Factors affecting MAC Protocol Performance in Underwater Wireless Sensor Networks

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ABSTRACT
Underwater wireless sensor networks (UWSNs) has gained attention to researcher due to their wide range of applications. However, due to their power constrains and limitations, an energy efficient MAC protocol is required. Existing MAC protocols for terrestrial WSNs are not sufficient to solve the issues in UWSNs. Therefore, to design a new MAC protocol for UWSNs it is required to study the factors which cause the performance degradation of MAC protocols. In this paper, the various factors which affect the performance of MAC protocols has been highlighted in terms of energy efficiency, throughput, packet delivery ratio and delay. In addition, this paper also focuses on simulation-based experimental results to compare the performance of MAC protocols with respect to data rate factor.

Keywords
Underwater wireless sensor networks, MAC protocols, environmental factors

1. INTRODUCTION
Underwater wireless sensor networks (UWSNs) consists of a huge amount of wireless sensor devices which are deployed and networked with acoustic links to carry out shared monitoring works over a predestined area [1]. Some of the applications of this research are disaster prevention, environmental monitoring, ocean sampling networks, mine reconnaissance, assisted navigation and distributed tactical surveillance [1]. Each of the sensor node of UWSN consists of a transceiver unit, a power supply unit, a sensing unit and a processing unit. The components of sensing unit are: analog to digital converter and the sensors. The sensor nodes may have underwater application dependent machineries such as mobilizer, power generator and a location finding system [1, 2]. Cost is the main issue of the sensor nodes in underwater environments. Also, since the concern field is often very vast, this results in widespread use of mobile sensor and sparse deployment [2]. Therefore, if we use the radio frequency communication techniques in UWSNS as used in Terrestrial wireless sensor networks (TWSNs) [3], then the propagation delay in UWSNS will be very high with the velocity of light [4]. So, the sensor node uses acoustic channel [5] for communication. However, it has also some limitations like multi-path, path loss, high delay variance, noise and doppler-spread [6] which are the primary factors to maximize the lifetime of a node or networks. Additionally, it is not always feasible to replace or to recharge the worn out and exhausted batteries for sensor nodes in UWSNs,

In addition to the above, other important existing issue of UWSNs communication is, it uses magneto inductive communication [7] and optical communication [8], which cannot give the ideal solution for underwater communication. Also, when a sensor node uses a common wireless channel there is chances of disagreement within the sensor nodes. In this situation, a MAC protocol plays an important role to make a decision. The MAC protocol of UWSNs works on top of physical layer. The salient features of good MAC protocol are flow control, packets framing and error correction of data in the physical layer. The MAC protocol always keeps the energy efficiency into consideration which is very significant to UWSNs life and normal operation. Although there are several MAC protocols available for TWSNs, yet it is not possible to use them for UWSNs because of their long propagation delay and there characteristics [3, 4]. Thus, it is require to designing a new MAC for UWSNs considering the energy efficiency of performance metrics in terms of throughput, delay, packet delivery ratio (PDR) and reliability. So, before designing the new protocols for that domain, we need to first highlight those factors which are the main cause those affect the performance of existing MAC protocol.

This paper mainly discuss about the effecting environmental factors which may influence the desired performance of the UWSNs. Moreover, it also presents the simulation based experimental results for showing the performance of MAC protocols under various factors.

The rest of this paper is organized as follows: Section 2 provides a brief review of MAC protocols. A systematic study of the effects of environmental factors on the performance of MAC protocols is given in section 3. The determining factors those affect the performance metrics of MAC protocols in UWSNs are discussed in Section 4. Simulation studies of the factors those affect throughput, PDR and delay in MAC protocols are presented in Section 5. Finally, we conclude the paper in section 6.

2. EXISTING MAC PROTOCOLS
A survey with performance analysis of energy-efficient MAC protocols for UWSNs is available in literature [9]. In this section, we review some of the existing MAC protocols for UWSNs.

Although there are many MAC protocol for TWSNs, they are not applicable to UWSN due to long propagation delay and the characteristics of underwater environment. Many proposed MAC protocols focus on UWSNs, these protocols have been proposed to overcome the effect of long propagation delay, such as low channel utilization, hidden terminal problem and exposed terminal problem.

