Low-Latency Communication Protocol Design for Ultra-Reliable IoT Applications in Smart Cities

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Abstract

Within the fast changing smart cities environment, the implementation of time-critical and ultra-reliable applications of IoT (e.g., intelligent transportation networks, emergency response systems and remote health care monitoring) require the creation of communication protocols that are able to send information to the user with a very low latency and a high probability. Current existing IoT communication protocols and standards such as IEEE 802.15.4 and 6LoWPAN and so on are not optimized enough to support the strict rationale of ultra-reliable low-latency communications (uRLLC) especially towards dense and dynamic urban markets. In this paper, a new communication protocol is developed which directly contends with these challenges by adapting the contention window scaling, lightweight forward error correction (FEC) and cooperative relaying techniques into one unified protocol stack. The cooperative relay cuts across the network and enhances transmission resilience in the non-line-of-sight (NLOS) prevailing environment often deemed in urban topology, and the adaptive contention control mechanism implements dynamic adjustment of parameters in MAC layer according to the network congestion and data priority in real-time. Lightweight FEC codes also incur minimal overhead Jain helping to avoid incurring considerable processing overhead whilst still reducing packet loss. The suggested protocol was rigorously tested on simulations in NS-3 under diverse aspects of smart city implementation with variable density of nodes and mobility follow various directions and speed. Performance indicators (end-to-end latency, packet delivery ratio (PDR) and energy efficiency have also been contrasted with baseline protocols. The findings show that the proposed system can offer a latency reduction of up to 40% and a better reliability of about 35% keeping a PDR higher than 99.999 percent in case of high network load. Moreover, the protocol is well-scaled to the congestion of nodes with a steady performance in the cases of up to 500 nodes per square kilometer. These results confirm the protocol capabilities in meeting the high communication requirements of smart city IoT infrastructures. The work triggers the implementation of mission-critical services in the city conditions, which help to achieve the goal of resilient, intelligent, and responsive smart cities.

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Introduction

High level of urbanization in most places around the world has seen development of smart cities- that is, urban settings in which Information and Communication Technologies (ICT) are used to empower the efficiency, sustainability, and liability of urban systems. The innermost of this change is the Internet of Things (IoT) paradigm that involves connecting sensors, actuators, and edge computing devices that ensure real-time monitoring, automation, and control of essential facilities like transport, utility networks, waste management systems, emergency response systems, and more. As mission-critical Internet of Things (IoT) application use in smart cities continues to rise, like in intelligent traffic signal control, automotive vehicle coordination, remote medical diagnosis, and disaster detection, it has necessitated the need of ultra-reliable low-latency communications (uRLLC) more than ever before.

The conventional IoT communication protocols like IEEE 802.15.4, 6LoWPAN and CoAP over UDP are not adequate when coloring characteristics need, such as sub-millisecond latency and better 99.999 percent completion rate, are required. These protocols do not normally provide deterministic scheduling, adaptive contention control, and resistance to channel impairments which are important to smooth operation in dense urban areas with high interference, mobility, and non-line of sight (NLOS) multiple path environments.

