Energy-Efficient Multichannel MAC Protocol Design for Bursty Data Traffic in Underwater Sensor Networks

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Abstract

How to reduce power consumption is a critical issue in Underwater Sensor Networks (UWSNs) since sensor nodes have limited energy resource. Utilizing multiple channels and duty cycling may help conserve energy because transmission collisions and idle listening can be reduced. Bursty traffic is common in UWSN; however, we do not find satisfactory solutions that can deliver this type of traffic efficiently in a duty-cycled environment. In this paper, we propose a multichannel energy-efficient MAC protocol, DMM-MAC, that is suitable for transmitting bursty traffic in a duty-cycled UWSN. Built on top of MM-MAC, a node running DMM-MAC needs only one modem. DMM-MAC can operate in a more realistic multi-hop environment, instead of a simplified single-hop network, without the information of relative distances or propagation delays to other nodes. Utilizing the proposed dynamic duty cycling mechanism, nodes running DMM-MAC can deliver bursty traffic efficiently. Simulation results verify that DMM-MAC conserves energy and enhances network performance when compared to MM-MAC.

Index Terms
underwater sensor networks, MAC protocols, duty cycle, bursty traffic.

I. INTRODUCTION

Underwater Sensor Networks (UWSNs) enable wide range of applications such as environment monitoring and disaster prevention. Underwater sensors often communicate through acoustic signals
but can also communicate through optical signals [12], [13]. UWSNs are primarily application driven systems. For example, in an application of offshore drilling in deep waters, a floating rig or an operation vessel is typically used to collect sensory data from sensors deployed on the seabed for monitoring, navigation or other purposes. Hence, a UWSN can be considered as a network consisting of sink nodes and sensor nodes. Sensor nodes are deployed into a connected network to gather sensory data and send these data to the sink node. In UWSNs, information is typically carried by acoustic signals since radio signals attenuate rapidly under water. Compared to radio transmissions in traditional wireless sensor networks (WSNs), acoustic transmissions have limited available bandwidth, long propagation delay, and expensive transmit power consumption.

Sensor nodes are typically battery-powered. Therefore, reducing power consumption to prolong network lifetime is always a critical issue in UWSN. One way to conserve energy is to reduce transmission collisions. To do this, in some existing centralized UWSN protocols [7], [16], the sink node arranges a collision-free schedule for all the nodes. A limit of these protocols is that they can only operate in a single-hop network. Some other contention-based protocols reduce collisions by reducing the number of negotiations [8], [10], [21]. However, these protocols are single-channel solutions and suffer from serious collisions in a heavily loaded network with extensive contending nodes. Utilizing multiple channels in a heavy-loaded network also reduces transmission collisions because contending nodes are distributed to different channels [6]. Therefore, it is desirable to use multiple channels in UWSNs whenever possible. Designing a multichannel protocol is challenging because issues such as channel allocation, multichannel hidden terminal, and missing receiver must be addressed [29]. MM-MAC [6], one of the few multichannel MAC protocols for UWSNs, employs the concept of cyclic quorum systems to solve the multichannel issues mentioned above. MM-MAC successfully reduces transmission collisions. However, MM-MAC does not work well in a bursty
traffic network because it is designed for transmitting constant-bit-rate traffic.

Another way to conserve energy is to reduce energy consumption in idle listening. In traditional WSNs, several proposals, such as S-MAC [27], Q-MAC [3], LE-MAC [4], and SS [5], apply duty cycling, i.e., sensor nodes go to sleep periodically, to save energy. In UWSN, few protocols have applied a duty-cycled mechanism for power saving. UWAN-MAC [23] and the one proposed by Azar et al. [1] are two such duty-cycled proposals.

