Diff-MAC: A QoS-Aware MAC Protocol with Differentiated Services and Hybrid Prioritization for Wireless Multimedia Sensor Networks

M. Aykut Yigitel, Ozlem Durmaz Incel, and Cem Ersoy
Computer Networks Research Laboratory, Netlab
Department of Computer Engineering
Bogazici University
34342, Istanbul, Turkey
aykut.yigitel@boun.edu.tr, ozlem.durmaz@tam.boun.edu.tr, ersoy@boun.edu.tr

ABSTRACT
Popularity of Wireless Sensor Networks (WSNs) combined with the multimedia requirements of new applications have enabled Wireless Multimedia Sensor Networks (WMSNs) which commonly carry heterogeneous traffic. In order to deliver multiple types of traffic with different requirements in highly resource constrained sensor networks, Quality of Service (QoS) provisioning becomes unavoidable. In this work, we propose Diff-MAC; a QoS-aware and priority-based MAC protocol for WMSNs. Diff-MAC aims to increase the utilization of the channel with effective service differentiation mechanisms while providing fair and fast delivery of the QoS-constrained data. Performance evaluation results of Diff-MAC, obtained through extensive simulations, show significant improvements, in terms of latency, data delivery and energy efficiency, compared to two other existing protocols.

1. INTRODUCTION
Wireless Sensor Networks (WSNs) are applied in various fields ranging from border surveillance, to target tracking, to telepresence, and growing requirements of these applications have created the Wireless Multimedia Sensor Networks (WMSNs) [1]. WMSNs are composed of embedded cameras and microphones besides traditional scalar sensors and generally carry heterogeneous, Quality of Service (QoS)-constrained traffic. In order to create a better global view of the observed phenomena or support latency-intolerant real-time applications, QoS support mechanisms become necessary for WMSNs.

The term QoS, in fact, refers to control mechanisms that orchestrate the resource reservation rather than the provided service quality itself. International Telecommunication Union (ITU) Recommendation E.800 (09/08) has defined QoS as: “Totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service”. Simply or practically, QoS brings the ability of giving different priorities to varied users, applications, data flows, frames or packets by controlling the resource sharing, hence achieving service differentiation among classes to provide better performance over others according to their requirements [3]. Thus, service differentiation constitutes the substantial part of the QoS support.

In case of WMSNs that deliver various types of traffic like video, voice, event-driven, periodic or best effort, QoS support mechanisms are utilized to prioritize and manage the resource sharing according to the requirements of each traffic class. Since Medium Access Control (MAC) layer rules the sharing of the medium and all other upper-layer protocols are bound to that, it has the ability to severely affect the overall performance of the WMSNs. Therefore, MAC layer becomes a proper choice to implement QoS support.

In this work, we propose Diff-MAC; a new QoS-aware and priority-based MAC protocol for WMSNs. Diff-MAC is designed with key features to support service differentiation and QoS provisioning to deliver heterogeneous traffic. These features include: i) fragmentation & message passing, ii) adaptive contention window adjustment, iii) adaptive duty cycling, iv) intra-node & intra-queue prioritization. Although some of these key components have been integrated in previous MAC protocols for WMSNs [11, 12, 14, 15, 17], Diff-MAC is the first all-in-one QoS-aware MAC protocol.
proposed for WMSNs that dynamically adapts the use of its resources to meet the requirements of different traffic classes. We evaluate the performance of Diff-MAC with extensive simulations for three different classes of traffic co-existing in the network: real-time (RT) multimedia traffic, non-real-time (NRT) traffic and best effort (BE) traffic, and compare its performance with SMAC [19] and another QoS-aware MAC protocol proposed for WMSNs [17]. The following are some of the key contributions of this work and highlights of Diff-MAC:

- The built-in fragmentation and message passing feature of Diff-MAC fragments the long video frames into smaller video packets and reserves the medium to send these packets as a burst which in turn reduces the retransmission cost of long messages in case of MAC failures.
- Diff-MAC can adjust its contention window (CW) size according to the dynamic traffic requirements to reduce the number of collisions and keep the packet latencies as small as possible.
- Diff-MAC adapts its duty cycle (DC) according to the dominating traffic class in the network and balances both energy consumption and delay. For instance, due to the stringent delay requirements of real-time multimedia traffic, sensor nodes adapt a higher duty cycle whereas if the flowing traffic has a best-effort characteristic, sensors adjust their duty cycles to lower levels to conserve energy.
- Intra-node and intra-queue prioritization feature of Diff-MAC provides fair delivery of the data among all sensor nodes and among all traffic classes respectively to avoid intolerable performances.
- Diff-MAC exhibits better performance in terms of delay and delivery rate for RT and NRT traffic while it keeps the energy consumption at an acceptable level, and it exhibits better energy efficiency in terms of BE traffic while it keeps the delay at lower levels compared with SMAC and the MAC protocol proposed in [17].

The remainder of the paper is organized as follows: In Section 2, previously proposed QoS-aware MAC protocols are surveyed. Details of the system model and key features of Diff-MAC are explained in Section 3. An example application scenario, details of the system/simulation parameters, and comparative performance analysis of Diff-MAC are presented in Section 4. Finally, Section 5 draws the conclusions and provides possible directions for future research.

2. RELATED WORK

In the literature, there are many protocols proposed for wireless networks to provide QoS support [16, 18]; however WSNs have additional challenges and constraints compared to traditional wireless networks like random and mostly redundant deployment, severe resource scarcity, high node density [3, 8]. Therefore, there is a growing demand to develop resource efficient QoS-aware protocols to enable WMNs to operate more efficiently with heterogeneous traffic. Although there are many MAC layer proposals for WSNs [7], most of them mainly focus on energy efficiency and scalability while leaving the QoS perspective aside, and very few of them focus on QoS provisioning [11, 12, 14, 15, 17]. There are also some proposals for real-time communication on WSNs [2, 13] and some others on QoS-aware Body-Area Sensor Networks [20], however, these do not address certain requirements of WMSNs that carry multiple types of traffic.

One of the MAC protocols proposed to meet the QoS requirements of the WSNs is PSIFT [14] and uses a CSMA/CA based medium access scheme. PSIFT is a QoS-aware protocol designed for event-driven applications and it is based on the previous SIFT protocol [9]. The main idea of SIFT is to relay first $R$ of $N$ reports belonging to a particular event as fast as possible. Prioritization is done dynamically in PSIFT based on the traversed number of hops of the packets.

Q-MAC [11] introduces inter-node and intra-node scheduling algorithms to select the next serviced sensor node and queue. There are four factors determining the transmission urgency of a node: packet criticality from application point of view, traversed hop count of the packet, remaining energy of the sensor node and queue’s proportional load.

PQ-MAC [15] is a hybrid TDMA and CSMA based protocol and has two phases: setup and transmission. Global clock synchronization, neighbor discovery and slot assignment are done at the setup phase where real data communication takes place at the transmission phase. Owner sensor node of a specific transmission slot assigned in the setup phase has an exclusive right to send data in it. If the owner of the slot does not have any data to send or has lower priority data, non-owners of the slot can contend for the slot based on priorities of their data.

The closest work to ours is introduced by Saxena et al. [17] where they use a CSMA/CA approach and assume three types of traffic carried in the network: streaming video, non-real time and best effort. Basically, their MAC scheme periodically monitors the dynamics of the sensor nodes and the medium, and collects relevant network statistics like transmission failures and transmitted traffic type. Accordingly, the protocol updates the CW size and duty cycle of the sensor nodes, based on the gathered information. CW adaptation is performed in a “stop-for-a-round” fashion and differentiation is provided by varying the up and down scale factors for different traffic classes. Consequently, CW size for higher priority traffic decreases faster than the lower priority where an increase is performed more slowly. Duty cycle is adjusted directly according to the dominating transmitted traffic from a sensor node. Although, CW size and duty cycle adaptation are common features between our protocol and Saxena et al. MAC, we use a different approach for CW size adaptation. Saxena et al. MAC waits for other sensor nodes to adjust their CW size whereas Diff-MAC continuously adapts the CW size regardless of the neighboring sensor nodes, hence achieves more suitable CW sizes faster.