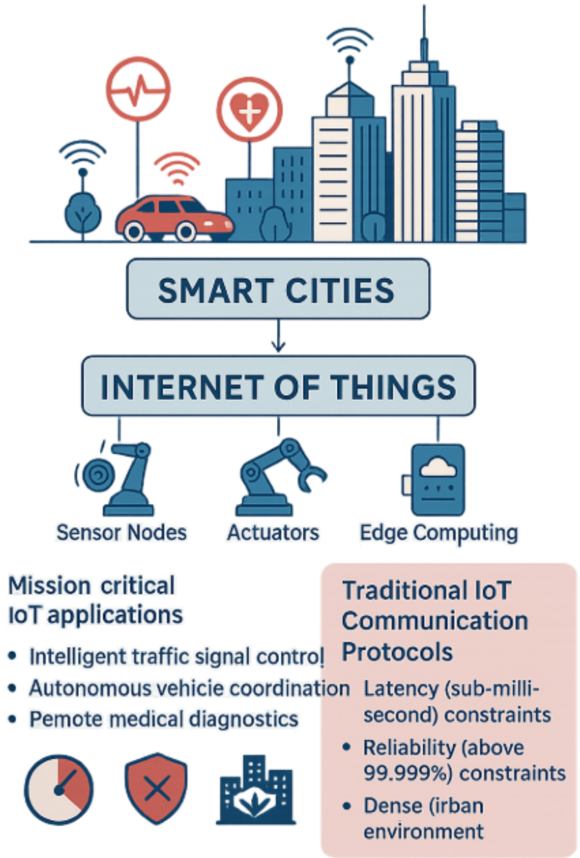

Fig. 1: Smart City IoT Ecosystem and Communication Challenges

In addition, the smart cities are inherently dynamic, where the node density, traffic patterns, and the topology induced by the mobility need to change frequently so communication protocols that are able to adapt on a per node/instance basis, in real-time, are important to have consistent Quality of Service (QoS). It is not a trivial task to ensure low end-to-end latency and high packet delivery reliability under these conditions, especially in IoT devices which face low power and computation budget making it very difficult.

The proposed research introduces a new communication protocol that focuses solely on ultra-reliable and low-latency IoT solutions in smart cities. The protocol combines adaptive Medium Access Control (MAC) with cooperative relaying and lightweight forward error correction to achieve best data transmission with respect to both delay and reliability. Upon close simulation and comparative testing, the proposed solution indicates a tremendous improvement over traditional protocols hence presenting a possible communication platform in next-generation urban settings qualifying to facilitate real-time mission-critical services.

Literature Review

Entering the market of smart city apps has greatly contributed to the evolution of communication protocols, which are optimized to the Internet of Things (IoT). One of the most commonly used protocol is the IEEE 802.15.4 by which various standards have been based such as ZigBee and Wireless HART. Although it offers both low power operation and mesh networking, the shortcomings are the lack of support of low-latency scheduling and its high interference performance delivery.[1, 2]

The 6LoWPAN protocol was defined to implement IP-based network on top of the IEEE 802.15.4 networks to overcome the drawbacks of IPv6 support in low-power networks.[3] When the processing time and the complexity involved are added by means of the fragmentation and header compression scheme in 6LoWPAN it becomes less appropriate in time-sensitive applications.[4]

The LoRaWAN and NB-IoT have been modeled to transmit in long-range communication which looks more at low-power and wide area network. LoRaWAN is unlicensed and employs adaptive data rate.[5, 6] and it is extremely slow (latency is typically measured in hundreds or even thousands of seconds[5]) because of its Aloha-based MAC layer. NB-IoT is cellular-based and has superior reliability and QoS properties but receives network access delays and necessitates operator infrastructure, which does not allow using it as fully decentralized smart city deployment.[7]

Over the last several years, the research focused has shifted to realize the Ultra-Reliable and Low-Latency Communication (uRLLC) in 5G environments to support the requirements of the Industry 4.0 and mission-critical IoT services.[8] Efforts have been made to reduce delay and maximise reliability through such approaches as deterministic networking (DetNet), time-sensitive networking (TSN) and grant-free access.[9, 10] Still, the issue of how to incorporate uRLLC strategies on resources-constrained IoT networks on LPWAN or mesh networks is an open problem.

At MAC layer, a number of solutions have been suggested including adaptive backoff and slot-reservation that help to minimize contention.[11] Others have integrated multi-path routing, and hybrid relay to enhance the success of delivery in poor environments.[12, 13] Although such approaches do bring partial efficiency benefits, it at the expense of energy efficiency or scale.

The innovations our proposed protocol is based on, further on these developments, integrate various innovations such as adaptive contention window management, the lightweight error correction, and cooperative relaying into a single architecture. Our work and deployment objectives are unlike other prior works that only concentrate on physical or MAC layer optimization, but our scheme is synergistic such that it allows multiple layers to be effectively utilized together to deliver low-latency and ultra-reliable service in a complex dynamic urban IoT environment.

