A Time Synchronization Method for Underwater Wireless Sensor Networks

Chao Lu, Shuo Wang, Min Tan

The Key Laboratory of Complex Systems and Intelligence Science
Institute of Automation, Chinese Academy of Sciences, Beijing, China, 100190
Email: {chao.lv, shuo.wang, min.tan }@ia.ac.cn

Abstract: In this paper, a time synchronization method for Underwater Wireless Sensor Networks (UWSN), UA-TSP, is presented. The proposed method not only compensates the main time delay in acoustic communication, but also decreases the cumulate errors in the multi-hop scene through an loop convergence method. The implementation of UA-TSP is combined with the nodes discovering process, and less control frame is exchanged. The simulations and experiments results show that the method can reach a satisfactory tradeoff among the time synchronization precision, communication efficiency and power consumption.

Key Words: Time synchronization, Underwater acoustic, Underwater wireless sensor networks

1 INTRODUCTION

In sensor networks, time synchronization plays an important role for its applications [1]. The identical time would help to assign communication channels, process or fuse the sensing data, and predict system behaviors. Some typical applications of time synchronization in mobile underwater sensor networks are concluded as follows.

- Time-stamp. Time synchronization is an essential part for network schedule. Without it, Media access control (MAC) algorithms such as TDMA can not be used for the nodes to share the medium in time domain to eliminate transmission collisions and conserve energy.
- Scheduling. Time synchronization enables the mobile nodes to perceive events in the same time frame. Thus, some mobile nodes can coordinate their operations, or collaborate to complete a complex task on the basis of their time synchronized.
- Information-label. Data fusion is an example of such coordination in which data collected at different nodes are aggregated into a meaningful result.

Time synchronization has been studied in computer networks and embedded systems for decades [1] [2]. In traditional time synchronization methods, such as NTP, TPSN, RBS, nodes calibrate their local time with the received time label without any compensation. These methods can be used well in radio channel or centered networks in the condition that the propagating and sending time delay can be neglected, while these time delay is the main considered factors for improving the precision of time synchronization in UWSN.

In UWSN, acoustic communication magnifies the difficulties in wireless bandwidth, transmit energy, and channel propagation variations. Such difficulties bring more challenges to the time synchronization design for UWSN, which should be low power, good scalability, convergent in multi-hop scene.

Though some work has been done on channel propagating delay measurement in DMTS, the time synchronization error increases with hop numbers because of the error calculation of channel delay.

In this paper, a time synchronization method, UA-TSP, is presented. It not only compensates the main time delay in acoustic communication, but also decreases the cumulate errors in the multi-hop scene. The synchronization process is carried out while the node broadcasting itself, so more energy is saved because of less control frame data exchanged. Therefore, UA-TSP has good performance in acoustic peer to peer networks, such as low power, high precision.

The rest of this paper is organized as follows. Some underwater communication channel characteristics and main time delay are discussed in section 2. The design and implementation of UA-TSP are presented in section 3. The simulation and experiments results are given in section 4. Finally, we conclude the paper in section 5.

2 UNDERWATER ACOUSTIC CHARACTE-RISTICS AND TIME DEALY ANALYSIS

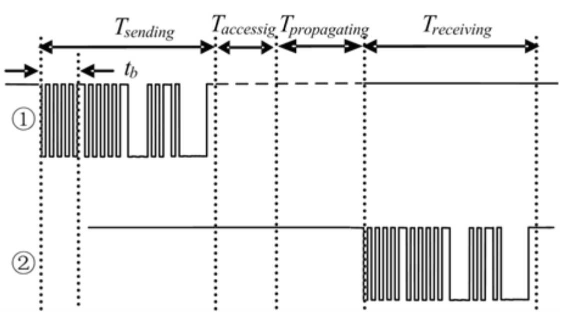
Long time delay of acoustic propagation has crucial influence on synchronization precision. In this section, underwater acoustic characteristics and the time delay in acoustic communication will be discussed in detail.

This work is supported by National Nature Science Foundation under Grants No.60635010 and No.60725309.

