A Comparative Performance Evaluation of Distributed Collision-free MAC Protocols for Underwater Sensor Networks

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Abstract: The design of Medium Access Control (MAC) protocols for UWSNs poses many challenges because of their long propagation delay, high mobility, limited bandwidth, and high bit error rate. Due to these unique acoustic channel characteristics, most contention-based MAC protocols are costly. Thus, collisions and retransmissions should be efficiently handled at the MAC layer in order to reduce the energy cost and to improve throughput and fairness across the network. As a consequence, they do not perform as efficiently as their achieved performance in terrestrial networks. In this paper, we evaluate the performance of three recently reported distributed collision-free MAC protocols; namely, ED-MAC, DL-MAC, and GC-MAC under various operational conditions. An extensive simulation study is carried out to compare the performance of these MAC protocols in terms of packet delivery ratio (PDR), throughput, and energy consumption with different scenarios (narrow and shallow networks) under varying traffic rates and numbers of nodes. Our study results showed that ED-MAC reaches the best energy efficiency in a narrow scenario with a light load than DL-MAC and GC-MAC protocols. While DL-MAC is a suitable choice for both scenarios among others in terms of flexibility. In terms of reliability and scalability, GC-MAC achieves the best performance in both scenarios than other protocols.

1 INTRODUCTION

Underwater sensor networks (UWSNs) have attracted a considerable attention to discover and monitor aquatic environments. This aims to improve ocean exploration and underwater applications such as environmental monitoring, early warning systems, disaster prevention, intrusion detection, military applications, and exploration of ocean resource (Ghoreyshi et al., 2017). In UWSNs, a sink is considered on the water surface, which is applicable to both an acoustic modem for underwater communication and a radio modem for out-of-the-water communications (from sink to satellite, and from satellite to monitoring centre) (Ghoreyshi et al., 2016; Alfouzan et al., 2016). Anchored nodes are located at the bottom of the ocean in predetermined locations to collect the information. That information is delivered to the sink using the relay nodes which are located between the sink and the anchored nodes at different depth levels. The anchored and relay nodes utilise acoustic signals to transmit the data packets (Ghoreyshi et al., 2018a).

Using acoustic signal differently affects the design of various services in UWSNs (Akyildiz et al., 2005). Specifically, it has completely changed the design of Medium Access Control (MAC) protocols compared to that of terrestrial networks (Hsu et al., 2009). Since radio wave cannot propagate in the underwater environment as efficiently as it achieved in terrestrial networks, currently acoustic communication has extensively been studied (Preisig, 2007; Ghoreyshi et al., 2018b). However, due to the unique characteristics of its acoustic channels such as slow signal propagation speed (about 1500m/s in water), limited channel capacity, and high dynamics of channel quality, MAC protocol design for underwater acoustic networks face several challenges. Particularly, the high propagation delay which significantly affects the MAC design strategy in UWSNs.

Existing MAC solutions are essentially focused on TDMA. This is mainly because FDMA is not proper for UWSNs due to the narrow bandwidth in underwater acoustic channel as well as the diffuse of limited band systems to fading and multipath. Moreover, CDMA is very robust to frequency selective fading caused by multiple paths. It is therefore unsuitable for UWSNs due to also its difficulties to address the near-far problem (Xie and Cui, 2007).

Among them, TDMA is the most promising multiple access technique for UWSNs. This is mainly

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because it allows the same frequency channel to be shared by dividing the signal into different time slots. Furthermore, it is able to maintain reliable transmission schedules by performing additional updating and scheduling phases to also remain all sensor nodes synchronised. TDMA also allows sensors, located out of each others' transmission ranges, to transmit data packets simultaneously without collision by using the concept of spatial reuse (concurrent sending in different neighbourhoods) (Alfouzan et al., 2018a). For these reasons, TDMA increases channel reuse and eliminate packet retransmissions, which results in decreased energy consumption and increased network throughput.

Recently, three new TDMA-based distributed collision-free MAC protocols, ED-MAC (Alfouzan et al., 2017; Alfouzan et al., 2018a), DL-MAC (Alfouzan et al., 2018b), and GC-MAC (Alfouzan et al., 2018c), have been reported in the literature with varied performance under various operational conditions and different assumptions. The aim of this paper is to compare the performance of these protocols under two different practical scenarios, namely shallow and narrow scenarios, and to investigate their reliability, scalability and flexibility under a wide range of experimental conditions.

The remainder of this paper is organised as follows. Section 2 describes and classifies the protocols that we have investigated. Section 3 investigates and compares the performance evaluation. Section 4 concludes the paper.

