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RESEARCH ARTICLE

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Edge-Intelligent Adaptive MAC Protocol for Ultra-Low-Power Wireless Sensor Networks

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Abstract

This paper presents an innovative Edge-Intelligent Adaptive MAC Protocol that will be proposed to achieve the optimal energy efficiency in low power Wireless Sensor Networks (WSNs). Conventional MACs lack the ability to diversify to frequency-varying network characteristics, leading to inefficient energy usage, especially in the WSN that has limited resources. The edge computing solution will be proposed in our solution, making it possible to perform intelligent changes in MAC protocol parameters in real-time real with adaptive duty cycling, transmission power, and schedule changes under local network conditions. The protocol can dynamically adjust to varying traffic conditions, node failures, battery levels by actively using edge devices (e.g., gateways or base stations) without affecting network performance, and using this to achieve better energy efficiency. We show by heavy simulations that the proposed protocol can save up to 70 percent of energy usage, increase the delivery ratio of packets as well as keep the latency low when compared to conventional protocols like TDMA, CSMA/CA, and EE-MAC. This paper will help to develop smarter and more efficient communication protocols to use in energy-constrained WSNs, and the potential areas of application include IoT, environmental monitoring, and industrial automation.

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Introduction

The blistering growth of Internet of Things (IoT) has preconditioned the adoption of the Wireless Sensor Networks (WSNs) in a variety of spheres as environmental surveillance, industrial control, and intelligent cities.[5, 10] Such networks have hundreds or thousands of ultra-low-energy sensor nodes that may be deployed in remote or remote areas, and changing the battery is impractical or potentially unfeasible. This means that energy efficiency is the most important design requirement to guarantee the network life since the life of a node will be directly proportional to its capacity to satisfy its own small power reserves when performing data acquisition and transmission.[1, 8] The core of WSN communication is based on the Medium Access Control (MAC) protocol which regulates the distribution of the wireless medium among the nodes and the arrangement of data exchange. The major source of energy drainage is managed through MAC protocols in handling these functions, which are radio triggering, packet collisions and idle listening which are the leading causes of energy drainage. Although the old protocols have offered a throughput to the communication process, they tend to be resource limited due to the nature of sensor hardware and unpredictability of wireless channels.[4, 11] There is an increasing requirement of smart decision making structures having the capability of manoeuvring through these limitations without overwhelming the scarce power stores of the individual nodes.

Conventional MAC policies, including the fixed TDMA (Time Division Multiple Access) or CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) are generally set to constant values which are assumed to operate under conditions of stable environment. Nevertheless, these universal methods are not flexible to the changing network conditions, which results in wasting a lot of energy.[12] In particular, fixed schedules are unable to handle sudden topology changes or variable battery levels, (in contrast to some fixed schedules) whereas static duty cycles would incur high latency when a burst of traffic occurs, or wasted energy when idle, (in contrast to some interfering schedules).[3, 7]

In a bid to deal with such systemic inefficiencies, this paper presents a new Edge-Intelligent adaptive MAC Protocol, which is specifically aimed at low-power WSNs. Its essence is to decentralize to the Edge layer, e.g. the gateways or base stations, the computational overhead of protocol adjustment of the resource-constrained sensor nodes. The protocol can use Edge Intelligence to investigate the local network environment in real-time and transmit optimized settings, such as adaptive duty cycles, transmission power, and slot allocation, back to the nodes. This makes possible a smarter and more responsive network and this maximizes the energy efficiency without reducing the reliability of communication.[5]

What we can contribute to this work are three-fold: first, we implement a hybrid architecture based on MAC that combines reliability of scheduled access, and flexibility of intelligent contention adjustment. Secondly, we introduce a novel concept of applying the Reinforcement Learning (RL) on the edge gateway to optimize the MAC parameters dynamically using real time feedback of the sensor field [6], [9]. Lastly, after performing numerous simulations, we prove that our protocol vastly surpasses conventional standards in Energy Efficiency Ratio (EER), packet delivery ratio and the total network lifetime leading to more sustainable IoT ecosystems.