RL-MAC [12] is a QoS-aware reinforcement learning based MAC protocol and uses a CSMA scheme. It adaptively changes the duty cycle of the sensor nodes based on not only local observations but also observations of the neighboring nodes. As a local observation, the number of successfully transmitted and received packets during the active time period is recorded to be used in the duty cycle adaptation along with proportional load of the queues. For neighbor observation, sender node records the number of failed transmission attempts for that particular data packet and sends this info to the receiver embedded in the data packet. By this way, RL-MAC tries to save energy while minimizing the number
of missed packets due to early sleeping. Three traffic categories are defined and service differentiation between them is implemented by varying the CW size of each class.

Previously proposed QoS-aware MAC protocols already defined many techniques to improve the efficiency of the QoS-provisioning. Nevertheless, they focus on some specific aspects and are far away from combining and melting these techniques into a single protocol to construct a complete solution for the MAC layer. Diff-MAC utilizes methods introduced by many previous studies in the literature and provides a fair all-in-one QoS-aware MAC protocol which is supported with an example scenario based on a surveillance application.

3. DIFF-MAC DESIGN AND ARCHITECTURE

In this section, we introduce Diff-MAC and its key features for QoS-provisioning and adaptation according to different types of traffic. Diff-MAC adopts a CSMA/CA based medium access with RTS/CTS and acknowledgements and Fig. 1 shows the state transition diagram for the operation of the protocol. Sensor nodes adopt a sleep-listen schedule to conserve energy and each node follows its own independent schedule, so that Diff-MAC does not require any synchronization between the neighboring sensor nodes. Diff-MAC manages the sharing of the medium by adapting various parameters according to the requirements of the flowing traffic in the network which are explained in the following subsections.

3.1 Fragmentation & Message Passing

Created video frames are relatively long messages and transmitting them as a single packet is too costly especially in case of MAC failures where retransmissions are required. Diff-MAC fragments the long video frames into smaller video packets and transmit them as a burst. Traditional RTS-CTS-DATA-ACK mechanism is used in Diff-MAC and once the medium is reserved, all packets of the corresponding video frame are sent as a burst using a mechanism similar to the message passing feature of SMAC [19] as shown in Fig. 1. In order to accurately obtain and give meaning to the packets of the relevant video frame, a field called “packet in frame” is added to the packet header structure. This field is used at the receiver side to assure consistency of the video frame. Moreover, neighboring sensor nodes around the source and destination pair turn their radios off and enter sleep state during a video frame exchange which in turn provides considerable amount of energy saving.

3.2 Contention Window Size Adaptation

The objective of this mechanism is to reduce the number of collisions and keep the CW size as small as possible in order to avoid unnecessary waiting time to reserve the medium by adjusting the current CW size of the sensor node based on the dynamic network traffic conditions.

In order to adjust the CW size adaptively, Diff-MAC periodically monitors the behavior of the network, with a period (Tc), and collects two related metrics about the current state of the network which are the total number of transmission attempts (At) and the number of collisions (Cc). Accordingly, a probability of collision (Pc) value can be computed for that observation frame. This obtained probability of collision is then used as an input for the CW adaptation algorithm and it is calculated by $P_c = \frac{C_c}{A_t}$.

![Figure 1: Simplified state transition diagram of Diff-MAC](image)

As seen in Algorithm 1, adaptation mechanism varies the current CW size corresponding to each traffic class between the maximum and the minimum values step-by-step. Diff-MAC runs the CW adaptation routine if and only if more than a certain number of transmissions (g) have been attempted during (Tc). Accordingly, redundant and inaccurate adjustments are prevented.

