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AN ENHANCED DYNAMIC TOKEN PROTOCOL FOR UNDERWATER ACOUSTIC SENSOR NETWORKS

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Abstract- The properties of underwater acoustic channel are quite different from those of terrestrial wireless sensor networks. There are many challenges to design an efficient media access control (MAC) protocol for underwater acoustic sensor networks (UWASNs). In order to overcome the long propagation delay and low available bandwidth of UWASNs, an enhanced dynamic token protocol (EDTP), is proposed in the paper. It uses token passing queue (TPQ) and TPQ backup method to transfer the token packets dynamically and efficiently, leading to improving the channel efficiency of the networks. Simulation results show that compared with the existing protocols, the proposed protocol can achieve a high throughput, a low packet drop ratio, and a low transmission delay.

Index terms: Underwater acoustic sensor networks (UWASNs), enhanced dynamic token protocol (EDTP), token passing queue (TPQ)

I. INTRODUCTION

Since underwater acoustic sensor networks (UWASNs) are useful for the oceanic environment monitoring, assisted navigation, disaster prevention and tactical surveillance, more and more researchers began to investigate this topic in recent years. The channel of UWASNs has many specific characteristics, such as long propagation delay, low available bandwidth, multi-path transmission, Doppler spread, many techniques for UWASNs, therefore, are different from those in terrestrial wireless networks [1, 2]. Including the routing and energy distribution technique [3, 4], designing a suitable MAC protocol is an important and challenging issue in UWASNs. Considerable research effort has been invested and many MAC protocols were proposed for UWASNs in recent years.

Schedule-based protocols are widely used for UWASNs for their simplicity. In [5] a spatial-temporal MAC (ST-MAC) scheduling for UWASNs based time division multiple access (TDMA) is proposed. ST-MAC uses spatial-temporal conflict graph and vertex coloring methods to overcome spatial-temporal uncertainty in UWASNs. In [6], an ordered carrier sense multiple access (Ordered CSMA) is proposed for single-hop UWASNs. The Ordered CSMA allows multiple carriers from multiple sources to propagate at the same time. The protocol greatly improves the channel utilization.

Besides the schedule-based protocols, contention-based protocols have also been paid close attention to for UWASNs. T-Lohi [7] is a tone-based contention protocol for single-hop underwater networks. By exploiting space-time uncertainty and high latency to detect collisions and count contenders, the T-Lohi protocol achieves a high throughput and reduces energy consumption. However, in the T-Lohi protocol, the duration of the CR is long so that the throughout is decreased. In [8, 9], two types of contention-based MAC protocols, modified from slotted ALOHA, are proposed for UWASNs. For solving the problems of space-time uncertainty and long propagation delay in UWASNs, the modified protocols reduce the collisions of the packets and improve the throughput of the networks. Inspired by the theory of compressed sensing and employing random channel access, a distributed energy-efficient sensor network scheme denoted by random access compressed sensing (RACS) is proposed in [10]. It is suitable for long-term deploying underwater networks with sparse phenomena and signals, in which saving energy and prolonging the network lifetime are of crucial importance. Slotted floor acquisition multiple accesses (SFAMA) [11] is another contention-based protocol based on FAMA for UWASNs. Compared to TDMA, SFAMA has no idle slot, and the nature of the random access leads to a higher throughput. However, because of the high propagation delay in UWASNs, the handshaking mechanism used in SFAMA still results in long delay. In [12], a handshaking-based MAC protocol based on the receiver reservation, namely RIPT protocol, is proposed for multi-hop underwater acoustic networks. The RIPT addresses the channel's long propagation delay characteristic by coordinating packets from multiple neighboring nodes to arrive in a packet train manner at the receiver. It achieves a high throughput, as well as maintaining a low collision rate for avoiding the hidden terminal problem. However, there are still some drawbacks for the RIPT protocol. It is difficult for the node to determine the time to initiate a ready-to-receive message in this protocol. And the four-way handshake also considerably reduces the throughput, especially in the presence of long propagation delay.