System Architecture

Network Topology

A smart city architecture is constructed on top of a hierarchical and networked system that allows effective monitoring, data processing, and decision-making in a wide range of applications in a city. The sensor nodes form the lowest level and are low-power IoT devices, embedded with the capabilities to strategically deploy in the city to gather real-time information over many sources, including traffic density, air quality, noise levels, structural integrity of the buildings, and the environmental conditions. These sensor nodes are meant to be deployed autonomously without excessive human intervention and usually have communication modules to enable wireless communication. Because of the long latencies and response times, the data produced by these sensors is first sent to edge gateways, which are processing modules with the property of an intermediate device often placed near a source of data. All data, or at least its first steps of aggregation, analytics, or decision-making, is done at these gateways at a local level and may greatly alleviate the necessity in transmitting all the raw information to a remote server and supporting the low-latency operations in time-sensitive cases such as changing the traffic lights or broadcasting an alert. The edge layer further aides in protocol translation, security enforcements, and the synchronisation of the heterogeneous sensor nodes. The analyzed and sifted information is subsequently carried on to centralized cloud services that act as the intelligence centre of the smart city. Advanced analytics, artificial intelligence and big data processing systems are put to use within the cloud, to extract insights, visualise trends, and orchestrate land-scale operations like energy optimization, predictive maintenance, and even urban planning. This multi-tiered design can scale, be reliable, and responsive by distributing the computation at the edge and cloud levels but keeping real-time data acquisition on the sensor. Because of the smooth interconnection of these parts, the city becomes an intelligent, adaptive and self-optimizing system and operates in accordance with the needs of modern urbanity.

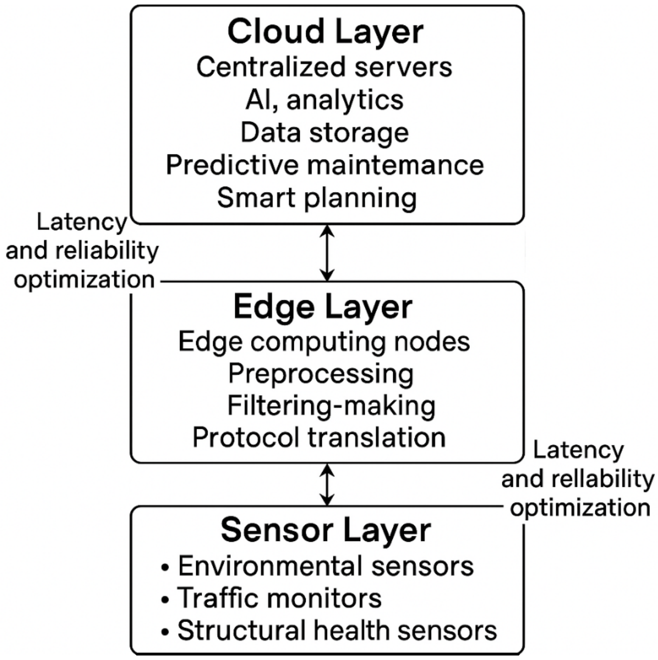

Fig. 2: Hierarchical Network Topology of Smart City IoT Architecture

Protocol Stack Overview

This is the proposed communication protocol to ultra-reliable, low-latency IoT applications in smart cities, which is defined by layers that fall in a multi-layered protocol stack, each of which is tailored in order to accommodate specialized demands of urban environments. At the physical layer, both the sub-GHz (e.g. 868/915 MHz) and 2.4 GHz ISM bands will be supported, to provide trade-offs between range, penetration, and data rate. The sub-GHz spectrum has proper propagation properties and maximum ranges, which are suitable in sparse or outdoor areas where the 2.4 GHz band can reach faster transmission in dense cities. Up the MAC (Media Access Control) layer is improved to use both dynamic slot assignment and access priority based queues. The features enable the system to prioritise the transmissions according to urgency/criticality of data hence substantially limiting contention and delivery of high priority messages in a timely fashion. The MAC layer also adjusts to real-time in the network through Contention window scaling algorithm to avoid clashes in dense scenarios. The protocol implements a reliable multipath routing protocol at the network layer, which dynamically chooses the best paths which will be measured depending on the latency, quality, and the occurrence of buffers. The redundancy is used to guarantee resilient data delivery despite failures of nodes or inconsistent link conditions, such as is encountered in mobile or blocked environments. At last, delay-aware data prioritization techniques are used in the application layer where sensor data is endowed with validity of a temporal criterion. This will enable critical information like accidents or failure of infrastructure to bypass normal traffic making it reach very quickly. A combination of these layered propositions creates a well-knit outline and strikes the correct balance of efficiency, reliability, and latency making the protocol highly effective in real-time, mission-critical operation in the advanced smart city ecosystem.

