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OMRI–MAC: Optimized Multi-transmission Receiver-Initiated MAC in Underwater Wireless Sensor Networks

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Abstract
Unlike terrestrial environment, the underwater environment possess additional and complicated challenges for wireless communication. For the underwater wireless communication, traditional radio wave communication is not feasible due to high channel fading and packet loss experienced high frequency communication that also reduces the communication range. Acoustic wave communication in dynamic underwater environment naturally inherits its own limitations that include low bandwidth, slow signal propagation speed, high packet loss and short communication range. Considering the UWSNs circumstances, protocols that can counter the high packet loss and low data rate are required. The MAC protocols designed for Underwater Wireless Sensor Network (UWSN) should incorporate changes in such a way that sensor nodes can have seamless and efficient communication while minimizing the effect of imposed constraints. In this paper, we therefore propose Optimized Multi-transmission Receiver-Initiated Medium Access Control (MAC) which considers harsh, lossy, and dynamic underwater environment. Our proposed method transmits optimized number of multiple packets to increase the successful packet delivery in harsh underwater environment with low data rate.

Keywords UWSNs · Receiver initiated MAC · MAC protocol · Multi-re-transmission mechanism · Channel aware transmission

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1 Introduction

With the technological advancement and technological development, the trend to explore human surrounding environment has increased among scientists and researchers due to the wide range of applications. The environment comprises of land and offshore environment. For terrestrial environment researchers significant research has been done that also includes terrestrial wireless sensor technology in which wireless sensors collect data and communicate with each other at radio frequencies according to the terrestrial environment. However, recently scientists have directed their attention towards offshore communication that comprise of surface of sea and underwater communication.

Unlike terrestrial atmosphere, the underwater environment possesses additional and complicated challenges for wireless communication. For the underwater wireless communication, traditional radio wave communication is not feasible due to high channel fading and packet loss experienced high-frequency communication that also reduces the communication range. However, due to the applications like underwater oil and gas exploration, pollution monitoring, tectonic plate monitoring and intrusion detection etc., UWSN and underwater communication is unavoidable in this advanced world. Inspired by the marine creatures communication, the most feasible underwater wireless communication mechanism comprises of acoustic wave communication [1]. Traditionally, the Underwater Wireless Sensor Network (UWSN) compromises of underwater sensor nodes deployed at certain depths from the surface of sea (Fig. 1) following an explicit network architecture [2]. These underwater sensor nodes collect the application specific data from their surrounding environment with the help of sensors installed in their circuitry. The collected data is then forwarded to the surface sink either following multi-hop mechanism that relay the collected data to the surface sink by means of acoustic communication follow some Medium Access Control (MAC) and Routing protocols [3]. The surface sinks forward the collected information to the on-shore monitoring station using the original infrastructure via radio link.

Acoustic wave communication in dynamic underwater environment naturally inherits its own limitations that include low bandwidth, slow signal propagation speed, high

