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Energy-Efficient Asynchronous QoS MAC Protocol for Wireless Sensor Networks

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Abstract

In recent years, wireless sensor networks (WSNs) have gained significant attention in both industry and academia. In WSNs, each sensor node is normally equipped with a small-size battery with finite capacity. Hence, energy-efficient communication is considered as a key factor for the extension of network lifetime. Formerly, a large number of Medium Access Control (MAC) protocols have been proposed to improve energy efficiency to prolong the network lifetime. There are applications that generate different types of data packets and require Quality of Service (QoS) without any disruption in network operation. Therefore, these applications need an energy-efficient QoS MAC protocol that can support QoS by considering energy efficiency as the primary goal to avoid any failure in the network. This article proposes an energy-efficient asynchronous QoS (AQSen) MAC protocol, called AQSen-MAC. The AQSen-MAC considers different types of data packets and uses two novel techniques: self-adaptation and scheduling to enhance energy efficiency, packet delivery ratio, and network throughput. Furthermore, in the protocol, the receiver adjusts its duty cycle according to the remaining energy to prolong the network operation. Finally, the performance of the AQSen-MAC protocol has been evaluated through detailed simulation using Castalia and compared with MPQ-MAC, PMME-MAC and QAEE-MAC protocols. The simulation results indicate that the AQSen-MAC protocol significantly reduces the energy consumption at the receiver of up to 25%, consumption per bit of up to 12.48%, and improves the packet delivery ratio and network throughput of up to 24% in the network.

1. Introduction

Internet of Things (IoT) is a fast-growing technology and is playing a vital role in many applications such as smart home infrastructure [1], wearable devices [2], building automation [3] and many others. Wireless sensor network (WSN) is a key component for the IoT [4-6]. A WSN consists of low-power, low cost and small-in-size sensor nodes, which have the ability to sense, measure, gather and process information (i.e. conductivity, temperature, pressure, etc.) gathered from the sensor coverage area [7, 8]. The sensor nodes can communicate wirelessly with each other. WSNs have a wide range of advantages in terms of scalability, deployment, simplicity, self-organizing capabilities and others [9] and have many applications including smart cities, food quality, and environment monitoring, industrial process monitoring, health-care, and others [10-12].

In WSNs, sensor nodes are traditionally powered by small batteries with limited capacity [13-16]. Hence, energy efficiency plays an essential role in the lifetime extension [17, 18]. This is due to some scenarios, for instance, volcano monitoring [19], where it is difficult to replace the battery frequently, hence, it requires a longer operational time. This has motivated the researchers to introduce energy-efficient schemes to prolong the network lifetime [16]. For example, the wake-up radio approach helps node to save energy by putting its main radio in the deep sleep mode [20, 21]. Recently, energy harvesting technology allows nodes to harvest energy from the surrounding environment and use the harvested energy to improve network performance [22-25]. For instance, QPPD-MAC [24], CEH-MAC [26] and PEH–QoS [27] schemes optimize the use of available energy to achieve better QoS in the network. Furthermore, QPPD-MAC [24] is developed for solar-based EH-WSNs, where each node harvests energy from the surrounding using a solar cell. The duty cycle management mechanism proposed in QPPD-MAC uses the harvest-store-consume design alternative and adjusts the receiver duty cycle based on three different ranges of the available energy. For example, if the node's energy is above 85%, the highest duty cycle of 1 is assigned to the node to improve the performance. However, when employed in battery-powered WSNs, it can lead to power outage rapidly due to the limited capacity, resulting in overall degradation in the network performance. In some applications such as mines monitoring [28], it is difficult to recharge the battery, hence, energy efficiency is still the prime consideration. In the past, considerable research work has been conducted to conserve energy, which mainly focused on Medium Control Access (MAC) optimization [29], routing algorithms [30], cross-layer optimization methods [31] and data fusion [32]. However, the major sources of energy consumption occur at the MAC layer in channel sensing, packet reception, and transmission, packet overhearing, idle listening, and collision [33].

The MAC protocol regulates the access of a common medium between sensor nodes [34]. In the literature, a large number of MAC protocols have been developed that focus on different applications and scenarios. TCH-MAC [35] and CTh-MAC [36] achieve better energy efficiency and throughput in the network. The protocol in [37] uses intra-cluster communication to save energy; RI-MAC [38] maintains energy efficiency while achieving good packet delivery ratio and packet delay. In [39] QTSAC is proposed to achieve better energy efficiency. However, many existing MAC protocols for battery-powered WSNs have limited support for QoS while considering energy efficiency and network lifetime as primary goals. The QoS is a set of services required by the application [24, 40]. For example, forest surveillance application generates different types of packets such as fire detection (high priority) vs wildlife monitoring (low priority). Thus, a fire detection data packet cannot tolerate a higher delay and needs to be delivered with 1 second [41, 42]. Moreover, the application also requires a longer network lifetime. Hence, such applications need QoS MAC protocol with the prime requirement of energy efficiency to avoid any disruption in the network. Furthermore, the protocol performance evaluation should also consider other QoS parameters such as packet delivery ratio, network throughput and delay in the network [43].

Hence, significant improvements were made to the MPQ-MAC protocol [44] to improve energy efficiency while supporting the priority of packets in the network. Therefore, this paper proposes an energy-efficient QoS MAC protocol for WSNs (AQSen-MAC), where the receiver node shares its wake-up time information with senders that helps in finding a rendezvous point for data transmission. The protocol uses the self-adaptation technique and considers the remaining energy of the receiver node to improve performance and avoid any network failure due to energy depletion, respectively. The results show that the AQSen-MAC protocol achieves better performance than other protocols.

The contributions of this work are as follows:

- An energy-efficient QoS MAC Protocol is proposed to support the priority of packets in the network.
- The protocol uses the self-adaptation technique by which the sender node holding a data packet avoids transmitting the packet when its remaining listening time is less than the minimum listening time required for successful packet transmission. It reduces packet loss and energy consumption of both the sender and receiver nodes.
- The receiver in the AQSen-MAC protocol shares its next wake-up time with sender nodes to improve coordination between nodes for priority data transmission.
- The mechanism by which the receiver node adjusts its duty cycle according to the remaining energy, helps to extend the network operation.
- The performance of the protocol is evaluated in the Castalia simulator for 10 hours of simulation time using the CC2420 radio module and TelosB sensor node. A comprehensive performance evaluation is conducted by considering all QoS parameters in terms of the average energy consumption at the receiver, energy consumption per bit, packet delivery ratio, network throughput, and the average delay for a priority data packet and all packets.
- Performance comparison with MPQ-MAC, PMME-MAC, and QAEE-MAC, which are well-known receiver-initiated QoS protocols for WSNs. The simulation results show that the proposed AQSen-MAC achieves better performance in terms of energy consumption at the receiver, energy consumption per bit, packet delivery ratio and network throughput.

The remainder of the paper is organized as follows: In Section 2, the related works are reviewed. The development of the AQSen-MAC protocol is discussed in Section 3. In Section 4, the performance evaluation of AQSen-MAC protocol is described, and the results are presented and explained in detail. Finally, the conclusion and future work are discussed in Section 5.

