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Slotted Aloha-FAMA: An Aloha and FAMA-Based MAC Protocol for Underwater Acoustic Networks

Dao Van Phuong
Ho Chi Minh City Industry and Trade College, Ministry of Industry and Trade, Viet Nam.

***Abstract* – Low bandwidth, long propagation delay, and high transmission power consumption of underwater acoustic networks (UANs) make these systems fundamentally different from the terrestrial radio networks. As a consequence, the MAC protocols of terrestrial radio networks cannot be applied directly in underwater acoustic networks. It necessitates a dedicated design of MAC protocols for underwater acoustic networks. In this paper, we propose a slotted Aloha and FAMA-based MAC protocol for underwater acoustic networks. In this protocol, the packets are exchanged between the source node and the intended destination node at the beginning of each time slotting to avoid collision. We use slotted Aloha protocol for single data packets, and the exchanged packets for this case are Data/ACK. For the train of data packets, we use a modification of slotted FAMA protocol (called slotted M-FAMA), and the exchanged packets for this case are RTS_Data/CTS/Data…Data/ACK. The combination of these two protocols is called slotted Aloha-FAMA (S-Aloha-FAMA). This protocol uses time synchronization and time slotting. Simulation results show that the S-Aloha-FAMA is able to achieve high and stable throughput performance, increase channel utilization while maintaining low collision rate.**

***Keywords* – Underwater Acoustic Communication Network, MAC Protocol, Slotted Aloha Protocol, Slotted FAMA Protocol.**

I. Introduction

The need for underwater communication network exists in applications such as pollution monitoring in environment systems, remote control in off-shore oil industry, collection of scientific data recorded at ocean-bottom stations, etc [1]. Underwater communication networks can be established by using acoustic waves[2]. In recent years, the research of the underwater acoustic networks (UANs) has been a hot topic. Generally, underwater acoustic channel poses challenges such as long latency and limited bandwidth to the MAC protocol design. Acoustic waves travel in underwater environment is very low (about 1500 m/s), which is five orders of magnitude slower than radio waves, this leads to high propagation delay that reduces the throughput of UANs [3]-[5]. The first task of MAC protocol for UANs is to prevent simultaneous transmissions that lead to packet collisions, and the second task of MAC protocol is to utilize the narrow bandwidth that improves the throughput of UANs. Selection of a suitable MAC protocol has a great impact on the system efficiency, and is especially important for underwater acoustic channels. Due to the long propagation delay of acoustic waves in underwater environment, current terrestrial MAC protocols are not suitable for UANs. For UANs MAC protocol, it necessitates a dedicated design of MAC protocols.

Many MAC protocols have been proposed for UANs. In [6], Xie and Gibson propose a centralized control approach. This protocol requires a master node to configure the data scheduling, and transmit the control messages to its slaves. In [7], Molins and Stojanovic propose slotted FAMA; the protocol requires precise time synchronization and RTS, CTS control packets, which leads to low throughput. When a node has a single packet to send, using S-FAMA with RTS, CTS control packets is very ineffective. Guo *et al*. introduces in [8] the propagation-delay-tolerant collision avoidance protocol (PCAP), which is a handshaking-based protocol. This protocol requires clock synchronization between neighboring nodes. It also requires RTS and CTS control frames, which leads to low throughput. In [9], Nitthita, *et al*. introduce two Aloha-based protocols, namely, Aloha with collision avoidance (Aloha-CA) and (Aloha-AN) Aloha with advance notification. These two protocols use the information obtained from overheard frames to calculate the busy time of neighboring nodes and avoid collisions. Nitthita, *et al*. propose another MAC protocol named multiple access collision avoidance with packet train for multiple neighbors (MACA-MN) in [10]. Chen *et al*. propose in [11] a Two Level Power Control (TLPC) MAC protocol to prevent Control/Data Collision (CDC) and problem and Underwater Large Interference Range Collision (ULIRC) problems. TLPC adapts the transmission power to resist interference and avoid collisions. In [12], Azar *et al*. introduce a MAC protocol that is based on reserved time slot. A time slot is allocated to each node for sending data in a way that the data does not collide with another node's data. A synchronization algorithm is employed to synchronize all nodes in a distributed manner. The listen/sleep periodic operation is used for saving energy due to long propagation delay and limited energy. In [13], Liao *et al*. propose a spatially fair multiple access control (SF-MAC) protocol called SF-MAC in UANs. This MAC protocol avoids collision by postponing the clear-to-send frame equal to period of request-to-send (RTS) contention period. The receiver collects RTSs from all the contenders during the RTS contention period and calculates the potential sending time of each of contender. It determines the earliest transmitter with a probability rule that compares with the first RTS. Yang *et al*. propose a novel handshaking-based MAC protocol, called as sender and receiver concurrent reservation (SRCR) protocol, for multi-hop UANs. The protocol adopts a concurrent reservation mechanism to allow the sender's neighbors and the receiver's neighbors to transmit packets during the communication between the

