Performance Analysis of P-CSMA for Underwater Acoustic Sensor Networks

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***Abstract*—In this paper, we investigate the performance of carrier sensing multiple access (CSMA)-based medium access control (MAC) protocol in fully connected underwater acoustic sensor networks (UWASNs). CSMA-based MAC protocols run inefficiently because of a new hidden terminal problem (we refer to it as "long-delay hidden terminal problem"). Based on our findings, this paper presents novel performance analysis model of physical CSMA (P-CSMA) for UWASNs. Compared with other analytical methods, the analysis model in this paper is closer to the actual network, in which the number of nodes is finite and propagation delays among certain nodes are variable. The close form expressions for throughput and packet loss ratio indicate that CSMA-based MAC protocols are influenced greatly by long-delay hidden terminal problem. Simulation results show the correctness of the analysis model.**

Keywords-Underwater acoustic sensor networks; Medium access control (MAC); Analysis

I. INTRODUCTION

The design of a medium access control (MAC) protocol is challenged by the distinguishing characteristics of an underwater acoustic channel. Underwater communication mainly uses acoustic channel with a low propagation speed of approximately 1500m/s, thus resulting in significantly long propagation delay. As shown in Fig.1, in a fully connected underwater acoustic sensor networks (UWASNs), at the beginning, data packet A is sent out by node A at time t0 and arrives at node B at time t_1.Because of variable propagation delays, data packet A arrives at node C at time t_2, node C couldn't catch any signal before t_3 and then sends out data packet C, which arrives at node B at time t_4. As a result, a collision is created at node B. We call this delay-related hidden terminal problem as "long-delay hidden terminal problem".

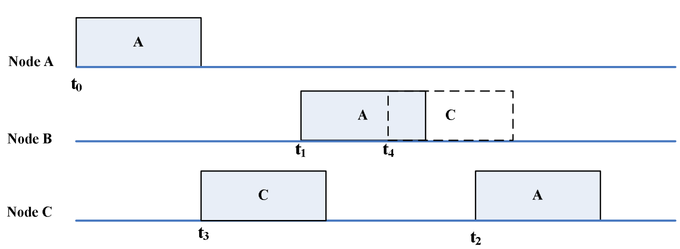

Figure 1. Long-delay hidden terminal problem

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Some analyses on MAC protocol have been done for UWASNs, but they all avoid the problem mentioned above. In [1], a model for analyzing ALOHA and p-persistent ALOHA variants for a simple multi-hop string topology has been presented. In [2], a propagation delay tolerant ALOHA protocol is proposed and analyzed. The authors propose a useful simple expression and assume there are many nodes in network. In [3], the authors analytically derive the throughput performance of multiple access collision avoidance (MACA) in a fully connected network, in which, propagation delays among nodes are all same. In [4], a MACA-based MAC protocol is analyzed in a Markov chain model. In this paper, we aim to present an analysis model to investigate the performance of carrier sensing multiple access(CSMA)-based MAC protocols resulted by new hidden terminal problem in fully connected UWASNs. Compared with other analytical methods, the analysis in this paper is closer to actual network. For example, the nodes are sparse distributed and the propagation delays are different.

The rest of this paper is organized as follows. In section II, we describe the physical CSMA (P-CSMA) protocol and propose its analysis model. We then present in section III the numerical and simulation results, meanwhile, we discuss the parameters of P-CSMA protocol. Finally, we give our conclusions in section IV.

II. ANALYSIS MODEL

A. Protocol Description

In P-CSMA, each node has three states: Idle, Receiving and Sending. In Idle, traffic loads are produced and nodes listen to the channel. In Receiving and Sending, physical signals are transmitted and received respectively. The protocol transfer mechanisms are as follows.

(1) When a node detects physical carrier in the channel it goes to Receiving while it is receiving the packet. After receiving packet the node goes back to Idle and continue to listen to the channel.