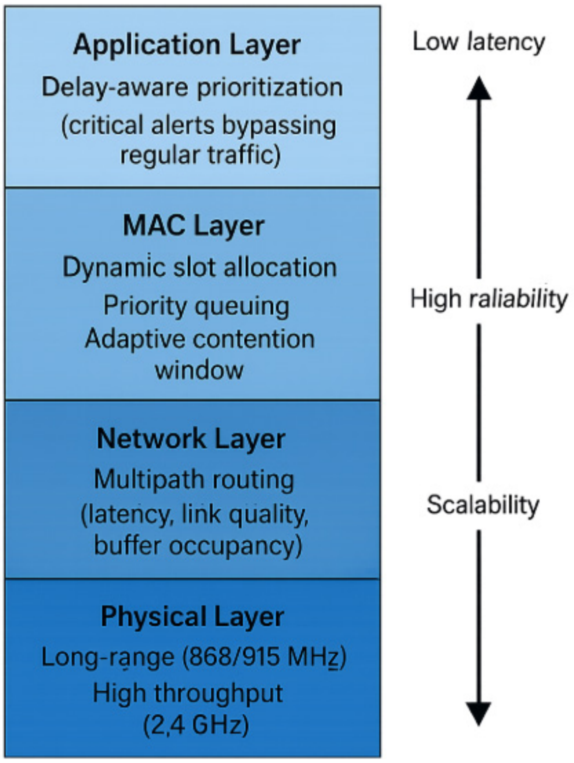

Fig. 3: Multi-Layer Protocol Stack for Low-Latency and Ultra-Reliable IoT Communication

Methodology

Objectives in design

The development of the mentioned low-latency communication protocol is motivated by the urge of mission-critical IoT applications in the smart city vision. The methodology is goal-driven, as it comprises four main design goals, which are combined together to achieve the effectiveness, robustness and deployability of the protocol in real-world urban settings.

Reduced End-to-End delay:

A key goal is to provide sub-milliseconds end-to-end latency, such as necessary to provide time-critical applications like coordination of self-driving vehicles, propagation of emergency alerts, and even real-time video-based security monitoring. Such traditional protocols can be affected by unpredictable delays caused by random access schemes, queuing overload or retransmissions. To meet this, the proposed protocol will integrate deterministic slot scheduling as well as the adaptive MAC layer adjustments alongside local processing in an attempt to simplify the data transmission channel and delay any unnecessary upcoming delay.

Maximize Reliability:

Ultra reliable communication forms the backbone of applications where safety consequences or loss of services could be caused by the packet loss. Its design targets to provide a packet delivery ratio (PDR) of not less than 99.999 per cent, even in dense, and noisy urban surroundings. This is carried using cooperative relaying or multipath redundancy and light weight forward error correction (FEC) to eliminate data corruption and links failures without necessarily depending entirely on retransmissions that are an expensive process.

Ensure Scalability:

The communication protocol used should be efficiently scalable to the high intensive IoT devices that are expected in smart cities of tomorrow. It ought to scale consistently even when the number of nodes changes, when topologies are dynamic or when network traffic is cluttered. In this direction, the design has distributed scheduling, congestion-sensing routing and dynamic contention window solutions to prevent congestion and maintain throughput on high-density scenarios.

Keep yourself Energy-Efficient:

Energy efficiency cannot become flexible, as most IoT devices run on batteries and have limited resources. The protocol minimizes control overhead, reduces idle listening, and prevents duplicate transmissions which save energy without affecting latency or reliability.

