A QoS-aware MAC protocol for large-scale networks in Internet of Things

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***Abstract*—Provisioning quality of service in a large-scale network of resource-constraint heterogeneous devices in Internet of Things is a huge task for providing better application service. Application wise QoS can be achieved by eliminating the unnecessary delay, increasing the throughput, utilizing the dedicated bandwidth fully and also reducing the energy consumption. In this paper, we proposed a scalable MAC protocol in the gap of reservation and contention based protocols. By utilizing the band-limited channels efficiently, this protocol upgrades the access priority of different IoT applications according to their QoS requirements. The proposed scheme also ensures fairness by allowing the low priority applications to transmit their messages by using a priority remodeling method. Our scheme outperforms the other MAC protocols like BaselineMAC, CSMA, HybridMAC and TMAC in terms of energy efficiency, scalability, and latency.**

***Index Terms*—Internet of Things (IoT), Quality of Service (QoS), Medium Access Control (MAC), Machine to Machine (M2M) Communication**

I. Introduction

Internet-of-Things (IoT) allows things to collect, analyze and exchange information without any human involvement. Therefore, it can be predicted that in near future billions of devices will be connected to the Internet and these influx of connected devices will play an important role in our day-to-day life such as making our life easier, increasing industrial productivity, helping in the business growth, and improving the quality of medical sector. Quality of Service (QoS) has a great significance over all IoT applications to provide better and efficient services towards the improvement of our modern world.

Although various application-specific QoS parameters are used in IoT, some parameters like energy efficiency, channel utilization, and delay are considered as a necessary parameter for providing better service in mission-critical applications. There are some protocols like COAP [1], MQTT [2], MQTT-SN[3], AMQP[4], DDS[5], which attempts to provide QoS in the application layer of IoT. However, the proper control on medium and its efficient utilization, and energy efficiency mainly depends on the functioning of MAC protocol.

In future IoT, billions of connected devices will communicate simultaneously. Collisions during transmission are remarkable when such a huge number of devices try to communicate among themselves [6]. Different IoT applications such as smart health-care, forest fire detection, and Vehicle-to-Vehicle (V2V) communication need some sort of QoS guarantee in terms of delay, throughput and so on. However, QoS provisioning over low-power tiny devices and limited channel bandwidth is considered to be a challenging task. The contention-based MAC protocol shows abysmal performance due to high collision in the presence of large number of nodes. Similarly, reservation-based MAC protocols cannot easily adapt to the dynamics of an IoT network. Hence, both the schemes do not provide a good solution in building up a scalable, flexible, and automatic communication structure for a dense heterogeneous Machine-to-Machine (M2M) network. So, in this new era of communication, the hybrid MAC schemes for sensor network take the attention of the researchers. It can dynamically adapt to the level of contention i.e., in low contention it behaves like Carrier Sense Multiple Access (CSMA); and under high contention, it behaves like Time Division Multiple Access (TDMA) [7].

The hybrid MAC protocols ([8], [6], [9], and [10]) available in the literature combine CSMA and TDMA based approaches to reduce the possibility of collision. However, provisioning QoS for critical applications and maintaining required scalability over multi-hop IoT is still an open issue. In this paper, we have proposed a hybrid MAC protocol to improve scalability and energy efficiency in large-scale IoT network. The proposed protocol ensures QoS with fairness by defining different contending priorities and allocating the channels accordingly over multi-hop network. The proposed group based channel access mechanism reduces collisions over multi-hop communication by scheduling the transmission of sensor and relay nodes over different time frames.

The rest of the paper is organized as follows. Background of the problem and related work is presented in Section II. Section III gives the details of the proposed scheme. Simulation and performance evaluation of the protocol is presented in Section IV. Finally, Section V concludes this paper.

II. Background and related works

Wireless Sensor Network (WSN) is an indispensable part of an IoT network. A large number of MAC protocols are designed for sensor network to provide efficient channel access. With reference to the requirements of IoT scenarios, we have discussed some of the MAC protocols in this section.