(2) With a packet ready to be transmitted in Idle, the node goes to Sending and sends packet immediately. After sending packet the node goes back to Idle and continue to listen to the channel.

Because of half duplex mode, nodes in P-CSMA couldn't receive and send at the same time, in other words, when nodes are in Receiving or Sending, they are in busy state and couldn't do any other things. Meanwhile, the nodes don't back off when they finish sending or receiving for the spatio-temporal uncertainty of UWASNs[6], which indicate that whether a node back off isn't a factor of collision.

For presentation brevity, we make the following assumptions.

(1) There is a node acted as a destination one in the network, which is the same away from other N sending nodes.

(2) The packet length is T, which is normalized to 1.The propagation delay is normalized to a.

(3) The traffic loads of a node follow a Poisson distribution with average λ packets per second. Then the traffic loads of the channel are $G = N\lambda$.

B. Protocol Analysis

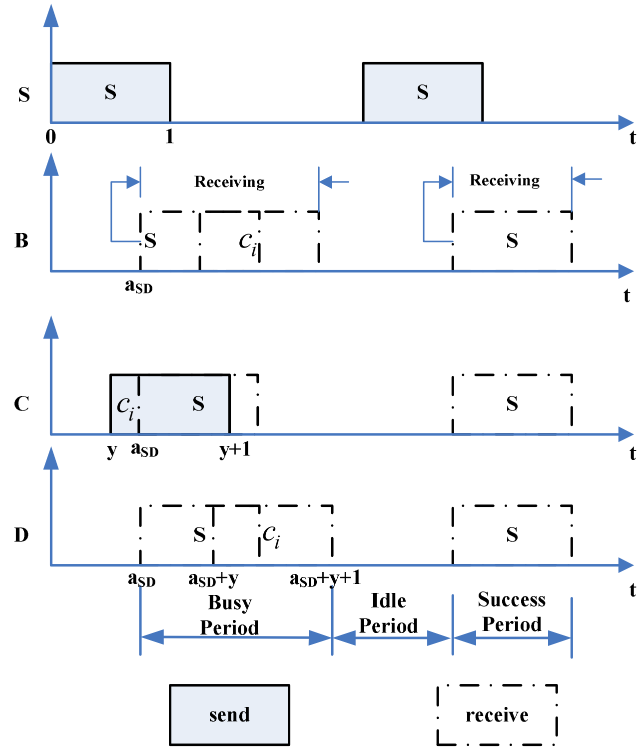
In order to analysis long-delay hidden terminal problem, we create analysis model of P-CSMA shown in Fig.2, among which, Fig.2(a) indicates the same propagation delay among any nodes, while Fig.2(b) indicates variable one. "S" stands for source node, "D" stands for destination node, "B" stands for those nodes that have catch channel signal and turn to Receiving state, and "C" stands for those nodes that maybe collide with packet S. In addition, propagation delay between node I and node J is normalized a_{IJ} by the packet length. Each node will "listen" to the channel before starting to transmit to avoid possible collisions with other ongoing transmissions. Let us assume that a certain node S first sends a packet while all other nodes are in Idle state. To simplify the discussion, assume that the time is 0. Seen from Fig.2 (a), propagation delays among any nodes are the same and denoted by a_{SD}. So, we investigate the interval $[0, a_{SD}]$ to derive throughput and packet loss ratio. Different significantly from Fig.2 (a), in Fig.2 (b), propagation delays between each node pair are different and denoted by a_{SB} , a_{SC} , a_{SD} and a_{CD}. So, we investigate the interval $[a_{SD}, a_{SD}+1]$ to derive throughput and packet loss ratio.

