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An enhanced adaptive duty cycle scheme for energy efficiency and QoS awareness in wireless sensor networks

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ABSTRACT

A Wireless Sensor Network (WSN) is a small device that has batteries and radios to connect to the internet. The main problem with WSNs is a limited energy source, energy studies needed to ensure that these sensor nodes can last longer, especially since a lot of energy is wasted during idle listening, overhearing, and data collision that occurs at the medium access control (MAC) layer. The common mechanism used for saving energy in WSN, specifically at the MAC layer is the duty cycle schedule. Duty cycling coordinates sleep-wake time sensor nodes to maximize network lifetime while achieving specific application goals such as high throughput or low latency. Duty cycling of every node should be adjusted separately at any runtime depending on the network conditions to achieve desired delay guarantees and energy efficiency. Recently, a few adaptive duty cycle schemes were introduced, these schemes have reduced energy consumption by some degree, this leaves an open end to the degradation of the quality of service. In this study, adaptive duty cycles enhanced with a priority queue where packet size is the parameter to adjust the duty cycle in order to get efficient energy consumption. A variant of packet size tested to ensure optimum quality of services (QoS). These factors determine the duration of a node's listen period for various packet transmission scenarios and requirements. As the result, the proposed Enhanced S-MAC (ESMAC) shows an improvement in the energy consumption and QoS compared to the default MAC protocol and S-MAC protocol. The success of this project will contribute to the performance improvement of sensing devices.

1. Introduction

Wireless sensor networks have facilitated the development of smart sensors. Smart sensors are small, with limited processing and computing resources, and are inexpensive compared to traditional sensors. These nodes can sense, measure, and gather information from the environment and, based on local decision processes, transmit sensed data to the user (Shallahuddin et al., 2020). Smart nodes are low-power devices equipped with one or more sensors, memory, a processor, a power supply, a radio, and an actuator (Sarang et al., 2020).

A variety of mechanical, thermal, biological, chemical, optical, and magnetic sensors may be attached to the node to measure environmental properties (Hasan et al., 2019). Since the nodes have limited memory and are typically deployed in difficult-to-access locations, a radio is used for wireless communication to transfer the data to a base station (e.g., a laptop, personal handheld device, or access point to a fixed infrastructure). The battery is the main power source; a secondary power supply that harvests power from the environment such as solar panels may be added depending on the appropriateness of the environment where the sensor will be deployed. Depending on the application and the type of sensors used, actuators may also be incorporated.

A WSN typically has little or no infrastructure. It consists of a number of sensor nodes (a few tens to thousands) working together to monitor a region and obtain data. There are two types of WSNs: Structured and unstructured. An unstructured WSN contains a dense collection of many sensor nodes and can be deployed in an ad hoc manner into the field (Yick et al., 2008). Once deployed, the network

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is left unattended to perform monitoring and reporting functions. Network maintenance such as managing connectivity and detecting failures is difficult because there are so many nodes (Bala and Packiam, 2019).

In a structured WSN, all or some of the sensor nodes are deployed in a pre-planned manner (Bala and Packiam, 2019). One advantage is that fewer nodes can be deployed with lower network maintenance and management cost. Fewer nodes can be deployed since nodes are placed at specific locations to provide coverage, in contrast with ad hoc deployment, which can have uncovered regions.

WSNs have great potential for many scenarios such as military target tracking and surveillance, natural disaster relief, biomedical health monitoring, and hazardous environment exploration and seismic sensing. In military target tracking and surveillance, a WSN can assist intrusion detection and identification (Yick et al., 2008). Specific examples include spatially-correlated and coordinated troop and tank movements. With natural disasters, sensor nodes can sense and detect environmental changes to forecast disasters before they occur (Yick et al., 2008). In biomedical applications, surgical implants can help monitor a patient's health. For seismic sensing, ad hoc deployment of sensors along the volcanic area can detect the development of earthquakes and eruptions. Unlike traditional networks, a WSN has its own design and resource constraints. Resource constraints include a limited amount of energy, short communication range, low bandwidth, as well as limited processing and storage (Yick et al., 2008). Design constraints are application-dependent and based on the monitored environment. The environment plays a key role in determining the network size, deployment scheme, and network topology. Network size varies with the monitored environment (Yick et al., 2008). For indoor environments, fewer nodes are required to form a network in a limited space, whereas outdoor environments may require more nodes to cover a larger area. An ad hoc deployment is preferred over pre-planned deployment when the environment is inaccessible by humans or when the network is composed of hundreds to thousands of nodes. Obstructions in the environment can also limit communication between nodes, which in turn affects the network connectivity (or topology). WSN research aims to meet the above constraints by introducing new design concepts, creating or improving existing protocols, building new applications, and developing new algorithms.

