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MC-UWMAC: A Multi-Channel MAC Protocol for UnderWater Sensor Networks

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***Abstract*—Fundamental differences between underwater acoustic propagation and terrestrial radio propagation impose the design of new networking protocols. In this paper, a multi-channel MAC protocol, MC-UWMAC, especially designed for underwater acoustic sensor networks, is proposed and evaluated. MC-UWMAC is a low power MAC protocol operating on multi-channel using a single slotted control channel and multiple data channels. To guarantee a collision free communication, MC-UWMAC uses a virtual grid based slot assignment linked with a quorum based data channel allocation. Specifically, control channel slots are dedicated for handshaking. Data transmission takes place in a unique data channel especially reserved for each communicating pair. Simulation results show that MC-UWMAC can greatly improve the network performance especially in terms of energy consumption, packet delivery ratio and end-to-end delay.**

***Index Terms*—UnderWater Acoustic Sensor Networks, TDMA, energy efficiency, multi-channel communication, performance analysis.**

I. Introduction

UnderWater Acoustic Sensor Networks (UW-ASNs) witnesses an increasingly growing interest in the last decade. UW-ASNs can be deployed to serve a wide range of collaborative applications such as, offshore exploration, tsunami warning, and mine reconnaissance [1]. Although acoustic transmissions is preferable than radio transmissions in underwater environment, serious challenges due to channel impairments face networking protocols to be tailored for underwater acoustic networks [1]. Indeed, in order to overcome the impairments of the acoustic channel and hence achieving smooth underwater communication, more complex signal processing is needed for communication over longer distances with much lower speed and thus much more energy is consumed when transmitting. Consequently, energy efficient communication protocols are required since underwater sensors are not only battery powered but also can not be easily recharged. In such harsh context, nodes require techniques that avoid unnecessary retransmissions due to collisions. In fact, collisions did not only waste energy but also consume time. Hence, conceiving an energy efficient MAC protocol especially tailored for UW-ASNs is of paramount importance as the MAC protocol is responsible for coordinating nodes' access to the shared wireless medium. To avoid transmission collision in UW-ASNs, some earlier MAC protocols [9], [10] propose a centralized solution where a particular node will be in charge of arranging transmission schedules for all the nodes. However, these protocols work only in a single hop underwater environment. In some other UW-ASN MAC protocols such as T-Lohi [6], slotted ALOHA [11], and slotted FAMA [5], time is divided into fixed-length slots and packets can be transmitted only at the beginning of a time slot. Similarly, these solutions may work properly in a single hop or lightly loaded environment. However, they generally do not function properly in a multi-hop network scenario with large number of sensor nodes heavily loaded. All of these protocols are based on the use of single channels. Recently, new technological advances in underwater devices and modem allow the usage of multiple channels for parallel communication. For instance, AquaNetwork is a modem from DSPCOMM that makes possible the usage of multiple acoustic channels in parallel. Such parallelism can efficiently ameliorate network throughput and reduce end-to-end delay and energy consumption. In this paper, we propose a multi-channel MAC protocol (MC-UWMAC) for UW-ASNs. MC-UWMAC allows parallel communication over multiple data channels. One single rendezvous channel (control channel) is devoted for handshaking to avoid the missing receiver problem faced especially in multi-channel communication scheme where a sender may fail to get in touch with a target receiver since they reside on different channels. For data communication over multiple data channels, we introduce a data channel allocation procedure based on the singleton intersecting quorum system where each pair of nodes is allocated a unique and different data channel from their respective neighbors. As such multiple simultaneous collision-free data communications may take place improving hence the overall network performance especially in terms of throughput and energy consumption. The remainder of this paper is organized as follows. Section II describes MC-UWMAC. In section III, we analyze the collisions occurrence in MC-UWMAC. In Section IV, we examine the performance of MC-UWMAC compared with MM-MAC [3] an existing multi-channel MAC protocol. Finally, we conclude this paper with a summary of our contributions.