Throughput can be defined as follows [5]:

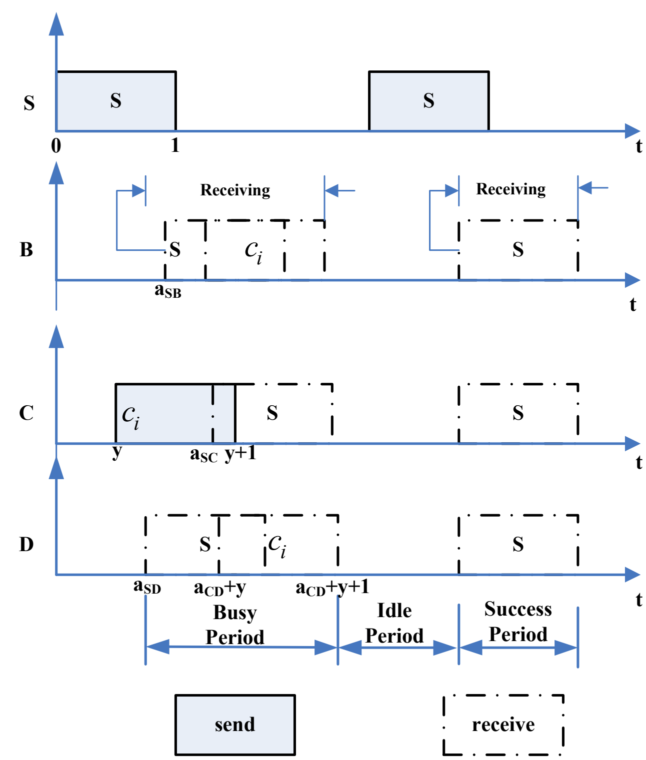
$$S = \frac{\overline{U}}{\overline{B} + \overline{I}} \tag{1}$$

where $\overline{U}$ is the average time while useful data is being sent (success period), $\overline{B}$ is the average time while channel is being used (busy period) and $\overline{I}$ is the average time between two busy periods (idle period).

When the propagation delay among any nodes are a_{SD}, namely an ideal network, nodes in group B who are in idle state between $[0, a_{SD}]$ will sense the channel busy and turn to Receiving state. Nodes in group C are ready to transmit packets before the moment a_{SD} .We define a random variable Y, which indicates the time of occurrence of the last packet arriving between $[0, a_{SD}]$. The transmission of all packets arriving in $[0,Y]$ will be completed at $Y+1$.



(a). Same propagation delay between nodes



(b). Different propagation delay between nodes

Figure 2. Analysis model of P-CSMA

The distribution function for Y is:

$$F_Y(y) = P\{no\ packets\ arrive\ at\ (0, a_{SD} - y)\}$$
$$= \begin{cases} 0 & y < 0 \\ e^{-(N-1)\lambda(a_{SD}-y)} & 0 \le y \le a_{SD} \\ 1 & y > a_{SD} \end{cases} \quad (2)$$

So, the expected value of Y is therefore given by

$$\begin{aligned} \overline{Y} &= \int_0^{a_{SD}} y \cdot F_Y'(y)dy \\ &= (N-1)\lambda \int_0^{a_{SD}} y \cdot e^{-(N-1)\lambda(a_{SD}-y)} dy \quad (3) \\ &= a_{SD} - \frac{1 - e^{-(N-1)\lambda a_{SD}}}{(N-1)\lambda} \end{aligned}$$

The average duration of a busy interval is:

$$\overline{B} = 1 + \overline{Y} = 1 + a_{SD} - \frac{1 - e^{-(N-1)\lambda a_{SD}}}{(N-1)\lambda} \quad (4)$$

In (3), if y is equal to 0, all neighbor nodes of S have no packets to send out before receiving the data packet from the node S. At the moment, the receiving node D can receive packet successfully, then the expected duration of the success period can be given by

$$\overline{U} = 1 * F_Y(0) = e^{-(N-1)\lambda a_{SD}} \quad (5)$$

The average duration of an idle period is given by

$$\overline{I} = \frac{1}{G} \quad (6)$$

Applying (4), (5) and (6) to (1), we can get the throughput as follows:

$$S_I = \frac{e^{-(N-1)\lambda a_{SD}}}{1 + a_{SD} - \frac{1 - e^{-(N-1)\lambda a_{SD}}}{(N-1)\lambda} + \frac{1}{N\lambda}} \quad (7)$$