Hybrid MAC protocols for UWASNs are paid close attention to recently. In [13], a distributed protocol for long-latency access networks (PLAN), based on CDMA technology, is proposed. In PLAN, a node uses a unique spreading code like a pseudo-random noise codeword (PN sequence) to encode its signal (such as RTS, CTS and data) before transmitting. So the intend receivers broadcast one CTS for a few accumulated RTS packets and receive signals from multiple senders at the same time. In [14], the authors combine both ALOHA and CDMA and propose a transmitter-based CDMA MAC protocol for UWASNs. They use a novel closed-loop distributed algorithm to set the optimal transmit power and code length to minimize the near-far effect [15]. The protocol achieves low channel access delay, low energy consumption and high network throughput. In [16], a hybrid spatial reuse time-division multiple-access (HSR-TDMA) protocol, based time division technology and direct sequence spread spectrum technology, is proposed. It improves the performances of the network for having overcome the near-far problem of UWASNs.

As mentioned above, although the current MAC protocols for UWASNs have improved the throughput by reducing the collision of the packets to some extent, the long propagation delay is still a challenge factor for designing a suitable MAC protocol for UWASNs. In schedule-based protocols, the slot is quite long for the long propagation delay, leading to reducing the network throughput. In the paper, an enhanced dynamic token protocol (EDTP), based dynamic token protocol (DTP), is proposed. It uses token passing queue (TPQ) and TPQ backup method to transfer the token packets dynamically and efficiently. It is put forward to adapt the networks with long propagation delay, limit bandwidth in UWASNs.

The rest of the paper is organized as follows. In Section II, the problem in UWASNs we aim to solve is stated. In Section III, an enhanced dynamic token protocol for UWASNs is proposed. In section IV, simulations are carried out, and the performance of the protocols is compared. Section V gives the conclusion and future work.

II. PROBLEM STATEMENT

A UWASN typically consists of an underwater sink located at the center of monitored areas, many underwater sensor nodes surrounding the sink, a surface station acting as a gateway between on-shore control center and the sink, as shown in Fig. 1.

For the peculiar properties of underwater acoustic channel, such as the long propagation delay, low bandwidth and frequency-dependent attenuation, it is very important to take these characteristics of the channel into account for designing MAC protocol in underwater acoustic networks.

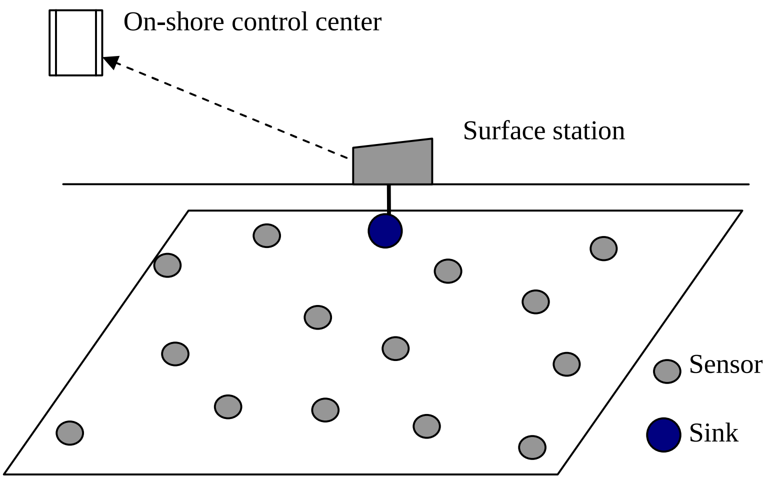


Figure 1. The architecture of the UWASNs

In the contention-based protocols, the competition phase may last for long time when there are many nodes competing for acquiring the channel. The long reservation delay reduces the network throughput. However, due to long propagation delay, the TDMA is not feasible in UWASNs.

And other schedule-based protocols are unsuitable since most nodes in UWASNs do not send or receive at the most time. The Ordered CSMA allows multiple carriers from multiple sources to propagate at the same time, and it improves the channel utilization greatly. However, the nodes must sense the carriers all the time, which increases the energy consumption, especially in a network with low traffic load.