The traditional IEEE 802.15.4-MAC [11] uses CSMA/CA mechanism to access the channel. The low-rate and low-duty cycle approach of the protocol provides energy efficient solution for WSN. To improve energy efficiency in 802.15.4-MAC further, S-MAC [12] was proposed where wake-sleep based scheduling approach is used to save energy during idle time. An enhanced MAC protocol based on S-MAC called Timeout-MAC (TMAC) [13] handles variable load using dynamic sleeping schedule. Other 802.15.4-based MAC protocols like X-MAC [14], B-MAC [15], Wise-MAC [16], and RI-MAC [17] proposes low power listening approaches which show suitability in energy constraint WSN. Wise-MAC notifies the sender node about the next wake up time for acquiring continuous transmissions. RI-MAC [17] supports continuous transmissions where the receiver uses a short beacon to inform the next wake-up time.

However, in the above mentioned protocols the probability of collision among the nodes is not minimized which greatly impacts on the overall performance of the network by lowering the efficiency and throughput. Therefore, B-MAC [15] proposes the idea of adopting dynamic duty-cycle based on the traffic pattern. The same thing is mentioned by MaxMAC [18], increases their duty-cycle while traffic rate cross the maximum threshold. pTunes [19] creates overhead and delay in the network, addresses self adapt channel model operation based on the collected information from the network. ContikiMAC [20] addresses few numbers of efficient ways in WSN network such as burst forwarding of data, phase-locking, and data packet strobe. In Z-MAC [7], nodes are divided into owner and non-owner and allowed the non-owner to use the vacant slot, means the slots which are not being used by the owner, adopting both CSMA and TDMA channel access mechanism. Queue-MAC [8] and hybridMAC [6] adopts hybrid of TDMA and CSMA scheme. Further, multi-hop forwarding and sub-channel allocation have not been integrated in [9]. The 802.11ah-based MAC protocol considers hierarchical grouping of a network for a large number of associated stations to improve simplicity and scalability [10]. QoS provisioning over multi-hop IoT-based network with the consideration of different groups of nodes having different requirements is still challenging. To satisfy such requirements using limited number of channels for massive number of devices spread over large coverage, a new MAC protocol needs to be designed.

III. The proposed protocol

Our proposed protocol is a hybrid MAC protocol designed for supporting a massive number of heterogeneous IoT devices, running in critical delay sensitive environment. The protocol allows nodes to take the transmission opportunity according to their requirements. Incorporation of QoS and fairness approaches, the proposed protocol improves scalability of a dense network.

The proposed protocol considers three types of nodes based on their functionalists, distributed in random geographical area. The Sink node is the edge node to utilize the sensed data. The Relay nodes works as a cluster head and remaining nodes are Sensor nodes. The densely spread Sensor nodes collect information from their surrounding environment and forward to their respective Relay nodes, further the Relay node sends the information to Sink node. A priority matrix is used for grouping different Sensor nodes based on their application requirement such as role, current event, and time. Though the higher prioritized nodes gets better channel accessibility, maintaining fairness among the remaining nodes is also a new adaptation in our proposed approach. However, optimization between the QoS and fairness is a challenging problem. To provide better efficiency, MAC data packet is modified. Two extra fields are added viz., packet length and priority without violating the IEEE 802.11.4 standard.

The packet size and priority is used in data packet to notify the parent relay about the upcoming frame, which helps the Relay node to easily manage the packet which further reduces overhead. In our proposed MAC protocol, Relay node used to send beacon in a regular interval of time. A Sensor node waits for a beacon and start contending in the dedicated contention period to send his data. If a Sensor node does not have anything to send simply goes to sleep mode which reduces energy consumption and hence increases the life time of the node. When a Sensor node gets beacons from the neighboring Relay nodes, he chooses the perfect Relay to transmit their information depending upon the link quality or some other factors which is not part of this paper. Basically, the selection of cluster head (or Relay) and structure of the topology is build by some upper level protocol like LEACH [21] or RPL [22].

A. System model

We have divided the overall system model into network and frame structure.

1) Network model: The network has a Sink node A, a set of Relay nodes R (R = $r_1, r_2, r_3, ..., r_n$), and a set of Sensor nodes S (S = $s_1, s_2, s_3, ..., s_m$). All the m Sensor nodes are divided into α number of groups i.e. G (G=$G_1, G_2, ..., G_\alpha$) with different priority P (P = $P_1, P_2, P_3, ..., P_\alpha$). Different IoT application contains different QoS parameters like ($L = l_1, l_2, l_3...l_\beta$). The priority values for a particular application can be calculated as

$$G_i = toDecimal(l_1, l_2....l_\beta)$$

Where, $l_{\beta-1}$ is more preferable QoS parameter than l_β. For example, as latency is the primary concern for the mission critical IoT applications, it will have higher priority level in the list and placed at the left most position of the list. An example of network architecture with different priority group can be seen in Fig. 1.

