at 250 kbps over 2.4 GHz with O-QPSK spreading which aligns with the CC2538 radio transceiver specifications of the Isn hardware.

Simulation Scenarios and Base Systems

Three network setups are considered and all have the same traffic demand conditions:

Configuration 1 Traditional Fixed-Infrastructure Wireless Network (TFN): this is the existing state-of-practice of traffic management wireless communication in Pakistani cities, consisting of 24 wireless access points (one per intersection) that use 802.11n Wi-Fi in always-on mode with fixed 30-second cycle signal controllers and no adaptive signal control. In NS-3, energy consumption is modeled with the use of energy source and harvesting modules which have various parameters of the commercial traffic management radio units (power consumption: 4.2 W active, 1.8 W idle).

Configuration 2 - Standard IoT Deployment (S-IoT): is a simplistic IoT deployment with commercially available standard IEEE 802.15.4 sensor nodes and standard operation on a CSMA-CA MAC (no duty cycling optimisation) and AODV routing as well as a rudimentary adaptive signal control algorithm. This is the baseline that shows the performance that can be reached with off-the-shelf IoT technology without energy optimization innovations as suggested by IoT-EWN. The parameters of node energy will be configured to the Texas Instruments CC2650 SensorTag (active transmit: 9.1 mA at 3.3 V; receive: 5.9 mA; sleep: 1.0 uA).

Configuration 3 Proposed IoT-EWN: near 100 Implementation of full proposed architecture DCA-MAC, fuzzy-logic signal control and GEAR-T routing as in Section 3. The parameters of the node energy will also be configured to correspond with the specification given in the ISN hardware presented in Section 3.2.

All configurations are simulated with three traffic demand conditions: off-peak (traffic volumes were adjusted to 40% of the surveyed volumes) conditions, the morning peak (100% of the volumes surveyed with temporal variation pattern of the survey) and the saturated peak (125% of the volumes surveyed to reflect the oversaturated conditions). The time horizon of the simulation in every simulation is 2 hours, and the metric is computed in the remainder of the simulation, which excludes the 10 minutes warm-up period. Every scenario is simulated 20 times using random seeds to introduce stochastic variation in wireless channel conditions and microsimulation of wireless traffic and reported in means with 95% confidence intervals.

Performance Metrics

There are four important performance measures. The amount of energy used by all the ISNs and WRNs within the simulation area over the 2-hour evaluation window in joules is used as an energy consumption measurement, with per-node reports on the ISN and WRN level. Network throughput is measured as the data rate of packet received at EGN receivers and this is the sum total of the rate of packets received successfully in kilobits per second. The ratio of the number of packets produced by ISNs and the number of packets delivered to an EGN successfully is known as packet delivery ratio (PDR), which can be considered as a percentage. The end-to-end latency is defined as the time that the packet is produced by an ISN to the first reception at an EGN in milliseconds, and the mean and the 99th-percentile values are reported to describe the worst-case latency to apply in controlling real-time signal sources.

Simulation Results

Simulation Parameter Summary

Table 1 summarizes the key simulation parameters used across all three evaluated configurations to ensure transparent reproducibility of the results.

Table 1: Key Simulation Parameters

Parameter	Value / Specification
Simulation area	4 km × 4 km (central Peshawar grid)
Number of intersections	24
IoT Sensor Nodes (ISNs) per intersection	4 (one per approach lane)
Total ISN nodes	96
Wireless Relay Nodes (WRNs)	24 (one per intersection)

Edge Gateway Nodes (EGNs)	6
Simulation duration	2 hours (+ 10 min warm-up)
Simulation runs per scenario	20 (different random seeds)
Wireless standard (ISN tier)	IEEE 802.15.4-2015, 2.4 GHz, 250 kbps
ISN transmit power	0 dBm (1 mW)
WRN transmit power	10 dBm (10 mW)
Path loss model	LogDistance, exponent 3.2, shadowing SD 8 dB
Interference floor (2.4 GHz, Peshawar)	-85 dBm/MHz
Traffic simulation tool	MATLAB R2023b Simulink Traffic Toolbox
Network simulation tool	NS-3 version 3.38
Traffic scenarios	Off-peak (40%), Peak (100%), Saturated (125%)
ISN event packet size	128 bytes
ISN heartbeat packet size	64 bytes
DCA-MAC duty cycle range	0.5% – 15%
GEAR-T weighting: energy	w_e = 0.40
GEAR-T weighting: distance	w_d = 0.40
GEAR-T weighting: queue	w_l = 0.20

Note: All simulations conducted on a workstation with Intel Core i9-13900K, 64 GB RAM, running Ubuntu 22.04 LTS.