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sender and the receiver in [14]. In [15], the authors introduce a novel approach based on concurrent, bidirectional data packet exchange to improve the data transmission efficiency. The authors propose an asynchronous handshaking-based MAC protocol which is called bidirectional-concurrent MAC with packet bursting (BiC–MAC).

The MAC protocols above have focused on reducing or eliminating packet collisions, it is not a general communication case that focuses on the individual communication cases. While the original MAC is not designed for underwater acoustic networks where long propagation delays are prevalent, it does not yield for long propagation delay in underwater environment. The original Aloha-based MAC protocol is simple and inefficient because it doesn't use any intelligent method to reduce packet collisions[2]. For the slotted Aloha protocol[9], when a node has a train of data packets to send, the waiting time for each ACK packet to response each data packet is very ineffective. For the slotted FAMA protocol, when a node has single data packets to send, each one of these single data packets need three control packets (RTS, CTS, ACK) [7]. In this case, using slotted FAMA is very ineffective. Therefore, there is a need to modify the original slotted FAMA and Aloha protocols to improve throughput performance, increase channel utilization while maintaining low collision rate. In this work, we propose a combination of slotted Aloha and a modification of slotted FAMA protocols for underwater acoustic networks. In our protocol, the packets are exchanged between the source node and the intended destination node at the beginning of each time slot to avoid collisions. We use slotted Aloha protocol for the cases of single data packet, and the exchanged packets for this case are Data/ACK. We modify the slotted FAMA protocol for the cases of data packets train (called slotted M-FAMA),and the exchanged packets are RTS_Data/CTS/Data…Data/ACK. The description of slotted M-FAMA protocol in detail will be discussed later.

The rest of this paper is organized as follows. Section II describes the S-Aloha-FAMA protocol that we propose for UANs. We present the simulations and carry out to compare the performance of the proposed scheme with slotted FAMA and slotted Aloha in Section III. Finally, we give our conclusions in Section IV.

II. Slotted Aloha-FAMA Protocol Design

As we discussed, using the original slotted FAMA and Aloha protocols in underwater acoustic networks would not be efficient due to the requirement of the RTS, CTS, ACK packets for single data packets, and the waiting time for each ACK packet to response each single data packet. To overcome this problem, we use a combination of slotted Aloha and slotted M-FAMAMAC protocols (called S-Aloha-FAMA). In this protocol, the time is slotted and each packet (RTS_Data, CTS, Data, ACK) has to be transmitted at the beginning of one slot. The slot length is calculated to ensure absence of data packet collisions, which will be discussed later. When a node has a single packet to deliver, it uses slotted Aloha MAC protocol to transmit its packet. When a node has a train of data packets to deliver (the number of data packets ≥ 2), it uses slotted M-FAMA MAC protocol to transmit. Figure 3 shows a transmission of single data packet and data packets train. For slotted Aloha protocol, we use the original slotted Aloha protocol[2].