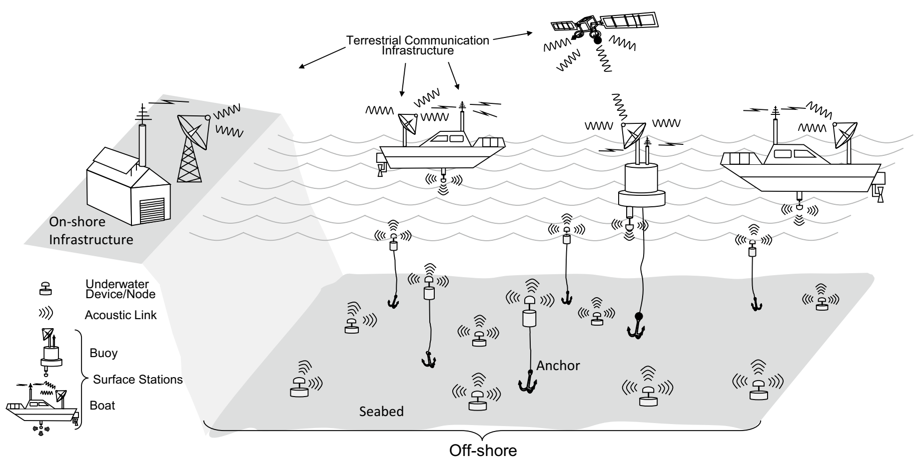

Fig. 1 Underwater sensor networks

packet loss and short communication range of up to 1.5–2 Km [4]. As the physical layer technology designed for terrestrial environment fails in underwater environment, similarly, if the Medium Access Control (MAC) protocols, designed for terrestrial communication are applied in underwater environment as it is, they cant serve the purpose and eventually will fail to provide successful communication [5]. The MAC protocols designed for Underwater Wireless Sensor Network (UWSN) should incorporate changes in such a way that sensor nodes can have seamless and efficient communication while minimizing the effect of imposed constraints. Among the MAC protocols, RI-MAC rev up the throughput and packet delivery ratio noteworthy. The scheduling in RI-MAC enable to verify if data packets are to be transmitted from the sender node to receiver node. Following the schedule the receiver node sends a beacon, then the sender nodes which receives the beacon forwards the data packet to the receiver node. However due to the UWSNs environment, the chance of packet loss is very big [6]. We therefore propose Optimized Multi-transmission Receiver Initiated (OMRI) MAC protocol to maximized the success of packet delivery in UWSNs transmission.

The rest of paper is structured as follows. Section 2 briefly introduces the related work. In Sect. 3 we introduce our proposed OMRI–MAC and followed by the performance evaluation in Sect. 4 Finally, we conclude our paper in Section.

2 Related Work

To have successful communication along with high throughput, delay tolerant energy-efficient MAC protocols are required that can also overcome the problem of large propagation delay [7, 8]. Researchers have come up with receiver initiated MAC protocols as one of the possible solution. Receiver-initiated schemes operate and function with significant difference as compared to the traditional sender initiated MAC protocols in which transmission and data communication is decided and initiated by the sender node [9–12] with different or same duty cycling mechanisms. However, in due to continuous awakening of nodes especially receiver nodes, such protocols consume considerable amount of energy and face packet collisions along with inefficient channel utilization.

Based on time synchronization, MAC protocols are further classified into synchronous and asynchronous duty cycle protocols. A variant of conventional TDMA protocol is proposed in [13] that achieves high channel utilization with effective management than the maximum utilization possible in traditional TDMA protocols. Spatial-Temporal Conflict Graph (STCG) is proposed in [14] that proposes solution to counters the delay caused in result of exposed node terminal problem while communicating in synchronized manner. Staggered TDMA Underwater MAC Protocol (STUMP) [15] exploits position diversity that uses the propagation delay information to prioritize the conflicting packet transmissions to manage collision. Although due to the harsh and dynamic nature of underwater wireless acoustic communication channel, synchronous duty cycle based MAC protocols result in high packet loss ratio as compared to asynchronous duty cycle based MAC protocols [16].

AS far as in the asynchronous category, a four-way handshake protocol named Receiver-Initiated Packet Train (RIPT) protocol is proposed in [17], in which after initiating the packet transfer, the receiver builds the schedule of transmissions based on the propagation delay from its neighboring nodes. A multi-receiver MAC (MR-MAC) protocol is proposed in [18] in which using one handshake, more than two nodes can communicate with the receiver without collision. In [19], channel reservation is done by the nodes that intend to send the data to the intended receiver in channel reservation phase and then an order list is calculated. The data transmission is scheduled according to the requests made in the order list. In addition, the propagation delay is exploited to adjust the transmission of control packets to avoid any possibility of collision.

However, in UWSNs the MAC protocol utilized in terrestrial network is not feasible [20]. Considering the unique underwater environment, we propose multiple packet transmission RI-MAC. As multiple packets are transmitted, the receiver node can receive at least one packet which removes the need for retransmission from the sender node. Moreover, for the energy efficiency, both sender and receiver nodes have their dynamic sleep/wake-up schedule.