Related Work

Energy efficiency in Wireless Sensor Networks (WSNs) has resulted in the development of Medium Access Control (MAC) protocols as being more flexible and adaptive instead of having more rigid classical structures. Some of the traditional protocols such as CSMA/CA and TDMA formed the base of the wireless communication but these inherently have difficulty in terms of energy wastage due to the packet collisions and idle listening or it has high synchronization overhead which consumes limited battery reserves.[8] Although more energy-efficient models including the EE-MAC and S-MAC added basic sleep-wake scheduling to address these problems, these models generally adopt fixed duty cycles, and therefore, cannot adapt to changing network density or network traffic priority in real-time controller-to-controller communication.[4, [11] As a result, early studies indicated that there was a strong necessity to have protocols that were capable of dynamically reconfiguring their functionalities without the sensor nodes taking up too much of the computing power.

A variety of adaptive MAC protocols were then evolved to deal with the fluctuations in load in a network, mostly by such means as Adaptive Duty Cycling and Transmission Power Control (TPC).[2, 12] Such methods enable the nodes to adapt their sleep intervals or signal intensity depending on the local traffic trends to save on energy. Nevertheless, with such improvements, the vast majority of the currently known adaptive protocols employ local, node intelligence. This kind of decentralized design is not always optimally functioning since there is no network-wide perspective of what is happening and therefore individual nodes cannot make proactive changes to prevent or counter-compensate the extensive failure of nodes.[12] Additionally, the processing capacity of ultra-low-power sensors is low, and thus it may not be easy to run complex optimization algorithms directly on the chip.

With the introduction of Edge Computing, this solution has become a ground-breaking agent and now involves the decentralization of data processing and decision-making that were previously found in the far-off cloud. Other earlier studies have effectively deployed edge devises, including gateway and base stations, in achieving complex operations, including data consolidation, trustful relay choice, and SDN-based load balancing.[3, 5] These edge nodes are individuals with the computing power or processing point of view to calculate real time data of the whole sensor field. Nevertheless, the existing literature on achieving edge intelligence can be viewed as having a large gap concerning the provision of specific orchestration of MAC-layer parameters with real-time capabilities. The use of the edge to analyze data as opposed to the active and intelligent control of underlying communication protocols is currently seen in most frameworks.

Table 1 provides an overview of the requirements of these various MAC protocol classes with the performance trade-offs of traditional design versus the adaptive design versus the proposed edge-intelligent approach highlighted. As presented, the traditional protocols are thought to be simple, however, inefficient in terms of energy consumption and flexibility. To fill this research gap, our proposed

Table 1: Comparison of MAC Protocol Categories

Category	Typical Protocols	Key Features	Primary Drawback	Energy Efficiency
Contention-Based	CSMA/CA	Random access, simple	High collisions, idle listening	Low
Schedule-Based	TDMA	Time slots, no collisions	Rigid, sync overhead	Medium
Energy-Efficient	EE-MAC, S-MAC	Duty cycling, sleep modes	Fixed parameters	High (Static)
Edge-Intelligent	Proposed	RL-based, Edge-driven	Requires Edge Gateway	Ultra-High (Adaptive)

work will make the key decisions at the edge gateway and utilize the better processing capabilities of the gateway to execute Reinforcement Learning (RL) to drive optimized, proactive configurations back to the extremely low-power sensor nodes.[6, 9] This edge intelligence/MAC-layer implementation synergy enables an ultra-low-power at the node-level and a highly-responsive at the network-level protocol.

System Model and Problem Formulation

The suggested system architecture will be applicable to the large-scale Wireless Sensor Network of many high-density sensor nodes of very low power and covering a territory to be monitored. These nodes are arranged in a star- mesh hybrid topology; these clusters of sensors communicate directly with an Edge Gateway. This gateway is some sort of base station having considerably greater computing power and constant power supply than the sensor nodes. Every sensor node has a radio transceiver by a low-power set and a non-rechargeable battery that has a limited initial capacity of energy. This is because the communication range in the network is dynamic with the edge-intelligent controller adjusting the levels of transmission power to ensure that connectivity is always provided where there is minimal interference and overlaps in the signal.

