Journal of Zhejiang University-SCIENCE C (Computers & Electronics)
ISSN 1869-1951 (Print); ISSN 1869-196X (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Funneling media access control (MAC) protocol for underwater acoustic sensor networks*

Guang-yu FAN†1,2, Hui-fang CHEN†‡1, Lei XIE1, Kuang WANG1
(1*Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China*)
(2*School of Electronic Information, Shanghai Dianji University, Shanghai 200240, China*)
†E-mail: fgyright@126.com; chenhf@zju.edu.cn

Received Nov. 3, 2010; Revision accepted Apr. 6, 2011; Crosschecked Sept. 1, 2011

Abstract: Due to the characteristics of the underwater acoustic channel, such as long propagation delay and low available bandwidth, the media access control (MAC) protocol designed for underwater acoustic sensor networks (UWASNs) is quite different from that for terrestrial wireless sensor networks. In this paper, we propose a MAC protocol for the UWASNs, named the funneling MAC (FMAC-U), which is a contention-based MAC protocol with a three-way handshake. The FMAC-U protocol uses an improved three-way handshake mechanism and code division multiple access (CDMA) based technology for request-to-send (RTS) signals transmitting to the sink in order that the sink can receive packets from multiple neighbors in a fixed order during each round of handshakes. The mechanism reduces the packet collisions and alleviates the funneling effect, especially alleviating the choke point of the UWASNs. Simulation results show that the proposed FMAC-U protocol achieves higher throughput, smaller packet drop ratio, lower end-to-end delay, and lower overhead of the control packet compared to the existing MAC protocols for UWASNs.

Key words: Underwater acoustic sensor networks (UWASNs), Funneling media access control (MAC), Funneling effect, Three-way handshake
doi:10.1631/jzus.C1000388 **Document code:** A **CLC number:** TN929.3

1 Introduction

Since underwater acoustic sensor networks (UWASNs) are useful in a number of applications, such as oceanic environment monitoring, oceanic geographic data collection, offshore exploration, and assisted navigation, more and more researchers have begun to investigate this topic.

The channel of UWASNs has many specific characteristics, namely long propagation delay, low available bandwidth, multi-path transmission, and Doppler spread. Many techniques for UWASNs, therefore, are different from those in terrestrial wireless networks (Akyildiz *et al.*, 2005). The propagation delay of an underwater acoustic channel is five orders of magnitude higher than that in a terrestrial radio channel. The available bandwidth, determined by both transmission range and frequency, is usually within the limit of 40 km·kb/s (Partan *et al.*, 2006). In UWASNs, designing a suitable MAC protocol is an important and challenging issue due to these specific channel characteristics (Akyildiz *et al.*, 2005; Partan *et al.*, 2006; Pompili and Akyildiz, 2009). Considerable research efforts have been made and many MAC protocols have been proposed for UWASNs in recent years.

Because of the simplicity, the schedule-based protocols are widely used in UWASNs. Hsu *et al.* (2009) proposed a spatial-temporal MAC (ST-MAC) scheduling scheme for UWASNs based on the time division multiple access (TDMA). ST-MAC

---

‡ Corresponding author

* Project (No. 2009AA093601-3) supported by the National High-Tech R & D Program (863) of China

uses the spatial-temporal conflict graph and the vertex coloring method to overcome the spatial-temporal uncertainty in UWASNs. Park and Rodoplu (2007) proposed a listening time scheduling scheme for UWASNs in which all nodes have specific duty cycles. A sender tells others its own schedule so that other nodes will go to sleep and wake up at the proper time. However, these schemes work well only when the nodes transmit data periodically.

Since the code division multiple access (CDMA) technology is robust to frequency-selective fading and it is easy to compensate for the effect of multipath, it is the most promising physical layer and multiple access technique for UWASNs. Tan and Seah (2007) proposed a distributed CDMA-based MAC protocol for UWASNs, the protocol for long-latency access networks (PLANs). The PLAN protocol is based on a three-way handshake and each sensor node uses a unique spread-spectrum code to encode the signals before transmitting. The codes are orthogonal; the nodes in the networks, therefore, can receive signals from multiple nodes at the same time. The PLAN protocol reduces the number of control packets by broadcasting one clear-to-send (CTS) packet for a few accumulated request-to-send (RTS) packets, improves the network throughput by minimizing packet loss resulting from unsynchronized data transmissions, and reduces the energy consumption of the nodes. Pompili *et al.* (2009) proposed a transmitter-based CDMA MAC protocol for UWASNs, which combines the ALOHA scheme with CDMA, and uses a closed-loop distributed algorithm to set the optimal transmit power and code length for minimizing the near-far-effect (Muqattash *et al.*, 2003). This protocol achieves short channel access delay, low energy consumption, and high network throughput.