2. Related Work

In WSNs, MAC protocols can be categorized into three classes, namely contention-free, contention-based and hybrid protocols as in Figure 1 [45-47]. The contention-free protocols assign variable or fixed time slots to each sensor node for data transmission [48]. This allows nodes to access the channel in the allocated time slots and as a result, collisions in the network are reduced. ETPS-MAC [49] uses a scheduling algorithm that considers energy and traffic load factors while assigning priority to the node. However, nodes are required to exchange their time slots information frequently with each other which incurs additional packet overhead. Furthermore, nodes waste channel bandwidth when they do not have any packet to transmit in their time slots.

The contention-based protocols avoid time slots overhead for packet transmission among nodes and allow them to access the medium randomly. Thus, the risk of collision may increase, which can be avoided by employing different mechanisms, i.e. carrier sense multiple access (CSMA). The contention-based protocols can be further classified into synchronous and asynchronous [50]. In synchronous such as S-MAC [51], T-MAC [52], DW-MAC [53], DSMAC [54], SMACS [55], and PQMAC [56], nodes are required to follow a common listening time in a virtual cluster, where nodes can exchange the data packets. EEQ-MAC [57] and DQTSM [58] support QoS and also achieve better energy efficiency in the network. However, the tight synchronization requires additional overhead that leads to limitations in terms of adaptability, scalability, robustness, and others.

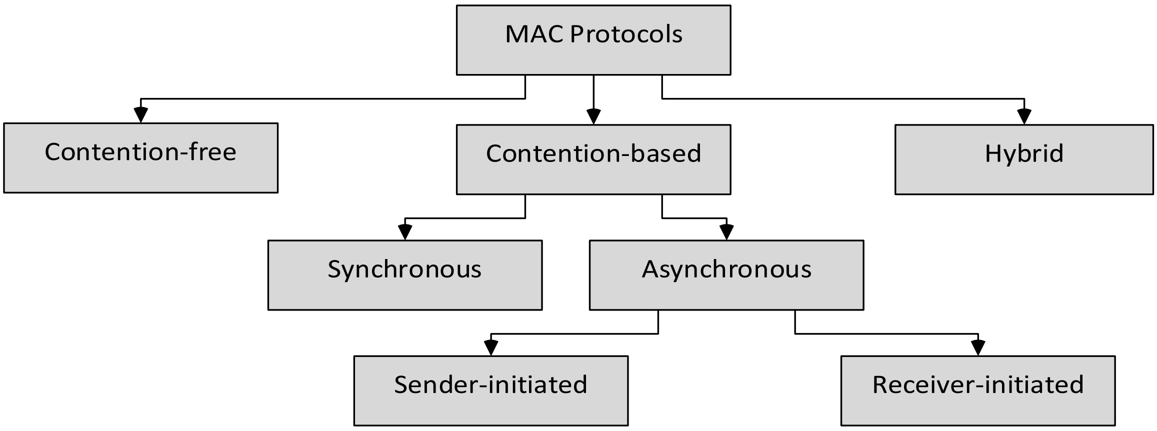


Figure 1: Categorization of MAC protocols [45-47]

In the asynchronous approach, nodes do not require synchronization and consequently, each node can wake-up and sleep independently [38]. Thus, nodes require a rendezvous point for data communication. Comparisons suggest that asynchronous schemes are more energy-efficient than synchronous [59, 60]. The asynchronous protocols are further divided as either sender-initiated or receiver-initiated protocols [61]. The sender-initiated protocols such as B-MAC [59], X-MAC [62] use preamble sampling or low power listening (LPL) technique to establish a communication link between the receiver and sender nodes. These protocols shift the burden at the sender side to initiate the communication, where the node with a data packet transmits a preamble before sending its actual data packet.

The receiver upon waking up detects the preamble and waits for the data packet. In this scheme, the preamble transmission requires a longer time and thus, the sender node holding a data packet is required to wait until the channel becomes free which causes an increase in packet delay and a decrease in network throughput [38]. On the other hand, in receiver-initiated schemes such as RI-MAC [38], RICER [63] and AW-RB-PS-MAC [64] the receiver starts communication by broadcasting a wake-up beacon to informs all senders that it is available to receive the data packets. The sender node with a data packet turns on its radio and listens for the wake-up beacon. Upon receiving the beacon, the sender sends the packet and then, it waits for the acknowledgment packet. The receiver-initiated protocols perform better in terms of energy efficiency than sender-initiated protocols [38, 65].

Formerly, several receiver-initiated QoS MAC protocols have been proposed that consider the priority of data packets such as QAEE-MAC [66], MPQ-MAC [44] and PMME-MAC [67]. QAEE-MAC proposed to support the priority of packets by reducing the delay for the higher priority packets. The receiver initiates communication by broadcasting a wake-beacon that is defined by its duty cycle and then initiates a waiting timer T_w, to receive Tx beacons from senders. On the other side, the sender node with a data packet waits for the receiver wake-up beacon. After receiving the beacon, it transmits the Tx beacon that contains the packet priority and source address. The receiver collects Tx beacons from sender nodes and waits for the completion of the waiting timer. Then, it selects the highest packet priority node and sends the Rx beacon to all senders that includes the address of the selected node. After receiving the Rx beacon, the selected node sends the packet to the receiver and waits for the acknowledgment packet while other nodes go to sleep. However, it supports only two priority level and the receiver needs to wait until the waiting timer expires. As a result, the node with the highest priority packet experiences a higher delay and it also consumes extra energy in idle listening.

Hence, MPQ-MAC [44] and PMME-MAC [67] have been developed to support the multi-priority of packets. MPQ-MAC aims to reduce the delay for the highest priority packet and improve energy efficiency in the network. The protocol follows the receiver-initiated approach and assigns four types of priority levels based on a number (*R*) generated between 0 and 1. It uses a novel technique by which the receiver controls the waiting timer T_w, according to the packet priority. Hence, the receiver after receiving the highest priority Tx beacon cancels the waiting timer to reduce the delay for the highest priority packet. Similarly, PMME-MAC proposed to support the multi-priority of the packets and assigns the channel access probability according to the packet priority level. It provides a higher value of access probability to the highest priority packet and vice versa. As a result, the sender node with the highest priority packet gets to access the medium earlier when compared to other priority packets. Moreover, it cancels the waiting time when it receives the first Tx beacon from the sender node to reduce the packet delay.

However, these QoS protocols have the following limitations. First, sender nodes holding data packets do not have any information related to the wake-up schedule of the receiver. Thus, nodes wait for a longer time for the wake-up beacon, which increases delay and energy consumption. Second, once wake-up beacon is received, the node with data packet goes directly for channel sensing without checking its remaining listening time, which can lead to packet loss and energy consumption at both receiver and sender sides. Third, the receiver operates on a fixed duty cycle that uses a significant amount of energy, so, this may cause a failure in the network operation. Finally, their performance evaluations have not included all QoS metrics such as energy efficiency, packet delivery ratio, network throughput, and packet delay. For instance, the performance of QAEE-MAC has not been evaluated in terms of packet delivery ratio and network throughput and also has not been compared with any other protocol. Similarly, energy efficiency and network throughput parameters have not been included in the performance evaluation of PMME-MAC. Table 1 shows some prominent QoS MAC protocols for WSNs.

