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A Context-Adaptive Hybrid MAC Scheme for Provisioning QoS and Energy Savings in Delay Sensitive Wireless Sensor Network Application

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ABSTRACT
An effective WSN communication protocol can help IoT applications to offer faster services in an efficient way. In order to reduce the energy consumptions various MAC protocols are introduced by the researchers based on duty cycle mechanism. However, none of the existing MAC protocols have been able to successfully balance the need for high power efficiency, low latency, and excellent QoS. A context-adaptive hybrid MAC (CA-HMAC) protocol is proposed in this paper for providing a higher degree of energy conservation under low traffic loads, and better transmission rates under high traffic loads. It presents hybrid scheduling algorithm to handle packet collisions, control idle listening, and conserve energy. The proposed protocol also focuses on adjusting power for packet transmission and data prioritization, followed by delay-aware routing mechanism. The design of the proposed MAC protocol is carried out in such a way that its response is faster towards executing its operation associated with duty cycle and packet transmission. The design and development of the proposed scheme is carried out on MATLAB tool. The experimental results show, that the proposed MAC protocol outperforms similar existing techniques in terms of throughput, remaining energy, and reduced packet delay.

General Terms
Medium Access Protocol, Wireless Sensor Network

Keywords
Internet of Things, Hybrid Medium Access Protocol, Quality of Service, Energy Efficiency

1. INTRODUCTION
There is growing interest in wireless sensor networks (WSNs) because they provide the ability to communicate, compute, and sense data through a large number of nodes. In recent years, low-cost sensing devices have enabled WSNs to be suitable for many applications, including patient monitoring, military surveillance, environment monitoring and home automation (Fahmy, 2021) [1]. Today, sensor networks have become an integral part of the Internet of Things (IoT), enabling sustainable development of smart applications such as smart cities, industry 4.0, critical applications such as smart healthcare, smart elderly care monitoring and smart transportation (Sharma et al., 2020) [2]. In these applications, it is crucial to ensure that sensor devices have the longest possible lifetime and packet delivery times are as short as possible to ensure acceptable quality of service (Gulati et al., 2022) [3]. It is common for any sensing applications to send data packets through multiple hops between source nodes and sink nodes. The challenge is to find a path that delivers all data packets within the required timeframe, taking into account factors energy efficiency and Quality of Service (QoS) at the same time. There has been a great deal of effort put into maintaining a balance between latency, power cost, and QoS (Kaur and Kumar, 2019) [4].

Literature shows that researchers address latency and QoS requirements simultaneously, but at the expense of higher power consumption (Singh et al., 2020) [5]. Energy efficiency is of the utmost importance since sensor nodes have limited power sources and degradation over time can lead to network failure. To minimize energy waste due to overhearing, various techniques have been developed, such as directional antennas, power-controlled transmissions, and address-based filtering. There is no doubt that energy efficiency is a priority need in any form of communication protocol design in WSN. It is inevitable that critics will question whether communication can be made sustainable and efficient, and which solution works better.

1.1 Causes of Energy Dissipation
Collisions of packets are a primary cause of energy wastage, occurring when a sensor node receives multiple packets simultaneously (Singh et al., 2021) [6]. As a result, colliding packets are discarded and retransmitted, resulting in increased energy dissipation. Secondary causes include overhearing, where a node receives packets that are intended for other nodes. High node density resulting in heavy traffic can cause more energy loss (Ezhilarasi et al., 2018) [7]. The third major factor is overhead associated with control packets, while the fourth factor is ideal or passive listening, which involves intercepting potential traffic through ideal channels (Singh et al., 2015) [8]. Energy dissipation can also be caused by transmitting messages when the destination is not ready, known as over emitting.

It is possible to address the above-mentioned causes of energy dissipation by designing an adaptive, and lightweight medium access control (MAC) protocol. The majority of existing MAC protocols in WSN are based on low duty-cycle operations (Alfayez et al., 2015) [9]. This means that each node switches between active and inactive states and only turns on its radio from time to time to save power (Maitra et al., 2016) [10]. Unfortunately, none of the existing MAC protocols have been able to successfully balance the need for high power efficiency, low latency, and excellent QoS.