There exist several kinds of reporting models for sensor networks, such as periodical reporting, reporting by querying, and event-driven reporting. In periodical reporting, sensor nodes report sensory data to the sink node periodically. This kind of reporting usually generates stable and predictable traffic. In reporting by query and event-driven reporting, nodes report to the sink node when a query is received or a particular event is triggered, respectively. Both kinds of reporting models usually generate bursty traffic. In a network with bursty traffic, protocols that use fixed duty cycle [1], [23] do not perform well since they cannot quickly deliver the explosive traffic. To the best of our knowledge, there is no dynamic-duty-cycled solution for UWSNs. There is a dynamic-duty-cycled protocol, LE-MAC [4], in traditional WSN. However, LE-MAC achieves dynamic duty cycling with possibly many unnecessary transmissions. This makes LE-MAC unsuitable for UWSNs wherein transmissions consume a lot of power. In this paper, we propose a multichannel energy-efficient MAC protocol, DMM-MAC, to effectively transmit bursty traffic in a multi-hop and duty-cycled UWSN. Nodes running DMM-MAC deliver bursty traffic by dynamically adjusting their duty cycles. Simulation results verify that DMM-MAC enhances network performance dramatically.

The rest of the paper is organized as follows: Related works are reviewed in Section II. Our MAC protocol is described in Section III. Simulation results are shown in Section IV. Finally, conclusion remarks are given in Section V.
II. RELATED WORK

Most existing UWSN MAC protocols use only a single channel. In ordered CSMA [7] and a TDMA-based protocol [16], the sink node determines a collision-free transmission schedule for all the sensor nodes based on their locations. These two protocols require the sink node to be aware of the relative distances or propagation delays to all the sensor nodes. In an underwater environment, exact location information is not easy to obtain and may vary over time due to the existence of wind and ocean currents [9]. A node running T-Lohi [26] which is a low energy consumption MAC protocol issues a short low-power tone signal to reserve the channel before sending a packet. If multiple nodes send their tone signals, these nodes perform a back off mechanism to resolve the contention where the contention window size for each node is determined by performing contender counting. Another protocol, APCAP [15], increases channel efficiency in a long-propagation-delay network by applying parallel transmissions. A hybrid MAC protocol [17] combining scheduled access and random access attempts to provide the benefits of both access schemes. This protocol improves energy efficiency in that the scheduled scheme eliminates collisions while the random scheme adapts to changing traffic conditions. A flaw of these protocols mentioned above is that they operate properly only in a single-hop environment.

Some single-channel protocols can operate in a multi-hop network. In slotted ALOHA [24] and slotted FAMA [20], to overcome the transmission collision problem resulting from long propagation delay, time is divided into slots of the same size and packets can be sent only at the beginning of each slot. In slotted ALOHA, it is shown that the collision probability is proportional to the packet transmission time. The collision probability is minimized when the length of a slot is the sum of the maximum transmission delay and the maximum one-hop propagation delay. In slotted FAMA, a time slot is also set to the sum of the maximum transmission time and the maximum propagation delay.
delay in the network. A major difference between these two protocols is that 4-way handshaking (RTS/CTS/DATA/ACK) is utilized in slotted FAMA while 2-way handshaking (DATA/ACK) is used in slotted ALOHA. A drawback of slotted FAMA is that two nodes successfully exchanging RTS/CTS packets are not guaranteed to send their data without collisions in a multi-hop environment. Some other protocols, such as MACA-MN [8], RIPT [10], and ROPA [21], are all based on RTS/CTS handshaking to negotiate data transmissions. In these protocols, time is divided into frames and each frame consists of a control period and a data period. To increase channel utilization, nodes running these protocols are enabled to use one control packet to negotiate transmissions to/from multiple nodes. C-MAC [19] is a TDMA-based protocol which works in a multi-hop environment. In C-MAC, a network is divided into several cells, each of which is assigned a proprietary time slot. Nodes in a cell can only transmit their data at the time slot being assigned to the cell. C-MAC works only if each node is aware of its relative physical position to the sink. This implies higher hardware cost because extra positioning devices may be needed.