2 DESCRIPTION OF THE PROTOCOLS

This section presents a description of each collision-free MAC protocol. It is then followed by a classification that includes all the requirements and properties of each, as illustrated in Table 1.

2.1 ED-MAC

An Efficient Depth-based MAC protocol (ED-MAC) has been proposed in (Alfouzan et al., 2017; Alfouzan et al., 2018a) with the aim of improving the energy efficiency, throughput, and fairness. It is a reservation-based MAC protocol in which a duty cycle mechanism is used by assigning time slots to every individual node in the network in a distributed manner. This is used to reduce the energy consumption by using a wake-up scheduling scheme; nodes are awake in some slots to transmit or receive data and are asleep over the remaining slots.

ED-MAC operates in three phases: initial, scheduling, and normal operational phase. In the first phase, all the sensors randomly transmit a number of small beacons to detect their one-hop neighbouring nodes. The length of the initial phase is a predefined fixed value for all sensors.

The primary goal of the scheduling phase is to allocate a unique time-slot to every sensor in the network. A timer is utilised at every sensor to prioritise slot reservation depending on the sensor depth; the deeper the sensor, the higher priority to reserve a slot. This timer lets a sensor which is located in a deeper area to reserve a slot sooner than its above neighbourhoods. The value of this timer at each sensor is given by (Alfouzan et al., 2017; Alfouzan et al., 2018a):

$$T_{sch} = \left(\frac{2M_{Depth}}{M_{Depth} + N_{Depth}} \times T_{Delay} \right) - T_{Delay}, \quad (1)$$

where M_{Depth} is the depth of the network area and N_{Depth} is a sensor depth in the network. T_{Delay} is the length of the scheduling phase that is a predefined fixed value, set during the deployment process based on the application requirements. The value of T_{Delay} depends also on the density of the nodes in an underwater area. This phase is significantly shorter than that of the normal operational phase.

The third phase, the normal operational phase, is divided into a number of rounds. Each of them includes a number of slots. Sensors in each round are aware of their reserved slots, and other slots that reserved by their neighbourhoods. Thus, all sensors can schedule to wake-up either to send their own data packets during the reserved slots or to receive a data packet from a neighbouring sensor. They switch to a sleeping mode in the remaining slots when there is no data transmission or reception.

2.2 DL-MAC

A Depth-based Layering MAC protocol (DL-MAC) has been proposed in (Alfouzan et al., 2018b) to improve energy efficiency, reliability, and flexibility. This is achieved by dividing the aquatic network area into a number of horizontal layers to avoid any chance of vertical collision. A simple clustering approach for one-hop neighbouring sensors are utilised to also avoid any possibility of collision between sensors in the same layer. Therefore, DL-MAC is able to address spatial-temporal uncertainty, the near-far effect, and any hidden/exposed terminal problems.

In DL-MAC, sensors in the network operate in three phases: updating, scheduling, and operational. The goal of the updating phase is to gather information about one-hop neighbouring nodes. This is performed by exchanging some updating messages. The length of this phase is a constant value set during the deployment time for all sensors.

The purpose of the second phase, the scheduling phase, is to assign a time-slot to every individual sensor in the network to access the medium with no chance of collision. This is achieved by dividing the network into multi layers, grouped into three frames, and every frame is also divided into a number of sub-frames. Each sub-frame consists of a number of time-slots. A distributed clustering approach is utilised to allow cluster heads, CHs, selecting unique sub-frames, which should be different from the adjacent clusters. By using a simple clustering approach, every cluster head is eventually able to assign all its cluster members, i.e., those are located within a one-hop neighbourhood, different time slots. Through this principle, every sensor in the network has a different time-slot in any two-hop neighbourhood; hence no collisions can occur. To determine a CH, this model gives higher priority to a sensor that can cover more sensors in its 1-hop range at the same layer. This is applied via a timer-based approach, called degree timer, which can be given by (Alfouzan et al., 2018b):

$$T_d = (d_{max} - d_s) \times (T_{sch}/d_{max}) \pm \lambda \tag{2}$$

where d_s denotes the sensor degree and d_{max} indicates the maximum node degree in the network topology. This can be estimated based on the sensor deployment process, number of sensor nodes, and network dimensions and it can also be known to all nodes during the deployment time. T_{sch} is the scheduling interval time and λ is a short random time duration to differentiate the underwater sensor nodes with the same d_s.