3 Proposed Scheme

In this section, we present our proposed Optimized Multi-transmission Receiver Initiated (OMRI) Medium Access Control (MAC) scheme which considers the harsh, lossy and dynamic underwater environment. The objective of the proposed OMRI–MAC is to achieve maximum successful packet delivery with efficient resource management at the cost of multiple transmissions. For the energy efficiency, both sender and receiver nodes have their dynamic sleep/wake-up schedule. On receiver nodes request, the sender nodes transmit the collected data towards the receiver node. We also introduce the concept of Manager Node (MN) which manages the information of each sender node when the receiver node is still asleep. When receiver node awakes the MN forwards the wake-up schedule table of the sender nodes to the receiver node for the data collection.

The network topology is as shown in Fig. 2. The nodes are deployed in star-topology with receiver node located in the center while the other sender nodes on periphery. Shaded region is considered as harsh, lossy, and dynamic underwater environment.

3.1 Initialization Phase

The initial phase begins with the awakening of the first sender node. The sender node wakes up when it has a data to transmit. After the Clear Channel Assessment (CCA), the wake-up sender node transmits K Hello Packets (HP) to find the intended receiver. Where k is the number of Hello Packets defined as a network parameter. The HP contains information regarding Sender Node ID, Receiver Node ID, Sender Nodes Residual Energy, Number of Packets transmitted, packet sequence number and packet type field. After sending the k number of HPs, the sender node waits to get reply from any other awake node. If there is no reply for certain period of time named as Decision Pending Phase (DPP), the sender node takes the role of Manager Node (MN).

DPP is calculated as follows.

$$DPP = 2 \times Prop_{Delay_{max}} + 2 \times GT + TRT_{K\_packets}, \tag{1}$$

where DPP is the Decision Pending Phase, $Prop_{Delay_{max}}$ is the maximum of Propagation Delay, GT is the Guard Time, $TRT_{K\_packets}$ is the Transmission Time for k number of packets.

The role of Manager Node is as mentioned:

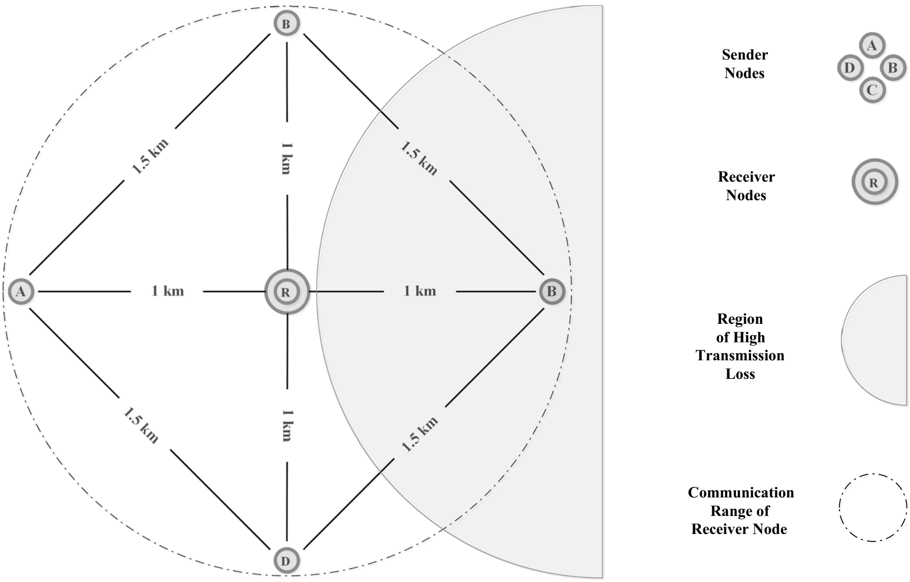

Fig. 2 Network topology

1. Manages the sender nodes which awakes.
2. Manages wake-up schedule of sender nodes.
3. Calculate the SPTR of sender nodes.
4. Receiver node takes decision by the wake-up schedule and SPTR transmitted from the Manager Node.

The SPTR is calculated as shown below:

$$SPTR(\%) = \frac{Number\ Of\ Packets\ Received}{Number\ Of\ Packets\ Totally\ Sent} * 100 \tag{2}$$

When any other node wakes up, following the same procedure, it transmits k number of HP. When the MN receives some of the transmitted K packets, then it will calculate the SPTR.

