TLPC: A Two-Level Power Control MAC Protocol for Collision Avoidance in Underwater Acoustic Networks

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***Abstract*—Due to the nature of water, sound wave is used for underwater transmission instead of radio wave. Long propagation time and a variant attenuation model are two major concerns in MAC protocol design for underwater transmission. Although IEEE 802.11 DCF is the most famous MAC protocol, it does not work well in underwater environments. Therefore, according to the acoustic attenuation model, Control/DATA Collision (CDC) problem and Underwater Large Interference Range Collision (ULIRC) problem are conducted for underwater acoustic networks. This paper proposes a Two Level Power Control (TLPC) MAC protocol to prevent CDC and ULIRC problems. Taking interference into consideration, TLPC adapts the transmission power to resist interference and avoid collision in order to enhance network throughput. TLPC can not only prevent CDC and ULIRC problems but also can reduce the energy consumption of stations. Simulation results show that TLPC outperforms against other protocols in number of collisions and network throughput.**

I. Introduction

With the advancement in radio frequency (RF) technology, wireless communication has been widely used in human life. To design a wireless media access control (MAC) protocol, hidden terminal problem is one of major concerned issues. Recently, this issue has been transferred from terrestrial wireless networks to underwater acoustic networks (UANs). Therefore, the features of water have become key factors to design MAC protocols for UANs.

IEEE 802.11 DCF (Distributed Coordination Function) [1], which is a well known MAC protocol for hidden terminal problem avoidance, does not work well in UANs. The procedure of RTS and CTS exchanges can not suspend hidden STA in time due to long propagation delay in UANs. Therefore, the collision problem termed as Control/DATA Collision (CDC) problem, which will be discussed in next section, is likely to happen.

Recently, a lot of researches pay their attention on MAC protocol designs to avoid collisions in UANs. In [2], the concept of the ”slot” is used for collision avoidance. A transmission must start at the beginning of a slot, where the slot size is set as a maximum propagation delay time plus a CTS transmission time. In [3], the durations between the time to transmit an RTS and the time to receive a CTS and between the time to transmit a CTS and the time to receive DATA are set to twice of a maximum propagation delay to avoid collision for the sender and the receiver. However, if STAs are deployed densely, the channel utilization in [2], [3] will decrease due to the long waiting time. In [4], some transmission strategies are proposed for collision avoidance. However, synchronization is required and it is not practical in UANs.

On the other hand, a STA not prohibited from transmission by either RTS or CTS is still possible to interfere with the reception of the receiver [5]. Therefore, in [5], a MAC protocol names CCR (Conservative CTS Reply) is proposed to solve this problem. In CCR, a STA replies a CTS for an RTS request only when the receiving power strength of that RTS is larger than a certain threshold, even if the RTS is received successfully and this STA is idle [5]. In [6], a virtual and physical carrier sensing mechanism is used for prohibiting interfering STAs from transmission. However, these approaches [5], [6] are designed for terrestrial networks, not for UANs.

In this paper, a kind of the large interference range collision problem, named Underwater Large Interference Range Collision (ULIRC) problem, is introduced. Therefore, in this paper, two collision problems, CDC and ULIRC problem, are investigated. A MAC protocol, named Two-Level Power Control (TLPC), is proposed to prevent CDC and ULIRC problems for UANs in this paper. TLPC can not only prevent CDC and ULIRC problems but also can reduce the energy consumption of stations.

The remainder of this paper is organized as follows. In Section II, the two collision problems, CDC and ULIRC, are introduced. In Section III, the interference range of a STA is derived and analyzed. The TLPC MAC protocol is described in Section IV. Simulation results are demonstrated in Section V. Finally, Section VI concludes the paper.

II. Preliminary

The four-way handshaking mechanism is designed to solve the hidden terminal problem in terrestrial networks and is not suitable to apply directly to UANs. The propagation speed of sound is about 1500 m/s and is much slower than that of radio wave. Therefore, to avoid the hidden terminal problem in UANs, two collision problems, termed CDC and ULIRC problems should be considered and solved.

