Collision Avoidance Energy Efficient Multi-Channel MAC Protocol for UnderWater Acoustic Sensor Networks

Fatma Bouabdallah, Chaima Zidi, Raouf Boutaba, *Fellow, IEEE*, and Ahmed Mehaoua

Abstract—Collisions in underwater acoustic networks can not be tolerated due to the fundamental differences between underwater acoustic propagation and terrestrial radio propagation. Thus, conceiving medium access protocols that avoid collision to the most possible extent is of paramount importance. In this paper, a multi-channel MAC protocol, MC-UWMAC, especially designed for underwater acoustic sensor networks, is proposed and evaluated. MC-UWMAC is an energy efficient MAC protocol that aims at achieving a collision free communication. MC-UWMAC operates on a single slotted control channel to avoid the missing receiver problem and multiple data channels to improve the network throughput. To guarantee to the most possible extent a collision free communication, MC-UWMAC uses two key newly designed procedures: i) a grid based slot assignment procedure on the common slotted control channel that approaches the 2-hop conflict free slot assignment and ii) a quorum based data channel allocation procedure. More precisely, according to MC-UWMAC, a sender uses its own dedicated slot on the common control channel for handshaking with an intended neighbor receiver. However, data transmission takes place in a unique data channel especially reserved for this pair of neighbor nodes. In fact, MC-UWMAC reserves for each pair of neighbor nodes a unique data channel that aims at being 2-hop conflict free. As such, the probability of collision is highly reduced and even completely mitigated in some scenarios. In addition, by using multiple channels, MC-UWMAC allows multiple data communications along with handshaking on the common control channel to take place at the same time and hence the network throughput as well as energy efficiency are improved. Simulation results show that MC-UWMAC can greatly improve the network performance especially in terms of energy consumption, throughput, and end-to-end delay.

Index Terms—UnderWater acoustic sensor networks, MAC, multichannel communication, performance analysis, energy conservation

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1 INTRODUCTION

UnderWater Acoustic Sensor Networks (UW-ASNs) have witnessed an increasing interest in the last decade. Indeed, UW-ASNs can be deployed to serve a wide range of collaborative applications such as, offshore exploration, tsunami warning, and mine reconnaissance [1]. Conceiving network protocols especially tailored for underwater acoustic networks faces serious challenges. First, the propagation speed for an acoustic link is 1,500 meters/sec, 2×10^5 times lower than the speed of a radio link [1], [2], [3]. This means that the propagation delay is 2×10^5 times longer for an acoustic link. Second, in acoustic links, the transmit power is not only too high but also dominates the receive power. Indeed, the transmit power is typically 100 times more than the receive power. For example, in WHOI Micro-Modem [4], the transmit power is 10 W which is 125 times of the receive power (80 mW). In addition, note that batteries of underwater sensors are not only energy constrained but most importantly cannot be easily recharged, since for instance solar energy cannot be exploited. Finally, the available bandwidth is highly limited due to the harsh environment features including transmission loss, noise, and high propagation delay.

Consequently, acoustic underwater communications are expected to achieve lower throughput while consuming larger amount of power compared to their terrestrial radio counterparts. To overcome theses challenges, designing effective Medium Access Control (MAC) protocol for UW-ASNs is of paramount importance since the MAC protocol is responsible for coordinating nodes' access to the shared wireless medium. Indeed, the crucial task of a MAC protocol is to prevent simultaneous transmissions. It has to resolve transmission collisions of data packets while guaranteeing low channel access delays, fairness among the nodes in a network and energy efficiency especially for energy constrained networks. The effectiveness of the MAC protocol operations in harsh UW-ASNs environments greatly impacts network utilization.

Collisions are more critical in UW-ASN since they dramatically decrease network performance especially in terms

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of throughput and energy consumption [3]. The impact of collisions is even worse in heavily loaded UW-ASNs. Hence, collisions in UW-ASNs have to be avoided to the most possible extent.

In this paper, we focus on multi-hop sparse heavily loaded UW-ASNs and propose a medium access protocol with the goal of avoiding collisions in order to enhance network performance. To avoid collisions in UW-ASNs, some earlier protocols [5], [6] propose a centralized solution where a particular node is in charge of arranging transmission schedules for all the nodes. However, these protocols perform efficiently only in a single hop underwater environment. In some other TDMA-based UW-ASN MAC protocols such as T-Lohi [7], slotted ALOHA [8], and slotted FAMA [9], time is divided into frames that are further divided into fixed-length slots and a communication can be initiated only at the beginning of a time slot. Similarly, these solutions perform well mainly in a single hop or lightly loaded context. However, they generally do not function properly in a multi-hop, heavy load network scenario with a large number of sensor nodes. Indeed, these earlier protocols (summarized in Table 1) by design have been mainly conceived for single hop UW-ASNs; either to ignore the collision impact as in [5] and [9] or as a starting point to assess their proposal performance with expected later improvements in multihop scenario as in [6] and [9]. In [8] authors show that the protocol suffers from low channel utilization in a single hop scenario which is likely subject to deterioration in a multihop scenario.

In this paper, a multi-channel MAC protocol (MC-UWMAC) for UW-ASNs is proposed and evaluated. Our ultimate aim is to conceive a low power MAC protocol especially tailored for sparse heavily loaded underwater sensor networks. Recall that in event-driven reporting applications and on-demand reporting, sensor nodes are expected to generate bursty traffic. Indeed, in event-driven applications, like Tsunami warnings, flood detection, once a pre-specified event occurs, the reporting task is initiated and hence bursty heavy load traffic emanates from detecting nodes. Moreover, in on-demand reporting applications, communication is initiated by the sink, and sensors send their data in response to an explicit request which will also generate bursty traffic.

To design a multichannel MAC protocol, general issues such as “when and which node can use which channel” must be addressed. Traditionally, channel negotiation is done through the exchange of control messages. Such mechanisms are however not efficient in UW-ASNs because of the long propagation delay and considerably higher transmission power. Consequently, such negotiation based techniques are expected to highly increase the end-to-end delay while introducing extra power consumption especially in UW-ASNs due to significant signaling overhead. Therefore, in UW-ASNs, these channel assignment and transmission scheduling problems should be solved in an energy-efficient way, preferably without requiring extra control packets exchange. Moreover, the inherent missing receiver problem typical in multichannel communication schemes, which occurs when a sender fails to reach its intended receiver because they do not reside on the same channel, has to be carefully addressed in underwater acoustic context.

To handle the aforementioned issues, we define and adopt the concept of singleton-intersecting quorum systems to devise MC-UWMAC that has several attractive features. First, equipped with one modem, each sender will have a dedicated data channel to communicate with a given neighbor such that potential collision among neighbors is avoided in any data channel. According to MC-UWMAC, each underwater sensor will be assigned a subset of data channels such that a unique and different data channel is dedicated for possible communication with every neighbor. Note that, this unique data channel allocated for every pair of nodes is different from all the other data channels allocated to all possible pair of nodes in the neighborhood. As such, the hidden node problem is avoided during data communication. Second, thanks to the use of a common control channel along with an availability table, each sender is guaranteed to meet its receiver and hence, the missing receiver problem is solved. Moreover, even with the use of a unique control channel, MC-UWMAC succeed to guarantee to some extent a collision free handshaking on the common control channel. In fact, MC-UWMAC targets to allocate to each sensor node in a given neighborhood, a unique 2-hop conflict free slot of time for possible handshaking on the single slotted common control channel which reduces the energy wastage due to possible damaging collision during handshaking. Third, credited to the separation of control and data channels, control and data packets transmissions in MC-UWMAC will not only ovoid collisions among them but can also take place at the same time which will improve network throughput. Simulation results demonstrate that the proposed MC-UWMAC significantly improves the network throughput and energy efficiency especially for heavy loaded traffic patterns.

The main contributions of this paper can be summarized as follows:

- We propose an energy efficient multichannel single rendezvous MAC protocol, MC-UWMAC, that targets collision free communication in sparse heavy loaded networks without any extra message exchange in order to increase the network throughput and energy efficiency. Indeed, by using a simple and successful handshaking process on a common slotted control channel (RTS/CTS), a node will be able to achieve a successful data communication by avoiding to the most possible extent collision on both control and data channels. Note that, in our work we opt for the use of a common control channel in order to avoid the missing receiver problem which is inherent in a multichannel communication scheme and may adversely impact the network throughput.
- To avoid control packets collision on the common control channel, we propose a TDMA-based communication. More precisely, we propose a grid based slot assignment procedure that approaches the 2-hop conflict free and collision free slot assignment while using a reduced frame size. It is worth pointing out that our slot assignment procedure does not require any extra control message exchange among nodes in order to help them deciding their slot numbers which will further reduce energy consumption. Indeed, by assuming that every sensor node knows its own geographical coordinates, it will be able to determine its slot number. The slot assignment procedure is considered as one of the main contributions of this work.
- To mitigate data collision, we assign to every underwater node a subset of data channels such that a unique and different data channel is dedicated for

TABLE 1
A Recap Table for Underwter MAC Protocols

	Reference	Main idea	Technique	Limitation
Single Channel	Ordered CSMA [5]	Uses a round-robin scheduling and CSMA to avoid collisions. It allows multiple carriers from multiple sources to propagate at the same time.	Fixed Transmission order. Without the handshake mechanism and control packets. Immediate Transmission after data reception of the previous scheduled transmitter.	Single hop networks
	[6]	TDMA-based MAC protocol especially tailored for underwater environment that adopts sleep strategy to save energy.	Present a mechanism for nodes to avoid collision by appropriately adjusting the guard time between slots according to the distance between the nodes.	Single hop networks
	T-lohi [7]	CSMA-based MAC protocols. Nodes contend to reserve the communication channel to send data.	Each frame is divided into a reservation period (RP) and a data transfer period. Each RP is further partitioned into contention rounds (CRs) until one node successfully reserves the channel.	T-Lohi requires a node to be idle and listen to the channel in each contention round. $\Longrightarrow$ low channel utilization
	[8]	Improve the performance of slotted Aloha in space-time variable underwater environment.	Adding guard bands to the transmission slots.	Analysis of slotted Aloha with equal guard bands only for Single and equidistant receiver.
	Slotted FAMA [9]	Combines carrier sensing with handshaking to avoid hidden terminal collisions.	Time is slotted. Each packet, either control or data, has to be sent at the beginning of one slot $\Longrightarrow$ All nodes in the same neighborhood will have a complete knowledge of ongoing transmissions and hence avoid collisions.	Mobile AUV networks.
Multiple Channels (Single Rendez-vous)	RCAMAC [15]	A reservation based RTS/ CTS UW-MAC protocol.	Entire bandwidth is divided into two channels. 1-: control channel with less bandwidth. 2- data channel with much more bandwidth.	Single cell scenario where all nodes are within the same neighborhood.
	CUMAC [16]	Utilizes the common control channel for neighbors cooperation. Multiple data channels.	Control channel goals: 1- select an available free data channel 2-detect collision.	message exchanged to achieve such objectives are energy and delay consuming.
Multiple Channels (Multiple Rendez-vous)	MM-MAC [3]	Cyclic Quorum Based Multiple handshaking/ negotiation channels	Time divided into superframes: control and data periods. Control period : default slots and switching slots. At default slots, a node stays on its default channel waiting for transmission. At switching slots, a potential sender may switch to its intended receivers default channel to initiate a transmission.	1-Procedure to compute the default and switching slots is not foolproof. 2-Notification messages are energy and delay consuming
	DMM-MAC [17]	Uses multiple channels with duty cycling to achieve energy conservation.	Built upon MM-MAC. It combines duty cycling scheme with MM-MAC. In each wakeup frame, the MM-MAC protocol is applied.	Same as MM-MAC

possible communication with each neighbor. The data channel subsets construction and assignment that satisfy such requirements are also considered as significant contributions of this work.