In general, MAC protocols for UWSNs can be categorized into contention based MAC protocols and contention-free MAC protocols. In contention based MAC protocols, single wireless communication medium is allocated on demand and shared by all users. This type of protocol is suitable for bursty nature of traffic under light to moderate load. The UWAN-MAC [10], RMAC [11], $TMAC_U$[12], DACAP [13], Slotted FAMA [14], RIPT [15], MR-MAC [16], SFAMADT [17], ROM-MAC [18] and UMMAC [19] are some of the examples of contention based MAC protocols. On the other hand, the contention-free MAC protocols which is also known as scheduled based MAC protocols because the sensor nodes maintain a schedule. This type of protocol reserves resource for individual user. So, these contention free MAC protocols are not suitable for large-scale UWSNs. The ACMENet [20], MU-Sync [21] are some of the examples of contention based MAC protocols. Moreover, based on topology of a network, MAC protocols those are available in recent literature are also categorized as Ad-hoc based MAC protocols and cluster head based MAC protocols. The Adhoc based MAC protocols are appropriate for real time data transmission. Whereas, the cluster head based MAC protocols are suitable for avoiding collision incurred by propagation delay of underwater environments. The ad-hoc based MAC protocols are UWAN-MAC [10], DACAP [13], Slotted FAMA [14], aloha based protocols are available in literature. On contrary, the cluster head based MAC protocols are based on TDMA protocol which are distributed at regular distances and select all cluster-head after forming clusters. The ACMENet [20], MU-Sync [21] and SYNC-MAC [22] are some of the examples of cluster based MAC protocols which minimizes the chance of data collision and avoids energy consumption. The limitations of cluster head based protocol are: nodes transmit packet within allocated time slot, difficulties on time synchronization because of long propagation delay, possibility of data collision in real implementation. However, in the following, we briefly describe these protocols.

In [12], TMACu has been proposed for UWSNs. It is originally a MAC protocol for TWSNs, called TMAC [23]. TMAC was modified for underwater environment by P. Xie [12]. The major revisions of the protocol are: active time to incorporate propagation delay, and RTS/CTS method modified to adapt long delay network. Carrier sensing method was not adopted since it does not make much sense in UWSNs.

Since, energy efficiency is important for UWSNs, in an attempt to improve energy efficiency and channel utilization, UWAN-MAC protocol has been proposed in [10]. It is a distributed energy efficient, collision avoidance, contention based and scalable MAC protocol for UWSNs which works even with unknown long propagation delay. Energy efficiency is the sole performance metric in UWAN-MAC to a certain extent than bandwidth utilization. This protocol avoids packet or data collision by using adaptive TDMA time schedule approved by shared neighbors. UWAN-MAC protocol works on the postulation of synchronizing the sensor node transmissions through adaptive TDMA and reducing energy consumption through sleep and wake up modes. Synchronization is a challenge for UWAN-MAC protocol, but it takes care of both the energy saving and propagation delay of UWSNs.

Another method to improve energy efficiency has been proposed called Reservation based MAC [11] (RMAC), whose intend goals are to minimize energy consumption and to provide fairness. To decrease the energy consumption in overhearing and idle state, each sensor node works in sleep and listen modes from time to time for same durations. And each node arbitrarily chooses its own schedule for data communication. Therefore, no synchronization is required. However, RMAC evade data packet collision by maintaining a time schedules for transmissions of sensed data and control packets at both the sender nodes and receiver nodes. RMAC solve the exposed terminal problem and save energy

3. ENVIRONMENTAL FACTORS AND THEIR EFFECTS

In this section, a comprehensive analysis of various environmental factors and their affect on the MAC protocol performance of UWSNs are discussed. The most important environmental factors are temperature, transmission range, deployment, ambient noise, salinity, range and node mobility. Moreover, we study the impact of those factors on energy efficiency, throughput, packet delivery ratio (PDR) and delay. Several environmental factors might contrarily influence the communication quality between sensor nodes in UWSNs, contrasted with the communication that happens on terrestrial WSNs. Some of the main considerations those impact on UWSNs communication are shortly revised in the following subsections.