A. *The Slotted Aloha Protocol* [16].

When a node has one data packet to deliver, the node waits until the beginning of next slot and transmits its data packet. This data packet is received by the destination node and all the other nodes in the range of the source node within the slot time. The destination node then responds an ACK packet at the beginning of the next slot. This ACK packet is also received within the slot time by the source node and all the other nodes in neighborhood of the destination node. If the source node does not receive an ACK packet within this slot time, it will retransmit its data packet at the beginning of next slot. A successful single data packet transmission of slotted Aloha protocol is illustrated in Figure 1

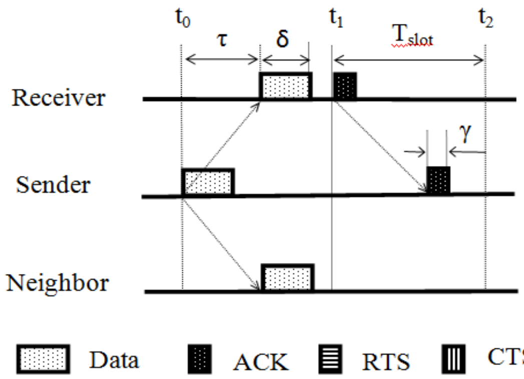

Fig. 1. A successful single data packet transmission of slotted Aloha protocol

B. *The Slotted M-FAMA Protocol*

When a node has a train of data packets to send it wait until the next slot and transmits two packets in this slot, one RTS packet and the first data packet of data packets train. There is a narrow slot time of t_{guard} between these two packets. These two packets are received by the destination node and all the other nodes in the range of the source node within the slot time. The destination node then responds a CTS packet at the beginning of the next slot. This CTS packet is also received within the slot time by the source node and all the other nodes in the neighborhood of the destination node. When the source node has received the CTS it knows that it has permission to transmit its data packets train, so it waits until the beginning of the next slot and then starts sending the next data packets. When the destination node has received the entire data packet it sends an ACK packet to indicate that the transmission has been successful. And it will send an NACK packet if the transmission is unsuccessful. A successful handshake of slotted FAMA protocol is illustrated in Figure 2.

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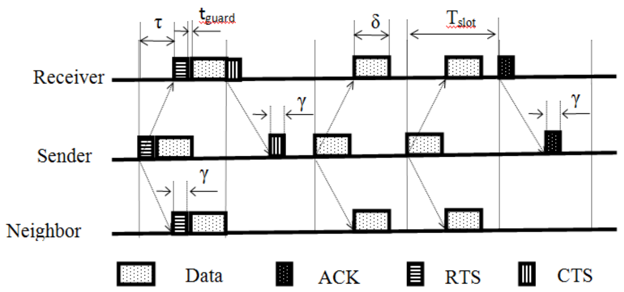

Fig. 2. A successful handshake of slotted FAMA protocol

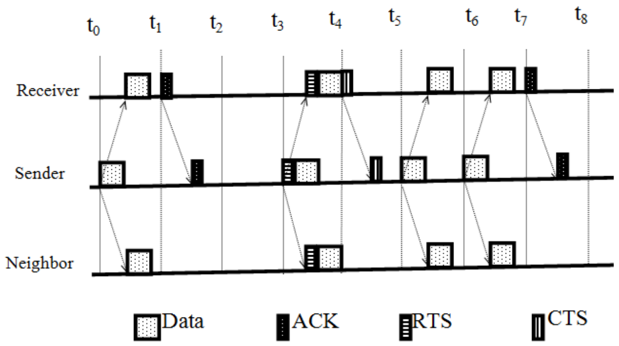

Fig. 3. A successful transmission of a single data packet and data packets train of slotted Aloha-FAMA

When a node is being Idle state (in this state, a node is ready to transmit or receive packet), it receives a packet from the channel. The type of packet received will determine its actions as listed below.

- After receiving a Data packet intended for itself, this node knows that this is a single Data packet, which the sender need to send to it. It replies by an ACK packet immediately, and then goes to Idle state.
- After receiving a RTS packet intended for itself, this node knows the number of data packets, which the sender node will send to it. This node will wait to receive the first data packet after a period of t_{guard} expire, and send a CTS packet at the beginning of the next slot. It will wait to receive enough the number of data packets from the sender node and replies an ACK packet when the data reception has successfully ended and goes to Idle state.
- After receiving an RTS packet intended for another node (xRTS packet, this packet has the information of the number of data packets of the sender node to send), this node knows that the number of data packets the sender node need to send. This node goes to Backoff state, and waits long enough to allow the sender to transmit the entire its data packets and receive the corresponding ACK packet.
- After receiving a CTS packet intended for another node (xCTS packet), this node must go to Backoff state and wait long enough to allow the receiver to receive the entire its data packets and send the corresponding ACK. Since this node has received the CTS packet, it will also receive the ACK packet and will thus know that data transmission has ended successfully.
- After receiving a Data packet intended for another node (xData packet), this node must wait to receive the subsequent ACK or NACK packet.
- After receiving an ACK packet intended for another node (xACK packet), this node only has to wait until the end of this slot since the data transmission has successfully ended.
- After receiving a NACK packet intended for another node (xNACK packet), this node must wait long enough to allow for the train of data packets to be retransmitted and a new ACK or NACK to be sent.

