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An Effective Collision Avoidance Protocol for Underwater Sensor Networks

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Abstract—In traditional terrestrial radio transmissions, the challenges of transmissions in underwater sensor networks (UWSNs) include lower transmission rate, longer delay time, and higher power consumption. In such a circumstance, the negative effects of transmission collisions deteriorate. Most of the existing UWSN medium access control (MAC) protocols handle the collision problem in a single-hop or light-loaded environment. They fail to function effectively in a multihop network consisting of more sensor nodes with heavier traffic loads. Using the concept of cyclic quorum systems, we propose a distributed multiple-rendezvous multichannel MAC protocol, MM-MAC, in this paper to reduce collision probability. The advantages of the proposed protocol are threefold: 1) Only one modem is needed for each node to solve the missing receiver problem which is often encountered in multichannel protocols; 2) multiple sensor node pairs can complete their channel negotiations on different channels simultaneously; and 3) data packets will not be collided by control packets and vice versa.

Index Terms—Multichannel MAC protocols, quorum systems, underwater sensor networks (UWSNs).

I. INTRODUCTION

Underwater sensor networks(UWSNs) enable a wide range of applications, including environment monitoring, tactical surveillance, disaster warning and many more. A UWSN consists of two nodes: sensor nodes and sink nodes. Sensor nodes collect sensory sensory data and send them back to sink nodes which provide interfaces to users. Since radio does not work well in underwater environments. The challenges of acoustic transmission include the following.

1)Long propagation delay: The propagation speed for an acoustic link is 1500m/s,2×10^5 times lower than the speed of a radio link. This means that the propagation delay is 2×10^5 times longer for an acoustic link

2)Expensive transmitting power consumption: Power consumption for transmitting and receiving is similar in radio links. However, in acoustic links, transmit power dominates and is typically 100 times more than the receive power

3)Lower available bandwidth: Influenced by harsh environment such as transmission loss, noise,a nd high propagation delay,the available bandwidth is limited and depends on both range and frequency.Table I shows typical relationship between bandwidths of the underwater channel and transmission ranges

TABLE I
RELATIONSHIP BETWEEN BANDWIDTH AND TRANMISSION RANGE IN UWSN CHANNELS

Range (km)	Bandwidth (kHz)
> 1000	< 1
$10 \sim 100$	$2 \sim 5$
$1 \sim 10$	10
$0.1 \sim 1$	$20 \sim 50$
< 0.1	> 100

Existing radio-based single-transceiver multichannel MAC protocols do not work properly in underwater environments due to the acoustic transmission features. To design a multichannel MAC protocol, general multichannel issues such as "when and which node can use which channel" must be addressed. Traditionally, channel assignment is done through control message exchanges. Such negotiation based mechanisms are not optimal in UWSN because of long propagation delay. They also suffer from extensive power consumption and significant signaling overhead. A detailed review of existing multichannel MAC protocols can be found in Section II. In UWSN, these channel assignment and transmission scheduling problems should be solved in an energy-efficient way. In addition, to overcome the challenges of acoustic transmissions, an underwater multichannel MAC protocol also has to avoid the missing receiver problem which occurs when a sender fails to access its intended receiver because they do not reside on the same channel. To handle these issues, we adopt the concept of cyclic quorum systems in a clever way such that the MM-MAC has several attractive features. First, equipped with one modem, each sender is guaranteed to meet its receiver through utilizing the concept of cyclic quorum systems. That is, the missing receiver problem is solved. Second, multiple node pairs can complete their channel negotiations on different channels simultaneously. This avoids producing a bottleneck on any channel. Third, credited to the separation of control and data packet transmissions, control and data packets will not collide with each other. Simulation results verify that the proposed MM-MAC significantly improves network throughput and efficiency.

II. RELATED WORK

Existing underwater MAC protocols can be classified as centralized and distributed. In centralized MAC protocols [1], [2], [3], there is generally a special node that is responsible for scheduling the transmission of the whole network. In or- dered carrier sense multiple access [9], the coordinator finds the optimal transmission sequence among nodes according to their locations. The coordinator informs all the nodes about this transmission schedule such that each node knows when to transmit. A time division multiple access (TDMA)-based scheme was proposed in [2] where the sink node is required to know the distances to all its neighbors. The sink node schedules the transmission sequence and notifies all the nodes through a super frame. The efficiency reservation MAC protocol [3] groups nodes according to their directions to the sink. Nodes belonging to the same group can transmit their packets in a pipelined and collision-free way. All the protocols mentioned earlier operate in a single-hop environment. They fail to apply to general multihop underwater applications.