1.2 Characteristics of Good MAC Protocol

When developing a reliable MAC protocol for a WSN, energy efficiency must be the primary consideration in design to prolong network lifespan. Meanwhile, protocol design features should be context-adaptive and capable of adapting to changes in network size and topology. Furthermore, throughput, latency, and QoS are also very important aspects that should be considered as secondary characteristics of a good MAC protocol.

1.3 Materials and Method

This paper proposes a context-adaptive Hybrid MAC (CA-HMAC) protocol for provisioning higher energy conservation when there is a low traffic load and it offers better data transmission rates when there is a high traffic load. This scheme uses a hybrid scheduling algorithm to achieve efficiency, and network adaptability to handle packet collisions, and control idle listening as well as energy dissipation. Additionally, packet transmission incorporates power adjustment and data prioritization features, followed by delay-aware routing. The design of the proposed MAC protocol is lightweight concerning its practical utility in delay-aware WSN applications.

2. RELATED WORK

The literature is rich with varieties of MAC protocols for WSN using different techniques such as duty cycle, meta-heuristic-based schemes, game theory, cross-layer based approaches and machine learning driven MAC protocols. A brief review of the existing MAC protocols using different schemes are given in table 1.

Table 1. Summary of existing MAC protocols

Ref	Method	Protocol Type	Objective	Remark
[11]	Sensor MAC	Synchronous TMDA	Periodic sleeping of nodes in channel	Reduces latency and saves energy
[12]	Timeout MAC	Asynchronous CSMA	Adaptiveness into duty cycle	Reduces energy, minimizes collisions
[13]	Hybrid MAC	Synchronous TMDA	Dividing the channel into a set of TDMA slots using CSMA/CA	Improves throughput and conserve energy
[14]	Game-theoretic MAC	Asynchronous CSMA	Tuning of contention |window	Throughput, reduced packet-loss-rate
[15]	Game theory approach	Asynchronous CSMA	optimization to map the cost of MAC parameters.	Enhanced energy
[16]	WSN scheduling using a greedy approach	Asynchronous CSMA	Increase network throughput	Increase network throughput
[17]	Metaheuristic approach	Asynchronous	Optimization in scheduling	Reduces the end-to-end delay
[18]	Fuzzy Logic + swarm optimization	Asynchronous	Optimizing parameters responsible of energy dissipation	Improves network throughput and end-to-end delay
[19]	Evolutionary Algorithm for Scheduling in WSN	Asynchronous CSMA	goal of minimizing the delay	Decreases end-to-end delay
[20]	recurrent neural network mac protocol	Asynchronous CSMA	Avoidance of packet Collison	Enhances network throughput and decreases collisions
[21]	deep neural networks	Asynchronous	Realtime scheduling and power allocation	Decreases end delay and packet loss

3. IMPLEMENTATION STRATEGY

The proposed system adopts analytical research methodology for implementing the proposed system. The initial process of proposed system is subjected to the network modeling to understand WSN deployment scenario. The analytical formulation for network modeling is discussed as follows:

3.1 Network Model

The WSN network model considered in this research work is meant to support multi-event data collection process in large scale application assisted by IoT ecosystem. For example, critical patient monitoring or elderly monitoring systems where various sensor nodes continuously collect data and send it to a base station (BS). This data from the BS will be accessed through the IoT gateway and will be available to the end user (doctors, family, or any related entity) on the server from any location. The simulated network model of interest for the proposed CA-HMAC protocol is shown in Figure 1.