According to the calculated SPTR, MN transmits number of Hello Reply Packet (HPT) to make sure that receiver node receives at least more than one packet. In the packet it contains Sender Node ID, Receiver Node ID, Sender Nodes Residual Energy, Number of Packets transmitted, the packet sequence number, packet type field, SPTR and next wake-up schedule. Pictorial representation of the fields of control packets (HP and HPT) is shown in Fig. 3. After the transmission, MN goes to sleeping mode for efficient energy management. Then the other node which has higher residual energy takes over the role of MN after

Sender ID	Receiver ID	Residual Energy	No of packets to send	Packet Sequence Number	Packet Type Field	Next Wake-up Schedule	SPTR

Fig. 3 Control packet structure

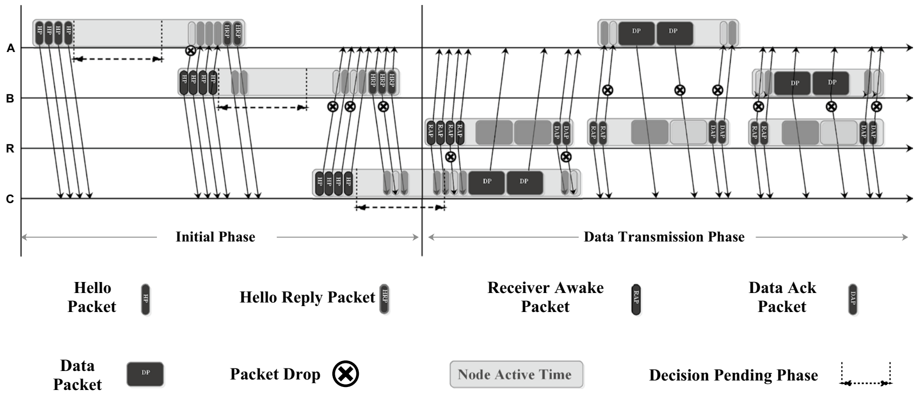

Fig. 4 Primary communication stage

receiving the HPT from the original MN. All the sender nodes which has a data to transmit follows the same method.

For example as shown in the Fig. 4, initial phase begins with the awakening of the first sender node A. After CCA period, the sender node A transmits four HP which is defined as network parameter (K = 4) to find the other wake up node. If there is no response for the time of WT, the first wake up node A takes the role of MN. The next sender node B wakes up and forwards four HP to MN after CCA period. As MN was able to receive three packets out of four, so the SPTR between node B and node A is 75% (3/4).

$$x = \frac{1}{\frac{NumberOfPacketsReceived}{NumberOfPacketsTotallySent}} \begin{cases} \lceil x \rceil + 1, & \text{with no decimal point} \quad (3) \\ \lceil x \rceil, & \text{with decimal point} \quad (4) \end{cases}$$

Number of Packets to Send calculated by SPTR

According to the formula (3) and (4), HRP to be transmitted from MN to node B is two. Therefore MN transmits two HRT to Node B and as mentioned before, HP contains Sender Node ID, Receiver Node ID, Sender Nodes Residual Energy, Number of Packets transmitted, the packet sequence number, packet type field, SPTR and next wake-up schedule. After MN transmits the HRT to Node B, it goes to sleep mode for the efficient energy management until the next wake up schedule. Node B which receives the HRT takes the role of MN as the node B has higher residual energy than node A.

In same method, sender node C wakes up and transmits four HP to MN node which is node B. Two HP out of four is received by MN, so the SPTR is 50% between node B and node C. Three HRP are transmitted to Node C from MN by the result of formula (3). In HP, SPTR of Nodes between B,C and wake-up schedule of Node B is additionally included in wake-up schedule table and transmitted. After transmission MN goes to sleep mode and node C takes over the role of MN.