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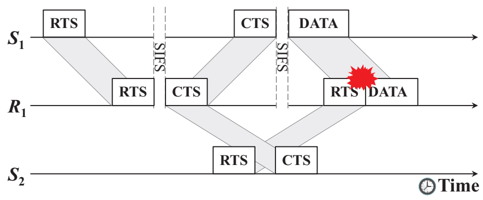
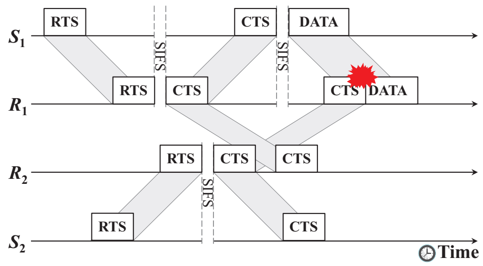


(a) RTS collides with DATA.



(b) CTS collides with DATA.

Fig. 1. Scenarios of the CDC problem.

A. Control/DATA Collision (CDC) Problem

In UANs, the four-way handshaking mechanism can not solve the hidden terminal problem well due to the long propagation delay. Take Fig. 1(a) as an example. Suppose S_1 and R_1 are a transmission pair and S_2 is a neighbor of R_1. When S_1 has DATA to send, S_1 and R_1 will exchange RTS and CTS. After that, S_1 can transmit DATA to R_1. In terrestrial networks, four-way handshaking can prevent neighbors from transmission. Thus, the hidden terminal problem can be solved. However, in UANs, RTS and CTS can not propagate to neighbors of the sender and the receiver immediately due to the propagation delay. In this situation, before receiving the CTS transmitted from the receiver, if S_2 has DATA to send, it will transmit an RTS. The RTS transmitted by S_2 will then collide with DATA sent by S_1 at the receiver site.

On the other hand, CTS may also collide with DATA, as shown in Fig. 1(b). Assume two transmission pairs, S_1 transmits to R_1 and S_2 transmits to R_2, are in the network. Although these two transmission pairs exchange RTS and CTS successfully, the CTS sent by R_2 may collide with the DATA at R_1 due to the propagation delay. Therefore, the collision problem mentioned above is termed CDC problem.

The effectiveness of CDC can be analyzed as follows. Let E_{CDC} be the effectiveness of the CDC problem. E_{CDC} is estimated as follows.

$$E_{CDC} = \frac{A_{unwarned}}{A_{TR}}, \tag{1}$$

where $A_{unwarned}$ denotes the area where has not been covered by the RTS and the CTS, as shown in Fig. 2. A_{TR} denotes the area of a transmission range. In Fig. 2, S is the sender and R is the receiver. The gray region means the area where has been covered by RTS and CTS. I is a potential interfering STA. Note that when a STA is located in $A_{unwarned}$, it is a potential interfering STA.

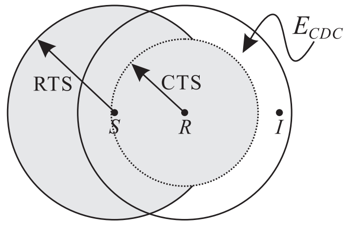


Fig. 2. The effectiveness of the CDC problem.

Let D_{SR} denote the distance between the sender and the receiver. According to Eq. (1), the relationship between E_{CDC} and D_{SR} is depicted in Fig. 3, where the frequency of the acoustic wave is 100kHz and the transmission range is 1127.3m. As shown in Fig. 3, the shorter the D_{SR} is, the higher the E_{CDC} is. In other words, the probability that the CDC problem happens is high. However, if D_{SR} is close to a transmission range, the probability to have the CDC problem is small.