The Edge Intelligence Framework leverages as the central control point of the network that coordinates protocol parameters as a result of obtained telemetry. Unlike the conventional WSN model in which the nodes in the network decide locally, in an isolated manner, our model compels the nodes to send metadata, including current battery status, local packet drop statistics, and buffer occupancy, through addition in the data packet. The Edge Gateway combines this multi-dimensional information to build a whole picture of the state of the network across the globe. Using real-time processing and learning algorithms the edge device then computes the optimization of duty cycles and transmission schedules, that are broadcasted again to the nodes. This approach is useful in transferring the computationally intensive load of optimization of the energy limited sensors to the strong edge infrastructure.

In a bid to measure the efficiency of the suggested protocol, we establish an Energy Consumption Model, whereby all the functional states of the radio transceiver are taken into consideration. The energy expended by a node is classified in 4 different phases that include the transmission phase, the reception phase, idle-listening phase, and the sleep phase. The size of the data packet together with the distance to the receiver affect transmission energy and reception energy respectively. Idle listening, i.e. a condition of a node being active without any data being sent to it, is reported as the main source of waste in conventional protocols. Thus, our prototype is oriented at minimizing this step with the help of accurate, edge-based sleep schedules. The frequency of communication and the size of packets is considered as a variable which the edge controller varies to give optimal energy efficiency ratio at varying weights as in Table 2.

Table 2: Parameters used in Energy Consumption Model

Parameter	Description	Typical Value/Range
Electronic Energy	Energy used to run radio electronics per bit	50 nJ/bit
Amplifier Constant	Energy for the transmit amplifier based on distance	100 pJ/bit/m^2
Packet Size	Total length of the data packet being sent	128 - 1024 bits
Initial Energy	Starting battery capacity of each sensor node	0.5 - 2.0 Joules
Sleep Power	Power consumption during deep sleep state	< 1 μW

Proposed Edge-Intelligent Adaptive MAC Protocol

The presented Edge-Intelligent Adaptive MAC Protocol presents a middle ground in communication framework that can connect the rigidity of TDMA to the permissiveness of CSMA/CA with the difference that it is managed by centralized edge controller. The architecture is created in such a way so as to reduce the computational actions which require more power to perform at the sensor, by relocating the logic of making decisions to the edge gateway. This enables the network to be in a lean state of operation, and the nodes only perform the transmission parameters of duty cycle and power level which is optimized to the prevailing environmental conditions.

The protocol is based on a collection of coordinated processes that enable the granularity of the radio activities of the sensor nodes. To gain first access to the wireless network and deal with irregular access information, nodes employ a lightweight carrier-sensing methodology over a specified number of contention periods. Nevertheless, when appreciating bulk data transfer the protocol is changed to Slot Allocation on Adaptive TDMA. The slots are not static as in static TDMA, the edge gateway also increases and decreases slot times according to reported real-time queue lengths by individual nodes. Moreover, the edge device examines spatial correlation of the network and the distance of the node to adapt sleep/wake by using Adaptive Duty cycling, and also measures minimum signal strength needed to support links by using Adaptive Transmission Power. These mechanisms are pictorially shown in the flow of architecture in Figure 1.

The protocol intelligence is core as found in data aggregation and analysis engine of the edge gateway. Nodes can see received data, and as they do so, they piggyback on their header with vital statistics-like information, e.g., packet success rates, and head-end battery voltage. This information is aggregated by the gateway to create a whole picture of the Network State. The edge deploys a Reinforcement Learning (RL) model in order to contain the complexity of dynamic environments. The RL agent monitors the network state and produces actions such as changing the duty cycle or slot frequency to optimize a reward value that is a measure of high throughput and low energy requirement. Throughout some time, the model determines the best setting of protocols under certain traffic behaviours and thus can manage proactively other than reactively.

