Research on Cluster-based MAC Protocol for Underwater Acoustic Sensor Networks

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Abstract

Underwater acoustic sensor networks (UWASNs) are significantly different from packet radio networks.The long propagation delay and low bit rates make the existing MAC protocols designed for radio channels are not applicable in UWASNs. In this paper, a new MAC protocol, Cluster-based Underwater MAC (CUMAC) is proposed for UWASNs application. The goal of CUMAC is to improve channel utilization and energy efficiency in UWASNs. CUMAC protocol deploys several sensor nodes around a dynamically selected cluster head, where the data sensed by sensor nodes should be transmitted to. All transmissions are initiated by the cluster head and packets from multiple sensor nodes arrive in a packet train manner at the receiver without collisions. Simulation results show that CUMAC indeed offer higher channel utilization and improve energy efficiency comparing with other protocols. And more the preliminary sea trial experiments based on research prototype established by ourselves is proposed. The results have confirmed that CUMAC is feasible in actual underwater acoustic channels. The new proposed protocol also presents a reference for the MAC development for future UWASNs at the same time.

Keywords*:Underwater acoustic sensor networks,Media access control (MAC),Cluster*

1. Introduction

Recently,there has been a growing interest in underwater acoustic sensor networks(UWASNs).UWASNs can be applied to oceanographic data collection,pollution monitoring,offshore exploration,disaster prevention,assisted navigation and tactical surveillance[1]-[3].Due to the shared communication medium,an efficient medium access control (MAC) protocol is very important to the final performance of UWASNs.

The design of a MAC protocol is challenged by the distinguishing characteristics of an underwater acoustic channel.Underwater communication mainly uses acoustic channel with a low propagation speed of approximately 1500m/s,thus resulting in significantly long propagation delay.Another unique characteristic of underwater acoustic channel is its narrow available bandwidth,which leads to low data rate[4].

the two mentioned-above characteristics of the acoustic channel are the key factors that prevent the direct application of the terrestrial MAC protocols in UWASNs.So,various MAC protocols have been proposed for UWASNs.The first class is ALOHA-based protocols[5]-[7],of which pure ALOHA and slotted ALOHA have been studied.Pure ALOHA’s performance remains same as in RF,while the benefit of synchronization in slotted ALOHA is completely lost due to long propagation delay.Later are MACA-based protocols[4][8]-[12].In these protocols, a handshake is used prior to transmission of data packets,which prevents collisions betweeen two or more nodes transmitting at the same time,but the long propagation delay makes it very expensive to transmit multiple control packets before every data packet transmission.In addition to the two classes mentioned-above,T-Lohi is a new class of dirtributed and energy-efficient MAC protocol for UWASNs[13][14].T-Lohi emploies a novel tone-based contention resolution mechanism to detect collisions and uses low-power wake-up receiver to significantly reduce energy consumption.By comparing with our novel MAC protocol, the three classes mentioned-above will be simulated in this paper,namely,ALOHA,UMACA and TLOHI.

In this paper,we aim to design a MAC protocol with high channel utilization and energy efficiency for UWASNs.We propose a new cluster-based MAC protocol,called CUMAC.We assumed all sensor nodes (SNs) in UWASNs are divided into several clusters.All data sensed by SNs in a cluster will be transmitted to the cluster head (CH).The CHs are dynamically selected by the upper-layer protocols.The assumption is reasonable because more and more clustering algorithms have been found recently[15]-[18].We concentrate on the intra-cluster transmission in this paper,while inter-cluster transmission will be seen in our other work. All transmissions are initiated by the CH and packets from multiple SNs arrive in a packet train manner at the receiver without collisions.What's more,with the maturity of our underwater communication research prototype[19][20],a sea trial based on our research prototype has been done.

The rest of this paper is organized as follows.In section 2,we proposed briefly the CUMAC protocol.We then present in section 3 the scheduling algorithm used in CUMAC.Section 4 describes the simulations and sea trial results that were carried out to compare the performance with others.Finally,we give our conclusions in section 5.

2. CUMAC Protocol

In this section,we first introduce how to get propagation delay between SNs and CH in initialization phase.After that,we describe the handshake process in data transmission in details.Finally, we discuss the performance such as energy efficiency,network expansibility and traffic suitability in CUMAC.Table 1 shows the notations that will be used.

