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Guard Time Settings in TDMA Family MAC Protocol for Underwater Sensor Networks

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In order to increase the network efficiency in TDMA protocols with the fixed guard time for underwater sensor networks, a new guard time setting approach between consecutive packets considering the uncertainty of the underwater acoustic propagation delay is proposed in this paper. By using a collision model of the two adjacent packets, the relationship of the guard time and the distances between the receiving node and the sending nodes under the given collision probability is analysed. The guard times can be varied with the distances between the receiving node and the sending nodes under the given collision probability, which can overcome the disadvantages of the previous TDMA protocols with the low network efficiency. Theoretical analysis and simulations show that this approach can reduce the idle time of channel and improve the efficiency of underwater acoustic sensor networks. The proposed approach is suitable for single hop underwater acoustic sensor networks based on continuous time allocation TDMA protocols and can be easy to extend to the tree-like hierarchical topology.

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1.Introduction

The underwater sensor network (USN) differs from the terrestrial wireless sensor network (WSN) in many respects[1,2]. In particular, the propagation speed of the underwater acoustic channel is much lower than that of the radio channel and it varies with the temperature, salinity, depth and the other environmental factors. The unique characteristics of underwater channels require very efficient and reliable new data communication protocols for USNs, especially the MAC protocols[3-5].

TDMA is a good candidate and has been widely used in USN because it is simple, effective[6,7]. Since the data packets are transmitted only within the given time slots, the transmitter can be shut down for the most of time, which enables the nodes to reduce energy consumption effectively. The traditional TDMA requires the data transfer to be completed in a single time slot and the time slot should be long enough to avoid collisions due to the differences in propagation delays, which results in low channel utilization. Regarding the low channel utilization of the traditional TDMA in USN, there have been some improvements. In the continuous time allocation TDMA protocols[8-10], the center node schedules the data packets sent from each sensor node arrive consecutively. However, due to the large propagation delay variation in underwater channels, the protocols have to add the guard times between adjacent packets and avoid collisions. The guard time must be large enough to avoid possible collisions due to the variation of the propagation delay. So the challenging is how to set the optimal value of the guard times.

This paper proposes an effective approach to set guard times in USN. Based on the collision model of two adjacent packets, the relationship between the guard times and the distances between the center node and the sensor nodes is analysed, then the guard time setting policy are suggested based on this relationship. The simulation results show the effectiveness of this approach.

2.Continuous Time Allocation TDMA Protocol

In the traditional TDMA, the packets are transferred at the beginning of the each time slot as shown in Fig.1.

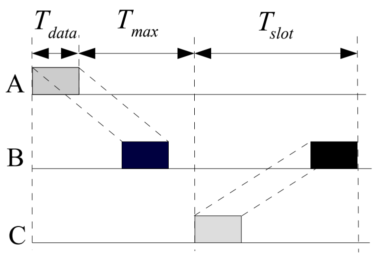


Figure 1: The time slot of the traditional TDMA

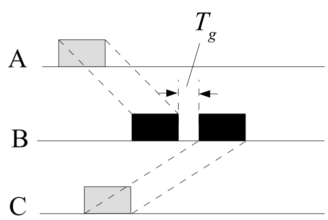


Figure 2: The packet transfer for the continuous time allocation TDMA

The length of time slots T_{slot} is equal to the sum of the packet transmission time T_{data} and the maximum propagation delay T_{max} in the network. The continuous time allocation TDMA protocols can reduce the idle time in underwater channels, as shown in Fig.2. Because the propagation speed is variable in underwater channels, it is necessary to set the guard time T_g between two adjacent packets large enough in order to avoid collisions. In existing continuous time allocation TDMA protocols, the guard time is usually set to a fixed value by considering the maximum propagation delay in networks, which results in low network efficiency.

