Energy Efficient Quality Assurance MAC Protocols in WSN

Rinkuben N Patel, Nirav V. Bhatt

***Abstract**: The key aim of the proposed research is to perform an analysis of various QoS aware MAC protocols for WSN based on simulation and literature both. The proposed work represents the designs and methodologies of different MAC protocols. And also classify the various MAC protocols based on media access and allocation of schedule for communication among the sensor nodes. The proposed work performs the analysis by designing, developing and analyzing various quality aware MAC protocols for Wireless sensor network. This paper describes the detailed analysis of different channel access methods of a network. It also depicts detail algorithms of SMAC and describes the procedure of data communication in TMAC, BMAC, and ZMAC. Also, simulate the SMAC and TMAC protocols to analyze energy efficiency as a QoS parameter. The simulation of SMAC and TMAC data transmission is done in network simulator 3 by using various network parameters. In this research the QoS parameters like Energy, Throughput, delay and, latency are analyzed by simulation and literature respectively. A new research always starts with analysis of existing one. So, Analysis of different MAC is useful for the WSN research community to propose and develop a QoS aware MAC protocol.*

Keywords: Analysis, Delay, Energy, MAC, QoS, Throughput, WSN

I. INTRODUCTION

WSN is made up of small intelligent devices known as sensor devices. Various types of WSN are terrestrial WSN, underground and underwater WSN [24], multimedia WSN and mobile WSN[9]. Sensors having sensing, buffering and transmission capabilities. Medium access and efficient data communication is a goal of the MAC layer. The various task of MAC is channel access, node wakeup, and sleep schedule, listening and transmitting to the network and sensing. Routing in WSN is different from traditional IP Networks. Moreover, limitation like node's energy, limited storage and computation capability, dynamic network topology, asymmetric links, and a network size makes MAC protocols different from traditional network protocols [23]. Various routing protocols are designed by the research community [4]. For routing each node talking to multiple nodes, sometimes hundreds of thousands of nodes make it complicated and inefficient at the energy and storage level.

Routing in WSN is categorized as location-based routing, flat routing, and hierarchical routing [14]. In hierarchical routing, Nodes in a network perform different activities. In location-based routing, the position of a node is considered for routing of data. In flat routing, all nodes assign a similar task in a network. Adaptive routing protocols are the protocols that control the system parameters in a specific situation and it behaves accordingly. The routing techniques are also classified as per its routing needs like single path routing and multi-path routing [10], query-based routing, QoS based routing, negotiation-based routing, and coherent based routing. These categories are classified based on the operation done by the network.

The WSN is event-driven networks where, the event occurred and based on that the node in a network perform the sensing task, transmitting task, and receiving task. And action will be taken as per the received information by the base station. Simultaneously, a network shares the same channel for transmission and receiving of data. So, the higher traffic in a network leads to the delay of sensitive information and because of that retransmission of packets may take place for accuracy. And, retransmission of data leads to collision and affect the energy level of a network. Therefore we need a network that achieves the maximum number of QoS parameters like throughput, delay, success rate, packet loss, path length, low energy consumption, load balancing, and network lifetime [9]. The aim of this paper is an analysis of some standard MAC protocols like SMAC, BMAC, TMAC, and ZMAC.

QoS requirements in WSN has been studied very widely [2][11][12][13][17]. WSN MAC protocols are classified based on channel access and according to its design goals [2][1]. For the different applications of WSN, there are different technical issues and different QoS requirements. The research community has pointed out various open research issues in WSN [5]. Previously WSN comes into existence, the energy efficiency was the primary requirement [3]., and only the best effort data delivery was sufficient as a QoS. For energy consumption, many protocols are developed and designed like ESDCH[18]., SMAC, TMAC, DMAC, RMAC, PSIFT, TRAMA, and many others; however, by the time, design of MAC protocols focuses on different design goals like packet delay, jitter, network throughput, and latency. And also different criteria are available which are used to classify the protocols. In the industrial context, energy efficiency has the same priority equal to requirements like reliability, low-delay, and robustness [2]. In early development stages, the designers of a network protocol were mostly concerned with energy-efficiency because sensor nodes are usually limited in power capability.