The operational phase is divided into a number of cycles, each consisting of three frames. Each frame is composed of k sub-frames. Frames and sub-frames are used to avoid vertical layers and horizontal cluster interference respectively. Each sub-frame also encompasses a number of slots. At each cycle, every sensor is aware of its frame, sub-frame, and its own reserved slots, as well as the slots reserved by its neighbouring sensors. They can therefore be scheduled to wake-up either to transmit their own data packet during the reserved slots or to possibly receive a data packet from a neighbouring sensor. They are asleep in the remaining slots when there is no data transmission or reception.

2.3 GC-MAC

A collision-free Graph Colouring MAC protocol (GC-MAC) has been proposed in (Alfouzan et al., 2018c) which aims to achieve better performance in terms of throughput, energy efficiency, and fairness than other collision-free MAC protocols. GC-MAC uses the concept of graph colouring to develop a reservation-based contention-free MAC protocol. This has been achieved by using a distributed clustering approach for up to two-hop neighbouring sensors and then to address the hidden and expose node problems by removing the possible colour conflict in two-hop neighbouring graph. Using a TDMA-like approach, GC-MAC is able to assign a time-slot, colour, to every individual node in the network in a distributed manner. Nodes with the same colours can thus transmit concurrently without collision. Nodes are awake in some slots to transmit or receive data packets and asleep over the remaining slots.

GC-MAC includes three phases to operate, which are initial, scheduling, and operational phase. In the initial phase, two rounds of beaconing are conducted to discover two-hop neighbouring sensors. This is performed by exchanging some beacons between sensors. The length of this phase is set as a constant value for all sensors during the deployment time.

The primary goal of the scheduling phase is to assign different colours to all nodes which are located within any two-hop neighbourhood using a simple a clustering approach. This is achieved by allowing a cluster head (CH), which is determined as the closest sensor to a reference point during the first phase, to assign a different colour for all its one-hop neighbouring (inner) sensors. Afterwards, the outer sensors, those located outside the cluster, decide about their own colours individually. By the end of the scheduling phase, every sensor node has a various colour in any two-hop neighbouring graph and hence no collision can occur.

The operational phase is divided into a number of rounds. Each round consists of a number of time-slots. These time-slots are reserved by assigning a various colour to each. Nodes with the same colour can transmit data packets at the same time without any collision while the hidden and exposed node problems are properly addressed. In this phase, the sensor nodes wake-up and sleep periodically. In other words, sensors can schedule to wake-up to send their own data packets during the reserved slots or to receive a data packet from a neighbourhood, while they are asleep in other remaining slots when there is no data transmission or reception.

2.4 Qualitative Comparison

In this section, we classify each protocol (ED-MAC, DL-MAC, and GC-MAC) requirements and properties, and compare them qualitatively.

Table 1 lists all assumptions in which every pro-

Table 1: Comparisons of the collision-free MAC protocols for UWSNs.

	ED-MAC	DL-MAC	GC-MAC
Category	TDMA-based	TDMA-based	TDMA-based
Year	2017	2018	2018
Schedule	Distributed	Distributed	Distributed
TDMA status	Adaptive slotted	Adaptive slotted	Adaptive slotted
Network division	No	Divided to layers	Divided to cubes
Clustered	No	Yes	Yes
neighbourhood info	One-hop neighbours	One-hop neighbours	Two-hop neighbours
Priority	Depth-based timer	Degree timer	Node ID
Random time	No	Yes	No
Synchronised	Yes	Yes	Yes
GPS	No	No	Yes
Number of slots	$2 \times N_{max}$	Equal to d_{max}	Fixed
Conflict Avoidance	No	No	Yes

tocol is based on. In fact, they are all classified as a TDMA-based duty-cycle MAC protocols while the basic information required for their operation are different.

During the deployment process, DL-MAC and GC-MAC require the network area to be divided into a number of layers and cubes, respectively, to improve the efficiency of their distributed scheduling. ED-MAC, however, does not require any network divisions. At the same time, its function is not based on any kind of clustering, whereas this is one of the requirements of DL-MAC and GC-MAC.

During the first phase, ED-MAC and DL-MAC require to exchange one-hop neighbouring information to be obtained before the scheduling phase. In their scheduling phases, both protocols set their priority timers differently. More specifically, ED-MAC's timer is used at each node to prioritise slot reservations depending on the node depth; the deeper the node, the higher the priority to reserve a slot. Equation 1 demonstrates how the priority of each sensor node is calculated. In DL-MAC, the degree timer is used in each sensor node to start the scheduling phase; a node with higher d-hop neighbouring nodes, which can cover more nodes in its 1-hop range at the same layer, has a higher priority to become a cluster head (CH) than other nodes. Equation 2 gives the degree timer of each node in the network, considering a short, random time duration, λ, to differentiate the sensor nodes that have the same sensor degree, d_s.