Algorithm 1 CW Adaptation Algorithm

1: CW$_{cur} = \left(CW_{min} + CW_{max}\right)/2$
2: Observe transmission attempts (At) during (Tc)
3: if ($A_t < g$) then
4: go to Step 2
5: if ($P_c(t) < P_c(t-1)$) then
6: $\Delta CW = \alpha_{down}(CW_{min} - CW_{cur})$
7: else
8: $\Delta CW = \alpha_{up}(CW_{max} - CW_{cur})$
9: $CW = CW_{cur} + \Delta CW$
10: go to Step 2

Two methods are utilized for service differentiation within CW size adaptation context. The first method sets the speed of the CW adaptation based on the traffic type by controlling the adaptation coefficients. Diff-MAC increases the CW size faster for lower priority traffic, on the other hand, decreases faster for higher priority traffic, which means $\alpha_{up}(RT) < \alpha_{up}(NRT) < \alpha_{up}(BE)$ and $\alpha_{down}(RT) > \alpha_{down}(NRT) > \alpha_{down}(BE)$ where $\alpha$ represents the CW adaptation coefficient. Moreover, different up and down coefficients are used for the same priority traffic like $\alpha_{up}(RT) < \alpha_{down}(RT)$ and $\alpha_{up}(BE) > \alpha_{down}(BE)$ in order to decrease latencies of the delay-intolerant RT data. Therefore, CW size of the RT class decreases sharper than it increases. Although CW adaptation mechanism of Saxena et al. MAC [17] seems to be similar to ours, one can easily understand that they are very different in many ways actually.

The second method for service differentiation is setting different maximum and minimum CW sizes for each traffic class, hence giving different priorities for reserving the medium. To increase the throughput and decrease the latency of the higher priority traffic, we set $CW_{RT} < CW_{NRT} < CW_{BE}$ and give precedence to higher priority traffic. Since
we use non-overlapping CW sizes, this statement holds for both minimum and maximum CW sizes.\footnote{In Section 4.2 we present the values for the mentioned parameters used in Diff-MAC.}

Although Diff-MAC dynamically adapts the CW size to the current network conditions, the minimum and the maximum CW sizes of the traffic classes have to be selected carefully. Instead of selecting random values for these variables, we adopt the CW size calculation method introduced in [6] where energy-optimizing and delay-optimizing CW sizes are derived as a function of the number of contending nodes. Since we can extract the average number of contending sensor nodes by the method given in [5], CW sizes of Diff-MAC can be easily calculated.

3.3 Dynamic Duty Cycling

Aim of this mechanism is to reduce both packet latencies and idle listening. Similar to the CW adaptation mechanism, Diff-MAC observes the total number of processed packets (created, received or relayed) every $T_a$ seconds and classifies them based on their belonging traffic classes. After the classification, Diff-MAC sets the active time of a node according to the currently dominating traffic class to refrain from both idle waiting time caused by the sleeping next hops and unnecessary waste of energy caused by idle listening. Every traffic class has a corresponding active time where $T_{ABE} < T_{ANRT} < T_{RT}$ and Diff-MAC directly adjusts the listen duration of the sensor nodes. Consequently, the nodes which dominantly process RT data, i.e. source and the relay nodes between the detection area and the sink, stay awake longer and provide fast delivery of the video data. If the total number of processed packets is smaller than a certain threshold ($\sigma$), the active time of the sensor node is set to the smallest level since the traffic on the node is negligible.

3.4 Intra-node & Intra-queue Prioritization

There is a tradeoff in the operation of multi-queue and single-queue QoS-aware MAC protocols. Main drawback of the single-queue scheme is the high cost of managing the relatively long queues. Since packets with different priorities are stored in the same queue, it is difficult to keep them sorted and process the packets according to their priorities. On the other hand, multi-queue scheme chops the long single queue into pieces and constitutes smaller queues with different priorities. Thus, packets can be served with a simple FIFO fashion and additional sorting or searching operations are not required. However, multi-queue systems have to tradeoff the accuracy of prioritization if there are more priority levels than the available number of queues since all packets in the same queue are treated as the same, i.e., with equal priority. Moreover, in case of multi-queue systems, a fair packet scheduler must be integrated to the MAC protocol to select the next serviced queue based on the requirements of the classified traffic. If not, explicit precedence might cause the lower priority traffic to starve and suffer from intolerable performance.