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But now the research community has focused on various parameters like multi-task support and efficient delivery of busty traffic [17]. Parallel to the growth of WSN applications, the WSN applications have a requirement of higher bandwidth and low delay to satisfy this necessity of a network. The QoS requirements of various applications are the lifetime of a network, data reliability, power efficiency, and location-awareness and collaborative-processing [8]. These QoS factors will affect the selection of routing protocols for a particular application. In some applications (e.g., some military applications) the data should be delivered within a specified time with little less delay [7]. Most of WSN future applications will require timely delivery of data. Moreover, a variety of the applications yield to heterogeneous WSNs composed of multimodal sensor nodes. Multi-modal sensor nodes means to provide more than one functionality by delivering multiple types of traffic in a network. Therefore a novel MAC Protocol that can fulfill the application requirements regarding delay guarantee for each kind of traffic is required. WSN needs protocols which easily meet the QoS parameters in each layer of the communication protocol stack [2]. In 2013 Jian-ha wang and Yan yu., work on throughput for surveillance applications and achieves a throughput of a network. In WSN each node generates management packets and data packets where management packets are generated periodically, and data packets are event-driven. They assure that both types of packets should be delivered in a given time deadline. These WSNs should meet three requirements are high throughput, service differentiation, and long life of the network. MCSMAC [3] is more optimized and efficient than SMAC in terms of energy consumption. To achieve a Specific QoS, we require a proper suitable channel access policy for MAC development. Here we have discussed various channel access methods like TDMA (Time Division Multiplexing) – Has a natural advantage of collision-free medium access. It has a pitfall like a clock drift problems and low throughput at low traffic loads because of an idle slot [20]. CSMA has a lower delay and good throughput potential at lower traffic loads. FDMA offers a collision-free medium, but it requires additional circuitry to dynamically communicate with different radio channels. Dynamic communication in FDMA increases the cost of the sensor nodes which is contrary to the aim of WSN. CDMA also offers a collision-free medium, but its high computational requirements are a significant obstacle for the less energy-consumption objective of sensor networks. In a contention-based scheme, nodes run to access the shared medium. It is simple to implement and more suitable for infrastructure-less networks. Compared to TDMA, CSMA scheme does not require any additional information about network traffic, infrastructure, size, and density. Contention-based scheme easily handles busty traffic load because nodes do not have to follow the schedule for transmission [21].

SMAC is designed to achieve energy-efficiency, scalability and low collision. Source of energy wastage in a network are a high collision, overhearing, control overhead, and Idle listening. SMAC tries to decrease energy waste from all the sources which are mention above [15][20].

The organization of this document is as follows. Section 2 (Analysis of QoS aware MAC), Contains a detailed study on various QoS aware MAC protocols. Section 3 (Performance Analysis and Comparison of Existing MAC), presents the comparison of SMAC and TMAC and the result of the research is discussed in Section 4(Result and Discussion). In Section 5 (Conclusion) the conclusion of a paper is described. And In Section 6, the list of abbreviated words is provided. References are listed in Section 7.

II. ANALYSIS OF QOS AWARE MAC

A. SMAC: Sensor MAC is an energy-efficient MAC protocol designed and developed by Wei-Ye [22]. It achieves energy efficiency by node listen and sleep schedule mechanism. Sleep periods in SMAC conserve energy and improve the network lifetime by saving energy. It uses a static sleep period, and it reduces idle listening time by periodic sleep schedule. Frame = an active listening time of a node + a sleep time of a node. Each node tries to wake up after the sleep period and listen to the medium to ensure that any other nodes in a network try to communicate with it or not. SMAC gives freedom to the nodes about choosing their sleep and wakes up schedule. Moreover, to reduce control overhead, neighbor nodes synchronize together. Nodes in a network send a SYNC packet by periodically broadcast to their next nodes and inform about the scheduled time for sleep and listen to activities. When a node sends a SYNC packet, the period is known as the Synchronization period. SMAC uses the approach of the 802.11 protocol for RTS /CTS exchange and also use the CA scheme. Because of static sleep and listen schedule SMAC issues a problem of energy waste and fairness.

Major features in SMAC are as follows: Periodic Listen and sleep schedule, Avoid the collision, also avoid the Overhearing.