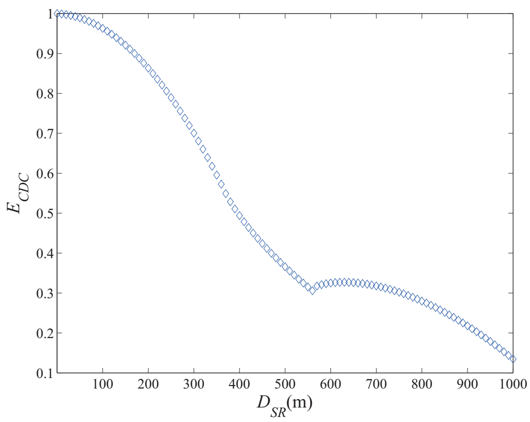


Fig. 3. The effectiveness of the CDC problem in terms of D_{SR}.

B. Underwater Large Interference Range Collision (ULIRC) Problem

In [5], [7], collisions may happen even if the interfering STA is not located within the ranges of the RTS and CTS transmissions, which is termed Large Interference Range Collision (LIRC) problem. Before describing the LIRC problem, two communication ranges, termed transmission range (TR) and interference range (IR) are defined as follows [6].

*Definition 1 (**Transmission Range (TR)**):* is defined as the range within which a frame can be successfully received and correctly identified. ■

*Definition 2 (**Interference Range (IR)**):* is defined as the range within which the receiving STA will be interfered by other STAs and thus suffer a frame loss. ■

Fig. 4 illustrates the LIRC problem. When a signal is transmitted from S to R, an interference range will be induced at the receiver by this signal, as the dotted circle in Fig. 4. If a STA located within the IR but outside the TR, as the STA I shown in Fig. 4, emits a signal, this signal will cause

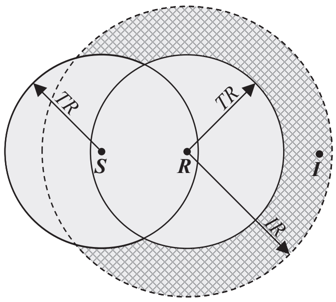


Fig. 4. An illustration of the LIRC problem.

a collision at the receiver. Similarly, this kind of collision problem can also happen in UANs. In this paper, ULIRC is used instead to differentiate the LIRC problem in UANs from in the terrestrial networks.

III. Derivation of Interference Range in UANs

Without loss of generality, S and R respectively indicate the sender and the receiver. Let P_t be the transmission power of S and P_r be the receiving signal strength of R. According to [8], [9], the propagation of acoustic wave can be modeled as below.

$$P_r = \frac{P_t}{A(D_{SR}, f)}, \tag{2}$$

where $A(D_{SR}, f)$ is an attenuation function. The attenuation of acoustic wave is affected by the propagation distance l and the acoustic frequency f and is denoted $A(l, f)$. By [10], $A(l, f)$ can be formulated as the following equation.

$$A(l, f) = l^k * \alpha(f)^l, \tag{3}$$

where k is an energy spreading factor. In general, k is set to 1 for cylindrical spreading and 2 for spherical spreading[1]. $\alpha(f)$ (in dB/km) is an absorption coefficient and is dependent on frequency f (in kHz). By [10], $\alpha(f)$ can be obtained as follows.

$$10log\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75*10^{-4}f^2 + 0.003. \tag{4}$$

Fig. 5 illustrates the attenuation of acoustic wave in terms of D_{SR}, where $k = 1$. The attenuation of acoustic wave increases when D_{SR} or the frequency increases.

According to [6], [11], whether a packet can be successfully received or not should satisfy the following two conditions.

C1 $SNR_r \geq SNR_{th}$: the receiving Signal-Noise Ratio (SNR), SNR_r, should be greater than or equal to an SNR threshold, SNR_{th}.

C2 $P_r \geq P_{th}$: the receiving signal strength of R should be greater than or equal to a signal strength threshold, P_{th}.

In **C1**, SNR_r can be formulated as below.

$$SNR_r = \frac{P_r}{R_{RN} + P_{CN}}, \tag{5}$$

[1]The spreading of an acoustic signal in underwater for a short distance propagation ($< 500m$) is spherical and that for a long distance propagation is cylindrical [10].