This paper is organized as follows. Section 2 presents the state of the art related to the focus of this paper. Section 3 presents a detailed description of our MC-UWMAC. Section 4 provides a collision study in MC-UWMAC. The results are provided in Section 5, where we compare the performance of our proposal with a related existing multi-channel MAC protocol MM-MAC[3]. This paper concludes with a summary of our contributions.

2 RELATED WORK

In the past decade, underwater acoustic networks have gained significant interest in the research community. Due to the unique characteristics of the underwater channel, simply applying the terrestrial wireless sensor networks solutions would not achieve acceptable network performance. Therefore, dedicated solutions should be developed in almost every layer of the protocol stack. Authors in [2], [10] provide an overview of existing networking protocols for underwater networks. In [2], the authors provide a brief overview of MAC, routing and transport protocols for UW-ASNs, where all the described MAC protocols use a single channel, unlike our proposed multi-channel solution. Authors in [10], present a thorough overview of Physical, MAC and routing protocols for UW-ASNs. With respect to MAC protocols, authors in [10] focus on single channel works using either FDMA, CDMA or TDMA techniques. In this section, we focus on multi-channel MAC protocols especially designed for UW-ASNs. Table 1 provides a taxonomy and a summary of these protocols.

Underwater MAC protocols can be classified into two categories: the MAC protocols with single channel and the MAC protocols with multiple channels. The single channel underwater MAC protocols use only one channel for communication [5], [6], [7], [8], [9]. Consequently, channel seizing methods should be performed before any data transmission either through handshaking messages or time slots assignment as summarized in Table 1. Different from single channel UW-MAC protocols, multiple channel protocols rely on more than one channel for communication. Recent studies on multichannel MAC protocols for underwater acoustic sensor networks [11], show that such a parallelism can highly enhance the network throughput, reduce the channel access delay, and save energy consumption [12], [13]. Moreover, the rapid development of underwater acoustic modem [14] has also enabled the use of multiple acoustic channels in parallel.

Moreover, it is worth pointing out that using a multi-channel communication scheme allows multiple simultaneous transmissions emanating from close senders, naturally contentious, to take place, thing that was impossible with the single channel scheme. Indeed, using multi-channel MAC scheme, nodes within the neighborhood of each others can simultaneously and successfully transmit packets provided that they are on different data channels. As such, the average end-to-end delay is expected to be highly reduced even if the transmission time is increased due to reduced data channel width. Indeed, further dividing the limited bandwidth into smaller data channels will inevitably increase the transmission time, note, however, that the channel access delay will be reduced and collision will be highly avoided such that the end-to-end delay is expected to be reduced which is extremely important in long delay underwater acoustic sensor networks.

Multichannel MAC protocols can be further classified into two categories: single rendezvous and multiple rendezvous. In the next two sections, we review existing multi-channel MAC protocols on both categories.

2.1 Single Rendezvous Multi-Channel MAC Protocols for UW-ASNs

In single rendezvous multi-channel MAC protocols, there are one common control channel and multiple data channels. The node with outgoing packets will exchange some control information over the single control channel to agree on the data channel. The major advantage of this approach is that it highly alleviate the missing receiver problem which is inherent to the multichannel communication scheme, where a potential sender may fail to reach to a target receiver since they reside on different channels. However, this common control channel can clearly become a bottleneck especially in dense high traffic networks.

One of the first work in single rendezvous multi-channel MAC protocols for UW-ASNs is RCAMAC [15]. RCAMAC is a Reservation Channel Acoustic Media Access Protocol based on RTS/CTS handshaking on a common control channel. Accordingly, the entire bandwidth is divided into two channels. One is a control channel with less bandwidth. Another is the data channel with much more bandwidth. By doing so, the authors show that better network throughput as well as more energy efficiency are achieved.

CUMAC [16] is a more recent example of single rendezvous approach especially conceived for underwater acoustic sensor networks. CUMAC mainly utilizes the common control channel for neighbors cooperation to first select an available free data channel and second to detect collision with a simple tone device designed for the distributed collision notification. Although CUMAC aims at providing a collision free communication, the message exchanged to achieve such objective are energy and delay consuming in long delay high power underwater acoustic sensor networks.

2.2 Multiple Rendezvous Multi-Channel MAC Protocols for UW-ASNs

As opposed to single rendezvous multi-channel MAC protocols, device pairs using multiple rendezvous MAC protocols can conduct simultaneous handshaking on distinct channels. The rational behind it is to overcome the potential single control channel bottleneck. However, since there are multiple rendezvous channels, special and careful coordination is required to guarantee that two devices can get in touch on the same channel. Note that, with multiple rendezvous multi-channel MAC protocols, the missing receiver problem is susceptible to get accentuated which may prevent regular spontaneous communication unless a special mechanism is provided to handle it.

One of the most recent MAC solution was proposed in [3] and called MM-MAC protocol. MM-MAC aims at using a single modem to emulate multiple transceivers. Based on the cyclic quorum systems concept, nodes running MM-MAC can perform their channel negotiations on different channel simultaneously while avoiding to some extent the missing receiver problem. Accordingly, the time is divided into a series of superframes. Each superframe is further divided into control and data periods. For each control period, control slots are partitioned into default slots and switching slots such that every node will be allocated some defaults and switching slots. At default slots, a node stays on its default channel (each node is supposed to have its own default channel), waiting for transmission requests. At switching slots, a potential sender may switch to its intended receiver's default channel to initiate a transmission. To solve the missing receiver problem, the authors use the cyclic quorum concept to guarantee the overlapping between the default slots and the switching slot between any pair of nodes. That being said, the proposed procedure to compute the default and switching slots does not really guarantee the overlapping constraint which is mandatory for the proper functioning of the protocol. Moreover, MM-MAC relies on notification messages broadcasting in order to inform neighboring nodes about any chosen data channel and hence avoid possible collisions on data channels. Indeed, once a sender and receiver succeed their handshaking process, both of them will repeatedly send a notification message at each of the remaining control minislots to declare that a given channel has been reserved. Such excessive sending of notification messages will highly consumes the network resources especially in terms of energy.

DMM-MAC [17] is another example of multiple rendezvous multi-channel MAC protocols for UW-ASNs. Built upon MM-MAC, It combines duty cycling scheme with MM-MAC in order to further save energy consumption. The combination is rather intuitive as simply, in each wakeup frame, the MM-MAC protocol is applied.

3 MC-UWMAC: A MULTI-CHANNEL MAC PROTOCOL FOR UW-ASNS

3.1 Why Single Rendezvous Multi-Channel Under-Water MAC Protocol?

Adopting a single rendezvous multi- channel MAC protocol for UW-ASNs that are naturally sparse can be highly justified and beneficial since it will avoid any unnecessary extra message exchange to find the intended receiver and decrease collision probability in a given data channel since every node has a complete view of the data channels availabilities. Moreover, it is completely true that our proposed MAC protocols targets especially sparse heavy loaded UW-ASNs which may insinuate that the common control channel will be highly solicited and thus the collision problem may be worsen, thing that is not at all true. Indeed, once a handshaking is successfully achieved on the common control channel, MC-UWMAC allows every source node to send as much data packets as it has in its own buffer for the intended receiver on the dedicated data channel. Thus, one RTS/CTS exchange on the common channel will be enough to handle multiple data packet transmissions to the same receiver on the same data channel and hence the collision problem will not be accentuated on the common control channel.

3.2 Why Slotted Control Channel?

In MC-UWMAC, the control channel is chosen to be slotted. Slots of constant duration are grouped into TDMA frame (or frame for short), of length n, and numbered. Nodes access the common channel according to the predetermined TDMA schedule that specifies in details which nodes are to send in each slot of the frame. In MC-UWMAC, we opt for TDMA access technique rather than carrier sensing in order to ensure to some extent a collision free communication over the common control channel in addition to the guaranteed collision free communication over any data channel. Indeed, in long delay networks such as UW-ASNs, adopting exclusively carrier sensing to access the common channel will cause a long delay hidden terminal collisions as explained in Section 3.2.2 where two pairs of neighboring nodes in the same vicinity may succeed in their handshaking nearly at the same time because of long propagation delay and hence collisions that are supposed to be naturally avoided by CSMA/CA protocols are no longer mitigated which question the usefulness of carrier sensing in UW-ASNs [16]. Therefore, from the start most of the proposed solutions for UW-ASNs combine carrier sensing with TDMA in order to enhance the proposed protocols performance [5], [6], [7], [8], [9].

In simple contention-based single rendezvous multichannel MAC protocols, the data channel assignment is normally integrated into the RTS/CTS handshaking process on the control channel. However, for single-transceiver contention-based multichannel schemes in long-delay underwater networks, simple RTS/CTS negotiation approaches are not as efficient as they used to be in terrestrial wireless sensor networks. Indeed, in addition to the traditional multi-hop hidden terminal problem for the single channel network, underwater networks will more suffer from two new hidden terminal problems that are intrinsic in the new underwater acoustic network context: multichannel and long-delay hidden terminal problems.

3.2.1 Multichannel Hidden Terminal Problem

Multichannel hidden terminal problem was first introduced in [12] for nodes with single transceiver. Indeed, if the node has only one transceiver, it can listen either on the control channel or on a data channel, but not on both which may lead the node to lose control of the data channels availabilities and hence potential collisions on busy data channels may occur. For instance, suppose that two nodes, say A and B, previously communicating in data channel j, initiate a new communication in data channel i that was already reserved by a neighbor pair during their communication in data channel j. Indeed, with a single transceiver, nodes will lose control of the data channels availabilities once they move to a data channel and hence data collisions my happen on data channel i due to disruption from the pair A and B. Obviously, multichannel hidden terminal problem can be easily avoided by having one dedicated transceiver continuously listening on the control channel. In this case, at least two transceivers are needed on every node which is a costly solution especially when using underwater acoustic transceivers. Instead, another solution that was introduced by [16], is based on initiating a cooperative collision detection mechanism that requires extra messages exchange in order to prevent data collisions. For energy efficiency, our MC-UWMAC solution guarantees a collision free data communication without requiring any extra message exchange to negotiate the channel availability thanks to our quorum construction and allocation procedures as detailed in Section 3.4.