Figure 5 shows the network topology with SPTR and the distance between nodes. In Fig. 5, the SPTR between node A and node B is 75%, which was mentioned in previous section. The SPTR of sender node A and receiver node R is 83% calculated using the distance and SPTR of node A and B. Following the same method SPRT between sender node B and receiver node R, sender node D and receiver node R is calculated respectively. However, in the shaded region

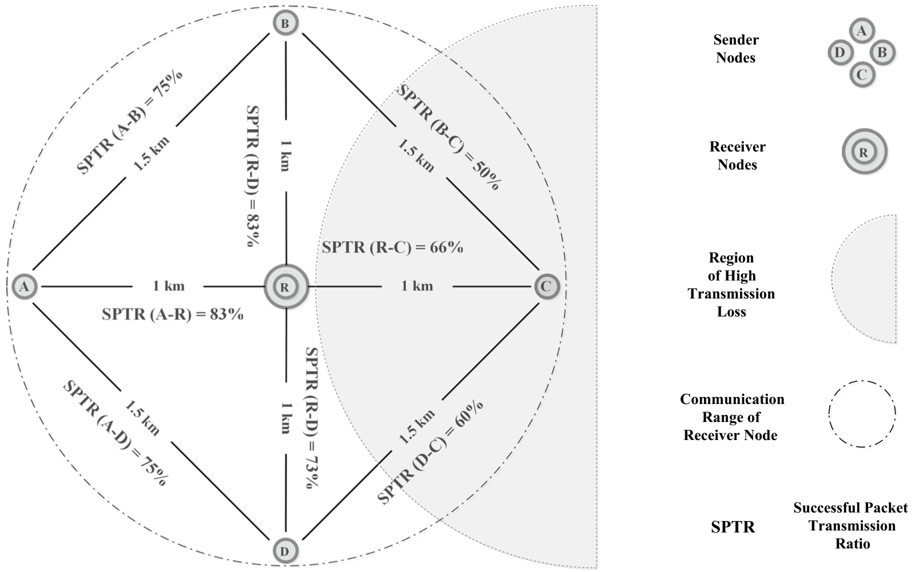

Fig. 5 Network topology with SPTR

due to the circumstance it has high transmission loss causing low SPTR compared to non-shaded region.

$$SD = -\frac{50}{3}x + 100 \tag{5}$$

where SD is the SPTR of two nodes, x is the distance between the two nodes.

3.2 Data Transmission Phase

Here, we discuss each sender nodes data transmission according to SPTR calculated from Initialization Phase. With the utilization of SPTR which is calculated between the sender nodes, we calculate the SPTR between the sender nodes and the receiver node.

When the receiver node R wakes up, it broadcasts k number of Receiver Awake Packet (RAP) which is defined as network as network parameter as it is a Receiver Initiated. Then the MN which receives the RAP calculates the SPTR between the receiver node and itself. With the SPTR, the MN node transmits number of Data Packets (DP) to receiver node R on the bases of SPTR. In the Data Packet (DP) (Fig. 6) it contains Sender Node ID, Receiver Node ID, Collected Data, Number of Packets to send, Packet Sequence Number, Packet Type Field, SPTR of all sender nodes, and Wake-up Schedule of all sender nodes. Then the receiver node R which receives the DP replies back with Data ACK Packet (DAP) for

Sender ID	Receiver ID	Collected Data	No of packets to sent	Packet Sequence Number	Packet Type Field

Fig. 6 Data packet structure

acknowledgement. After forwarding the DAP the receiver node goes to sleep mode until the next sender node wake up time according to the wake-up schedule received from MN. Also, MN which receives DAP goes to sleep for the energy efficiency.

Continuing the example from the Initialization Phase regarding Fig. 4, receiver node R transmits four Receiver Awake Packet (RAP) to MN which is node C, requesting for the data. MN receives three RAP from the receiver node R, so the SPTR between node C and receiver node R is 75%. As the SPTR is 75% MN node transmits two Data Packet (DP) to receiver node R. After receiving DP, node R replies back with two Data ACK Packet (DAP). As the receiver node R is aware of wake-up schedule of each sender nodes, node R goes to sleep until the next data transmission period. MN node also goes to sleep after receiving DAP from the receiver node. Just before the sender node A wakes to transmit the data, receiver node wakes as it is aware of the wake-up schedule of every sender nodes. Moreover, as receiver node is aware of SPTR of each node it transmits two RAP requesting for the data from node A. After node A receives RAP, it transmits two DP for successful data transmission. Then the receiver node receives DP and transmits two DAP to node A and goes to sleep until the next data transmission from the sender nodes. Likewise, node C which receives DAP from the receiver node goes to sleep. In same method node Bs data transmission proceeds.