C. Throughput Analysis

1. Slotted Aloha Protocol

Figure 1 show the transmission periods of slotted Aloha protocol. In the slotted Aloha protocol, the probability of no collisions is the probability that no neighbors transmit within a time slot (the vulnerable interval of length T) used by a given node. The throughput equation of slotted Aloha protocol is given by [16].

$$S_1 = T_{slot}\lambda e^{-T_{slot}\lambda} \quad (1)$$

Where $\lambda$is offered channel traffic rate,$T_{slot}$is slot size.

2. Slotted M-FAMA Protocol

The network layout is shown as Figure 4. The sender node T has a total of N neighbors (in this case, $N = 3$, numbered 1 through 3 in the figure 4). Each of them has Q neighbors which are hidden from T ($Q = 2$, the gray nodes in the figure 4). Figure 2 show the transmission periods of slotted M-FAMA protocol. In this protocol, we consider slotted M-FAMA with the assumptions that the slot size is equal to $T_{slot} = \tau + \gamma + t_{guard} + \delta$. And τ is the propagation delay, γ is the transmission time of RTS, CTS, ACK packets, $\delta$is the transmission time of Data packet, t_{guard} is the mine slot time between RTS and Data packet.

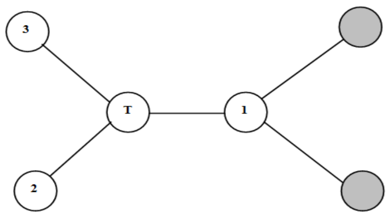

Fig. 4. network layout

Throughput per node (S) can be defined as[7], [17]:

$$S_2 = \frac{\bar{U}}{\bar{B}+\bar{I}} \quad (2)$$

Where $\bar{U}$ is the average time while useful data is being sent, $\bar{B}$ is the average time while channel is being used (busy period), $\bar{I}$ is the average time between two busy periods (Idle time), these values are given by [7].

$$\bar{I} = \frac{1}{(N+1)\lambda} \quad (3)$$

$$\bar{U} = \frac{\delta}{(N+1)} P_s \quad (4)$$

$$\bar{B} = \bar{T}_{fail} + \bar{T}_{suc} + \bar{T}_{defer} \quad (5)$$

Where λ is the average packet per second which is the arrivals follow a Poisson distribution, P_s is the probability of success (no collision) on the channel[7].

$$P_s = \prod_1^N e^{\lambda T_{slot}} \prod_1^N \left(\prod_1^Q e^{-\frac{\lambda}{N} T_{slot}} \right) = e^{-\lambda(N+Q)T_{slot}} \quad (6)$$

$\bar{T}_{fail}$ is a period of collisions on the channel, the value of $\bar{T}_{fail}$ is[7].

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$$\bar{T}_{fail} = \frac{2T_{slot}(1-P_S)}{N+1} \quad (7)$$

$\bar{T}_{suc}$ is the time during which a train of data packets is being successfully sent. In our slotted M-FAMA protocol, RTS and the first packet of the data train are sent together, CTS, ACK packet and each next data packet needs one slot to be sent. The duration of a successful period (T) includes the RTS, CTS, a train of n ($n \geq 2$) data packets (not include the first data packet), and ACK packet, i.e.,$T = (n+3)T_{slot}$. Hence, the duration of a successful transmission is:

$$\bar{T}_{suc} = T.P_s \quad (8)$$

$\bar{T}_{defer}$ is the time during which the sender node cannot send due to transmissions from other nodes because the channel has been acquired to send a train of data packets by another node. The deferral time equals $(n+1)T_{slot}$ Hence,

$$\bar{T}_{defer} = (n+1)T_{slot}\frac{QP_s}{N+1} \quad (9)$$

Substituting Eqs. (7), (8), (9) into Eq. (5) and then substituting Eqs. (3), (4), (5) into Eq. (2), we obtain the throughput of slotted M-FAMA protocol for a certain node.