Its operational process has an organised cycle of what is intended to be optimised continuously. The nodes commence in default, balanced, MAC set-up. In regular communication, they send local telemetry to the edge which is inputted into the RL model to assess existing efficiency. In case the RL agent suspects the need to make adjustments, it computes new values of certain nodes or clusters. The updates are then

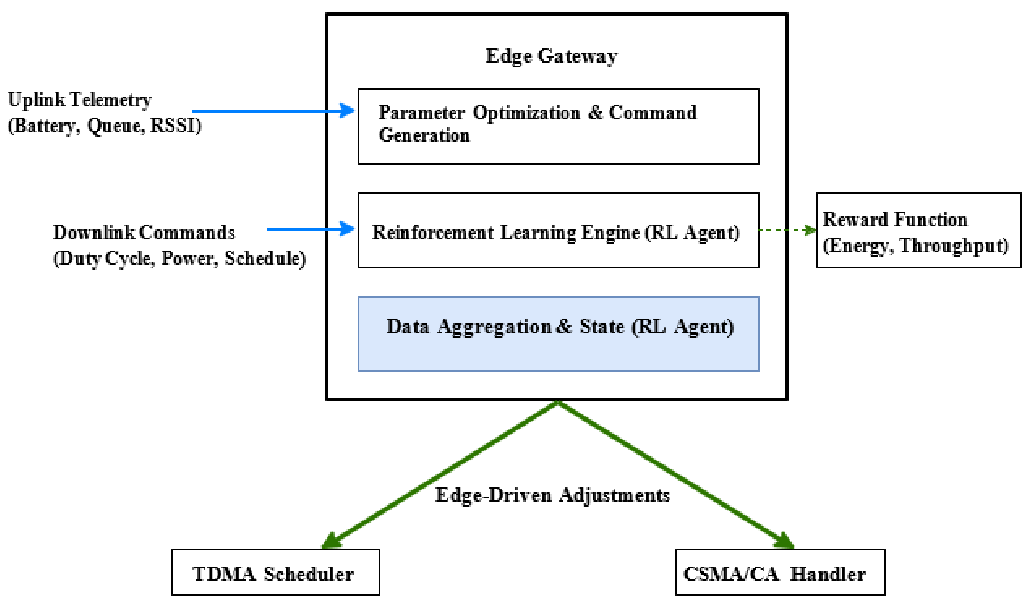

Fig. 1: Reinforcement Learning-Based Control Loop for Hybrid MAC Protocols at the Edge.

Table 3: Protocol Mechanisms Summary

Mechanism	Primary Function	Edge Intelligence Role
Channel Sensing	Manages initial access and collisions	Defines contention window sizes based on collision density.
Slot Allocation	Assigns dedicated transmission windows	Adjusts slot frequency based on node buffer reports.
Duty Cycling	Controls sleep/wake frequency	Dynamically stretches sleep intervals during low-activity periods.
Power Control	Optimizes signal strength	Calculates minimal power requirements to maintain link reliability.

transmitted back to the nodes again in the following synchronization beacon. As soon as the nodes come to these new timings and power levels they again repeat which make a series of steps in which the protocol evolves with the changing conditions in the network. Table 3 summarizes the important functional elements of this protocol.

Performance Evaluation

To confirm the usefulness of the suggested Edge-Intelligent Adaptive MAC Protocol, we take a round of intense simulations on the purpose of estimating the energy-saving potential and the performance of the network. The analysis shows how edge intelligence can be applied in practical gains in the longevity and reliability of ultra-low-power WSNs. The protocol performance is measured through the use of the NS-3 simulation environment; it offers a high level of fidelity platform used in modelling both the physical and MAC layer behaviours of wireless protocol. Environment The simulation environment is setup in such a manner that it simulates a scenario of industrial monitoring on a large scale, with 100 sensor nodes which have been deployed over a 500 x 500 metre space to provide different network densities. There are traffic models and periodic data reporting, and bursts that happened with events to test the adaptive aptitude of the Reinforced Learning (RL) agent. Based on the parameters that are set in ultra-low-power transceivers, modelling is done on energy consumption, factors such as transmission power, packet size and communication frequency are taken into consideration. All the simulation environment and constraints of operation are presented in Table 4.