The hybrid protocols [35, 36, 68] use the features of both contention-free and contention-based protocols for better network performance. For example, TCH-MAC [35] combines TDMA and CSMA schemes to provide better energy efficiency in a network. However, the use of TDMA structure increases protocol overhead and complexity, which limits the scalability of the protocol [69].

Thus, there is a requirement to propose an energy-efficient MAC protocol for WSNs that can use techniques to find a rendezvous point for priority data transmission between nodes and improve energy efficiency to prolong the network lifetime.

Table 1: Comparative analysis of different priority MAC protocols.

Protocol	Clock synchronization	Packet priority	Adaptive duty cycle	Idle listening
MPQ-MAC [44]	No	Yes	No	High
PQMAC [56]	Yes	Yes	No	Low
EEQ-MAC [57]	Yes	Yes	Yes	Low
QAEE-MAC [66]	No	Yes	No	High
PMME-MAC [67]	No	Yes	No	High

3. Development of AQSen-MAC Protocol

This section focuses on the design of the AQSen-MAC protocol. The main goal is to improve energy efficiency while considering the priority of data packets. To achieve the goal, the protocol design consists of three major components; basic communication overview, data transmission, and energy-aware duty cycle management.

3.1 Basic Communication Overview

The AQSen-MAC protocol follows the receiver-initiated approach as given in Figure 2. The receiver node wakes up and broadcasts a beacon, named wake-up beacon (WB). Then, it starts the waiting timer (T_w) to collect the incoming Tx beacon (TxB) from senders. The receiver node includes the source address (SA) and its next duty cycle (d_c) in the wake-up beacon, as shown in Figure 3. The sender nodes holding different types of data packets: urgent (emergency alarm), most important (real time), on-demand (important) and periodic (normal), wait for the receiver beacon to start communication. The highest P_4 priority is assigned to the urgent data as it cannot tolerate much delay as shown in Table 2.

After receiving the wake-up beacon, the sender checks if the remaining listening time (T_{RL}) is greater than the minimum listening time required for successful packet transmission (T_{Tx}). Then, it performs a clear channel assessment (CCA) to check the channel. If the channel is free, it transmits the Tx beacon using the *p*-persistent CSMA scheme. The Tx beacon has four fields: priority (P), SA, destination address (DA) and NAV (Network Allocation), as shown in Figure 4. Otherwise, it goes to sleep and saves energy. The time required to switch the radio state and process a data packet is called short interframe space (SIFS).

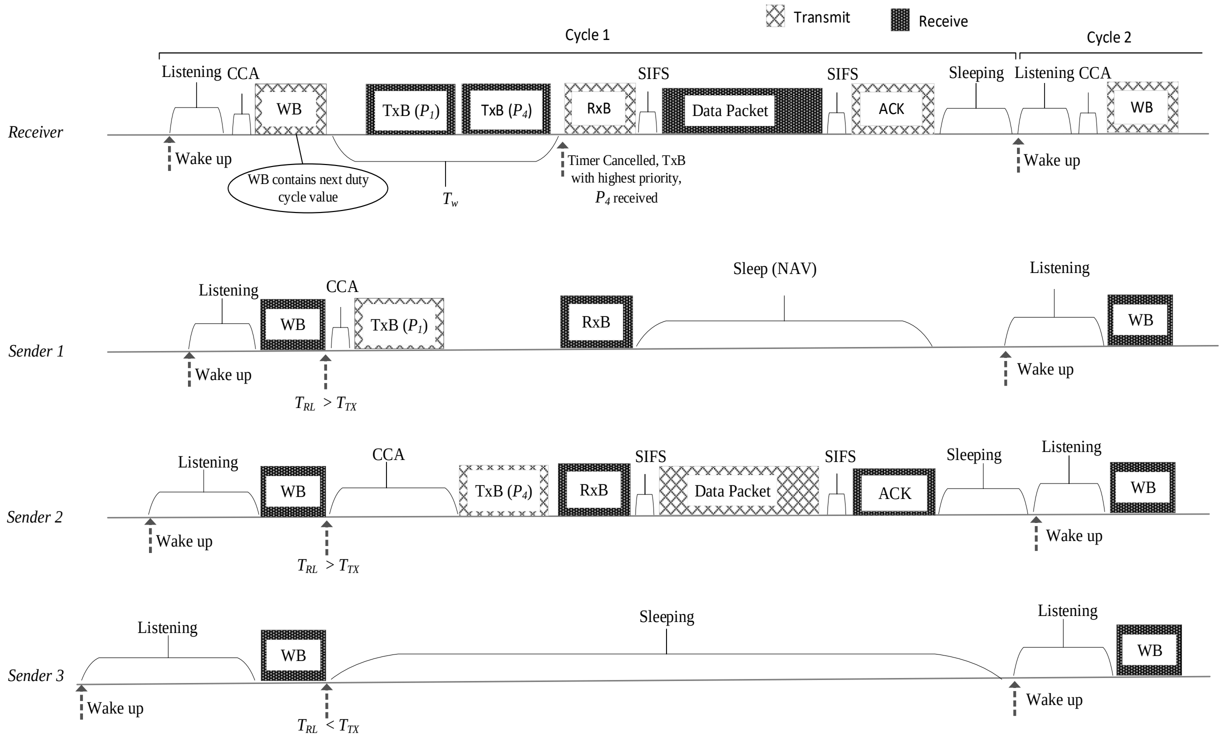


Figure 2: Communication overview of AQSen-MAC protocol.

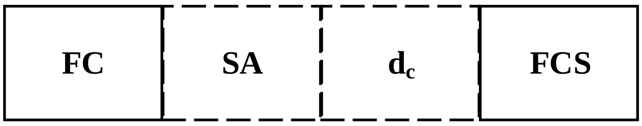


Figure 3: Wake-up beacon (WB). FC and FCS represent Frame Control and Frame Check Sequence fields, respectively.

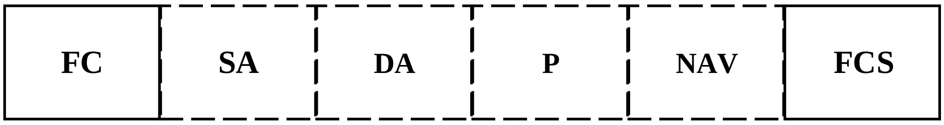


Figure 4: Tx beacon (TxB).

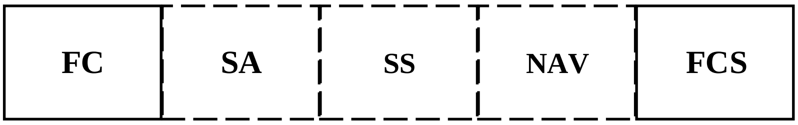


Figure 5: Rx beacon (RxB).

Table 2: Priority levels.