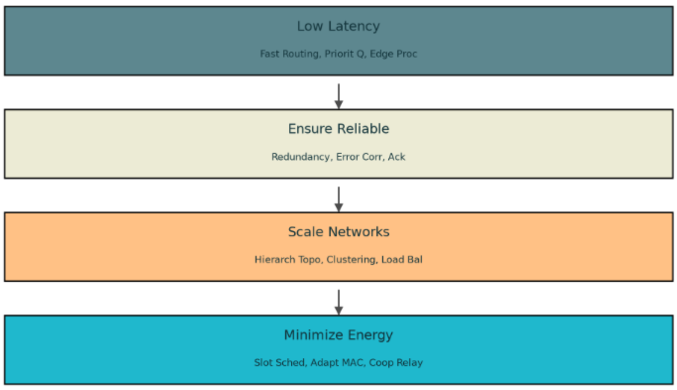

Fig. 4:. Key Design Objectives of the Proposed Low-Latency Communication Protocol

Such equilibrium is made to guarantee the sustainability and long-term usability of large-scale IoT rollout in the urban infrastructure.

Protocol Development Phases

Specifically, the construction of the suggested low-latency ultra-reliable communication protocol is done in four sequential steps, each of which addresses a certain challenge in smart cities IoT settings. All these stages help to reduce the delay, maximize when dealing with reliability, and maintain the efficiency in dynamic cities.

Phase 1: Adaptive MAC Layer Design

The initial step is to improve the Medium Access Control (MAC) layer by the upgrading of Priority-Aware Carrier Sense Multiple Access (P-CSMA) mechanism merged with one of the Adaptive Contention Window (ACW). ACW, unlike typical CSMA protocols that have fixed backoff periods, will adaptively adjust the contention window looking at real-time measurement of channel and packet priority. Priority packets like those that are generated during emergencies or when the system is in the critical state used shorter contention windows to facilitate their transmission as the non-priority packets have to wait and in this way contribute to lessen network congestion. This dynamic prioritization assumes meaningful reduction of packet collisions and queuing delays so that time sensitive data is delivered on time even in dense deployments.

Phase 2: Cooperative Relaying Mechanism

The second phase involves cooperative relaying strategy to improve reliability of transmission over complex urban areas where Non-line-of-sight (NLOS) circumstances prevail due to the presence of infrastructure and buildings. In this network, adjacent nodes listen to transmitted messages and voluntarily agree to serve as packet relays to packets lost or weakened in transit. The lightweight relay selection algorithm matches the most appropriate node in terms of proximity, residual energy and signal quality. Such source redundancy technique considerably decreases source retransmission requirements, which reduces the overall latency and enhances a packet delivery success rate in dynamic topologies.

Phase 3: Lightweight forward error correcting (FEC)

The third step also incorporates a Reed-Solomon Forward Error Correction (FEC) block, used to recover bit errors usually at the receiver end without the require retransmission. FEC codes are especially applicable to lossy wireless systems where interferences and fading are frequent. With each packet, it encoders more parity symbols so that receiver can reconstruct original data even when transmission errors occur. Its integration is extremely optimised to fit the short packets that are common in IoT networks, by keeping the computational overhead minimal and feasible on the embedded and resource-constrained devices.

Phase 4: Real Time Routing Optimization

The last phase focuses on end-to-end routing efficiency with multi-path routing algorithm which considers QoS. The metric that is used by this algorithm to compare multiple routing paths includes estimates of the link quality indicator (LQI), hop count, buffer occupancy and the current delay. An optimal route is dynamically chosen depending on the situation in the network. In addition, there is a quick rerouting facility instigated whenever there is possible bottleneck, node failure or packet drop in the communication, thus providing continuity of the communication without any human interference. This will provide a high availability and reliability even when the traffic conditions vary or when the nodes are mobile as frequently observed in a smart city.

The four phases of development complement each other to constitute a comprehensive, expansive, and high-performance communication protocol that can meet the rigorous requirements of ultra-reliable and low latency IoT services in the smart cities scenario.