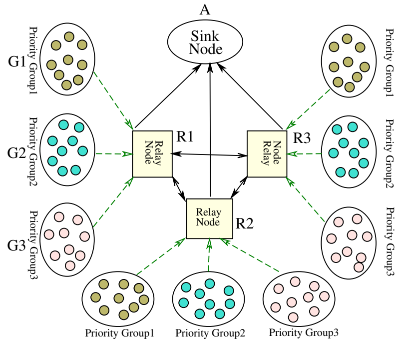

Fig. 1: The proposed network architecture considering different priority groups

2) Frame structure: The considered frame is combination of beacon period (BP), reservation period ($TDMA\_P$), contention period ($CSMA\_P$) and burst period ($Relay\_P$). Relay node broadcasts scheduling and other management information to the sensor nodes during BP period. In $TDMA\_P$, reservation based transmission takes place, however at the beginning, it remains idle and from the next frame, i.e., after the contention phase ($CSMA\_P$), Relay node schedules burst transmission for Sensor node in $TDMA\_P$. The $Relay\_P$ is used by the Relay node to communicate with other Relay and Sink node. The overall frame time F_t can be calculated as $F_t = BP + TDMA\_P + CSMA\_P + Relay\_P$. Further, the TDMA frame $TDMA\_P$ is divided into smaller slots, i.e., $TDMA\_P = slot\_1, slot\_2, ..., slot\_k$. For example $slot\_i$ is allotted to a Sensor node s_j for its transmission. The frame structure of the proposed protocol can be seen in Fig. 2.

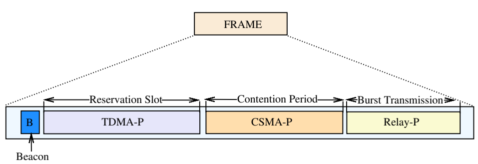

Fig. 2: Time frame structure of the proposed protocol

B. Working principles

This section describes the working principles of the proposed MAC protocol.

1) Priority wise grouping: Our proposed protocol divides the nodes into groups and allows each group to contend in different time frame. Grouping is done based on node's priority. Same priority's nodes are assumed to be in the same group. It does not based on the geographical location of nodes. When a large number of devices try to communicate at a time, this grouping scheme will reduce the collision probability which results in saving energy and reducing delay.

$$A = G_1 + G_2 + G_3 + ... + G_i + ... + G_\alpha$$

Where, all the nodes (i.e., A) are divided in to some groups (say α numbers of groups) based on their priority. Only one node of a group allows to access the channel at a time.

Suppose each group G_i, contains N numbers of nodes then there will be total αN numbers of nodes. In worst case scenario, all the the αN nodes try to access the channel at the same time when grouping is not considered resulting more collision hence more energy consumption and more delay in the network. When the grouping is done, from all the αN numbers of nodes, only a single node from a group G_i gets the opportunity to send his packet.

The probability of the successful node S can be calculated as

$$\begin{aligned} P_s &= P((A \cap G_1) \cup (A \cap G_2) \cup \\ &\quad ... \cup P(A \cap G_i) \cap .... \cup (A \cap G_\alpha)) \end{aligned} \tag{1}$$

As $G_1, G_2, G_3........G_\alpha$ all are mutually exclusive groups in terms of priority so we can replace the union (i.e. $\cup$) operator in the above Eq. (1) by the $+$ operator.

$$\begin{aligned} P_s &= P((A \cap G_1) + (A \cap G_2) + \\ &\quad ... + P(A \cap G_i) + ... + (A \cap G_\alpha)) \end{aligned} \tag{2}$$

Now if we consider that group G_i is containing the highest priority nodes among all the other groups, then we can write the Eq. (2) as below because only the nodes from G_i will contend for the channel.

$$\begin{aligned} P_s &= P((A \cap G_i) + 0 + 0 + ... + 0) \\ &= P(A \cap G_i) \end{aligned} \tag{3}$$

Which means only a single node from G_i gets the opportunity to transmit its packet. Now Using the conditional probability we can write the Eq. (3) as

$$\begin{aligned} P_s &= P(S/G_i) \\ &= (1/N) \end{aligned} \tag{4}$$

Where, S is the successful node from group G_i. From, the Eq. (4) we can conclude that the probability of collision will be decreased as N numbers of nodes contending instead of αN numbers of nodes for channel when we use the grouping system among the nodes.