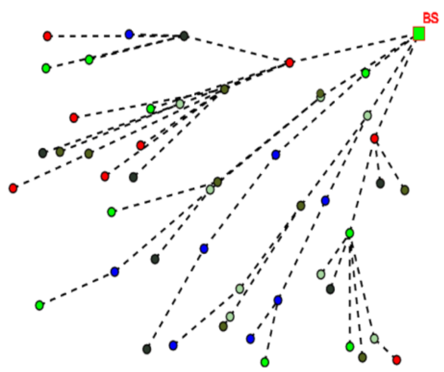

Fig1: Architecture of Simulated Network Model

The network design adopts a random placement strategy for N (50 for example) sensor nodes (SNs) in the deployment region of size (100×100). The network modeling also considers flexible deployment of the BS either inside or outside sensing region. Within a network, multiple nodes may need to send packets simultaneously at any time, for this reason, the maximum communication radius (cR) is considered to be the same for all nodes. In this process, a connection matrix is first constructed by computing a Euclidean distance among the nodes and then neighbor discovery process is carried out by incrementing value of cR for each simulated SNs as shown in Figure 2.

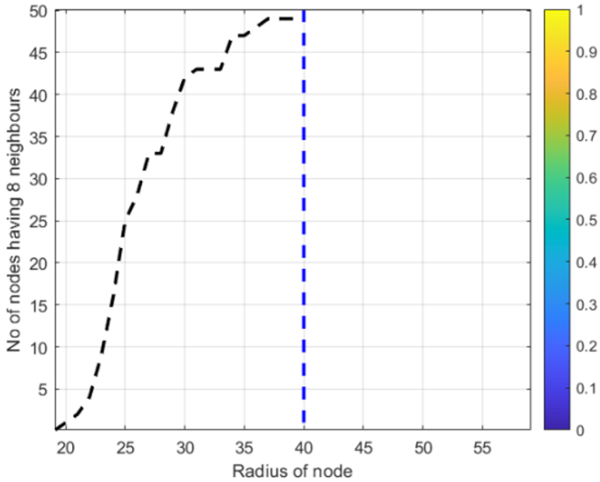

Fig 2: Communication radius for neighbor discovery

A closer analysis reveals that for each SN to have 8 neighbors, the minimum value of cR needs to be set to 20 and the maximum value to 40 to have a full coverage in the entire network. Here, each SNs acts as a relay for its neighbors to carry out data transmission efficiently sources to the BS, in a hop-to-hop approach. Also, another distance matrix is computed to link SNs to BS. As shown in Figure 1 the SNs are clustered into different groups since the network model simulates heterogeneous sensor. In order to control the energy dissipation in the network, the study devices a power adjustment strategy with dual mode of transmission and reception defined in the energy consumption model discussed in next section.

3.2 Energy Model

The major amount of energy of SNs are consumed in the communication, and data processing operations. Therefore, the study considers estimation of energy cost as energy consumed in transmittance (Tx) and receptance (Rx). The computation of overall energy E usage by sensor nodes in the proposed system can be given by the following numerical expression:

$$E_{usage}(SNi) = E_{Tx} + E_{Rx} \; \ldots (1)$$

In the above numerical expression 1, the variable E_{Tx} is the transmission energy and E_{Rx} refers to receiving energy, which can be computed as follows:

$$E_{Rx}/E_{Tx} = \alpha + \beta + \gamma \; \ldots (2)$$

Where,

$$\alpha = \gamma e_{Rx/Tx} \times t_{Sync} \ldots (3)$$

$$\beta = e_{Rx/Tx} \times t_{Dreci/forw} \ldots (4)$$

$$\gamma = e_{Rx/Tx} \times t_{Ack} \ldots (5)$$

In the above numerical expression (2), the variable $e_{Rx/Tx}$ refers to the receiving/transmittance energy and variable t_{Sync} time spent in the synchronization process. In equation 4 $t_{Dreci/forw}$ denotes to time spent in receiving/forwarding data, while the variable t_{Ack} indicates product of time spent for the acknowledgement

4. PROPOSED CA-HMAC

With the proposed MAC protocol, transmission latency is reduced and data throughput is improved with high traffic loads while energy is conserved on sensors with low traffic loads. It is possible to set up different duty cycles for data transmission based on the sensor demands; the higher the duty cycle, the more data the sensor will send to the transmission queue. The sensor enters sleep mode if it is experiencing radio channel competition and cannot relay data, in order to save energy.