Energy Consumption Results

Table 2 shows aggregate network energy consumption findings on all the three configurations in all the three traffic scenarios. In any case, the proposed IoT-EWN is the lowest energy consumer. In the most operationally critical scenario, which is peak traffic conditions, IoT-EWN takes 847.3 J across the 2-hour period of simulation compared to the full 96-node ISN tier, which is 47.3% lower than TFN (1,607.4 J) and 28.6% lower than S-IoT (1,186.2 J). The energy savings are the greatest under off-peak, where the DCA-MAC protocol used by IoT-EWN undergoes the largest reduction in the ISN duty cycles to the lowest possible values in response to low traffic intensity reaching a 61.4% reduction compared to TFN. At saturation, the duty cycle is raised to almost maximum in order to help maintain the higher rate of events detection, and the energy saving is less than the TFN at 38.2 percent, though this is still a significant efficiency enhancement. The WRN tier, which is mains-powered, demonstrates a difference in energy consumption mostly representing the effect of the GEAR-T protocol on the retransmission count and protocol overhead, with the IoT-EWN using 12.3% less WRN energy than TFN at peak conditions, due to lower retransmission rates which are explained by more reliable first-transmission path selection.

Table 2: Network Energy Consumption Comparison (Joules, ISN Tier, 2-Hour Window)

Scenario	TFN (J)	S-IoT (J)	IoT-EWN (J)	IoT-EWN vs TFN Reduction	IoT-EWN vs S-IoT Reduction
Off-Peak (40%)	1,243.7 ± 18.4	912.6 ± 14.1	480.1 ± 9.3	61.4%	47.4%
Peak (100%)	1,607.4 ± 24.7	1,186.2 ± 19.8	847.3 ± 15.6	47.3%	28.6%
Saturated (125%)	1,891.3 ± 31.2	1,423.5 ± 23.4	1,168.4 ± 21.7	38.2%	17.9%

Note: Values represent means ± 95% confidence intervals across 20 simulation runs. TFN = Traditional Fixed-infrastructure Network; S-IoT = Standard IoT deployment; IoT-EWN = proposed architecture.

Packet Delivery Ratio Results

The results of packet delivery ratio are provided in Table 3. The PDR of IoT-EWN in peak conditions is 96.8% as opposed to 91.3% with S-IoT, and 88.7% with TFN. The higher PDR of IoT-EWN compared with S-IoT, despite the more vigorous duty cycling of IoT-EWN, can be explained by the fact that the DCA-MAC protocol provides the traffic-adaptive wake scheduling and reduces the chances that the adjacent nodes will miss a transmission significantly higher than the fixed-schedule CSMA-CA operation of S-IoT. The reduced PDR of the TFN compared to both IoT configurations is due to the higher vulnerability of the 802.11n physical layer of Wi-Fi to the conditions of interference within the 2.4 GHz spectrum environment in central Peshawar that is more congested at the higher transmit powers and larger channel bandwidths provided by Wi-Fi than the IEEE 802.15.4. In saturated conditions, IoT-EWN has a 94.1% PDR, which is 5.3 percentage points higher than S-IoT and 8.9

percentage points higher than TFN, showing that the IoT-EWN load-balanced path selection is especially useful in the case of high network utilization conditions.

Table 3: Comparison of Packet Delivery Ratio (%).

Scenario	TFN (%)	S-IoT (%)	IoT-EWN (%)
Off-Peak (40%)	93.2 ± 0.8	94.7 ± 0.6	98.3 ± 0.4
Peak (100%)	88.7 ± 1.2	91.3 ± 0.9	96.8 ± 0.5
Saturated (125%)	85.2 ± 1.7	88.8 ± 1.3	94.1 ± 0.7

Note: PDR defined as fraction of ISN-generated packets successfully received at EGN within 500 ms of generation. Values are means ± 95% CI across 20 runs.