In order to fulfill the requirements of the QoS-constrained traffic and provide fairness among all nodes in the network, priority assignment methods need to be studied firstly. Priorities can be assigned in a static, dynamic or hybrid manner. Static priority assignment is rather simple and easy to implement. However, statically assigned priorities might not be practical to adapt to the changes in the network conditions. On the other hand, dynamic priority assignment methods take the current network conditions into consideration and mostly require some additional information and operations to decide on the priority. Hybrid methods utilize both static and dynamic assignment methods and determine the priority of a packet based on several criteria.

Diff-MAC adopts a hybrid approach and maintains different priority packet queues for each traffic class, as depicted in Fig. 2. Efficient scheduling mechanisms are needed to provide fairness among different priority traffic in multi-queue systems. Most of the proposed protocols employ explicit prioritization and serve higher priority queues always first since this sharing model is easy to implement. In this work, we utilize packetized Weighted Fair Queuing (WFQ) method [4] where each queue has its own weight. Packet scheduler of Diff-MAC selects the next serviced packet based on weights of the queues. With WFQ, the medium sharing rates among the traffic classes can be adjusted easily by changing the corresponding queue weights. This brings the ability of controlling the medium access, hence relative throughput for each traffic class. Besides, increase in the diversity of the traffic class to be sent at the contending sensor nodes reduces the collision rate since each traffic class uses different CW size.

Majority of the queuing systems use a FIFO model to manage and determine the next packet to be processed. However, resource constrained nodes may lack memory to allocate separate queues for each priority or there might be excessively too many priority levels. Hence, group of packets belonging to similar priority levels have to be stored in the same queue. Because of this, some additional intra-queue management mechanisms can be adopted for better network performance at the expense of keeping the queues sorted. In order to provide more precise prioritization, Diff-MAC assigns the priorities of the packets based on their traversed hop count in a dynamic manner which is named as Traversed Number of Hops Based Prioritization (TNHBP). TNHBP gives precedence to the packets for which more energy, bandwidth, memory and time have already been allocated. Since dropping these packets will be more costly, TNHBP prevents waste of network resources by relaying them to the next hop immediately. Therefore, Diff-MAC provides a two-level hybrid prioritization scheme, first being the type of traffic class and second being the traversed hop count among the packets of the same traffic class. TNHBP keeps the packet queues sorted according to the traversed hop counts rather than searching the whole queue for finding the highest priority packet. Therefore, TNHBP requires a search operation with a worst and average case complexity of $O(\log n)$ to find an index for a new coming packet and a shift operation to free space prior to insertion. With the integration of TNHBP, Diff-MAC drops the packets already queued for a longer time, i.e. closer to miss deadline, among

![Figure 2: Multi-queue architecture of Diff-MAC](image-url)
the same priority packets, rather than dropping the newly created or received packets.

4. APPLICATION SCENARIO AND SIMULATION

4.1 Scenario

Since the effect of an employed protocol on the overall performance of the network is highly application dependent in WSNs, we set up an example scenario, suitable for WMSNs. Although various other application fields can be found, our main theme will be security surveillance for which the primary concern is the fast and reliable delivery of the created video data related to the observed phenomena. Accordingly, video frames will be the first traffic class carried by our network and will be given the highest priority. In order to accurately detect and eliminate the threats in such a surveillance scenario, we also collect non-visual information about the area under observation such as temperature, radioactivity, sound, light, vibration or pressure which is given the second priority. As the third traffic class, auxiliary control packets are carried by the network including the location information of the sensor node, remaining energy, current operation parameters like camera observation angle (COA), image quality, orientation angle. As a result, we have three traffic classes which are real-time (RT), non-real-time (NRT), best effort (BE), in the same sequence as their priorities, and this scenario will be our basis for evaluating the performance of Diff-MAC.