The wireless token ring protocol (WTRP) [17] is good for wireless networks with varying topologies. And it can reduce the packets collisions for nodes taking turns transmitting and giving up the right to transmit after a specified amount of time, leading to improving efficiency of channel. The dynamic token protocol (DTP) [18] improves the robust of the protocol by transferring the token packets with a neighbor order list in each node, and it can work well in multi-hop networks with many nodes. However, they can not work well in the networks with the states of the links change quickly, for example, the links become available soon after they are failed. Moreover, it is difficult for nodes to maintain the token ring in WTRP, or DTP, in the underwater networks, which are usual varying, and not full connected.

In order to solve the problems, mentioned above, especially to prevent the long reservation delay in the contention-based protocols, and the long propagation delay in the schedule-based protocols, an enhanced dynamic token protocol (EDTP) is investigated for UWASNs, in the paper.

III. THE ENHANCED DYNAMIC TOKEN PROTOCOL

In the paper, an enhanced dynamic token protocol (EDTP) is proposed for UWASNs. The details of the proposed EDTP are presented in this section.

a. The frame structure in the EDTP

In the EDTP, a node receives the token from its predecessor, transmits data, and passes the token to its successor. Here is an illustration of the token frame, as shown in Fig. 2.

FC stands for Frame Control and it identifies the type of packet, such as Token, Joint Ring, Leave Ring, Data, etc. In addition, the source address (SA), destination address (DA), ring address(RA), number of nodes in the ring (NN), number of hops in the ring (NHOP) and number of circles (NCIRCLE) are included in the token frame. The RA refers to the ring to which the token belongs. The NN is the total number of nodes in the ring. The NHOP is initialized to zero and incremented by every node that passes the token. The NCIRCLE is the number of circles the ring having gone through.

FC	RA	SA	DA	NN	NHOP	NCIRCLE	
1	6	6	6	2	4	4	Bytes

Figure 2. The token frame structure

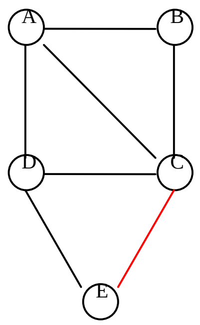
b. The overview of the EDTP

In EDTP, each node keeps an order list with its neighbor nodes, namely token passing queue (TPQ). The nodes in a ring transfer the token using the TPQ. The TPQ in each node is updated by each time of token is passed. The detail is that, when a node has received the token and finished its data transmission, it transfers the token to the first node in its TPQ, takes the node out of the TPQ and inserts it to the end of the TPQ. It is important for the node to make sure that, it has transferred the token successfully to its successor. After the node transferring the token, it will not stop sensing the channel, until it receives data or token transmitting from its successor.

Here is an example, as shown in Fig. 3. There are 5 nodes in the network, and the initial TPQ in each node (A, B, C, D, E) is (BCD, AC, ABED, ACE, CD), separately. When the connections are all available, the order list of the token passing is (A, B, C, E, D, A). When node C has failed to transfer the token to node E, since the link between node C and E is unavailable, node C transfers the token to node D, the second node in its TPQ. Node C backups its TPQ, and deletes node E from its TPQ, for the unavailable link between node C and E.

After node E receiving the token from node D and finishing its data transmission, node E will fail to transfer the token to node C, since the link between node E and C is still unavailable, and node E will transfer the token back to node D. Node E deletes node C from its TPQ. The order list of the token passing is (A, B, C, D, E, D, A).

When node A receives the token again, and the value of NHOP in the token is bigger than that of NN, it realizes that one of the links is failed, it reset the value of NN, and starts a new circle of the token passing. Compare with the initial TPQs of the nodes, the length of the order list increases. At the next circle of the token passing, the length of the order list will be bigger than that of the initial order list, even if the link between node C and E becomes available again.