In addition to these schedule-based protocols, the contention-based protocols for UWASNs have also been investigated widely. T-Lohi (Syed *et al.*, 2008) is a tone-based contention protocol for single-hop underwater networks. In the T-Lohi protocol, time is divided into frames consisting of two parts, the reservation period (RP) and the data period. The RP is further partitioned into contention rounds (CRs). Any node that wants to send a data packet first transmits a tone in a CR. If no other tones are received from neighbors, the node is successful in the channel reservation, and transmits the packet in the following data period. By exploiting space-time uncertainty and long latency to detect collisions and count contenders, the T-Lohi protocol achieves a high throughput and reduces the energy consumption. However, the T-Lohi protocol is designed for single-hop underwater networks, and the duration of the CR is long, which leads to a low throughput.

In UWASNs, avoiding a hidden terminal problem is important for the nodes to transmit data efficiently. Since not all of the nodes are within the transmission range of each other, transmission going on in one part of an area may not be received somewhere else in the same area. As shown in Fig. 1, node B can hear both A and C, while A and C cannot hear each other. When C attempts to transmit while A is transmitting data to B, it considers the channel free, and transmits its data. Hence, the collision of the data from C and A occurs. This is the hidden terminal problem which results in data collisions, low throughput, and high energy consumption.

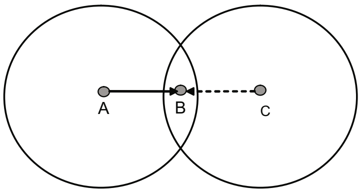

Fig. 1 The hidden terminal problem where a collision of the data from nodes C and A occurs

To avoid the hidden terminal problem, the handshake mechanism used in the traditional medium access collision avoidance (MACA) (Karn, 1990) protocol is also widely used in MAC protocols for underwater networks. According to MACA, a node having a data packet to send first transmits an RTS packet. The intended receiver responds with a CTS if it receives the RTS correctly. Upon reception of the correct CTS, the sender transmits its data packet. The RTS-CTS handshake mechanism in the MACA makes the sender and its intended receiver detect collisions by establishing a request-response dialogue between them.

Guo *et al.* (2009) proposed an adaptive propagation delay tolerant collision avoidance protocol (APCAP) based on the RTS-CTS handshake mechanism. With a series of improvements to the conventional MAC mechanisms, the APCAP allows a sender to do other actions while waiting for the CTS packet from the receiver. The improved handshaking mechanism enhances the network throughput with long propagation delay. The distance-aware collision avoidance protocol (DACAP) (Peleato and Stojanovic, 2007) is also a contention-based protocol for UWASNs using the RTS-CTS handshake mechanism. According to the long propagation delay in UWASNs, the DACAP lets a sender add a waiting period between receiving the CTS packet and sending the data packet, and allows the destination to send a warning packet to the source to cancel a transmission if it receives an RTS packet from another node.

Slotted FAMA (Molins and Stojanovic, 2007) is another contention-based protocol based on the floor acquisition multiple accesses (FAMA) (Fullmer and Garcia-Luna-Aceves, 1995) for UWASNs. In this protocol, all nodes share common slot synchronization and initiate the RTS-CTS handshake at the beginning of a slot. Compared with TDMA, the Slotted FAMA protocol has no idle slot problem, and the nature of the random access leads to a higher throughput. However, due to the long propagation delay in UWASNs, the handshaking mechanism used in the Slotted FAMA protocol still results in a long delay (Casari *et al.*, 2008).

Extending the traditional multi-hop hidden terminal problem in single-channel networks, Zhou *et al.* (2010) considered the long-delay hidden terminal problem and the multi-channel hidden terminal problem in the underwater networks, called triple hidden terminal problems. To resolve triple hidden terminal problems, Zhou *et al.* (2010) proposed the CUMAC-based RTS-CTS handshake mechanism as well as the cooperation of neighboring nodes for collision detection and notification. The cooperation of neighbors for collision detection greatly improves the network throughput and energy efficiency.

Moreover, the protocols based on receiver reservation have also been investigated for UWASNs. Chirdchoo *et al.* (2008) proposed a receiver-initiated reservation-based protocol for UWASNs, called receiver-initiated packet train (RIPT). It is also a random access MAC protocol for multi-hop networks. In the RIPT protocol, the long propagation delay problem is resolved by coordinating packets from multiple neighbors to arrive in a packet chain manner at the receiver. The RIPT protocol achieves a high and stable throughput performance, while maintaining a low collision rate, because the hidden terminal problem does not exist in the receiver-initiated protocol. However, there are still some drawbacks in the RIPT protocol. It is difficult for the node to determine the time to initiate a ready-to-receive (RTR) message in this protocol. And the four-way handshake mechanism of the protocol also considerably degrades the network throughput, especially in a long propagation delay environment.

As mentioned above, although the existing MAC protocols for UWASNs have improved the throughput by mitigating the hidden terminal problem and reducing the packet collisions to some extent, they fail to address the funneling effect (Ahn *et al.*, 2006). In this paper, a contention-based MAC protocol with three-way handshake is proposed for UWASNs. It uses an improved three-way handshake to reduce the packet collisions and to make the sink receive packets from multiple neighbors in a fixed order during each round of handshakes. And the proposed MAC protocol is adapted for the networks with long propagation delay and limited bandwidth.

