A Full-Duplex Based Protocol for Underwater Acoustic Communication Networks

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Abstract—**Energy consumption and channel access time are two of the most crucial design issues in underwater acoustic communication networks since prolonging the network lifetime and improving the network throughput depends on the efficient energy resource management and channel access rules. This paper proposes a new full-duplex based and distance aware channel access protocol for ad-hoc underwater acoustic communication networks. The protocol saves transmission energy by avoiding collisions while maximizing throughput, and solves the hidden/exposed terminal problems efficiently. It is based on the full-duplex communication where we virtually separate the channel into two portions, using different frequency bands and different modulation/demodulation to transmit control packages and data packages separately. This protocol achieves a throughput several times higher than that of the traditional CSMA, while offering similar savings in energy. We have evaluated performance, efficiency and engineering feasibility of this protocol by both simulations and sea trails.**

Keywords—underwater acoustic communication networks; full-duplex; distance aware; channel access protocol; hidden terminal and exposed terminal

I. INTRODUCTION

The past decades have seen a growing interest in underwater acoustic communication because of its applications in marine research, oceanography, marine commercial operations, the offshore oil industry, and the defense sectors [1-3]. With the advances in acoustic modem technology, research in underwater communications today is focusing on the design of the first wireless networks [4]. Challenges of the underwater acoustic environment include a severely limited bandwidth, poor quality of the physical link, and high latency caused by the low speed of propagation [5]. As a result, direct application of the existing medium access control (MAC) protocol designed for terrestrial wireless networks often results in an inefficient use of system resources.

While communicating, the power required for transmitting is much greater than that required for receiving. Therefore, it is important to avoid packet collisions at the receiver when long data packets are being sent [6]. According to this fact, several MAC protocols that are particularly suited to the underwater acoustic channel were designed, such as sleep scheduling based protocols [7-8], and hand-shaking based protocols [9-10]. However, these protocols require long hand-shakes and some level of synchronization between the nodes which is a very complicated task in underwater acoustic communication networks. in this paper, we address the problem of improving the performance of Carrier Sense Multiple Access (CSMA), a hand-shaking based protocol.

In the traditional CSMA protocol, upon receiving a request-to-send (RTS), a node (receiver) immediately replies with a clear-to-send (CTS), then waits for the data packet. During this course, the receiver will not response to any other nodes since the channel has been reserved by the earlier node (the node to whom it had sent the CTS). This mechanism will raise two problems: First, collisions will occur during the data receiving course at the receiver end, as the other nodes will continuously send RTS to reserve the channel if they did not hear or receive CTS. Second, end-to-end delay will be prolonged, as the overall hand-shake procedure need to be rerun if the reservation failed nodes wants to get a reaccess to the channel.

In addition, the currently common used acoustic modems are operating in half-duplex, the communication node cannot send and receive data at the same time. This mechanism sometimes causes problems such as hidden terminal and/or exposed terminal. Hidden terminal would cause data collisions due to its deafened hearing to the sending node while exposed terminal would cause extra end-to-end delays due to its over hearing to the sending node [11].

Here, we propose a full-duplex based and distance aware CSMA protocol for ad-hoc underwater acoustic communication networks. In this protocol, full-duplex modem is used to achieve transmission and reception of data simultaneously. Furthermore, data exchanging from different nodes to a common destination can be made concurrently without collision by taking advantage of the long propagation delay.

The rest of this paper is organized as follows: Section II we detail the design of our full-duplex based protocol and the performance of this protocol is studied via extensive simulations in Section III. In Section IV, we conducted a sea trail to validate the practicability of the proposed protocol. We conclude with directions for future work in Section V.

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II. Protocol Description

A. Full-Duplex Communication Scheme

The basic idea here is to separate the communication channel into control channel (ch1) and data channel (ch2) virtually, assign different frequency bands (f1, f2) and different modulate/demodulate approaches (m1, m2) to transmit control packages and data packages. This schematic reduce the interference from bidirectional communication as much as possible. Fig.1 shows the full-duplex communication working schematic. Control packages like RTS, CTS are transmitted in virtual control channel (ch1, f1, m1), while data packages are transmitted in virtual data channel (ch2, f2, m2).