3.1 Water Temperatures and Ambient (Hydraulic) Pressure

Speed of sound in underwater environment is a function of water temperature (T), ambient pressure (P) and salinity (S). Here, the temperature and ambient pressure are dependent on depth (D) but salinity is independent of this. It has been observed that high ambient pressure at the base of ocean can influence the signal communication [24]. According to J. Kuperman [25], speed of sound (C) in m/s can be numerically represented by equation 1, where depth (D) measure in meters, temperature (T) in degree centigrade and salinity (S) in parts per sec.

$$C = 1449.2 + 4.6T - 0.055T2 + 0.00029T3 + (0.34 - 0.01T)(S - 35) + 0.016D \quad (1)$$

Temperature instability affects signal communication in underwater environments [24]. In general, water temperature varies from top layer to bottom layer of underwater environment (or ocean), which in turn effects speed of sound (or acoustic signal). For example, speed of sound near sea surface in polar region increases as temperature increases in a summer season. Whereas, in non-polar regions, temperature is low at sea surface, leading to minimum sound speed. A comparative study [25] of the effect of temperature in different depth level on speed of sound in underwater environment is given in Table I. In general, speed of sound varies as depth increases as shown in Table I. However, the ambient (depth) pressure is not significant in shallow water. Thus higher speed of sound exists near sea surface in summer due to heating, whereas sound speed is same in all parts in winter due to mixing of wind and wave.

Density of water increases as temperature decreases. The temperature of water decreases from shallow to bottom of the ocean. So, density of ocean water increases as one move to bottom of the ocean [26]. Temperature and salinity of water are the important factors those make density of water less or more.

3.2 Salinity

The ocean water is denser (1027kg/m3 at the surface) than both pure water (100kg/m3) and fresh water, in light of the fact that dissolved salt increase the mass by a larger extent than the volume. One of the reasons behind high density of ocean water is the presence of salt in it, which in turn affects the underwater communication process in UWSNs. As the level of salt in water increases, density of water increases which results in delay in signal path [27]. In addition, the point of freezing of seawater decreases as salt concentration increases [26].

Table 1. Effect of Temperature and Depth on Speed of Sound

Layer No	Underwater Regions (Shallow to Deep Bottom)	Temperature(T) or Depth (D)	Remarks / Reasons for T or D changes	Effects on Sound Speed (S)
1A	Sea Surface (non Polar Regions)	T Increases	T: afternoon effect	S Increases with T
1B	Sea Surface (polar regions)	T coldest	T coldest near to surface	Minimum sound speed
2	Mixed Layer (Isothermal)	T constant, D increase	Wind and wave mixing takes place. D: ambient pressure	S Increases with D
3	Thermocline Layer	D increase	T changes more rapidly with D	S Decreases with D
4	Below thermocline layer	T constant, D increase	D increases with ambient pressure	S increases with D
5	Deep sound channel axis	D constant	Between deep isothermal region and mixed layer	Minimum sound speed
6	Deep isothermal region	D increase	D:ambient pressure	S Increases with D
7	Sea Surface (polar regions)	T coldest	T coldest near to surface	Minimum sound speed

3.3 Depth

Depth of sea or distance (transmission range) between two sensor nodes in UWSNs affects the path loss (P) of a signal. According to [28], P can be model as equation 2. Here, d is the transmission distance, f is the signal frequency, k models the spreading loss and a is absorption coefficient.

$$P(d,f) = dka(f)d \quad (2)$$

$$Q(t) = x(f,d,s,r) + w(t) + n(t) \quad (3)$$

Absorption coefficient (a) can be obtained using thorp empirical equation as shown in equation 3. Where, Q(t): propagation loss from sender node N1 to receiver node N2, x(): propagation loss function without random and periodic components, f: signal frequency, d:distance between N1 and N2, s:depth of N1, r: depth of N2, w(t): periodic signal loss function due to wave movement and n(t): signal loss due to error or random noise [28].

3.4. Underwater Current

The alterable stream of underwater current speed impacts relative position of sensor nodes in the UWSNs. This likewise influences the communication quality on account of the noise created by them. Sensor nodes in underwater environments are costly and the fields of concern in underwater environments are often very vast, which results in widespread use of mobile sensors and sparse deployments [2]. Sensor nodes can be either deploy in mass or one by one in the sensor field [5]. After organization and deployment of sensors in sensor fields, topology of sensor nodes may change because of progress in sensor nodes position, remaining energy and reachability. Moreover, topology of sensor nodes may also change due to underwater currents.