MM-MAC [6] is a multichannel MAC protocol for UWSNs. Depending on whether multiple transmission pairs can accomplish handshaking simultaneously or not, multichannel protocols can be classified into two categories: single-rendezvous and multi-rendezvous. Multi-rendezvous MAC protocols are more efficient than single-rendezvous ones because they utilize channels more efficiently. To the best of our knowledge, MM-MAC which uses the concept of cyclic quorum systems to solve the multichannel problems is the only multi-rendezvous multichannel MAC protocol for UWSNs. However, designed for transmitting constant-bit-rate traffic, MM-MAC does not work well in a bursty traffic network.
III. PROPOSED MAC PROTOCOL

The proposed dynamic-duty-cycled multiple rendezvous multichannel MAC protocol, DMM-MAC, is described in this section. Nodes running DMM-MAC operate in a multihop network. They are equipped with one modem and do not need to know the relative distances or propagation delays to other nodes. Some other assumptions in this paper are listed below.

- There are totally $m$ equal-bandwidth channels.
- Nodes are time synchronized. There exist many time synchronization mechanisms [9], [25] in the literature. Here we do not discuss time synchronization methods.
- A node is aware of the identifier (ID) of each of its one-hop neighbors\(^1\).

A. Cyclic Quorum System

DMM-MAC is built on top of MM-MAC which utilizes the concept of cyclic quorum systems. To describe a cyclic quorum system, we need the definition of a quorum system.

**Definition 1.** Given an universal set $U = \{0, ..., n-1\}$, a quorum system $Q$ under $U$ is a collection of non-empty subsets of $U$, each called a quorum, which satisfies the intersection property: $\forall G, H \in Q : G \cap H \neq \emptyset$.

The cyclic quorum system, a kind of quorum system, is constructed from a difference set. The definitions of difference set and cyclic quorum system are as follows.

**Definition 2.** A subset $D = \{d_1, ..., d_k\}$ of $\mathbb{Z}_n$ is called a difference set under $\mathbb{Z}_n$ if for every $e \neq 0 \pmod{n}$ there exist at least two different elements $d_i$ and $d_j \in D$ such that $d_i - d_j = e \pmod{n}$.

**Definition 3.** Given any difference set $D = \{d_1, ..., d_k\}$ under $\mathbb{Z}_n$, the cyclic quorum system defined by $D$ is $Q = \{CQ_0, ..., CQ_{n-1}\}$, where $CQ_i = \{d_1 + i, ..., d_k + i\} \pmod{n}$, $i = 0, .., n-1$.

\(^1\)A node’s ID can be its MAC address. Similar to other MAC protocols, a node can obtain the MAC address of its neighbors in the network initialization phase. The neighbor information can also be collected when a neighbor discovery scheme is executed [22], [28].
For example, $D = \{0, 1, 3\}$ is a difference set under $\mathbb{Z}_6$. The set $Q = \{CQ_0, CQ_1, ..., CQ_5\}$, where $CQ_0 = D$, $CQ_1 = \{1, 2, 4\}$, $CQ_2 = \{2, 3, 5\}$, $CQ_3 = \{3, 4, 0\}$, $CQ_4 = \{4, 5, 1\}$, and $CQ_5 = \{5, 0, 2\}$, is a cyclic quorum system under $\mathbb{Z}_6$. And $CQ_i$, $i = 0, ..., 5$, is a cyclic quorum. A detailed review of quorum systems can also be found in the literature [18].