B. Full-Duplex Based and Distance Aware CSMA protocol

The protocol is specified as follows. Upon receiving a RTS, the receiver immediately replies with a CTS, then waits for the data packet. If, after sending the CTS, it overhears another RTS (let's denote it as RTS_1 for distinguishing from the earlier RTS) from the other nodes, it first calculate the time duration for finishing this new transmitting course, then responses to the RTS_1 sender. If the new transmitting course can be finished before the arrive time of the data from the earlier reserved node, then it can be carried out immediately, otherwise, it need wait till the earlier reserved communication has been finished. These two different case of the receiver handles the new coming RTS can be detailed as follows.

1) Start the new transmitting course immediately: Assume that the receiver sent CTS_0 to $sender_0$ (the earlier RTS sender) at t_0, their distance is d_0, and the data packet lasts T_{data0} seconds; the new arrival RTS_1 from the $sender_1$ arrived at t_1, its data packet lasts T_{data1} seconds, and the distance between receiver and $sender_1$ is d_1; all control packets have the same length, T_{cts} means the CTS packets last time. If

$$2\frac{d_1}{c} + T_{data1} + T_{cts} < 2\frac{d_0}{c} - (t_1 - t_0) \quad (1)$$

That means the new transmitting course can be finished before the earlier reserved data arrives, then the receiver sends CTS_1 to $sender_1$ to start data transmitting immediately. This procedure can be depicted as Fig.2 (a) shows.

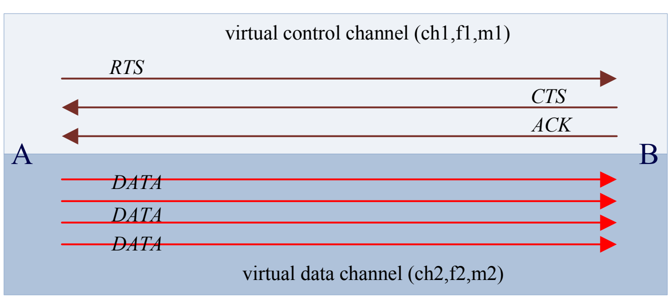


Fig. 1. Full-duplex communication working schematic diagram.

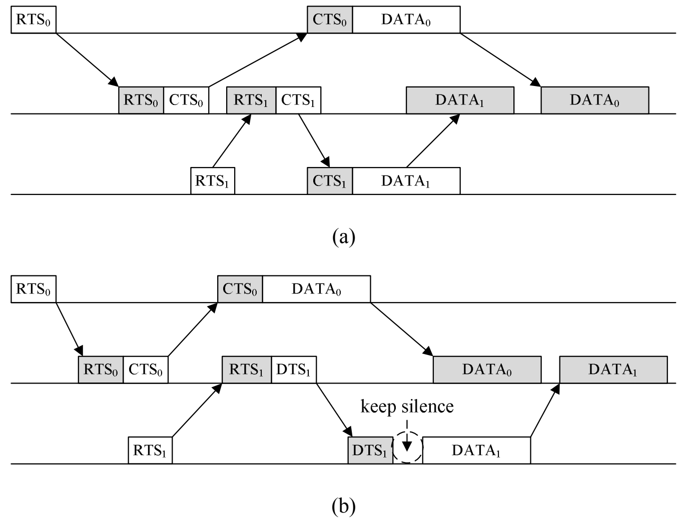


Fig. 2. Schematic of handling for the new coming RTS (a) in case 1: start the new transmitting immediately, (b) in case 2: delay the new transmitting course.

2) Delay the new transmitting course: If

$$2\frac{d_1}{c} + T_{data1} + T_{cts} > 2\frac{d_0}{c} - (t_1 - t_0) \quad (2)$$

That means the new transmitting course can not be finished before the earlier reserved data arrives, then the receiver sends DTS (delay-to-send) to $sender_1$ to delay the new transmitting. The sender1 keeps silence until the current transmitting course has finished according to the DTS contained information, then sends its data directly without any channel reservation. This procedure can be depicted as Fig.2 (b) shows.