Since continuous video frame generation from all sensor nodes will be a waste of critical resources, target detection mechanism is used to trigger the video streaming. A sensor node generates video frames only when the target is within the camera’s field-of-view (FoV), i.e., moving between A and B as shown in Fig. 3. The time spent between A and B is called the dwell time which can be calculated as $T_{dwell} = \frac{d_{AB}}{V}$, where $d_{AB}$ is the distance of $|AB|$ and $V$ is the velocity of the target. Thus, a camera working with $K$ frames per second (fps) creates a video stream of $K.T_{dwell}$ frames.

4.2 Simulation Parameters

For the performance evaluation of Diff-MAC, each case is simulated 10 times with different seeds using the OPNET modeler environment. In compliance with our application scenario introduced in Section 4.1, we have a square shape surveillance area and a single sink deployed to the upper left corner of this area for forwarding the gathered information to a safe zone. Deployed sensor nodes are equipped with a camera and have the ability to compress the produced video in the form of sequence of images. Quality of the produced video can be controlled by changing the created image fps and accuracy of the scalar data can be controlled by changing the packet interarrival times. Different traffic loads offered to the network for performance evaluation as shown in Table 1.

In the simulations, each video frame has a size of 10 Kbits which will be fragmented into 1 Kbits-long data packets. NRT and BE packets are 200 bits long and packet interarrival times are Poisson distributed. Target is assumed to be pedestrian which moves in the surveillance area according to the Random Waypoint Mobility model and its velocity is constant, 1 m/s. We applied binary detection model where target is sensed with the maximum probability of 1 when it is within the FoV of the sensor node as seen in Fig. 3.

With help of two methods [5,6] discussed in Section 3.2; minimum CW sizes of RT, NRT and BE traffic are calculated as 4, 12, 24 where the maximum CW sizes are 12, 24, 36 respectively. Respective adaptation coefficients are 0.12, 0.17, 0.3 for increment and 0.3, 0.17, 0.1 for decrement. As shown in Fig. 4, which is a result of Algorithm 1 presented in Section 3.2, CW size of the higher priority traffic decreases faster and increases slower than lower priority traffic. Moreover, CW size of the higher priority traffic decreases faster than it increases and CW size of the lower priority traffic increases faster than it decreases.

Selected DC for dominating RT, NRT and BE traffic are 95%, 60% and 40% respectively which equals $TA_{RT} = 95\text{msec}$, $TA_{NRT} = 60\text{msec}$ and $TA_{BE} = 40\text{msec}$. Although these values seem to be high at first sight, we should note that the sensor nodes are operating in a heterogeneous WMSN

<table>
<thead>
<tr>
<th>Traffic Class</th>
<th>RT (fps)</th>
<th>NRT &amp; BE (sec)</th>
<th>Average Created Traffic (Pkt/Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>2</td>
<td>12</td>
<td>23.14</td>
</tr>
<tr>
<td>Type 2</td>
<td>4</td>
<td>10</td>
<td>31.65</td>
</tr>
<tr>
<td>Type 3</td>
<td>6</td>
<td>8</td>
<td>43.96</td>
</tr>
<tr>
<td>Type 4</td>
<td>8</td>
<td>6</td>
<td>58.12</td>
</tr>
<tr>
<td>Type 5</td>
<td>10</td>
<td>4</td>
<td>83.25</td>
</tr>
<tr>
<td>Type 6</td>
<td>12</td>
<td>2</td>
<td>139.32</td>
</tr>
</tbody>
</table>

![Figure 3: Camera detection model](image)