2 System model and problem statement

Fig. 2 shows a typical architecture of the UWASNs. An underwater sink is located at the center of the monitored area, a lot of underwater sensor nodes deployed surrounding the sink, and a surface station acting as a gateway between the on-shore control center and the sink. The information generated in the sensor field transmits hop by hop from sensor nodes to the sink, and the gathered information at the sink is forwarded to the surface station via cable. Finally, the information is received by the on-shore control center with radio signals from the surface station.

In the UWASNs, the sink is assumed to be a sufficient energy supply and capable of handling multiple parallel communications with senor nodes. All sensor nodes are homogenous and quasi-stationary, and can adjust the transmission range with power control.

In Fig. 2, since the information generated at sensor nodes is transmitted hop by hop to the sink in a many-to-one pattern, the funneling effect (Ahn *et al.*, 2006), as shown in Fig. 3, appears. The number of the sensor nodes near the sink is much smaller than that of the sensor nodes far from the sink. Therefore, each sensor node near the sink needs to transmit more packets than that far from the sink. And the neighboring nodes of the sink transmit the most packets. The area around the sink is the choke point of the network.

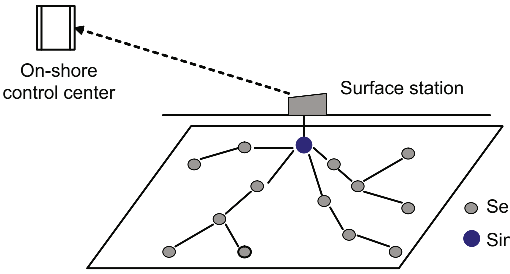

Fig. 2 A typical architecture of the underwater acoustic sensor networks (UWASNs)

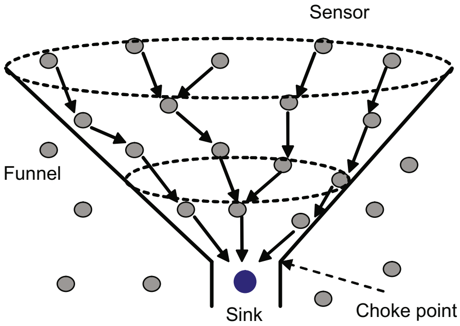

Fig. 3 Funneling effect in the underwater acoustic sensor networks (UWASNs)

In the UWASNs, when packets move closely toward the sink, the traffic intensity increases. Hence, the funneling effect leads to increase not only in the packet collisions, network congestion, and packet loss, but also in the energy consumption of the sensor nodes near the sink.

Because of the long propagation delay and the low available bandwidth, alleviating the funneling effect is a necessary issue for designing the MAC protocol in UWASNs. Although the throughput is improved by mitigating the hidden terminal problem and reducing the packet collisions to some extent, the existing MAC protocols for UWASNs do not take the funneling effect into account. The RTS-CTS handshaking mechanism and the CDMA-based method in the PLAN make the receivers receive data concurrently from multiple sources, which is good for alleviating the funneling effect. The protocol may be more reasonable, however, if it had considered that the nodes in the system are faced with quite great spread-spectrum gain and quite long orthogonal codes for the distributed transmitter-oriented code assignment. The great spread-spectrum gain probably reduces the network throughput. Furthermore, the decoding system in the nodes increases the complexity of the structure of the equipment. On the other hand, in terrestrial wireless sensor networks, the funneling-MAC (Ahn *et al.*, 2006) is proposed to solve the funneling problem with a hybrid TDMA/CSMA approach. However, due to the long propagation delay, TDMA is not feasible in UWASNs.

Therefore, to alleviate the funneling effect and improve the performance of the MAC protocol, we investigate the MAC protocol based on the CDMA technology and improve the three-way handshake mechanism for UWASNs with the network architecture shown in Fig. 2.

3 FMAC-U protocol

The FMAC-U protocol is a contention-based MAC protocol with a three-way handshake. It uses a simple approach to avoid packet collisions and make the sink receive packets from multiple neighbors in a fixed order during each round of handshakes.

3.1 The three-way handshake

In the FMAC-U protocol, time is slotted and each sensor node transmits the packet at the beginning of a slot. A three-way handshake (RTS/CTS/DATA), as illustrated in Fig. 4, is used.

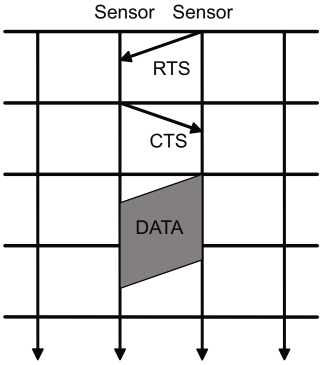

Fig. 4 A handshake between sensor nodes

A sensor node that wants to transmit data packet(s) first initiates a handshake to its intended neighbor by broadcasting an RTS packet in the following slot. The RTS packet includes the sender

ID, the receiver ID, the size of the DATA packet, and the time flag. When an intended node, which is currently not involved in a handshake with another node, and also not required to remain quiet, receives the RTS packet, it responds with a CTS packet in the next slot. And then, receiving the CTS, the sender transmits its data in the next slot.