Data type	Priority	Max. delay limit	Example
Urgent	P_4	1	Emergency alarm
Most important	P_3	2	Real time
Important	P_2	3	On-demand
Normal	P_1	4	Periodic

On the other side, the receiver node collects Tx beacon from the sender and checks its priority field. If P_4 priority appears, then it cancels the T_w timer to reduce the delay for the highest priority packet and it transmits the Rx beacon to all senders which contains the address of the selected sender (SS), as given in Figure 5. Once Rx beacon is received, the selected sender transmits the packet and waits for the acknowledgment (ACK packet), which indicates successful packet transmission. Meanwhile, the non-selected senders go to sleep and will wait for the next cycle.

3.2 Data Transmission

The receiver and sender nodes wake up and sleep independently. Therefore, the node holding a data packet spends a significant amount of energy in the idle listening for the wake-up beacon. To address the challenge, the protocol uses self-adaptation and scheduling techniques.

In the former, after receiving the wake-up beacon, sender nodes check their remaining listening time, T_{RL}. If $T_{RL} > T_{Tx}$, they sense the medium for Tx beacon transmission using the *p*-persistent CSMA mechanism. Else, the sender node avoids channel sensing and goes to sleep to minimize energy consumption and packet retransmission. Consider a scenario for data transmission as shown in Figure 2, where *Sender 1* (S_1) and *Sender 2* (S_2) *transmit* Tx beacons with P_1 and P_4, respectively. However, *Sender 3* goes to sleep and waits for the next cycle. The receiver after receiving both Tx beacons from S_1 and S_2, checks the priority. It selects the sender node that has P_4 priority and cancels the T_w timer to reduce the delay. Then, it broadcasts Rx beacon which includes the address of S_2. After receiving the Rx Beacon, S_2 sends the actual data packet while other non-selected nodes go to sleep and wait for wake-up beacon in the next cycle. In case when more than one Tx beacons are received with the same priority, then the receiver selects the node based on the first received Tx beacon. In case when P_4 does not appear, then the receiver waits until T_w timer expires. Once T_w expires, it selects the sender node that has the highest priority among all received Tx beacons. In the worst scenario, a sender node with P_1 priority may contend with several new nodes that have P_4 priority. In this case, unfortunately, it will only get the opportunity to send its data packet after all the nodes with P_4 priority. However, this occurs rarely and its occurrence probability decreases with the number of nodes with P_4 priority. This is a tradeoff in the AQSen-MAC protocol as it ensures that the P_4 priority node is able to send its packet faster than normal packets.

In the latter, the receiver node includes its next duty cycle in the wake-up beacon which allows the sender nodes to adjust their sleeping time accordingly and wake up slightly before the receiver for data transmission. This technique helps in coordination between the receiver and sender nodes for successful data transmission and also reduces energy consumption in idle listening.

3.3 Energy-aware Duty Cycle Management

The receiver node is equipped with a small size battery with limited capacity and its energy level decreases with time. Thus, the node can only operate for a longer period of time if it uses its energy more effectively. Therefore, the receiver in AQSen-MAC protocol adjusts its duty cycle, d_c according to the remaining energy in order to extend the network lifetime. The receiver node decreases the duty cycle by increasing its sleep duration (T_{sleep}) in order to conserve energy. As a result, it sustains its operation for a longer period of time. The d_c can be calculated using the following formula

$$d_c = \frac{(E_L - E_{th})}{(100\% - E_{th})} \tag{1}$$

where E_{th} (10%) is the threshold energy level, which is used to ensure that the node does not exhaust completely. The remaining energy (E_L) in percentage (%) is shown as follows

$$E_L = \frac{E_r}{E_{\max}} \times 100\% \tag{2}$$

where E_r and E_{max} denote the remaining energy and maximum battery capacity in joules, respectively. The calculated d_c value can be used to determine the sleep duration (T_{sleep}) of the node as shown in the following equation

$$T_{sleep} = \frac{T_{listen} \times (1 - d_c)}{d_c} \tag{3}$$

where T_{listen} represents the total listening time.

4. Results and Discussion

The performance of the AQSen-MAC protocol is evaluated through Castalia 3.3 [70] Simulator. Castalia simulates sensor applications using CC2420 radio module parameters [71], including sensor node TelosB [72]. The CC2420 radio is extensively used in sensor applications and has four operational states: Sleep, Reception, Transmission, and Idle listening. Table 3 shows the power consumption of CC2420 in each state. It can be noticed that both receive and idle states consume the same power [45]. In AQSen-MAC protocol, when the number of sending nodes is higher per receiver, then waiting time T_w will also increase, resulting in higher energy consumption. Hence, it is resolved by considering a network that consists of several smaller sized clusters where the number of sender nodes per receiver is small. Therefore, a star network is implemented to demonstrate the features of the AQSen-MAC protocols as shown in Figure 6. The clustering in a large network helps to improve energy efficiency and scalability [16, 73]. In addition, it also widely used in modelling of effective solutions to minimize the suppression of malware actions in WSNs [74, 75]. In the network topology, the receiver node is located at the center while other nodes are randomly positioned in a square area of 30 m × 30 m. Each sender node generates a total of 36,000 packets with a rate of 1 packet per second, where the size of the data packet is 28 bytes. The performance of the AQSen-MAC is evaluated for all QoS parameters in terms of average energy consumption at receiver, energy consumption per bit, packet delivery ratio, average network throughput and delay for priority and all data packets. Moreover, the protocol performance is also compared with MPQ-MAC, PMME-MAC, and QAEE-MAC, which are well-known receiver-initiated QoS protocols. The receiver's initial energy is set to a fixed value of 75% in all protocols and the receiver adjusts its duty cycle according to the remaining energy level. The receiver in MPQ-MAC, PMME-MAC, and QAEE-MAC operates on a fixed duty cycle of 0.72. All protocols use the p-persistent CSMA mechanism for the Tx beacon transmission and the p value is set as $1/n_s$, where n_s represents the total number senders. In addition, they assign the packet priority randomly based on a number (R) generated between 0 and 1. In PMME-MAC, the p value is set according to the packet priority level, as given in Table 4. The simulation parameters are given in Table 5. For comparison, the linear priority assignment type of PMME-MAC is implemented.