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II. MC-UWMAC: Multi-Channel MAC protocol for UW-ASNs

MC-UWMAC is a low power 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 is 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 where T_{SLOT} is equal to $T_{RTS} + T_{CTS} + 2 * T_{PROP}$. Indeed, as represented in Fig. 2, 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. According to MC-UWMAC, to appropriately

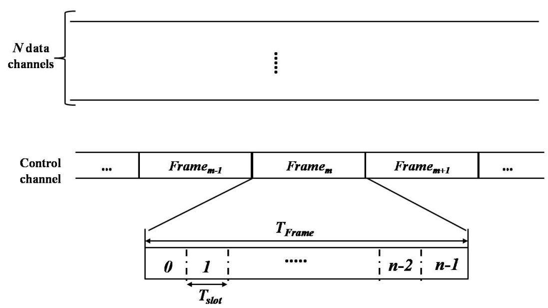

Fig. 1. MC-UWMAC frame structure.

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. 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

$$\forall u \text{ and } \forall \{v,\ w\} \in N_e(u),\ w \neq v, => S_{q_u} \cap S_{q_v} \neq S_{q_u} \cap S_{q_w} \quad (1)$$

where $N_e(u)$ is the list of u's one hop neighbors. In other words, in u's neighborhood, data channel CH_{uv} will be only allocated for data exchange between u and v, meaning that no other neighbor of u and v is using CH_{uv} to communicate with any one of its own neighbors. Therefore, not only collisions among neighbors is mitigated but also collisions due to hidden node is 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.

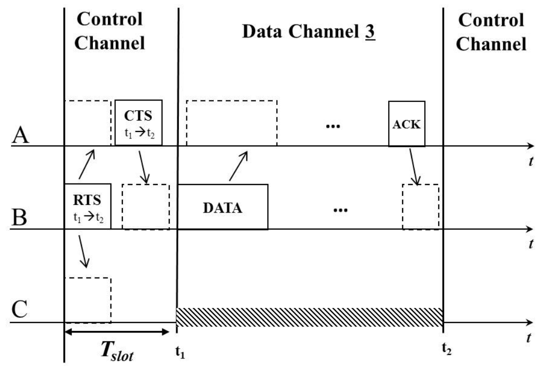

Fig. 2. An example of MC-UWMAC successful data communication.

A. Slot Assignment Procedure

In order to be energy efficient, we strive for proposing a slot allocation procedure that does not require any extra packet exchange among neighbors. To do so, let us suppose that we have a two dimensional sensor field of length L and of width l where N_{tot} nodes with a transmission range R_t are 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 some extent, for each node u to choose a slot s_{q_u} different from all its neighbors. For this reason, we propose that a node u's slot s_{q_u} $(1 \leq q_u \leq n)$ has to be computed as follows:

$$s_{q_u} : q_u = (i_u - 1) + (j_u - 1)\, p \quad (2)$$

where

$$i_u = \lceil \frac{x_u}{R_C} \times p \rceil \quad (3)$$

$$j_u = \lceil \frac{y_u}{R_C} \times p \rceil \quad (4)$$

$$p = \lceil \sqrt[2]{n} \rceil \quad (5)$$

$$x_u = X_u - \lfloor \frac{X_u}{R_C} \rfloor \times R_C \quad (6)$$

$$y_u = Y_u - \lfloor \frac{Y_u}{R_C} \rfloor \times R_C \quad (7)$$

$$R_C = \frac{p}{(p-1)} \times R_t + \epsilon \quad (8)$$

As shown in Fig. 3 the main idea behind the proposed slot allocation procedure is to virtually partition our field into a grid of squares of side R_C. The square of size R_C is built such that nodes in two adjacent squares are guaranteed to be non-neighbors. In other words, R_C must satisfy the following

$$\frac{R_C}{p} \times (p-1) > R_t \quad (9)$$

Once our field is virtually divided into a grid of squares of side R_C, we further partition every square into a smaller squares of side $\frac{R_C}{p}$ such that the total number of squares is $p^2 = n$. By doing so, we aim at locating every sensor inside a unique square and hence it will be assigned a unique slot number. Fig. 3 shows a slot assignment example for a network randomly deployed. According to our formulas, p is equal to 3 and each node will acquire a slot number in {0,1,2,3,4,5,6,7,8} as n equals 9. (i_u, j_u) are the small square indexes inside the corresponding large square of side R_C and q_u is the small square number. q_u will be the slot number assigned to node u. For example, the slot number q_u of node u (in Fig. 3) is 0.