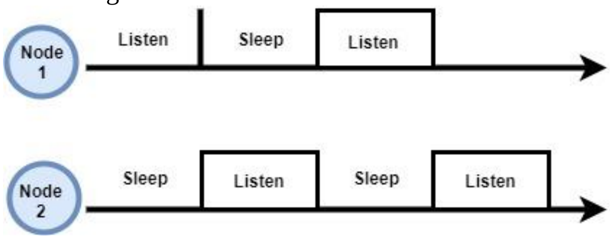

Fig. 1. SMAC Protocol Sleep Listen Schedule of nodes

SMAC sense both the channels, virtual and physical. For the hidden node terminal problem, it uses RTS and CTS mechanism. However, broadcasting in a network does not use RTS/CTS or ACK scheme. In SMAC, the long uncast message is divided into small TOS_MSG by upper layer and the RTS/CTS reserve the medium for the entire message. All immediate nodes of the sender and receiver go to the sleep state and save the energy. Listen and sleep schedule is followed by every node of the network. When a node boots up, it listens for the fixed SYNC period and tries to listen to the SYNC packet. It does not send the SYNC packet first. If a node receives a SYNC packet from neighbor then it follows the neighbor schedule otherwise choose its schedule for communication in a network. If two neighbors have a completely different schedule then a problem of neighbor node discovery arises.

The duty cycle and schedule start time in SMAC are user-configurable.

There is a tradeoff between latency, fairness, and Energy. SMAC achieves energy, but its compromises with other parameters like Latency and Fairness.

Steps of Communication in SMAC

Step 1: Start
Step 2: If [Boot uptime of a node "N"] Then
Node "N" listen for a fixed SYNC period.
else
Node "N" Try to transmit a SYNC packet in a network.
Step 3: If [Node "N" receives a SYNC packet from a neighbor node] Then
Follow then neighbor schedule.
Modify a schedule table of its network.
Else
A node "N" can choose its schedule instead of following other schedules.
Node "N" broadcast its schedule and modify a schedule table.
Step 4: If [Node "N" receives a data packet from the upper layer] Then
Buffer it or drop it.
Step 5: Node "N" set a START frame
Node "N" sends control packets to avoid a collision.
Step 6: If [Node "N" receive RTS packet] Then
Node "N" check its schedule and send CTS to intended node and
Wait for the packets to receive.
Else If [Node "N" received a CTS] Then
It starts transmission
Else
Node is in the sleep state.
Step 7: If [Node "N" is in listen to state and completed its communication] Then
It checks its schedule.
if [Nodes "N" active time is not completed] Then
wait to complete it
else
Update the schedule table and
Node "N" broadcast to neighbor node about its schedule.
The node' sleep schedule starts.
Step 8: If [Nodes sleep time gets completed] Then
Go to Step 1.
Step 9: End

B. TMAC Protocol.

TMAC protocol is design and developed to overcome the static active and sleep schedule of SMAC protocol. Because of the static schedule of SMAC protocol, it leads to energy waste when communication is already completed. TMAC follows the dynamic action and sleeps schedule. The node goes to sleep state if no event has occurred for a specified time. TMAC protocol has some procedures like switch between active or sleep period, receiving of data, data transmission, least idle listening period, and control packet exchange events.

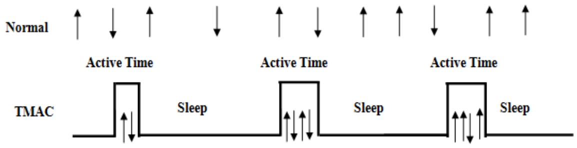

Fig. 2. Communication in TMAC [19]

Node's Active time - T_A, Contention time - C_T, Length of RTS Packet - L_{RTS}, Turnaround time - T_{TA}, Length of CTS packet - L_{CTS}

$$T_A > C_T + L_{RTS} + T_{TA} + L_{CTS}$$

TMAC leads to high delay and latency compared to SMAC Protocol, but it is more energy-efficient than SMAC Protocol. TMAC protocol can handle the variable load of traffic because it has a dynamic schedule for node sleep state and node wake upstate. However, the pitfall of TMAC is a dilemma of before time sleep in which nodes may sleep as per their activation time, and because of that the message is not fully received and gets lost when the message is long. TMAC protocol allows the node for sleep schedule after some amount of time when all the traffic in a network has done. It reduces the idle listening period by transmitting all messages in a burst, and it sleeps between bursts. The active time of a node should be large to overcome early sleep problems when the length of a message is long.