In distributed MAC protocols, all nodes are equal and con- tend to access the channel. A low energy consumption MAC protocol, T-Lohi, is proposed in [4]. Nodes running T-Lohi contend to send a short tone to reserve the channel in the reservation period. If only one node sends a tone, the data period begins, and the node can transmit its data. Otherwise, reservation period is extended, and contending nodes back off and try again later. Contending nodes also perform contender counting to set their contention window sizes. To save energy, the receiver circuit is powered off by default. It is activated when a tone is detected by the low-power wake-up receiver. A wake-up tone is also transmitted at the beginning of any data to ensure that the receiver is ready for later data transmission. T-Lohi also works in a single-hop network.

In slotted ALOHA [7], time is divided into slots of the same size. Packets can be sent only at the beginning of each slot. The authors show that the collision probability is proportional to the packet transmission time. They also show that the collision probability is minimized, at the expense of longer delay, when the size of a slot equals to the maximum propagation delay of the network. Slotted FAMA [5] is an improvement of FAMA [6]. In the original FAMA, the lengths of request to send (RTS) and clear to send (CTS) packets should be greater than the maximum propagation delay to avoid packet collision. This produces severe power consumption burden in UWSN. To overcome this, a similar technique to slotted ALOHA is adopted: Time is also divided into equal slots, and packets can be sent at the beginning of each slot. A slot is set to the duration of transmitting a data packet plus the maximum network propagation delay. The difference between these two protocols is that four-way handshaking RTS/CTS/DATA/ACK is utilized in slotted FAMA while only DATA/ACK is applied in slotted ALOHA. The downside of slotted FAMA is that, in a multihop environment, the RTS/CTS packets may collide with data packets. That is, two nodes that successfully exchange RTS and CTS packets are not guaranteed to have a collision free data transfer.

According to whether multiple transmission pairs can accomplish handshaking simultaneously or not, Multichannel MAC protocols in terrestrial wireless networks can be classified into two categories: single rendezvous and multiple rendezvous. In the single-rendezvous class, asynchronous Multichannel coordination protocol (AMCP) [8] uses one control channel and n data channels. Each node locally maintains an n-entry channel table to keep track of the usage of data channels. Channel negotiation between a transmission pair is achieved through the control channel. After a successful negotiation, both nodes switch to the scheduled channel, for example, channel x, for data transmission. When data transmission is finished, both nodes will switch back to the control channel and set all data channels except x to be unavailable for a certain period of time. Such settings can avoid the multichannel hidden terminal problem. Similar to AMCP, load-balance based MAC (LBM) [9] utilizes one control channel and n data channels. LBM aims to balance load sharing among channels during the channel allocation. Nodes running LBM will use the channel that is available and has the lowest utilization ratio for data transmission. In multi-channel MAC (MMAC) [8], all nodes initially listen on the default channel during the announcement traffic indication message (ATIM) window. At this window, channel negotiation between a transmission pair is achieved through ATIM/ATIM-ACK/ATIM-RES packets. At the end of each ATIM window, nodes that have successfully completed channel negotiation switch to the negotiated channel to fulfill their data transmission. Although there is no dedicated control channel in MMAC, the ATIM window can be considered as a common control period which still produces a bottle neck. An unsatisfactory feature of these single-rendezvous solutions is that the control channel/period becomes a bottleneck which limits the overall network utilization.

The quorum-based channel hopping (QCH) system [10] uti- lizes the quorum concept to overcome the problem that a cognitive radio network is unable to maintain a common control channel. Two kinds of QCH systems are proposed. In syn- chronous QCH systems, time is divided into a series of frames, and *m* channels are selected as rendezvous channels. For each *m* consecutive frames, one distinct rendezvous channel is as- signed to each frame.