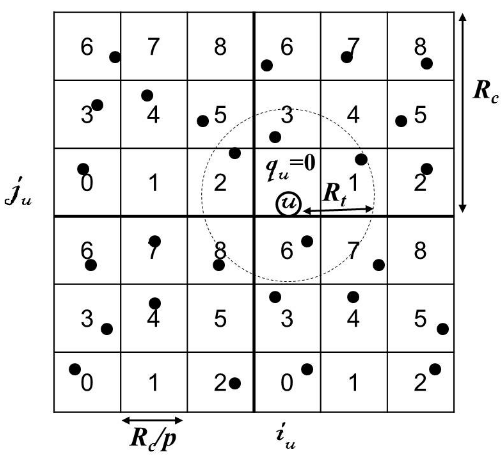

Fig. 3. Slot Assignment example (p=3).

B. Quorum based Channel Allocation

The main idea behind MC-UWMAC is how to build our n subsets of data channels $S_0, S_1, \ldots, S_{n-1}$ of length $(n-1)$ each, such that we guarantee the unique singleton intersection among pairwise neighboring nodes, and hence the multi-channel 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 [12] and for MAC protocol design in wireless networks [14], [13] and recently for UW-ASNs [8]. A quorum system can be defined as follows.

Definition 1: In general, a quorum system Q under a universal set U = {1,…,N}, is a collection of non-empty subsets of U, which satisfies the intersection property: $\forall G, H \in Q$; $G \cap H = \emptyset$.

Definition 2: A quorum system Q under U, is said to be a singleton-intersecting quorum system if the pairwise intersections among quorums is singleton. In other words, $\forall G, H \in Q$; $|G \cap H| = 1$.

Definition 3: A singleton-intersecting quorum system Q under U, is said to be a unique singleton intersecting quorum system if the pair-wise intersections among subsets of Q is a unique different singleton. In other words, $\forall G, H, I, J \in Q$ such as $G \neq H \neq I \neq J$; $G \cap H \neq I \cap J$ 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. Therefore, once the data channel subsets are created, each node will select a different subset S_{q_u}, based on its slot number q_u as explained in the previous section. As such, we guarantee that the quorum and slot allocations are unique and most importantly without any extra message exchange among nodes.

III. Collision analysis

In underwater multi-channel environment, collisions are essentially induced by the multi-channel hidden terminal and the long delay hidden terminal problem as explained in [4]. Thus, MC-UWMAC is conceived to provide a collision free communication in order to maximize the packet delivery ratio and to minimize the network energy consumption by avoiding those problems thanks to our key procedures: our quorum set construction and the TDMA-based communication on the common control channel. Nevertheless, in some MC-UWMAC settings, collisions may occur since our slot 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. 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 same 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. Let *T* be the total number of small cells and τ the percentage of cells with more than one node. In Table. I, we represent *T*, p and τ for different nodes number N_{tot}. **E**ach calculated parameter is obtained from 100 deployment trials for each total number of nodes, randomly deployed over a square field of side length $5Km$.

Clearly, according to Table. I, τ is negligible. Note that a maximum of only 3% of small cells will contain nodes having the same slot number. Hence, collisions due to RTS simultaneous transmission are expected to be low. Nevertheless, to deal with such unlikely collisions, MC-UWMAC uses an efficient back-off mechanism to schedule retransmission

TABLE I
SLOT ASSIGNMENT PARAMETERS FOR DIFFERENT NODES NUMBER.