2) Upgrading contending priority mechanism for fairness: According to our proposed MAC, always a higher priority node gets higher opportunity to send his packet first. This scheme helps the delay sensitive applications by allowing them to transmit their packets as soon as possible, however in some situations because of this access mechanism, low priority packets will suffer from starvation. To overcome this problem, we proposed a priority up-gradation model by which low priority nodes upgrade their priorities when it continuously fails to access the channel.

The up-gradation of the priority is done by a simple mathematical formula. Suppose, a low priority node P_{ini} has already failed d times to transmit. Then the priority of the node P_{ini} will be incremented in the next frame as

$$P\_new = P\_ini(1 + \gamma)^d$$

Where P_{ini}, is the initial priority of the node, P_{new} is the new priority value after incrimination, γ ($\gamma = 0$ to 1)is an incremental factor and $d (d = 1, 2, 3, ..., \hat{n})$ is the number of attempts the device already failed.

3) Working of the contention period ($CSMA\_P$): In this period, nodes contend for the channel to transmit their data based on their priorities. The early chances are given to the higher priority nodes by maintaining the backoff time. The higher priority nodes get less backoff time while the low priority nodes get higher backoff time as shown in Fig. 3. Some low priority nodes might fail to access the channel to transmit data in the current $CSMA\_P$ because of their low priority. As shown in Fig. 3, node-1 cannot send his data during the current frame's $CSMA\_P$. In this case, node-1 has to wait for the next beacon, i.e., next frame to transmit his data. Node-1 then upgrades its priority using the above mentioned formula. Here, each node is restricted to send more than one packet in $CSMA\_P$, which again lowers the contention. Node-5 has the highest priority so he gets the first chance to transmit his packet and rest of the nodes also get the opportunity to transmit their packets according to their priorities.

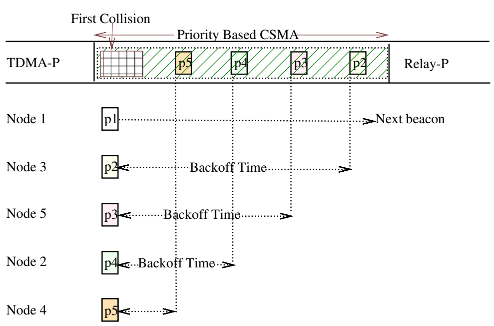

Fig. 3: CSMA period of the Proposed MAC

4) Working principle of reservation slot ($TDMA\_P$): After successful contention in the $CSMA\_P$ period, a Sensor node will wait for the next beacon. During $Relay\_P$ period of the current frame, Sensor nodes will go to sleep mode to save their energy. When a node receives next beacon transmitted by his parent Relay just after the $Relay\_P$ period of the previous frame, the Sensor node verifies whether his name is in the TDMA-list carried by the beacon message or not. If the list carries, then from the list, node calculates his wake up time to transmit and goes to sleep mode till his transmission time. Thus nodes save their energy rather than wasting it by listening to others transmissions. Fig. 4 shows the working principle of the $TDMA\_P$. After successful transmission if the node has to send something immediately it goes to sleep mode till contention period of the current frame otherwise goes to sleep until next data to send.

According to the Fig. 4(b), Node 4 calculate the wake up time as
Node $4_{wakeTime}$ = T_{slot} * $\sum_{i=1}^{Prev-1}$ N_{slot}[i]
Node $4_{wakeTime}$ = T_{slot} * [4+5+2]
Where, T_{slot} is the TDMA slot duration.

C. An example scenario

A pictorial view of the work flow of our proposed MAC protocol can be seen in Fig. 5 . At the very beginning of the frame (i.e., frame 0) all the nodes having data to send will try to access the channel in $CSMA\_P$. Assume that some higher priority nodes- node-4, node-2, and node-1 successfully access the channel in this period. However, node-3 and node-5 has failed to get the opportunity to transmit their packets, hence they will wait for the next beacon. These nodes will upgrade their priorities and go to the sleep mode. Node-4, node-2 and node-1 piggybacked their packet size and priority. Therefore, in the next frame (i.e., frame 1) Relay node assigns $TDMA\_P$ slots for transmission according to their priority. In frame 1, node-5, node-3, and node-2 contends for the channel again. Although node-2 has higher priority but node-5 also upgraded his priority and so node-5 is given higher preference than node-2 and allowed to transmit before node-2 in the $TDMA\_P$ slots of next frame (i.e., frame 2). As node-3 failed to grab the channel for two consecutive attempts, so in the frame 2, node-3 and node-2 gets the chance to transmit. This mechanism of our proposed MAC protocol provides fairness by allowing all the nodes to transmit their packets and also provides best QoS by allowing the high priority nodes to transmit their packets first.