A frame consists of *k* slots, and each user chooses a quorum under Z_k. Users tune their transceivers to the rendezvous channel associated with the frame during the quorum slots and switch to a random channel during the other slots. Through the intersection property of quorum systems, a user is guaranteed to inhabit to the same channel with any other user in any frame. A problem of this mechanism is its inefficiency. In each frame, users are guaranteed to commu- nicate only in the associated rendezvous channel. The other channels are underused. In asynchronous QCH systems, users select two cyclic quorum systems to construct their channel hopping sequences: Users are fixed on one channel for each of the two quorum systems. Two nodes are also guaranteed to hop to the same channel at some time slot. However, the flexibility of the asynchronous QCH is limited in that at most two channels can be used.

In the multiple-rendezvous class, the protocol proposed in [11] divides each node's *k* transceivers into *fixed interface* and *switchable interfaces*. Each node has one fixed interface and is switched to a fixed channel, waiting for data from the other nodes. The other $k - 1$ transceivers are switchable interfaces. A data transmission from node A to node B is enabled by tuning one of node A's switchable interfaces to node B's fixed channel. The primary channel assignment based MAC (PCAM) protocol [12] adopts a similar mechanism. In PCAM, each node is equipped with three transceivers. The *primary transceiver* stays tuned on a fixed channel. Two nodes communicate with each other using the primary transceiver if their fixed channel is the same. Otherwise, the sender's *secondary transceiver* is switched to the receiver's fixed channel. The third transceiver is used for broadcasting control information. The division of fixed (primary) and switchable (secondary) transceivers makes these protocols multiple-rendezvous ones. However, equipping each node with multiple transceivers is undesirable because of increased hardware cost. In Y-MAC [13], a TDMA-based protocol, time is divided into a series of frames. Each frame consists of a broadcast period and a unicast period while each period has multiple time slots. Broadcast messages are exchanged in broadcast periods using the well-known base channel. During a unicast period, each node wakes up on the base channel at its own receive time slot. If a node, for example, node A, receives a message during its time slot on the base channel, it hops to the next channel for the next time slot. The next channel is determined by a channel hopping sequence generation algorithm. Nodes that have a message to node A hop to the same channel and compete again. The others remain on the base channel. If node A receives messages continuously, it hops to another channel every time slot. Y-MAC achieves partial multiple rendezvous in that a continuous receiving node uses channels other than the base channel (except for the first receiving). The channel hopping sequence generation algorithm is required to guarantee that no two-hop neighbors hop to the same channel. However, the detail of the algorithm is left unspecified. The scalability may also be a problem for Y-MAC since two-hop neighborhood must be considered for the time slot allocation.

III. PROPOSED MULTICHANNEL MAC PROTOCOL

The proposed MM-MAC is designed for a heavily loaded underwater sensor networks where contention is severe.It utilizes the concept of cyclic quorum systems to achieve channel allocation and to solve the missing receiver problem

A.MM-MAC Protocol

The MM-MAC protocol aims to use a single modem to emu- late multiple-transceiver multiple-rendezvous solutions such as those in [17] and [22]. The assumptions that we made in the paper are listed as follows.

1) Totally, *m* equal-bandwidth channels are available.

2) Each node is equipped with one half-duplex modem which is able to switch to any channel dynamically.

3) Nodes are time synchronized. There exist some UWSN clock synchronization schemes [14]. In MU-Sync [14], both large and time-varying propagation delays are considered.

4) Each node knows the identifications (IDs) of its one-hop neighbors. This information can be collected during the network initialization phase.

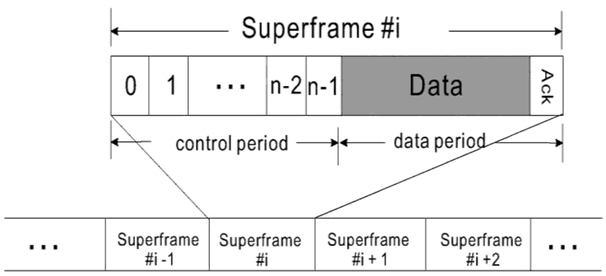


Fig. 1. MM-MAC frame structure.

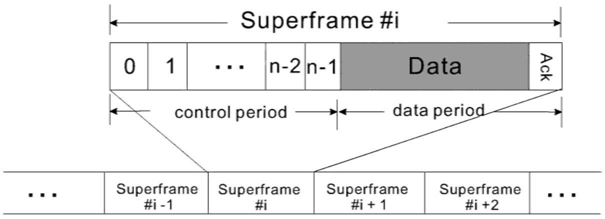
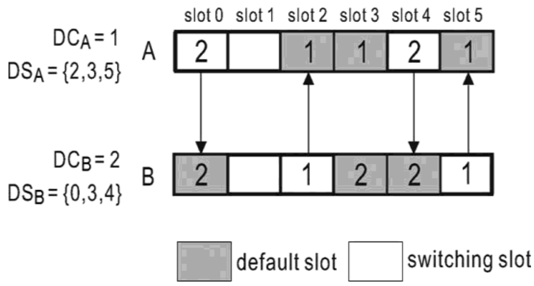


Fig. 2. Example of MM-MAC channel and slot allocation.