N_{tot}	10	15	20	25	30	35	40	45	50
p	3	3	3	3	4	4	4	4	4
T	100	100	100	100	255	255	255	255	255
$\tau(\%)$	2	3	3	3	2	2	3	3	3

attempts. Indeed, once a collision is detected, a node waits a random number of frame periods T_{FRAME} (so called back-off delay) before attempting to retransmit the RTS message. Retransmissions are scheduled according to the binary exponential back-off strategy. To each TDMA slot s, an integer variable $BI\left(s\right) \geq 1$ is associated. Whenever the sender node experiences a collision in slot s, it first doubles $BI\left(s\right)$ (up to maximum value of BI_{max}) and then chooses the back-off delay, randomly and uniformly, from interval $[1, BI\left(s\right)]$. During the back-off period, nodes keep listening to the control channel. When a CTS packet is received in slot s, the sender resets the back-off interval to $BI\left(s\right) = 1$. In MC-UWMAC, BI_{max} is set equal to the maximum number of nodes in the same small cube sharing the same slot number.

IV. Performance Evaluation

Inspired by the the discrete-event underwater acoustic network simulators developed in [2] and [3], we have implemented our multi-channel underwater acoustic network simulator to assess the performance of MC-UWMAC. In our simulations, we consider a network of 49 nodes uniformly deployed over a square area of length $5Km$- supplied with constant bit rate traffic. The transmission range is 1 Km and the nominal speed of sound in water is $1500m/s$. Data and control packets are of size 200 and 20 bytes, respectively. Control slot duration is 2 s long. We employed the energy consumption model as used in [3], where the transmit power is 125 times the receive power. In addition, we assume that nodes have a buffer for each neighbor and perform a continuous monitoring of the target area where four sinks are placed at the corners. Each simulation runs for 3600s.

A straightforward study would impose to assess the performance of our proposal as function of p. The traffic rate of each node is set to 0.01 packet/s and p varies from 2 to 4. Recall that p is $\lceil \sqrt[2]{n} \rceil$ such that n is the maximum neighborhood size which denotes the number of small squares inside the big one of side R_C. Every small cell will be assigned a number q_u. Our proposal dictates that every sensor u located in a given small cell q_u will be allocated the quorum S_{q_u} and the slot number q_u of the control channel frame. Our ultimate objective is to provide every sensor in a given neighborhood with a unique slot number and a unique quorum number. Note however that if more than one node resides in the same small square they will be assigned the same slot which may cause collisions during the control packet handshaking and possibly during the data communication. A possible solution to deal with the aforementioned problem is to further reduce the size of small cell (by increasing p) such that we guarantee that only a unique sensor is located in every small cell and thus every sensor will have its own unique slot and hence collision free communication is absolutely assured.

Fig. 4 depicts the collision probability on the control channel as function of p. Observe that, as explained above, the collision is inversely proportional to p value. When p increases, less nodes will co-exist in the same small cell which reduces the collision due to simultaneous RTS transmissions. That is why, $p = 4$ scheme has the less experienced collisions. Moreover, increasing p increases N the number of available data channel. Recall that $N = \frac{n(n-1)}{2}$ where $n = p^2$. Consequently, further parallel non-collided data transmissions over the network is favored which improves the packet delivery ratio as shown in Fig. 5. However, when p increases, the end-to-end delay will increase (see Fig. 6) not only because the frame duration is increased but also because the increased number of available data channel decreases the width of each channel leading to an increased transmission delays in addition to the long propagation delay. In Fig.7, we represent the energy consumption per useful bit for each p value. **Notice that** the energy consumption increases with p. As mentioned before, increasing p will increase the number of data channel, and hence decreases the available data bandwidth. Owing to the bandwidth-energy relationship, reduced bandwidth will enlarge the transmission and reception delays and thus more energy is consumed. To recapitulate, the simulation results reveal that reducing p will reduce the end-to-end delay and the energy consumption due to the increased data channel bandwidth, but on the opposite hand, it reduces the packet delivery ratio due to the increased collisions. To guarantee a reasonable delivery ratio while reducing at the same time the end-to-end delay and the energy consumption, we can assert that 3 is the optimal p value of our protocol for the studied network model. Recall that p depends extremely on the specific properties of related network topology since p calculation relies on the maximum neighborhood size. That's why, p will be set to 3 in the next set of simulations in order to compare the performance of our protocol with MM-MAC protocol [3] since it motivates our study. MM-MAC uses the concept of cyclic quorum systems to solve the missing receiver problem and it operates with four channels (of capacity 1 kb/s each), six control slots (2s long each) and a data period of 8s long.