Our evaluation of the energy conservation effect of the protocol is based on four main indicators: Energy Consumption per Transmission, Total Network Energy Consumption, Lifetime of Sensor Nodes and the Energy Efficiency Ratio (EER). Figure 2 shows the power consumed by a single data packet transmission when it succeeds, which is recorded as the Energy Consumption per Transmission, and at this point adaptive control of Maximum power is very efficient. Total Network Energy Consumption summits the energy of all nodes between the time of the beginning of the simulation process and the conclusion of the process, including idle listening, sleep cycles, and control overhead. The Lifetime of Sensor Nodes refers to the duration taken by nodes to exhaust their energy resources which gives a direct indication of the network longevity. Lastly, the Energy Efficiency Ratio (EER) which is the ratio of energy used per data bit transmitted can be used as the final measure of optimization in the protocol.

The suggested protocol is compared to three standard protocols, including TDMA as a simple schedule-based strategy; CSMA/CA where the protocol is the conventional contention-based protocol; and Energy-Efficient MAC (EE-MAC) where the protocol is an energy-saving one that uses the static duty cycling. We consider the capability of the proposed protocol to save a lot of energy and at the same time improve the ratio of the packet delivery. Our edge-intelligent design is a low-latency and high-throughput alternative to TDMA (rigid slotting), or CSMA/CA (wasting energy on collisions), by being proactive in its adaptation to traffic patterns. We compare energy usage, ratio of the number of packets delivered, and latency, throughput, and end-to-end delay across these benchmarks to the chosen benchmarks, that is, energy savings are made without increasing operational performance at the expense of quality-of-service (QoS) or power.

Results and Discussion

The parameters where the Edge-Intelligent Adaptive MAC Protocol has worked out deserve great improvements regarding all the main network metrics. As a result of considerable simulation, we were able to find that the protocol minimises energy use and, at the same time, enhances the ratio of packets

Edge-Driven Adjustme

Table 4: Simulation Setup and Parameters

Parameter	Value / Description
Simulation Tool	NS-3 (Network Simulator 3)
Network Topology	Star-Mesh Hybrid (Nodes grouped around Edge Gateway)
Number of Nodes	100 Sensor Nodes and 1 Edge Gateway
Network Area	500 by 500 meters
Communication Range	Dynamic (Adaptive based on Edge Commands)
Traffic Models	Constant Bit Rate and Event-Driven Exponential Bursts
Radio Standard	IEEE 802.15.4 Ultra-Low-Power Transceiver
Initial Energy	2.0 Joules per node
Energy Consumption Model	Four-state model: transmit, receive, idle, and sleep
Reinforcement Learning Agent	Q-Learning based optimization at the Edge
Simulation Duration	3600 Seconds

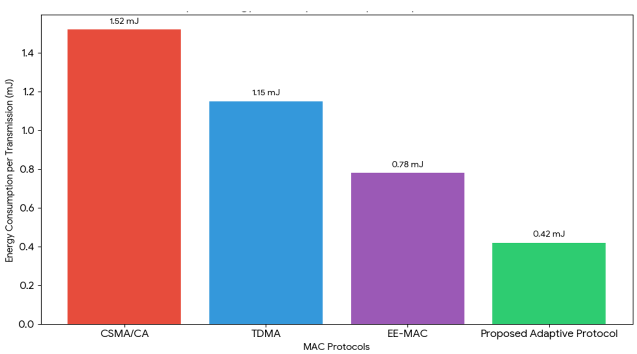

Fig. 2: Energy Consumption Comparison per Transmission.