By substitution of $G = N\lambda$, $k = (N-1)/N$, we can get

$$S_I = \frac{kGe^{-kGa_{SD}}}{kG(1 + a_{SD}) + e^{-kGa_{SD}} + k - 1} \quad (8)$$

Compared with ideal network, in actual network, we assume that the propagation delay between sending nodes and receiving node are same as a_{SD}, but the propagation delays among sending nodes are different. When source node S transmits a packet at the time 0, the packet will stay node D at $[a_{SD}, a_{SD}+1]$. Similar to Fig.2 (a), we define a random variable Y, which indicates the time of occurrence of the last packet arriving between $[a_{SD}+Y, a_{SD}+Y+1]$.

The distribution function for Y is:

$$F_Y(y) = P\{no\ packets\ arrive\ at\ (a_{SD} + y, a_{SD} + 1)\}$$
$$= \begin{cases} 0 & y<0 \\ e^{-(N-1)\lambda(1-y)} & 0 \le y \le 1 \\ 1 & y > 1 \end{cases} \quad (9)$$

So, the expected value of Y is therefore given by

$$\begin{aligned} \overline{y} &= \int_0^1 y \cdot F_Y'(y)dy \\ &= (N-1)\lambda \int_0^1 y \cdot e^{-(N-1)\lambda(1-y)} dy \\ &= 1 - \frac{1}{(N-1)\lambda}[1 - e^{-(N-1)\lambda}] \quad (10) \\ &= 1 - \frac{1}{kG}(1 - e^{-kG}) \end{aligned}$$

where $G = N\lambda$, $k = (N-1)/N$.

The average duration of a busy interval is:

$$\overline{B} = 1 + \overline{Y} = 2 - \frac{1}{kG}(1 - e^{-kG}) \quad (11)$$

In (10), if y is equal to 0, all neighbor nodes of S have no packets to send out before receiving the data packet from the node S. At the moment, the receiving node D can receive packet successfully, then the expected duration of the success period can be obtained as follows:

$$\overline{U} = e^{-kG} \quad (12)$$

While Simulate P-CSMA Protocol in actual network, we set switching time denoted as t_{sw} between sending and receiving. In simulation, t_{sw} is set to 0.75. Thus the average duration of an idle period is given by

$$\overline{I} = \frac{1}{G} + t_{sw} \quad (13)$$

Applying (11), (12) and (13) to (1), we can get the throughput as follows:

$$S_R = \frac{e^{-kG}}{2 - \frac{1}{kG}(1 - e^{kG}) + \frac{1}{G} + t_{sw}} \quad (14)$$

With same propagation delay among any nodes, propagation delay serves as investigation period. The probability of a packet could be received successfully is no transmission of packet in investigation period. So the probability of collision is shown in the following equation:

$$\begin{aligned} P_{C\_I} &= 1 - P(no\ packets\ will\ be\ sent\ in\ a_{SD}) \\ &= 1 - e^{-(N-1)\lambda \cdot a_{SD}} \quad (15) \\ &= 1 - e^{-kG \cdot a_{SD}} \end{aligned}$$

When the propagation delay among any nodes in network is different, every neighbor node of S get channel's busy state at different moment. So only if sending interval between two nodes two times as much as the length of data packet, data packets arriving at receiving node will not collide with each other. Thus the probability of collision among data packets is:

$$\begin{aligned} P_{C\_R} &= 1 - P\,(\textit{no packets will be sent in 2 units of time}) \\ &= 1 - e^{-2(N-1)\lambda} \\ &= 1 - e^{-2kG} \end{aligned} \tag{16}$$