Therefore, the throughput of slotted Aloha-FAMA for a certain node, and it is valid for a static single-hop network as follow:

$$S = \frac{L}{M}S_1 + \frac{M-L}{M}S_2 = \frac{L}{M}T_{slot}\lambda e^{-T_{slot}\lambda} + \frac{M-L}{M}.\frac{\lambda\delta P_S}{\lambda T_{slot}[2(1-P_S)+(N+1)(n+3)P_S+(n+1)QP_S]+1} \quad (10)$$

Where M is the total of the number of data packets, and L is the total of the number of single data packets.

III. Simulations and Results

The simulations are implemented for three MAC protocols that are slotted Aloha, slotted FAMA and slotted Aloha-FAMA protocols. The network is a 6-node static network and consists of one master node and five transmitter nodes. The master node acts as AP and receives data from the Nodes 1 - 5. They are distributed in a region of 5km width and 5km length randomly at 1000m depth for five transmitter nodes. Each node is assigned an ID number as an address of its own while in intercommunication. The figure 5 shows the topology of the simulation network. A complete network simulator has been implemented within the OPNET environment. Each node acts independently from the others and sends petitions to the channel following a Poisson distribution with an average of one arrival per 60 seconds, each arrival is a train of data packets of one to three packets randomly. The acoustic propagation speed is assumed to be 1500m/s. Our simulation study only focuses on the slotted Aloha-FAMA's performance in the MAC layer. The channel is assumed to be error-free. The buffer size is set to 100 each. All the protocols in our simulation study are medium access MAC protocols that require time synchronization.

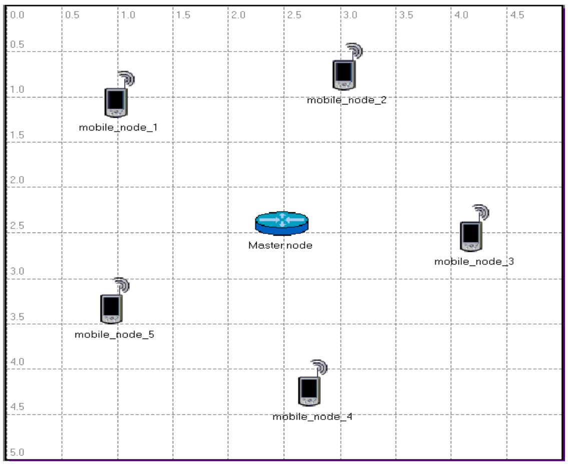

Fig. 5. Underwater acoustic network topology

Generally, the simulation parameters are set as follow: The bandwidth is $10\,kHz$ and the fundamental frequency is set $10\,kHz$. All their transmit power is set as $100\,W$. Data frame size is $1152\,bit$, transmission data rate is 1024 $bit\,/\,s$. RTS, CTS, ACK packets size is set as $100\,bit$. The max BER threshold is set as 0.33. The geometrical spreading coefficient k is 1.5. QPSK modulation is used, and simulation time is set as 1 hour.

In underwater acoustic network, average of channel utilization, collision status, the throughput, average of End-to-End delay, are the important performance indexes. The following shows the simulation results under the multi-sequence simulation mechanism using OPNET tool.

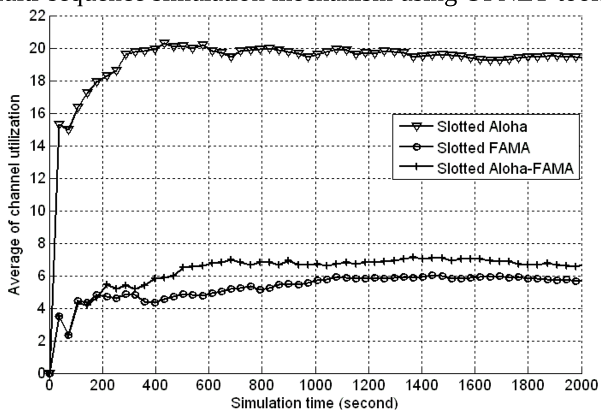

Fig. 6. The average of channel utilization of slotted Aloha, slotted FAMA, slotted Aloha-FAMA protocols in UAN