Underwater current is one of the main reasons for node mobility in ocean, which may cause link failure. Such link failure will contrarily affect quality-of-service support and routing. Moreover, traffic intensity, control overhead and network size affect network scalability. These factors alongside inborn attributes of UWSNs may bring about flighty varieties in the general UWSNs performance. Evaluating the impacts of these factors will manage the outline decision and tradeoff. For instance, assume node mobility is appeared to greatly affect normal control overhead than some other factors. These would recommend those planning and designing algorithms which can adjust to node mobility would have the best effect on UWSNs performance [29].

3.4 Ambient Noise

In general, ambient noise level means noise or interference level factor that affect underwater communication. Noise in UWSNs can be natural or man-made. Man-made noises are due to machinery noise and shipping activities, while natural noises are due to underwater currents, seismic or biological activities and hydrodynamics. Sources for ambient noise (Na) in UWSNs are: shipping (Ns), turbulence (Nt), thermal noise (Nh) and wave (Nw). As given in previous work [28] ambient noise can be modeled as in equation 4. Moreover, ambient noise is dependent on deployment of sensor nodes in UWSNs.

$$Na(f) = Ns(f) + Nt(f) + Nh(f) + Nw(f) \quad (4)$$

Reference [30] reported findings of the impact of environmental noise on the MAC protocol performance. Environmental noise may have different effects on different MAC protocols. In all cases, environment noise may degenerate information or data frames. In the RTS/CTS based MAC, the RTS/CTS control frames might likewise be ruined by environmental nois e. In the preamble based MAC, a sender might wrongly decipher a noise as the tone of its receiver node and along these lines begin to transmit to a non-ready receiver node. Additionally, environmental noise in the control channel may interfere with the transmission of a sensor node.

4. EFFECTS ON PERFORMANCE METRICS

The determining factors those affect the performance metrics of MAC protocols in UWSNs are shortly describes as follows:

4.1 Throughput

In [29], the results clearly indicate that number of source nodes does not affect throughput but the throughput has impact of network size. Large network size results in enhanced throughput. In addition, impact of routing protocol is irrelevant on throughput. If energy efficiency and throughput is a key concern, then source routing has a tendency to be a “superior” outline decision than dispersed routing. In the next section, with simulation studies we will discuss how the various factors such as data rate, hop length, and network topology can affect throughput.

4.2 Delay

Outcomes of [31], reveals that application demand for throughput and noise level does not affect the latency. However, protocol used is responsible for almost all of the type of delay. We will discuss how the various factors such as data rate, hop length and network topology can affect delay in the next section.

4.3 Energy Consumption

From [31], it can be summarized that the noise level does not affect the energy consumption. The application demand for throughput, the protocol use and the interaction between sensor nodes almost equally affect the energy consumption. At low throughput or at low data rate, few MAC protocol require a little bit less energy than other. However, energy consumption increases at high throughput or at high data rate.

Study from [29] reveals that energy consumption is strongly affected by network size. As network size increase the average energy consumption is decrease. Additionally, they also said that the impact of number of sources is negative. However, increase the number of sources may increase the average power consumption. Naturally, this is sensible for huge network with stable traffic load. Basically, with increasing of traffic sources enhances the routing load of each mobile host, resulting in increased power consumption.

4.4 Packet Delivery Ratio (PDR)

In [32], authors studied the impact of environment parameters such as temperature and humidity on the physical layer and connection quality. A few trends are clearly identifiable from results of experiments in [32]. First, the quality of communication decreases as one progress from open to spruce and up to beech (that is the quantity of trees and foliage increases). The trend is more marked during summer. The difference in PDR of the order of 15-20% is observe while moving from open to spruce and from spruce to beech. Second, the seasonal variation also induces dramatic changes in connection quality. The connection quality is worse in winter than summer due to the presence of snow. In case of spruce, difference in PDR can be as high as 30% at high power. Third, during winter the difference in PDR between spruce and beech type of forest are negligible. As discussed in [32], this is not true for other parameters related to connection quality. However, through the macroscopic lens provided by the network-wide average PDR, it appears like the combination of snow and vegetation yields the same effect regardless of the density of the latter. Similarly, in presence of obstacles and variation in density of water will have high impact on communication pattern in UWSNs. Thus, non-environmental factors can affect performance of any MAC protocols of UWSNs in terms of PDR. In the next section, we will discuss how the various factors such as data rate, hop length and network topology affect PDR with the help of simulation studies.