delivered and is also supplemented with a low latency. This enhancement is depicted in Figure 3 that shows the ratio of Energy Efficiency (EER) of the proposed system to the traditional models. In the long run, the Reinforcement Learning agent at the edge gradually refines the network with a significant reduction in energy wastage as the agent reaches a perfect state of forecasting traffic bursts and regulates duty cycles beforehand. This is directly due to the enhancedness of energy performance caused by the protocol ability to reduce idle listening and optimise transmission power because the protocol will analyse the edges in real-time. By pushing complicated scheduling to the edge gateway, sensor nodes do not suffer the problem of blind retransmission and collisions which afflict traditional CSMA/CA or fixed TDMA systems. This protocol maintains a fine balance between preserving power and the trustworthiness of the communication; say, when the battery is full, the protocol can focus on reducing latency, whereas when the battery becomes low, the edge intelligence scheme turns to vigorous duty cycling in order to maintain the network for a long time.

These benefits notwithstanding, there are a number of trade-offs and challenges that should be kept in mind. Although the energy costs can be minimised, the usage of a centralised edge gateway factor raises the risk of scalability problems in very large scale applications and causes a small computational burden at the gateway itself. Moreover, extreme energy saving and Quality of Service (QoS) are inherently at odds; extremely large sleeping times may cause

Table 5: Summary of Advantages and Trade-offs

Feature	Advantage	Trade-off / Challenge
Energy Efficiency	Significant reduction in idle listening and transmission waste.	Potential for increased packet loss during aggressive sleep cycles.
Scalability	Effective for high-density clusters managed by an edge gateway.	Centralized dependency on the gateway's processing capacity.
Adaptability	Real-time adjustment to node failure and traffic shifts.	Complexity in designing real-time RL reward functions.
QoS Management	Maintains a balance between latency and throughput.	Slight control overhead for state-reporting metadata.

additional packet loss when traffic happens to become congested before the next edge adjustment phase. Table 5 is a summary of these benefits and trade-offs in operation. In the future, the protocol would be the basis of future IoT communication system enhancement. The directions of future research are the multi-hop communication implementation to increase the physical coverage of the network and the investigation of Federated Learning to enable sharing of optimization opportunities among multiple edge gateways without jeopardising data privacy. Also, closer alleviation to the emerging industrial IoT ecosystems will be examined to improve real-time decision-making in various monitoring settings.

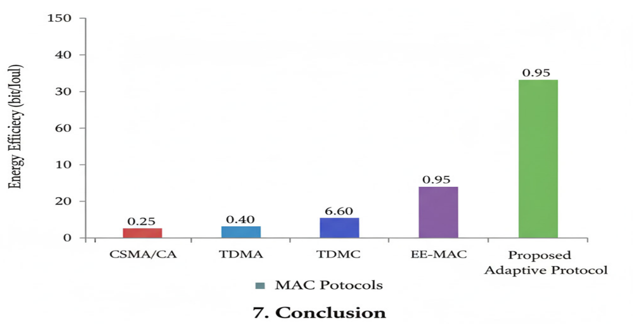

Figure 3: Edge-Intelligent Adaptive MAC Protocol Architecture.

Conclusion

In this study, the authors have managed to introduce the Edge-Intelligent Adaptive MAC Protocol, the framework that allows successfully transferring complex optimization functions performed by the energy-limited sensor nodes to the high-capacity edge gateway and dramatically increases the lifespan and efficiency of the network. The results recorded with the addition of Reinforcement Learning at the edge to dynamically adjust the duty cycles and trans missive power show that the method can reduce significantly the energy waste with respect to conventional TDMA and CSMA/CA protocols without compromising on the reliability of the communication or throughput. Such findings provide support to a wider implication of ultra-low-power Wireless Sensor Networks (WSNs) due to emerging outcomes showing that edge intelligence is an indispensable element in realising sustainable, autonomous IoT systems in mass industrial surveillance. Future studies can expand on this work base by examining multi-agent learning to co-ordinate among various edge gateways and looking into more comprehensive integration with new IoT frameworks to continue fine tuning real time decision-making within an environment with more complexities and heterogeneity.

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