3.3 Primary Stage and Secondary Stage

In this section, we describe the overall transmission. The description will be split into three parts Primary Stage, Secondary Stage, and Fixed Time Period Stage. As shown in the Fig. 4, Primary Stage is the combination of Initialization Phase and Data transmission Stage.

In Secondary Phase, the k number of Hello Packets and the calculation of SPTR is omitted for the energy efficiency. For the Initial Phase in Secondary Stage, the number HP and HRP are utilized from the numbers that were defined in Primary Stage. As the number of packets in Primary Stage was decided for the most efficient transmission, it will be utilized in Secondary Stage too. Also DPP in Secondary Phase is equal to Initial Phase. The Data Transmission Phase in Secondary Stage is same with Primary Stage as it has same number of packets sent from the sender nodes as shown in Fig. 7.

After the Primary Stage, Secondary Stage is repeated N number of times for Fixed Time Period as shown in Fig. 8.

Due to the environmental changes in underwater, it is not possible to maintain the same environment for long period of time. Especially, the change of underwater temperature makes great changes to the transmission range which gives a great influence on the data transmission. However, based on the result of [21, 22], it is shown that the underwater temperature does not show big difference for 2 h and for this period of time it will not have significant effect on data transmission. Therefore our OMRI–MAC repeats the Initialization for decision of number of packets and new SPTR in every 2 h after the Fixed Time Period.

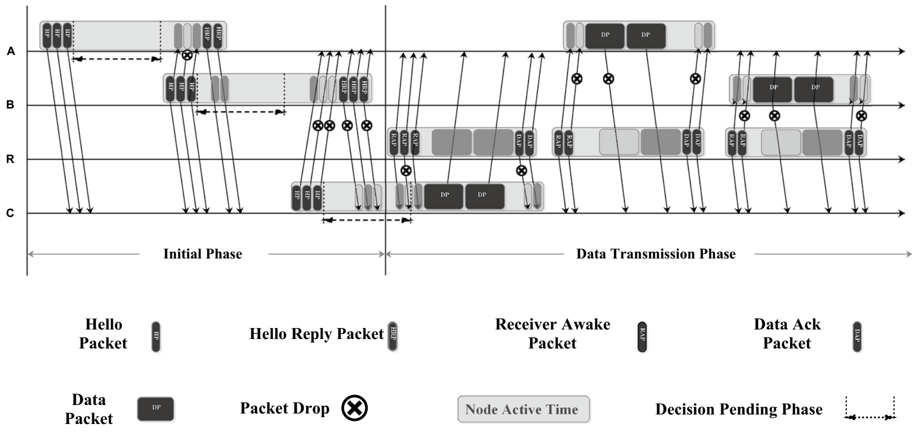

Fig. 7 Secondary communication stage

4 Performance Evaluation and Results

4.1 Simulation Environment

In this section, we describe the simulations performed to evaluate the performance of our OMRI–MAC protocol. In this evaluation existing Receiver-Initiated MAC protocol is compared with our protocol OMRI–MAC in underwater environment. For simulation, the simulation platform is Underwater Acoustic Network (UAN) module, an Network Simulator 3.25 based underwater network simulator. With UAN we have conducted the simulation of OMRI–MAC and RI-MAC. AcousticModemEnergyModel from NS-3 is used for the energy model. The power consumption of the energy model set to basic. The transmission model is similar to [23], where the reception power and idle listening power are same and set to 0.158 W, sleeping mode is set to 0.058 W, and 50 W is set for transmission power. The underwater signal speed is fixed at 1500 m/s and PHY is based on uan-phy-gen from ns-3 The network topology is shown in Fig. 8, receiver node is located at the center and the sensor nodes are located in star topology. As we are considering the harsh, lossy, and dynamic underwater circumstance, the packet loss rate were set 12.