TMAC use fragmentation for long message and reserve a medium to send those frames in a burst. Acknowledgment scheme is used for error messages and their recovery. Every node in a network periodically wakes up to communicate with its immediate neighbor and then go to a sleep state until the next frame to send and at the same time, new messages are inserted in a queue. Nodes in a network communicate using Acknowledgement, RTC, and CTS. TMAC uses the FRTS and full buffer priority scheme to overcome the early sleep problem. The node which has a packet to send overhear a CTS packet can broadcast an FRTS Packet. The node which receives an FRTS packet set is NAV and goes to sleep mode. After communication, the node wakes up to receive data from FRTS sender, when node N's sending buffer gets full and it received a sending request from another node "M", It replies with the RTS packet instead of CTS. By using this mechanism node "N" takes the opportunity to transmit data from its buffer. Once the data are sent from the buffer, it will reply with CTS to receive the data from another node. This way it introduces a flow control mechanism.

C. BMAC Protocol

Berkeley MAC (BMAC) is low energy, CSMA based MAC protocol. It is a MAC protocol which minimizes the idle listening by long preamble before each packet, to wake up a receiver. Features of BMAC are to reduce control overhead because it uses the CSMA scheme without RTS/CTS, optional LPL, and optional ACK packets. Design considerations for BMAC protocol are:

Simple CSMA.
Configurable options for LPL and ACK.
Minimize idle listening.
Periodic sensor data transfer.

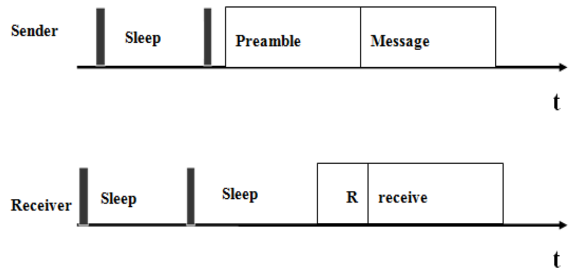

Fig. 3. BMAC Protocol Sender Receiver States

The LPL scheme determines the channel status by quick sampling. For a low duty cycle, Nodes periodically sleep and perform LPL. Node does not synchronize on listening time. The sender uses log preamble before sending each packet to get up the receiver. The preamble technique is similar to the preamble technique in ALOHA but is tailored to different radio characteristics.

The Major Advantage of BMAC protocol is it works in a completely unsynchronized environment. However, the sender gains additional overhead to liven up the unsynchronized receiver from sleep.

The methodology of BMAC protocol:

Before the transmission of a packet, it takes a sample of the channel. If a current noise floor is above the sample then it presumes that the channel is free and transmits immediately. To ensure a busy channel: It takes five samples of the channel and if no outlier found then it predicts that the channel is busy. Simultaneously it takes a random back-off. When the channel is clear, the noise floor is updated. Like just after packet transmission the noise floor is updated. BMAC Searches for outliers in received signals. As, if an outlier exists during channel sampling, then BMAC declares that the channel is clear because in a network valid packet could never have an outlier much below the noise floor. BMAC has cons of a long preamble, long delay and overhearing issue.

BMAC as certain key challenges

To ensure the reasonable length preamble, the check interval should be very short. To save energy from the receiver side, the carrier sense duration has to be very short. To reduce latency and energy consumption at the sender, the carrier sense has to be very accurate. To achieve an accurate carrier sense, it uses the CCA scheme. In CCA it tells that what is noise and what is a signal.
As per the analysis, we can say that,

BMAC = CSMA without CTS and RTS + LPL +Noise Error Estimation + Explicit ACK.

D. ZMAC - Zebra MAC

ZMAC is developed on top of the BMAC protocol. ZMAC uses features of both CSMA and TDMA protocols. CSMA is active when the traffic load is at a low level, and TDMA is active when the traffic load is at a high level [16].
ZMAC introduces a switching overhead between CSMA and TDMA. After activation of a node, it sends a ping packet that contains information about sending the node itself and all the information that has been collected through the direct neighbors of the node. By pinging mechanism, a sensor node can get information about the one-hop neighbors and the two-hop neighbors.

TDMA allocates a time slot, and at a time of time slot allocation in the algorithm, it provides the list of neighborhood list. The developers used the distributed algorithm to know as DRAND. The DRAND ensures that no two indirect neighbors receive the same time slot.

ZMAC senses the carrier first, before communicating with other nodes in a network. Each node assigns a time slot based on TDMA. If a channel is assigned to node x for communication, and node x does not have any data to communicate then, after a predefined time a channel is given to another node but only direct neighbor gets the higher chance for channel access. The node broadcasts the explicit congestion message to its two-hop neighborhood when heavy traffic found in a network.
CSMA is energy efficient, and TDMA is effective to avoid a collision in a network. So, by avoiding idle listening, the CSMA protocol saves energy and decreases the collision. Simultaneously TDMA saves energy and leads to high channel utilization.
The ZMAC protocol suffers from switching overhead costs between TDMA and CSMA.