2. Related works

Formerly, several MAC protocols have been proposed for WSNs and can be divided into contention-free, contention-based, and hybrid protocols. Contention-free protocols assign fixed or dynamic time slots to each node for communication; therefore, nodes can only access the medium in the given time slots, which helps reduce network collision. However, the sensor nodes need to frequently exchange the time schedule, which incurs additional overhead. Furthermore, such protocols require time synchronization (Muzakkari et al., 2020).

Contention-based protocols avoid overhead and synchronization requirements by allowing nodes to access the medium randomly. Because of this, there is a risk of network collision, but this is mitigated by employing mechanisms to minimize their occurrence. These protocols can be further sub-categorized as synchronous or asynchronous. Synchronous MAC protocols are S-MAC, T-MAC, DSMAC, and DW-MAC. In this approach, the sensor nodes follow a common sleeping schedule in the virtual cluster. PQMAC is a synchronous MAC that addresses QoS by considering the priority of the data packets in BP-WSNs. However, synchronous MAC protocols require tight synchronization among sensor nodes and do not support individual duty cycling, which hampers its ability to adapt to dynamic conditions in EH-WSNs.

3. Synchronous MAC protocol

S-MAC is designed to reduce idle listening, collisions, and overhearing by putting nodes in listen/sleep periods. Fig. 2 shows that while the listen periods in S-MAC are fixed, the duration of the sleep period depends on a predefined application-based duty cycle factor. In S-MAC, the listen period is divided into SYNC and data periods. During the SYNC period, the node receives the SYNC packet from its neighbors and stores it. In the data period, an exchange of data packets occurs, which includes a request to send (RTS), clear to send (CTS), DATA, and/or acknowledgment (ACK) messages. High latency occurs in S-MAC as a result of its fixed sleep periods; to resolve this an adaptive listening mechanism was introduced. Therefore, when a node overhears an ongoing transmission from its neighbor, it will only wake up to receive a packet destined for it at the end of that transmission period, else it will go back to sleep mode. Some improvements are proposed in to overcome the problems with S-MAC.

T-MAC was proposed to improve the energy efficiency of S-MAC, especially under variable traffic conditions and to solve the S-MAC fixed duty cycle 215 by prematurely sending nodes back to sleep mode in the absence of any event for a given period known as 'Time Active" (TA) period. In T-MAC, nodes transmit messages in bursts. Similar to S-MAC, T- MAC also uses the RTS-CTS-ACK scheme. Better results are achieved with T-MAC under variable traffic. Both S-MAC and T-MAC use SYNC messages to schedule duty cycling and packet transmission; this requires a substantial amount of energy even in the absence of traffic. T-MAC achieves better energy efficiency by reducing collisions and redundancy since nodes go back to sleep mode in the absence of any activity during the TA period (at the detriment of high latency and reduced throughput). In T-MAC, packets are sent in bursts; as a result, a delay is minimized. However, T-MAC suffers from an early sleeping problem that was later solved by the introduction of future-request-to-send (FRTS).

DS-MAC (Wang et al., 2019), introduced the dynamic duty cycle feature to S-MAC to reduce latency for delay-sensitive WSN applications. Nodes share one-hop latency values within the SYNC period. In DS- MAC, nodes begin transmission with the same duty cycle. At a point where a receiver node identifies that a one-hop latency value is high, its sleep period is shortened and the node broadcasts it within its current SYNC period. Consequently, when a sender node receives notice of a decrease in sleep-period, it performs a check for packets intended for that receiver node, if there is any packet destined for the receiver in its queue, the node then doubles its duty cycle whenever its battery level exceeds a fixed threshold. The duty cycle is doubled; as such, the schedules of neighbor nodes will not be affected. DS-MAC achieves better latency compared to S-MAC because it uses less frame duration; therefore, it achieves less throughput in high traffic. DS-MAC also achieves a better average power consumption per packet compared to S-MAC.