3.2 The improved three-way handshake

In the traditional MACA protocol, when an intended receiver receives more than one RTS packet from its neighbors, it does not respond because it cannot distinguish these RTS packets when they arrive in the same slot. Because of the funneling effect, the sink usually receives more than one RTS packet from its one-hop neighbors. If the sink ignores these RTS packets according to the traditional MACA protocol, RTS packets as well as time slots used by RTS packets are wasted, which leads to a low network throughput.

In the FMAC-U protocol, when the sink receives more than one RTS packet from its one-hop neighbors, it calculates the number of DATA slots (i.e., $\mathrm{TS}_{\mathrm{requested}}$) requested by RTS packets and tries to allocate its available slots (i.e., $\mathrm{TS}_{\mathrm{available}}$). Upon completing the slot assignment, the sink transmits the CTS packet in the following slot. The CTS packet contains the number of DATA slots assigned to each neighbor, the order of transmission, and the time flag.

Receiving the CTS packet, the one-hop neighbors, which have been allocated at least one DATA slot by the sink, compute the time when they start to transmit the DATA packet(s), and transmit the DATA packet(s) in the corresponding allocated slot(s) (Fig. 5).

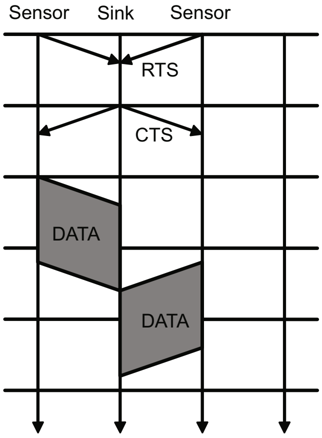

Fig. 5 A handshake between sensor nodes and the sink

3.3 DATA slot assignment method

To assign the DATA slots effectively, when the sink receives more than one RTS packet from the one-hop neighbors, it randomly marks these neighbors with different numbers, which indicate different priorities. Then the sink assigns its available slots as follows. If $\mathrm{TS}_{\mathrm{requested}} \leq \mathrm{TS}_{\mathrm{available}}$, the sink assigns all of the DATA slots freely; otherwise, it assigns the available slots to neighbors according to their prioritites.

Here we give an example to show the results of the DATA slot assignment method. The sink with six available DATA slots (i.e., $\mathrm{TS}_{\mathrm{available}}$=6) receives three RTS packets from three neighbors, called the neighbor one, neighbor two, and neighbor three, who request nine DATA slots (i.e., $\mathrm{TS}_{\mathrm{requested}}$=9). The priority and the DATA slots of the three neighbors are listed in Table 1. Since $\mathrm{TS}_{\mathrm{requested}} > \mathrm{TS}_{\mathrm{available}}$, three DATA slots are assigned for both neighbor two and neighbor three, and no DATA slots are assigned for neighbor one.

Table 1 The results of the DATA slot assignment method

Node ID	Priority	Number of DATA slots	
		Requested	Assigned
1	3	2	0
2	2	3	3
3	1	4	3

3.4 Collision of RTS packets resolution mechanism

When several RTS packets from one-hop neighbors arrive at the sink in the same slot, the packet collision takes place. To deal with the collision of RTS packets, each one-hop neighbor of the sink pre-processes the RTS packet by spreading the RTS packet with a spreading sequence.

In the initialization phase, the sink assigns a pseudorandom binary spreading sequence to each one-hop neighbor. It is assumed that the spreading sequence is orthogonal and has a much higher bit rate than that of the system. When a neighbor

i wants to transmit a DATA packet, it generates an RTS packet, RTS_i, and pre-processes the RTS_i with its spreading sequence, c_i. Then,

$$\mathrm{RTS}_i^{'} = \mathrm{RTS}_i \oplus c_i. \tag{1}$$

Receiving the $\mathrm{RTS}_i^{'}$, the sink extracts RTS_i as follows:

$$\mathrm{RTS}_i = \mathrm{RTS}_i^{'} \oplus c_i. \tag{2}$$

3.5 State transitions

In the FMAC-U protocol, each sensor node has four states (Fig. 6): IDLE, wait for CTS (WFCTS), wait for DATA (WFDATA), and QUIET. When the sensor node is in the IDLE state, it can receive the packets from its neighbors and transmit the corresponding packets. The WFCTS state means that a sensor node is waiting for the CTS packet from the intended receiver after it transmits an RTS packet. The WFDATA state means that a sensor node is waiting for the DATA packet(s) from the intended source after it transmits a CTS packet. When the sensor node is in the QUIET state, it can receive the packets from its neighbors, but it is prohibited from transmitting message. The state transition is shown as follows.