3.2.2 Long-Delay Hidden Terminal Problem

The inherent long propagation delays of the underwater acoustic channel introduce another kind of hidden terminal problem where two pairs of neighbor nodes in the same vicinity may succeed to reserve the same data channel nearly at the same time because of long propagation delay, as shown in Fig. 1. At the beginning, all nodes are listening to the control channel. Suppose that node A starts sending a RTS message to node B to communicate on data channel i. Shortly after, a node C neighbor of A and B starts sending a RTS to node D to communicate also on data channel i, since

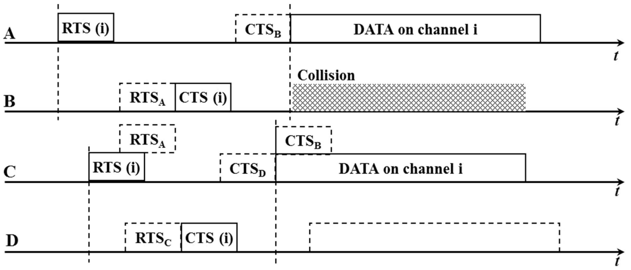

Fig. 1. Long-delay hidden terminal problem.

it didn't yet receive node A's RTS. Node B correctly receives node A's RTS and reply by the CTS. Shortly after, D receives the RTS from C. Node D being neither a neighbor of B nor a neighbor of A will normally sends its CTS. Consequently, both pairs of nodes will initiate data communication on channel i nearly at the same time. This problem is usually insignificant in terrestrial radio networks due to the extremely high propagation speed of radio signal. For long-delay underwater acoustic networks, however, this problem has to be considered and well addressed. In brief, new solutions are highly required in order to effectively solve the triple hidden terminal problems in single-transceiver multichannel long-delay underwater networks.

Our MC-UWMAC protocol is proposed to tackle efficiently these new challenges. Opting for time division multiplexing technique was the first step to cope with the triple hidden terminal problem in addition to our quorum and slot allocation procedures explained in Section 3.4 Indeed, by assigning to each node its own slot, we avoid concurrent simultaneous reservation of the same data channel and hence the long delay hidden terminal problem is overcome. As for the multichannel hidden terminal problem, it will be efficiently addressed by our quorum construction and allocation procedures.

According to MC-UWMAC, the control channel is temporally shared by all nodes in UW-WSN, and communication is halfduplex: node v cannot send one message and receive another simultaneously. All node clocks are synchronized to a common global time [18], and time is slotted. Each node i is allocated a predefined slot in the frame, such that i's slot number is different from all its neighbors slot numbers. Consequently, each node access, in a given neighborhood, is scheduled to a predetermined time. Note that, every slot number can be spatially reused by different nodes far apart from each others.

More precisely, let us consider the time diagram shown in Fig. 2.

We define the slot time as

$$T_{SLOT} = T_{RTS} + T_{CTS} + 2 \times T_{PROP}, \tag{1}$$

where T_{RTS} and T_{CTS} refer to the RTS and CTS messages transmission times in the common channel, respectively. Note that here, the main objective of deploying RTS/CTS scheme is to establish a rendezvous with the intended receiver rather than avoiding collision like in CSMA scheme. For more details the reader is referred to Section 3.5. T_{PROP} refers to the propagation time over the transmission distance R_t

$$T_{PROP} = \frac{R_t}{V_s}, \tag{2}$$

where V_s refers to the nominal speed of sound in the water $V_s = 1500\ \text{m/s}$.

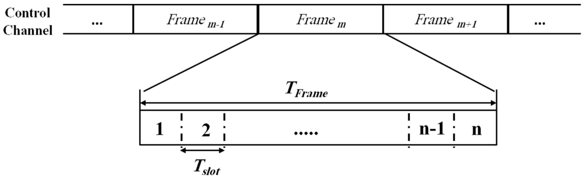

Fig. 2. MC-UWMAC frame structure.

In large TDMA-based multihop wireless sensor networks, slots within a fixed-length frame need to be spatially reused in order to increase the network throughput. In other words, the same slot number has to be shared among several nodes geographically quite separated from each other. Although the undeniable benefits of the spatial reuse, it may cause the so called slot assignment conflicts between nodes. A k-hop slot assignment conflict is defined in [19] as one in which a pair of nodes k hops away is assigned the same slot. The presence of k-hop slot assignment conflicts, especially where $k \leq 2$, causes collisions that should be properly handled. Contrarily, slot assignment is defined to be a 2-hop conflict-free if the slot $S(v)$ used by a node v is not reused in the 2-hop neighborhood of $v, N_{\leq 2}(v)$ and hence collision is completely mitigated. In our work, we will propose our own slot assignment procedure aimed at being 2-hop conflict free without any extra message exchange between the nodes. Our goal is to provide to the most possible extent a collision free communication while avoiding any extra message exchange among nodes as such the network throughput highly increases and so does the energy efficiency.

By taking advantage of the underwater acoustic networks characteristics, namely low density, we aim at closely approaching the 2-hop conflict-free slot assignment, while using a reduced frame length of size n, where n can be the maximum neighborhood size and most importantly without imposing any message exchange among neighboring nodes which makes our protocol more energy efficient.

3.3 Overview

MC-UWMAC is a multi-channel medium access control protocol designed for multi-hop underwater acoustic wireless sensor networks using a single modem to emulate multiple transceiver solutions. MC-UWMAC operates on single control channel and multiple data channels of total number $N = \frac{n(n-1)}{2}$ where n can be the maximum neighborhood size in the network. Specifically, there is a common slotted control channel and N equal-bandwidth data channels. In the common control channel, which is the default active channel, time is divided into series of frames. Each frame is further divided into n slots such that every node in a neighborhood will be assigned a unique slot of duration T_{SLOT} for possible handshaking. Indeed, to enable a data communication between a sender A and a receiver B, A and B must first successfully exchange RTS and CTS packets during A's slot then they have to switch to the same appropriate data channel. Note that, once A and B are in the appropriate data channel, they may remain as long as A has packets for B provided that they announce the end time of communication to their respective neighbors during the handshaking. In other words, the time in MC-UWMAC is only slotted according to the control channel as opposed to MM-MAC [3] where the frame is divided into control and data periods. Consequently, we may expect from MC-UWMAC to achieve better network throughput as the frame length is of reduced size.

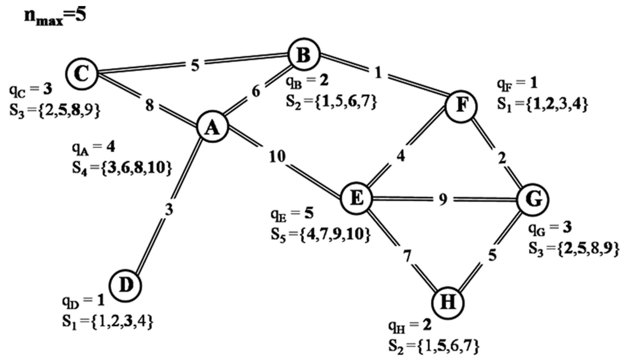

Fig. 3. Example of channel assignment ($n_{max} = 5$). The precised number on every link denotes the common dedicated data channel.

According to MC-UWMAC, to appropriately select a data channel for possible communication, each node u will be assigned a subset of data channels S_{q_u} of length $(n-1)$ that may be used by u for data communication with the $(n-1)$ possible neighbors. Any node v , neighbor of u will be assigned another subset of data channel S_{q_v} different from S_{q_u} but they intersect exactly in one common data channel that will be used by u and v for their communication. Hence at maximum n different subsets will be assigned in any given neighborhood provided that the respective subsets of any two neighbors should satisfy the non empty intersection property for possible data communication. As explained in the next section, we will show how to build the subsets of data channels and how to allocate them such that n different subsets will be sufficient enough to serve all the nodes in the network while achieving a collision free communication among them. Note that, in MC-UWMAC, we impose that the pairwise intersection between S_{q_u} and any S_{q_v}, v neighbor of u, is a singleton CH_{uv} such that any two neighbors will have at their disposal a unique data channel to communicate on, for collision avoidance purposes. According to MC-UWMAC, the following property should be satisfied

$$\forall u, \forall \{v,\ w\} \in N_e(u),\ w \neq v => S_{q_u} \cap S_{q_v} \neq S_{q_u} \cap S_{q_w}, \quad (3)$$

where $N_e(u)$ is the list of u's one-hop neighbors. In other words, data channel CH_{uv} will be only allocated for data exchange between u and v, meaning that no other neighbor of u or v is using CH_{uv} to communicate with u or v , respectively. Therefore, not only collisions among neighbors is mitigated but also collisions due to hidden node is completely avoided and hence a collision free communication is guaranteed on data channel. Note however that the same CH_{uv} may be reused in a two hop far neighborhood which boosts the spatial reuse inside the network. To recapitulate, MC-UWMAC aims at achieving a 2-hop conflict-free data channel subset assignment as shown in Fig. 3. By doing so, we aim at increasing the network throughput while being extremely energy efficient by completely mitigating collisions in any data channel. Moreover, MC-UWMAC proposes a data channel allocation scheme that allows each node to know in advance its own subset of data channels and which data channel to be used with every neighbor, for possible communication, without any extra packet exchange provided that every node knows its own geographical coordinates as well as the ones of its one hop neighbors. Given that the UW-ASNs are sparse, we expect that acquiring such information is easily manageable. Consequently, and more importantly we further decrease the energy consumption by avoiding any overhead that might be produced to appropriately select an available free data channel as in CUMAC [16] , where the nodes have to cooperatively negotiate the list of available data channels using RTS/Beacon/CTS. Moreover, according to MC-UWMAC, during the data communication between u and v, we guarantee a collision free communication since CH_{uv} is supposed to be only used by u and v and hence the multichannel hidden terminal is mitigated. Most importantly, as explained in the next section, our proposed data channels allocation scheme does not require any extra packet exchange to guarantee that almost all the neighbors in a given node neighborhood will select different data channel sets as represented in the example of Fig. 3 where for every node in the network, a unique and different data channel is associated to each one of its neighbors.

It is worth pointing out that, we will adopt the same procedure for the slot allocation on the control channel among neighboring nodes. Here again n slots will be sufficient enough to highly decrease the collision probability during handshaking on the control channel, where n is the maximum size of one hop neighborhood. That being said, MC-UWMAC does not fully guarantee the exclusive 2-hop conflict free assignments of data channel sets as well as time slots, that's why MC-UWMAC will be supplied with a backoff mechanism (as explained in Section 3.5.4) to deal with unlikely collision.

3.4 Data Channels Subsets Construction and Allocation

In this section, we present the most important concepts in our protocol, namely 1) How to build the n subsets of data channels of length $(n-1)$ each, such that the pairwise intersection between any 2 sets is a unique singleton and 2) How to allocate them to sensor nodes such that to maximize the probability of collision free communication. Note that, the same data channel subsets assignment procedure will be used for time slot allocation.