In the first phase of GC-MAC, however, two-hop neighbouring information is required to be obtained before the scheduling phase. The goal of exchanging the two-hop neighbouring information during the first phase is to detect the hidden terminal nodes which are located outside the two-hop neighbouring district of each other. After creating the neighbouring graph, N_g, by each sensor node, the nearest node's distance to a reference point, rp, becomes a CH, which is responsible for independently choosing a colour for itself and different colours for its cluster members (CMs). Nodes which are located between two adjacent cluster heads within more than two-hop neighbouring nodes decide their own colours individually; the lower the node ID, the higher the priority to select the first available colour among others.

According to the number of slots, each protocol has its own algorithm and assumptions which it uses to divide its operational window differently. In ED-MAC, for instance, the number of slots is double the maximum number of nodes in a neighbourhood, N_{max}, in order to exclude the possibility of concurrent data transmission from a sensor located outside a one-hop neighbourhood and the node within the neighbourhood. Meanwhile, in DL-MAC, the number of slots is proportional to the maximum node degree found in the one-hop neighbourhood graphs, d_{max}. In GC-MAC, the number of slots depends on the duration of the operational phase as well as the slot length, which is equal to the propagation delay plus a small guard time to ensure that a packet is entirely received at the destination before data transmission by another node can begin.

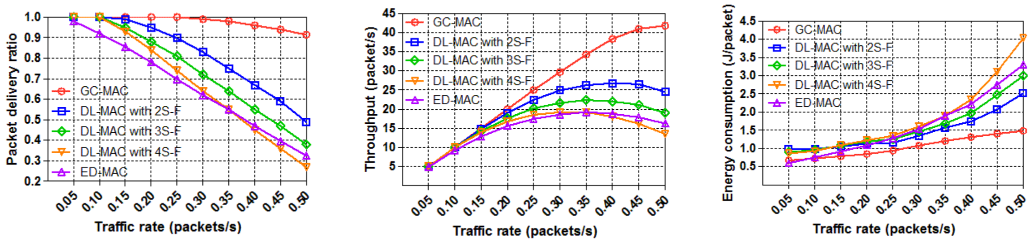
In addition, GC-MAC the only protocol among the selection discussed here to introduce the concept of conflict detection (CD). The primary goal is to detect and resolve any conflicts that may occur between sensor nodes during the scheduling phase.

3 PERFORMANCE EVALUATION

In this section, we first discuss the simulation scenarios and settings used in our comparison study in the Aqua-Sim underwater simulation (Xie et al., 2009). We then define the metrics used in our performance study. Finally, we compare the design trade-off between ED-MAC, DL-MAC, and GC-MAC within the various given scenarios and networks.

3.1 Simulation Scenarios and Settings

We implement our ED-MAC, DL-MAC, and GC-MAC protocols in Aqua-Sim, which is an NS-2 based simulator for UWSNs. In our simulations, we consider two scenarios, each of which is evaluated with reference to two parameters: the traffic rate, and the number of nodes. In the first scenario, all the underwater sensor nodes are randomly distributed in a 3D shallow region of $500m \times 500m \times 250m$. In the second scenario, the sensor nodes are randomly deployed in 3D narrow region of $300m \times 300m \times 600m$. The following parameters are used in all scenarios, unless noted otherwise: the traffic rate increases from 0.05 up to 0.5 packets per second. In this set, we randomly distributed 100 sensor nodes in the given two scenarios. The node density is also increased from 50 to



(a) PDR (b) Throughput (c) Energy consumption

Figure 1: Shallow region scenario: PDR, Throughput, and Energy consumption vs. Traffic rate.

500 sensor nodes within the same two scenarios. In this case, the traffic rate is fixed at 0.1 packets per second. In both scenarios, the power consumption on transmission mode is 2 Watts, the power consumption on receive mode is 0.75 Watts, and the power on sleep mode is 8 mW. The data packet size is set to 1000 bits, and all other control packets are set at 100 bits. The channel bit rate (i.e., bandwidth) is set at 10 kbps and the maximum transmission range is 100 meters.

It should be noted that all the results are averaged over 20 runs, and that each is obtained with a randomly generated topology in each scenario. The total simulation time for each run is set to 3600 seconds. In our simulation setup, the length of the first phase is a predefined fixed value for all sensor nodes, which is set at each sensor before deployment. Thus, we consider this phase to be 30 seconds in all three MAC protocols. The second phase, the scheduling phase, also uses a predefined constant interval set for all sensors at the deployment time based on the application requirements. Hence, we consider the scheduling phase, T_{sch}, to be 90 seconds in these reported MAC protocols, except GC-MAC which includes the conflict detection interval, T_{cd} added to its scheduling phase. The T_{cd} is set at 30 seconds.