![Figure 4: Effect of adaptation coefficients $\alpha_{up}$ & $\alpha_{down}$ on the convergence of CW sizes for each traffic class](image)
Table 2: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surveillance Area</td>
<td>400 x 400m²</td>
</tr>
<tr>
<td>Network Size</td>
<td>100 Nodes</td>
</tr>
<tr>
<td>Deployment Type</td>
<td>Uniform Random</td>
</tr>
<tr>
<td>Video Frame Size</td>
<td>10 Kbits</td>
</tr>
<tr>
<td>Video/Scalar Packet Size</td>
<td>1 Kbits/200 Bits</td>
</tr>
<tr>
<td>Camera Frame Rate</td>
<td>2 to 12 fps</td>
</tr>
<tr>
<td>Packet Interarrival Time</td>
<td>12 to 2 sec</td>
</tr>
<tr>
<td>Camera Observation Angle</td>
<td>52 deg.</td>
</tr>
<tr>
<td>Depth of Field</td>
<td>30m</td>
</tr>
<tr>
<td>Transmission Rate</td>
<td>250 Kbps</td>
</tr>
<tr>
<td>Video/Scalar Buffer Size</td>
<td>50 Kbits/4 Kbits</td>
</tr>
<tr>
<td>Target Mobility Model</td>
<td>Random Waypoint</td>
</tr>
<tr>
<td>Target Velocity</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Routing Algorithm</td>
<td>GPSR</td>
</tr>
<tr>
<td>Detection Model</td>
<td>Binary FoV</td>
</tr>
<tr>
<td>Max. Communication Range</td>
<td>80m</td>
</tr>
<tr>
<td>Queue Weights (RT/NRT/BE)</td>
<td>0.7/0.2/0.1</td>
</tr>
</tbody>
</table>

and deliver QoS constrained, delay-intolerant real-time traffic with only 250Kbps transmission rate. The energy consumption values for transmission, reception, idle and sleep is 27 mJ, 10 mJ, 10 mJ and 1 μJ respectively in compliance with the Crossbow Mica mote products. GPSR [10] is used as the routing protocol and important parameters used in the simulations are summarized in Table 2.

4.3 Simulation and Performance Evaluation

Performance of Diff-MAC is evaluated with extensive simulations and compared with Saxena et al. MAC [17] and SMAC [19] protocols. We select SMAC as a competitor of our protocol since it is a basic and well-known MAC protocol for WSNs and Saxena et al. MAC is the closest protocol in the literature to our protocol.

Fig. 5 presents successfully received traffic rate at the sink node with the x-axis showing different traffic loads given in Table 1. 95% confidence intervals are included for assuring the sufficiency of number of simulation repetitions. All protocols achieve nearly the same traffic delivery rate for lightly loaded cases since most of the packets are successfully delivered. However, Diff-MAC achieves higher throughput and outperforms both its competitors as the offered traffic load increases, as a result of its adaptation and resource management features.

Fast delivery of produced traffic from sensor nodes to sink node is one of the primary goals of the MAC layer protocols and becomes necessary for the real-time or critical data. Fig. 6 presents the results in terms of latency. Diff-MAC achieves lower end-to-end latencies for each traffic class and provides fast delivery of the data whereas Saxena et al. MAC performs very badly for BE traffic since the other traffic classes are always prioritized. Although SMAC achieves reasonable packet latencies without any service differentiation, we must recall from Fig. 5 that comparative packet delivery ratio of SMAC is very low. In other words, this average is computed over less packets in case of S-MAC. Since the GPSR routing protocol may also effect the source-to-sink delay of the traffic, buffer delay, i.e., medium access delay, of the protocols are also examined and depicted in Fig. 7 for pure performance evaluation of the MAC layer. Diff-MAC processes the received packets rapidly and exposes lower queueing delay.

When we look at the comparative energy consumption of the protocols in Fig. 8, we see that Diff-MAC consumes less energy in most of the conditions, except with the two heaviest loads (Type 5 and Type 6). In these two cases, Diff-MAC succeeds to deliver much more packets than the other protocols which is the reason for higher energy consumption. Hence, it can be concluded that Diff-MAC adapts well to
the current network conditions in order to deliver as many packets as possible. The energy consumption variation of SMAC is lower since it utilizes a fixed DC of 50% which translates to an average DC for Diff-MAC for different types of traffic.