AEE-MAC is proposed to optimize energy efficiency. Similar to S-MAC, AEE-MAC uses duty cycling to save energy by avoiding idle listening. AEE-MAC decreases overhearing by putting nodes with no packets to sleep mode on receipt of CTS destined for other nodes. The protocol incorporates three optimization schemes: 1) adaptive sleeping and reusing of the channel; 2) use of combined SYNC and RTS control packets; and 3) use of combined ACK and RTS control packets in a bi-directional and multi-hop data transmission. Adaptive sleeping and reusing of channels reduce the idle listening of the S-MAC protocol by combining the duration of the communication in the control packets. The combination of SYNC and RTS control packets decides the actual network traffic load by setting nodes back into sleep mode if there are nodes with packets to transmit during the active period. The combination of RTS and ACK control packets reduces overhead and collision while creating better channel utilization.

SRI-MAC is a synchronous duty cycle protocol; it adopts the principle of receiver-initiated data transmission. In SRI-MAC, the receiver node transmits beacon signals advertising that it is awake and ready to receive data. The beacon comprises the receiver's id and the duration allocation period (DAP), which relies on the number of the receiver's neighbors. The value is used as a common factor to generate back-off values for collision avoidance. Upon receiving a beacon, each sender node transmits an RTS packet comprising the node id, the id of the intended receiver and the data size. The receiver will then transmit a CTS packet, which assigns time slots to senders that registered via the RTS packet. At this juncture, the communication period starts and senders wake up based on a predetermined order. In an event where a receiver hears nothing from the sender, the receiver's beacon will go unanswered and thus no CTS will be transmitted. After passing an interval of a duration specified by DAP within the beacon, the channel will be considered idle by other potential receivers.

In RP-MAC, the receiver sends a preamble message, not the sender. As shown in Fig. 2, changing the paradigm offers great benefits. When node A wants to send data to node C, the sender does not have to transmit a preamble at all. Instead, the sender listens to the preamble messages from the neighbor nodes. While node A is listening to the preamble messages, nodes B and D wake up and each sends a preamble message. Unlike the traditional preamble alternating 0 and 1, our preamble message contains the source address. So, node A receives these preamble messages and removes them, because the sender realizes that they are not the receiver that node A wants to communicate with. After that, node C wakes up and sends a preamble message. Then, node A receives it and replies with an ACK message, because node C is the right receiver. At this point, node A starts to transmit the intended data to node C.

DAP introduced energy savings since only nodes taking part in communication are involved in the initial information period where the receiver announces itself and then can stay asleep for the remainder of the time slot.

4. Priority queue

The packet or task scheduling schemes are classified based on several factors, including Deadline, Priority, and Packet Type (Karthikeyan et al., 2014). PQ, better known as Head-of-line priority, is the first priority queue learned in 1954. This method of PQ works to receive data packets and divide them into groups according to their respective priorities. This PQ determines the priority of the data using Poisson and exponential distribution. The result will generate a waiting time; if the waiting time if it exceeds the finite value, it will get high priority, whereas a waiting time that is lower than the finite value will get a low priority. The finite value is determined by the average delay in the packet.

WRRPQ (Weighted Round Robin with Priority Queue) is a combination of PQ and WRR. This algorithm is applied only to data packets with high priority; other data packets will be treated as usual using the Round Robin (RR) principle. RR divides tasks into queues evenly, regardless of the number of packets or the importance of packets or packet sizes.

CQ (Custom Queuing) assigns a percentage of the bandwidth to each queue to assure predictable throughput for other queues. It is designed for environments that must guarantee a minimal level of service to all traffic.

WFQ (Weighted Fair Queuing) allocates a percentage of the output bandwidth equal to the relative weight of each traffic class during periods of congestion.

5. Adaptive duty cycle based on the priority queue

In wireless communication, enhancing packet delivery through wireless links can be developed by using packet scheduling algorithms. The packet scheduling scheme is used to select which packet to be dropped or serviced and ensures packet delivery based on priority and fairness with minimum latency; it can also guarantee QoS, which, in turn, increases transmission rate (Karthikeyan et al., 2014). The servicing and dropping of the packets will be based on network parameters such as bandwidth, packet arrival rate, as well as packet deadline, and packet size. Scheduling of packets will be done in a scheduler; the scheduler will find it difficult to handle each and every packet due to high packet rate, low bandwidth, and less packet size (Karthikeyan et al., 2014). As a result, the scheduler will select certain packets based on various algorithms.