The available bandwidth of an underwater acoustic communication channel is severely limited because of the transmission loss which increases with the frequency and the range [4]. A medium-range communication system operating over several kilometers has a bandwidth on the order of 10kHz, while a short range communication system operating over several tens of meters may be available more than 100kHz. Within the limited bandwidth, the signals are subject to multi-path propagation through the channels whose characteristics vary with time and are highly dependent on the location of the transmitters and receivers. Combating multi-path propagation to achieve a high data throughput is considered to be the most challenging task for an underwater acoustic communication system. In this paper, we choose 32kHz as the carrier frequency of underwater acoustic signal, and the bandwidth is limited in 5kHz.

In [4][6], TDMA was proved to be more suitable for underwater acoustic channel access than FDMA and CDMA, because FDMA and CDMA need more band width which is unavailable in the underwater acoustic channel. However, TDMA must take the long time guards into account due to the underwater channel's large propagating delay and delay variance. Moreover, the variable delay makes it a challenge for TDMA to realize precise time synchronization with a common timing reference. The main time delay in underwater acoustic communication is analyzed as follows, and also is compensated in UA-TSP.

Kopetz and Schwab [5] divided packets transmitting delay into four parts, as shown in Fig. 1.



① denotes transmitting the command frame (TX data)
② denotes receiving the command frame (RX data)

Fig. 1. Components of Packets delay

- Sending time, $T_{sending}$, the time which is spent in assembling a packet and queuing in sender. In this paper, the data rate is set to be 256bps, and a data frame of time synchronization includes 13 bytes (each bytes includes 10 bits). Therefore, the sending time can be got with the follows.

$$T_{sending} = 13 \times 10 \times \frac{1}{256} = 0.508S$$

- Accessing time, $T_{accessing}$, the time which is spent in waiting for channel access, and it is mostly related with MAC type. For UWSN, TDMA is used for medium access control, and each node accesses the channel in time as its slot arrives. Therefore, $T_{accessing}$ can be ignored in UWSN.
- Propagating time, $T_{propagating}$, the time which is spent in traveling the acoustic channel between the sender and the receiver. It has been measured while the network is configured, and the detailed measuring method was presented in another paper.
- Receiving time, $T_{reciving}$, the time which is spent in processing the received packets and delivering the packets to the upper layer in the receiver. It is similar to the sending time.

Underwater acoustic communication is apt to be influenced by such factors as multi-path interference, reflecting signal, underwater noise. The phase of demodulated signal usually varies in the maximum range of 1/6 code length, which is denoted as T_{phase}.

In conclusion, the total delay time in time synchronization for UWSN can be expressed as follows.

$$T_{total} = T_{propagating} + T_{sending} + T_{phase} \quad (1)$$

3 DESIGN AND IMPLEMENTATION OF UA-TSP

UA-TSP is designed and implemented with two parts, the node local real time and the synchronization protocol. They are presented as follows.

3.1 Time synchronization method

The bias is ignored in the process of time synchronization (finishing in one hour), and the precision of time synchronization is only concerned with time delay compensation and synchronization algorithm.

All nodes' clock cycles are same, so the received time label and the local time label have the same credited degree. After compensating to the received time label, the nodes average it with their local time label, and then update the local time label with the average results. In the process of averaging, the compensation is also reduced by half. Therefore, in a multi-hop network, the front compensation error will do less effect for the following nodes, and this character is one of the shortcomings for other time synchronization methods, such as DMTS.

In UA-TSP, each sensor node's local time label will be updated with the following equations after it received a time synchronization packet.

$$t_i^{'} = \frac{t_i + (t_r + C_i^{(r)})}{2} \quad (2)$$

In equation (2), t_i and $t_i^{'}$ denote the local time label of node i before and after synchronized with node r separately, t_r denotes the received time label from node r, $C_i^{(r)}$ denotes the time delay compensation for the time label of node r.

Then the timer of node r will be restarted from the updated label, $t_i^{'}$, and how the node local time operating will be discussed in section 3.2.

3.2 Design of node local real time

A low cost, low power underwater sensing node is presented in [5], which is equipped with an acoustic modem and some sensors, as shown in Fig. 2 and Fig. 3. A precise oscillator is very helpful to the proposed time synchronization method.