4.1 Sync State Process

The synchronization (SYNC) process between network nodes is done through the cluster concept. When a WSN network node becomes active, it begins the process of waiting and listening. If there is no nay node listening for a certain time, it chooses the time frame schedule and sends a SYNC signal. The SYNC signals contain timing until the next timeframe begins. If the node listens for a sync signal from another node during startup, it follows the schedule in the sync signal and sends its own sync signal accordingly. Nodes occasionally retransmit their SYNC. When a node has a schedule, but it listens for a sync signal that differs from another node's schedule, it will use both schedules to confirm successful communication between nodes with different schedules. This SYNC process occurs in the same group of nodes, and the calling nodes perform grouping to simulate a cluster mechanism, where the nodes in the WSN network do not necessarily follow the same schedule. In the simulated clustering process, each node builds a 1-hop neighbor list, using this information, each node can build a 2-hop neighbor list, each node has a unique id. The node can forward multiple transmissions suffering from collision because it has multiple neighbor nodes. As well as supporting this function, an energy-saving routing strategy also calculates the multi-hop path value. Depending on the duty cycle, each CA-HMAC timeframe has a limited sync period, fixed-length data span, and sleep period. It is important to select the duty cycle so that the sleep period of the time slot is sufficient to send packets with ACKs to the nodes with important data.

4.2 Packet Prioritization

The CA-HMAC proposes sorting packets based on their weight, i.e., delay characteristics and remaining energy, and storing them in the queue list. As soon as the sender sensor node sorted the packet and realized its weight, it stored it in the queue list according to its sensitivity. Sensed transmission data that requires a random backoff is requested in a scheduled interval if the data is critical. The node runs CCA control flow to analyze the channel status. If the slot is idle, the node will forward the data. If the slot is busy, it will wait for the idle time, and then repeat the above process. It is important to note that when claiming slots for pairs of communicating nodes, sensor nodes perform link scheduling. During the sleep state, the node turns off its receiver, the sleep duration is fixed using a timer mechanism, and when the timer expires, the node enters the wake-up state. Turn on the receiver, start listening, and enter the idle listening state. If the sensor node receives any transmit or receive signal, it performs a broadcast schedule, otherwise, it goes to sleep after a timeout.

4.3 Delay Aware Packet Routing

The proposed CA-HMAC mechanism here determines the maximum number of communication links necessary for collision-free, QoS-aware data transmission. The route selected by the mechanism proposed here involves more sensors and has a small distance between them. It is not recommended to take a route with fewer nodes and a longer distance between them. Within multi-hop neighbor nodes, multiple transmission is possible without conflict. This process can be understood by the following scenario shown in Figure 3. Furthermore, the system considers the transmission power adjustment mechanism in order to find a maximum number of optimal communication links that do not interfere with each other, thus providing more opportunities for more communication links.

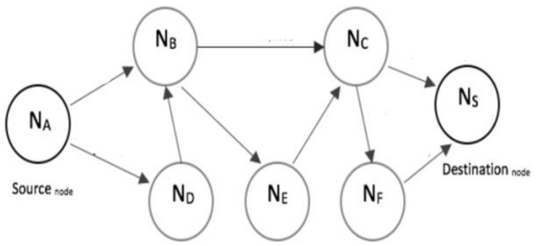

Fig 3: Packet routing process

The energy factor and delay factor are taken into account when establishing and selecting the path. According to the figure, there is an optimal number of paths for transmitting packets from the source to the destination. The path that consumes the least energy will be a suitable transmission path, whereas if the path is selected according to the delay factor, the route with the least delay will be chosen.

4.4 Power Adjustment

According to the proposed scheme, RTS and CTS messages are forwarded with maximum power P_{max}. Nodes receiving RTS messages will respond with CTS messages at allocated maximum energy E_{max}. As a result of receiving a CTS message, the source SN calculates the expected energy p_{exp} using the received and transmitted energy levels E_r and E_{max} as follows:

$$E_{exp} = \left({}^{E_{max}}/_{E_r} \times Rx_{cut\_off} \right) \times k \quad \dots (6)$$

Where, Rx_{cut_off} denotes threshold value meant for required lower signal strength and k denotes constant.