MAC is divided into two sub-layers, logical link, and medium access control. Between these two sub-layers, an interface queue takes place. The task for the queue is to hold the packet before sending it out to its destination through a physical layer. The physical layer examined here is a wireless medium. In the interface queue, packet priority is divided into three categories: High, medium, or low priority. In this study, packet size has been set to several sizes; namely, 3KB, 2KB, and 1KB. Packet size exceeding 3KB will be counted as a high priority, packet size less than 1KB gets the lowest priority, while packet size exceeding 1KB but less than 3KB is counted as a priority medium (Table 1).

Fig. 1 shows where queue management is taking place.

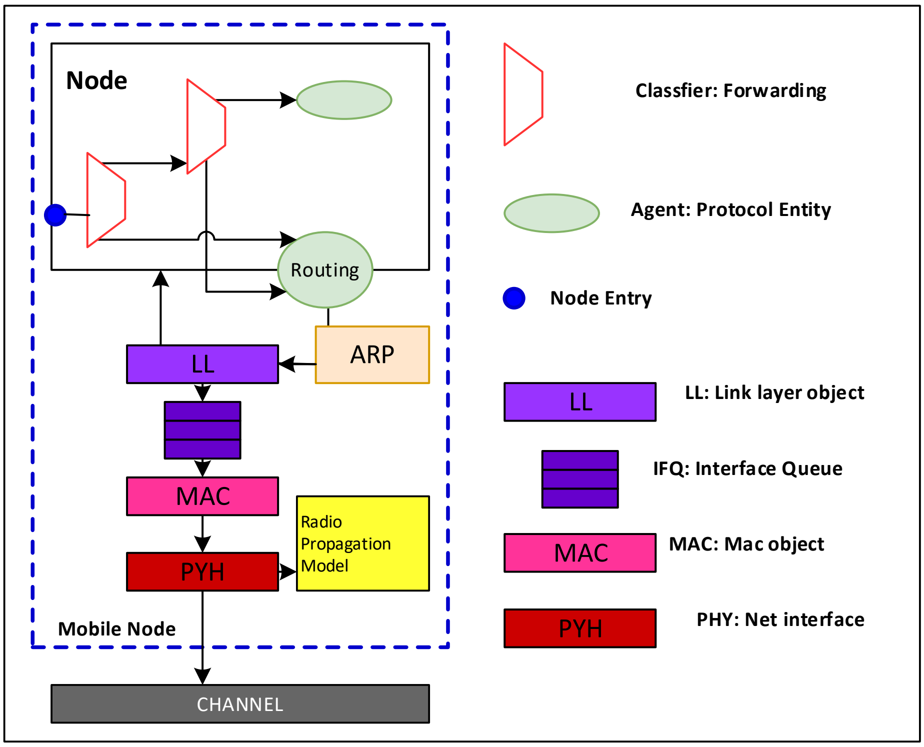

Fig. 1: Where queue management is taking place

Table 1: Packet priority

Priority	Packet Size
High	3KB
Medium	2KB
Low	1KB

In Fig. 2, after packets were passed to the data link layer, Link Logical Control (LLC) or Link Logical Unit (LLU) will be prepared to be transmitted through the media. To achieve this, packet data will be lined up in the queue, which will be divided into the categories previously outlined. The filter process takes place to divide packet data by using the algorithm below. The algorithm will recognize packet data based on size and suitable priority.

The program above shows how the packet is entered into the queue. Before the packet enters the queue, the queue is first given a limit “queue size”, which has been set to 50. The data packet that will enter the queue will be checked first for size in order to determine its priority.

Network topology refers to the arrangement of nodes in a network. There are a few types of network topology; in this case, the random network topology is applied to the WSN. There are 30 nodes that move randomly, as shown in Fig. 3 and one sink node. The sink node is used to receive all data from sensor nodes. The simulation used is Network simulator 2 (NS2), which is the second network simulator version. The parameters in this simulator have been set as in Table 2.

Table 2 and Table 3 show the initial settings in NS2 simulations. Simulations times are in seconds; 100s is set for this study. The number of sensor nodes is set to 30, which includes one sink node. The data rate controls the flow of data during the transmission and determines how much data can be sent in one second. Before MAC can transfer bit data through the medium, the segment data needs to be queued in the queue length. Table 3 explains the behavior of the node and the energy reduction while in transmission, receiving, and idle modes.

