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MAC Protocols in Underwater Wireless Sensor Networks: Issues and Simulations

Reza Mohammadi [*] , Seyyed Yahya Nabavi, Reza Javidan

Department of Computer Engineering and Information Technology, Shiraz University of Technology, Shiraz, Iran

r.mohammadi@sutech.ac.ir , y.nabavi@sutech.ac.ir ,javidan@sutech.ac.ir

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Abstract

Underwater Acoustic Wireless Sensor Network (UAWSN) uses acoustic signals to transmit data. Acoustic signals in underwater environment have high bit error rate, long propagation delay and limited bandwidth. Another constraint in UWASN is energy. Due to these constraints, design of energy and bandwidth efficient and propagation delay aware MAC protocol is a great challenge in UWASN. Underwater sensor nodes have to share medium. The main role of the MAC layer protocol is to decide when a node accesses a shared medium and to resolve any conflicts between nodes. In this paper, we evaluate the performance of three famous underwater MAC protocols UWAN-MAC[1], R-MAC[2] and Slotted FAMA[3] in terms of packet drop rate, throughput and energy consumption. We have used Aqua-sim simulator to evaluate MAC protocols.

Keywords: *Underwater MAC protocols, R-MAC, UWAN_MAC, Slotted FAMA, Underwater coustic wireless sensor networks, Underwater simulation*

1. Introduction

Underwater sensor networks consist of sensor nodes that perform data collection about water environment and forward collected data to the sink node. Nowadays UAWSN are used for applications like environmental monitoring, mine reconnaissance, disaster prevention, assisted navigation undersea exploration and distributed tactical surveillance [4].

Underwater environment is very different from the open ground environment. The pressure, humidity, and changing environment are the main restrictions against the design of the underwater sensor networks. Therefore, integrating the recent advanced technology

With the underwater sensor networks should be considered carefully. Acoustic communications are the typical physical layer technology in the underwater networks. In fact, radio waves propagate through conductive sea water only at extra low frequencies (30 - 300 Hz), which require large antennae and high transmission power. Optical waves do not suffer from such high attenuation but are affected by scattering. Thus, links in the underwater networks are usually based on acoustic wireless communications[2],[4].Even there exist many recently developed network protocols for wireless sensor networks, the unique characteristics of the underwater acoustic communication channel require very efficient and reliable new data communication protocols [5].Major challenges in the underwater acoustic networks are:

1. Propagation delay is five orders of magnitude higher than in radio frequency terrestrial channels and is also variable;
2. The underwater channel is severely impaired, especially due to the multipath and fading problems;
3. The available bandwidth is severely limited;
4. High bit error rates and temporary losses of connectivity (shadow zones) can be experienced;
5. Sensors may fail because of fouling and corrosion;
6. Battery power is limited and usually batteries cannot be easily recharged, also because solar energy cannot be exploited.
7. In the shallow waters, there are many problems regarding multipath and seabed and surface scattering.

The MAC layer protocols operate directly on top of the physical layer. The main role of the MAC layer protocol is to decide when a node accesses a shared medium and to resolve any conflicts between nodes. The MAC layer protocols perform tasks such as addressing flow control, framing and correcting communication errors occurring at physical layer.

Existing MAC layer protocols can be divided into two categories. Contention free or schedule based protocols and contention-based protocols. Contention based protocols allow nodes to access the shared medium at the same time and provide methods to reduce the number of collisions. Contention based protocols are suitable for distributed topologies. CSMA is one of the contention based protocols that used to reduce collision between two or more stations [7]. If propagation delay is small compared to the packet duration and network is fully connected, CSMA is efficient [3]. CSMA has hidden terminal and exposed terminal problem. In Figure 1, hidden terminal problem occurs when node A and node C cannot overhear each other's signals. Hence it is possible for C and A, to send data to B simultaneously, causing a collision at B. Exposed terminal problem occurs when C can send data to D, but it overhears an ongoing transmission from node B to node A and decide to wait.

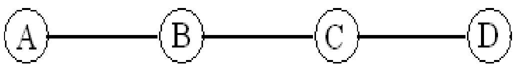

Figure 1. Hidden and expose terminal problem [2]

To address these two problems MAC protocols use RTS/CTS control packets. When a node want to send data to another node, it send RTS (ready to send) packet to receiver. When receiver received RTS, it responds with CTS (clear to send) packet. Other nodes that overhear RTS or CTS know that a data transfer will occur, and they wait.