3.Guard Time Setting based on the Collision Model of Two Adjacent Packets

3.1 Variation characteristics of underwater acoustic propagation delay

Underwater acoustic propagation speed C (in *m*/*s*) can be modeled as the following in [11]:

$$C(z,S,t) = 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 + \left(1.333 - 0.126t + 0.009t^2\right)(S-35) + 16.3z + 0.18z^2 \tag{3.1}$$

where t=T/10 , T is the temperature in ℃ , S is the salinity in *ppt*, and z is the depth in *km*. As known in (3.1), the acoustic propagation speed is a function of some environmental factors. Besides, water current and turbulence also affect the acoustic propagation speed. All these factors contribute to the uncertainty of the propagation delay. The acoustic propagation speed in the different underwater environments is generally in the range of (1460*m*/*s*, 1520*m*/*s*), and the center value is 1500*m*/*s*[11]. In this paper the variation of the underwater propagation delay is assumed to be a Gaussian distribution and the statistical characteristic of propagation delay varying with the distance between nodes is analyzed. If the average distance between transmitter-receiver nodes is denoted as R, the packet propagation delay can be obtained as D=R/C, where C is the average underwater acoustic speed and its value is C = 1500*m*/*s*. In practice, there exists variation of propagation speed and it is functions of transmitter-receiver distance. Accordingly, the packet arrival time at the receiver is also Gaussian distributed. For the convenience of analysis, the maximum value of the variation of the propagation speed is denoted as $\varsigma C_{\max}$ and the maximum variation of the inter-nodal propagation delay is denoted as $\varsigma D_{\max}$. Then the propagation speed is in the range of $(C-\varsigma C_{\max}, C+\varsigma C_{\max})$ and the relationship between $\varsigma D_{\max}$ and $\varsigma C_{\max}$ can be expressed as:

$$D \pm \varsigma D_{\max} = R \big/ \left(C \mp \varsigma C_{\max}\right) \tag{3.2}$$

From equation (3.2), $\varsigma D_{\max}$ is obtained as:

$$\varsigma D_{\max} = \Delta C_{\max} \, R \big/ \left[C\left(C \pm \varsigma C_{\max}\right)\right] \tag{3.3}$$

Denoting $k_{\max} = \dfrac{\varsigma C_{\max}}{C\left(C \pm \varsigma C_{\max}\right)}$, $\varsigma D_{\max}$ is simply expressed as:

$$\varsigma D_{\max} = k_{\max} R \tag{3.4}$$

This equation describes that the maximum variation of the inter-nodal propagation delay increases along with the propagation distance. Considering $\varsigma C_{\max} = 40$ *m*/*s*[11], we can get $k_{\max} = 1.8265 \times 10^{-5}$. It is difficult to know the exact relationship between the propagation delay variation ςD and the propagation distance R. Considering the Gaussian distribution, the values less than three standard deviation away from the mean account for 99.73% of the set, then we know $\varsigma D < 3\sigma$, where σ is the standard deviation of the Gaussian distribution. That is, we can assume $\varsigma D_{\max} = 3\sigma$. Combining (3.4), σ can be written as

$$\sigma = \frac{1}{3}\varsigma D_{\max} = \frac{1}{3} k_{\max} R \tag{3.5}$$

The variation of the acoustic propagation delay in underwater increases with the propagation distance.

3.2Relationship between the collision probability and the guard time

Since the underwater acoustic propagation speed is not fixed, the underwater inter-nodal propagation delay is variable. It may bring collisions between the adjacent packets in the continuous time allocation TDMA protocols for USN. The collision model of the two packets arriving at the receiving node consecutively is shown in Fig.3. Both the packet *i* and the packet *i*+1 are sent independently by the two sensor nodes. Attention here the number "*i*" is the sequence number for every sensor node in packet sending order[6] in the network.