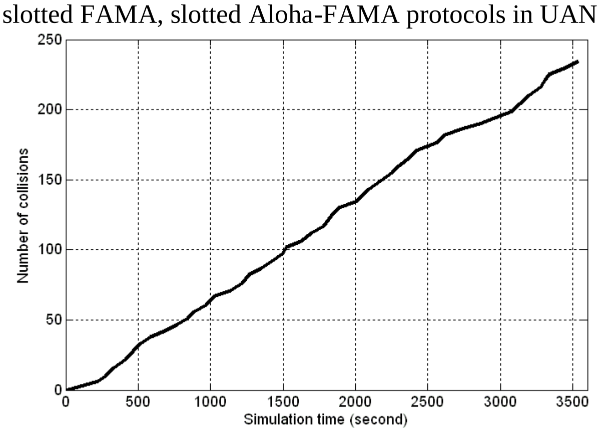

Fig. 7. The average of collision status of slotted Aloha protocol in UAN

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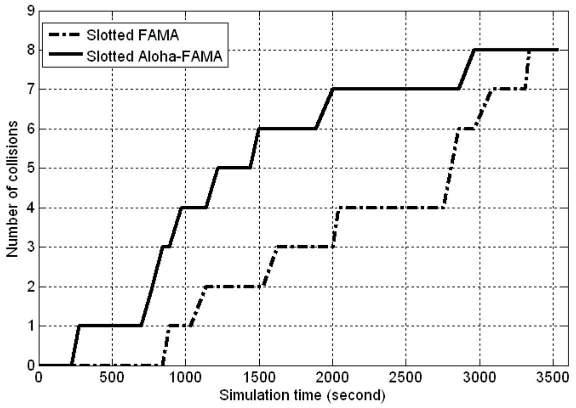

Fig. 8. The average of collision status of slotted FAMA and slotted Aloha-FAMA protocols in UAN

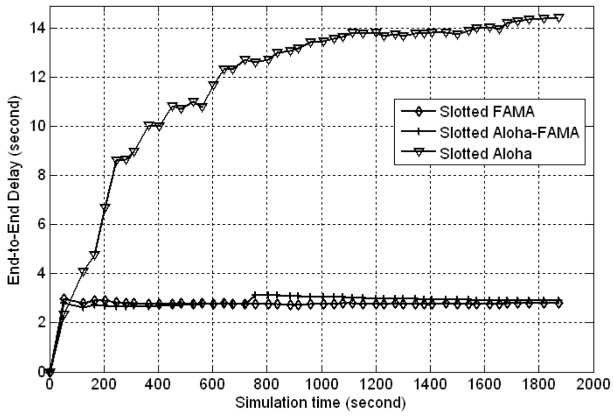

Fig. 9. The average of End-to-End delay of slotted Aloha, slotted FAMA, slotted Aloha-FAMA protocols in UAN

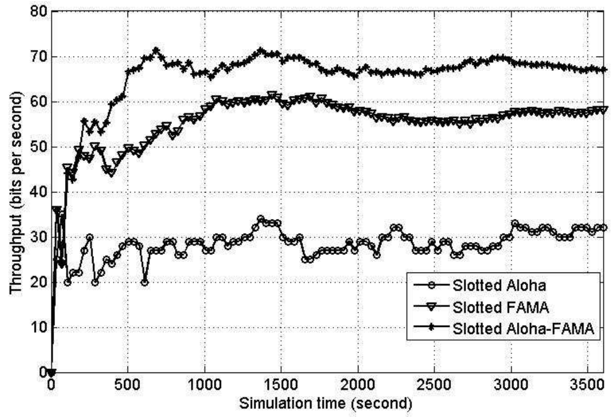

Fig. 10. Throughput of slotted Aloha, slotted FAMA and slotted Aloha-FAMA protocols in UAN