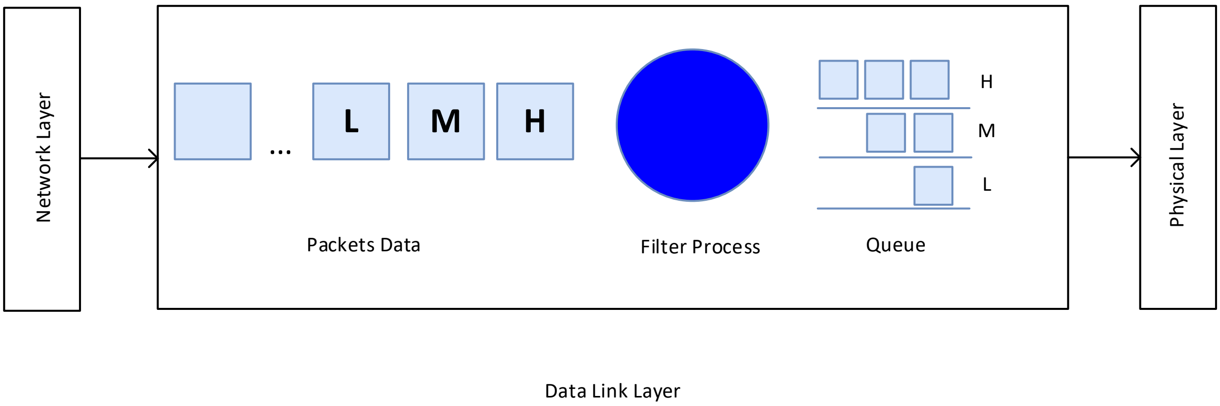

Fig. 2: Queue framework

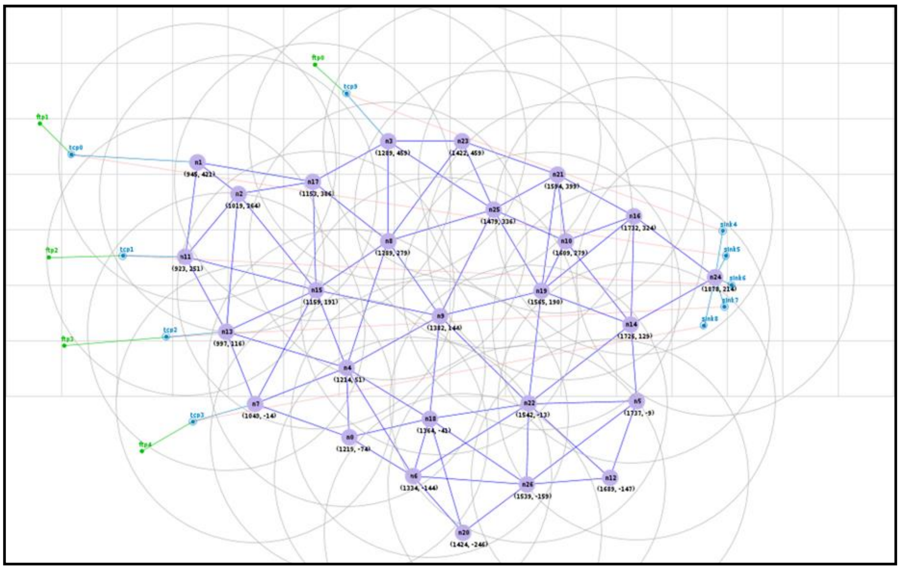

Fig. 3: Network topology

Table 2: Parameter settings

Parameter	Value
Simulation time	100s
Sensor node	30
Area	500 x 500
Data Rate	1.0 mbps
Queue length	50
Duty Cycle Start	70%

Table 3: Energy settings

Parameter	Value
Initial energy	1000 J
Receiving energy	1.0 W
Transmitting energy	1.0 W
Idle energy	1.0 W
Sleep energy	0.001 W

Adaptive duty cycle is determined by packet size, where the larger the packet size the longer the sender node will be active. The duty cycle calculation will be determined based on formula 1 where P_s is packet size, P_n is the number of packets and Q_l is queue length:

$$d_c = \frac{P_s * P_n}{Q_l} * 100\% \tag{1}$$

Usage of energy is based on Table 3, where all node activities have their own energy consumption. Energy consumption is reduced over the time when the node receives or transmits data. Formula 2 shows the calculation of energy consumption of one node, where E_c is the energy consumption, E_i is the mean initial energy (set based on Table 2) and E_f is the final energy after the simulation ends.