C. Hidden Terminal and Exposed Terminal Problem Solution

When CSMA protocol is applied, hidden/exposed terminal scenario will raise two types of collision: control packet to control packet collision and control packet to data packet collision. The former collision happens in a low probability since the control packet is usually very short, while the latter is the main collision. The hidden/exposed terminal problems can hardly be solved in the current underwater acoustic communication systems as they are commonly run in single channel mechanism and the modems are operating in half-duplex, but they can be solved efficiently in the proposed protocol.

*1) Hidden terminal problem solutions:*Hindden terminal is the node positioned within the receiver' cover range but without the sender' cover range. As Fig.3 (a) shows, node A is the sender, node B is the receiver and node C is the hidden terminal. We divide the problems into two cases for discussion. In the first case, node C tries to send message while node A is transmitting data to node B. We call this condition as hidden sending terminal problem. In this condition, when node B receives the RTS from node C, it would send DTS to C to stop

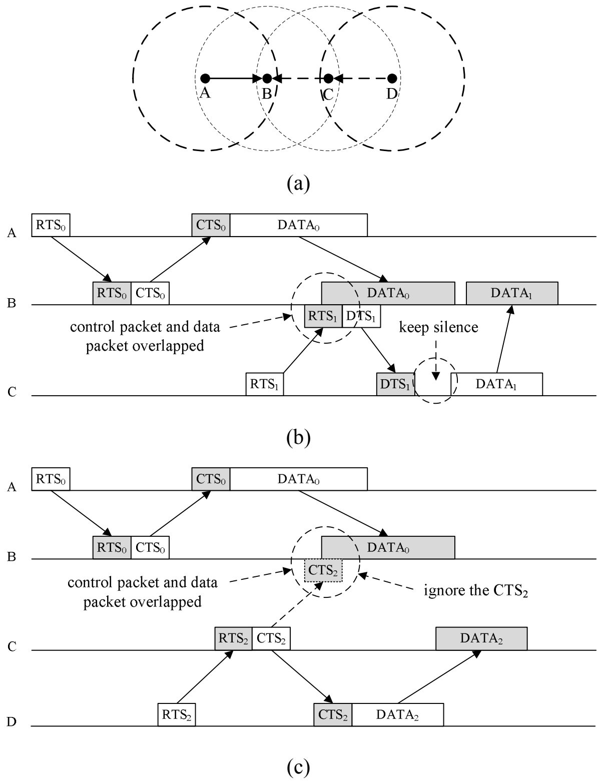


Fig. 3. Schematic of (a) the hiddden terminal problems (b) hadling for the hidden sending terminal problem (c) handling for the hidden receiving terminal problem.

this communication course immediately, thus, data collision at node B could be avoided and node C will keep silence till the current communication has been finished according to the information contained in DTS, then starts its data sending immediately without any channel reservation. This procedure can be depcted as Fig.3 (b) shows. The second case consists of node D sending RTS to node C while node A is transmitting data to node B. We call this condition as hidden receiving terminal problem. In this case, node B ignores the CTS which is from node C to node D, and the data link for node C and node D will be established, thus, end-to-end delay can be shortened. This procedure can be depicted as Fig.3 (c) shows.

2) Exposed terminal problem solutions: Exposed terminal is the node positioned within the sender' cover range but without the receiver' cover range. As Fig.4 (a) shows, node A is the receiver, node B is the sender and node C is the exposed terminal. For this problem, the solution is similar to that for the hidden terminal problem. We also divide the problems into two cases for discussion. In the first case, node C tries to send message while node B is transmitting data to node A. We call this condition as exposed sending terminal problem. In this condition, if node C is trying to send data to node B, node B will send DTS to delay the node C's sending course to avoide the data collision at node B. Upon receiving the DTS from node B, node C keep silience till the current trnasmitting epoch has been finished, and then start transmit data to node B directly without any channel reservations. This procedure can be depcted as Fig.4 (b) shows. Otherwise, if node C is trying to send data to node D, then node B will ignor the received RTS from node C as this transimitting would not interupt its work, the communication link from node C to D can be established. As a result, end-to-end delay is shortened. This procedure can be depcted as Fig.4 (c) shows. In the second case, if node D sends RTS to node C when node B is transmitting data to node A, we call this condition as exposed receiving terminal problem. In this condition, node C sends DTS to node D immediately once it hears the RTS form node D, to avoid the data collision at node C. Upon receiving the DTS, node D goes to slience state, then trnasmit its data to node C directly after a sepcific while accoring to the DTS information. This procedure can be depicted as Fig.4 (d) shows.