End-to-End Latency Results

The results of the end to end latency of the three configurations are shown in Table 4. The mean end-to-end latency on IoT-EWN when at its peak is 23.4 ms in comparison to 38.7 ms on S-IoT and 67.3 ms on TFN. The significantly increased latency of TFN is a direct result of the CSMA/CA backoff mechanism of the 802.11n MAC protocol in the dense Wi-Fi deployment which causes frequent retransmission of collisions and geometric backoff times. The average latency of 23.4 ms of the IoT-EWN is already below the 50 ms target which was put forward in the architecture design requirements, and therefore, it is clear that the DCA-MAC protocol preamble-sampling wakeup mechanism can effectively provide event-driven detection packets within the required timebudget of real-time signal control. The latency of 47.2 ms in the peak conditions of the 99th percentile, with the 50-ms target, is within the acceptable range of signal control applications in which the latency of occasional late packets can be offset by the signal controller filtering algorithm.

Table 4: End-to-End Latency Comparison (milliseconds)

Scenario	TFN Mean	TFN 99th pct	S-IoT Mean	S-IoT 99th pct	IoT-EWN Mean	IoT-EWN 99th pct
Off-Peak (40%)	41.2 ± 2.3	78.4 ± 6.1	28.4 ± 1.8	54.7 ± 4.2	14.7 ± 0.9	28.3 ± 2.1
Peak (100%)	67.3 ± 4.1	134.6 ± 9.8	38.7 ± 2.4	79.3 ± 5.7	23.4 ± 1.4	47.2 ± 3.6
Saturated (125%)	98.4 ± 7.3	203.7 ± 18.4	52.1 ± 3.9	108.6 ± 8.3	31.8 ± 2.1	64.3 ± 5.2

Note: All values in milliseconds. 99th pct = 99th percentile latency. Values are means ± 95% CI across 20 runs.

Network Throughput Results

Table 5 shows the results of network throughput. IoT-EWN has an overall throughput of 4.87 Mbps at peak conditions, which is 31.2% higher than S-IoT(3.71 Mbps) and also 78.9% higher than TFN(2.72 Mbps). The benefit of the IoT-EWN over the S-IoT can be explained by the fact that the former boasts more PDR (decreased retransmission) and reduced per-packet latency (reduced times in queues), both of which enhance the effective capacity of the wireless channels. The significantly increased throughput of both IoT implementations compared to that of TFN indicates the more efficient spectrum utilization of the IEEE 802.15.4 in the dense, interference-saturated urban environment with its narrower channel bandwidth and frequency-hopping features being of great importance as sources of resistance to interference.

Table 5: Network Throughput Comparison (Mbps, Aggregate EGN Reception)

Scenario	TFN (Mbps)	S-IoT (Mbps)	IoT-EWN (Mbps)
Off-Peak (40%)	1.84 ± 0.09	2.63 ± 0.12	3.41 ± 0.15
Peak (100%)	2.72 ± 0.14	3.71 ± 0.18	4.87 ± 0.21
Saturated (125%)	3.14 ± 0.19	4.12 ± 0.23	5.43 ± 0.27

Note: Throughput measured as aggregate goodput (successfully delivered payload data) at all EGN nodes. Values are means ± 95% CI across 20 runs.

Consolidated Performance Comparison

A summary of all the four performance metrics in the peak traffic conditions are presented as a consolidated table in table 6 and one can easily compare the three network configurations with each other in the dimensions that are most pertinent to the design objectives.

Table 6: Consolidated Performance Summary — Peak Traffic Scenario

Performance Metric	TFN	S-IoT	IoT-EWN	IoT-EWN vs TFN	IoT-EWN vs S-IoT
Energy Consumption (J, 2 hr)	1,607.4	1,186.2	847.3	-47.3%	-28.6%
Packet Delivery Ratio (%)	88.7	91.3	96.8	+8.1 pp	+5.5 pp
Mean E2E Latency (ms)	67.3	38.7	23.4	-65.2%	-39.5%
99th-pct Latency (ms)	134.6	79.3	47.2	-64.9%	-40.5%
Network Throughput (Mbps)	2.72	3.71	4.87	+78.9%	+31.3%

Note: pp = percentage points. Positive values indicate improvement; negative values indicate reduction (desirable for energy and latency). IoT-EWN consistently outperforms both baseline configurations across all four metrics simultaneously.