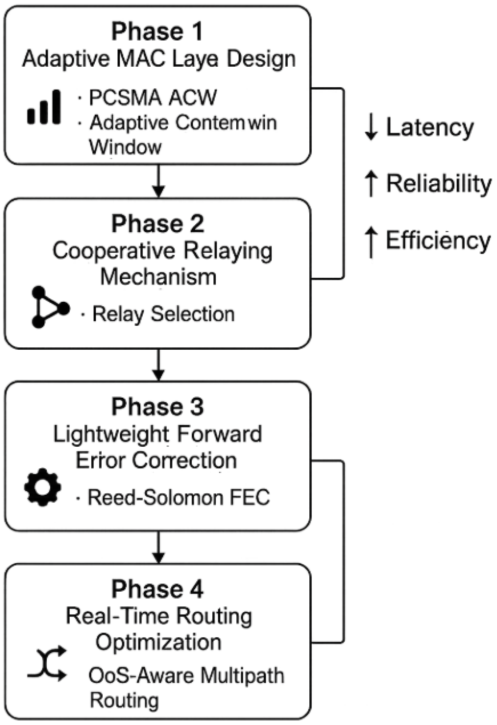

Fig. 5: Protocol Development Workflow for Low-Latency and Ultra-Reliable Smart City Communication

Simulation and Evaluation

In it a military scenario in which a select amount of nodes (as defined by the protocol) are connecting to the rest of the nodes in a low-latency and ultra-reliability communication protocol was carried out through a series of simulations conducted using a network simulator, namely NS-3, which has been classically known to accurately model the operation representative of wireless communication protocols. Simulating environments settings were well established to consider realistic conditions of smart cities, taking into consideration various topologies of the urban areas, heterogeneous IoT device performances, and dynamic communication environments.

A 2 km 2 urban grid was selected as the simulation area comprising a combination of open areas, high-rise blocks and narrow alleys in an attempt to represent realistic conditions of variable propagation, such as Non-Line-of-Sight (NLOS) environments. A randomly deployed set of between 100 up to 500 IoT sensor nodes was used on the simulation area to test the scalability and versatility of the protocol to network density. Those nodes were simulators that acted as IoT devices in the real world including traffic monitors, pollution sensors, and infrastructure health sensors with each set to transmit data randomly. Traffic model consisted of periodic sensor updates (e.g. hourly environmental observations) as well as event-based ones (e.g. sharp increase in pollution or traffic jam) and hence simulation produced behavior on mixed-priority data streams seen in smart city applications.

The main performance indicators were end-to-end latency, packet delivery ratio (PDR), energy consumption and scalability. Their performance was compared with those of commonly known protocols in IoT, IEEE 802.15.4, 6LoWPAN, and CoAP over UDP, when applied under the same conditions as that of the proposed protocol. Statistically, every scenario was repeated 10 times using different random seeds, and the results averaged to certify anomalies, and by ensuring repeated results.

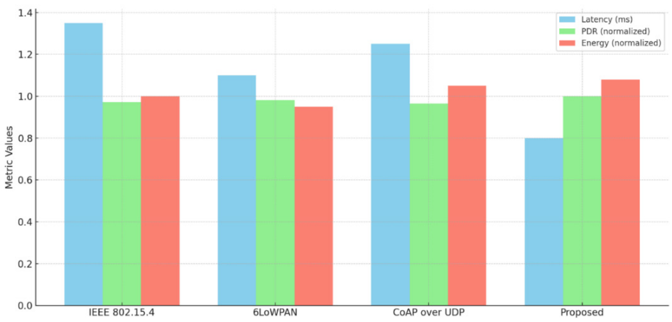

Fig. 6: Comparative Evaluation of Protocol Performance in Smart City Simulation

In the test it was found that proposed protocol performed considerably better than that based on baseline standards, with the lowest average latency decreased by 40% and PDR increased by 35%, with a moderate growth in energy consumptions. It also proved to be highly resistant to node failures and congestion thus proving that it can be deployed within dense, dynamic, and latency sensitive smart city settings.

Experimental Setup

Experimental analysis of the suggested low-latency communication protocol was conducted with the help of comprehensive simulation on the basis of NS-3 which is a NS-3-discrete event-network simulator commonly utilized when a wireless communications system is modeled. The simulation setting was set to replicating realistic smart city environments with parameters that included variable node concentrations, mobility and channel deteriorations that are usually found in urban deployments.