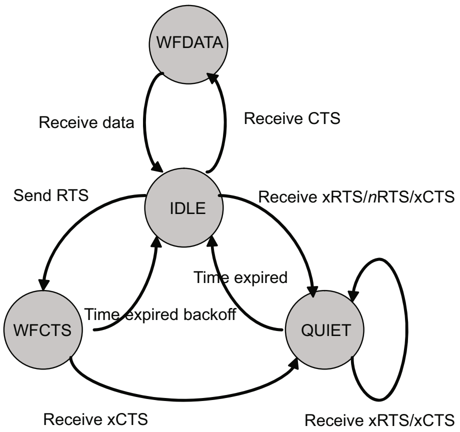

Fig. 6 The state transition of sensor nodes in the FMAC-U protocol (WF: wait for)

Starting from the IDLE state, if the sensor node generates one or more packets, it sends an RTS packet at the next slot and goes to the WFCTS state. After receiving the CTS packet in two slots (current slot and the next one), it sends DATA packet(s) in the assigned DATA slot(s) and returns to the IDLE state. If no CTS packets are received during these two slots, the sensor node waits for a random number of slots computed using the binary exponential backoff algorithm, and returns to the IDLE state.

If the sensor node receives an xCTS (the CTS intended for another node) in the WFCTS state, it ignores any xRTS (the RTS intended for another node) or RTS packet and goes to the QUIET state, and waits for Q_0, where Q_0 is the maximum time of the overheard control packet's quiet duration. When the quiet time has expired, the sensor node returns to the IDLE state.

If the sensor node in the IDLE state receives an RTS packet for itself, it transmits the CTS packet at the next slot and goes to the WFDATA state.

When the sensor node in the WFDATA state receives the DATA packets, it returns to the IDLE state.

If the sensor node in the IDLE state receives an xRTS or xCTS or receives more than one RTS (nRTS) packet for itself, it goes to the QUIET state and waits for Q_0.

If the sensor node in the QUIET state receives an xRTS or xCTS packet, it remains in the QUIET state for an extended period. The extended period depends on max(Q_1, Q_2), where Q_1 and Q_2 are the local quiet duration and the quiet duration of the received control packet, respectively.

Since the sink does not transmit packets actively, it has three states: IDLE, WFDATA, and QUIET (Fig. 7). When the sink is in the IDLE state, it can receive the packets from its one-hop neighbors. The WFDATA state means that the sink is waiting for the DATA packet(s) from the intended one-hop neighbors after it broadcasts a CTS packet. When the sink is in the QUIET state, it can receive the packets from its neighbors, but it is prohibited from transmitting message. The state transition is shown as follows.

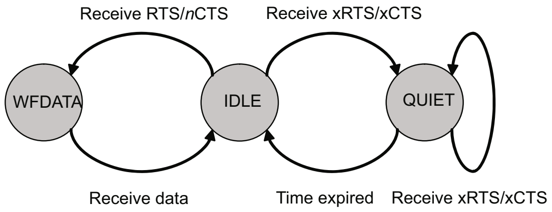

Fig. 7 The state transition of the sink (WF: wait for)

There are three cases for the sink in the IDLE state: (1) If the sink receives an RTS packet for itself, it transmits the CTS packet at the next slot and goes to the WFDATA state. (2) If the sink receives more than one RTS packet, it calculates the number of the requested DATA slots, allocates the available slots, broadcasts the CTS packet at the next slot, and goes to the WFDATA state. (3) If the sink receives any xRTS or xCTS packets, it goes to the QUIET state.

If the sink in the WFDATA state receives the DATA packets, it returns to the IDLE state.

If the sink in the QUIET state receives any xRTS or xCTS packets, it remains in the QUIET state for an extended period according to the local quiet duration and the quiet duration of the received control packet. If the quiet time has expired, the sink returns to the IDLE state.

3.6 Fairness bit

To prevent the sink from occupying the channel for too long, a fairness bit is used. When the sink has just been released from a handshake loop, it sets the fairness bit to be '0'. When the value of the fairness bit is '0', the sink does not respond to any RTS packets from one-hop neighbors.

The fairness bit can be reset only when the sink has received at least one CTS packet from one-hop neighbors, which means at least one of one-hop neighbors has received DATA packet(s) from other nodes at that time. However, if the duration of the fairness bit set to be '0' is longer than a threshold, it will be reset to be '1' to avoid deadlock.

In the FMAC-U protocol, with improved three-way handshake mechanism and CDMA-based technology for RTS packets, the sink can receive several RTS packets from its one-hop neighbors in the same slot. Unlike the PLAN, the one-hop neighbors of the sink use only unique spread-spectrum code to pre-process its RTS packets to the sink rather than to pre-process all of the packets in the FMAC-U protocol. The protocol reduces the overhead of control packets and improves the performance of data transfer at the choke point of the network. Therefore, the network throughput is improved.

4 Simulation results

We evaluated the performance of the proposed FMAC-U protocol with simulation under different traffic loads. The performance metrics are defined in Eqs. (3)–(6).

The throughput is the ratio of the total packets received by the sink to the packets it can receive through the simulation time. The packet drop ratio is the ratio of the total number of packets dropped by sensor nodes to the number of their generated packets. The end-to-end delay is the average time of packets received from its generation to reception. The control packet overhead is the average number of control packets used for each packet received by the sink.