	TPQ_A	TPQ_B	TPQ_C	TPQ_D	TPQ_E	TPQBAC_C
Token passing	BCD	AC	ABED	ACE	CD	
A→B	BCD	CA	BEDA	CEA	CD	
B→C	CDB	CA	EDAB	CEA	CD	
C→E failed	CDB	CA	EDAB	CEA	CD	
C→D	DBC	AC	DAB	EAC	CD	EDAB
D→E	BCD	AC	ABD	EAC	CD	EDAB
E→C failed	BCD	AC	ABD	ACE	D	EDAB
E→D	BCD	AC	ABD	ACE	D	EDAB
D→A	BCD	AC	ABD	ACE	D	EDAB

Figure 3. The token passing in the EDTP

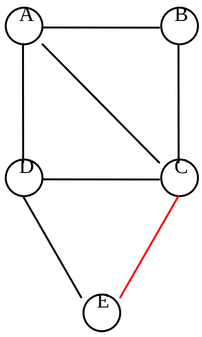
c. The TPQ backup method in the EDTP

In order to resolve the problem mention above, and make the length of the order list keep small, TPQ backup method is used in the EDTP.

As the same example shown in Fig. 3, when the link between node C and E is unavailable, and node C has failed to transfer the token to node E, node C transfers the token to node D. Node C backups its TPQ (EDAB), and updates its TPQ by deleting node E.

When the token goes through the node C again in the next circle of token passing, node C has detected that there is TPQBAC, it will try to transfer the token to node E, the first node in its TPQBAC, as shown in Fig. 4. When the token is transferred from node C to node E successfully, node C resets it TPQ with its TPQBAC, and clears its TPQBAC. When the node E has successfully received the token from node C, it inserts node C to the end of its TPQ as a new neighbor.

When node A receives the token again, and the value of NHOP in the token is smaller than that of NN, it realizes that one of the links is recovered, it reset the value of NN, and starts a new circle of the token passing. The order list of the token passing is (A, B, C, E, D, A). After that, the length of the order list decreases to the same value as that in the initial state.



	TPQ_A	TPQ_B	TPQ_C	TPQ_D	TPQ_E	TPQBAC_C
Token passing	BCD	AC	ABD	ACE	D	EDAB
A→B	BCD	CA	BDA	CEA	D	EDAB
B→C	CDB	CA	DAB	CEA	D	EDAB
C→E	DBC	AC	EDAB	EAC	DC	EDAB
E→D	DBC	AC	DABE	ACE	DC	NULL
D→A	BCD	AC	ABED	ACE	CD	NULL

Figure 4. The TPQ backup method in the EDTP

d. Performance analysis

The throughput is a basic performance metric for MAC protocols. Throughput can be defined as the ratio of the average length of the time by transmitting data packets to the average length of the time in each period, as can be written as follows:

$$G = \frac{\overline{U}}{\overline{T}} \tag{1}$$

where $\overline{T}$ is the average duration of each period, and $\overline{U}$ is the average time during a busy period for the channel being used to transmit data packets.

It is supposed that, there are N nodes in the circle in the network, and S nodes, which going to transmit their data packets in the period. It is also supposed that, there are M hops that the token packet is transferred in each circle. When the token packet passes nodes once in each circle, the value of M is equal to that of N. Since the token packet may pass some nodes more than once, the value of M may be more than that of N some times. When the propagation time of each neighbor nodes is τ, the transmission time of each data packet is δ, λ is the arrival parameter of the Poisson process, the duration of each period can be written as

$$T = S\delta + M\tau \tag{2}$$

The probability of a node being to transmit a data packet, when it owns the token packet, is $\rho = \lambda T$. And the probability of S nodes being to transmit a data packet, when it is owning the token packet, can be written as

$$P(S = x) = \begin{cases} C_N^x \rho^x (1-\rho)^{N-x}, 1 \le x \le N \\ (1-\rho)^N, x = 0 \end{cases} \tag{3}$$