5. EXPERIMENTAL RESULTS

In this section, a simulation study of the factors that affects throughput, delay, PDR and energy efficiency is presented using a NS-2 based tool called Aqua-Sim [12]. Three MAC protocols are considered for simulation study: RMAC, UWAN-MAC and TMAC. The protocols are chosen because of the following reasons: RMAC [11] and UWAN-MAC [10] are among the first to be proposed and specifically designed with efficient communication methods to work in UWSNs, which offer high energy efficiency and reasonable data transport capabilities. Moreover, TMAC [23] is among the first to be proposed and specifically designed with efficient communication methods to work in TWSNs. TMAC has later been modified by P. Xie [12] for underwater environment.

To evaluate the performance of MAC protocols in terms of these factors, we consider a two-hop network topology is considered as shown in Fig.1, where one is receiver, two are sender and rest of the nodes are gateway. In this topology, a two-hop network with five nodes which are separated 20 m apart from each other and keeping hop length constant. Here, the variable data rates are used to compare these three protocols. The performance comparison is discussed in the following subsections.

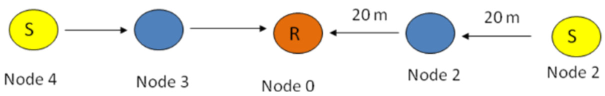

Fig. 1 Network topology with five nodes

5.1 Throughput, Delay and PDR with Respect to Data Rate

In this subsection, three metrics are measured: throughput, delay and PDR as shown in Fig.2, Fig.3 and Fig.4 respectively. These figures represent the corresponding outcomes, from which we can conclude that RMAC can achieve more throughput than TMAC, UWAN-MAC in linear network topology. TMAC is a TWSNs protocol modified by P.Xie [12] for UWSNs, hence throughput fluctuate because of various environmental factors like interference, attenuation and delay. As data rate increases, the delay for TMAC and UWAN MAC varies, but RMAC delay is almost stable and less for linear topology network. RMAC is advantageous over TMAC and UWAN MAC in terms of delay for linear topology network, but PDR of TMAC is more than RMAC and UWAN-MAC.