3.2 Performance Metrics

We define the most important metrics in medium access control protocols during this comparison study to evaluate the performance of ED-MAC, DL-MAC, and GC-MAC protocols as packet delivery ratio (PDR), throughput, and energy consumption per packet successfully received in joules. These metrics are defined as follows:

The packet delivery ratio, PDR, is defined as the ratio of the packets successfully received to the total packets generated in the network. The network throughput is defined as the number of successful received packets divided by the simulation time. The energy consumption per packet is obtained by dividing the overall energy usage in the network by the successfully delivered data packets, where the energy consumption here is measured in joules per packet.

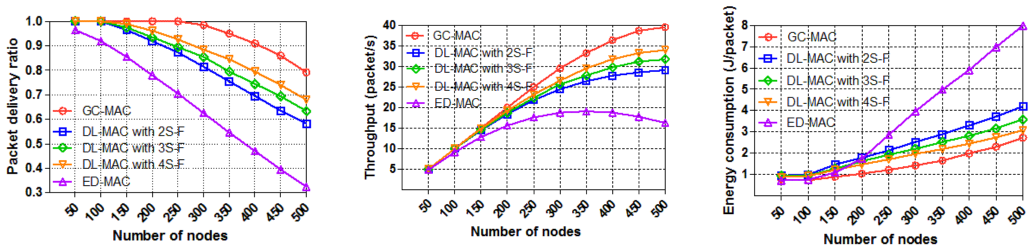
3.3 Simulation Evaluation

In this section, we present the results of the comparative performance evaluation of the protocols described in Section 2. We first display the simulation results of the shallow region scenario, before going on to demonstrate the simulation results of the narrow region scenario.

3.3.1 Shallow Region Scenario

In this scenario, we first evaluate the PDR, throughput, and energy consumption under varying traffic rates in all three MAC protocols, as illustrated in Fig. (1). In this case, the number of nodes is set to 100 sensor nodes.

Fig. (1a) shows the PDR as a function of data generation rate. With a low traffic load, the PDR for all protocols is 100%. When the traffic load further increases, the PDR of ED-MAC and DL-MAC (with 4 and 3 sub-frame configurations) significantly decreases. Due to the fact that the scheduling design of ED-MAC is based on depth criteria, it is more suitable to a narrow region rather than a shallow one. With a medium traffic rate (0.25 packets per second), GC-MAC performs best in terms of packet delivery ratio by delivering all the data packets. As the traffic rate further increases, GC-MAC still has the ability to deliver most of the packets, followed by DL-MAC with only 2 sub-frames. This is mainly because GC-MAC employs the conflict detection mechanism during its scheduling phase. Regarding the DL-MAC, because the traffic rate has a reverse relationship with the duration of the operational window, DL-MAC with 2 sub-frames performs better than DL-MAC with 3 and 4 sub-frame conflagrations. DL-MAC with 3 sub-frames also outperforms DL-MAC with 4 sub-frames. This is due to the fact that the higher the traffic rate, the lower the duration of the operational cycle; hence, no more available slots can be reserved.



(a) PDR (b) Throughput (c) Energy consumption

Figure 2: Shallow region scenario: PDR, Throughput, and Energy consumption vs. Number of nodes.

As can be seen in Fig. (1b), the network throughput of all protocols is proportional to the traffic rate. When the traffic load increases, the throughput of all protocols increases correspondingly up to their saturation points. ED-MAC and DL-MAC (with 3 and 4 sub-frames) achieve their maximum capacities sooner than GC-MAC and DL-MAC do, with 2 sub-frames, within 0.35 packets per second. DL-MAC with 2 sub-frames and GC-MAC reach their capability regarding handling data packets within 0.40 and 0.50 packets per second respectively. We can observe that GC-MAC outperforms all the other protocols in terms of throughput with the same traffic rates. This phenomenon is particularly evident in the case of GC-MAC, because it employs an effective conflict detection algorithm to avoid collisions, thus considerably improving network throughput.