The average number of nodes, transmitting their data packets in a circle, is

$$\overline{S} = \sum_{x=1}^{N} x \cdot P(S = x) \tag{4}$$

The average duration of a period can be written as

$$\overline{T} = \overline{S}\delta + M\tau \tag{5}$$

The average data packets transmitted in a period is

$$\overline{U} = \overline{S}\delta \tag{6}$$

Substituting Eqs. (3), (4), (5) and (6) into Eq. (1), we obtain the throughput of the network is

$$G = \frac{\overline{S}\delta}{\overline{S}\delta + M\tau} = \frac{\Re(\lambda)}{\Re(\lambda) + abN} \tag{7}$$

where $M=aN$, $\tau=b\delta$, $\overline{S} = \Re(\lambda)$. It is clear that, the value of $\Re(\lambda)$ increases when the value of λ increases. As shown in Eq. (7), we can observe that, the throughput of networks increases when the number of nodes in the networks increases. The throughput of networks also increases when the arrival of the data packets increases. When $\rho \ge 1$, then $\overline{S} = N$, in which, all nodes will transmit their data packets in each period, the value of the throughput of networks reaches maximum, shown as follows

$$G_{max} = \frac{1}{1+ab} \tag{8}$$

As shown in Eq. (8), we can observe that, the value of parameter a increases when the hops of token passing increases, leading to reducing the throughput of the networks.

e. Discussion

As mentioned above, in EDTP, when a node has failed to transfer the token, since the link is unavailable, the node will backup its TPQ in TPQBAC, before updating the TPQ. When the link is available again, the node can use the TPQBAC to recover the order list of the token passing. The length of the order list can be kept with a low value, comparing with DTP. In the network shown in Fig. 3, the length of the order list of the token passing in EDTP is 5, while the length of that in DTP is 6, leading to improving the performance of the networks.

IV. SIMULATION RESULTS

To evaluate the performance of the EDTP, simulations under different traffic load were carried out. The performance of the proposed protocol, in terms of the throughput, the packet drop ratio, and the transmission delay, is compared to existing protocols, namely, TDMA and DTP. The performance metrics are defined as shown in Eq. (9) to Eq. (11).

$$Throughput = \frac{No.\ of\ Packets\ \mathrm{Re}ceived \times Packets\ Length}{Data\ Rate \times Simulation\ Time} \tag{9}$$

$$Drop\ Ratio = \frac{No.\ of\ Packets\ Droped}{No.\ of\ Packets\ Generated} \tag{10}$$

$$Transmission\ Delay = \frac{\sum (Time\ of\ Packets\ Transmitted - Time\ of\ Packets\ Generated)}{No.\ of\ Packets\ \mathrm{Re}ceived} \tag{11}$$

The topology used for simulations is randomly generated, and there are 5 nodes randomly deployed in a 6*6 km area. The transmission range is 5 km. So that there will be some nodes out of transmission range of other nodes, and there will be two hops in the network in simulations. Moreover, the probability of a link becoming unavailable or available is set as 0.3. All sensor nodes are equipped with a half-duplex, omni-directional transceiver. The data rate of nodes is 1kbps. The length of DATA packet is 500 bytes and the length of a token packet is 29 bytes. The length of time slot, in TDMA protocol, is 8.2 s. The acoustic propagation speed is 1500 m/s.

a. Throughput

Fig. 5 shows the comparison of the throughput of three protocols. From Fig. 5, we can observe that the throughout of three protocols increases along with the increase of the traffic load when the traffic load is relatively small, and it becomes a relatively stable value, along with the increase of the traffic load after reaching peak values. The throughput of the three protocols is relative the same as each other, when the traffic load is low. The throughput of EDTP protocol increases faster than the other two protocols, when the traffic load becomes high. The maximum value of the throughput of TDMA, DTP, and the proposed protocol is 0.473, 0.625 and 0.797 kb/s, respectively, when the traffic load is 1.88 kb/s. The maximum value of the throughput of the proposed protocol is almost two times of that of TDMA protocol.