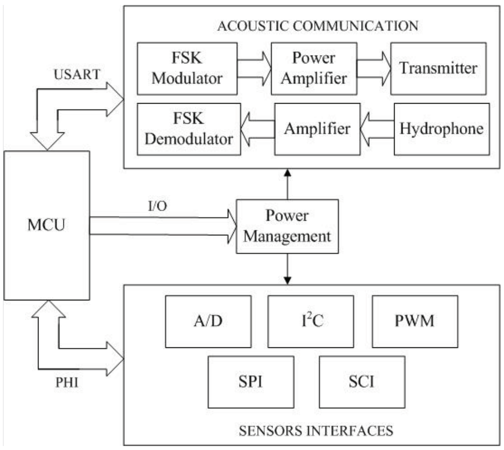


Fig. 2. Diagram of the low-cost sensing node

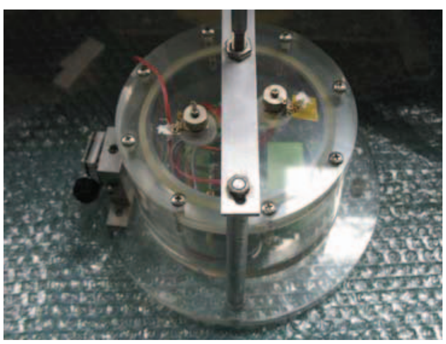


Fig. 3. Picture of the node

Hardware oscillators, which implement an approximation *C(t)* of local time *t*, are mostly equipped as an assist of MCU clock. The angular frequency of a hardware oscillator determines the clock rate.

Each node local time, $T_i(t)$, can be expressed as follows

$$T_i(t) = \frac{1}{f_0}\int_0^t f_i(t)dt + C_i(t_0) \qquad (3)$$

Where f_0 is the nominal value of the oscillator, $f_i(t)$ is the real operating frequency, t_0 is the initializing point, $C_i(t_0)$ is the time value of t_0. Usually, there are a little offset between f_0 and $f_i(t)$ which is caused by environment temperature, humidity, or small errors from manufacture process. f_i/f_0 is called the relative frequency offset which is limited between 1-p and 1+p, and p is the absolute frequency offset margin, which is mostly limited between 1 and 100 PPM (Parts Per Million) and can be compensated by some algorithms.

Fig. 4 shows the hardware oscillator implementation. The AVR micro-controller has Timer/Counter Oscillator pins (TOSC1 and TOSC2), and the crystal chip can be connected directly between the pins. The selected oscillator is a 32.768 kHz watch crystal. Thus, a local timer is built, and the local time is configured with the following format.

Year, Month, Day, Hour : Minute : Second : Millisecond : Microsecond

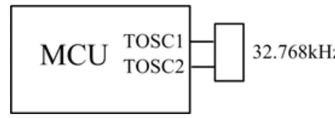


Fig. 4. Oscillator connected with MCU

Although the oscillators of different nodes have a small frequency offset, the bias among different nodes local time increase slowly with the time elapsed. The bias can achieve several seconds after continually working for some days. However, the differences among the node local time must be no more than one second for avoiding the channel collisions in our system, because the time guard of TDMA is set to be one second. For achieving time synchronization to all nodes, the next section will give a detailed solution for UWSN.

3.3 Design and implementation of UA-TSP

As mentioned above, there are many limitations for time synchronization in UWSN, such as low power, high precision, and good scalability. We conclude the requirements of time synchronization firstly as below. [3]

- Energy efficiency. Synchronization schemes should take into account the limited power supply in sensor nodes.
- Precision. The request of precision, or accuracy, may vary significantly with specific applications and the purpose of synchronization.
- Scalability. Synchronization scheme should scale well with increasing number of nodes in high density network.
- Scope. The synchronization scheme may provide a global time base for all nodes in the network, or local synchronization only among spatially close nodes.
- Cost and size. Underwater sensor nodes are very small and inexpensive devices. Therefore, attaching relatively large or expensive hardware on a small cheap device is not a logical option for synchronizing sensor nodes.