**B. Dynamic duty cycling**

The core mechanism of DMM-MAC is the dynamic duty cycling scheme. This scheme enables each node to adjust its duty cycle dynamically according to traffic condition and thus, bursty traffic can be delivered more efficiently. In the dynamic duty cycling scheme, time is divided into a series of cycles. A cycle consists of several frames and can be partitioned into an active section and a sleep section as shown in Fig. 1. In each cycle, the time interval when a node stays awake is called the active section; the duration a node enters sleep mode is called the sleep section. Both sections comprise many frames. Initially, nodes have the same initial duty cycle and wake up at the first frame of each cycle (denoted as the initial wake up frame). To accommodate the sudden explosion of traffic, nodes are allowed to remain awake for some more frames after the initial wake up frame (denoted as the extended wake up frames) to extend active section dynamically. To achieve dynamic duty cycling, a node remains active if it may be a recipient in the near future. Specifically, each node maintains an *extension bit* indicating if any signal is sensed in the past $T_{\text{overhearing}}$ seconds. The extension bit is set to one at the beginning of each cycle and resets to zero if no signal has been sensed for continuously $T_{\text{overhearing}}$ seconds. A node without pending packets can switch to sleep mode only if its extension bit is zero. This dynamic duty cycling scheme can also be applied to other slotted protocols such as slotted FAMA. It should be noted that the energy cost of nodes running the dynamic duty cycling scheme is low because receiving power consumption is relatively low in UWSNs.
Fig. 1 is an example of the dynamic duty cycling operation. Four nodes, A, B, C, and D, form a
chain network where each node can only communicate with its direct neighbor nodes. The parameter
$T_{overhearing}$ is set to the length of a frame. In cycle $i$, node B sends a packet to node A at frame 0.
Recognizing signals in frame 0, nodes A, B, and C stay awake at frame 1; meanwhile, node D will
switch to sleep mode at frame 1 since no signal is sensed in the past $T_{overhearing}$ seconds. In frame
1 of cycle $i$, node C sends a packet to node B. Without sensing any signal during frame 1, node A
will go to sleep at frame 2. In cycle $i+1$, all the nodes have no data packet to send and thus they
stay awake only in the initial wake up frame.

When a node wants to forward a newly received packet, it may not find its next hop due to early
sleep. For example, considering Fig. 1 again, if the ultimate destination of the packet from C in
frame 1 of cycle $i$ is A, any transmission attempt from node B to node A at the frame 2 of cycle $i$
will fail since node A is in sleep mode then. To avoid such useless attempts, in each cycle, a node
can only send those packets that have arrived before that cycle.

C. The DMM-MAC protocol

The DMM-MAC protocol combines the dynamic duty cycling scheme and the MM-MAC protocol.
In each wake up frame, the MM-MAC protocol is used to handle channel negotiation and data
transmission such that collisions can be reduced. The dynamic duty cycling scheme is applied to
determine if a node should have additional wake up frames.
To facilitate our description, the MM-MAC protocol is briefly introduced first. In MM-MAC, time is divided into a series of superframes. Each superframe is further divided into a control period and a data period as shown in Fig. 2. A control period consists of \( n \) slots, numbered from 0 to \( n - 1 \), where the value of \( n \) is determined by the integer set from which the adopted difference set is derived. For example, if a difference set under \( \mathbb{Z}_6 \) is adopted, the value of \( n \) is 6. Each slot in a control period contains two minislots, at the beginning of which control packets can be sent. The length of a minislot is equal to the sum of the control packet transmission time and the maximal one-hop propagation delay. Such a setting is necessary for correct carrier sensing in UWSNs. After a successful RTS/CTS exchange, two nodes can communicate in data period. At the end of each data period, there is a duration reserved for the ACK packet transmission. Consider a network in which a control packet is 20 bytes and a data packet has a maximal size of 200 bytes, the capacity of a channel is 1 kbps, the transmission range is 1 km (which implies that the maximal one-hop propagation delay is 0.67 seconds), \( n = 6 \), and four data packets can be sent in a frame. In such a network, the length of a minislot in control period can be set to 1 seconds (no less than \( 0.67 + 20 \times 8 \text{ bits/1 kbps}=0.83 \text{ seconds} \)) while the length of a data period can be set to 8 seconds (no less than \( 0.67 + 4 \times 200 \times 8 \text{bits/1kbps} + 0.67 + 20 \times 8/1 = 7.89 \text{ seconds} \)). This means that the length of a frame is equal to \( 1 \times 2 \times 6 + 8 = 20 \) seconds. It should be noted that the control period is an overhead and the partition of control/data period may be unnecessary in terrestrial radio networks.