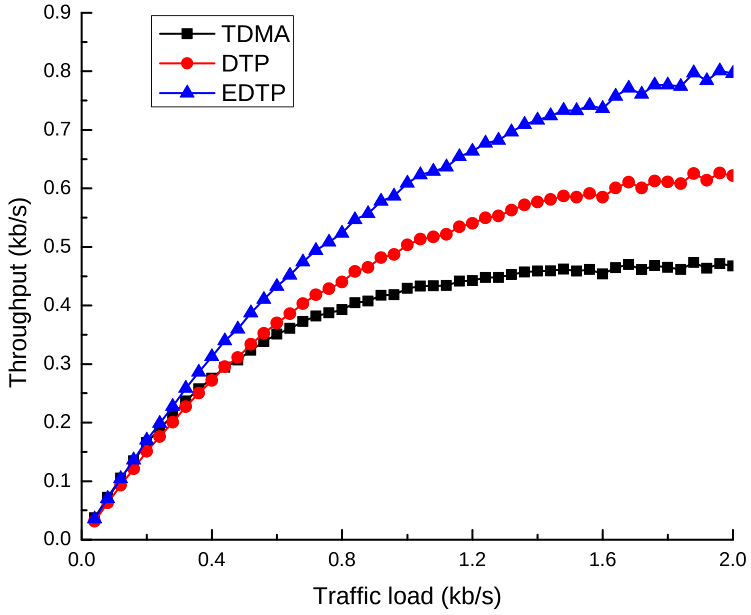


Figure 5. Throughput

From Fig. 5, we observe that the maximum throughput of EDTP is the highest among the three protocols, since it reduces the length of the order list, leading to improving the channel efficiency. The maximum throughput of DTP is slightly lower than that of EDTP protocol, since the length of the order list in DTP is longer than that in EDTP. Moreover, we can also observe that the maximum throughout of TDMA protocol is the smallest among three protocols. The reason is that, the nodes only transfer token packets, in EDTP and DTP protocols, when they have not any data packets to send, while the slots are assigned to the nodes static, in TDMA protocol, and the length of the slot time in TDMA protocol is long.

b. Packet drop ratio

The comparison of the packet drop ratio of three protocols is shown in Fig. 6. From Fig. 6, we observe that the packet drop ratio of three protocols increases along with the increase of the traffic load. The packet drop ratio of the proposed protocol is the smallest among these protocols. This is because the back order list used in the proposed protocol can improve the efficiency of the channel. And the packet drop ratio in TDMA protocol is the largest among the three protocols, since the length of the slot time in TDMA protocol is long, which makes senders wait too much time to send their packets.