$$E_c = E_i - E_f \tag{2}$$

Packet delivery ratio (PDR) is the ratio of packets successfully received by the destination node to the number of the total packet sent. PDR is also used to measure the quality of services (QoS) on the network. The high number of PDR mean the network is in high QoS. To determine PDR, formula 3 is used to calculate the ratio.

$$PDR = \frac{P_r}{P_t} * 100 \tag{3}$$

Opposite to PDR, packet loss is used to measure QoS. The lower the number the packet loss number, the better the QoS in a network. There are many causes of packet loss, one is network congestion. Network congestion reduces QoS and occurs when the node handles more data than it can handle, leading to the data being dropped or blocked. To calculate packet loss, formula 4 is used, where packet loss P_l is equal to packet delivery P_d over number of packets sent P_t.

$$P_l = \frac{P_d}{P_t} * 100 \tag{4}$$

6. Results and discussion

The results of this study will now be discussed, with an understanding of how the priority queue is given (Section 3). To determine the effectiveness of the study conducted, QoS tests, such as energy consumption, packet loss, and packet delivery ratio (PDR) will be tested on the results using NS2 simulation.

Fig. 4 shows the energy usage between three MAC protocols, ESMAC, SMAC, and the default MAC protocol for WSN, 802.11. The graph shows that the energy usage for ESMAC is lowest at the end of the simulation compared to other protocols. Thus, ESMAC gives better energy performance. By using packet priority, ESMAC saves energy because the duty cycles depend on the packet priority. After the queue is empty, nodes will get into sleep mode. This differs from the other two protocols, where duty cycles are fixed, whereas in SMAC, sleep mode will be initiated after the duty cycle ends, and 802.11 has no sleep mode.

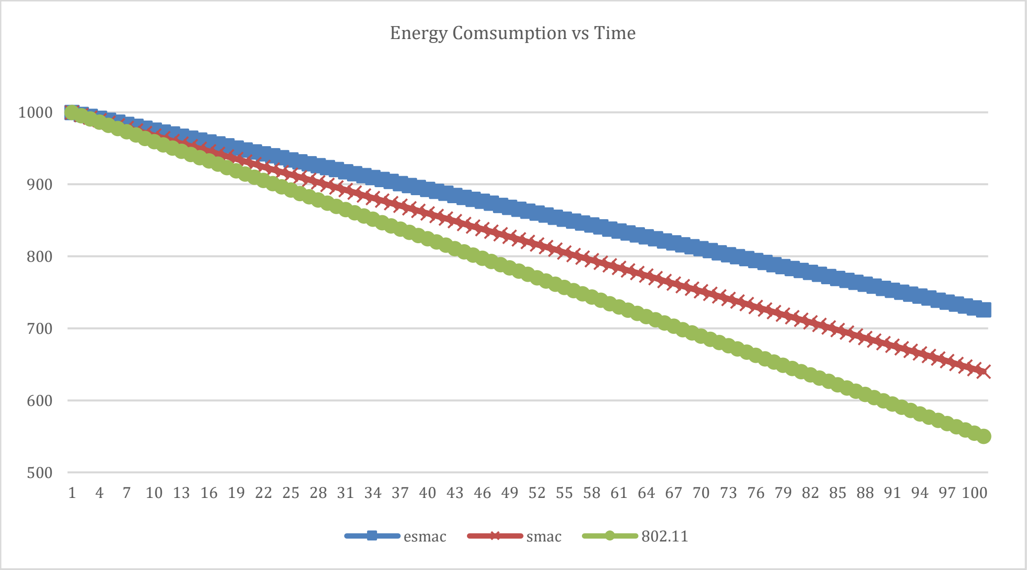

Fig. 4: Energy consumption vs simulation time in seconds

PDR is the percentage of total generated packets or sent packets from source to destination node over the total number of delivery packets in network. The PDR shows the maximum number of packet data that have reached their destination. Fig. 5 shows that PDR for ESMAC is higher for low and medium priority packets than that of the other two protocols. This is because ESMAC gives more time to ensure all data reaches the destination. For high priority packets, ESMAC and SMAC give a similar same result because both protocols send data until the queue is empty before it turns to sleep mode. The default protocol gives a low PDR for all packet priority because it has a longer duty cycle compared to others so that nodes can send the packet until the end of its queue, whereas other nodes must wait and drop the packet when the deadline of the packets is reached.