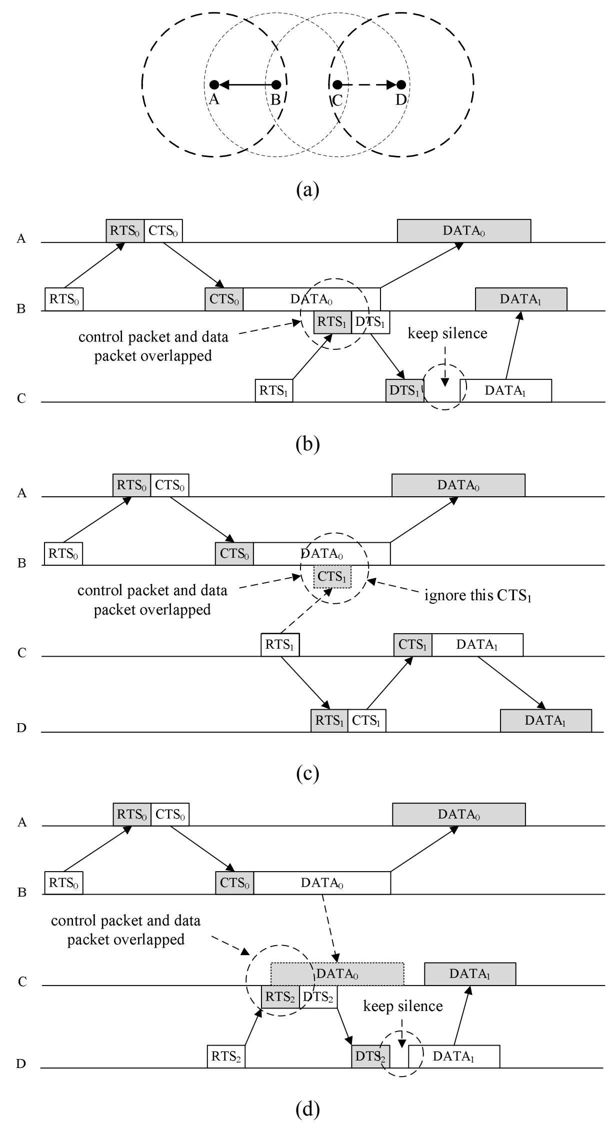


Fig. 4. Schematic of (a) the exposed terminal problems, handling for the exposed sending terminal problem of (b) node C to B (c) node C to D, and (d) hadling for the exposed receiving terminal problem of node D to C.

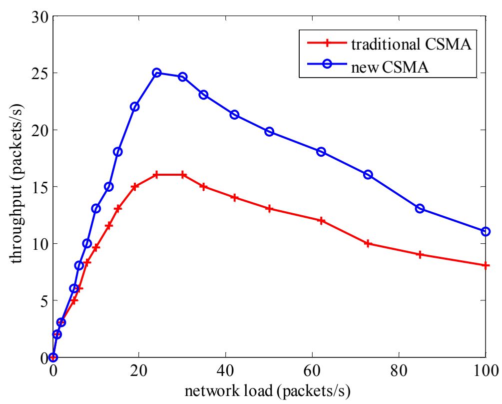
III. SIMULATION RESULTS

To assess the performance of the proposed protocol, simulations were carried out both in software and on semi-physical simulation platform.