III. PERFORMANCE ANALYSIS AND COMPARISON OF EXISTING MAC PROTOCOLS

A. Comparison of SMAC and TMAC

From the analysis of TMAC and SMAC protocols, we can conclude that SMAC consumes more energy than TMAC protocol, because of its static duty cycle. Whereas TMAC is more energy efficient because of its dynamic duty cycle. The idle listening problem of SMAC protocol leads to more energy wastage compared to TMAC Protocol.

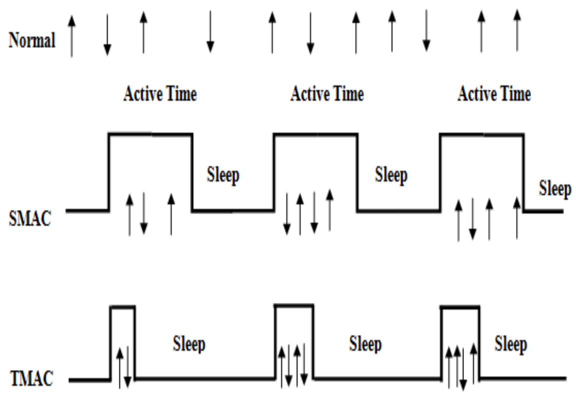

Fig. 4. Comparison of TMAC and SMAC [6]