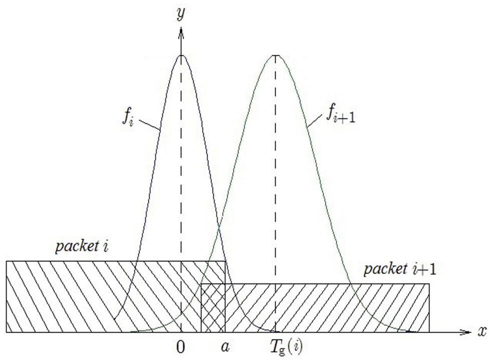


Figure 3: The collision model of two adjacent packets

f_i is the distribution function of the tail of the packet *i* at the receiving node and can be expressed as

$$f_i(x) = \frac{1}{\sigma_i\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma_i^2}} \tag{3.6}$$

f_{i+1} is the distribution function of the head of the packet *i*+1 and can be expressed as

$$f_{i+1}(x) = \frac{1}{\sigma_{i+1}\sqrt{2\pi}} e^{-\frac{(x-T_g(i))^2}{2\sigma_{i+1}^2}} \tag{3.7}$$

where $T_g(i)$ is the guard time between packet *i* and packet *i*+1. In (3.6) and (3.7), σ_i and σ_{i+1} are respectively written as

$$\sigma_i = \frac{1}{3} k_{\max} R_i \tag{3.8}$$

$$\sigma_{i+1} = \frac{1}{3} k_{\max} R_{i+1} \tag{3.9}$$

where R_i is the propagation distance between the receiving node and a sending node *i* and R_{i+1} is the propagation distance between the receiving node and a sending node *i*+1. In Fig.3, the *x* coordinate value of the tail of packet *i* is defined as *a*. If *x* coordinate value of the head of packet *i*+1 is less than *a*, it means that a collision between the two packets will occur. So, for any value *a*, the collision probability of two adjacent packets is as follows

$$dP_c = f_i(a)da \int_{-\infty}^{a} f_{i+1}(x)dx \tag{3.10}$$

Because the value *a* is in the range of $(-\infty, +\infty)$, the collision probability of two adjacent packets can be obtained as

$$P_c = \int_{-\infty}^{\infty} f_i(a) \int_{-\infty}^{a} f_{i+1}(x) dx da \tag{3.11}$$

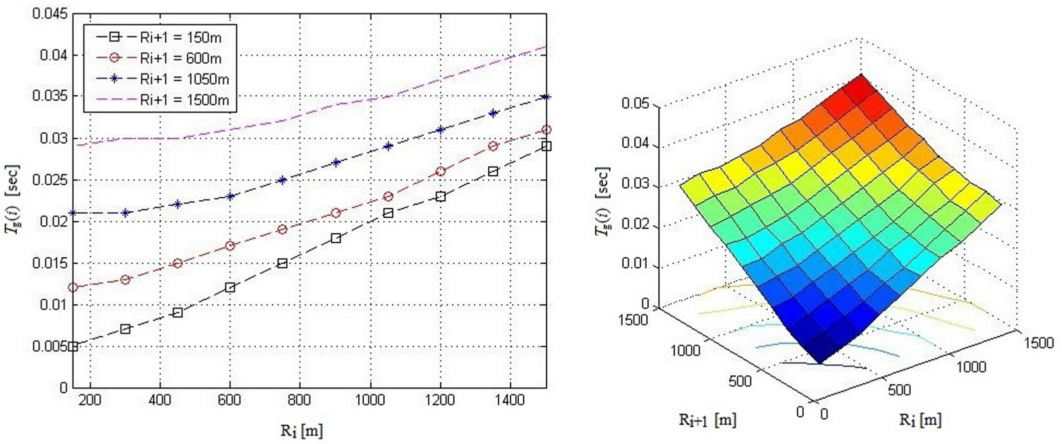
Solving (3.11), the collision probability is

$$P_c = \frac{1}{2} + \frac{1}{2}\int_{-\infty}^{+\infty} \frac{1}{\sigma_i\sqrt{2\pi}} e^{-\frac{a^2}{2\sigma_i^2}} erf\left(\frac{a - T_g(i)}{\sigma_{i+1}\sqrt{2}}\right) da \tag{3.12}$$

As shown in (3.12), when $T_g(i)$=0, that is, there is no guard time between two packets, P_c=0.5 and P_c decreases with increasing $T_g(i)$.