A. MC-UWMAC vs MM-MAC

We analyze the system performance of MC-UWMAC and MM-MAC while varying the traffic rate from 0.01 to 0.2 packets/s.

Fig. 8 shows that MC-UWMAC outperforms MM-MAC by achieving a packet delivery ratio above 90%, regardless the traffic rate. Note that, MC-UWMAC achieves a packet delivery improvement up to 20% over MM-MAC. The main reason behind it is that according to MC-UWMAC, nodes can transmit as much data as they have in their queue for a given neighbor for each successful handshaking at the control channel. While with MM-MAC, the limited data period imposes a maximum predefined number of data (4 data packets) to be sent during

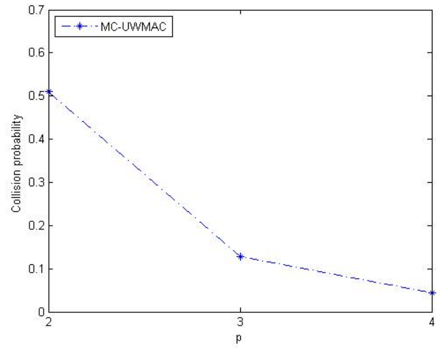

Fig. 4. Collision probability.

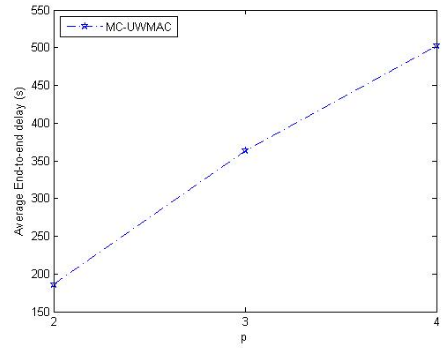

Fig. 6. End-to-end Delay

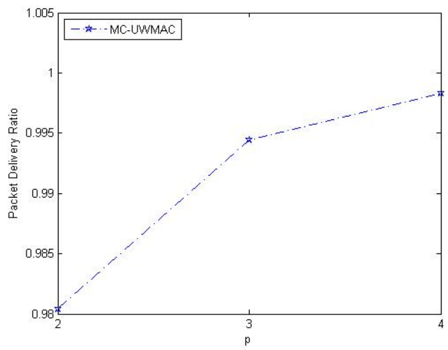

Fig. 5. Packet Delivery Ratio

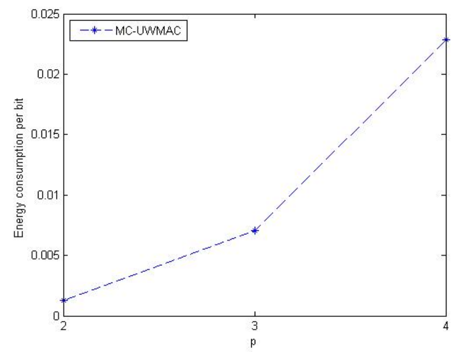

Fig. 7. Energy consumption per bit

each frame time. Note that, for both protocols, the packet delivery ratio decreases with the traffic rate because of the increased experienced collision. Indeed, MC-UWMAC achieves the highest delivery ratio since it experiences the smallest number of collisions as it is tailored to avoid collisions. Recall that thanks to our quorum and slot assignment procedures, we aim at providing to the most possible extent a collision free communication. 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 **did not** conceive any solution to deal with collision and hence repetitive collisions may happen. Nevertheless, as mentioned before, with MC-UWMAC, unlikely, co-existing nodes in the same small cube will probably cause simultaneous RTS transmissions. However, MC-UWMAC provides a back-off strategy to avoid repetitive collisions allowing nodes to defer their transmission attempts.