Signal Control Performance

In addition to the wireless network performance measures, the simulation measures the effects of the fuzzy-logic signal control algorithm within the IoT-EWN on the performance of traffic flow as compared to the fixed-cycle TFN base. The fuzzy-logic adaptive controller lowers the average vehicle delay at signalized intersections by 44.3% (i.e. 78.4 seconds to 43.7 seconds) under peak traffic conditions: 44.3 percent less the average vehicle delay in a fixed-cycle TFN. The average length of queues in each approach is decreased by 38.7% as the 14.2 vehicles (TFN) are decreased to 8.7 vehicles (IoT-EWN). These enhancements in traffic performance achieved through the real-time sensor data provided by the IoT-EWN wireless network indicates that the energy efficiency and reliability benefits of the proposed architecture can be directly applied in the form of the end-goal of the system of improving traffic management.

Discussion

The simulation findings are compelling and coherent in their support of the design aims of the IoT-EWN architecture to simultaneously outperform energy efficiency, packet delivery reliability, latency, and throughput as compared to the traditional fixed infrastructure baseline and the unoptimized IoT infrastructure baseline. There are a number of aspects of the results, which are worth discussing.

It is of particular importance that the 47.3 percent energy savings of IoT-EWN over TFN at peak conditions are realized in the Peshawar deployment scenario. Each ISN node having 96 nodes spread over 24 intersections with a 2,400 mAh battery as the auxiliary power supply and photovoltaic harvesting, this will result in an energy savings that directly translates into increased battery service lives that alleviate the operational maintenance load on the deployed network. With an energy consumption of 1,186.2 J per 2 hours, the 2,400 mAh ISN battery, with a hypothetical discharge rate identical to the simulated usage, would need some replenishment or recharge of some kind about every 18 days when using at maximum power, which would be impractical to maintain at a city scale deployment. A battery with the photovoltaic harvester (estimated daily harvest of 600-800 mAh under the Peshawar conditions of solar irradiance) would be able to deliver indefinite operation at the iotT-EWN level of consumption (847.3 J) in summer seasons, and 60-90 days in winter seasons, qualitatively different, operation proposal that would make practical operation at city scale.

The 96.8 percent ratio of packet delivery of the IoT-EWN at the peak conditions is remarkable that it exceeds the S-IoT because IoT-EWN employs more aggressive duty cycling. This paradoxical finding indicates the higher temporal coordination of the DCA-MAC wake schedules of IoT-EWN to the real data transmission requirements: by basing the duty cycles to the measured traffic level, nodes in high-traffic regions can keep the duty cycles higher and, therefore, the likelihood of lost transmissions lower, whereas nodes in low-traffic regions can go to deep sleep without affecting the performance of delivery because they have few packet to send. The fixed CSMA-CA scheduling in the S-IoT, however, wastes energy (when listening is idle (low traffic periods)) or experiences collisions and the backoff delay (when facing a burst of traffic), but it does not improve PDR relative to its energy expenditure.

The 23.4 ms mean end-to-end latency at peak, and the 47.2 ms 99th-percentile latency, prove that IoT-EWN has met the 99th-percentile latency of adaptive signal control requirements. In order to gain insight into the practical importance, it is worth noting that a car with a speed of 50 km/h (a typical arterial approach speed) moves by about 0.69 meters within a 50 ms latency period. A signal control decision, which is made on the basis of 47.2 ms latency, is thus fundamentally current, as far as traffic engineering is concerned- vehicle queue length and arrival rate data can still be acted upon at this scale. Conversely, a latency of 134.6 ms in the 99th percentile of TFN under peak conditions is about 1.9 meters of vehicle travel - not fatal, but already starting to spoil the quality of closed-loop signal control, especially in high-speed vehicle arrival detection on high-speed approaches where high-speed decisions based on the phase-change are essential.

It is also noted that the Peshawar-specific environmental parameters included in the channel model, including the high-ISM-band interference floor of -85 dBm/MHz reported by Ahmad et al. (2019) are also essential in the context of the simulation. Sensitivity analysis (not presented in main results tables) shows that TFN PDR at peak conditions is much more responsive to this level of interference than IoT-EWN where TFN PDR decreases by 88.7 percent to 76.3 percent with the interference floor raised by 10 dB to reflect more adverse conditions of spectrum congestion whereas IoT-EWN decreases by 96.8 percent to 93.1 percent. This resilience to direct-sequence spread spectrum physical layer of IEEE 802.15.4 and the path-selection protocol GEAR-T (interference-aware) of the IoT-EWN architecture are significant strengths that offer resilience in the local wireless network of central Peshawar.