If keep the distribution of traffic load unchanged, we short the length of packet to *m*, $0 < m < 1$. Thus the probability of collision among data packets is present below:

$$P_{C\_R\_L} = 1 - e^{-2kmG} \tag{17}$$

Exceptionally, given the BER denoted as P_e , the probability of error in a packet containing L and mL bits, the probability of collision is expressed as follows:

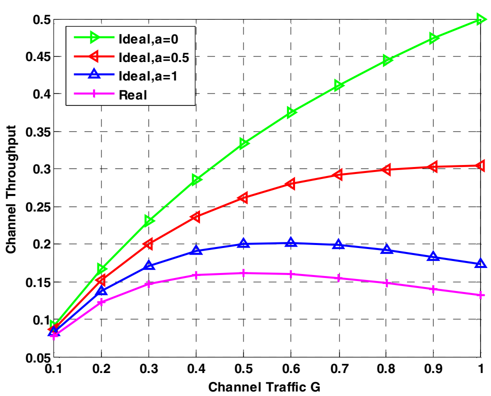
$$P^{e}_{C\_R} = (1 - e^{-2kG}) \cdot (1 - P_e)^{L} \tag{18}$$

$$P^{e}_{C\_R\_L} = (1 - e^{-2kmG}) \cdot (1 - P_e)^{L \cdot m} \tag{19}$$

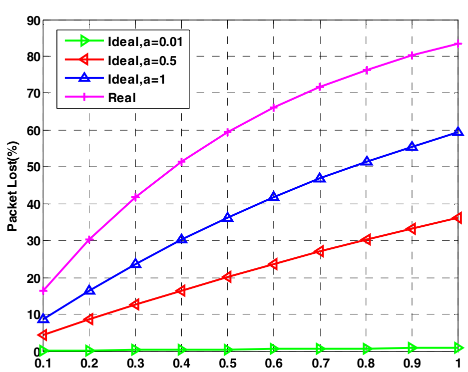
III. RESULTS AND DISCUSSIONS

A. Numerical Results

Based on (8), (14), (15) and (16), the performance of throughput and packet loss ratio are shown in Fig.3 and Fig.4.



(a). Throughput

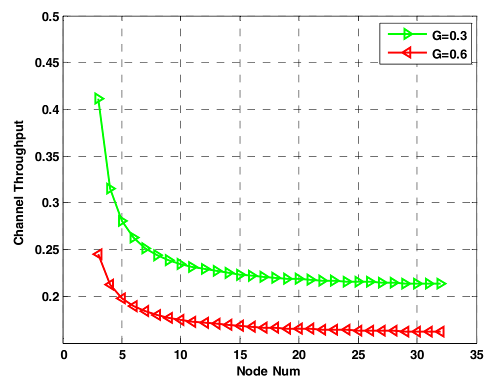


(b). Pack loss ratio

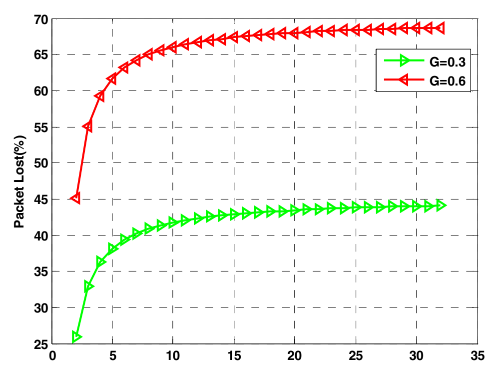
Figure 3. Performance in ideal and actual netork

In ideal network, with the smaller propagation delay, the higher throughput and the lower packet loss ratio are. With same propagation delay, the state of channel and the state of receiving nodes are alike. So, physical carrier sensing has certain effect in avoiding collision. Moreover, the shorter propagation delay, the better effect of avoiding collision is. In contrast, in actual network, the state of receiving nodes and the state of channel which is derived from carrier listening is inconsistent in most cases. Thus, physical carrier sensing brings little effect in avoiding collision and the performance has a worse result.