First, we compared OMRI–MAC and RI-MAC with the number of received packets. As shown in Fig. 9 the proposed OMRI–MAC showed more efficient compared to RI-MAC. In RI-MAC when packet loss occurs, it retransmit after the procedure of RTS/CTS. However,

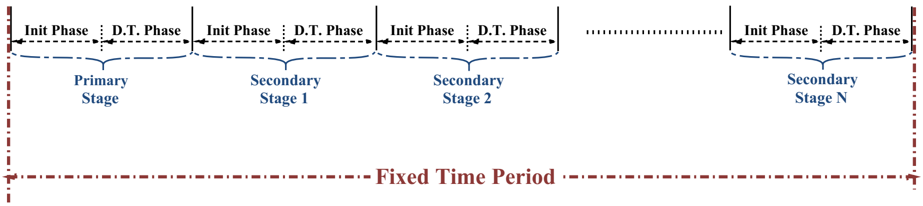

Fig. 8 Communication for fixed time period

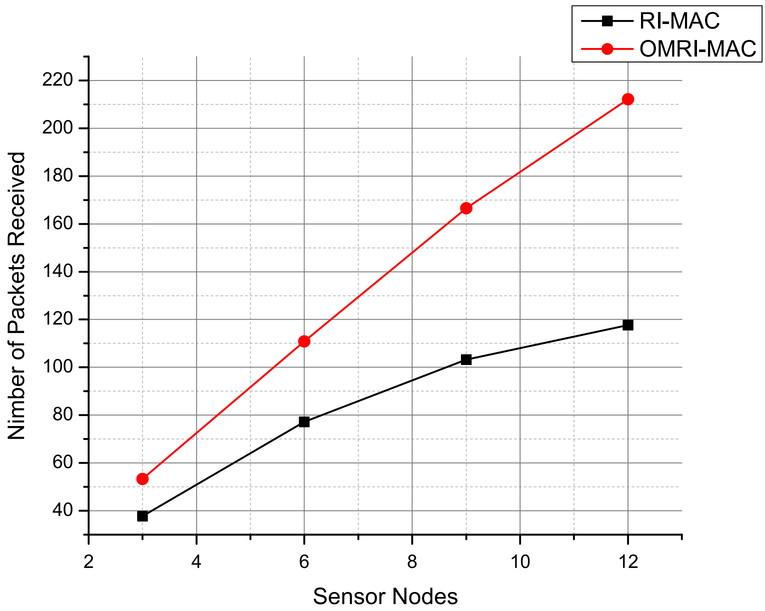

Fig. 9 Number of received packets

in proposed OMRI–MAC transmits multiple packets for receiver to receive at least one packet. In OMRI–MAC, through formula (3) and (4) it transmits most optimized number of packets from the sender node to the receiver node and for this reason the number of packet received show more efficient compared to RI-MAC. This result show higher difference as the number of sender node increases which makes higher possibility of collision.

4.2 Simulation Results

We evaluate the residual energy of each sender nodes for our proposed OMRI–MAC and RI-MAC. We observed that our proposed OMRI–MAC showed more efficient energy consumption as shown in Fig. 9. Even with the multiple packet transmission of OMRI–MAC, it showed higher residual energy than RI-MAC in Fig. 10 which indicates that the retransmission from packet lost has critical usage of energy considering the network environment.

Finally, we have investigated the time difference of packet generation time. In Fig. 11, as the number of sender node increases, the time difference between packet increases. With the increase of sender nodes, the number of sender nodes to participate in competition for packet transmission also increases. In this competition the sender node which fails to transmit first has to wait for the next competition causing the packet transmission delay.

In proposed OMRI–MAC, it shows high performance even the number of sender node increases as the reliability is high due to multiple transmission of packets. However, RI-MAC shows inefficient results for time difference as it only transmits packet once which has high possibility of packet loss and need for retransmission. Therefore, proposed OMRI–MAC shows significant difference for time difference in receiving packets compared to original RI-MAC.