The whole network architecture is shown in Fig. 5, which is divided into many clusters according to the ranges between sink nodes and sensor nodes. And a cluster with 5 nodes including one sink node and four sensor nodes is taken out, as shown in Fig. 6. In the network, terrestrial server broadcasts the standard time through radio communication periodically. After the sink nodes receive the standard time label, UA-TSP will be started from the sink nodes.

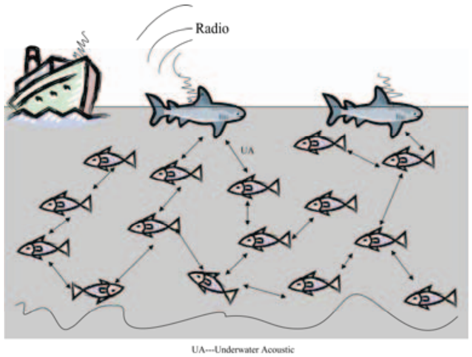


Fig. 5. Framework of the whole network

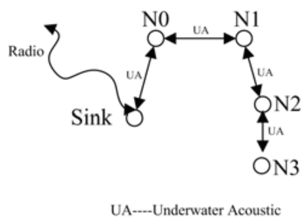


Fig. 6. A cluster for time synchronization

After the nodes are distributed under water, they will do nothing until the synchronization command is received. And they only update their time label with the received time label before the nodes start working. When the sink nodes start UA-TSP, other nodes obey the rules presented in section 3.1 to update their time label. As their time slots arrive, they broadcast their local time. The synchronization times is controlled by the sink node.

After some synchronization rounds, all nodes' local time will be converged to be identical within an acceptable error. The Implementation of UA-TSP is described as the following pseudocode.

Synchronization algorithm for underwater acoustic sensor networks

For each sensor node n_i in the network do
if it is the sink node **then**
if the local time has been updated by the terrestrial server and has not broadcast local time or has not complete UTSP **then**
Broadcast its local time in the format of the synchronization command
else return
else if it is sensor node **then**
if it has never synchronized **then**
Keep idle status and nothing to do till synchronization command is received and then update local time.
else if it has received synchronization command **then**
Average the received time and local time to update its local time, and then broadcast the local time in its time slot
else return
else return

4 SIMULATIONS AND EXPERIMENTATIONS

In this section, several simulations and experiments were done to verify the proposed UA-TSP.

4.1 Simulations with network simulator

We have done some simulations about UA-TSP on network simulator version 2 (NS-2). The signal liner topology is the most basic one,

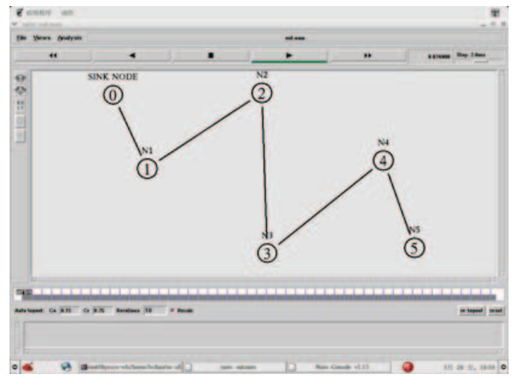


Fig. 9. Simulation Scene

Some simulation parameters are listed in Table.1.

Table.1 Simulation Configuration

Parameters	Value
Node numbers	6
Baud rate	256 bps
MAC type	TDMA
Synchronization rounds	5

As shown in Fig. 9, 5 nodes enter the scene one by one, and then form the topology. Sink node broadcast its initial time, and then the synchronization process is carried out as the previous description.

Mean-square deviation of the clustered nodes local time shows the method convergence effect. As shown in Fig. 7, the mean-square deviation of nodes' local time decreases with the synchronization round numbers, and it changes little when the round number is more than 5. Therefore, with the consideration of the precision and energy consumption, a reasonable choice is 5 rounds in each synchronization process.