To enable a communication, the sender and the receiver must switch to the same channel con-
currently. MM-MAC cleverly partitions control slots into default slots and switching slots. A node stays on its default channel waiting for transmission requests at default slots. At switching slots, a node may switch to its intended receiver’s default channel to send a request. Each node uses a cyclic quorum under $\mathbb{Z}_n$, which is selected based on its ID and the sequence number of the current superframe to identify its default slots. Specifically, a node $i$’s default channel, $DC_i$, and default slots, $DS_i$, at the current superframe are assigned as follows.

$$DC_i = \text{node}_ID_i \pmod{m}$$

$$DS_i = CQ_j,$$

where $j = (\text{node}_ID_i + \text{Superframe}_ID) \pmod{n}$.

where $\text{node}_ID_i$ is the identifier of node $i$ and $\text{Superframe}_ID$ is the sequence number of the current superframe. It is shown that one of a sender’s switching slots intersects with at least one of the receiver’s default slots [6]. To initiate a transmission, a sender contends to access a channel by sending an RTS packet at an overlapping slot. After a successful RTS/CTS negotiation, both sender and receiver will alternately send a notification packet (NTF) at the remaining minislots to declare that the channel is reserved.

The way that DMM-MAC applies the dynamic duty cycling mechanism to MM-MAC protocol

![Fig. 3: Flowchart of DMM-MAC](image)
is as follows. The operation of a superframe in MM-MAC is mapped to that of a wake up frame in DMM-MAC. The value of $T_{overhearing}$ is set to the length of a superframe in MM-MAC (or equivalently, the length of a frame in DMM-MAC). Such a setting enables a possible sender to meet its intended receiver at least once in each frame. For nodes running DMM-MAC, the default channels and default slots are assigned in a slightly different way when compared to MM-MAC. Specifically, a node $i$'s default channels and default slots are given by
\[ DC_i = (\text{node\_ID}_i + \text{frame\_ID} + \text{cycle\_ID}) \pmod{m} \]

\[ DS_i = CQ_j, \]

where \( j = (\text{node\_ID}_i + \text{frame\_ID} + \text{cycle\_ID}) \pmod{n} \).

where \( \text{frame\_ID} \) and \( \text{cycle\_ID} \) is the sequence number of the current frame and current cycle, respectively. It should be noted that nodes running DMM-MAC do not rely on propagation delay to schedule their transmissions. Instead, they rely on \( \text{node\_ID}, \text{frame\_ID}, \) and \( \text{cycle\_ID} \) to determine their schedules. Using this default channel assignment scheme, nodes will have different default channels in different frames within a cycle. When a sender \( i \) has data for a node \( j \), \( i \) may first choose the best channel \( c \) that has the lowest combined impact of attenuation and noise to \( j \) and then tries to communicate with \( j \) at the frame wherein \( j \) switches to \( c \). Also, using the default slot assignment scheme, nodes have different default slots in different frames. This provides the randomness for nodes to access a channel. Moreover, recall that nodes contend to access a channel, a node is unlikely to seize a channel continuously for a long time if there exist other contenders. The flowchart of the DMM-MAC protocol operation of each cycle is shown in Fig. 3. The flowchart of the MM-MAC protocol is also provided in Fig. 4 because it is executed in each wake up frame.

Fig. 5 is an example of DMM-MAC operation under \( Z_6 \) with three channels numbered from 0 to 2. Four nodes, A, B, C, and D with ID 0, 1, 2, and 3, respectively, form a chain network where each node can only communicate with its adjacent nodes. In frame 0, which is an initial wake up frame, node A transmits to node B using channel 2. Node C also wants to communicate with node B initially; however, recognizing the NTF packet from node B in slot 2, node C changes its destination to node D using channel 1. In frame 1, all nodes have no pending data to send but all of them do not go to sleep until frame 2 where they have sensed the channel being idle for continuous \( T_{overhearing} \).