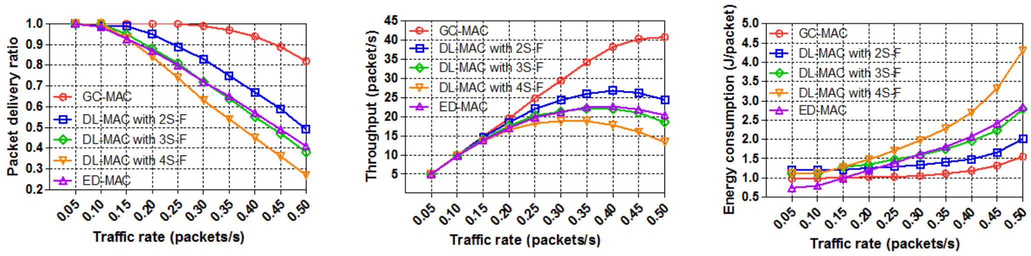
Fig. (1c) confirms what we have already seen in both Fig. (1a) and Fig. (1b). All the protocols are using a reliable and efficient mechanism for channel access and a very limited number of small packets during the initial and scheduling phases in order to eliminate collisions and achieve high throughput. However, Fig. (1c) also shows the energy usage per data packet successfully received. On the one hand, ED-MAC consumes less energy than any other protocol during all traffic rates. This is mainly because it has fewer requirements than the others during the deployment process as well as the first and second phases, such as multi layers in DL-MAC and reference points in GC-MAC. On the other hand, ED-MAC spends a higher amount of energy per data packet successfully received than the others, because it delivers a lower amount of packets than GC-MAC and DL-MAC with both 2 and 3 sub-frame configurations, as depicted in Fig. (1a). GC-MAC consumes lower energy in total, therefore it is the best protocol in terms of energy consumption per packet. It is more interesting to observe that DL-MAC with 4 sub-frames consumes more energy per packet at a high traffic rate. This happens because the higher the traffic rate, the lower the cycle duration; therefore, there is a short number of slots, causing high competition between nodes to reserve those limited slots, and thus greater energy consumption.

In this scenario, we also evaluate the performance of all the protocols in terms of PDR, throughput, and energy consumption under varying number of nodes, as shown in Fig. (2). This figure illustrates how sparse and dense sensor nodes in a shallow network can affect the protocols, and examines the scalability and flexibility among them.

Fig. (2a) illustrates the PDR as a function of number of nodes. In this figure, GC-MAC clearly outperforms all other protocols by handling all data packets up until 250 nodes. When the node density further increases, the PDR of GC-MAC slightly decreases by almost 20%. This is because of its efficient scheduling and the conflict detection mechanism that used during the scheduling phase. However, when the node density is low, ED-MAC delivers most of the packets (almost 98%). When the node density is increased, the PDR of ED-MAC decreases correspondingly to only deliver 31% with a high dense network. This is mainly because the ED-MAC policy depends on the nodes' depth, i.e., the deeper the node, the higher the priority to reserve a slot. ED-MAC does not consider horizontal hidden and exposed nodes located in shallower areas.

It is noteworthy that DL-MAC with higher sub-frame configurations performs better than DL-MAC with lower sub-frames. In this figure, DL-MAC with 4 sub-frames outperforms DL-MAC with 2 and 3 sub-frames. This is because a higher number of sub-frames implies the ability to handle more nodes. DL-MAC, with a higher number of sub-frames as a function of the number of nodes, gives the opposite results when it is as a function of the traffic rate as depicted in Fig. (1a). This is because the traffic rate has a reverse relationship with the duration cycle, as mentioned earlier, while the number of nodes does not, meaning that when the node density increases, the traffic rate is kept fixed at 0.1 packets per second.

Changing the node density from 50 to 500 nodes generates the results shown in Fig. (2b) which shows that all the throughput of the protocols begin with



(a) PDR (b) Throughput (c) Energy consumption

Figure 3: Narrow region scenario: PDR, Throughput, and Energy consumption vs. Traffic rate.

5 packets per second when the node density is low. As the node density further increases, the throughput of the protocols rises significantly and eventually reaches saturation point. In contrast, GC-MAC has a higher throughput than the others by reaching nearly 40 packets per second within 500 nodes. DL-MAC, with three different configurations shows better throughput than ED-MAC during all numbers of nodes. In particular, DL-MAC with 4 sub-frames is able to handle more data packets than DL-MAC with 2 and 3 sub-frames by almost 21.4% and 6.3% respectively, with a high node density. ED-MAC achieves almost 20 packets per second within 350 nodes, and it then degrades as the node density increases. This is because the ED-MAC's scheduling policy does not take the horizontal two-hop neighbourhood into account. It is therefore not a suitable choice for a shallow network.