5. EXPERIMENTAL RESULT

In this section, we discuss the outcome of the proposed hybrid context adaptive MAC system and the performance analysis thereof. The proposed system is implemented using a numerical tool (MATLAB). Table 2 shows the various simulation parameters taken into account.

Table 2. Simulation Parameters

Parameters	Values
Number of SNs	200
Simulation Boundary	$100m^2$
Base Station	1
Msg Inter Arrival Period	1-10s
Duty Cycle	15%
Sync-active	20%
RTS/CTS-active	80%
Data transmission sleep time	80%
Ack-Sleep	20%
Number of Cluster	2
Frame Size	1 sec
Probability of Priority Message	20%
Threshold value for the buffer size	4 packets
Data packet length	20 bits
Channel capacity	20kb/s

Table 3 presents the quantified outcome for assessing the performance of the proposed system in terms of average packet delay over different traffic rates (message inter arrival time). The graph trend from Figure 4 indicates that the proposed system provides better performance when it comes to packet delay as demonstrated by the average packet delay measured by the sensor nodes. Additionally, Q-MAC offers higher performance compared to S-MAC based on graph trends, whereas S-MAC underperforms comparatively. In addition to offering less energy consumption per bit, hybrid MACs can be validated for their effectiveness if they are more efficient. The remaining energy as illustrated in figure 5 is the subject of another analysis.

Table 3. Inter arrival time Vs Average Packet Delay

Msg Inter Arrival time (seconds)	Average Packet Delay		
	Proposed	S-MAC	Q-MAC
1	103	120	104
2	49	60	51
3	38	40	39
4	25	30	25.8
5	20	23	20.6
6	18	20	19
7	17	19	18
8	15	18	16
9	12	16	13
10	9	11	10

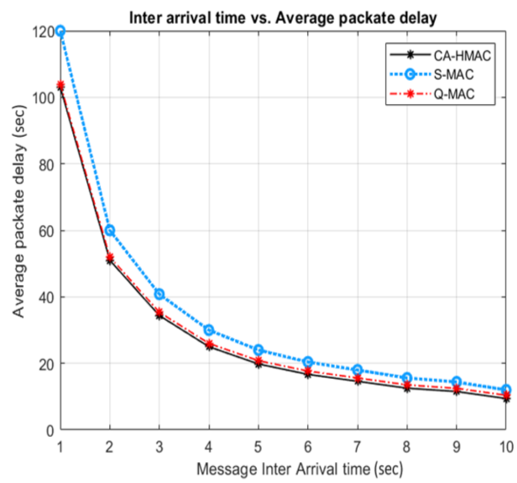

Fig 4: Analysis of average packet delay

Table 4 presents the quantified outcome for assessing the performance of the proposed system concerning remaining energy message inter arrival time. The graph trend from Figure

5 shows the analysis of performance for remaining energy at sensor nodes for the proposed system, the existing system SMAC, and the Q-MAC system. Message interval times are varied for the performance analysis. Energy efficiency is higher in the proposed system than in the current one, based on the graph trend. A key reason why the proposed protocol maintains higher energy levels on resource-constrained nodes is the attuned transmission power strategy since it emphasizes energy conservation and provides efficient data transmission based on the dynamic management of nodes' active and sleep slots. Nevertheless, existing systems do not implement dynamic slot management. In addition to supporting efficient data transmission under light and heavy traffic scenarios, the proposed protocol is designed to support an effective scheduling mechanism. This proposed method, therefore, is slightly better than existing methods, but trades off efficiency and latency.