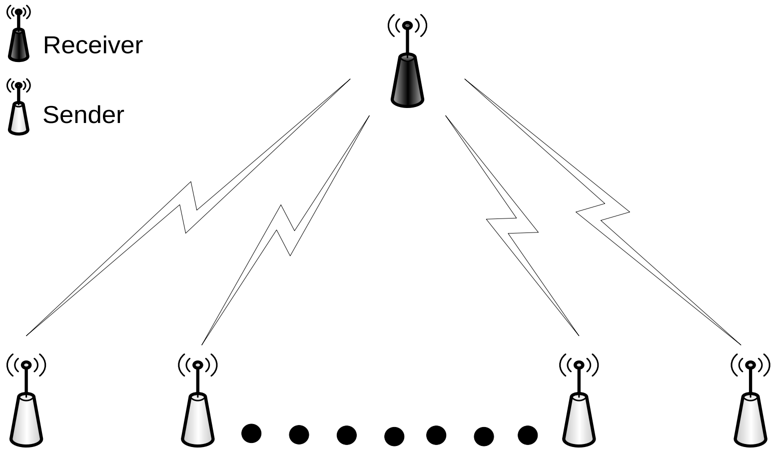


Figure 6: Studied network topology

Table 3: Power consumption in CC2420 [71]

Radio state	Power consumption (mW)
Transmission	57.42
Reception	62.04
Idle listening	62.04
Sleep	1.4

Table 4: Packet priority assignment

Priority	R	P (Linear type)
P_4	$0 < R \leq 0.25$	0.4
P_3	$0.25 < R \leq 0.5$	0.3
P_2	$0.5 < R \leq 0.75$	0.2
P_1	$0.75 < R \leq 1$	0.1

Table 5: Parameters used for the performance analysis of AQSen-MAC protocol

Parameter	Value
Simulation time	10 h
Sender nodes	1 to 7
Area	30 m × 30 m
Sensor node	Telos Rev B
Operating voltage	2.1 V
Size of data packet	28 bytes
Size of Tx beacon	14 bytes
Size of Rx beacon	13 bytes
ACK packet size	11 bytes
Wake-up beacon size	9 bytes
Data rate	250 kbps
Slot time	0.32 ms
CCA check delay	0.128 ms
SIFS	0.192 ms
T_w	5 ms
Packet rate	1 packet/s
Listen time	17 ms
Retransmission limit	10
Buffer size	32
Frequency	2.4 GHz
E_{max}	810 Joules
E_{th}	10 %

Figure 7 shows the receiver energy consumption (E_T) in all protocols with the varying number of senders. The formula to calculate the energy consumption of a node is as follows

$$E_T = \sum_{i=0}^{n} P_i \times t_i \tag{4}$$

where n, i, P and t represent the number of states, radio state, power consumption rate and the time spent in state i.

It is observed that the AQSen-MAC provides a significant reduction in energy consumption of up to 15% than other protocols, which helps the receiver to operate for a longer period of time. This is due to the fact that the receiver node adjusts the duty cycle according to its remaining energy. The remaining energy decreases with time and therefore, it also reduces the duty cycle by increasing the sleep duration to save energy. In MPQ-MAC, PMME-MAC, and QAEE-MAC, the receiver operates with a fixed duty cycle of 0.72 and therefore, its remaining energy declines rapidly. Hence, it becomes non- operational after a few hours (≈ 5.5h), when its remaining energy goes below the threshold level E_{th} (10%), which caused an operational disruption in the network. It can also be seen that the receiver consumes more number of sender nodes increases, which consumes more energy.

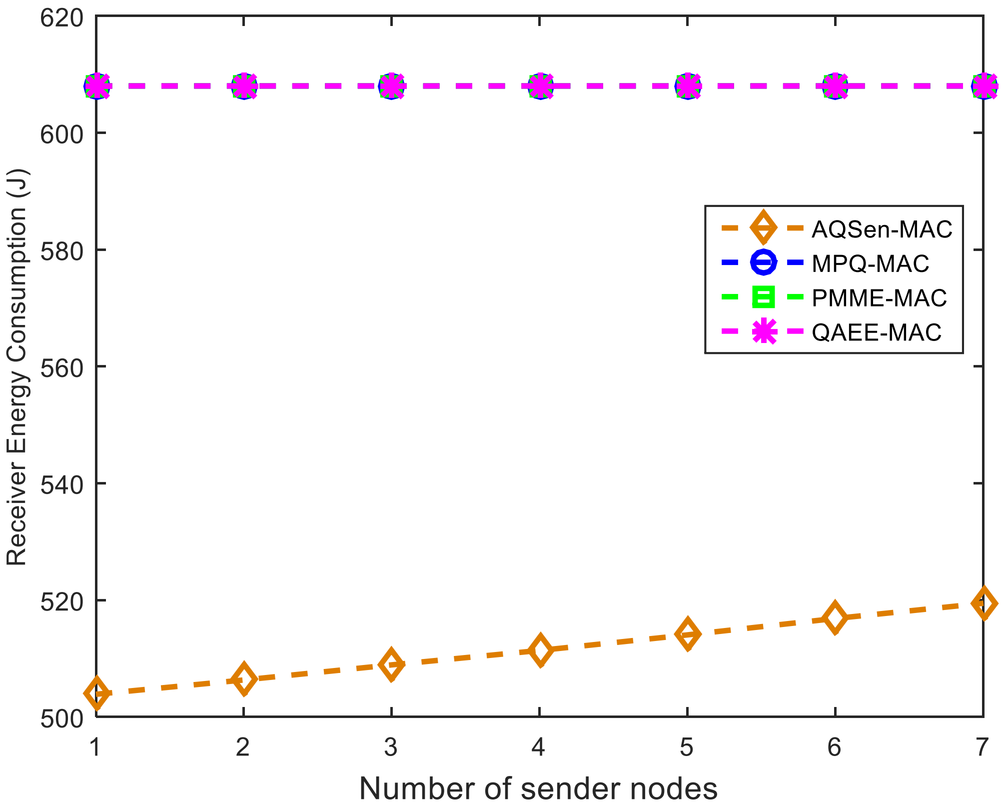


Figure 7: Average receiver energy as a function of the number of sender nodes (from 1 to 7)

Figure 8 shows the remaining energy of the receiver when the number of sender nodes is 7. The receiver's initial energy is set to 75% of total capacity in all protocols. In AQSen-MAC, the remaining energy decreases to 10.9% after 10h, while MPQ-MAC, PMME-MAC, and QAEE-MAC used all of their energy and became non-operational after 5.9h, 7h, and 5.6h, respectively. This is because the AQSen-MAC uses its remaining energy to adjust the duty cycle. Hence, it conserves energy by increasing its sleep time and as a result, its remaining energy does not drop below the E_{th} level. It can also be seen that the PMME-MAC operates for a longer period of time when compared to both MPQ-MAC and QAEE-MAC. The reason is that the receiver cancels the T_w timer when it received the first Tx beacon, which helps to conserve energy and increases its operation time.