Fig. (2c) illustrates the relationship between Fig. (2a) and Fig. (3b). This figure confirms the best protocol performance in terms of energy consumption. It can clearly be seen that GC-MAC displays the best performance in terms of energy consumption per data packet over the other protocols during the whole node density. It is followed by DL-MAC with 4 sub-frames, which consumes less energy than DL-MAC with 3 and 2 sub-frame configurations. ED-MAC, however, spends less energy within 50 and 100 nodes, before increasingly consuming higher energy per packet up to almost double the others with a high dense network. This is because, as shown in Fig. (2a), it delivers fewer packets than the other protocols and at the same time, it consumes more energy in joules than the others.

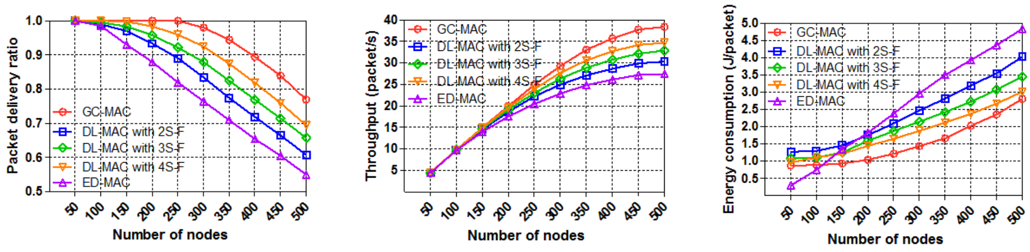
3.3.2 Narrow Region Scenario

In the second scenario, we assess and investigate the performance of the protocols within a narrow underwater network in terms of PDR, throughput, and energy consumption under varying traffic rates, as depicted in Fig. (3).

Fig. (3a) shows that the PDR of the three protocols is proportional to the traffic rate, and that the PDR of GC-MAC reduces to almost 93% and 80% corresponding with a traffic rate of 0.4 and 0.5 packets per second respectively. This is because a higher traffic rate leads to a lower duration of operational round, resulting in the channel capacity being achieved. Similar phenomena are also observed with ED-MAC and DL-MAC in three different configurations. However, by carefully considering collision avoidance, GC-MAC achieves fairly good results for packet delivery ratio compared to the others. The result of DL-MAC with 4 sub-frames is very low with a high traffic rate because the duration cycle becomes low; therefore, nodes are unable to find a free time-slot, i.e., a medium channel is divided into three frames, each frame consists of 4 sub-frames, and each sub-frame includes a number of slots which is insufficient for the one-hop neighbouring nodes.

Fig. (3b) presents the network throughput of all protocols as a function of the traffic rate. The throughput of the protocols is observed to increase as the traffic rate increases. This is because the traffic rate does not exceed the network capacity. Within a traffic rate of (0.3 and 0.4 packets per second), the network congested, resulting in a decreasing throughput for ED-MAC and DL-MAC with all sub-frame configurations with a growth in traffic rate, except the GC-MAC trends of 40 packets per second at 0.45 and 0.50 traffic rates. This is mainly because any possibility of collisions is removed by applying the conflict detection interval at the end of the scheduling phase. Therefore, the GC-MAC always achieves the best throughput compared to ED-MAC and DL-MAC with different sub-frame configurations.

Fig. (3c) shows the results in terms of energy efficiency, i.e., the energy consumed per successfully delivered packet. We can first observe that ED-MAC is more energy efficient than the others at low traffic rates, because of the lower requirements it faced during the scheduling phase than other protocols, resulting in a high delivery rate and low energy consumed. It is more interesting to observe that although GC-MAC consumed more energy than the others at



(a) PDR (b) Throughput (c) Energy consumption

Figure 4: Narrow region scenario: PDR, Throughput, and Energy consumption vs. Number of nodes.

high traffic rates, it can still be considered to have the best energy efficiency at medium and high traffic rates. This is because its delivery rate outperforms that of all the other protocols at medium and high traffic rates, as shown previously in Fig. (3a). DL-MAC with 4 sub-frames, however, is considered inefficient because it spends double the energy of GC-MAC at a medium traffic rate. With a high traffic rate, DL-MAC with 4 sub-frames also consumes nearly three times more energy than GC-MAC.

This scenario also allows a comparative evaluation to be carried out of the performance of ED-MAC, DL-MAC, and GC-MAC in terms of PDR, throughput, and energy consumption under different sets of node density, as presented in Fig. (4). This figure shows how sparse and dense nodes in a narrow network can affect the performance of the three MAC protocols, and how scalable and flexible their designs are.