In contention free protocols, only one device can access the shared medium at any given time and is suitable for centralized topologies. Some of the contention free protocols are TDMA, FDMA and CDMA. FDMA isn't suitable for underwater environment, because available bandwidth is limited and FDMA divides bandwidth into several sub-bands and assigns one of them to a particular node [6]. Also TDMA and

CDMA aren't useful for acoustic networks, because these protocols have some problems such as synchronization and near far problem [2]. Underwater MAC layer protocols should consider node mobility, low bandwidth, energy efficiency and long propagation delay. Due to the long propagation delay and node mobility and other underwater environment constraints, distributed topologies are used more than centralized topologies. Hence contention based protocols such as R-MAC [2]; Slotted FAMA [3] and UWAN-MAC [1] are useful for such topologies. In this paper, we describe these protocols and evaluate their performance. We consider throughput and energy consumption parameters for this evaluation.

The rest of this paper is organized as follows. Section 2 describes the MAC protocols that we consider in this paper. The performances of three MAC protocols are evaluated in section 3. Finally, section 4 concludes the paper.

2. Description Of The Protocols

2.1. *UWAN-MAC*

UWAN-MAC proposed by M. Kyoung Park and V. Rodoplu [1]. The main goal of UWAN-MAC design is energy efficiency. Since sleep mode energy consumption is less than idle listening mode, UWAN-MAC try to increase sleep mode interval in each node to reduce energy consumption.

In Figure 2, node A broadcasts its SYNC packet that contains its transmission cycle period "TA" at the beginning of its cycle period and goes to sleep. Node B that is close to the node A receives SYNC packet. Receiving SYNC packet allows node B to wake up at the correct time to listen to node A without the knowledge of the propagation delay. In this scheduling algorithm, there is no need for clock synchronization, because nodes use relative time stamp.

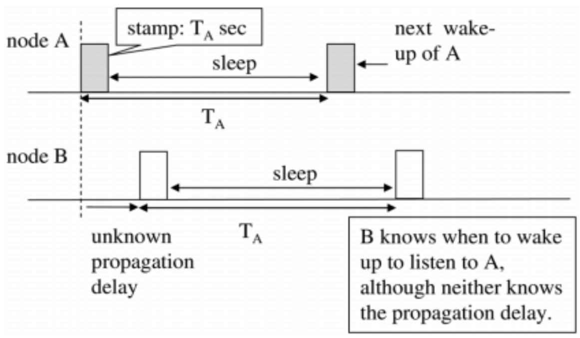

Figure 2. Listen cycle determination in UWAN-MAC [3]

In this protocol, initial transmission time selected randomly by each node. In initialization period each node broadcasts its SYNC message and receives its neighbor's SYNC packets, remains waiting until the beginning of the next cycle, as can be seen in Figure 3. Each node inserts Ti to its SYNC packet to tell its neighbors that it will send data again after this time period. When network initialized, Ti is equal to To for all nodes to initialize their transmission and listen schedules. Each node selects its transmission start time randomly in interval [0, To) and broadcasts and sends its SYNC packet to its neighbors. After initialization phase, every node has its listening and transmitting periods and wakes up in listening period for receiving its neighbor's packets or wakes up in transmitting period for transmitting its own data.

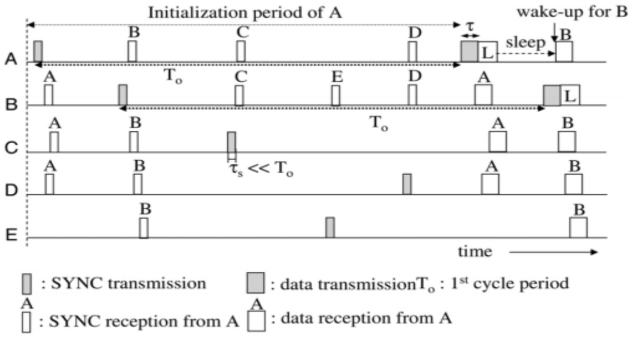

Figure 3. Initialization phase in UWAN-MAC [3]

UWAN-MAC is suitable for networks with the stationary nodes and is energy efficient protocol [1]. Since UWAN-MAC use only one control packet, it is bandwidth efficient. Main disadvantage of UWAN-MAC is that collision can occur when a node is transmitting.