3.4.1 MC-UWMAC Quorum Construction

The main idea behind MC-UWMAC is how to build our subsets of data channels of length $(n-1)$ each, such that we guarantee the unique singleton intersection among pairwise neighboring nodes, and hence the multichannel hidden terminal problem is avoided without requiring any extra messages exchange among nodes. Thus, the collision free communication on any given data channel is insured. To do so, we utilize the concept of quorum systems that have been widely used for mutual exclusion in distributed systems [20] and for MAC protocol design in wireless networks [21], [22], [23], [24] and recently for UW-ASNs [3], [17]. A quorum system can be defined as follows.

Definition 1. *Given a universal set $U = \{u_1, \ldots, u_N\}$, a quorum system Q under U is a collection of non-empty subsets of U, each called a quorum, which satisfies the intersection property: $\forall \{G, H\} \in Q; G \cap H \neq \emptyset$.*

Elements of a quorum system are simply called quorums. For example, $Q = \{\{1,2\},\{1,3\},\{2,3\}\}$ is a quorum system under $U = \{1,\ 2,\ 3\}$. There are many quorum systems, such as the cyclic quorum system, the grid quorum system, and the torus quorum system. We create our own quorum system that satisfies the functional requirements of our multichannel MAC protocol: MC-UWMAC. Accordingly, our quorum system will be mainly used for data channel selection between any two neighbor nodes as opposed to MM-MAC protocol [3], where the quorum system is used to select communication slots as explained in [3]. In other words, every quorum in our system represents a subset of data channels to be allocated to an underwater sensor node. The first main characteristic that should be satisfied by our target quorum system is that the pairwise intersection between any 2 quorums is a singleton. Therefore, any two neighbors will have at their disposal a single common data channel that will be used for possible data exchange between them. Consequently, our target quorum system can be now defined as follows.

Definition 2. *A quorum system* Q *under* $U = \{u_1, \ldots, u_N\}$, *is said to be a singleton-intersecting quorum system if the pairwise intersections among quorums is singleton. In other words,* $\forall G, H \in Q; G \cap H = \{u_i\}$.

For instance, the quorum system $Q = \{\{1, 2, 3\}, \{1, 4, 5\}, \{1, 6, 7\}, \{2, 4, 6\}, \{2, 5, 7\}, \{3, 4, 7\}, \{3, 5, 6\}\}$ is a singleton-intersecting quorum system under $U = \{1,\ldots,7\}$. Note that Q in this example is the finite projective plane quorum system used by Maekawa [25] in his mutual exclusion algorithm. Now, the second main characteristic that should be also fulfilled by our target quorum set is the unique singleton intersection between any two quorums. In other words, any pair of quorums should intersect in a unique different element from all the other possible pairwise intersections. Therefore, two pairs of nodes will never have the same common data channel to communicate on and hence simultaneous collision free communication emanating from neighbors can take place. Formally, our target quorum system can be finally defined as follows:

Definition 3. *A singleton-intersecting quorum system* Q *under* $U = \{u_1, \ldots, u_N\}$, *is said to be a unique singleton-intersecting quorum system if the pair-wise intersections among quorums is a unique different singleton. In other words,* $\forall \{G, H, I, J\} \in Q$; $G \neq H \neq I \neq J; G \cap H \neq I \cap J$ *and* $G \cap H \neq G \cap I$.

For instance, the finite projective plane quorum system $Q = \{\{1, 2, 3\}, \{1, 4, 5\}, \{1, 6, 7\}, \{2, 4, 6\}, \{2, 5, 7\}, \{3, 4, 7\}, \{3, 5, 6\}\}$ is a non unique singleton-intersecting quorum system, while the quorum system $Q' = \{\{1, 2, 3\}, \{1, 4, 5\}, \{2, 4, 6\}, \{3, 5, 6\}\}$ is indeed a unique singleton intersecting quorum system.

The MC-UWMAC protocol dictates that the data channel allocation scheme provides each underwater node with a set of data channel such that each node neighborhood of maximum size n has to be a unique singleton-intersecting quorum system. We devote the next section to show how to construct a unique singleton intersecting quorum system containing n quorums, where n is the maximum neighborhood size, each quorum is of size $(n-1)$, $(n-1)$ is the maximum number of neighbors for each node, using the minimum number of distinct element $\{u_1, \ldots, u_N\}$.

Theorem 1. *Given* n, *the system* $Q = \{S_1, \ldots, S_n\}$, *where*

$$\begin{cases} S_1 = \{1, 2, \ldots, n-1\}, \forall 1 < j \leq n;\ \mathrm{card}(S_j) = n-1 \\ \text{and } S_j = \{(S_1)_{j-1}, \ldots, (S_{j-1})_{j-1}, (S_{j-1})_{n-1} + 1, \\ \ldots, (S_{j-1})_{n-1} + (n-j)\}((S_p)_q \text{ refers to the } qth \\ \text{element of } S_p). \end{cases}$$

is a unique singleton-intersecting quorum system under U=$\{1, \ldots, N\}$ *where* N, *the number of distinct element, is equal to* $\frac{n(n-1)}{2}$.

Proof.

- First, let us show that $Q = \{S_1, \ldots, S_n\}$ is a quorum system where each quorum is of length $(n-1)$. Clearly

$$\begin{cases} \mathrm{card}(S_1) = n-1, \text{ and} \\ \mathrm{card}(S_j) = j-1+n-j = n-1; \forall 1 < j \leq n. \end{cases}$$

Moreover, by quorum construction, $\forall \{i, j\}; 1 \leq i, j \leq n$ and $i \neq j$

$$\begin{cases} \text{if } i < j \text{ then } (S_i)_{j-1} \subset \{S_i \cap S_j\} \\ \text{else } (S_j)_{i-1} \subset \{S_i \cap S_j\}. \end{cases}$$

Consequently, $Q = \{S_1, \ldots, S_n\}$ is a quorum system.

- Now, let us demonstrate by recurrence that the pair-wise intersections among $(S_i)_{1 \leq i \leq n}$ quorums is a singleton.

\- For a given n and according to S_j definition

$$\begin{cases} S_1 = \{1, 2, \ldots, n-1\}, \\ \text{and} \\ S_2 = \{1, n, \ldots, 2n-3\}, \end{cases}$$

hence $S_1 \cap S_2 = \{1\} = (S_1)_1$.

Note that, in S_2, except the first element 1, all the others are greater than $n-1$ and thus no one of them can be an element of S_1.

– Suppose that up to $k < n, \forall \{i, j\} \leq k$, $i \neq j$ and $i < j$ then $S_i \cap S_j = \{(S_i)_{j-1}\}$.

Let us now demonstrate by contra-position that for iteration $k+1$, $\forall i \leq k$, $S_{k+1} \cap S_i = \{(S_i)_k\}$.

By construction, $S_{k+1} = \{(S_1)_k, \ldots, (S_k)_k, (S_k)_{n-1}+1, \ldots, (S_k)_{n-1}+(n-(k+1))\}$.

Accordingly $(S_i)_k \subset \{S_{k+1} \cap S_i\}$.

Suppose that $card(S_{k+1} \cap S_i) \geq 2$, consequently there must be m, $m \neq i$ and $1 \leq m \leq k$ such that $(S_m)_k \subset \{S_{k+1} \cap S_i\}$ since all the elements $\{(S_k)_{n-1}+1, \ldots, (S_k)_{n-1}+(n-(k+1))\}$ of S_{k+1} are created only at step $k+1$ and hence they do not exist in any other previous set S_j, $1 < j \leq k$.

Since $m \neq i$ and $1 \leq m \leq k$, if $m > i$ then $S_i \cap S_m = \{(S_i)_{m-1}, (S_m)_k\}$. Unless, we prove that $(S_i)_{m-1}$= $(S_m)_k$, $S_i \cap S_m$ is not a singleton.

Since $m > i$, hence all the elements $\{(S_m)_m, \ldots, (S_m)_{n-1}\}$ are strictly greater than any element in S_i. Hence, $(S_m)_k > (S_i)_{m-1}$ and thus $S_i \cap S_m$ is far from being a singleton which contradicts our hypothesis that up to $k < n, \forall \{i, j\} \leq k$, $i \neq j$ and $i < j$ then $S_i \cap S_j = \{(S_i)_{j-1}\}$.

Consequently, $Q = \{S_1, \ldots, S_n\}$ is a singleton-intersecting quorum system.

– In order to prove the pair-wise difference among the intersections, we suppose that $i < j < k < m \leq n$. Hence

$$\begin{cases} S_i \cap S_j = \left\{(S_i)_{j-1}\right\}, \\ \text{and} \\ S_k \cap S_m = \left\{(S_k)_{m-1}\right\}. \end{cases}$$

Let us demonstrate by contra-position that $(S_i)_{j-1} \neq (S_k)_{m-1}$. Suppose that $(S_i)_{j-1}$= $(S_k)_{m-1}$ then $S_i \cap S_k =$

$\{(S_i)_{k-1}, (S_i)_{j-1}\}$ which contradicts the pair-wise singleton intersection among S_i.

Thus $Q = \{S_1, \ldots, S_n\}$ is a unique singleton-intersecting quorum system.

– In order to find the total number of distinct needed elements to construct Q, we point out that at each step k, when newly creating S_k, there are $(n-k)$ elements that are newly introduced compared to all previous sets $\{S_1, \ldots, S_{k-1}\}$. Thus, $N = \sum_{i=1}^{n-1}(n-i) = \frac{n(n-1)}{2}$.