D. Relay to Relay communication

In $Relay\_P$, Relay to Relay communication is established. Fig. 6 shows a similar scenario, where Relay 1 is the sender Relay and Relay 2 is the receiver Relay. Sender sends stream of preamble packets to the receiver before sending the actual data packet. If the receiver is available to accept the packets from sender then it immediately sends an acknowledgment. After receiving the acknowledgment sender starts transmitting the data packets to the receiver. If the sender does not get any acknowledgment from receiver then it will continuously send preamble packets to the receiver until acknowledged.

IV. PERFORMANCE EVALUATION

We have evaluated the performance of the proposed model in Castalia 3.2 [23] module for OMNeT++ network simulator.

For the performance evaluation, we considered different parameters like transmission rate, transmission radio power, number of nodes to see the effectiveness of the proposed protocol. Further, we compared our proposed scheme with some existing protocols- traditional CSMA/CA, BaselineMAC [24], TMAC [13], Hybrid-MAC [6] protocol. Results on packet received per node, end-to-end latency, and energy consumption for different numbers of nodes are shown below.

A. Packet Received per Node

Fig. 7 shows the total numbers of packets received by the Relay nodes. Different network size and with different data rates has been considered for the evaluation. In the figure, X-axis and Y-axis shows the data rates (in kbps) and numbers of packet received by Relay nodes respectively. The ratio of Sensor node and the Relay node is taken as 10:1. When we

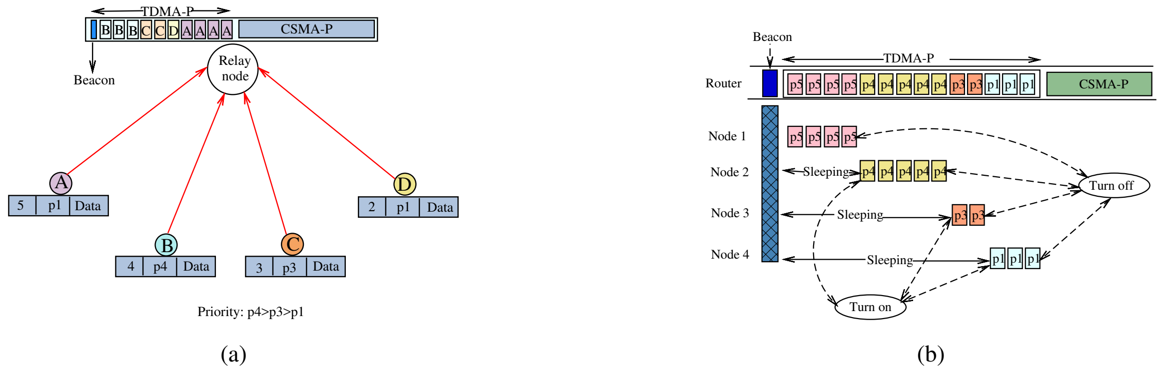

Fig. 4: (a) Nodes sending their packet in the contention period, (b) Nodes sending according to parent router assignment