Experienced collisions have also a great effect on the end to end delay achieved by both protocols. As shown in Fig. 9, at lower rate, the end-to-end delay for both protocols increases with the traffic rate. Note that MC-UWMAC performs the lowest end to end delay as it is mainly experiencing the lowest number of collision. Moreover, since there is no separation between control and data period in MC-UWMAC, as soon as a pair of communicating nodes succeed their handshaking, they directly switch to the intended data channel. In other words, nodes did not have to wait till the expiration of the control period to start transmitting their data as in MM-MAC. Hence, not only simultaneous data communication can occur separately in different data channels but also the handshaking process in the common control channel naturally continue to take place at the same time. Contrariwise in MM-MAC, time is rigidly slotted into control and data periods of fixed size which imposes to postpone data transmission till the start of the data period, which is not only a time consuming task but also an energy wasting process as nodes continue transmitting and receiving a notification packet (to inform neighbors by the chosen data channel) for the rest of control period. At higher traffic rate, for MM-MAC, the increased collision will prevent data from reaching the sinks, only the sink-closest-nodes will be able to transmit directly their data, which reduces the end-to-end delay of successfully received packets. While for MC-UWMAC, facing collisions, nodes adopt a back-off strategy which delays packet transmission and increases the end-to-end delay. Finally, in Fig. 10, we represent the energy consumption per useful bit for both protocols. MC-UWMAC is the most energy efficient protocol as MC-UWMAC naturally mitigates the effect of collisions without requiring any extra packet exchange among nodes, as opposed to MM-MAC, where notification messages has to be continuously sent during

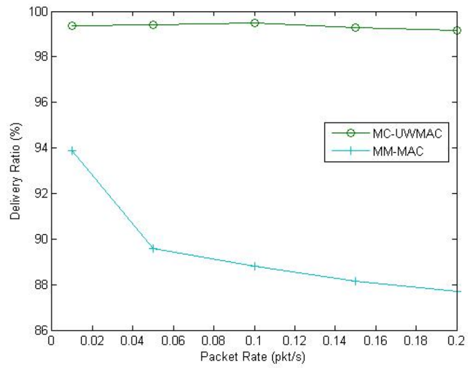

Fig. 8. Packet Delivery Ratio for MC-UWMAC vs MM-MAC.

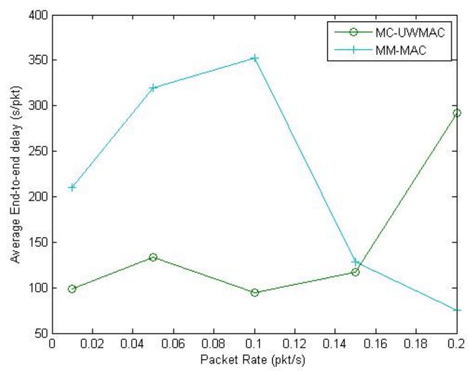

Fig. 9. End-to-End Delay for MC-UWMAC vs MM-MAC.

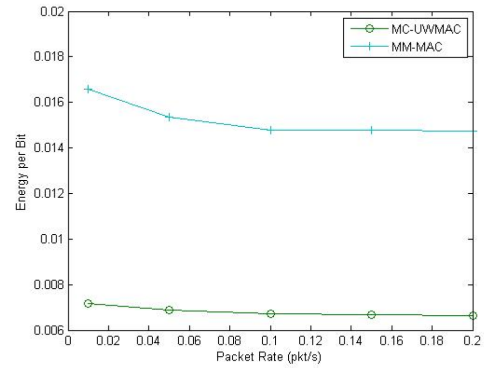

Fig. 10. Energy consumption per bit for MC-UWMAC vs MM-MAC.

the control period in order to avoid collision which is an energy consuming procedure.