Table 1. Notations used for explaining the CUMAC protocol

Notation	Description
$\tau_{\max}$	The maximum propagation delay between SN and CH predefined
$\tau'_{\max}$	The actual maximum propagation delay between SN and CH, less than $\tau_{\max}$
τ'_i	Propagation delay between i# SN and CH
τ_i	Virtual propagation delay between i# SN and CH
τ_f	The maximum drift of propagation delay at one transmission round
t_{syn_tx}	The absolute time SYN is transmitted by CH in initialization phase
t_{syn_rx}	The absolute time SYN is received by SN in initialization phase
t_{pos_rx}	The absolute time POS is received by CH in initialization phase
t_{ack_tx}	The absolute time ACK is transmitted by CH in the phase of Confirm and Check for New
t_{ack_rx}	The absolute time ACK is received by new SN in the phase of Confirm and Check for New
τ_{pw}	Timeout at SN to respond CH with POS
τ_{tw}	Timeout at SN to respond CH with TSK
τ_{dw}	Timeout at SN to transmit DATA
τ_{sw}	Timeout at SN to respond CH with SYNACK
τ_G	Guard time to protect against random drifts resulted by location and clock
T_{pos}	Transmission time of POS packet
T_{tsk}	Transmission time of TSK packet
T_{data}	Transmission time of DATA packet
T_{synack}	Transmission time of SYNACK packet

2.1. Initializaton phase

In UWASNs,the reception of packet not only depends on the uncertainty of transmission time but also that of propagation delay.The latter will be eliminated after CH gets the propagation delay between each SN and itself in initialization phase.

The CH first broadcasts a control packet called SYN and specifies the transmitting time t_{syn_tx} in SYN.Upon receiving SYN,each SN specifies the arrival time t_{syn_rx} and waits for a certain period of time τ_{pw}(how to get the value of τ_{pw} can be seen in 3.1).As long as τ_{pw}

expires,each SN transmits an acknowledgement packet ,denoted as POS.Upon receiving POS,the CH specifies arrival time t_{pos_rx} .Then the propagation latency $\tau_i^{'}$ between the CH and i# SN can be calculated as the following equation.

$$\tau_i^{'} = (t_{pos\_rx} - t_{syn\_tx} - \tau_{pw})/2 \tag{1}$$

After calculating all actual propagation delay between SNs and CH in the cluster,the CH packets these message into a control packet called Pos_Table and broadcast it to all SNs.Then all SNs get the actual propagation delay between other SNs and the CH.The working process is illustrated in Fig.1.At the end of the phase ,the actual max propagation delay $\tau_{\max}^{'}$ is known to all nodes within the cluster.

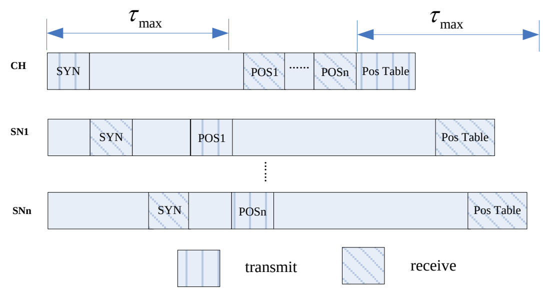


Fig. 1. The initialization phase to get propagation delay

2.2. Handshake process

Handshake initiated by CH is divided into the following three phases.

The first phase is Query.The CH broadcasts a QUE message firstly.Upon receiving the QUE,each SN backs off a certain period time of τ_{tw} (how to get the value of τ_{tw} can be seen in 3.2) according to the known value $\tau_{\max}^{'}$ and then sends a TSK message out,which includes some useful information such as the number and priority of packets to be sent.After receiving all TSKs transmitted by all SNs,the CH decides the number of packets to be sent for each SN and transmitting order,and then broadcasts these information packeted in Tsk_Table message.

The second phase is Data Transmission.In this phase,each SN has successful received Tsk_Table message and refers the arrival time as synchronization.After waiting for a certain period of τ_{dw} (how to get value of τ_{dw} can be seen in 3.3),each SN sends packets out .The number and order are decided by received Tsk_Table message.In this phase, packets from multiple SNs arrive in a packet train manner at the CH without collisions.