2.2. *R-MAC*

R-MAC proposed by P. Xie and J. Cui in [2]. The main goals of R-MAC are energy efficiency and fairness. R-MAC avoids data packet collision, schedules the transmissions of data packets and control packets. R-MAC also solve exposed terminal problem. In R-MAC, instead of using RTS/CTS to avoid data packet collisions, the transmission of control packets and data packets are scheduled at both the sender and receiver. To reduce the energy consumption on idle state and overhearing, in R-MAC each node works in listen and sleep modes periodically. In R-MAC each node has three phases, named latency detection, period announcement and periodic operation.

In latency detection phase, each node power on and randomly selects a time to broadcast a control packet, called ND (neighbor discovery). When a node receives NDs packet from its neighbors, it stores the arrival times of these packets, selects a time to send ACK-ND (acknowledge packet) randomly. ND and ACK-ND have the same size. After receiving ACK-ND, the source node can compute propagation latency.

In periodic announcement phase, each node randomly schedules and broadcasts its own start time of listen/sleep periodic operations for third phase. This packet called SYN. When a node receives broadcast packets (SYN) from its neighbors, converts the received schedules to its own schedule. In this phase, each node can record the schedules of its neighbors to its own schedule.

In periodic operation phase, each node wakes up and sleeps periodically. In this phase nodes communicate by exchanging REV/ACK-REV/DATA/ACK-DATA packets. If a node wants to send data, it sends a REV packet to reserve a time slot at the receiver. When receiver is ready for receiving data, it will notify all its neighbors by ACK-REVs about reserved time slot. All nodes that overhear ACK-REVs will be silent in their corresponding time slots. Hence sender can send data packet at the reserved time slot. Data packets are transmitted in a burst and each node can queue its data for the same receiver and sends all the queued data packets. To improve the channel utilization and reduce the control packet overhead, the receiver sends an ACK-DATA packet to the sender at the end of the burst transmission.

R-MAC is a fair MAC layer protocol. Because in R-MAC by transmitting REV and ACK-REV packets, an intended receiver can provide equal opportunities to make reservation for all its neighbors. This protocol works fine when no new node joins the network and all nodes are static.

The advantage of R-MAC is that no synchronization and centralized scheduling is required. The disadvantage of R-MAC is that there is no technique proposed when a node wants to change its transmission schedule or a node failure occurs or a new node joins to the network [8].

2.3 Slotted FAMA

Slotted FAMA proposed by M. Molins and M. Stojanovic [3]. This protocol is based on FAMA [9]. FAMA use RTS/CTS message exchange for transmitting data. In FAMA, to overcome MACA protocol problems, RTS length should be greater than maximum propagation delay and CTS length should be greater than twice maximum propagation delay plus RTS length. FAMA is not suitable for underwater environment; Because RTS and CTS length depend on propagation delay which is higher in underwater environment [3]. If RTS/CTS is not used, collision can occur. Slotted FAMA was proposed to overcome this problem. In Slotted FAMA, time is divided into slots and each packet has to be transmitted at the beginning of one slot. Slot length should be $\tau + \gamma$, where γ is the transmission time of CTS packet and τ is maximum propagation delay. It is guaranteed that CTS or RTS packet transmitted at the beginning of a slot is receives by all neighbors.

In Slotted FAMA when a node has a packet to send, it waits until the next slot and sends an RTS packet. The RTS packet is received by the receiver node and all nodes in the neighborhood of the sender node within the slot time. At the beginning of the next slot, the receiver node sends a CTS packet. The CTS packet is received within the slot time by the source node and all nodes in the neighborhood of destination node. Neighbor nodes after overhearing CTS should wait until source node transmit entire data packet and receive ACK packet. When the source node receives CTS packet, it waits until the beginning of the next slot time and transmit the data packet. Neighbor nodes after overhearing data packet should wait long enough until destination node transmit ACK or NACK packet. When the destination node received the data packet successfully, it sends an ACK packet to the source node, else it sends NACK. Neighbor nodes after overhearing ACK should wait until the end of the slot. If neighbor nodes hear NACK, they should wait until transmission is complete and new ACK is sent. Figure 4 illustrates a successful handshaking.