To enable a communication, a transmission pair must switch to the same channel at the same time. That is, the most im- portant job is the joint allocation of channel and time for all the nodes in the network. In MM-MAC, time is divided into a series of superframes. Each superframe is further divided into control and data periods, as shown in Fig. 4. The control period consists of n slots, numbered from 0 to $n-1$. The value n is decided by the integer set from which the adopted difference set is derived. For example,if a difference set under Z_6 is adopted,the value of n is six. Each slot in the control period contains two minislots. Control packets can be sent at the beginning of each minislot. The length of a minislot is equal to the control packet transmission time plus the maximal one-hop propagation time. A control period is immediately followed by a data period which is dedicated to data transmission. To increase network utilization, the length of a data period is long enough to transmit several packets. At the end of each data period, there is a minislot reserved for transmitting an ACK packet. Note that the changes of physical properties of water, such as temperature, pressure, density, viscosity, and the chemistry of the medium contents, affect the acoustic transmission speed which produces varied propagation delays. To handle such a variety, a guard time can be included in the superframe length setting. This provides the correctness of MM-MAC at the expense of a little efficiency reduction.

For each control period, control slots are partitioned into *default slots* and *switching slots*. At default slots, a node stays on its *default channel*, waiting for transmission requests. At switching slots, a node may switch to its intended receiver's default channel to initiate a transmission. Each node selects its default channel from its node ID. To solve the missing receiver problem, besides node ID, we use a cyclic quorum G_i and Z_n along with the sequence number of the current superframe to identify a node's default slots.Specifically a node I's default channel(denoted as DC_i) and default slots at the current superframe (denoted as DS_i) are chosen as follows:

$$DC_i = node\_ID_i \pmod m$$

$$DS_i = G_j, j = (node\_ID_i + SF\_ID) \pmod n$$

where $node\_ID_i$ is the ID of node i and SF_ID is the sequence number of the current superframe. We include the sequence number of the current superframe in the default slot selection for the sake of fairness: Each node will eventually adopt all different quorums with equal probability.

The proposed channel and time slot allocation achieves multiple rendezvous in that multiple transmission pairs can concurrently complete handshaking at any control slot. An example of default channel and default slot allocation under Z_6 with four channels (numbered from 0 to 3) can be found in Fig. 5. Nodes A and B, with IDs 1 and 2, respectively, are within each other's transmission range. Assume that the sequence number of the current superframe is 1, and we choose the difference set {0, 1, 3} under Z_6 as G_0. The shaded time slots are default slots. The number in each slot is the channel that should be switched to. When node A has packets pending for node B, node A switches to node B's default channel (channel 2) at its switching slots. In this example, node A can send RTS to B at time slots 0 and 4. Similarly, if node B has packets to A, the transmission can be done in time slots 2 and 5 through channel 1.

It should be noted that two nodes selecting the same cyclic quorum have no overlapping of default and switching slots. Thus, they may never meet each other if their default channels are different. To solve this problem, one of the nodes, for example, the one with smaller ID, can temporarily change some of its default slots to switching slots. This method is simple but the missing receiver problem may bother, although the probability is low. It can also be solved by asking a common neighbor node that has a different cyclic quorum to relay their traffic, if we handle this problem in the network layer. In such a case, route discovery between the common node and the two nodes must be applied. This method involves cross-layer operation.

Nodes running MM-MAC allocate a separate buffer for each of their neighbors to keep packets pending for them. Each node also maintains a free channel list to keep track of available channels. During the control period, each node checks its buffers, and the node with the most pending packets will be selected as its destination.[4] To initiate this transmission, RTS and CTS packets are exchanged at an overlapping slot. Nodes that overhear an RTS or a CTS packet will update their free channel list. After a successful RTS/CTS negotiation, a notification packet (NTF) will be sent by both sender and receiver at each of the remaining control minislots to declare that the channel has been reserved. Receiving this NTF, other nodes will modify their own free channel lists and will not try to access the channel. Note that free channel list modification may enable a node to reselect its destination. If neither CTS nor NTF is correctly received, a sender will resend the RTS until the retry limit is reached.