We compared the performance of the proposed protocol to that of two existing MAC protocols for UWASNs, namely the Slotted FAMA protocol and the RIPT protocol.

The network topology used for simulation is shown in Fig. 8. There are 24 static sensor nodes deployed in a grid topology and the sink is located at the center. It is assumed that the traffic load is divided evenly among all sensor nodes according to the Poisson distribution and that the sink is the only destination for all packets. To make the results easy to interpret, the static routing protocol is used (Fig. 8). Therefore, some packets arrive at the sink with one-hop routes while the rest with two-hop routes.

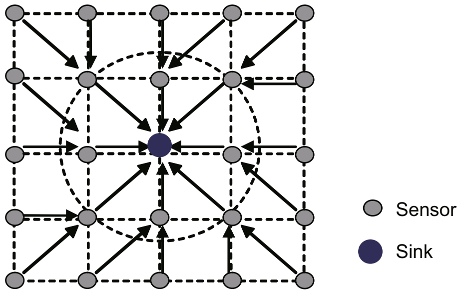

Fig. 8 Grid topology for simulation

In the network, the grid spacing is 5 km, and the transmission range is set to be 1.75 times the grid spacing, such that each sensor node has exactly eight neighbors in its transmission range. All sensor nodes are equipped with a half-duplex, omni-directional transceiver with the fixed data rate of 1 kb/s. The lengths of the DATA packet and control packet are 500 and 12.5 bytes, respectively. The size of time slot in the Slotted FAMA protocol and the FMAC-U protocol is 4.1 s. The acoustic propagation speed is 1500 m/s. In the RIPT protocol, the average time interval between initiating RTRs at a node (T_{avg} in Chirdchoo *et al.* (2008)) is 100 s,

$$\text{Throughput} = \frac{\text{number of received packets} * \text{packet length}}{\text{data rate} * \text{simulation time}}, \tag{3}$$

$$\text{Packet drop ratio} = \frac{\text{number of dropped packets}}{\text{number of generated packets}}, \tag{4}$$

$$\text{End-to-end delay} = \frac{\sum_i (\text{reception time of packet } i - \text{generation time of packet } i\,)}{\text{number of received packets}}, \tag{5}$$

$$\text{Control packet overhead} = \frac{\text{number of control packets}}{\text{number of received packets}}. \tag{6}$$

the number of DATA slots currently reserved at the receiver (M_{train} in Chirdchoo *et al.* (2008)) is initialized to be 1, and the maximum allowable value of M_{train} ($M_{\text{train,max}}$ in Chirdchoo *et al.* (2008)) is 50. In the Slotted FAMA protocol, the $M_{\text{train,max}}$ is 2, considering that there is only one sender to transmit data through a handshake. In the FMAC-U protocol and the RIPT protocol, the $M_{\text{train,max}}$ for the sink is 50.

4.1 Throughput

The comparison of the throughput of three MAC protocols for UWASNs (Fig. 9) shows that the throughput of three MAC protocols increases with the increase of the traffic load when the traffic load is relatively small, and it decreases with the increase of the traffic load after reaching peak values. The maximum values of the throughput of the Slotted FAMA, RIPT, and FMAC-U are 0.005, 0.01, and 0.0146 kb/s when the traffic loads are 0.0075, 0.0175, and 0.0275 kb/s, respectively. The maximum throughput achieved is only 0.0146 kb/s, partly because of the long propagation delay and the collision of the packets from multiple senders.

The throughput of the proposed FMAC-U protocol is the highest among the three MAC protocols, and the throughput of the RIPT protocol is higher than that of the Slotted FAMA protocol. The reason is that the packet train can be transmitted from several one-hop neighbors in the RIPT and FMAC-U protocols, while only one of one-hop neighbors in the Slotted FAMA protocol during each round of handshakes. A three-way handshake is used in the FMAC-U protocol, while a four-way handshake is used in the RIPT. Note that the simulation results shown in Fig. 9 are generated for specifically given values of parameters. The maximum throughput in the FMAC-U protocol is greater than that of the other two protocols since it has alleviated the funneling effect in UWASNs.

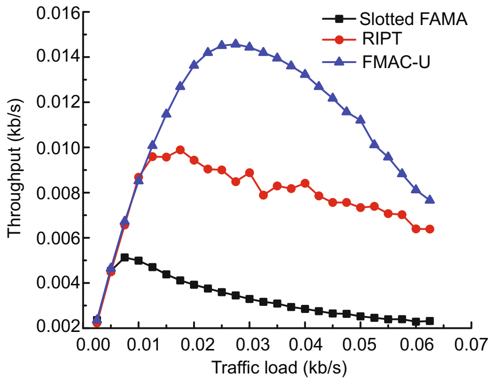

Fig. 9 Comparison of the throughput of the three MAC protocols for UWASNs

4.2 Packet drop ratio

The comparison of the packet drop ratio of the three MAC protocols (Fig. 10) shows that the packet drop ratio in all the three protocols increases when the traffic load increases. The packet drop ratio in the FMAC-U protocol is smaller than that of the Slotted FAMA protocol. The packet drop ratio in the FMAC-U protocol is smaller than that of the RIPT, but the result is reversed when the traffic load is about 0.01 kb/s. The reason is that the three-way handshake is used in the FMAC-U protocol, while the four-way handshake is used in the RIPT. Moreover, the packet chain travels in a many-to-one traffic pattern only between the sink and its one-hop neighbors in the FMAC-U protocol, while the packet chain travels in this pattern all over the network in the RIPT protocol.