The final phase is Confirm and Check for New.Upon receiving all data packts,the CH checks out these packets and forms the check information into ACK message.Then the CH brodcasts an ACK message which not only checks out the data packets for current SNs but also informs newly comers.Upon receiving ACK message, the newly comers will transmit SYNACK message τ_{sw} later(how to get value of τ_{sw} can be seen in 3.3).The CH then enters into initialization phase to update all propagation delay.If no newly comer,the CH will sleep or initiate a new data transmission round.

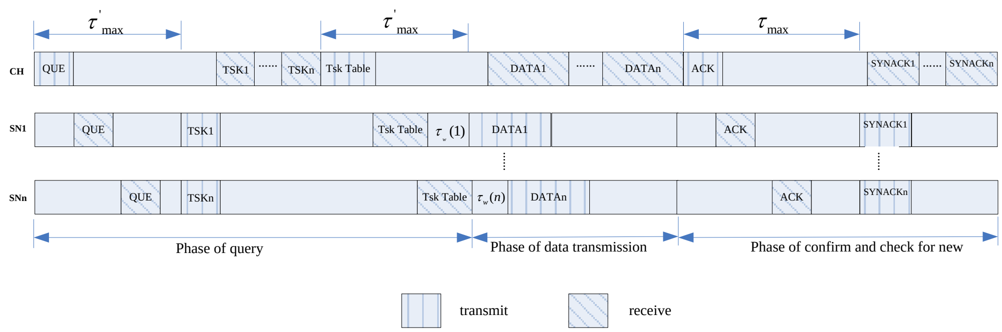


Fig.2. Handshake process in data transmission

2.3. Performance discussion

The methods of power control are convenient to be used for each SN based on the knowledge of the propagation delay.On the one hand,the nodes may adjust transmit power according to their propagation delay.On the other hand,the SN will regard CH's control packets as synchronization and enter sleeping state when they are idle.The two mentioned above will save power.

If there are newly comers in the cluster,identity validation will be used in the phase of Confirm and Check for New.If batteries run out,the CH will get the knowledge in time at current round and broadcast at the next round.If the SNs just fail for a short term,they will be treated as newly comers.The three circumstances mentioned-above will not disrupt the ongoing communication.So CUMAC possesses strong network expansibilty.

For traffic with burst or steady,important or minor,the SNs may indicate their demand in the phase of Query.The CH will respond these requests and schedule the order and number of packets for all SNs.So CUMAC also possesses traffic suitability.

Based on the analysis above,CUMAC owns good energy efficiency,network expansibility and traffic suitability.

3. Scheduling algorithm without collisions

In order to avoid collisions,on the one hand,each SN will defer its corresponding respondence for a certain period of time named $\tau_{pw}, \tau_{tw}, \tau_{dw}$ and τ_{sw} respectively in each phase.On the other hand, a guard time named τ_G also be provided to eliminiate collisions resulted by random drift.

3.1. Scheduling algorithm for POS

If there are multiple SNs with same propagation delay or the difference is small,POS message may be corrupted at the CH,which is illustrated in Fig.3.Because the propagation delay diffence $\Delta\tau$ between SN_m and SN_n is less than the length of POS T_{pos},POS message will corrupt at the CH.

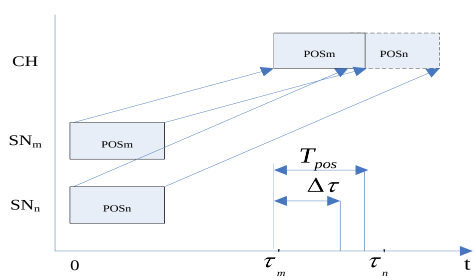


Figure 3. Collision in the phase of get propagation latency

In the phase,each SN has no knowledge of propagation delay between other SNs and the CH.The following schedule has been designed to eliminate POS's collisions based on the assumption that ID numbers owned by SNs are unique and the maximum propagation delay

$\tau_{\max}$ is predefined.

Suppose there are N SNs in the cluster.After sending SYN message out,the CH will reserve N slots for all SNs' respondence.The first slot is for 1# SN,the second slot is for 2# SN,and so on,which is illustrated in Fig.4.