To get more insight into the set construction procedure, let us build the different sets for instance when $n = 9$. According to the proposed procedure, a unique singleton-intersecting quorum system composed of 9 sets containing each 8 elements can be build as follows:

$$\begin{aligned}
S_1 &= \{1,2,3,4,5,6,7,8\}\\
S_2 &= \{1,9,10,11,12,13,14,15\}\\
S_3 &= \{2,9,16,17,18,19,20,21\}\\
S_4 &= \{3,10,16,22,23,24,25,26\}\\
S_5 &= \{4,11,17,22,27,28,29,30\}\\
S_6 &= \{5,12,18,23,27,31,32,33\}\\
S_7 &= \{6,13,19,24,28,31,34,35\}\\
S_8 &= \{7,14,20,25,29,32,34,36\}\\
S_9 &= \{8,15,21,26,30,33,35,36\}.
\end{aligned}$$

Observe that the total number of distinct elements to construct the unique singleton intersecting quorum system is indeed $\frac{n(n-1)}{2} = \frac{9\times 8}{2} = 36$. □

3.4.2 Quorum and Slot Allocation Procedure

Once the singleton-intersecting quorum system $Q = \{S_1, \ldots, S_n\}$ is built, the issue now is how to allocate the different S_q $(1 \le q \le n)$ to the sensor nodes such that each sensor node has a different set compared to all its neighbors. To do so, let us suppose that we have a sensor field of length L and of width l , where N_{tot} nodes with a transmission range R_t each are manually and randomly deployed. We suppose that the geographical coordinates of a node u is (X_u, Y_u). In order for our MC-UWMAC to work conveniently, we have to guarantee, to the most possible extent, for each node u to choose a set S_{q_u} of data channels different from all its neighbors. Moreover, in order to be energy efficient, we prefer that the quorum allocation procedure does not require any extra packet exchange among neighbors. To do so, we propose that a node u's quorum set S_{q_u} $(1 \le q_u \le n)$ has to be selected as follows:

$$S_{q_u} : q_u = (i_u - 1) + (j_u - 1) \times p, \tag{4}$$

where

$$i_u = \left\lceil \frac{x_u}{R_C} \times p \right\rceil \tag{5}$$

$$j_u = \left\lceil \frac{y_u}{R_C} \times p \right\rceil \tag{6}$$

$$p = \lceil \sqrt{n} \rceil \tag{7}$$

$$n = \left\lceil \frac{N_{tot}}{\lceil \frac{L}{R_C} \rceil \times \lceil \frac{l}{R_C} \rceil} \right\rceil \tag{8}$$

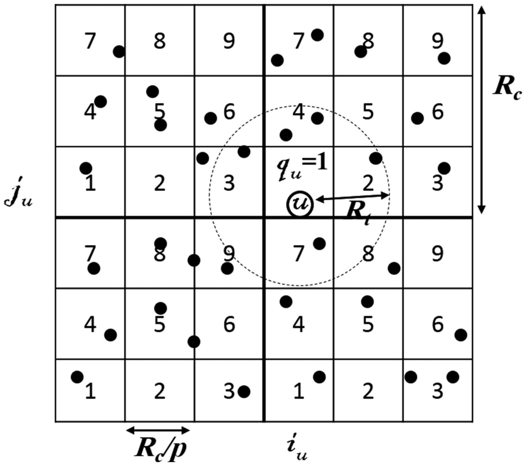

Fig. 4. Grid based virtual partition($n_{max} = 9$).

$$x_u = X_u - \left\lfloor \frac{X_u}{R_C} \right\rfloor \times R_C \tag{9}$$

$$y_u = Y_u - \left\lfloor \frac{Y_u}{R_C} \right\rfloor \times R_C \tag{10}$$

$$R_C = \frac{p}{(p-1)} \times R_t + \epsilon. \tag{11}$$

As shown in Fig. 4 the main idea behind the proposed quorum allocation procedure is to virtually partition our field into a grid of cells of side R_C. The cell of size R_C is built such that nodes in two adjacent cells are guaranteed to be non neighbors. As depicted in Fig. 4, R_C should be chosen such that nodes located at the cell center will have all their neighbors only inside that cell. In other words, R_C must satisfy the following:

$$\frac{R_C}{p} \times (p-1) > R_t. \tag{12}$$

According to Eq. (7), n denotes the maximum neighborhood size. Note that, once the p is computed, the n value has to be updated accordingly. For instance, if the maximum neighborhood size is 7 then p will be set equal to 3 and hence the total frame length as well as the number of quorum is $n = 9$. (x_u, y_u) are the relative coordinates of a node u inside its own cell of side R_C. Once our field is virtually divided into a grid of cells of side R_C, we further partition every cell into smaller ones of side $\frac{R_C}{p}$ such that the total number of cells is $p^2 = n$. By doing so, we aim at locating every sensor inside a unique cell and hence it will be assigned a unique slot number. Note that, (i_u, j_u) are the small cell indexes inside the corresponding large one of side R_C and q_u is the small cell number as shown in Fig. 4. q_u will be the slot number assigned to node u.

The proposed channel allocation scheme is expected to highly decreases the probability of collision while guaranteeing multiple simultaneous data communication which improves the overall network performance especially in terms of throughput and energy efficiency.

Similarly, a node u will choose the slot s_{q_u} in the control frame. As such, we guarantee that the quorum and slot allocations are unique and most importantly without any extra message exchange among nodes. It should be noted that more than one node may select the same quorum number and thus the same slot number, if they reside in the same small cell. Note however that, even in this case, collisions are not systematic as it can be expected. For more details, the reader is referred to Section 4, where a thorough collision study is provided. In the worst case, suppose that more than one node are sharing the same quorum, thus, they will have $(n-1)$ common data channels to communicate on, as opposed to MM-MAC protocol where choosing the same quorum set will prohibit any communication between those nodes. Hence, in MC-UWMAC, depending on the announced data channel occupancy in their respective neighborhoods, these nodes may choose the smallest available data channel number during the handshaking process.

It is worth noting that under mobility condition, MC-UWMAC needs to be rerun in order for the nodes to compute their new slot number and new data channels subset. However, knowing that the underwater mobility is relatively reduced, it is fair to state that MC-UWMAC would not need to be frequently re-executed. Indeed, In the underwater environment, sensor nodes move with the water currents whose speeds depend on the water depth. Authors in [26] point out that harsh current's speed can reach a maximum of $2.5\ \mathrm{m/s}$ at the water surface while it varies between $0.02-0.1\ \mathrm{m/s}$ at deep water. Thus, opting for a deep deployment of the sensor nodes will avoid MC-UWMAC to be rerun frequently as the water current speed is reduced. Most importantly, according to MC-UWMAC operation, a sensor node needs to re-calculate its new slot number and data channels subset index only if it leaves its cell of side length $\frac{R_C}{p}$. Knowing that MC-UWMAC was conceived for sparse underwater sensor network, the value of p is relatively small and hence the cell size is relatively large and thus MC-UWMAC will naturally tolerate sensor motion. For instance, for $n=6$ and $R_t=1\ \mathrm{km}$, p will equal 3 and $R_C=1.5\ \mathrm{km}$ and thus the length of the cell side is equal to $500\ \mathrm{m}$. In this case, according to MC-UWMAC, as long as a sensor node is moving inside its cell of side length $500\ \mathrm{m}$, there is no need to rerun the slot and quorum construction procedures as they will provide the same values. As for determining the geographical coordinates, UW-ASNs have nowadays at their disposal a number of accurate and energy efficient localization techniques such as [27], [28], [29] and [30].

3.5 Protocol Description

In this section, we provide a detailed description of our MC-UWMAC protocol by describing the sender and the receiver behaviors.

3.5.1 Sender Behavior

By default, every sensor node in the network listen on the common channel. A node m having a packet to transmit will send a RTS message on its scheduled slot s_{q_m} to a well defined receiver. Note that, the RTS packet basically includes the destination identifier, the end time of data transmission depending on the number of packets in the queue destined to the receiver. In order to avoid triggering a communication with a busy node, every underwater sensor must maintain a table called hereafter meeting table. This table simply contains a list of in-progress communications with their associated members as well as corresponding end times. Before transmitting, a node m first check its meeting table. If the potential receiver is busy, then m will defer its transmission till the mentioned end time of communication in its meeting table. Otherwise, the sender proceed sending its RTS on its scheduled slot s_{q_m}. If the RTS is successfully received then the receiver will send back a CTS and move to the appropriate data channel. After receiving the CTS, the sender may immediately move to the intended data channel. It is worth pointing out that if the sender does not receive the CTS then it will presume a collision and hence defer its access and go through the backoff procedure as explained in Section 3.5.4.

3.5.2 Receiver Behavior

Having no packet to send or waiting for its own slot, each underwater sensor node has to listen on the common control channel. Once a RTS packet is correctly received, first the sensor node verifies if it is the actual target receiver of the RTS packet. If so, the receiver starts by sending a CTS confirming the data communication on the well known data channel as such any useless possible invitation from one of the receiver's neighbor is avoided. However, if the received RTS was intended to another node, the overhearer keeps track of the sender and receiver identifiers along with the presumed data channel as well as the end time of communication in the meeting table. By doing so, the overhearer avoids triggering a communication with a busy node (the sender or the receiver). Similarly, the overhearer keeps track of all the previously mentioned information if it receives a CTS packet. Therefore, any underwater sensor node wishing to send a data packet to a well defined node, first it has to check its meeting table. If the intended node is not busy, the node will proceed sending a RTS packet in its own slot. Otherwise, it has to defer its RTS transmission till the precised end time of communication in the meeting table.

Note that, since the underwater sensor networks are by nature sparse, each sensor node will have only a few neighbors. Consequently, the meeting table is manageable even with very limited memory resources.

The working process of MC-UWMAC from the sender and receiver sides are shown in the flowcharts of Figs. 5 and 6, respectively.

3.5.3 More Bit

An important detail of the MC-UWMAC protocol, which is also found in a number of MAC protocols for sensor networks [31], [32], is the presence of a more bit in the header of data packets. When this bit is set to 1, it indicates that more data packets destined to the same sensor node are waiting in the buffer of the transmitting node. When a data packet is received with the more bit set, the receiving sensor node continues listening on the same data channel without sending the acknowledgment. Consequently, remaining on the same data channel, the sender will proceed transmitting the following data packet right after sending the previous one, especially without getting back to the common channel in order to take a new appointment (i.e.; by sending a new RTS) with the same previous receiver. Therefore, the end-to-end delay is decreased and the throughput flowing through a given forwarder is increased.

3.5.4 Collisions Processing in MC-UWMAC

MC-UWMAC is conceived to provide collision free communication since the ultimate objective of MC-UWMAC is to maximize the throughput. Indeed, recall that thanks to our

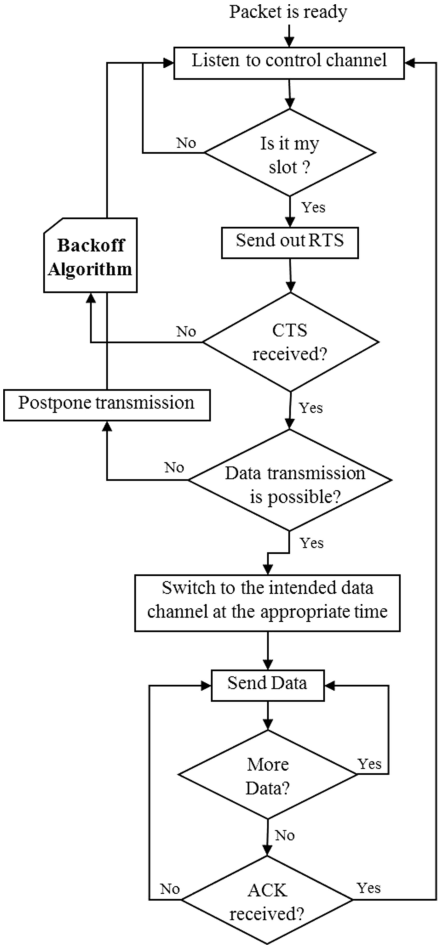

Fig. 5. Flowchart of the sender behavior.

quorum set construction, the multichannel hidden terminal problem is avoided. Moreover, thanks to the TDMA-based communication on the common control channel, we avoid the long delay hidden terminal problem. Nevertheless, in some MC-UWMAC settings, collisions may occur since our slot and quorum assignment procedure is not completely 2-hop conflict free. That being said, in MC-UWMAC, unlikely collisions may happen only in the control channel saving thus data channels from undesirable costly collision. Indeed, in a given data channel, the collision is completely avoided thanks to the handshaking process in the common control channel along with the meeting table management and the quorum system construction procedure. Consequently, in MC-UWMAC, data communication is guaranteed to be collision free.