Different from traditional analysis, which always presumes that the number of nodes is infinite, Fig.4 shows the performance of throughput and packet loss ratio when the number of nodes is finite. When the number of nodes is less, throughput is higher and packet loss ratio is smaller at the same traffic loads. Increasing the number of nodes, traffic loads are distributed to every node and the probability of collision increase accordingly, which resulted in lower throughput and higher packet loss ratio. When the number of node is more than 20, the performance tends to be stable.



(a). Throughput



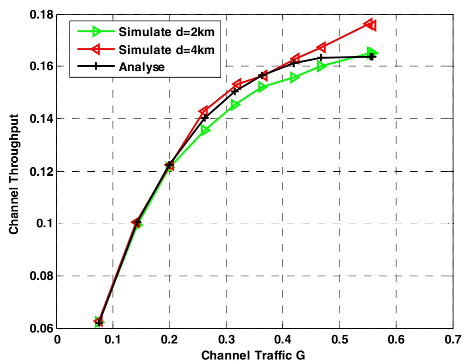
(b). Pack loss ratio

Figure 4. Performance as a function of node number

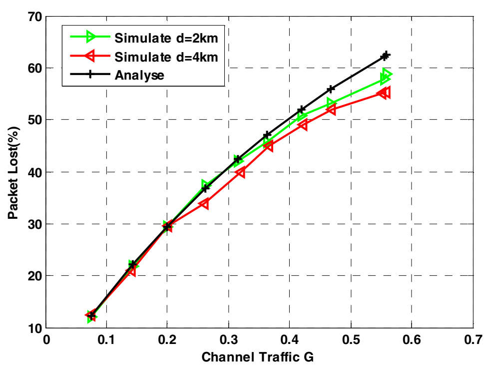
B. Simulation Results

In order to verify the analytical results, we do simulation based on practical underwater acoustic environment to studying throughput and packet loss ratio as a function of propagation delay and the number of nodes.

In our simulation, there are eight or four sending nodes around receiving node. Sending nodes are 2km or 4km away from receiving node. The propagation speed of acoustic signal is 1500m/s. The rate of data transmission is 1000bits/s. The packet length is 1000 bits



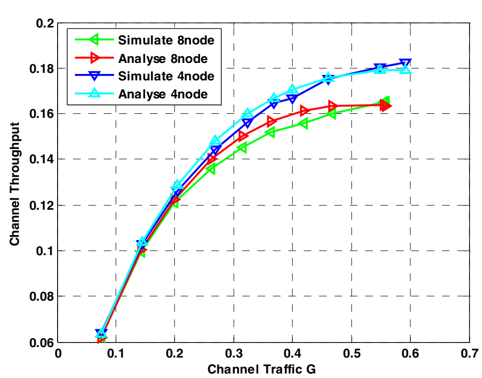
(a).Throughput



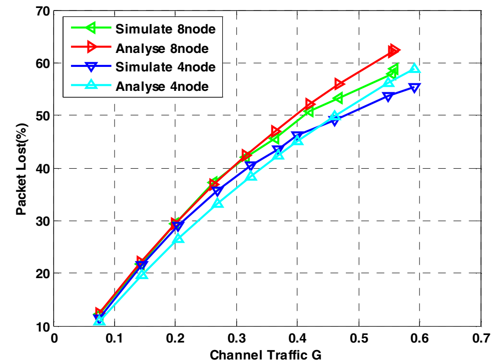
(b).Pack loss ratio

Figure 5. Performance in actual network

Analytical results show that throughput and packet loss ratio have nothing to do with propagation delay. However, in actual environment, with the difference of propagation distance, there are some differences in performance, which is shown in Fig.5. While the number of nodes is different, Fig.6 shows that the simulation results match analytical results well.