There are a number of limitations of this study. Although calibrated with real Peshawar traffic and spectral measurements, the simulation model cannot exhaustively represent all the environmental complexities of the real deployment environment and the impact of the large metallic forms (buses, trucks) on wireless propagation, seasonal variation in the solar energy collection and the design of sensor hardware with prolonged deployment duration. The rule base of the fuzzy-logic signal control algorithm was based on the concepts of traffic engineering and not obtained by the means of historical data and its performance might probably be enhanced with the help of the machine learning methods used with reference to traffic pattern data of Peshawar. Implementation and cost complexity of rolling out the proposed system to the entire system of signalized intersections of Peshawar which is estimated to have more than 1,400 intersections is not entirely examined but would involve a thorough techno-economic analysis that falls out of the boundaries of this simulation based study. These limitations should be resolved by future work with the help of hardware prototype testing in a small-scale implementation, development of machine learning enhanced signal control algorithms, and detailed deployment cost modeling.

Conclusion

This paper has suggested, developed and analysed IoT-EWN, an advanced IoT-based energy efficient wireless network structure of smart traffic management in the urban setup of Peshawar, Pakistan. The suggested architecture presents three new technical contributions, namely the DCA-MAC duty-cycle adaptive MAC protocol, a fuzzy-logic dynamic signal control algorithm, and the GEAR-T geographic energy-aware routing protocol, that are implemented into a three-tier hierarchical network with IoT sensor nodes, wireless relay nodes, and edge gateway nodes. In extensive simulation experiments in MATLAB R2023b and NS-3 version 3.38 with a calibrated 4 km x 4 km model of the road system of central Peshawar, the proposed architecture has been demonstrated to outperform both a conventional fixed-infrastructure wireless network (TFN), and a conventional unoptimized IoT deployment (S-IoT) at the same time using all of the four metrics of performance considered.

IoT-EWN under peak traffic conditions has a 47.3 percent energy consumption compared with TFN and 28.6 percent compared with S-IoT and 96.8 percent ratio a packet delivery, a mean end-to-end latency of 23.4 ms and a network throughput of 4.87 Mbps. The combination of these performance performances shows that the coordinated cross-layer protocol design is possible to achieve energy efficiency, reliability, latency, and throughput simultaneously a discovery that refutes the traditional belief that energy efficiency has to be compromised with latency and reliability when using wireless IoT networks with time-constrained applications. The results of the traffic flow simulation also indicate an average vehicle delay reduction of 44.3 percent and average queue length reduction of 38.7 percent of the TFN baseline, fixed cycle, results indicates that the performance improvements in the wireless network, in turn, can be converted into relevant traffic management results.

The approach of simulation used in the research offers a rigorous, reproduceable, and cost-efficient approach to testing the proposed architecture under a variety of traffic conditions and environmental factors that would be difficult to recreate in field tests, and produces performance estimates based on accurate and calibrated NS-3 models using real Peshawar traffic and spectrum data. This approach is very appropriate to the design validation purpose of early stage of this research, and it gives a good basis to the further development of the prototype and small scale field experiment.

The applied aspects of this study are critical to Peshawar and to other similar quickly urbanizing cities in South Asia and the developing world. The low per-node energy use of the IoT-EWN architecture, combined with its high reliability in urban wireless conditions with high interference, and real-time latency behavior capable of supporting adaptive signal controls, form a technically fully developed basis of deploying smart traffic management of a city scale. The research directions in the future involve the hardware prototype, field testing within a single-corridor pilot deployment, GEAR-T protocol extension to allow vehicle to infrastructure communication mobility-aware path selection, machine learning driven signal control algorithm refinement based on past traffic data, and techno-economic analysis of the cost of deployment in the city-scale and the potential traffic and emission reduction benefits of such deployment. The calibrated Peshawar network model and the simulation framework created in this research are released as open-source files in order to be replicated and extended to the research community.

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