3.3Guard time setting

The guard time between two adjacent packets under the given collision probability can be obtained by solving (3.12). However, $T_g(i)$ is difficult to be solved directly from (3.12), so the relationship between $T_g(i)$ and P_c is studied by numerical method and look-up table method. Fig.4 shows the relationship between the guard time and the distances between the receiving node and the two sending nodes when the collision probability is given as P_c=0.001.



(a) The guard time when R_{i+1} is fixed (b) The guard time when R_i and R_{i+1} are varied

Figure 4: The guard time varying with the distances between the receiving node and the two sending nodes

As shown in Fig.4, when the distances between the receiving node and the two sending nodes are in the range (100*m*, 1500*m*), the guard times are in (0.005*s*, 0.043*s*). The look-up table method can be used to determine the guard times in practice.

4.Simulations

In order to validate the effectiveness of the proposed guard time setting policy, we consider a single hop USN with star topology as shown in Fig.5.

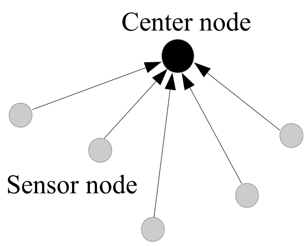


Figure 5: The single hop sensor network with star topology

The compared protocols include traditional standard TDMA with fixed time slots (Trad-TDMA), continuous time allocation TDMA with the fixed guard time(TDMA/fixed-T_g) and continuous time allocation TDMA with the varied guard time(TDMA/varied-T_g) proposed in this paper. The distance between the center node and every sensor node is a random number between 100*m* and 1500*m*. The collision probability is set as 0.001, that is, the collision of packets will practically never occur. The packet transmission time is set as 0.5*s*. Because the maximum propagation delay is 1*s*, the length of the time slots is also 1.5*s* in Trad-TDMA. From Fig.4, when the distances between the receiving node and the two sending nodes are 1500*m* respectively, the maximum value of the guard time is T_g=0.43*s*. This value is just the fixed guard time of TDMA/fixed-T_g. The guard time of TDMA/varied-T_g is varied with the propagation distances. In simulations, the results are averaged over 100 iterations. The performance parameters are the channel utilization and the average point to point delay. Fig. 6 shows the channel utilizations of three TDMA protocols with respect to the number of sensor nodes.

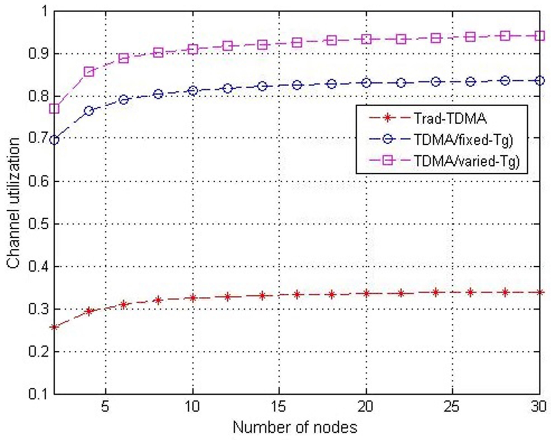


Figure 6: The channel utilization of three TDMA TDMA protocols

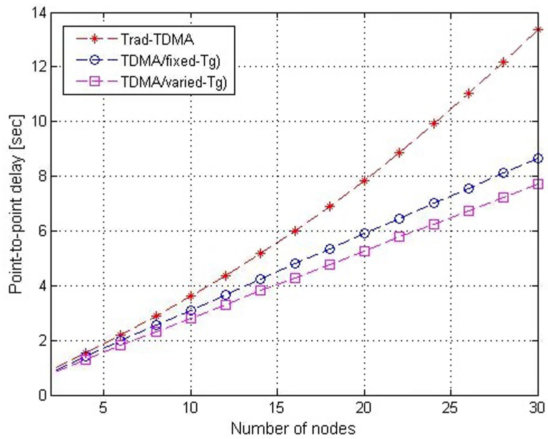


Figure 7: The point-to-point delay of the three protocols

From Fig.6, we can see that the channel utilization of Trad-TDMA is much lower than continuous time allocation TDMA protocol's. TDMA/varied-T_g proposed in this paper is superior to TDMA/fixed-T_g because the guard times of TDMA/varied-T_g are always shorter than that of TDMA/fixed-T_g. The channel utilization difference between TDMA/varied-T_g and TDMA/fixed-T_g becomes more remarkable as the number of sensor nodes N increases; TDMA/varied-T_g increases channel utilization by 9.5% when N = 30, compared to TDMA/fixed-T_g.