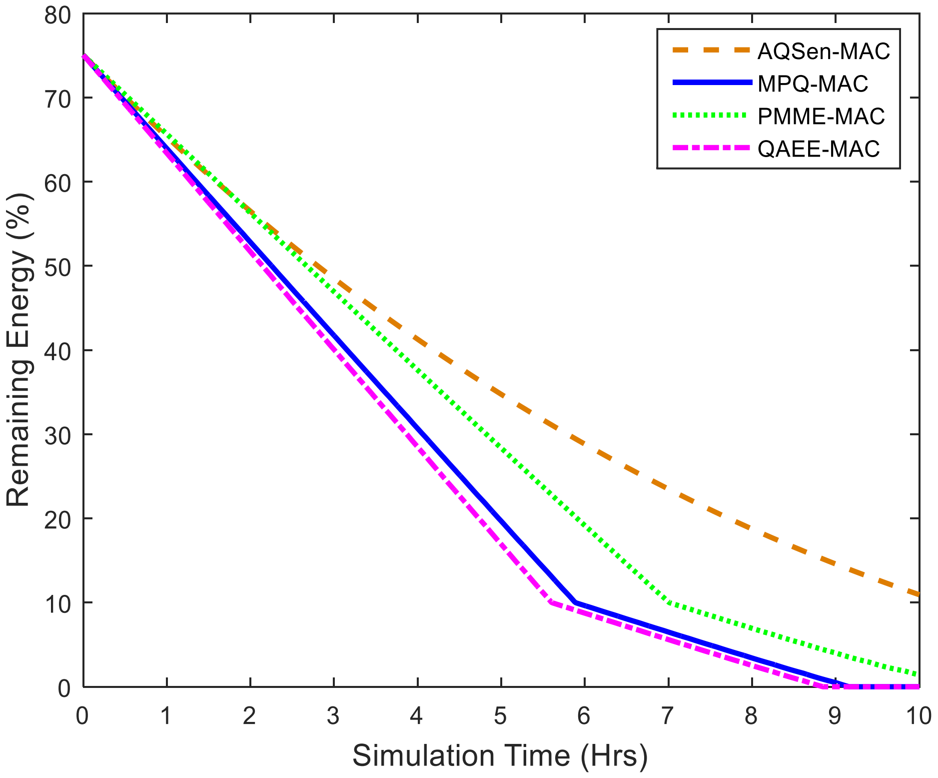


Figure 8: Receiver remaining energy when the number of sender nodes is 7

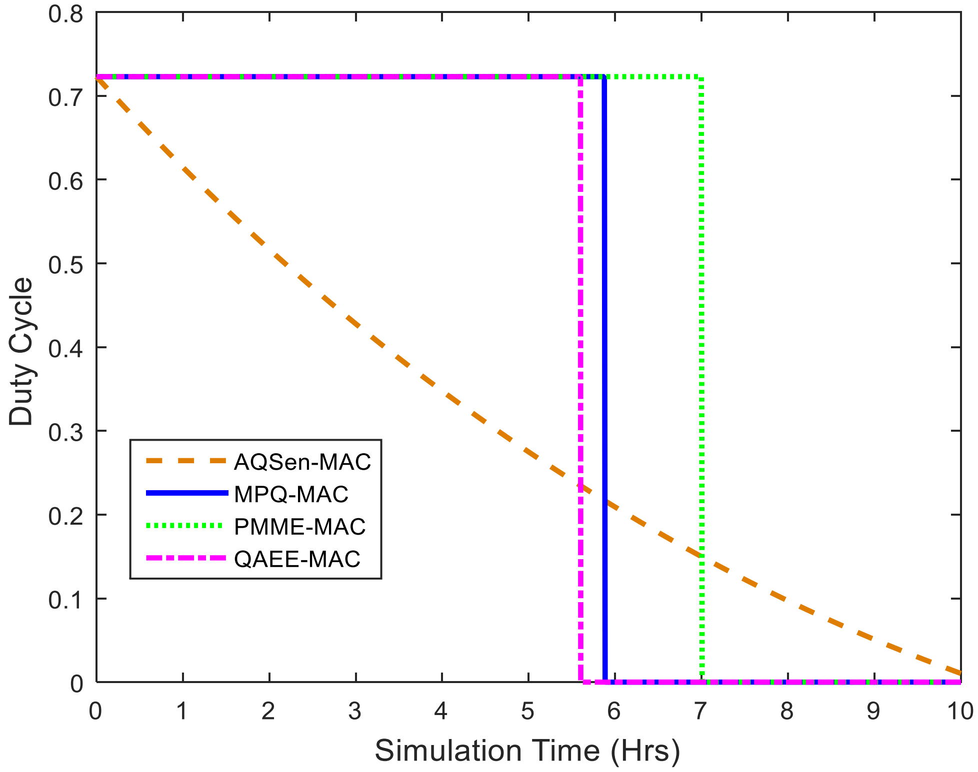
The duty cycle of the receiver corresponding to the remaining energy is shown in Figure 9. It can be seen that the AQSen-MAC adjusts its duty cycle based on its remaining energy. It decreases its duty cycle when it has the lower remaining energy and therefore, it does not suffer any disruption in the network. In MPQ-MAC, PMME-MAC, and QAEE-MAC, the receiver operates with a fixed duty cycle. When its remaining energy reaches the E_{th} level, it turns off the radio and goes to sleep, which causes a significant impact on network performance.

The packet delivery ratio (*PDR*) is defined as the total number of packets received by the receiver divided by the total number of packets transmitted by the sender nodes. The equation to calculate *PDR* is as follows

$$PDR = \frac{NP_{PktR}}{NP_{PktT}} \times 100\% \tag{5}$$

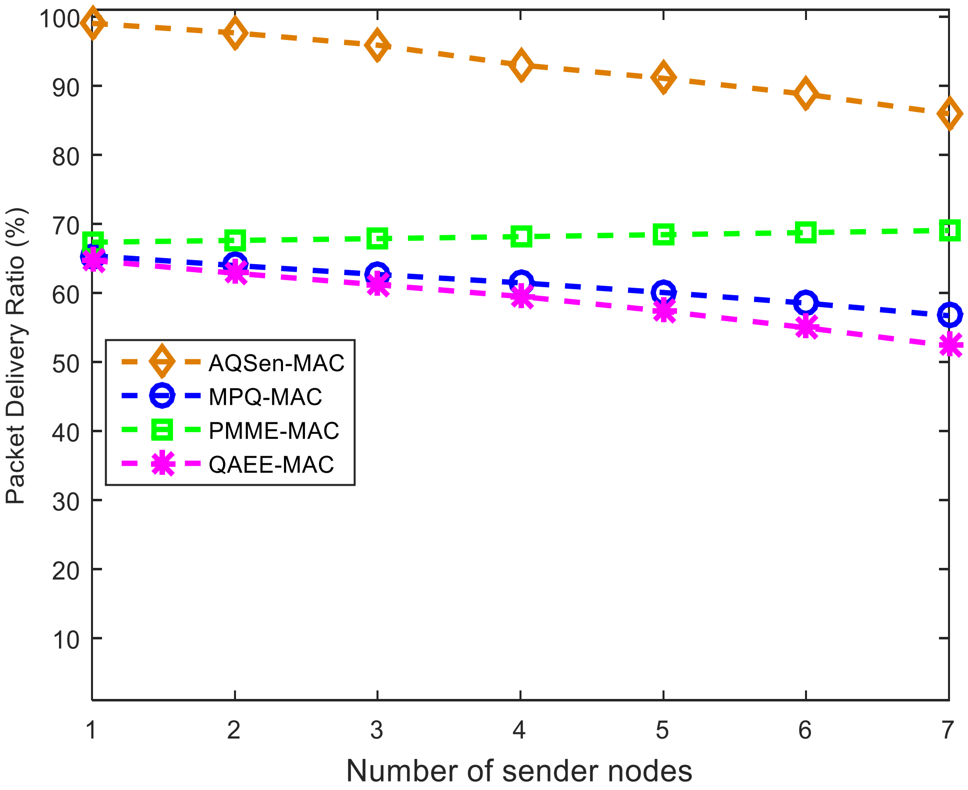
where NP_{PktR} and NP_{pktT} represent the total number of data packets received and transmitted, respectively.