Figure 4. A successful handshaking in Slotted FAMA [2]

To increase the efficiency, Slotted FAMA uses trains of packets technique. In this technique, each node has a local queue. When a node establishes communication with other node, it will transmit all packets in its queue that should be sent to the same node. Therefore one handshaking require for sending multiple packets.

In Slotted FAMA, use of ACK/NACK introduce exposed terminal problem. As can be seen in Figure 1, if node B receives an ACK packet from node A, then node C should not send and wait until transmission to be completed between node A and node B. Therefore use of ACK/NACK packet is only useful for a channel with high bit error rate and multiple hops.

Main advantage of Slotted FAMA is that it reduces collisions between data packets and doesn't require the size of data packets. Main disadvantage of Slotted FAMA is that it doesn't consider power control and energy consumption

3. Performance Evaluation

In this section, we compare performance of RMAC, Slotted FAMA and UWAN-MAC. We compare these protocols in Aqua-Sim, an NS-2 based simulator for underwater sensor networks [10].

Our simulations consider the following three scenarios:

Dense Topology: In this scenario, we consider throughput and energy consumption for the protocols. Table 1 shows the simulation parameters.

Table 1. Simulation parameters for dense topology

Variable	Attribute
Topology area	• 500m*500m
Topology depth	• 100 m
Transmission power	• 0.4 watt
Receive power	• 0.2 watt
Idle power	• 0.01 watt
Maximum transmission range	• 100 m
Routing protocol	• VBF(vector based forwarding)
Bandwidth	• 20 Kbps
Frequency range	• 30 KHz
Traffic Type	• CBR (data rate 0.02 packet per second)
Number of Nodes	• 30
Simulation Time	• 18000 Second(5 Hour)

The topology is shown in Figure 5. In this simulation, number of nodes are 30, which 15 nodes are sender and 15 nodes are receiver. Positions of each node are chosen randomly. Traffic type is constant bit rate. Each sender node sends 0.02 packets per second. On the other hand each sender node sends 50 packets in second. Simulation time is 5 hours.

As we can see, RMAC and UWAN-MAC energy consumption is lower than the Slotted FAMA. This is mainly caused by two factors. First, in RMAC and UWAN-MAC protocols, each node can switch to sleep mode after sending or receiving its data.

Second, Slotted FAMA doesn't consider energy conservation and doesn't have sleep mode. As shown in Figure 6, RMAC is much more energy efficient. Further, low energy consumption in RMAC caused by low data delivery throughput. Figure 7 shows the result of receiving throughput.

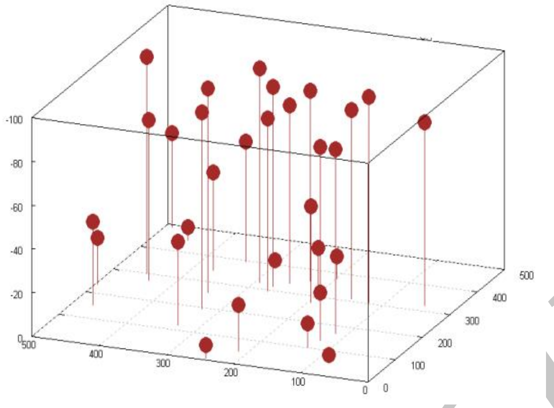

Figure 5. Sensor nodes in the dense topology.

The results of energy consumption are shown in Figure 6.