As can be seen in Fig. (4a), the PDR of GC-MAC remains constant at 100%, as it delivers all the data packets successfully up to a density of 250 nodes, then the delivery rate reduces significantly as the node density further increases. For DL-MAC with three different sub-frame configurations, the delivery rate with 2 sub-frames reduces sooner than DL-MAC with 3 and 4 sub-frames. As the node density increases, the PDR of DL-MAC with 2, 3, and 4 sun-frames is significantly reduced to deliver approximately 61%, 66%, and 70% data packets respectively in a high density network (with 500 nodes). This is because a higher number of sub-frames under a fixed traffic rate implies an ability to handle more nodes. However, the PDR of ED-MAC delivers most of the data packets up to 150 nodes, then it dramatically decreases as the number of nodes further increases. We can observe that the delivery rate of ED-MAC is good with an increased number of nodes, but compared with GC-MAC and DL-MAC, it has the lowest delivery rate with all numbers of nodes.

Fig. (4b) presents the results in terms of throughput. Within 50 and 100 nodes, the network throughput of all the protocols significantly increases while achieving 5 and 10 packets per second respectively. When the number of nodes further increases, the throughput correspondingly goes up and eventually reaches the channel threshold. In contrast, GC-MAC outperforms all the other protocols by handling more than 35 packets per second with high node density (within 450 and 500 nodes). Meanwhile, the throughput of ED-MAC handles lower data packets than the others. This is because ED-MAC has some limitations during its scheduling phase which do not apply to GC-MAC and DL-MAC. More specifically, ED-MAC's scheduling policy does not take the horizontal two-hop neighbouring nodes into account, meaning that a few collisions might occur among them when the number of nodes increases. DL-MAC is more scalable and fixable than other protocols in employing sub-frame configurations. For instance, DL-MAC with a lower number of sub-frames performs better than DL-MAC with higher sub-frames in terms of increasing the traffic rate and keeping the node density fixed. Conversely, when the number of nodes increases under a fixed traffic rate, DL-MAC with higher sub-frame configurations performs better than with lower sub-frames. This is mainly because the traffic rate has a reverse relationship over the duration of the operational cycle which, as well as a higher number of sub-frames, implies the ability to handle more nodes.

Fig. (4c) illustrates the energy consumption. This figure shows the best performance in terms of packet delivery rate along with the energy consumption associated with sparse and dense nodes. ED-MAC can be observed to have consumed less energy per packet than the others with 50 and 100 nodes. As the node density increases, its energy consumption rises sharply, reaching just over 4.6 joules per packet with 500 nodes. However, GC-MAC starts off constant by consuming 1 joule per packet until the number of nodes exceeds 200 nodes, then its energy consumption increases as the number of nodes increases too by consuming nearly 2.8 joules per packet with a high node density. Overall, GC-MAC performs well from 150 to 500 nodes, followed by DL-MAC with 4 sub-frames. This is because both protocols have more benefits than the others depending on their scheduling strategies, as has been explained above.

4 CONCLUSIONS

This paper has presented a comparative performance evaluation of three collision-free MAC protocols for channel access in underwater sensor networks. We have investigated several scenarios that are typical of the current underwater channel access research. The first scenario evaluated a shallow network area with low, medium, and high traffic rates as well as sparse and dense nodes under a fixed traffic rate. The second scenario examined the same parameters within a narrow network area. These scenarios are mainly used to study the three protocols' overall ability, scalability, and flexibility under sparse and dense sensor nodes as well as under light to heavy traffic. Our study points out that every protocol has its own advantages and disadvantages, which means that no protocol can fit all needs in all scenarios.

This study has concluded that ED-MAC achieves the best performance in a narrow scenario with a light traffic rate. It is able to handle 99% of the data packets at a lower energy cost than other protocols. However, it is not a suitable choice in a shallow scenario as it does not consider two-hop neighbouring nodes horizontally. To improve its performance in this region, more slots are needed to reduce the probability of collisions that may occur between nodes located horizontally. DL-MAC has the ability to perform better than ED-MAC in narrow and shallow regions by scheduling all nodes vertically and horizontally. This is because of its ability to address most of the MAC problems such as spatial-temporal uncertainty, the near-far effect, and any hidden/exposed terminal problems. In terms of flexibility, DL-MAC is more flexible than other protocols by dividing the network area into frames, and the sensors in each frame into sub-frames. It is, therefore, suitable for both scenarios. While GC-MAC has achieved the best performance than others in both narrow and shallow scenarios in terms of reliability and scalability. However, it has consumed more energy than other MAC protocols because of the conflict detection interval.

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