\(^2\)Here we use a chain topology to illustrate the operation of DMM-MAC for simplicity purposes. DMM-MAC is topology-independent and can be applied to any network topology. A more practical square network topology with randomly deployed nodes will be applied in the simulations.
DMM-MAC has several attractive features. Utilizing the dynamic duty cycling scheme, DMM-MAC effectively conserves energy and efficiently delivers bursty traffic. Energy conservation is achieved by applying duty-cycling while efficient bursty traffic delivery results from DMM-MAC’s ability of dynamic active section extension. DMM-MAC reduces collision probability by distributing contending nodes to multiple channels. Adopting the concept of cyclic quorum systems, DMM-MAC also guarantees a rendezvous between a node and its intended receiver.

It should be noted that DMM-MAC is a contention-based solution and thus, it is a good candidate in scenarios when a contention-based MAC scheme is preferred. Also note that DMM-MAC is a MAC protocol that is transparent to routing protocols. Similar to other UWSN MAC protocols, DMM-MAC can be used by any MAC-independent UWSN routing protocol.

IV. SIMULATION RESULTS

We have implemented an event-driven simulator using ns-2 (version 2.31) to evaluate the performance of the proposed DMM-MAC protocol. The MM-MAC protocol, the single-channel protocols ROPA and slotted FAMA (denoted as SFAMA in the figures) were also implemented for comparison purposes. In our simulations, a total of three 1 kbps channels are available for DMM-MAC and MM-MAC. For ROPA and SFAMA, one channel with 3 kbps is used. In each of our simulation runs, 49 nodes were uniformly deployed in a square area with a side length of 4 km to construct a connected topology. All the nodes are perfectly synchronized and report to the sink node which is located at the center of the area. In our simulations, nodes are labeled according to their hop count distance to the sink. A node that is \( i \) hops away from the sink relies on nodes that are \( i - 1 \) hops away from the sink to forward its data. Specifically, a node dynamically selects one of the candidate forwarding nodes as its next hop to the sink. The initial duty cycle is 20% for all the nodes. The transmission range is 1 km,
which implies that the maximal one-hop propagation delay is 0.67 seconds. The path loss and ambient noise are both considered [2]. The acoustic path loss is given by \( A(l, f) = (l \times 10^3)^k a(f)^l \), where \( l \) is the transmission range (in km), \( k \) is the spreading factor, and \( a(f) \) is the absorption coefficient. The ambient noise is defined as \( P_n(f) = 10\log(10^{N_s(f)/10} + 10^{N_w(f)/10}) + 10\log(B) \) where \( f \) is the center frequency of the narrowband signal. The successful reception rate varies depending on distance and frequency, instead of depending on the transmission range only. A control packet is 20 bytes and a data packet is 200 bytes. Bursty packets arrived to a node in a Poisson distribution with different rates. We have simulated three bursty models. For each burst arrival, the payload length for the arrival is uniformly distributed in a specific range. The range in models I, II, and III is [10,200], [200,400], and [400,600] bytes, respectively. The payload is split into as many different 200-byte data packets as needed. Energy consumption model follows an existing device where the power consumption for transmit, receive, idle, and sleep mode is 10 W, 300 mW, 80 mW, and 165 \( \mu \)W, respectively [14]. Both the MM-MAC and DMM-MAC were implemented using a cyclic quorum under \( Z_6 \). A control slot is 2 seconds long while a data period is 8 seconds long, including the duration to transmit an ACK packet. This means a maximum of four data packets can be sent in a frame. For ROPA, each frame can transmit four data packets. Each point in the figures is an average of 100 simulation runs and 10 different topologies. Each topology is used for 10 simulation runs while a simulation run simulates 3600 seconds.