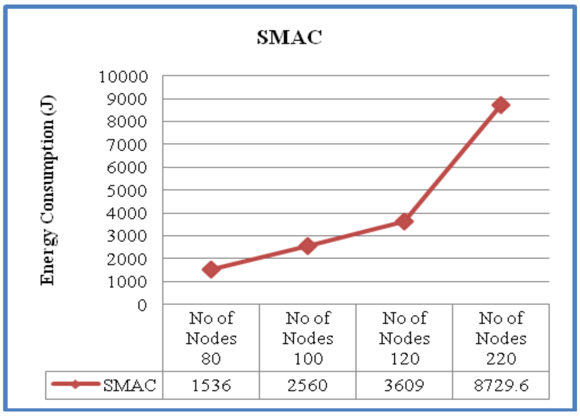

Fig. 5. SMAC Energy Consumption

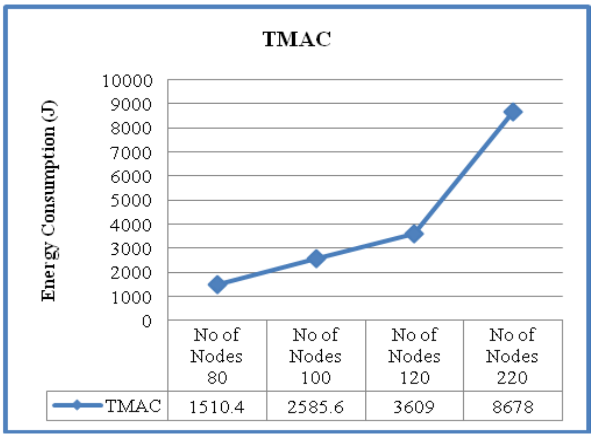

Fig. 6. TMAC Energy Consumption

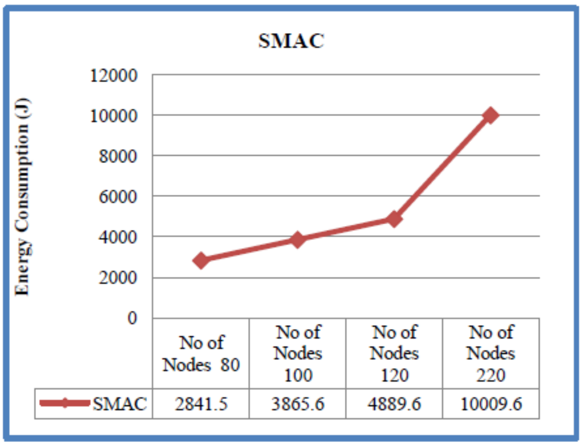

Fig. 7. SMAC Energy Consumption with different IPL

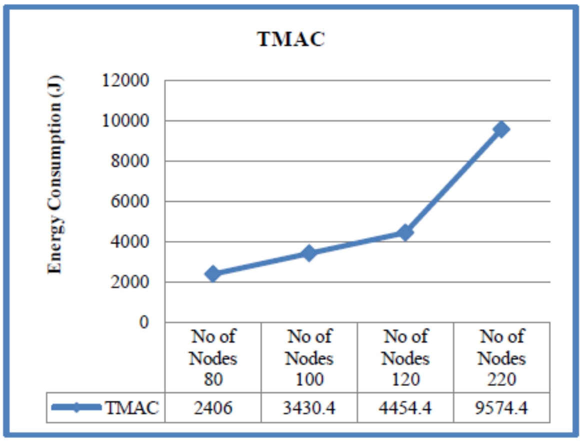

Fig. 8. TMAC Energy Consumption with different IPL

SMAC is less energy-consuming when there is low traffic n a network. While TMAC has higher performances in case of heavy traffic due to its dynamic sleep and listen to schedule. TMAC reduces the early sleeping problem using the adaptive duty cycle, overhearing and FRTS mechanism. We have simulated the SMAC and TMAC protocols in ns3. Created network topologies which consist of n- sensor nodes, n-sink based on the user-inputted value and 1-base station. Here we have considered 80,100,120 and 220 total nodes. For the Physical layer Model, we have used YanswifiModel which is available in the library of NS3. The inter Interval is 1.0 ms and the duty cycle is 1.0 sec. The Packet size is 1024 bytes and the initial energy of a model is set as per the number of sensor nodes. Wireless channel is used with 802.11 MAC type and performs the data transmission by using SMAC and TMAC Also plot the graph for Energy vs. Number of nodes. As per the simulation result of 100sec with a variant number of nodes, we have generated the result and we can conclude that TMAC is more energy-efficient than SMAC.

IV. RESULTS AND DISCUSSION

Table I: Comparison of SMAC and TMAC

No's of Nodes	Energy Consumption(Joule)	
	SMAC	TMAC
80	1536	1510.4
100	2560	2585.6
120	3609	3609
220	8729.6	8678

Table II: Comparison of SMAC and TMAC with different IPI

No's of Nodes	Energy Consumption with Different IPI(Joule)	
	SMAC	TMAC
80	2841.5	2406
100	3865.6	3430.4
120	4889.6	4454.4
220	10009.6	9554.4

Based on results of SMAC and TMAC energy consumption, here we have provided a comparison table .When network of 80 sensor nodes is created and simulate it for 100 seconds in ns3, the energy consumption of a network is ≈ 1536 Joule by SMAC protocol which is provided in fig. 5, ≈ 1510 Joule by TMAC protocol which is provided in fig. 6. By the above result of SMAC and TMAC it is proven that Consumed Energy of SMAC > Consumed energy of TMAC where 1536 J > 1510 J respectively. For network of 100 sensor nodes with 100 seconds of simulation, the energy consumption of a network is ≈ 2560 Joule by SMAC protocol which is provided in fig. 5, ≈ 2585 Joule by TMAC protocol which is provided in fig. 6. By the above results of SMAC and TMAC it is proven that Consumed Energy of SMAC > Consumed energy of TMAC where 2585 J > 2560 J respectively.

For network of 120 sensor nodes with 100 seconds of simulation, the consumed energy of a network is ≈ 3609 Joule by SMAC protocol which is provided in fig. 5, ≈ 3609 Joule by TMAC protocol which is provided in fig. 6. By the above result of SMAC and TMAC, we can that Consumed Energy of TMAC and Consumed energy of SMAC are almost same when we have simulated the network with 120 nodes. For network of 220 sensor nodes with 100 seconds of simulation time, the consumed energy of a network is ≈ 8729 Joule by SMAC protocol which is provided in fig. 5, ≈ 8678 Joule by TMAC protocol which is provided in fig. 6. By the above result of SMAC and TMAC it is proven that Consumed Energy of SMAC > Consumed energy of TMAC where 8729 J > 8678 J respectively.