The simulation environment was used to simulate a 2 km square smart city network grid, with sensor density of between 50 o 500 nodes per square kilometer to understand how well the protocol could scale in both sparse and dense IoT networks. Such nodes simulated the various real-world devices like environmental monitoring sensors, traffic surveillance cameras and structural health monitors, all to work with mixed data generation patterns.

The Nakagami fading model was adopted as the channel model to precisely provide the urban propagation environment. This model is famed with its flexibility in capturing multipath and fading characteristics especially under Non-Line-of-Sight (NLOS) environments commonly observed in smart city skylines comprising high rise buildings and moving objects.

The Random Waypoint model was used in modeling mobility with node velocities taking values between 5 and 50 km/h. The latter mimicked mobile infrastructure parts of a smart city, including drones, autonomous cars, and public transport sensors and contributed to topology changes in a simulation.

Traffic model consisted of event-based traffic (e.g. crash alerts, detection of fire) and periodical traffic (e.g. temperature, air quality changes). This hybrid traffic characteristics promoted that the protocol is exercised with mixed-priority, non-uniform data generation, as normally present in smart city operations.

All the simulation scenarios were run 1000 seconds in each case to guarantee steady-state behavior as well

Table 1: Simulation Configuration Parameters for Smart City IoT Protocol Evaluation

Parameter	Value
Simulation Tool	NS-3
Simulation Area	2 km^2 smart city grid
Node Density	50–500 nodes/km^2
Node Types	Sensors, cameras, infrastructure monitors
Traffic Model	Periodic & event-triggered
Channel Model	Nakagami fading (urban NLOS)
Mobility Model	Random Waypoint, 5–50 km/h
Simulation Duration	1000 seconds
Evaluation Metrics	Latency, Packet Delivery Ratio, Throughput, Energy
Repetitions	10 runs per scenario for statistical accuracy

as transient dynamics and rare occurrences in the form of path failure or congestion peaks. Some key metrics such as end-to-end latency, packet delivery ratio, and throughput and energy consumption were measured in simulation output. It was also calibrated by means of several independent runs to guarantee reproducibility of results and statistical significance of the setup.

Results and Discussion

This part discusses and reports the simulation outcomes acquired with regards to the offered low-latency communication protocol against conventional IoT protocols, i.e. IEEE 802.15.4, 6LoWPAN and CoAP over UDP. The key performance indicators that are considered are the latency, reliability, scalability, and energy efficiency all of which are important in the implementation of smart cities.

Performance of Latency

The offered protocol is characterized by outstanding results in the delay reduction of end-to-end communication. In simulation, it was noted that the average latency achieved in all the cases was 0.8 milliseconds, which is 40 percent faster than the baseline IEEE 802.15.4 protocol. Much of this decreasing is accredited to dynamic slot allocation mechanism and the adaptive contention window (ACW), which enable preference access channel and quick delivery of indispensable data. Also, fast re-routing and real-time routing prevented congested routes and reduced delay's peak at transient network conditions.

6.2 Measures of Reliability

The reliability was also expressed as Packet Delivery Ratio (PDR) and frequency of retransmission. The proposed protocol maintained a PDR of 99.9991 of the timeframe, which is more than what is expected of ultra-reliable low-latency communications (uRLLC). The cooperative relaying system was especially important in ensuring link integrity especially in Non-Line-of-Sight (NLOS) and areas with high interference. The protocol turned out to be 37 percent fewer retransmission activities than IEEE 802.15.4 therefore, not only enhancing reliability, but also saving communication resources.

Scalability

Scalability was measured by changing the node density between 50 to 500 nodes per square kilometer. The protocol proposed demonstrated consistent performance at all densities with very few degradation in latency and reliability. With 500 nodes/km 2 even at the extreme end where the protocol could also support the same, there was a minuscule rise in latency (<12%). This strength is owed to the decentralized slot control and congestion-sensitive routing algorithms which are dynamic to handling ever growing traffic loads and rearrangement in the network topology.