Packets created by the sensor nodes far away from the sink have to traverse more hops and delivery of these packets takes more time. Furthermore, explicit prioritization of the packet scheduler may bring an extra delay for the lower priority traffic which is the case with Saxena et al. MAC. However, critical events may also occur at the far end of the observation field and has to be delayed in a reasonable time duration. Fig. 9-12 are obtained under the heavily loaded (Type 6) traffic conditions to emphasize the contributions of WFQ and TNHBP clearly. Since video frames are triggered by an event and are generated by the nodes within a certain area, i.e., at a similar distance from the sink, prioritization of RT packets according to the number of hops does not provide significant improvements. Therefore, results for RT traffic are not presented.

Fig. 9 and Fig. 10 present the average source-to-sink latencies of NRT and BE traffic respectively. Performance of the Saxena et al. MAC becomes worse as the hop-count increases. Meanwhile, Diff-MAC provides fairness among all sensor nodes by minimizing the maximum of the packet latencies and tries to distribute delay evenly by integrating intra-node and intra-queue prioritization mechanisms.

Packets generated by the sensor nodes that are far away from sink are not only delivered with high latencies but are also more vulnerable to collision and buffer overflow. Hence probability of successful delivery of a packet drops as the distance between the source and destination increases. Diff-MAC overcomes this problem and provides fair delivery of packets among all sensor nodes regardless of their geographical position with integration of WFQ and TNHBP as seen in Fig. 11 and Fig. 12 which present the average successful delivery ratio of the created NRT and BE packets. Average distance to sink distribution of sensor nodes in the test cases can be found in Table 3, which explains the drop and increase in the performance of Diff-MAC with increasing hop counts.

Table 3: Distribution of Average Distance to Sink

<table>
<thead>
<tr>
<th>Distance to Sink (hops)</th>
<th># Sensor Nodes</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>2.75</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>6.75</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>11.25</td>
</tr>
<tr>
<td>4</td>
<td>54</td>
<td>13.5</td>
</tr>
<tr>
<td>5</td>
<td>63</td>
<td>15.75</td>
</tr>
<tr>
<td>6</td>
<td>76</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>67</td>
<td>16.75</td>
</tr>
<tr>
<td>8</td>
<td>36</td>
<td>9</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>3.75</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>1.5</td>
</tr>
</tbody>
</table>

5. CONCLUSION AND FUTURE WORK

We introduced Diff-MAC, a new QoS-aware and hybrid-priority based MAC protocol for heterogeneous WMSNs. Diff-MAC coordinates the medium access of each traffic class by using effective service differentiation mechanisms. Fragmentation and message passing feature of Diff-MAC reduces the retransmission cost and CW size adaptation mechanism tries to balance both energy consumption and delay. Moreover, dynamic DC mechanism prevents unnecessary idle waiting and early sleeping while integration of intra-queue and intra-node prioritization provides fair delivery of the data among all sensor nodes and among all traffic classes respectively to avoid intolerable performances. Results of extensive simulation runs based on a typical example WMSN ap-
under grant no FP7-ENV-244088 “FIRESENSE” and by the Bogazici University Research Fund under grant number 5146.

7. REFERENCES


6. ACKNOWLEDGMENTS

This work is supported by the Scientific and Technological Council of Turkey (TUBITAK) under the grant number 108E207, by the Turkish State Planning Organization (DPT) under the TAM Project number 2007K120610, by the European Community’s Seventh Framework Programme. The application scenario showed that Diff-MAC outperforms both Saxena et al. MAC and SMAC by achieving higher throughput and lower latencies with reasonable energy consumption. Currently, we are working on the implementation of the protocol on Crossbow Mica2 sensor devices and our initial experiments demonstrate that the protocol can successfully be executed on the devices despite the resource constraints, such as limited processing power and memory. We are also about to finish integrating a realistic link layer model to take the channel conditions and radio capabilities into account. As a future work, we will test the protocol on a network of devices with a mechanism for sleep-listen synchronization between the neighboring nodes. Also, performance of the QoS support might be improved by utilizing more decision parameters for packet prioritization like remaining energy or buffer load and by exploring cross-layer solutions.