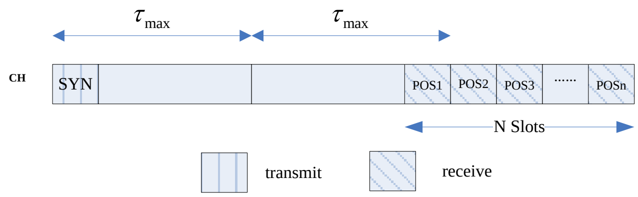


Figure 4. Collision avoidance in the phase of get propagation latency

After receiving the CH's SYN, SNs will send POS message out τ_{pw} later. The CH hopes to receive i# sensor node's POS at $2*\tau_{\max}+(i-1)T_{pos}$,i.e. the following equation should be satisfied.

$$2*\tau_{\max}+(i-1)T_{pos}=2*(t_{syn\_rx}-t_{syn\_tx})+\tau_{pw} \quad (2)$$

We can get the value of τ_{pw}.

$$\tau_{pw}=2*\tau_{\max}+(i-1)T_{pos}-2*(t_{syn\_rx}-t_{syn\_tx}) \quad (3)$$

Newly comer also will face similar problems in the phase of Confirm and Check for New.The collision avoidance strategy is as same as mentioned-above. After receiving the CH's ACK, j# SN will send SYNACK message out τ_{sw} later.The value of τ_{sw} can be get by the following equation.

$$\tau_{sw}=2*\tau_{\max}+(j-1)T_{synack}-2*(t_{ack\_rx}-t_{ack\_tx}) \quad (4)$$

3.2. Scheduling algorithm for TSK

When i# SN responds with TSK,it has get the knowledge of the propagation delay $\tau_i^{'}$ between the CH and itself and the actual max propagation delay $\tau^{'}_{\max}$ in the cluster. The value of τ_{tw} is decided by the difference of latency between adjacent SNs.Suppose the length of TSK is T_{tsk}.

a) If the diffenence of latency is greater than T_{tsk}, SN will send TSK message out τ_{tw} later after receiving QUE message.The value of τ_{tw} can be get through the following equation.

$$\tau_{tw}=\tau^{'}_{\max}-\tau_i^{'} \quad (5)$$

b) If the diffenence of latency is lower than T_{tsk}, The value of τ_{tw} can be get through the following equation.

$$\tau_{tw}=\tau_{i-1}^{'}-\tau_i^{'}+T_{tsk} \quad (6)$$

3.3. Scheduling algorithm for DATA

In the phase of Data Transmission,each SN will wait for a period of time τ_{dw} after receiving CH's Tsk_Table.In order to avoid collisions,waiting time τ_{dw} should contains the following two parts:

a.The first is $t_i^{(1)}$,which can be get by the following equation.

$$t_i^{(1)}=\tau^{'}_{\max}-\tau_i^{'} \quad (7)$$

b.The second is $t_i^{(2)}$,which can be get by the following equation.

$$t_i^{(2)} = t_{i-1}^{(2)} + n_{i-1} * T_{data} + \tau'_{i-1} - \tau'_i \tag{8}$$

where n_{i-1} is the packets number transmitted by the previous node, T_{data} is the length of DATA .We assum that (i-1)# node transmits packets followed by i# node.

So,the total waiting time τ_{dw} can be be get by following equation.

$$\tau_{dw} = \tau'_{\max} + t_{i-1}^{(2)} + n_{i-1} * T_{data} + \tau'_{i-1} - 2 * \tau'_i \tag{9}$$

3.4. Design of guard time

In UWASNs,the propagation delay will change randomly suffered by the location drift.Suppose the propagation speed of acoustic signal is 1500m/s,every 150 meters' drift will cause 100 million seconds' drift.On the other hand,as a result of local clock's random drift,transmit time at each SN isn't uniform.To resolve the two problems mentioned-above,there are the following strategies in CUMAC.

After getting the actual propagation delay τ'_i between all SNs and itself, the CH appoints a virtual propagation delay τ_i and then broadcasts it to all SNs in the cluster.Suppose the maximum drift of propagation delay at one transmission round is τ_f.As described in [3] and [21],node drifts at 1-3m/s and clock drifts at $1ppm$, τ_f is lower than 300 million seconds if one transmission round is 150 senconds.So τ_f is refered as 300 million seconds in CUMAC. An example is illustrated in Fig.5.