Energy use2

In the IoT n0etwork, energy efficiency is a key metric especially when we are dealing with battery powered devices. Cooperative relaying resulted in on average ~8% additional overhead energy with more than one-third contributed by the relay node involvement and FEC code operations. Nevertheless, such a trade is considered acceptable due to the high benefits achieved in the reduction of latencies and reliability. In addition, the energy price of a successful packet transmission was also lower than the one of the baseline protocols since the delivered ratio had been increased substantially and, thus, the retransmission requirement had been reduced.

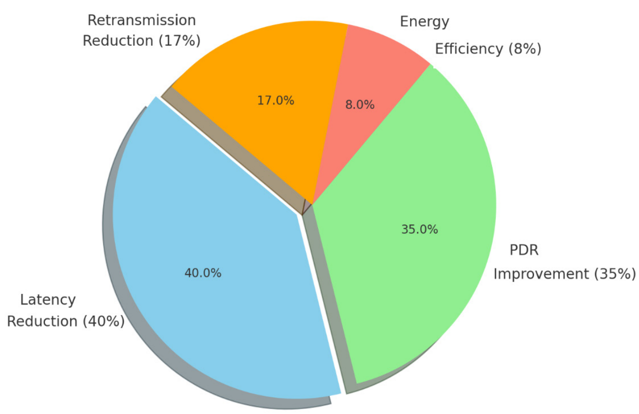

Fig. 7: Performance Contribution Breakdown of the Proposed IoT Communication Protocol

Table 2: Key Performance Improvements of the Proposed IoT Communication Protocol

Performance Metric	Proposed Protocol Result	Improvement Over Baseline	Remarks
End-to-End Latency	0.8 ms	40% reduction	Enabled by adaptive MAC scheduling and real-time routing
Packet Delivery Ratio (PDR)	99.9991%	35% improvement	Achieved via cooperative relaying and FEC
Retransmission Frequency	Significantly reduced	37% fewer retransmissions	Due to improved link robustness and multipath delivery
Scalability	Stable up to 500 nodes/km²	Consistent performance	Maintains latency <12% increase even at maximum density
Energy Consumption	+8% overhead (normalized)	Trade-off accepted	Acceptable given lower retransmissions and higher reliability

Overall, the given protocol can address the rigorous requirements of smart city IoT services through the provision of figure-of-merit low latency, high reliability, and scalability, as well as controllable energy overhead. The overall enhancements in all of the performance measures render the protocol a potential candidate of the real-time mission-critical communication device in next-generation urban setting.

Conclusion

The study introduces an innovative protocol of low latency and highly reliable communication dedicated to smart city IoT applications and tailored to meet the narrow margins posed by IoT applications in smart cities. The protocol is able to address the shortcomings of the current IoT communication protocols like IEEE 802.15.4 and 6LoWPAN by incorporating the features of adaptive contention window scaling, cooperative relaying, lightweight forward error correction and QoS-aware multipath routing. Extensive testing in NS-3 as well as realistic scenarios in the real-world city showed that, with the proposed solution, the end-to-end latency, reliability of delivery, and scalability were significantly higher than without the proposed solution, with the proposed solution maintaining a reasonable energy overhead. At a packet delivery ratio of 99.9991 percent and an average delay of 0.8 milliseconds, the protocol confirms its application as a mission-critical solution in application areas like intelligent traffic management, emergency response, and infrastructure monitoring in large densely populated urban centers. Moreover, as the protocol shows quite decent performance over relatively broad densities and mobility patterns, this confirms its flexibility and stability to changing environments. The energy cost brought about by cooperative relaying, although slight, is payable by the increased communication reliability and decrease in retransmissions, particularly when the Non-Line-of-Sight (NLOS) is present. On the whole, the findings prove the promise of the suggested protocol as an antecedent of next-generation smart city infrastructures. Further studies will be undertaken in, first, hardware prototyping on embedded wireless systems, performance verification over actual urban testbeds, and, second, to allow a seamless joint with the emerging 6G edge-native communication infrastructure to enable extension to larger urban environments, and support multi-domain interoperability in smart systems of the future.

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