Collisions in MC-UWMAC may happen only in the control channel if two or more nodes are sharing the same slot number. In other words, and according to our slot assignment procedure, if more than one node reside in the small cell then they will surely share the same slot in the TDMA frame, which may cause collision when sending the RTS packet to a common neighbor. According to MC-UWMAC, a collision is detected only after sending a RTS message for which no CTS is received. Once a collision is detected, a node waits a random number of frame periods (so called back-off delay) before trying to retransmit again the RTS message in the same slot. Retransmissions are scheduled according to the binary exponential back-off strategy. Accordingly, an integer variable $BI(s) \geq 1$ is associated to each slot s. Whenever the sender node experiences a collision in slot s, it first doubles $BI(s)$ up to maximum value of BI_{max}. Then, the sender chooses a random variable from interval $[1, BI(s)]$. Note that the selected random variable denotes the number of frames to wait before reattempting the RTS transmission. When a CTS packet is received in slot s, the sender resets the back-off interval to $BI(s) = 1$. In MC-UWMAC, BI_{max} is set equal to the maximum number of nodes in the same small cell sharing the same slot number. Finally, we brief that MC-UWMAC naturally avoids collision at the data channel without requiring any extra packet exchange among nodes and provides a recovery mechanism to deal with the unlikely collision in the common control channel. As opposed to MM-MAC and CUMAC, where messages has to be exchanged among neighbors in order to avoid collisions which is an energy consuming procedure.

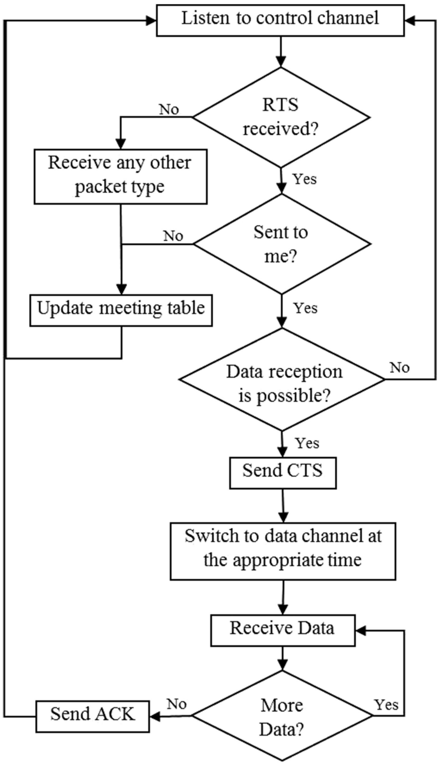

Fig. 6. Flowchart of the receiver behavior.

4 COLLISIONS ANALYSIS IN MC-UWMAC

In MC-UWMAC two nodes may experience a collision if and only if they exist in the same small cell of side $\frac{R_C}{p}$. In MC-UWMAC having nodes in the same small cell does not mean that they will systematically experience a collision. In order to gain more insights into the occurrence of collision in MC-UWMAC, let us closely inspect the MC-UWMAC behavior for different value of maximum neighborhood size n.

4.1 Neighborhood Size $n \leq 4$

In this case, we deal with an extremely sparse network where every node has at maximum 6 neighbors. Hence, our $p = 2$ and thus the size of the small cell is $\frac{R_C}{p} = 2 \times R_t + \varepsilon$. Consequently, nodes in the same small cell may be 2-hop away, or even more since the diagonal line size is $2\sqrt{2}R_t > 2 \times R_t$, and thus traditional collisions may not occur. However, they may suffer from hidden terminal collision if one of the 2 sending nodes is addressing a common

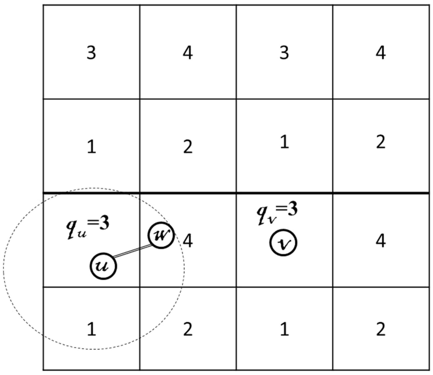

Fig. 7. Network virtual partition ($p = 2$).

neighbor. Looking at Fig. 7, reader may expect hidden terminal collision between nodes in different small cell but sharing the same slot number. Note however that since the size of the small cell is greater than $2 \times R_t$ then such collision is completely mitigated. Indeed, as depicted in Fig. 7, if node u and v initiate a communication simultaneously such that u is addressing node w then w will not suffer from collision since w is not a neighbor of v. Indeed, because of the small cell size, w can be either a neighbor of u or a neighbor of v and hence hidden terminal collision between different small cell sharing the same slot number can never happen.

4.2 Neighborhood Size $n > 4$

In this case, all the nodes in the same small cell are almost neighbors. Indeed, for $p = 3$ the size of the small cell is almost $\sqrt{2}R_t$ and for $p = 4$ the size of the small cell is $\frac{2}{3}R_t$. Note that the size of the small cell decreases when p increases. Consequently, they may suffer from traditional collision but never hidden terminal collisions. Note however that in this case, and according to MC-UWMAC, nodes in the same small cell will have complete and accurate knowledge of nodes availabilities as well as data channels availabilities since they are all neighbors of each others and hence collisions can be further reduced thanks to the meeting table management. That being said, a node may have some missing entries in its meeting table since it can be busy communicating in a data channel when a handshaking has been initiated in the common control channel. In this case, there is a risk that the node sends a RTS to a busy neighbor for which it will not receive a CTS and hence no data communication will be handled. This is actually the reason for which we conceive the RTS/CTS handshaking scheme in the control channel just to be sure that the intended receiver is free.

5 PERFORMANCE EVALUATION

We devote this section to analyze the performance of our protocol MC-UWMAC first, under regular topologies where every node has the same fixed number of neighbors; second, under random topology where every node has variable number of neighbors to evaluate whether the performance of our protocol can be compromised and how it compares with existing related protocols.

5.1 Numerical Simulation of MC-UWMAC under Regular Topologies

Topologies, where nodes are placed at the vertices of a regular shape and the shape edges are the links between nodes, represent the best case scenarios where MC-UWMAC performance is optimal for two main reasons. First, adopting a regular topology not only allows every node to have a similar and fixed number of neighbors n but most importantly it allows a conflict free slot assignment distribution using only n slots which will completely mitigate collisions. As opposed to a random topology, where the total number of slots equals $\left(\lceil\sqrt{n_{\max}}\rceil\right)^2$ where $n_{\max}$ is the maximum neighborhood size. Second, and consequently, under regular topologies, MC-UWMAC will operate under a reduced number of data channels while being completely collision free which increases the data channel capacities and hence the end to end delay as well as the throughput and energy consumption are optimized. For the aforementioned reasons, for regular topologies, we opt for the numerical simulation of our MC-UWMAC protocol where we consider a rather small network size containing 25 nodes to study the hop by hop performance of MC-UWMAC where every node is sending to every neighbor $\frac{A}{n}$ packets per unit of time, A is the packet generation rate. The numerical simulation settings are listed in Table 2.

TABLE 2
Numerical Simulation Parameters Setting

Simulation Time	7,200 s
Data Packet	200 B
(RTS/CTS/ACK)	20 B
Tx power	10 W
Rx power	80 mW
Acoustic speed	1,500 m/s
Max Packet sojourn	60 s
Slot duration	2 s
Total Bandwidth B	60 kHz

5.1.1 *Grid Topology*

The first case study considers a grid topology. Accordingly, every node has exactly four neighbors $n = 4$. Consequently five slots need to be assigned to neighbors such that nodes in the same neighborhood will have different slot numbers. The slots assignment as well as the considered network topology are shown in Fig. 8.

The associated data channels sets are built according to Theorem 1 as follows:

$$
\begin{aligned}
S_1 &= \{1, 2, 3, 4\} \\
S_2 &= \{1, 5, 6, 7\} \\
S_3 &= \{2, 5, 8, 9\} \\
S_4 &= \{3, 6, 8, 10\} \\
S_5 &= \{4, 7, 9, 10\}.
\end{aligned}
$$

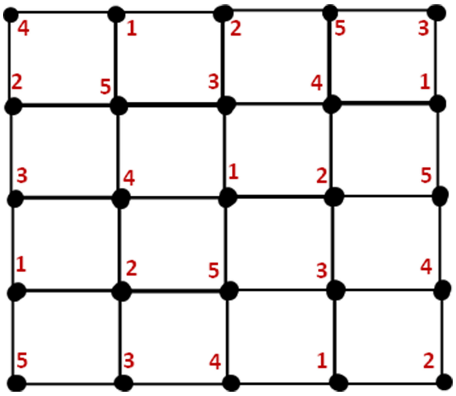

Fig. 8. Grid topology.

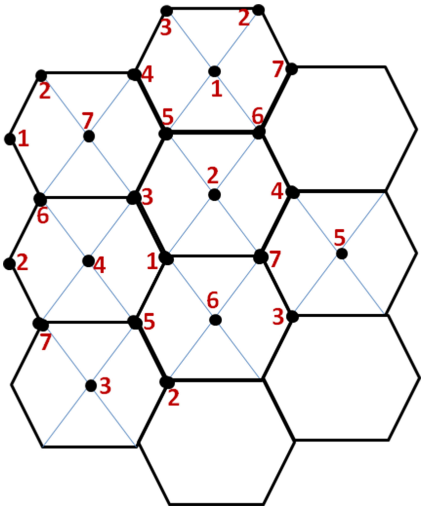

Fig. 9. Centered hexagonal topology.

Recall that a node assigned a slot i will have the data channels set S_i where every data channel in S_i will be used by the node for dedicated communication with a given neighbor.

5.1.2 Hexagonal Topology

Fig. 9 illustrates our second regular topology case study where nodes are organized according to a centered hexagonal topology. As shown in Fig. 9, the neighborhood size is 7, where every node is assigned a unique and different slot number.

The associated data channels sets are listed below:

$$S_1 = \{1, 2, 3, 4, 5, 6\}$$
$$S_2 = \{1, 7, 8, 9, 10, 11\}$$
$$S_3 = \{2, 7, 12, 13, 14, 15\}$$
$$S_4 = \{3, 8, 12, 16, 17, 18\}$$
$$S_5 = \{4, 9, 13, 16, 19, 20\}$$
$$S_6 = \{5, 10, 14, 17, 19, 21\}$$
$$S_7 = \{6, 11, 15, 18, 20, 21\}.$$

5.1.3 Non Centered Hexagonal Topology

According to this topology, nodes are only placed at the vertices of a virtual hexagon and hence every node is surrounded by exactly three neighbors. The slot assignment distribution is shown in Fig. 10.