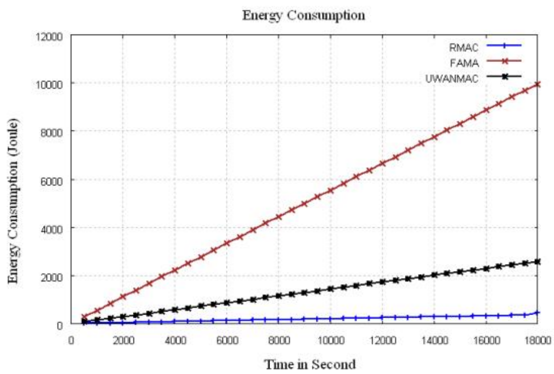

Figure 6. Energy consumption for first scenario

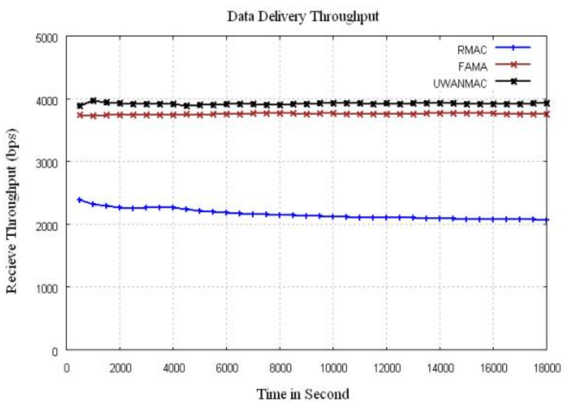

Figure 7. Receive throughput for first scenario

As shown in Figure 7, receiving throughput for UWAN-MAC and Slotted FAMA is higher. Because in RMAC, sender nodes choose transmission times randomly.

Moreover in RMAC it is possible that when a node sends packets, the other nodes are in sleep mode. Because topology is dense and number of sender nodes are relatively high it is possible that more nodes want to reserve channel and caused reduce performance of channel in RMAC.As we can see, Slotted FAMA and UWAN-MAC have high data delivery throughput in dense topology and RMAC has low data delivery throughput in dense topology.

Single sink: In this scenario, we compare receiving throughput, energy consumption for the protocols. Table 2 shows the simulation parameters.

Table 2. Simulation parameters for single sink topology

Variable	Attribute
Topology area	• 100m*100m
Topology depth	• 100 m
Transmission power	• 0.4 watt
Receive power	• 0.2 watt
Idle power	• 0.01 watt
Maximum transmission range	• 100 m
Routing protocol	• VBF(vector based forwarding)
Bandwidth	• 30 Kbps
Frequency range	• 25 KHz
Traffic Type	• CBR (data rate 0.05 packet per second)
Number of Nodes	• 9
Simulation Time	• 3600 Second(1 Hour)

The topology is shown in Figure 8. In this simulation, number of nodes are 9. Numbers of sender nodes are 8, and 1 node is sink. The other nodes transmit data to the sink node. The distance between ordinary nodes and sink node is 80 meters. Simulation time is 1 hour. Traffic type in this scenario is constant bit rate and each ordinary node sends 20 packets per second to the sink node. All nodes were located at a depth of 50 meters.

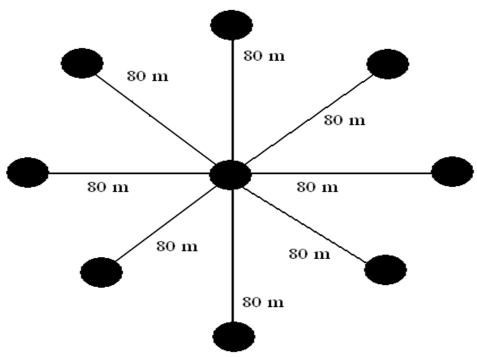

Figure 8. Sensor nodes position in the single sink topology

The receiving throughput is shown in Figure 9. From this Figure, we can see that the receiving throughput of Slotted FAMA and UWAN-MAC is much more than

RMAC in single sink topology. Because in RMAC all ordinary nodes want to reserve channel for sending data to the sink and caused collisions and low data delivery throughput. But Slotted FAMA uses RTS/CTS control packet and sink node informs other ordinary nodes with CTS packet. Moreover in UWAN-MAC all ordinary nodes announce sending time to the sink node and inform it.

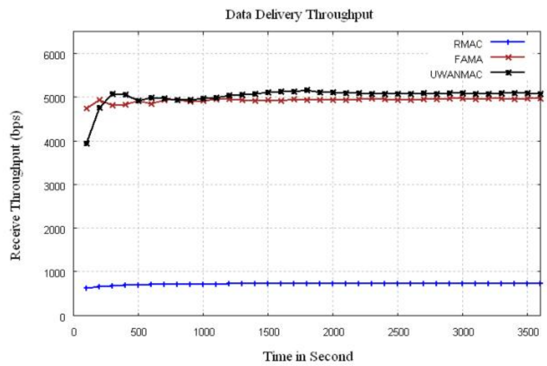

Figure 9. Receive throughput for the single sink topology

Figure 10 shows the result of energy consumption. From this Figure we observe that energy consumption is high in Slotted FAMA. Because according to the Figure 9, Slotted FAMA receives more packets than RMAC and in Slotted FAMA sleep mode is not considered. In this scenario RMAC and UWAN-MAC is more energy efficient than Slotted FAMA. Because in UWAN-MAC and RMAC, nodes can go to sleep mode when they don't send or receive. From Figure 10, we can see that the energy consumption in RMAC is lower than UWAN-MAC. Because receiving throughput in RMAC is lower than UWAN-MAC.