The results of aggregate throughput can be found in Fig 6. We can see that DMM-MAC performs much better than MM-MAC, ROPA, and slotted FAMA in all three bursty models. For example, in bursty model I with burst arrival rate of 0.05 burst/s, the throughput for DMM-MAC, MM-MAC, ROPA, and slotted FAMA is 292, 56, 15, and 5 bps, respectively. In bursty model III with burst arrival rate of 0.05 burst/s, the throughput for DMM-MAC, MM-MAC, ROPA, and slotted FAMA
is 502, 73, 27, and 19 bps, respectively. For DMM-MAC, the impact of different bursty models on throughput is clear. When the network is not overloaded, DMM-MAC has the highest throughput in model III and the lowest in model I. This is because the most volume of traffic is generated in model III and the least of that is generated in model I. In addition, the network is overloaded with the least burst arrival rate in model III. Although MM-MAC, ROPA, and slotted FAMA have similar trends, it is not easy to show those trends in Fig 6 because of the scale of the ordinate. This experiment verifies that using dynamic duty cycling is extremely effective for bursty traffic delivery. Nodes running DMM-MAC wake up longer when necessary to enable more transmissions. On the contrary, using a fixed duty cycle, MM-MAC, ROPA, and slotted FAMA are not suitable for bursty traffic.

Next, we observe the effect of different burst arrival rates on end-to-end delay. The results can be found in Fig 7. As expected, DMM-MAC outperforms MM-MAC, ROPA, and slotted FAMA. This is reasonable since nodes running MM-MAC, ROPA, and slotted FAMA have more backlogged packets. Also, longer delays are experienced for heavier traffic models. For example, in burst model
I with burst arrival rate of 0.15 burst/s, the delay for DMM-MAC, MM-MAC, ROPA, and slotted FAMA is 410, 884, 1042, and 1277 s, respectively; in burst model III with burst arrival rate of 0.15 burst/s, the delay for DMM-MAC, MM-MAC, ROPA, and slotted FAMA is 886, 1165, 1301, and 1563 seconds, respectively.

The results of power consumption for each successfully delivered data packet are shown in Fig. 8. When the packet arrival rate is very low (lower than 0.02 burst/s), MM-MAC is more energy-efficient since most extended wake up frames for nodes running DMM-MAC are unutilized. However, when the packet arrival rate is increased, retransmissions in MM-MAC, ROPA, and slotted FAMA produced by long delay or/and collisions consume a lot of energy. For DMM-MAC, in burst model I, the power consumption per data packet is decreased when the arrival rate is increased from 0.01 to 0.05 burst/s since more data packets can be sent in each wake up frame. When the burst arrival rate is higher than 0.05 burst/s, nodes experience more serious collision problem and thus consumes more power. However, when the packet arrival rate is higher than 0.01 burst/s, nodes running DMM-MAC consistently consume less power per packet when compared to nodes running MM-MAC, ROPA, and slotted FAMA. For example, in burst model I with burst arrival rate of 0.05 burst/s, the power
consumption per packet for DMM-MAC, MM-MAC, ROPA, and slotted-FAMA is 92, 153, 217, and 306 J, respectively.

![Graph showing power consumption vs burst arrival rate](image)

Fig. 8: Effect of different packet arrival rates on power consumption

V. CONCLUSIONS

In this paper, an energy-efficient multiple rendezvous multichannel MAC protocol for bursty data traffic in multi-hop UWSN is proposed. Utilizing dynamic duty cycling scheme, nodes running DMM-MAC switch between active and sleep modes effectively to deliver bursty traffic. A merit of DMM-MAC is that dynamic duty cycling is achieved without extra control packet exchanges. Applying MM-MAC during wake up frames guarantees a sender can meet its intended receiver. Simulation results verified that DMM-MAC performs better than the fixed-duty-cycle MM-MAC in terms of throughput, end-to-end delay, and power consumption. We believe that DMM-MAC is suitable for a practical UWSN where traffic arrives irregularly.

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