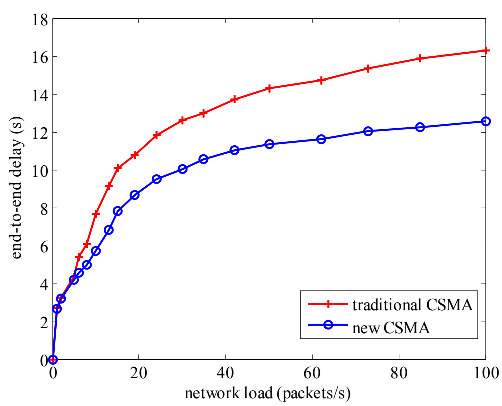
A. *Simulations in Software Enviromnet*

Software simulations were implemented in OMNeT++ 4.0. The simulation scenario was that of a 1 km by 1 km area with 10 nodes at a random location. RTS and CTS packets are 64 bits long, and DATA packets have 1024 bits. The transmission rate is 500 bps. Each node generates packets for random destinations according to a Poisson distribution, and has an infinite transmit queue. The energy consumption of sending is 10 W and 80 mW for receiving. The max transmit range we set here is 0.5 km.

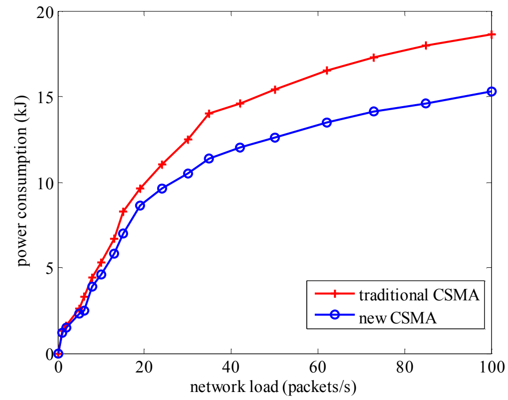
The performance of the proposed protocol was compared to that of the traditional CSMA protocol. We defined throughput as the total successfully received packets per second, and end-to-end delay as the time duration for a packet from start of transmitting to successfully be received. In simulation, statistics of the average throughput, end-to-end delay, and power consumption for each node were made, Fig.5 illustrates the results. As we can see, the new CSMA (the protocol proposed in this paper) earn a higher throughput and lower end-to-end delay than the traditional CSMA in the same condition. Sending a same quantity packets, the new CSMA cost less energy.



(a)



(b)

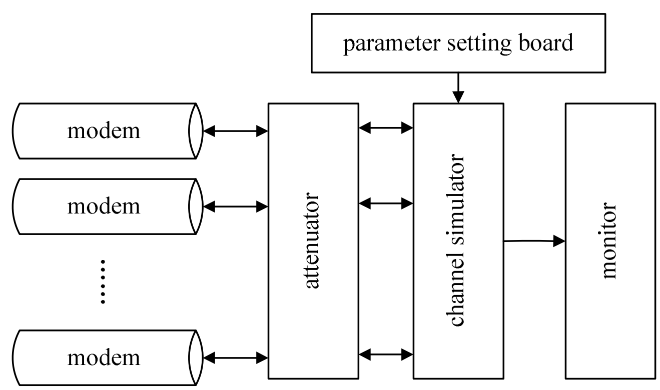


(c)

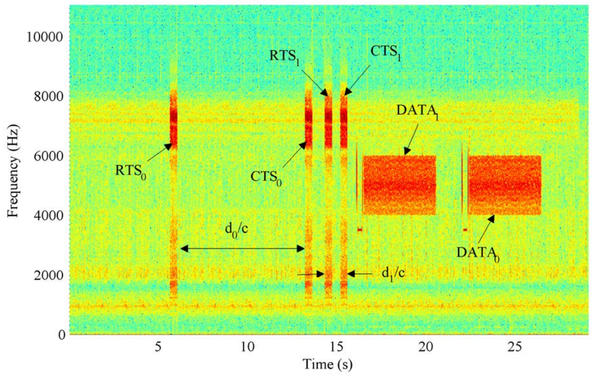
Fig. 5. Simulation results of (a) throughput comparison (b) end-to-end delay comparison (c) energy consumption comparison.