However, when SMAC and TMAC is simulated with variant inter packet interval, it is analyze that lower the inter packet interval values achieves the higher energy so to prove that, the different value of inter packet interval for SMAC and TMAC is given and compare them in figure 7 and 8 respectively. SMAC protocol transmission scheme use static listen-sleep schedule and because of that we need to manage the traffic in a way that the network can minimize the early listen and sleep schedule as well as idle listening schedule and over sleeping schedule. So, the IPI of 2.0ms is set for SMAC and simulate it for 100seconds with 80,100,120 and 220 nodes and get the resultant energy in joule like ≈2841, ≈3865, ≈4889 and ≈10009 respectively which is provided in fig. 7. The medium IPI which is 1.5ms is set for TMAC protocol because it uses dynamic listen and sleep schedule with various acknowledgement schemes and then simulate the network of 80, 100, 120 and 220 sensor nodes for 100 seconds with TMAC data transmission scheme and achieves the energy consumption in joule which are ≈2406, ≈3430, ≈4454 and ≈9574 respectively which is provided in fig 8. Here the energy consumption by SMAC is greater than the energy consumption of TMAC.

The comparison of SMAC and TMAC with same IPI and different IPI is shown in Table I and Table II respectively. And based on comparison of SMAC and TMAC we can say that energy consumption in TMAC is less than Energy consumption in SMAC.

The objective of the presented work is to analyze different QoS aware protocols for wireless sensor networks. As per the literature reviews, we analyze some of the QoS aware MAC like SMAC, BMAC, ZMAC, and TMAC protocols and analyze that TMAC was designed to meet the limitations of the SMAC protocols and it achieves greater performance in terms of Energy and Delay but having less throughput compared to SMAC. As per the literature analysis, we can state that ZMAC is a hybrid MAC that was designed by using the concept of BMAC and It achieves high throughput compared to BMAC but having more energy consumption and delay compared to BMAC.

Table III: Comparison of various MAC based on analysis

Protocol Name	Type	Synchronization (Time)	Energy Consumption	Latency	Delay	Throughput
SMAC	CSMA/CA	No	Higher than ZMAC, TMAC, BMAC	Low	High	High
ZMAC	CSMA/ TDMA	Yes	Higher than TMAC, BMAC	Low	High	High
TMAC	CSMA	No	Higher than BMAC	High	Medium	Low
BMAC	CSMA	No	Low	Low	Medium	Medium

V. CONCLUSION

In the proposed research the energy efficient quality assurance MAC protocols are designed, developed and analyzed based on network simulation as well as literature survey. First the algorithm of SMAC protocol is analyzes and designs a network in simulation tool ns3 using network parameters given in section III and perform a data transmission by using features of SMAC and TMAC both. By the simulation result we can conclude that TMAC achieves more energy compared to SMAC but TMAC introduce greater latency compared to SMAC. TMAC is designed to fulfill the QoS parameters which are not achieved by SMAC protocol. in proposed work BAMC and ZMAC are also analyzed by literature and as per the analysis we can conclude hat , the other QoS parameters called throughput is achieved by SMAC and ZMAC both. Finally, we can conclude that analysis of different MAC is useful for the research community to design and develop a new QoS aware MAC protocol which overcomes the problems of existing MAC protocols.

LIST OF ABBREVIATIONS

Abbreviation	Meaning
Ack	Acknowledgment
Aloha	Advocates Of Linux Open-Source Hawaii Association.
Bmac	Berkeley Medium Access Control
Ca	Collision Avoidance
Cca	Clear Channel Assessment
Cmac	Classifier Mac
Csma	Carrier Sense Multiple Access
Cts	Clear To Send
Dmac	Data Gathering Mac
Drand	Distributed Randomized Tdma
Fdma	Frequency Division Multiple Access

Frts	Future Request To Send
Ip	Internet Protocol
Lpl	Low Power Listening
Mac	Medium Access Control / Media Access Control
Mcsmac	Multi-Channel Medium Access
Netanim	Network Animator
Nav	Network Allocation Vector
Ns	Network Simulator
Qos	Quality Of Service
Rmac	Receiver Mac
Rts	Request To Send
Smac	Sensor Medium Access Control
Sync	Synchronization
Tdma	Time Division Multiple Access
Tmac	Timeout Medium Access Control
Tos_Msg	Tinyos Message
Trama	Traffic Adaptive Mac Protocol.
Wisemac	Wireless Sensor Mac
Wsn	Wireless Sensor Network
Zmac	Zebra Mac

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Availability of Data and Materials

The data supporting the conclusion of this article are included in the article. Any queries regarding these data may be directed to the corresponding authors.

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Conflict of Interest

We certify that there are no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. We declare "No conflict of interest".

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