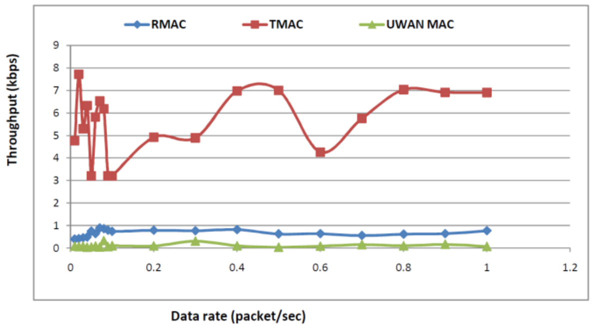

Fig. 2 Throughput vs Data Rate for linear network topology

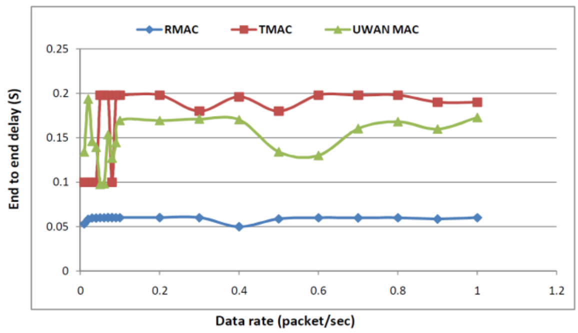

Fig. 3 End to End Delay vs Data Rate for linear network topology

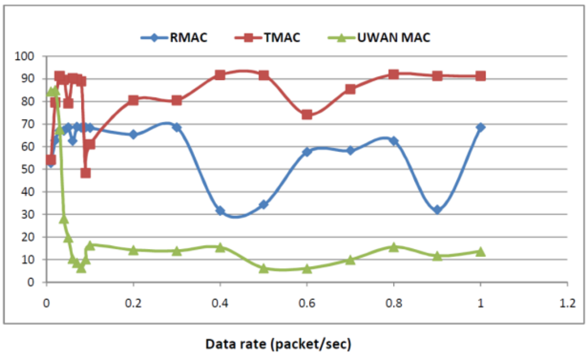

Fig. 4 Packet Delivery Ratio vs Data Rate for linear network topology

5.2 Energy Efficiency with Respect to Data Rate

In order to compare energy efficiency of MAC protocols, energy consumption with data rate are compared. Fig.5 shows that RMAC saves more energy than UWAN-MAC. The reason is that UWAN-MAC uses more duty cycle which spends more energy uselessly. Moreover, energy is spent in synchronizing nodes locally and to schedule data transmission among all neighbors. However, RMAC can save more energy since it spends less time in synchronizing and to prepare schedule with the help of cluster head. It is to be observed that TMAC is less energy efficient than RMAC and UWAN-MAC. It is obvious, because TMAC is a variant for terrestrial WSNs and not suitable for UWSNs, whereas RMAC and UWAN-MAC are designed for UWSNs.

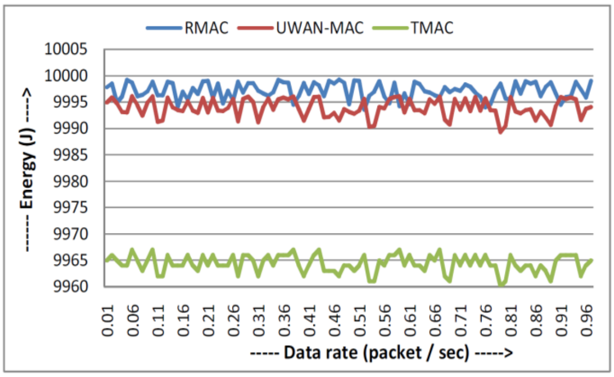

Fig. 5 Remaining energy vs data rate

The above result shows that data rate has the strongest impact performance responses followed closely by hop length and network topology. As the data rate increases throughput increases exponentially and goes to a stable state after reaching a threshold value. Due to the effectual collision avoidance strategy of MAC protocol, throughput stays stable at the threshold value while the data rate keeps on increasing, i.e. data rate has little effect after threshold value. However, delay rises dramatically as the data rate increases. It is because while the data rate increases there is more possibility of collision, and therefore more data packets will be lost, i.e. more delay is initiated. Data rate has little effect on energy efficiency and PDR, but PDR fluctuates due to network congestion leading to more collision. Similar observations are found both for simple network topology and linear network topology, but with a difference that value of throughput, delay and PDR fluctuates as the topology changes. It is due to the environmental factors that affect the performance of MAC protocols for UWSNs. Unlike UWAN-MAC, RMAC can be used for both simple and linear network topology with maximum hop length of two, for low packet delay network which requires high system energy efficiency, throughput and PDR. For both MAC protocols, as hop length increases, throughput decreases and delay increases. However, initially PDR increases with increase in hop length until a point where it starts to fall. Network topology, data rate and hop length will have a considerable impact on network performance. These factors alongside innate attributes of UWSNs may bring about unpredictable varieties in the general UWSNs performance. Measuring the impacts of these factors will direct the configuration decision and tradeoffs. For instance, suppose network topology is shown to have a greater affect on data rate than any other factor. This would propose that designing algorithms that adjust to network topology would have the best effect on network performance.

6. CONCLUSION AND FUTURE DIRECTIONS

In this paper, a comprehensive analysis of various environmental factors is presented which affect the MAC protocol performance of UWSNs. Moreover, the impact of the data rate factor with three MAC protocols has been investigated by simulation study. The simulation results has shown that the data rate has the strongest impact performance response followed closely by hop length and network topology. The data rate factor alongside innate attributes may bring unpredictable varieties in the general UWSNs performance. Hence, measuring the impacts of these factors will direct the configuration decision and tradeoffs. Future research will focus on designing an energy efficient MAC protocol for UWSNs while considering the performance metrics- throughput, delay, PDR and reliability.

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