B. *Simulations on Semi-Physical Platform*

We implemented the protocol in real modems and tested its performance in a semi-physical platform. The platform consists of attenuator, channel simulator, parameter setting board and monitor. The attenuator is used for attenuating the large signal from the amplifier output of the modem to a suitable value for the platform input. Channel simulator can simulate the signal attenuation, reverberation, propagation delay, noise and other influences generated by the underwater environment, and the input signal is modulated by the channel simulator. Parameters, such as the node location, distance and noise can be set on the parameter board. Signals in the channel simulator can be observed in real time through the monitor. Fig.6 (a) illustrates the setup of the semi-physical platform simulation. We controlled the data transmitting of each node manually and monitored the data transmitting course on the monitor to investigate whether the protocol is running satisfactorily. Initially, we set the distance of the nodes in a large difference, the data transmitting procedure as described in Fig.2 (a) was recorded shown in Fig.6 (b). Then, we change the node position to reduce the distance difference. Fig.6 (c) shows the recorded data transmitting procedure as described in Fig.2 (b).



(a)



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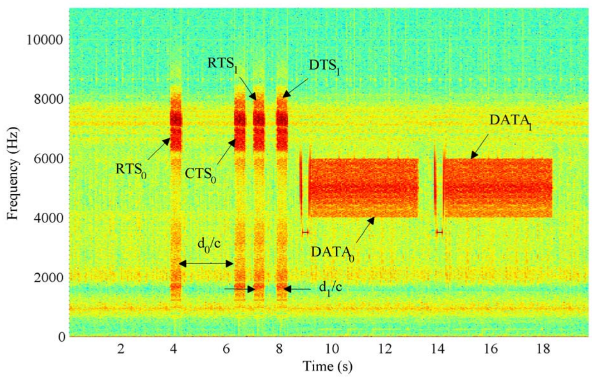
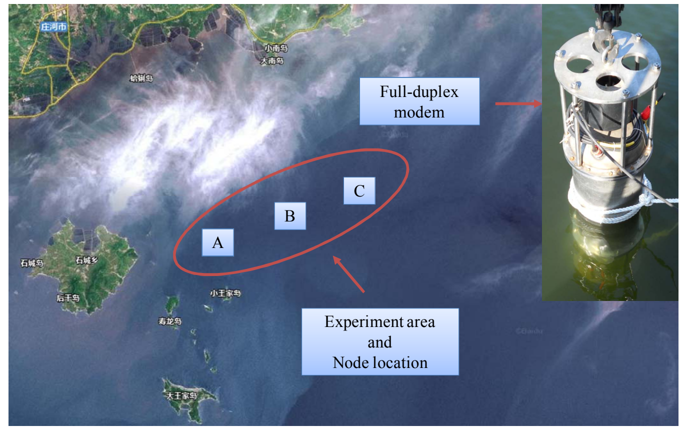


(c)

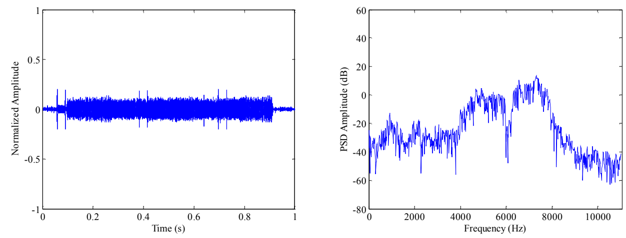
Fig. 6. Semi-physical platform simulation (a) setup schematic and monitor records of data transmitting procedure for (b) large distance difference (c) small distance difference.

IV. SEA TRAIL

Sea trial was conducted to validate the engineering feasibility of the full-duplex communication at the Yellow Sea near northeastern China. We designed and developed three full-duplex modems and they were applied in this trail. Direct Sequence Spread Spectrum (DSSS) approach was employed to modulate/demodulate the control packages at 6-8 kHz frequency band, while the data packages were modulated/de-modulated using Orthogonal Frequency Division Multiplexing (OFDM) approach at 4-6 kHz frequency band. In trail, these modems were set in a line with a distance of 100 m from each other, 10 m below the surface as Fig.7 (a) shows. Node C was used to simulate the hidden terminal and exposed terminal. We monitored the receiving signal at node B, the received original signal and its spectrum on hidden/exposed terminal conditions are separately shown in Fig.7 (b) and (c). As a statistic result, above 95% of the received packages can be decoded correctly either in hidden terminal conditions or in exposed terminal conditions.