Table 4. Inter arrival time Vs Remaining Energy

Msg Inter Arrival time (seconds)	Remaining Energy (J)		
	Proposed	S-MAC	Q-MAC
1	99.861	99.71	99.780
2	99.935	99.84	99.887
3	99.953	99.88	99.922
4	99.968	99.92	99.942
5	99.977	99.93	99.952
6	99.971	99.94	99.959
7	99.979	99.95	99.964
8	99.989	99.96	99.968
9	99.989	99.967	99.970
10	99.991	99.969	99.974

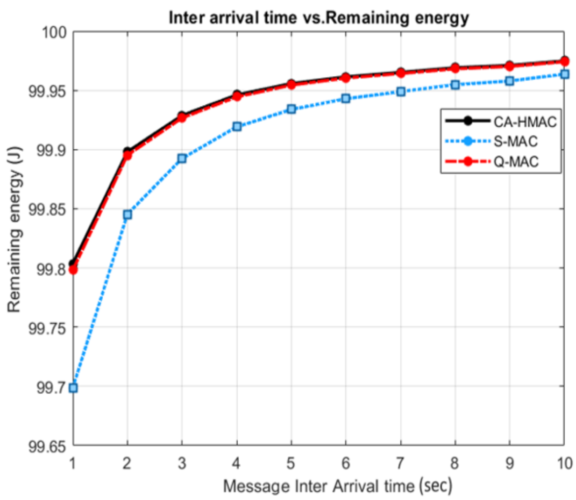

Fig 5: Analysis of remaining energy

Table 5 presents the quantified outcome for assessing the performance of the proposed system concerning energy consumption regarding different message inter arrival time. Based on the graph trend in Figure 6, the proposed method has better performance in comparison to other existing methods. There are two reasons for it: a simplified algorithm of the proposed MAC protocol and controlled transmittance energy for data transmission using dynamic slot management.

Table 5. Inter arrival time Vs Energy consumption per bit

Msg Inter Arrival time (seconds)	Energy Consumption per bit(J/bit)		
	Proposed	S-MAC	Q-MAC
1	0.99	1.509	1.0222
2	1.08	1.557	1.0556
3	1.09	1.585	1.0889
4	1.099	1.613	1.100
5	1.1111	1.674	1.1222
6	1.1667	1.699	1.1778
7	1.1889	1.700	1.1999
8	1.2000	1.770	1.2444
9	1.2111	1.772	1.2778
10	1.2889	1.933	1.3000

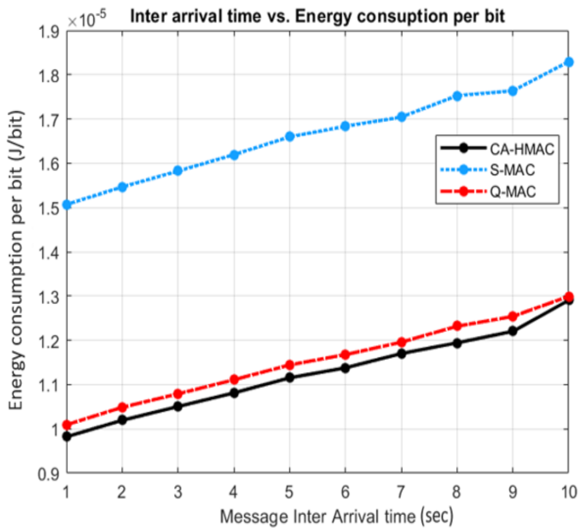

Fig 6: Analysis of energy consumption/bit

6. CONCLUSION

The research work reported in this paper has considered two important protocol design-based constraint problems, energy and QoS and proposed a context adaptive hybrid MAC scheme for low power duty cycle WSNs. The study first discusses the network module and then it briefly highlights the energy consumption model. The proposed MAC protocol uses integrated scheduling mechanism of both TDMA and CSMA. Also, introduction of energy adjustment followed by delay aware routing protocol reintroduced inter node data manipulation algorithm within significantly saves the network energy. The implementation of the proposed system is carried out on numerical computing tool and different performance parameters are considered for model assessment. From the experimental results, the proposed scheme outperforms similar protocol in terms of more energy saving, throughput and packet delay

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