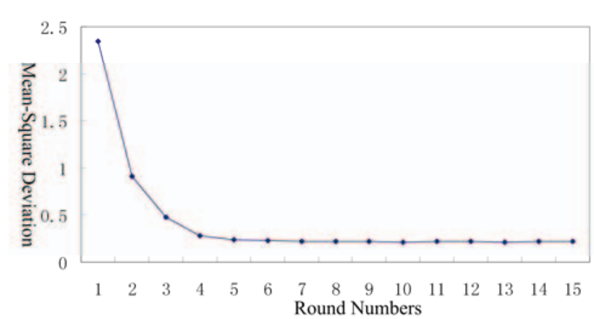


Fig. 7. Mean-square deviation variations with synchronization times

Time synchronization effect with hop numbers is also an important index in multi-hop networks. UA-TSP employs loop convergence method to decrease multi-hop effects, as shown in Fig. 8. In underwater acoustic communication, hop numbers are mostly less than 5 because of large propagating delay.

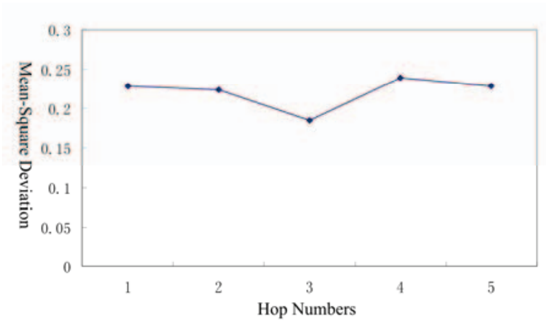


Fig. 8. Mean-square deviation variations with hop numbers

Time synchronization process simulation started at 1s, and time slot for each node was set with 5s. Mean-square deviation shows consensus of time synchronization in Fig. 10. Time differences between sink node (time reference) and other sensor nodes are shown in Fig. 11. In the synchronization process, the mean-square deviation decreases fast and stably, and converges to zero.

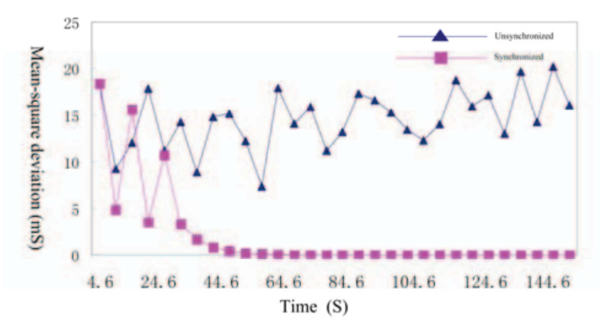


Fig. 10. Mean-square deviation variations in a synchronization period

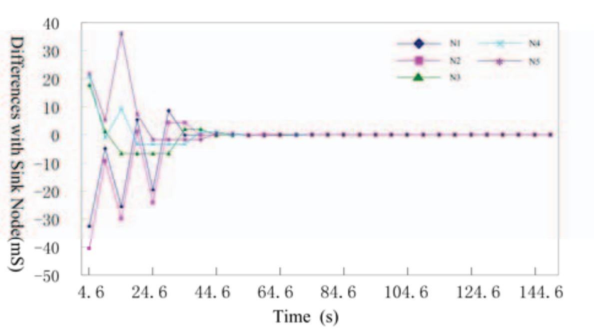


Fig. 11. 5 Convergence chart in a synchronization period

The simulation results show UA-TSP keeps high precise in multi-hop UWSN, and has good convergent efficiency. Therefore, UA-TSP is efficacious and reaches our requirements for UWSN.

4.2 Experiments

A hardware platform was established with several prototype nodes presented in section 3.2. And some experiments were done in tank to evaluate the proposed UA-TSP, as shown in Fig.12. The link status chart is shown in Fig.13. The nodes communicated with each other by the modulated acoustic signal. TDMA was employed to share the underwater acoustic channel.