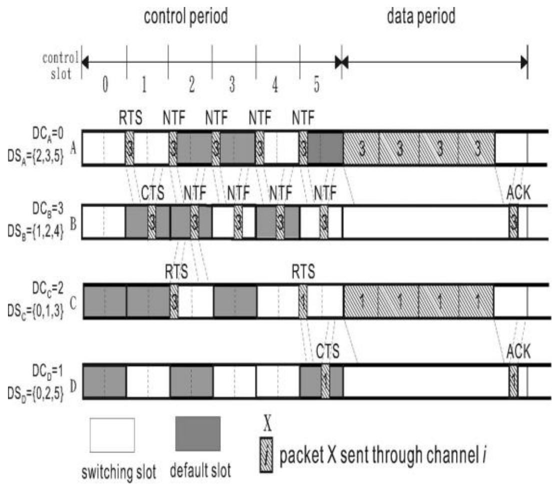


Fig.3. MM-MAC data transmission

Fig. 3 is an example of MM-MAC operation with four channels (numbered from 0 to 3) and six-slot control period. Assume that the sequence number of the current superframe is four and we choose the difference set {0, 1, 3} under Z_6 as G_0 . Four nodes A, B, C, and D, with IDs 4, 3, 2, and 1, respectively, form a linear topology (from left to right). It is a multihop environment in that nodes can only communicate with their adjacent nodes. Suppose that nodes A and C have pending packets for node B while node A succeeds to exchange RTS and CTS packets with B at slot 1. For the ensuing minislots, both A and B will broadcast NTF packets. Node C, trying to contact with B at slot 2 using channel 3, realizes that channel 3 has been reserved when an NTF instead of a CTS is received. Thus, node C changes its destination to the one that has the second most pending packets, node D in this example, and accomplishes handshaking at slot 5. At data period, both senders A and C send four data packets to their recipients B and D, respectively.

V. EXPERIMENTAL AND RESULT

MM-MAC reduces collision probability at the expense of a dedicated control period for transmission negotiation. Thus, when the network is lightly loaded, this control overhead may create a longer end-to-end delay, as shown in Fig. 4. However, as packet arrival rate enlarges, the reduced collisions compensate for the control overhead and enable MM-MAC to achieve the shortest end-to-end delays.

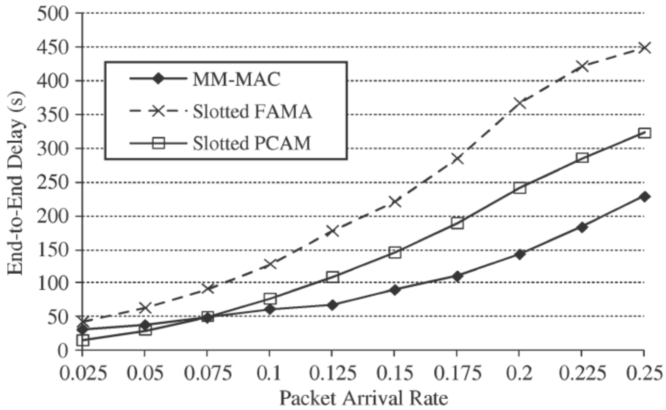


Fig. 4. Average delivery latency for the multiple-sink model.

VI CONCLUSION

Proposed approach relies on the MM-MAC protocol and cyclic quorum system. The cyclic quorum systems, nodes running multi channel MAC protocols are guaranteed to meet their intended receivers, which solves the missing receiver problem. The separation of control and data transmissions also helps reduce the collision probability of data packets. Energy saving protocol is implemented along with this process in which transmission range is adjusted based on the available energy and required coverage. Proposed scheme uses a multi channel MAC protocol for UWSNs it achieves a greater throughput and keeps the low retransmission overhead improvement over existing MAC protocols such as slotted PCAM.Performance evaluation is done based on the results of the simulation done using ns2.From the simulation results it is proven that the proposed multi channel MAC protocol exhibits with major metric throughput, delay, energy consumption and retransmission overhead has been improved compared to existing protocols.

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