Figure 10 presents the *PDR* of all protocols. It is seen that the AQSen-MAC outperforms other protocols by up to 24%. The first reason is that the AQSen-MAC does not face any disruption in the network and the receiver is available to receive the packets from senders. However, in other protocols the receiver becomes non-operational for more than 4h and as a result, the sender nodes drop the incoming data packets when the buffer limit is exceeded. The second reason is that the receiver broadcasts its next duty cycle which helps the sender nodes with packets to synchronize with the receiver for packet transmission. The third reason is that the sender node, after receiving the wake-up beacon, checks its remaining listening time. If it has enough time for a successful packet transmission then transmits the Tx beacon else, it goes to sleep, which also avoids the packet loss. It can also be noticed that the *PDR* decreases marginally for the higher number of senders, which is due to the fact that the retransmission limit is exceeded.



401

402 Figure 9: Receiver duty cycle when the number of sender nodes is 7



403

404 Figure 10: Average packet delivery ratio as a function of the number of sender nodes.

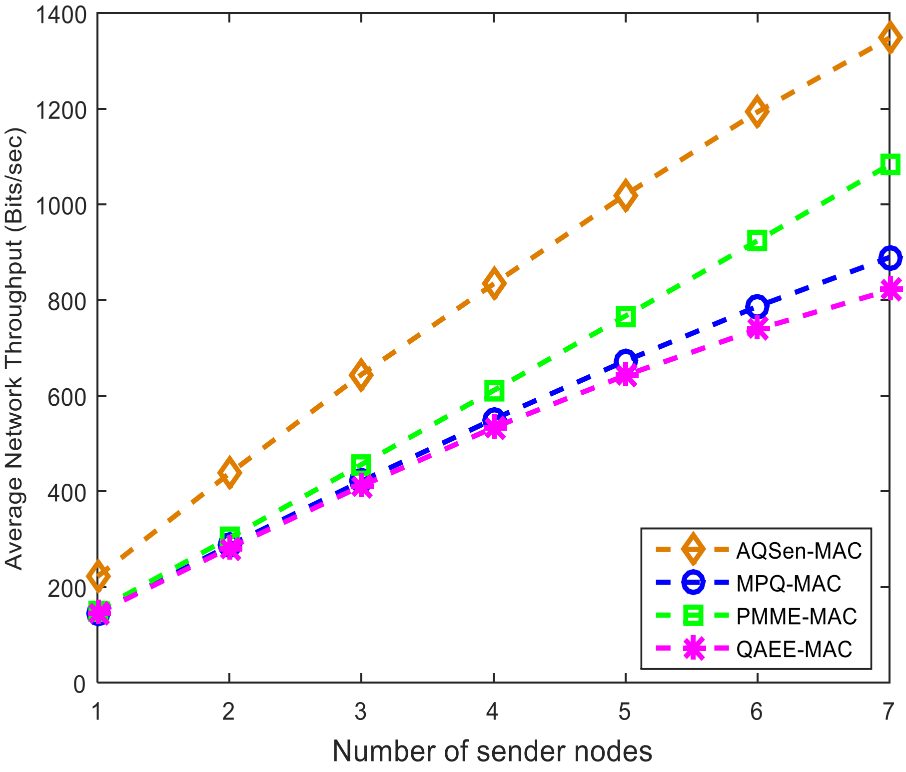


Figure 11: Average network throughput as a function of the number of sender nodes

The average network throughput (S) is defined as the number of data packets received at the receiver divided by the simulation time as shown below

$$S = \frac{NP_{PktR} \times L_{Pkt}}{T_s} \tag{6}$$

where L_{Pkt} and T_s denote the size of the packet in bits and simulation time in seconds, respectively.

Figure 11 shows the average network throughput performance comparison between the AQsen-MAC, MPQ-MAC, PMME-MAC, and QAEE-MAC. In all protocols, the network throughput increases linearly across the various number of sender nodes. It can be noticed that AQSen-MAC shows an improvement of up to 24% when compared to others.

The average energy consumption per bit (E) is shown in Figure 12, which is defined as the total energy consumed divided by the total number of data packets received, as shown below

$$E = \frac{E_T}{NP_{PktR} \times L_{Pkt}} \tag{7}$$

and for the calculation of E_T , (4) can be used.

The AQSen-MAC gives an improved performance of up to 30.76%, 12.48%, 36.99%, when compared to MPQ-MAC, PMME-MAC, and QAEE-MAC, respectively. The first reason is that the AQSen-MAC receives more packets than other protocols as shown in Figure 10. The second reason is that sender nodes after receiving the wake-up beacon, extend their sleep time for synchronization with the receiver, which also has influence on reducing energy at the sender side. It is observed that MPQ-MAC, PMME-MAC, and QAEE-MAC consume almost the same amount of energy, however, PMME-MAC transmits slightly more packets. Therefore, it shows better performance when compared to MPQ-MAC and QAEE-MAC.

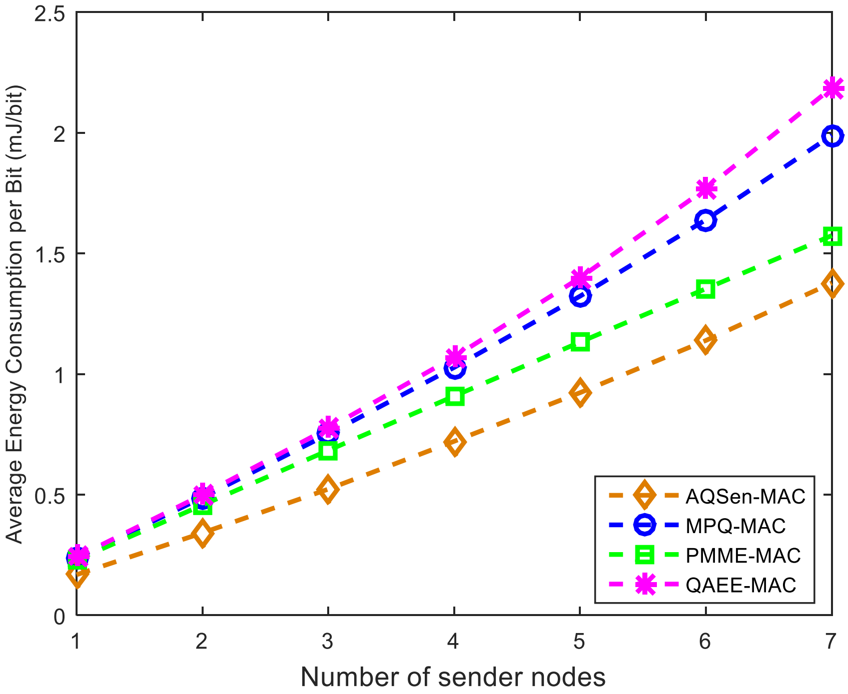


Figure 12: Average energy consumption per bit as a function of the number of sender nodes

The average packet delay (d_{ETE}) in all protocols is given in Figure 13. It is the time period between the generation of the packet until its reception at the receiver. The equation to calculate the average packet delay is as follows

$$d_{\mathrm{ETE}} = d_{\mathrm{queu}} + d_{\mathrm{trans}} + d_{\mathrm{prop}} + d_{\mathrm{proc}} \tag{8}$$

where d_{queu}, d_{trans}, d_{prop}, and d_{proc} denote queuing, transmission, propagation and processing delays, respectively.