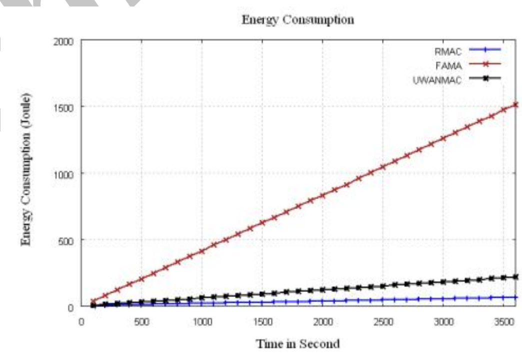

Figure 10. Energy consumption for the single sink topology

Pentagon topology: In this scenario, we compare receiving throughput, energy consumption and drop rate for the protocols. Table 3 shows the simulation parameters.

The topology is shown in Figure 11. In this simulation, number of nodes are 10. Numbers of sender nodes are 5 and numbers of sink nodes are 5. The ordinary nodes transmit data to the sink nodes. The distance between ordinary nodes and sink nodes is 50 meters. Simulation time is 2 hours. In this simulation we use CBR Traffic type with different data rates. All nodes were located at a depth of 50 meters.

The receiving throughput is shown in Figure 12. From this Figure, we can see that the receiving throughput of Slotted FAMA increases linearly as the data generation rate increases. Because Slotted FAMA doesn't reserve channel for transmission and it sends packets in the beginning of its slot if the medium is idle. Moreover as we will further discuss, Slotted FAMA has low drop rate. Receiving throughput in UWAN-MAC approximately for different data rate is constant. Also in RMAC after 0.4 packets per second receiving throughput is constant and approximately 5000 Kbyte. As we mentioned earlier, in RMAC and UWAN-MAC, each node first reserve channel for its transmission and after data rate 0.4 packets per second the traffic rate is relatively high, in RMAC and UWAN-MAC ordinary nodes can't reserve the channel immediately and caused high drop rate and low data delivery throughput. In Figure 12 as the traffic rate increases, the difference between Slotted FAMA and both RMAC and UWAN-MAC is more clear.

Figure 13 shows the result of energy consumption. From this Figure and Figure 12, we can conclude that the energy consumption increases when the number of received packets increases. From Figure 13 we observe that energy consumption is high in Slotted FAMA. This is mainly caused by three factors. First, Slotted FAMA uses RTS/CTS control packets and cause energy consumption. Second in UWAN-MAC and RMAC, nodes can go to sleep mode when they don't send or receive. But in Slotted FAMA, sleep mode is not considered. Third according to the Figure 12, Slotted FAMA receives more packets than UWAN-MAC and RMAC.

Table 3. Simulation parameters for pentagon topology

Variable	Attribute
Topology area	• 500m*500m
Topology depth	• 100 m
Transmission power	• 0.4 watt
Receive power	• 0.2 watt
Idle power	• 0.01 watt
Maximum transmission range	• 100 m
Routing protocol	• VBF(vector based forwarding)
Bandwidth	• 30 Kbps
Frequency range	• 20 KHz
Traffic Type	• CBR
Number of Nodes	• 10
Simulation Time	• 7200 Second(2 Hour)