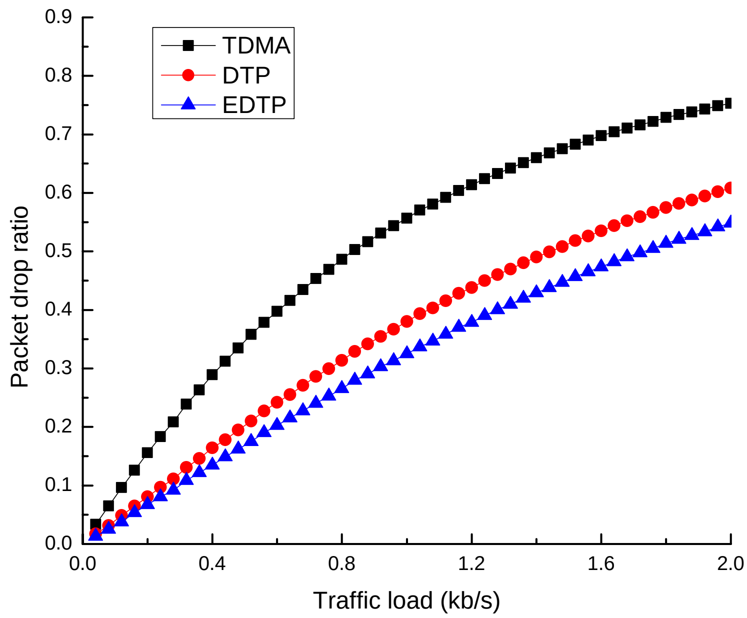


Figure 6. Packet drop ratio

c. Transmission delay

Fig. 7 shows the transmission delay of three protocols. From Fig. 7, we observe that the transmission delay increases when the traffic load increases. The transmission delay of the proposed protocol is the smallest among these protocols. The reason is that the length of the order list of the EDTP is short, and the efficiency of token passing is improved in the protocol. The transmission delay of DTP protocol is slightly larger than that of the EDTP, since the length of the order list of the DTP is long than that of the EDTP. Moreover, the delay performance of TDMA protocol is the worst. The reason is that, the length of the slot time in TDMA protocol is long, and the nodes cannot transmit their packets until their slot times come.

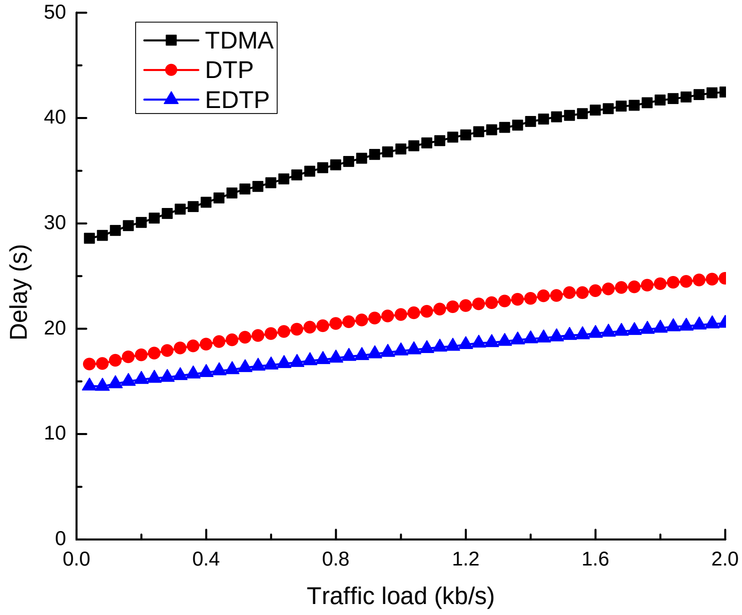


Figure 7. Transmission delay

d. The number of nodes in the networks

Fig. 8 and Fig. 9 show the throughput and the transmission delay of three protocols, in the networks with different number of nodes. From Fig. 8, we can observe that the throughout of EDTP and DTP protocols decreases when the number of nodes in the networks increases. The reason is that, the topology of the networks becomes complex, when the number of nodes in the networks increases, and the probability of the token packet going through some nodes more than once increases. We can also observe that the throughout of the DTP protocol decreases faster than that of the EDTP protocol, since the length of the order list of the DTP protocol is longer than that of the EDTP protocol, improving the transmission efficiency of the token packet. Moreover, the throughout of TDMA keeps almost the same when the number of nodes in the networks increases, since the ratio of the transmission time of the data packets does not change, when the number of nodes in the networks increases, leading to the relatively static value of the channel efficiency.