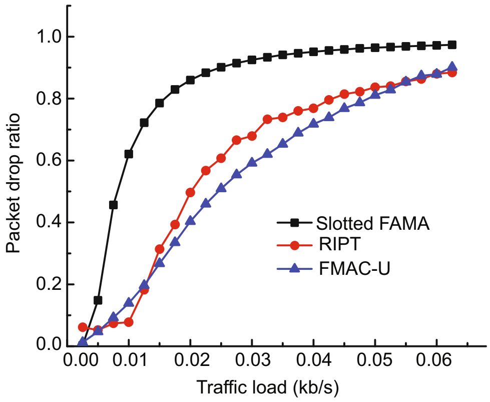

Fig. 10 Comparison of the packet drop ratio of the three MAC protocols for UWASNs

4.3 End-to-end delay

Fig. 11 shows the end-to-end delay of the three MAC protocols. The end-to-end delay increases when the traffic load increases. When the traffic load is low, the end-to-end delay of the FMAC-U protocol is the smallest. The reason is that the slots are used effectively in the FMAC-U protocol with a light traffic load. When the traffic load is larger than a value (0.015 kb/s in Fig. 11), the end-to-end delay of the Slotted FAMA protocol is slightly smaller than that of the FMAC-U. The reason is that the many-to-one traffic pattern is used in the FMAC-U protocol, while one-to-one traffic pattern is used in the Slotted FAMA. The performance of the end-to-end delay in the RIPT protocol is the worst among the three MAC protocols, because this protocol uses a receiver-initiated approach in which a sender cannot transmit its DATA packet(s) until a handshake is initiated by the receiver.

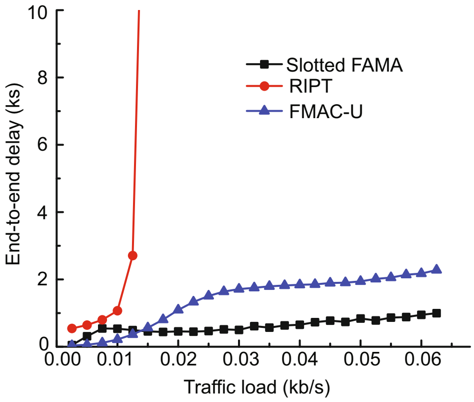

Fig. 11 Comparison of end-to-end delay of the three MAC protocols for UWASNs

4.4 Overhead of control packets

Fig. 12 shows the overhead of control packets (such as RTS and CTS) of the three MAC protocols. When the traffic load increases, the overhead of control packets in the FMAC-U and Slotted FAMA protocols increases, while the overhead of control packets in the RIPT protocol decreases. The reason is that when the traffic load increases, the collision rate increases and more control packets are used in the contention-based protocols, such as the FMAC-U and the Slotted FAMA. In contrast, the RIPT is a receiver-initiated protocol without the hidden terminal problem.

Moreover, the overhead of control packets in the FMAC-U and RIPT protocols is much less than that in the Slotted FAMA. The reason is that the many-to-one traffic pattern is used in the FMAC-U and RIPT protocols, such that a control packet can be transmitted by broadcasting.

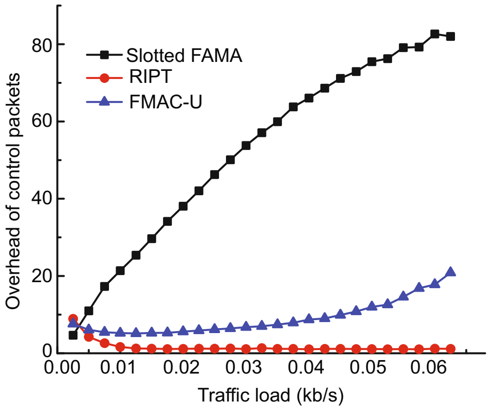

Fig. 12 Overhead of control packets of the three MAC protocols

5 Conclusions

We propose a MAC protocol for UWASNs, called the FMAC-U protocol, which is a contention-based protocol with a three-way handshake. The FMAC-U protocol uses CDMA-based technology to reduce the collisions of the RTS packets from different one-hop neighbors to the sink and makes the sink receive DATA packets from multiple neighbors in a fixed order during each round of handshakes.

Simulation results show that compared to previously proposed MAC protocols for UWASNs, the proposed FMAC-U protocol has better performance in terms of the high throughput, low packet drop ratio, low end-to-end delay, and low control packet overhead.