Figure 6 show the average of channel utilization of three protocols, it is quite low because the propagation delay of underwater acoustic channel is high while the available bandwidth of an underwater acoustic channel is limited. The average of channel utilization of slotted Aloha protocol is much higher than the FAMA and slotted Aloha-FAMA protocols but from the figure 7 and 8, we can observe that the packet collision of slotted Aloha is seriously. For one hour of simulation, the total of collisions of slotted Aloha protocol is about 135 times, while total of collisions of slotted FAMA and slotted Aloha-FAMA protocols is 8 times. The collision rate of slotted Aloha is high because this protocol does not use any handshake mechanism before transmitting data packets. For slotted Aloha protocol, the collision probability is low for single data packets, but for the train of data packets, the collision probability is high as show in figure 7 and 8. For slotted FAMA and slotted Aloha-FAMA protocol, although the channel utilization is lower than slotted Aloha protocol, but their collision status is very low. This is the result of the handshaking mechanism of these two protocols before transmitting data, which uses the RTS, CTS, Data, ACK packets exchange.

For the comparison of channel utilization and collision status between slotted FAMA and slotted Aloha-FAMA protocols, the collision status of two protocols are the same for one hour simulation time, but the channel utilization of slotted Aloha-FAMA is better than slotted FAMA protocol as shown in figure 6 and 8. Because of our protocol, we utilize the RTS's slot time to transmit the first packet of the train of data packet, and we do not use handshake mechanism for the single packets, this is to improve channel utilization and increase throughput UANs. The figure 10 shows the throughput at receiver of three MAC protocols. The throughput in slotted Aloha-FAMA is better than in slotted Aloha and slotted FAMA. The throughput of slotted Aloha is about 30bits per second, the slotted FAMA is about 60 bits per second, and the slotted Aloha-FAMA is about 70 bits per second. This is the result of using the combination of slotted Aloha and slotted M-FAMA into slotted Aloha-FAMA. The throughput of slotted Aloha is very low because of the retransmission of data packets and the time to transmit ACK packets to response each data packet in this protocol. For the slotted FAMA, the time to exchange control packets for each single data packets makes this protocol's throughput performance lower than slotted Aloha-FAMA.

Because of the packet collision of slotted Aloha protocol, the retransmission of data packets increase, the data packet in queue increase, this leads to End-to-End delay increase. As shown in figure 9, the End-to-End delay in slotted Aloha protocol is much higher than the slotted FAMA and slotted Aloha-FAMA protocols, the End-to-End delay is around 14 seconds. The End-to-End delay in slotted FAMA and slotted Aloha-FAMA protocols are the same, it is around 3 seconds.

IV. Conclusions

With the use of the acoustic channel in UANs, underwater networks are characterized by its narrow bandwidth and long propagation delay. In this paper, we have proposed and studied a new MAC protocol for multi-hop underwater acoustic networks based on the combination of slotted Aloha and slotted M-FAMA protocol, which is called slotted Aloha-FAMA. In our protocol, we use slotted Aloha protocol for single data packets, and slotted M-FAMA protocol for the train of data packets. This protocol uses time synchronization and time slotting for each node. Simulation results show that our protocol is able to achieve high, stable throughput

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performance and channel utilization while maintaining low collision rate.

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Author's Profile

Dao Van Phuong

was born in Hung Yen, Viet Nam, in 1981. He received the B.E. degree in Electronic Engineering and M.E degree in Image Processing from HCM City University of Technical Education, Viet Nam, in 2005 and 2009. He received Ph.D. in telecommunication science and engineering from the Southeast University, Nan Jing, China in 2014.

In 2014,he joined the Department of telecommunication science and engineering of Ho Chi Minh City Industry and Trade College, Viet Nam. In 2015 she joined the group of the researchers of Underwater communication networks of HCM City University of Technical Education, Viet Nam.

He research interests include Underwater Acoustic Communication Channel, MAC protocol for Underwater Acoustic Communication Channel.

Distributed Compressive Spectrum Sensing in Cognitive Underwater Ac oustic Communication, Optimal Power Allocation and Relay Selection for Relay Aided Cognitive Radio Network, Method of Emotion Recognition of Speed based on Simulated Annealing Genetic Algorithm and Support Vector Machine, Content – based image retrieval.

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