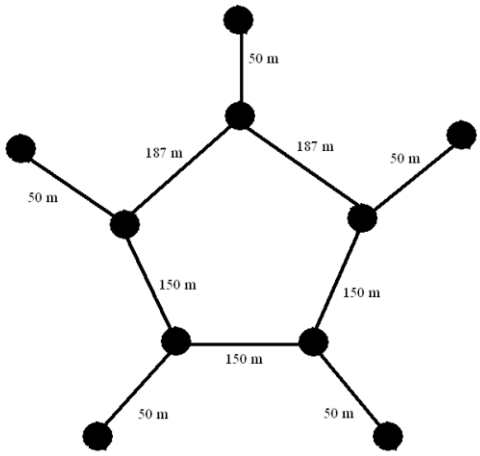

Figure 11. Pentagon topology

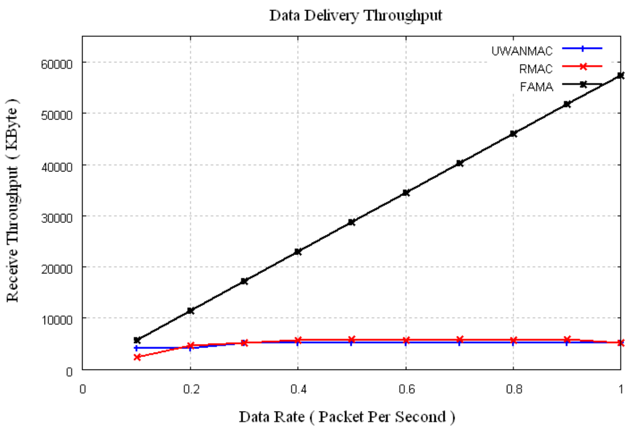

Figure 12. Receiving throughput in pentagon topology

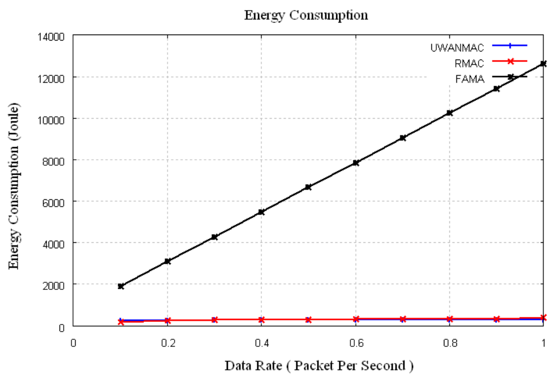

Figure 13. Energy consumption in pentagon topology

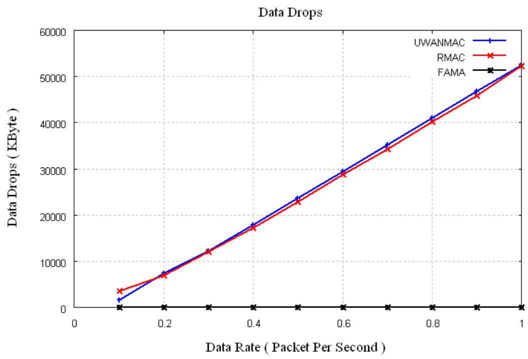

Figure 14. Drop rate in pentagon topology

The results for drop rate are shown in Figure 14. We can see that in RMAC and UWAN-MAC the rate of drop increases linearly as the data generation rate increases. Because in RMAC and UWAN-MAC, two nodes could have same transmission period, and collision can occur. Moreover as we mentioned earlier in RMAC and UWAN-MAC ordinary nodes can't reserve the channel immediately and caused high drop rate. In Figure 14, drop rate for different data rates in Slotted FAMA is approximately 0. Because in Slotted FAMA, each node exchanges RTS/CTS control packets for sending or receiving and notifies its neighbor nodes. As we mentioned earlier, the advantage of Slotted FAMA is that it reduces collisions between data packets.

4. Conclusion and further works

This paper has presented performance of three MAC protocols for channel access in underwater wireless sensor networks. In this paper, we have scrutinized different scenarios that are typical current underwater channel access scenarios. Simulation results show that no protocol fits all the needs. According to the simulation results, if we want to transmit much data to sink nodes and energy consumption isn't important, we can use Slotted FAMA. Because Slotted FAMA; uses bandwidth efficiently and doesn't consider energy limitations. Also if reliable communication is needed, Slotted FAMA and UWAN-MAC are better than RMAC. Otherwise if energy is limited and data is large, we can use UWAN-MAC. Simulation results show that energy consumption in UWAN-MAC is approximately the same as RMAC; but RMAC receiving throughput is less than UWAN-MAC. Since we can't recharge or change battery in underwater environment, both RMAC and UWAN-MAC are energy efficient and are useful for such an environment.

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