The aim of the FMAC-U protocol, however, is to alleviate the funneling effect, especially the choke point in UWASNs. We paid little attention to the algorithm in theory. In the future, we will concentrate on the development of a proper algorithm for order decision. The backoff algorithm, the slots assignment strategy, and the decision of the favor fairness bit are also important problems to be studied. Furthermore, the FMAC-U protocol for the terrestrial wireless networks is also an interesting research issue, especially in networks with long propagation delay.

References

Ahn, G.S., Hong, S.G., Miluzzo, E., Campbell, A.T., Cuomo, F., 2006. Funneling-MAC: a Localized, Sink-Oriented MAC for Boosting Fidelity in Sensor Networks. Proc. 4th Int. Conf. on Embedded Networked Sensor Systems, p.293-306. [doi:10.1145/1182807.1182837]

Akyildiz, I.F., Pompili, D., Melodia, T., 2005. Underwater acoustic sensor networks: research challenges. *Ad Hoc Networks*, **3**(3):257-279. [doi:10.1016/j.adhoc.2005.01.004]

Casari, P., Tomasi, B., Zorzi, M., 2008. A Comparison Between the Tone-Lohi and Slotted FAMA MAC Protocols for Underwater Networks. IEEE OCEANS, p.1-8. [doi:10.1109/OCEANS.2008.5152038]

Chirdchoo, N., Soh, W.S., Chua, K.C., 2008. RIPT: a receiver-initiated reservation-based protocol for underwater acoustic networks. *IEEE J. Sel. Areas Commun.*, **26**(9):1744-1753. [doi:10.1109/JSAC.2008.081213]

Fullmer, C.L., Garcia-Luna-Aceves, J.J., 1995. Floor acquisition multiple access for packet-radio networks. *ACM SIGCOMM Comput. Commun. Rev.*, **25**(4):262-273. [doi:10.1145/217382.217458]

Guo, X., Frater, M.R., Ryan, M.J., 2009. Design of a propagation-delay-tolerant MAC protocol for underwater acoustic sensor networks. *IEEE J. Ocean. Eng.*, **34**(2):170-180. [doi:10.1109/JOE.2009.2015164]

Hsu, C.C., Lai, K.F., Chou, C.F., Lin, K.C.J., 2009. ST-MAC: Spatial-Temporal MAC Scheduling for Underwater Sensor Networks. IEEE INFOCOM, p.1827-1835. [doi:10.1109/INFCOM.2009.5062103]

Karn, P., 1990. MACA—a New Channel Access Method for Packet Radio, ARRL/CRRL Amateur Radio. 9th Computer Networking Conf., p.134-140.

Molins, M., Stojanovic, M., 2007. Slotted FAMA: a MAC Protocol for Underwater Acoustic Networks. IEEE OCEANS - Asia Pacific, p.1-7. [doi:10.1109/OCEANSAP.2006.4393832]

Muqattash, A., Krunz, M., Ryan, W.E., 2003. Solving the near-far problem in CDMA-based ad hoc networks. *Ad Hoc Networks*, **1**(4):435-453. [doi:10.1016/S1570-8705(03)00045-3]

Park, M.K., Rodoplu, V., 2007. UWAN-MAC: an energy-efficient MAC protocol for underwater acoustic wireless sensor networks. *IEEE J. Ocean. Eng.*, **32**(3):710-720. [doi:10.1109/JOE.2007.899277]

Partan, J., Kurose, J., Levine, B., 2006. A Survey of Practical Issues in Underwater Networks. Proc. 1st ACM Int. Workshop on Underwater Networks, p.17-24. [doi:10.1145/1161039.1161045]

Peleato, B., Stojanovic, M., 2007. Distance aware collision avoidance protocol for ad-hoc underwater acoustic sensor networks. *IEEE Commun. Lett.*, **11**(12):1025-1027. [doi:10.1109/LCOMM.2007.071160]

Pompili, D., Akyildiz, I.F., 2009. Overview of networking protocols for underwater wireless communications. *IEEE Commun. Mag.*, **47**(1):97-102. [doi:10.1109/MCOM.2009.4752684]

Pompili, D., Melodia, T., Akyildiz, I.F., 2009. A CDMA-based medium access control for underwater acoustic sensor networks. *IEEE Trans. Wirel. Commun.*, **8**(4):1899-1909. [doi:10.1109/TWC.2009.080195]

Syed, A.A., Ye, W., Heidemann, J., 2008. Comparison and evaluation of the T-Lohi MAC for underwater acoustic sensor networks. *IEEE J. Sel. Areas Commun.*, **26**(9):1731-1743. [doi:10.1109/JSAC.2008.081212]

Tan, H.X., Seah, W.K.G., 2007. Distributed CDMA-Based MAC Protocol for Underwater Sensor Networks. 32nd IEEE Conf. on Local Computer Networks, p.26-33.

Zhou, Z., Peng, Z., Cui, J.H., Jiang, Z., 2010. Handling Triple Hidden Terminal Problems for Multi-channel MAC in Long-Delay Underwater Sensor Networks. IEEE INFOCOM, p.1-5. [doi:10.1109/INFCOM.2010.5462209]