Fig.7 shows the average point to point delays of the three TDMA protocols with respect to the number of sensor nodes. As shown in Fig.7, the point-to-point delay of the three TDMA protocols increase, as the number of sensor nodes increases. The increasing rate of the point-to-point delay in the continuous time allocation TDMA protocols is significantly lower than that in Trad-TDMA. It is shown that TDMA/varied-T_g is superior to TDMA/fixed-T_g as the number of sensor nodes increases.

5.Conclusion

Based on the uncertainly modeling of the acoustic propagation delay, a new guard time setting method for TDMA is proposed in this paper. It can be used in continuous time allocation TDMA protocols for USN applications. We firstly inferred the collision model of the two packets arriving at the receiving node consecutively and then the relationship between the guard time and the collision probability. The proposed guard time setting method makes the continuous time allocation TDMA performs better than that with fixed guard time. It's also superior to the traditional TDMA. This method is suitable for the design and developing of TDMA based USNs with star topology and can be easily extended to tree like hierarchical topology.

References

[1] I. F. Akyildiz, D. Pompili and T. Melodia. *Underwater acoustic sensor networks: research challenges*[J]. Ad Hoc Networks. 3(3):257-279(2005)

[2] J. Heidemann, W. Ye and J. Wills. *Research challenges and applications for underwater sensor networking*[C]. WCNC 2006. IEEE. Las Vegas, NV, USA. pp:228-235(2006)

[3] G. Acar, A. E. Adams. *ACMENet: an underwater acoustic sensor network protocol for real-time environmental monitoring in coastal areas*[C], IEE Proceedings-Radar, Sonar and Navigation. IFT. 153(4). pp:365-380(2006)

[4] M. K. Park, V. Rodoplu. *UWAN-MAC: an energy-efficient MAC protocol for underwater acoustic wireless sensor networks*[J]. Oceanic Engineering. 32(3):710-720(2007)

[5] C. Salvador, S. Antonio and C. J. Vicente. *Underwater Acoustic Wireless Sensor Networks: Advances and Future Trends in Physical, MAC and Routing Layers*[J]. Sensors. 14(1):795-833(2014)

[6] F. Tong, J. R. Lu. *A TDMA protocol for underwater acoustic network*[J]. Journal of China Institute of Communications. 24(4):104-109(2003) (In Chinese)

[7] Y. X. Zhong, J. G. Huang and J. Han. *A TDMA MAC protocol for underwater acoustic sensor networks*[C]. Information, Computing and Telecommunication, 2009. YC-ICT '09. IEEE Youth Conference on. IEEE. Beijing, China. pp:534-537(2009)

[8] L. Hong, F. Hong and Z. W. Guo. *A TDMA-Based MAC Protocol in Underwater Sensor Networks*[C]. Wireless Communications, Networking and Mobile Computing, 2008. WiCOM '08. 4th International Conference. IEEE. Dalian, China. pp:1-4(2008)

[9] S. Park. *An efficient transmission scheme for underwater sensor networks*[C]. Oceans 2009-EUROPE. IEEE. Bremen, Germany. pp:1-3(2009)

[10] K. Kredo, P. Djukic and P. Mohapatra. *STUMP: Exploiting Position Diversity in the Staggered TDMA Underwater MAC Protocol*[C]. INFOCOM 2009. IEEE. Rio de Janeiro. pp:2961-2965(2009)

[11] R. J. Urick. *Principles of Underwater Sound 3th Edition*[M]. McGraw-Hill(1983)