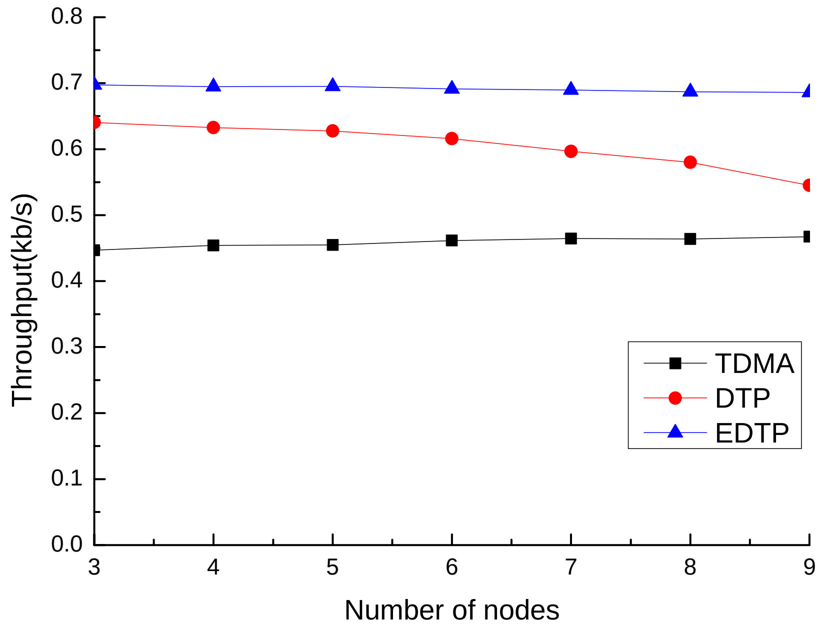


Figure 8. Throughput in the networks with different number of nodes

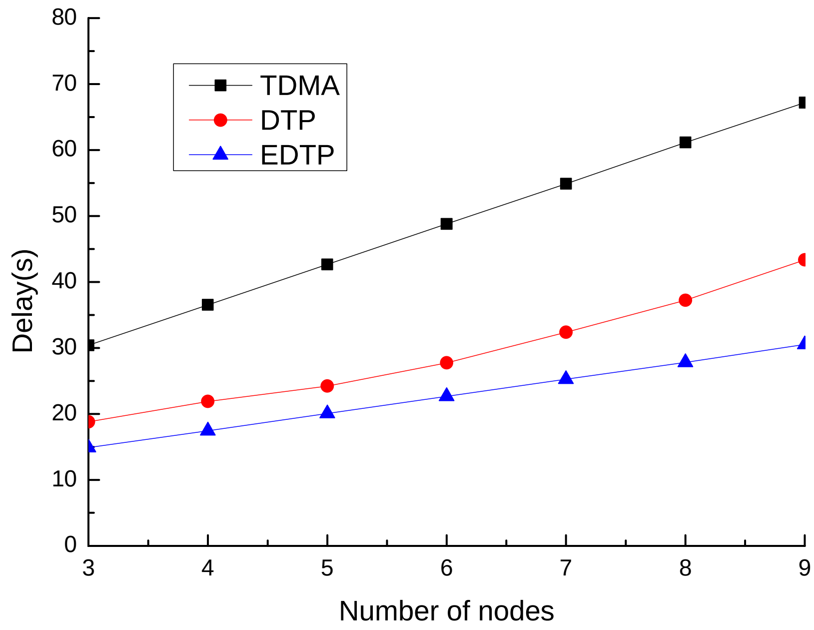


Figure 9. Transmission delay in the networks with different number of nodes

From Fig. 9, we observe that the transmission delay increases when the number of nodes increases. The reason is that, the topology of the networks becomes complex, when the number of nodes in the networks increases, and the probability of the token packet going through some nodes more than once increases, which make the nodes wait too much time for data transmission. Moreover, the transmission delay of TDMA protocol increases faster than the other two protocols. The reason is that, the length of the slot time in TDMA protocol is long and relatively static, and the nodes the nodes should wait more time for data transmission, when the number of nodes in the networks increases.

V. CONCLUSIONS

In this paper, an enhanced dynamic token protocol (EDTP), using token passing queue (TPQ) and TPQ backup method, is proposed for UWASNs. In the EDTP, the token packets are transferred with TPQ in each node, other than with a relative static order, using in the traditional wireless token ring protocols. The token passing method, as well as TPQ backup method, makes nodes, transfer the token packets dynamically and efficiently, and transmit their data packets without collision, leading to improving the channel efficiency of the networks.

Simulation results show that the maximum value of the throughput of the proposed protocol is almost two times of that of TDMA protocol. Moreover, the proposed protocol also achieves a lower packet drop ratio, and a lower transmission delay, compared to previous protocols.

Future work should be concentrated on the development of a proper algorithm for TPQ updating and maintenance, as well as a suitable protocol for networks with a large number of nodes.

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