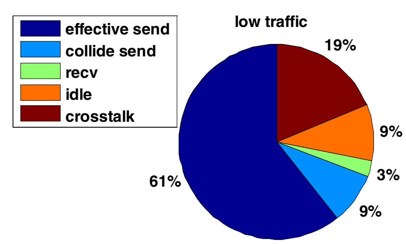
(a). Throughput



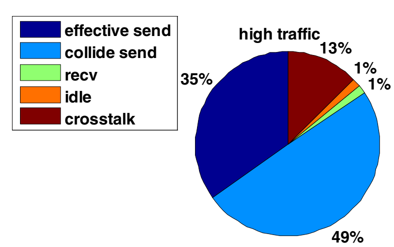
(b). Pack loss ratio

Figure 6. Performance with the variable node numbers

When investigating energy efficiency, we calculate transmit and receive power according to Thorp's formula and our underwater acoustic communication prototype. In the paper, we only give the results when the distance between sending node and receiving node is 4km. So the power of sending, receiving and idle are set to 70W, 3W and 80mW respectively. At the same time we define five states about energy consumption: effective send, collide send, receive, idle and crosstalk. Seen from Fig.7, when traffic is high, P-CSMA couldn't avoid collision and energy consumption is nearly half of the total energy. Another interesting conclusion is that whether the traffic is low or high, crosstalk is a key factor causing energy consumption.



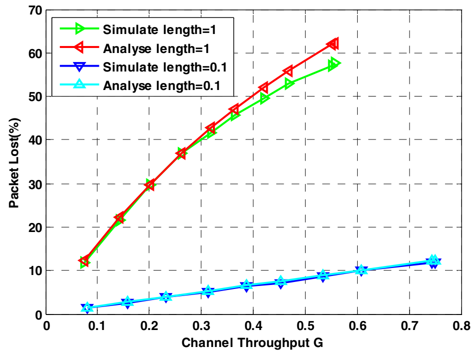
(a). When traffic is low



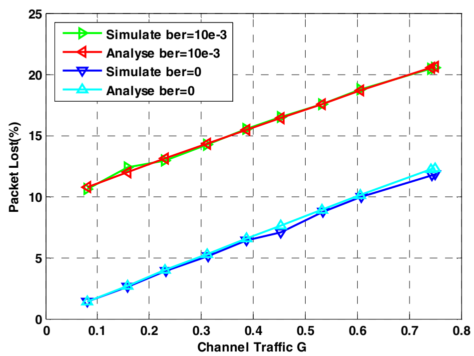
(b). When traffic is high

Figure 7. The proportion of energy consumption

C. Parameter Discussion



(a). With different packet length



(b). With different BER

Figure 8. Performance of packet loss ratio

If keep the distribution of traffic load unchanged, we short the length of packet length to 0.1, we can derive the performance of packet loss ratio shown in Fig.8 (a). As the length of data packet is shortened, packet loss ratio decrease greatly. Accordingly, though physical carrier sensing can't solve the problem of collision in actual environment, by shortening the length of data packet we can improve the probability of successful.

Bit error rate is always ignored when we study upper protocol. But bit error rate in actual underwater acoustic environment is frequently high and make a certain effect on protocol, which is shown in Fig.8 (b). When the length of data packet is 100bits and bit error is 10e-3, packet loss ratio increases by 10 percentage point compared with ideal channel.

IV. CONCLUSION

In this paper, we study the long-delay hidden terminal problem in fully connected UWASNs. From our work, we can draw the following conclusions. Firstly, long-delay hidden problem in UWANs includes two aspects, long delay and variable one, which lowers the performance of P-CSMA. Secondly, whether propagation delay is large or small, when traffic is high, P-CSMA in UWANs couldn't avoid collision effectively only through physical carrier sensing, but if combined with virtual carrier sensing in which short length control packets are used before sending data packets, the performance will be greatly improved. Lastly, avoiding collisions and reducing crosstalk are the two most effective measures in the design of energy efficiency MAC protocol.

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