It can be seen that the data packet experiences delay of around 70% in AQSen-MAC when compared to other protocols, however, the delay is still within an acceptable range (less than 0.35s). This is because of the duty cycle mechanism, where the receiver increases its sleep time to save energy. Hence, the sender node with the data packet waits longer for the receiver beacon, which increases delay. It can also be seen that the PMME-MAC achieves better delay performance than other protocols. The reason is that the receiver, after receiving the first Tx beacon cancels the T_{w} timer, which reduces the packet delay.

Figure 14 shows the average packet delay for the priority data packet in AQSen-MAC to that of MPQ-MAC, PMME-MAC, and QAEE-MAC. Only delays for the highest and lowest priority packets are shown for all protocols. It can be noticed that the AQSen-MAC protocol suffers more than 2-times higher delay for the P_4 priority packet when it is compared with other analysed protocols, as expected. The fact is that the AQSen-MAC tries to preserve energy using duty cycle adjustment, at a price of increased delay in order to avoid any failure in the network operation. Nevertheless, the AQSen-MAC still supports the highest priority packet and also provides packet delays that are within acceptable limits (less than 1 s).

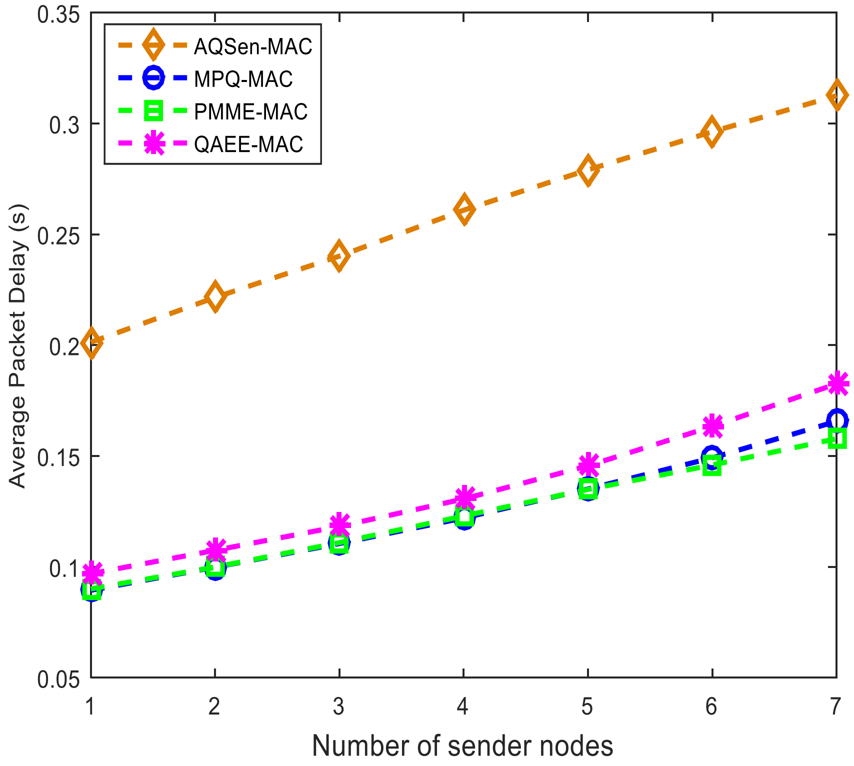


Figure 13: Average packet delay for data packet as a function of the number of sender nodes

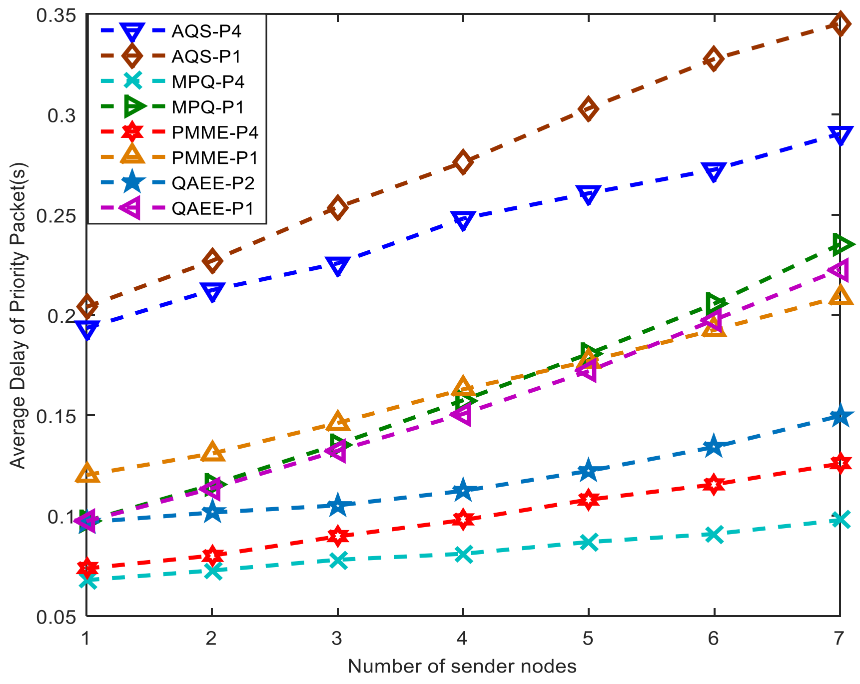


Figure 14: Average packet delay for priority data packet as a function of the number of sender nodes

5. Conclusion and Future Work

In this paper, an energy-efficient QoS MAC protocol has been proposed for achieving better energy efficiency while considering the priority of data packets. The AQSen-MAC protocol has used self-adaptation and scheduling techniques to improve energy efficiency and packet transmission in the network. The former helps to improve coordination between the receiver and sender nodes for packet transmission. In the latter, sender nodes avoid channel sensing to improve energy efficiency and packet delivery ratio. Furthermore, the protocol employs the energy-aware duty cycle management mechanism to prolong the network lifetime. The results show that the AQSen-MAC protocol provides a reduction in energy consumption at the receiver of up to 25%, consumption per bit of up to 12.48%, and improves the packet delivery ratio and network throughput by up to 24% in the network while maintaining its operation in the network. However, MPQ-MAC, PMME-MAC, and QAEE-MAC protocols were unable to sustain their operations and they became non-operational after 5.9h, 7h, and 5.6h, respectively. Finally, the AQSen-MAC MAC protocol can be used in applications that can tolerate a maximum delay of 1 s for the highest priority data packet and also require higher energy efficiency in the network.

The future work includes the extension of the AQSen-MAC protocol for solar-based energy harvesting WSNs. The performance will be evaluated on tests-beds using a mesh network under realistic energy harvesting scenarios.

Data Availability

The simulation parameters used in the performance analysis of AQSen-MAC are given in the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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