The associated data channels sets are listed below:

$$S_1 = \{1, 2, 3\}$$
$$S_2 = \{1, 4, 5\}$$
$$S_3 = \{2, 4, 6\}$$
$$S_4 = \{3, 5, 6\}.$$

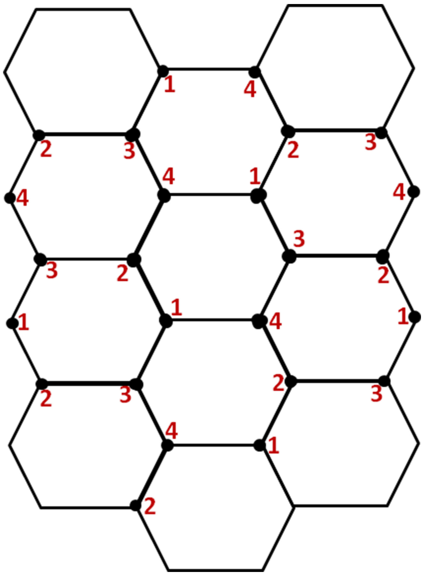

Fig. 10. Non-centered hexagonal topology.

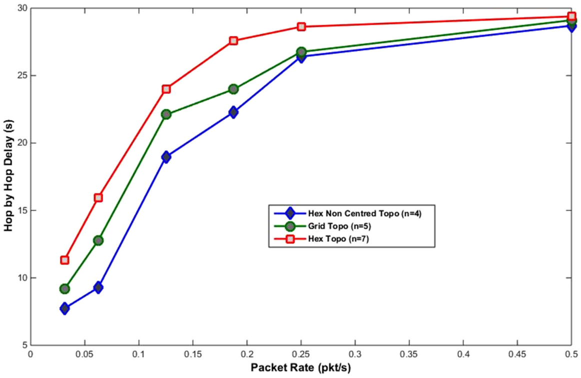

Fig. 11. Average hop-by-hop delay.

As explained earlier, in this section we are rather interested in analyzing the performance of MC-UWMAC on regular topologies on a hop by hop basis. Fig. 11 shows the hop-by-hop delay for the three topologies while varying the packet generation rate. As expected, in a similar collision free scenarios, the hop-by-hop delay is increasing as function of the packet generation rate. This increase is mainly due to the growth of the average waiting time (queuing time) as depicted in Fig. 13. Indeed, as the packet generation rate increases, the nodes are much busier and hence reaching to a free neighbor will be harder and needs more time. Although, according to our protocol, when a node succeeds in reaching a neighbor, it will deliver all the packets destined to this neighbor as a burst as shown in Fig. 12. Although, the average burst size is increasing with the packet generation rate, which improves the performance of MC-UWMAC, the waiting time is still dominating the hop-by-hop delay. A study of the correlation between the average waiting time and the average hop-by-hop delay, $\frac{waiting\_time \times hop\_by\_hop\_delay}{\|waiting\_time\| \times \|hop\_by\_hop\_delay\|}$, reveals a strong correlation of 99.5 percent for the three topologies. Fig. 14 depicts the hop-by-hop delay as function of the waiting time for the three topologies. As expected, the curves are almost linear which confirms the strong correlation between the waiting time and the hop-by-hop delay. Note that, the waiting time, according to our MC-UWMAC protocol is due to meeting table consultation which avoids trying to reach to a busy node and hence reduces collisions and saves energy. Observe that the average hop-by-hop delay for the three approaches is classified according to the neighborhood size. Indeed, the hexagonal topology is achieving the highest delay followed by the grid topology and last the hexagonal non centered topology. Recall that the data channel capacity is inversely proportional to the neighborhood size. In fact,

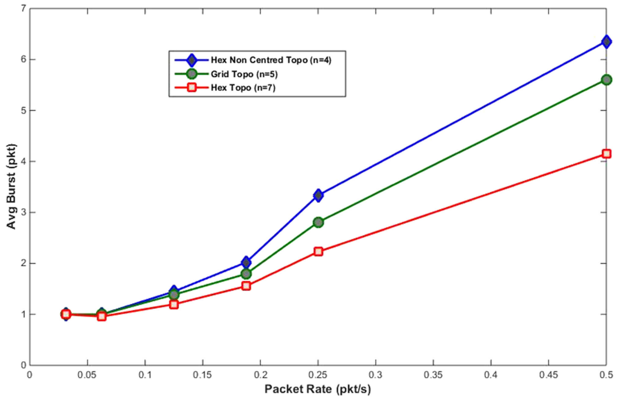

Fig. 12. Average burst size.

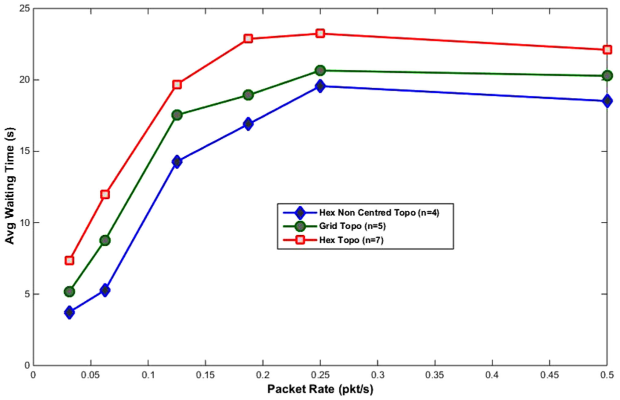

Fig. 13. Average waiting time (queuing time).

according to MC-UWMAC, the total number of data channels is $N = \frac{n(n-1)}{2}$ and hence the data channel bandwidth is $\frac{B}{N}$. Consequently, when we increase n, the data channel bandwidth is decreasing and hence the transmission delay is increasing.

Fig. 15 shows the average hop-by-hop throughput as function of the packet generation rate for the three approaches. As expected, in a collision free scenarios, the throughput is increasing with the packet generation rate since the total number of successfully received packets during the simulation time is increasing. Indeed, according to MC-UWMAC, increasing the packet generation rate will further justify the usefulness of the burst transmission as shown in Fig. 12 and hence, the average hop-by-hop throughput will considerably increase. Here again, the hexagonal non centered topology is achieving the highest throughput as it has the lowest neighborhood size followed in order by the grid topology and finally the hexagonal topology which has the highest neighborhood size ($n = 7$).

Finally, Fig. 16 depicts the average consumed energy per useful bit for the three regular topologies in our study. As expected, the energy efficiency of MC-UWMAC grows with the traffic rate. Indeed, based on the growth in the throughput as function of the traffic rate explained above, one would expect an increase in the energy consumption. However, according to MC-UWMAC, increasing the traffic rate will increase the burst size as shown in Fig. 12, and hence one handshaking exchange (RTS/CTS) will be enough to send more than one data packet. Consequently with a little bit more energy, the protocol is able to deliver many more packets. Here again, the hexagonal non centered topology achieves the highest energy efficiency since it has the smallest neighborhood size and thus has at its disposal the largest data channel capacity which reduces the transmission and the reception times and so their associated energy consumption.

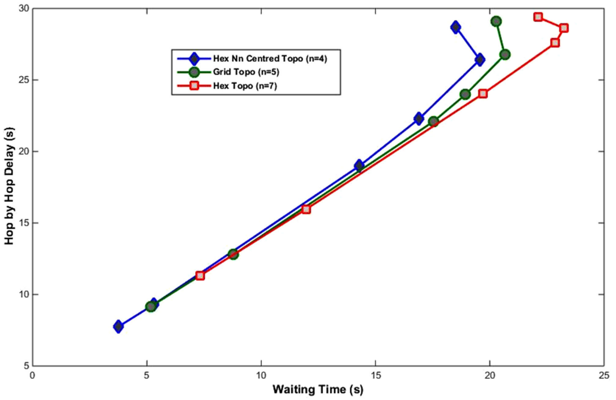

Fig. 14. Correlation between the hop-by-hop delay and the average waiting time.

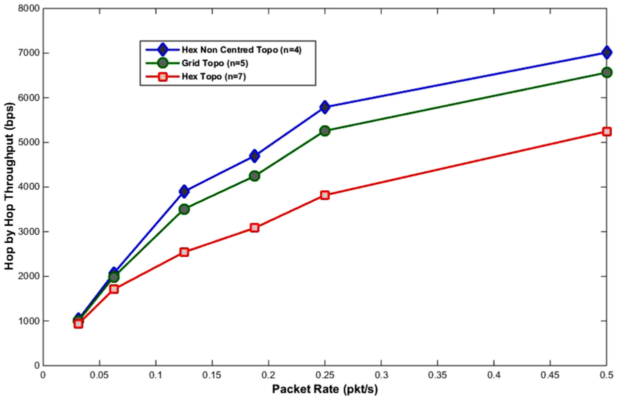

Fig. 15. Average hop-by-hop throughput.

5.2 MC-UWMAC Performance Under Random Topology

Inspired by the the discrete-event underwater acoustic network simulators developed in [3], we have implemented our multi-channel underwater acoustic network simulator to assess the performance of MC-UWMAC under random topology. In our simulations, we consider a network of 49 nodes uniformly deployed over a square area of length $5\ \mathrm{Km}$ supplied with constant bit rate traffic. The transmission range is $1\ \mathrm{Km}$ and the nominal speed of sound in water is $1500\ \mathrm{m/s}$. Data and control packets are of size 200 and 20 bytes, respectively. Control slot duration is $2\ \mathrm{s}$ long. We employed the energy consumption model adopted in [3], where the transmit power (10 W) is 125 times the receive power (80 mW). In addition, we assume that nodes have a buffer for each of its neighbors and perform a continuous monitoring of the target area where four sinks are placed at the corners. Each simulation runs for 3,600 s.

On our chosen random topology of 49 nodes, we run MC-UWMAC for different values of p and we compare it with MM-MAC[3]. Note that, every value of p lead to new frame size (p^2) and hence a new slot number as well as a new data channel subset for every node in the network. Moreover, choosing a new value of p will impact the total number of data channels ($N = \frac{n(n-1)}{2}$ where n is p^2) and hence the data channel

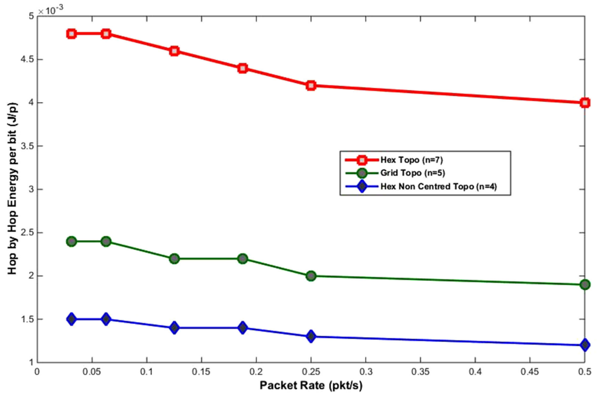

Fig. 16. Average consumed energy per useful bit.