(a)



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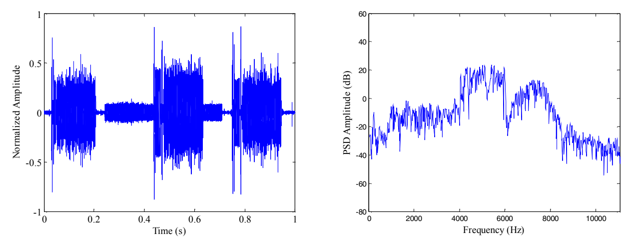

(c)

Fig. 7. Sea trail (a) setup schematic and monitor records of original signal and its spectrm on (b) hidden terminal condition (c) exposed terminal condition.

V. CONCLUSIONS

In this paper, we proposed a full-duplex based and distance aware MAC protocol for underwater acoustic communication network. This protocol can solve the hidden/exposed terminal problems efficiently, and achieve an improved performance as compared to the traditional CSMA protocol. Engineering feasibility of the full-duplex communication is validated through a sea trail by using the full-duplex modem developed by our laboratory. For future work, we planning to consider the problem of new nodes join or nodes drop out, and improve the modem robustness to implement a larger network to test the protocol.

ACKNOWLEDGMENT

This paper is funded by the International Exchange Program of Harbin Engineering University for Innovation-oriented Talents Cultivation, the National Natural Science Foundation of China under Grant No. 1127407 and National

High Technology Research and Development Program of China under Grant No. 2009AA093601-2.

REFERENCES

[1] J. G. Proakis and E. M. Sozer, “Shallow Water Acoustic Networks,” IEEE Communications Magazine, vol. 39, pp. 114-119, Nov. 2001.

[2] W. H, Liu, J. R. Zhang, and X. L. Yu, “An improved BEB algorithm for MAC protocol of underwater sensor networks,” in Proceedings of 2009 2nd IEEE International Conference on Broadband Network and Multimedia Technology, 2009, pp. 800-804.

[3] J. R. Zhang, G. Qiao, and C. Wang, “An intelligent management platform for underwater acoustic modem,” in Proceedings of 2012 5th International Symposium on Computational Intelligence and Design, 2012, pp. 93-96.

[4] X. Xu, E. Sang, G. Qiao, and J. Wang, “A new data acquisition and processing system for profiling sonar,” Journal of Marine Science and Application, vol. 7, pp. 168-173, Sept. 2008.

[5] E. M. Sozer, M. Stojanovic, and J. G. Proakis, “Underwater acoustic networks,” IEEE Journal of Oceanic Engineering, vol. 25, pp. 72-83, Jan. 2000.

[6] B. Peleato, and M. Stojanovic, “Distance Aware Collision Avoidance Protocol for Ad-Hoc Underwater Acoustic Sensor Networks,” IEEE Communications Letters, vol. 11, pp. 1025-1027, Dec. 2007.

[7] V. Rodoplu and M. K. Park, “An energy-efficient MAC protocol for underwater wireless acoustic networks,” in Proceedings of MTS/IEEE OCEANS Conference, 2005, pp. 1198-1203.

[8] W. Y eand J. Heidemann, “Ultra-low duty cycle MAC with scheduled channel polling,” in Proceedings of the 4th international conference on Embedded networked sensor systems, 2006, pp. 321-334.

[9] M. Molins and M. Stojanovic, “Slotted FAMA: a MAC protocol for underwater acoustic networks,” in Proceeding of OCEANS 2006-Asia Pacific, 2007, pp. 1-7.

[10] X. Guo, M. Frater, and M. Ryan, “A propagation-delay-tolerant collision avoidance protocol for underwater acoustic sensor networks,” in Proceeding of OCEANS 2006-Asia Pacific, 2007, pp. 1-6.

[11] Z. Zhou, Z. Peng, J.H. Cui and Z.H. Jiang, “Handling Triple Hidden Terminal Problems for Multichannel MAC in Long-Delay Underwater Sensor Networks,” IEEE Transactions on Mobile Computing, vol. 11, pp. 139-154, Jan. 2012.