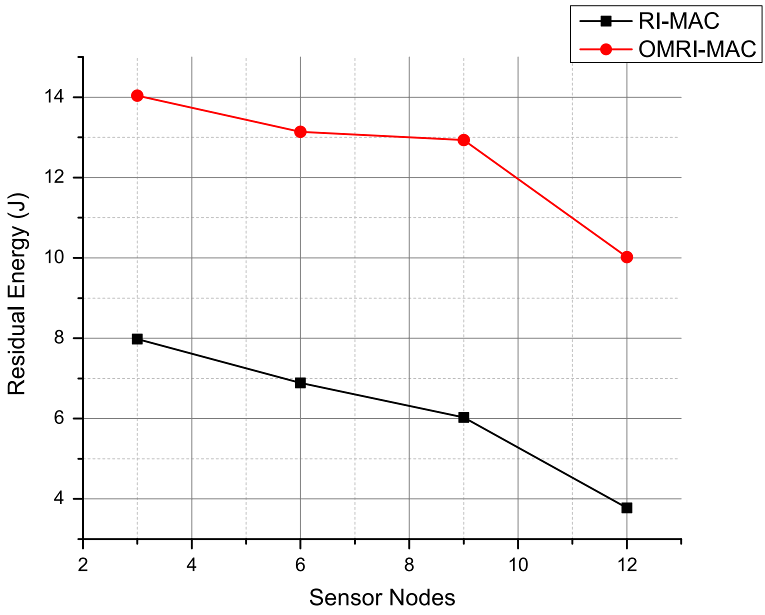

Fig. 10 Residual energy

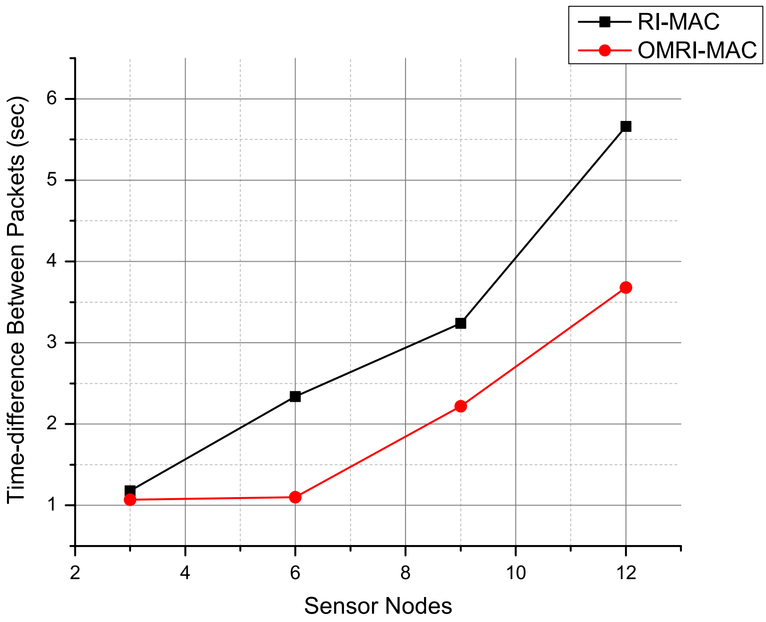

Fig. 11 Time difference between packets

5 Conclusion

We proposed Optimized Multi-transmission Receiver Initiated (OMRI) MAC protocol to increment of packet transmission ratio in harsh, lossy and dynamic underwater environment. In OMRI MAC, we aim for the maximum successful packet delivery with efficient resource management ate the cost of multiple transmission. Due to multiple packet transmission energy consumption shows higher than energy efficient protocol. However, with the optimization of the packet number calculated with successful packet transmission ratio, energy efficiency is also considered in our proposed OMRI–MAC.

Through the simulations, we found that OMRI–MAC shows significant increase in number of packets received compared to the original RI-MAC. Moreover, maximum transmission time which is the gap between the packet generation time also shows high performance compared to RI-MAC.

6 Future Work

In our future research, we will try to counter the challenges faced by OMRI–MAC in the UWSN. Since in OMRI–MAC due to multi-retransmissions the power consumption is not optimized. OMRI–MAC provides the trade off between residual energy and and performance of the system, however, there should be some safe limit for this mechanism. Similarly, in practical environment, it is hard to locate the sensor nodes with utmost accuracy. In our future work we will also try to consider underwater sensor network in which nodes will have mobility as well.

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