There are three SNs named SN1,SN2,and SN3 around the CH.The propagation delay between each SN and the CH are τ'_1, τ'_2 and τ'_3 respectively,which satifies $\tau'_1 \le \tau'_2 \le \tau'_3$. There are several concentric circles with certer at CH.The distance between adjacent solid and dashed circle is τ_f.The virtual propagation delay τ_i is designed by the following procedure.

a. let $\tau_1 = \tau'_1$;

b. when $i > 1$, $\tau_i = \begin{cases} \tau'_i & if\,(\tau'_i \ge \tau_{i-1} + \tau_d) \\ \tau_{i-1} + \tau_d & if\,(\tau'_i < \tau_{i-1} + \tau_d) \end{cases}$

Where $\tau_d = 2\tau_f$.Then we will get guard time

$$\tau_G = 2(\tau_i - \tau'_i)\,. \tag{10}$$

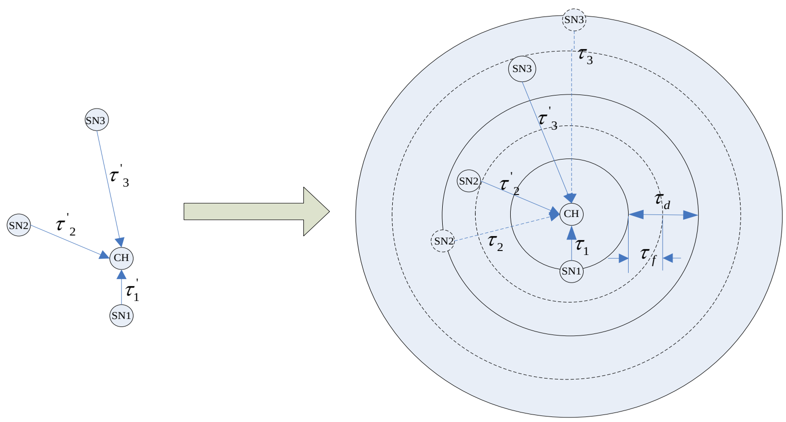
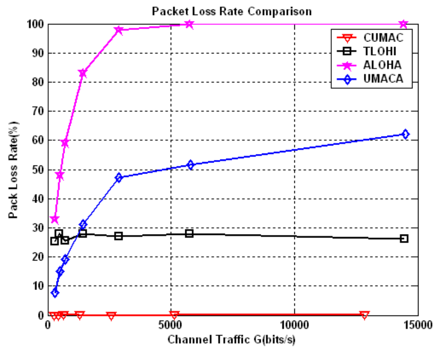


Figure 5. Virtual propagation delay between SNs and CH

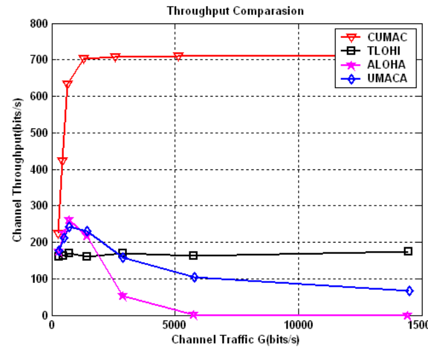
4. Simulation and experiment

4.1. Simulation analysis

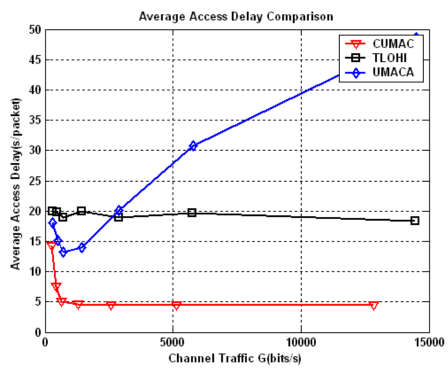
We implement CUMAC algorithms using OPNET. In our simulation, there are eight SNs around the CH. our four SNs are 1 km away from CH and the other four are 2 km away. The propagation speed of acoustic signal is 1500m/s.The rate of data transmission is 1000bits/s.The data packet length is 3200 bits and the maximum control packet length is 480 bits. The transmission power is 30 Watts, the receive power is 2Watts and the idle power is 100mW. The performance of CUMAC is compared with ALOHA, UMACA and TLOHI in throughput, packet lost rate, energy efficiency and access delay, which is shown in Fig.6.