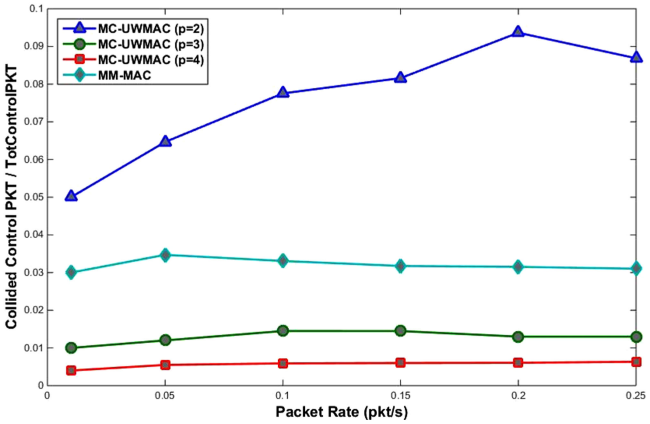

Fig. 17. Collision probability.

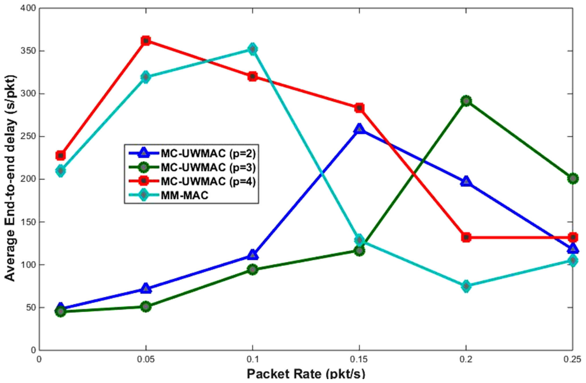

Fig. 18. End-to-end delay.

bandwidth. Consequently, varying p will help finding out the optimal value of p that optimizes the performance of MC-UWMAC in terms of throughput and energy per bit.

Fig. 17 shows the probability of collision on the control channel as function of the traffic rate for both our MC-UWMAC protocol for different p values as well as for MM-MAC protocol for comparison purposes. First, note that MC-UWMAC succeed to achieve very low collision probability, especially for $p = 3$ and $p = 4$, that is even lower than the one achieved by MM-MAC. Indeed, Thanks to our quorum and slot assignment procedures, we aim at providing to the most possible extent a collision free communication. However as mentioned before, co-existing nodes in the same small cell will probably cause simultaneous RTS transmissions. In this case, nodes will defer their transmission according to a backoff strategy to avoid repetitive collisions. The MM-MAC protocol was also conceived to provide a collision free communication but the proposed slot assignment procedure is not as efficient as ours since it relies on node ID, which did not guarantee the overlapping of default and switching slots of communicating nodes. Moreover, MM-MAC didn't conceive any solution to deal with collision and hence repetitive collisions may happen. Moreover, observe that the collision probability is decreasing with p. In fact, by increasing p, the size of the small cell is further reduced and hence we guarantee that only a unique sensor is located in every small cell and thus every sensor will have its own unique quorum and slot that is 2-hop conflict free and hence collision free communication is absolutely assured. Now, regarding the collision probability behavior as function of the traffic rate, as expected, the collision probability is increasing with the traffic rate till reaching saturation.

Now, we evaluate the performance of our protocol MC-UWMAC and compare it with MM-MAC in terms of end-to-end delay. It is worth pointing out that all the end-to-end delay curves show a quite similar behavior as function of the traffic rate (see Fig. 18). Most importantly, Fig. 18 exhibits a convex upwards behavior since it is a tradeoff between two compromises. First, increasing the traffic rate will not only increase the unlikely collision probability but most importantly it will increase the data packet average waiting time as nodes need to wait longer for a neighbor who is busy in delivering longer bursts of data packets as explained in Figs. 13 and 12. Second, for high values of the traffic rate, the burst size will considerably increase leading to a decrease in the end-to-end delay as once a node succeed its handshaking with an intended receiver it will be able to send much more data packets and hence compensate for the long waiting times which will further justify the burst sending feature in sparse heavy loaded networks. Notice that according to Fig. 13 the average waiting time starts by increasing then reaches a limit for high traffic rates. However, the average burst size keeps increasing. Consequently, for high traffic generation rates, with almost the same waiting time, sensor nodes will be able to send much more data packets which will inevitably decrease the end-to-end delay. Note that Section 5.1 has been added as a numerical simulation in order to better understand MC-UWMAC behavior and which criteria are impacting the end-to-end delay, throughput and the energy per bit in a collision free environment as the probability of collision in MC-UWMAC is very low. Now, assessing the performance of MC-UWMAC for different values of p, as expected the end-to-end delay is increasing with p mainly due to the reduced data channel bandwidth. Recall that, the total available bandwidth will be divided into N data channels where $N = \frac{n(n-1)}{2}$ and n is p^2. Thus increasing p decreases the data channel bandwidth which will increase the transmission times and hence longer delays are experienced. MM-MAC adopts the same behavior, namely the convex upwards aspect for the same reasons. However, MM-MAC ends up increasing again for the simple reason that the burst size for MM-MAC has a maximum value. Recall that time in MM-MAC is rigidly slotted into control and data periods of fixed sizes which imposes a limit on the number of sent data packets during the data period. Hence, a given sender will be obliged to start a new handshaking even if it still has data packets for the same receiver which is not the case for

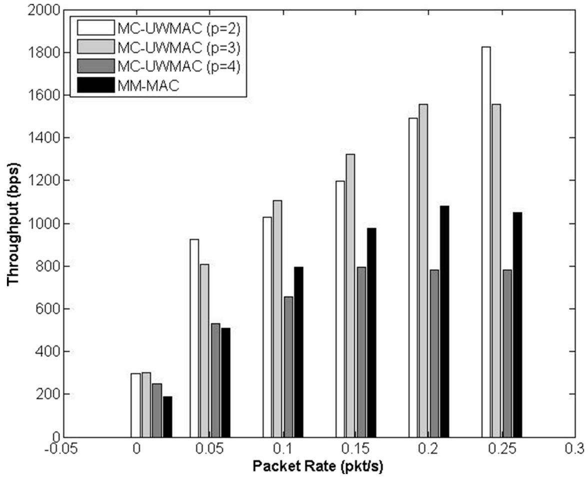

Fig. 19. Throughput.

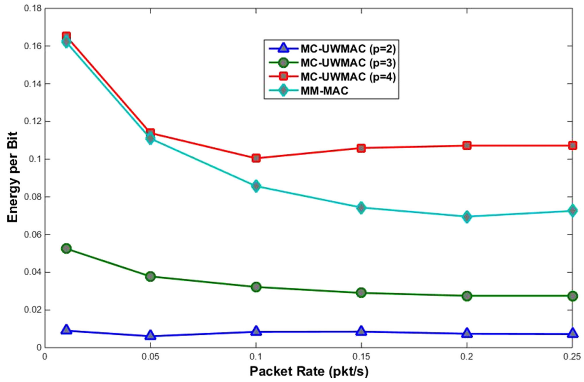

Fig. 20. Energy consumption per bit.

MC-UWMAC. Nevertheless, MM-MAC succeeds to achieve better end-to end delay for traffic rates between $[0.18, 0.25]$ while MC-UWMAC (for $p = 3$) clearly outperforms MM-MAC for traffic rates between $[0.01, 0.15]$.

Fig. 19 depicts the network throughput for both protocols as function of the traffic rate. For both protocols, the throughput increases with the traffic rate. Observe that, MC-UWMAC, especially with $p = 3$ and $p = 2$, outperforms MM-MAC in terms of throughput, regardless the generated traffic rate. Indeed, MC-UWMAC achieves up to 74 percent improvement in network throughput over MM-MAC for a traffic rate of 0.25 pkts/s. Consequently, we can state that MC-UWMAC handles heavy loaded networks, as well as light loaded ones, better than MM-MAC. Indeed, the main reason behind the degradation of MM-MAC throughput is the design of a control and data period of fixed duration. Actually, this separation between control and data period will not only limit the data period and increase the end-to-end delay and hence badly impact the throughput as explained above but also it will prohibit simultaneous data transmissions and handshaking among different pair of nodes. However, with MC-UWMAC, not only simultaneous data communication can occur separately in different data channels but also the handshaking process in the common control channel naturally continues to take place at the same time which will further increases the number of successfully received packets by the sinks.

Now, to get more insight into the energy efficiency of both protocols let us inspect the energy consumption per useful bit as function of the traffic rate. As shown in Fig. 20, MC-UWMAC ($p = 3$ and $p = 2$) is clearly more energy efficient than MM-MAC. The energy consumption for MM-MAC can be considered as closer to the case $p = 4$ where our protocol consumes more energy due to the reduced data channel bandwidth size which increases the transmission and reception time and hence the resulting energy consumption. $p = 2$ and $p = 3$ are clearly more energy efficient since they succeed to achieve much higher throughput while using a data channel of reasonable width. Moreover, it is worth noting that MC-UWMAC naturally avoids collisions and achieves high throughput without requiring any extra packet exchange among nodes. As opposed to MM-MAC, where notification messages has to be continuously sent during the remaining control period by any pair of nodes who have succeeded their handshaking in order to avoid data collision which is an energy consuming procedure.

As a recap, we recommend to set p either equal to 2 or 3 in order to increase the throughput while being energy efficient. However, $p = 4$ highly decreases the collision probability but provides reduced throughput and energy efficiency due to the reduced data channel bandwidth.

6 CONCLUSION

In this paper, we proposed a novel multichannel MAC protocol, MC-UWMAC, especially designed for the underwater environment. MC-UWMAC operates on single slotted control channel for handshaking and multiple data channels. To guarantee a collision free communication, MC-UWMAC employs two key related procedures: i) a grid based slot assignment on the control channel and ii) a newly designed quorum based data channel allocation which aims at guaranteeing for each pair of neighbor nodes a unique and 2-hop conflict free data channel for their data transmission. The quorum construction and slot allocation procedures, not only highly decreases the probability of collision but most importantly do not require any extra packets exchange between nodes which increases the energy efficiency of MC-UWMAC. Simulation results show that significant throughput improvement is achieved by our MC-UWMAC protocol since it allows multiple simultaneous almost collision-free communications to take place on the control channel as well as all available data channels. Moreover, MC-UWMAC is energy efficient since it avoids collision without requiring any additional control packet exchange among nodes. We believe that the proposed MAC protocol is a promising Multichannel communication scheme since it achieves better performance over MM-MAC [3], thanks to the careful design of MC-UWMAC.

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