V. Conclusion

In this paper, we proposed a novel multi-channel MAC protocol, MC-UWMAC, especially designed for the underwater environment. MC-UWMAC operates on a slotted single control channel for control packets handshaking and multiple data channels. To provide a collision free communication, MC-UWMAC employs two key connected procedures:i) a grid based slot assignment which accommodates the network specificities and does not require any extra packet exchange among nodes; and ii) a new designed quorum based channel allocation which guarantees a unique and different data channel for each two communicating neighbors. According to MC-UWMAC, handshaking and data communication can take place simultaneously at separate channels which eliminates completely collisions of control and data packets and reduces delays. Simulation results show that MC-UWMAC operates perfectly at light traffic as well as at heavy traffic. Moreover, MC-UWMAC achieves a significant performance improvement compared with MM-MAC [3].

References

[1] I. F. Akyildiz, D. Pompili, and T. Melodia, “Underwater Acoustic Sensor Networks: Research Challenges”, Ad Hoc Networks (Elsevier), vol. 3, no. 3, pp. 257-279, 2005.

[2] J.M. Jornet, “AUVNetSim: A simulator for underwater acoustic networks ”, Massachusetts Inst. Technol., Cambridge, MA, MIT Sea Grant Tech. Rep., 2008 [Online]. Available: http://seagrant.mit.edu/media/publications/MITSG-08-4.pdf.

[3] C.-M. Chao and Y.-Z. Wang, “Multiple Rendezvous Multichannel MAC Protocol Design for Underwater Sensor Networks ”, IEEE Transactions on Systems, Man, and Cybernetics: Systems, 43(1):128138, 2013.

[4] J. So and N. Vaidya, “Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using a Single Transceiver,” Proc. ACM MobiHoc, pp. 222-233, May 2004.

[5] M. Molins and M. Stojanovic, “Slotted FAMA: A MAC Protocol for Underwater Acoustic Networks,” Proc. OCEANS Conf.Asia Pacific, pp. 1-7, May 2006.

[6] A. Syed, W. Ye, and J. Heidemann, “T-Lohi: A New Class of MAC Protocol for Underwater Acoustic Sensor Networks,” Proc. IEEE INFOCOM, 2008.

[7] “AquaNetwork: Underwater Wireless Modem with Networking Capability,” http://bwww.dspcomm.com/products_aquanetwork.html, 2011.

[8] C.-M. Chao, Y.-Z. Wang, and M.-W. Lu, “Multiple-Rendezvous Multichannel MAC Protocol Design for Underwater Sensor Networks,”IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems, Vol. 43, No. 1, Jan. 2013, pp.128-138.

[9] Y.-J. Chen and H.-L. Wang. “Ordered CSMA: A Collision-Free MAC Protocol for Underwater Acoustic Networks”. In IEEE Oceans, pages 1–6, Sep. 2007.

[10] L. Hong, F. Hong, Z. Guo, and X. Yang. “A TDMA-Based MAC Protocol in Underwater Sensor Networks”. In IEEE WiCOM, Oct. 2008.

[11] A. Syed, W. Ye, J. Heidemann, and B. Krishnamachari. “Understanding Spatio-Temporal Uncertainty in Medium Access with ALOHA Protocols”. In ACM WUWNet, pages 535–547, Sep. 2007.

[12] W.-S. Luk and T.-T. Wong. “Two New Quorum Based Algorithms for Distributed Mutual Exclusion”. In IEEE ICDCS, pages 100–106, May 1997.

[13] C.-M. Chao and Y.-W. Lee. “A Quorum-Based Energy Saving MAC Protocol Design for Wireless Sensor Networks”. IEEE Transactions on Vehicular Technology, 59(2):813–822, Feb. 2010.

[14] J.-R. Jiang, Y.-C. Tseng, C.-S. Hsu, and T. H. Lai. “Quorum-Based Asynchronous Power-Saving Protocols for IEEE 802.11 Ad Hoc Networks”. In ACM MONET, pages 169–181, Mar. 2005.