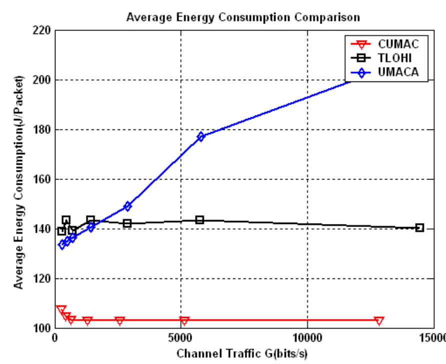
a. Packet loss rate



b. Throughput



c.Average acess time



d.Average energy consumed

Fig.3. Performance comparision

Seen from Fig.6 (a), the packet loss rate of ALOHA is higher than 30% even when the traffic is very low. And because of the serious collisions caused by ALOHA, the packet loss rate reached to 100% when the channel traffic exceed to 5000bits/s. Though the packet loss rate and throughput of UMACA is prior to ALOHA for the using of RTS/CTS handshake mechanism, the throughput is still in a low level compared with the other two algorithms(seen from Fig.6(a),(b)). The main reason is the hidden terminal problem resulted by the long propagation delay, which increases the collision possibility. And we also can see from Fig.6 (d) the average consumed energy is higher than the other two for the energy consumption in transiting control packets and unsuccessful data packets. From Fig.6, the performance of TLOHI is the most stable in the four algorithms whether the channel traffic is high or low, but the throughput is its bottleneck.

In CUMAC,the handshkes in several phases eliminate the uncertainty of location and transmit time scheduled by the CH so as to guarantee transmission orderly. All kinds of performance beacome stable when the tracffic load is saturated. What is more, the results of simulator close to the ideal performance.For example, the saturated throughput reaches to 700bits/s while the ideal one is 1000bits/s,the average access delay is 4.5 seconds while the ideal one is 4.2 seconds,the average consumed energy every data packet is 103 J while the ideal one is 96 J.

4.2. Sea trial results

Based on underwater acoustic communication research prototype established by ourselves, we present some sea trial results at Xiamen shallow port. In our sea trial experiment, three nodes are deployed. There are two SNs, one CH. 1# SN is 1100 meters away from 2# SN, 2# SN is 820 meters away from CH and 1# SN is 226 meters away from CH. The depth of water is 6 meters.The detail location map is shown in Fig.7, which is crawled from google map.

Figure 7. the envirement for sea trial

In physical layer,modulation scheme is OFDM and the effective transmission rate is 533bits/s.In data link layer, The data packet length is 1600 bits and the control packet length is 80 bits.The performance statistics of ALOHA, UMACA, TLOHI and CUMAC are illustrated in Table 2.

Table 2. Statistics for sea trial resuls

Protocol	**Transmission Number**	**Sucessful Receive Number**	**Sucessful Receive Rate(%)**	**Throughput (bits/s)**	**Access Time (seconds/packet)**
ALOHA	97	24	25	64	25
UMACA	62	57	92	152	10
TLOHI	38	36	95	96	17
CUMAC	56	56	100	150	10

From table.2, we find that the performance of ALOHA is the worst of four protocols. Its successful receive rate and throughput are lower than others. And the access time is more than others. The throughput of UMACA, CUMAC is almost the same, there are two main reasons. First, the number of packet train is random and the max is 10, i.e. 5 packets in each sensor node. The effect that improving the throughput by using packet train is less obvious. Second, the SNs are so sparse that the collisions could be easily avoided. Despite this, comparing the successful receive rate, throughput and accuss time of UMACA, TLOHI, CUMAC, we can make a conclusion that the comprehensive performance of CUMAC is the best. Specially, its successful receive rate reaches 100%. And this result is consistent with the simulation result.

5. Conclusion

We proposed a protocol called CUMAC to improve the performance of UWASNs.In CUMAC four strategies are implied to resolve the problem resulted by underwater acoustic envirment.The first is to get the knowledge of propagation delay between each SN and the CH prior to data transmission.The sencond is to initiate handshake by the CH.The third is to well-design each SN’s transmitting time. The final is to coordinate packets from multiple SNs to arrive in a packet train manner at the CH.Our simulation results illustrate that CUMAC possesses better performance in energy effeciency, network expansibility,traffic suitability and other traditional performace compared with other MAC protocols. What’s more,preliminary sea trial results match simulation results well. CUMAC could be a good reference for the MAC design in actual UWASNs.

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