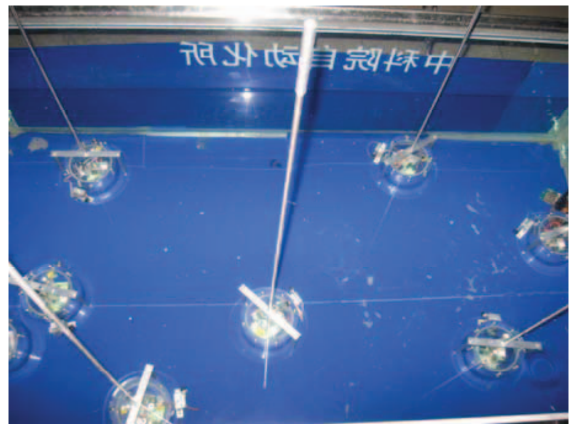


Fig. 12 Tank experiments scene

The transducers applied in the nodes transmit acoustic signal directionally. And also the reflected signal from the walls of tank is full of the space under water, because the tank is too small, just 1m*2m. However, a multi-hop peer to peer network can also be configured.

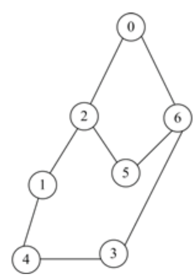


Fig. 13 Link status chart

Experiment parameters are given in Table.2.

Table.2 Experiment Configuration

Parameters	Value
Node numbers	7
Baud rate	256bps
Channel type	Ultrasonic
Carrier frequency	32kHz
MAC type	TDMA
System clock	8 MHz
Timer clock	32.768 KHz
Time slot size	10s
Synchronization round times	5

The Comparison of the initial time label and the synchronized time label of the 7 nodes are listed in Table.3. At first, the sink node receives time synchronization commands from the terrestrial sever and starts synchronization process. The sensor nodes are initialized with the received time firstly, and then UA-TSP is carried out among them.

Table.3 experiments results

		D	H	M	S	mS	uS
Unsynch-ronized	N0	27	22	10	49	475	830
	N1	27	22	10	52	136	322
	N2	27	22	10	46	439	26
	N3	27	22	10	41	453	766
	N4	27	22	10	39	211	975
	N5	27	22	10	55	343	475
	N6	27	22	10	43	286	713
Synch-ronized	N0	23	22	26	44	832	711
	N1	23	22	26	44	578	652
	N2	23	22	26	44	847	803
	N3	23	22	26	44	410	275
	N4	23	22	26	44	447	399
	N5	23	22	26	44	832	651
	N6	23	22	26	44	773	569

These experiments show that the time synchronization precision of UA-TSP is less than one second, which can meet the precision requirements of TDMA in UWSN.

5 CONCLUSION

Time synchronization plays an important role for all kinds of networks, which can make nodes synchronize and cooperate with each other to accomplish some complex tasks. However, less work has been done on time synchronization for underwater applications. In this paper, UA-TSP is proposed under the consideration of underwater acoustic characteristics and the synchronization precision improvement for UWSN. The precise local timer and the loop convergence method are integrated to implement UA-TSP. The results of simulations and experiments show that the proposed method is valid and satisfies the requirement of UWSN, in which TDMA is used for the underwater acoustic channel access control..

REFERENCES

[1] Li Q, Daniela R, Global Clock Synchronization in Sensor Networks, IEEE Trans. On Computers, Vol.55, 214~226, 2006.

[2] David L., Prescisions synchronization of computer network clocks, ACM/IEEE Trans. on Networking, Vol.6, 505~514, 1998.

[3] Su W, Ian F. A, Time-Diffusion Sysnchronization Protocol for Wireless Sensor Networks, IEEE/ACM Trans on Networking, Vol.13, 384~397, 2005.

[4] Ian F.A, Dario P, Tommaso M, Underwater acoustic sensor network: research challenges, Ad Hoc Networks, No.3, 257~279, 2005.

[5] Chao Lu, Shuo Wang, Min Tan, Design and Realization of sensor nodes for dense underwater wireless sensor networks [C], Proceedings of the 17th World Congress of The International Federation of Automatic Control, Seoul, Korea, July 6-11, 2008, pp. 12819-12824

[6] Kopetz H, Schwabl W, Global time in distributed real-time systems, Technical Report 15/89, Technische Universitat Wien, 1989.

[7] Carrick D, Iuliu V, Daniela R, An Underwater Sensor Network with Dual Communications, Sensing, and Mobility, OCEANS 2007 - Europe, 1~6, 2007