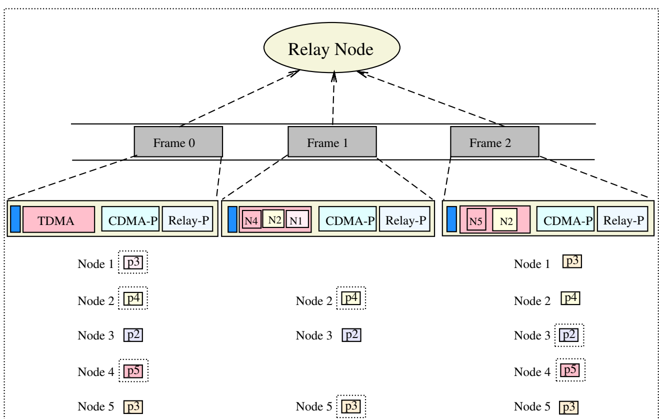

Fig. 5: Work flow of the proposed MAC

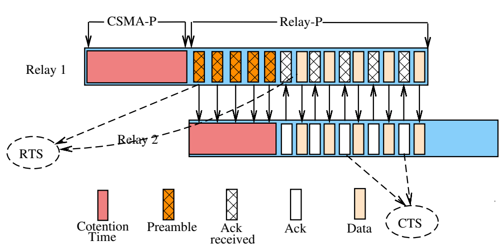

Fig. 6: Relay to Relay communication

had compared the packet received per relay node with the existing CSMA/CA and Hybrid-MAC protocols we found that our proposed MAC protocol performs better than traditional CSMA/CA and Hybrid-MAC protocol. Fig. 7 depicted our claim. The deep fades in the figure are caused by connection break between the Sensor nodes and Relay nodes during the simulation time. Because of the priority wise grouping scheme in our proposed protocol, collision between the nodes has been drastically decreased as we are allowing few nodes to contend instead of all the nodes. Therefore, the number of receive packet per nodes is higher than other compared protocols.

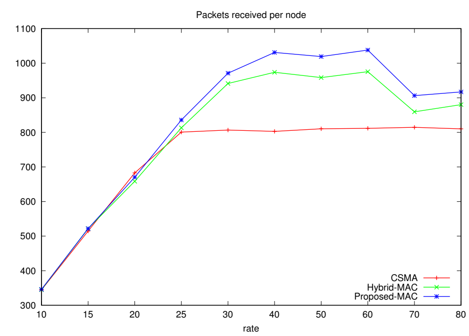

Fig. 7: Throughput over 800 nodes

B. Packet Latency

For the latency calculation we took 400 nodes with a fixed data rate i.e. 10Kbps. Fig. 8. shows the packet latency, where X-axis shows the time (in millisecond) and Y-axis is the numbers of received packets. From the graphs we can see that most of the packets are received within 100 milliseconds. But, initially it took more time because in the very beginning only CSMA/CA channel access mechanism is being used. Hence more contention among the nodes and resulting high collision and hence high latency. From the next frame we allow some nodes to transmit in the reservation period and hence it lowers collision in the contention period and reduce the latency. Latency of our proposed protocol is being compared with existing protocols i.e BaseLineMAC, TMAC, CSMA/CA, Hybrid-MAC and our proposed scheme shows better results than the other compared MAC protocols.

C. Energy efficiency

Fig. 9 depicted the energy consumption (in millijoules) with different data rates. It can be seen that the energy consumption does not directly depend on transmissions of packets; usually it depends on the states of the radio whether it is in wake or idle state. The primary reasons for power consummation in sensor network is the transmission and reception of packets. High energy consumption occurs in both transmission mode and receiving mode when the radio is active. In our proposed protocol, we allow the sensor node to sleep during their idle

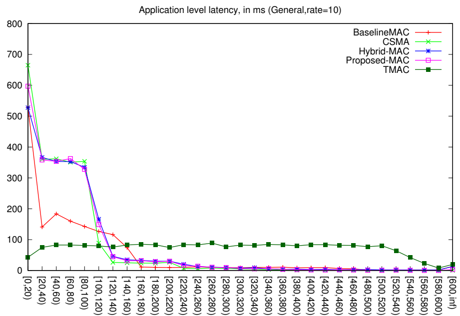

Fig. 8: Latency over data rate of 10 Kbps

time rather than listening to other transmissions which caused unnecessary energy consumption and therefore, our proposed MAC protocol is showing better result than the compared protocols like Baseline-MAC, TMAC and CSMA/CA MAC. Again because of the grouping wise access mechanism less amount of collision encountered which lowers the number of re-transmission and ultimately saves the energy consumption for the re-transmission.

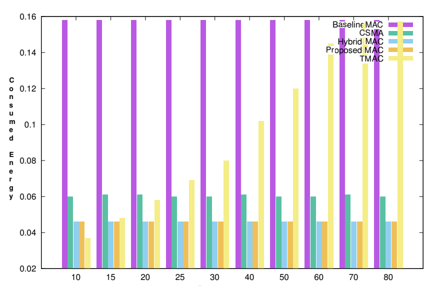

Fig. 9: Energy consumption at different data rates

V. Conclusion

In this paper, we have proposed a hybrid MAC protocol to enhance network scalability over multi-hop IoT scenarios. It shows better latency and energy efficiency which facilitates provisioning of QoS for different IoT applications. The proposed scheme provides fairness for the low priority applications by allowing them to transmit their messages using a priority remodeling method once they failed.

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