Packet loss occurs when the packet fails to reach its destination because of problems such as the end of the deadline, collusion, queue limit, or loss of connectivity. Fig. 6 compares the percentage of packet loss to packet priority. In this case, the percentage of the packet is low opposite to PDR; in this graph, the lower the number the better. Thus, it may be concluded that the ESMAC protocol has a low percentage of packet loss at low and medium priority, whereas SMAC has a low percentage of packet loss at high priority. The default protocol 802.11 generates a high percentage of packet loss because the number of packets generated is higher and the number of packets received at the destination is lower.

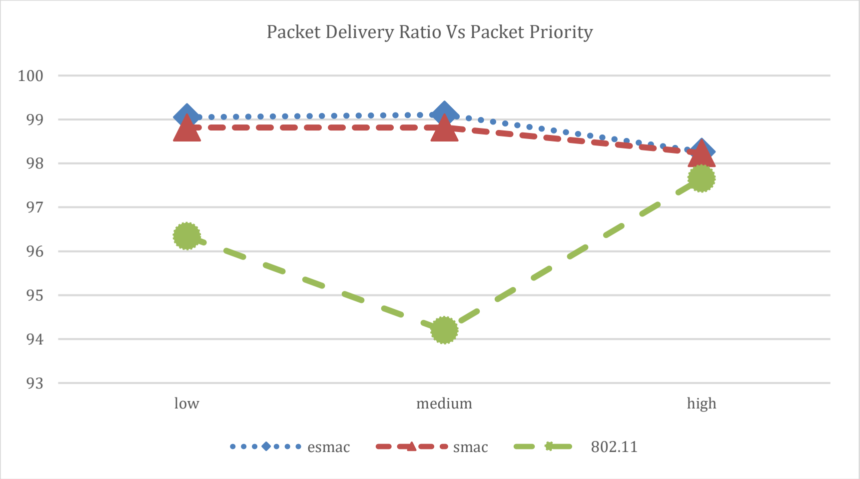

Fig. 5: Packet delivery ratio vs packet priority

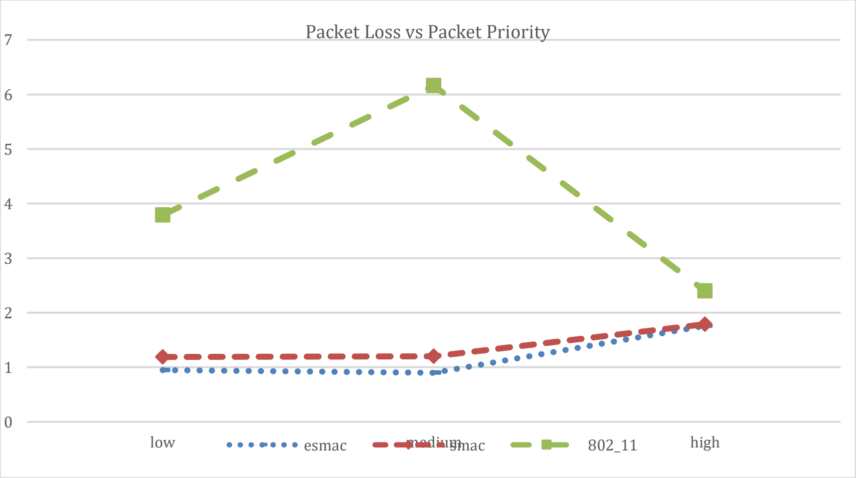

Fig. 6: Packet loss vs packet priority

7. Conclusion

In this study, adaptive duty cycles enhanced by using packet priority as a key parameter. Packet priority plays an important role in ensuring optimum quality of services. ESMAC provides improvement to some degree; specifically, ESMAC provides better performance if packet priority is used as the parameter to achieve high PDR and effective energy usage. Based on these results, every environment has its own optimum setting for the duty cycle. This is important to consider to ensure the quality of services in a network is at the optimum level and in the best condition. One drawback of this study is that packet delay increases if there are a lot of high-priority packets in the queue. ESMAC will only permit high-priority packets to be submitted out, while other packets with lower priority stay in queue until there are no higher priority packets available.

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Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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