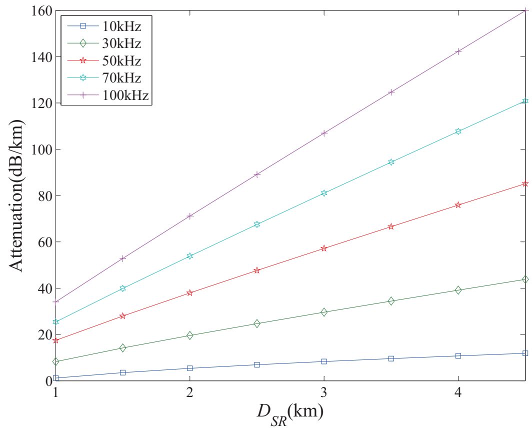


Fig. 5. The attenuation and absorption of acoustic wave in terms of D_{SR}.

where P_{CN} is the current noise power level and P_{RN} is the remaining noise power level that an STA can tolerate.

Let I be the closest neighbor not to interfere with the reception of R. For simplicity, P_{CN} can be viewed as a background noise and, by [8], [9], is approximated by $50 - 18 \log f$. Therefore, by Eq. (2), **C1** can be rewritten as follows.

$$\frac{\frac{P_t^S}{A(D_{SR},f)}}{\frac{P_t^I}{A(D_{RI},f)} + (50 - 18\log f)} \geq SNR_{th}, \tag{6}$$

where P_t^S and P_t^I are the transmission powers of S and I, respectively.

For simplicity, P_{CN} is ignored. Moreover, since, in most situations, the transmission range in UANs is greater than $500m$, let k set to 1. By Eq. (3), Eq. (6) can be reformulated as below.

$$D_{RI} * \alpha(f)^{D_{RI}} \geq \frac{P_t^I}{P_t^S} * D_{SR} * \alpha(f)^{D_{SR}} * SNR_{th}. \tag{7}$$

D_{RI} can be viewed as the IR of R. To derive D_{RI}, we introduce a Lambert W function [12], [13] to solve Eq. (7). The Lambert W function is in the form of as follows.

$$x = W(z), \text{ if } z = xe^x. \tag{8}$$

Thus, the interference range, IR, can be obtained as below.

$$IR = \frac{W(\frac{P_t^I}{P_t^S} * D_{SR} * \alpha(f)^{D_{SR}} * SNR_{th} * \ln\alpha(f))}{\ln\alpha(f)}. \tag{9}$$

According to Eq. (9), IR changes with P_t^S, P_t^I, D_{SR} and f. Fig. 6 illustrates the interference range in terms of D_{SR}, where SNR_{th} is set to 10dB and $P_t^S = P_t^I$. The higher the frequency, the smaller the interference range. As a result, the acoustic frequency f is set to 100 kHz for the following discussions due to its smaller interference range. Besides, the interference range is proportion to the increase of D_{SR} and, in most cases, is much larger than D_{SR}. It means that the ULIRC problem in UANs is much severer than the LIRC problem in terrestrial networks.

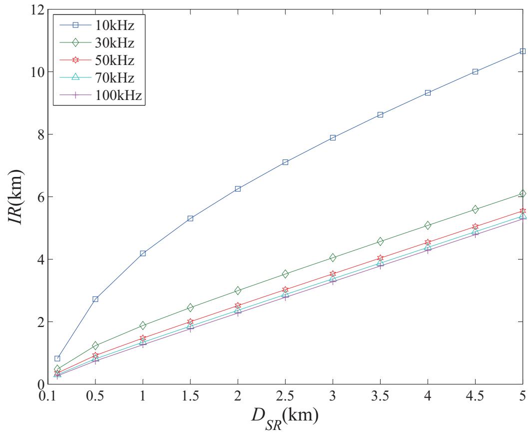


Fig. 6. An illustration of the interference range in terms of D_{SR}.

IV. The Two-Level Power Control MAC Protocol (TLPC)

In this paper, a two-level power control MAC protocol is proposed to avoid CDC and ULIRC problems. The basic idea and the details of the TLPC protocol are described as follows.

A. Basic Idea

ULIRC problem is mainly caused by the interference of a potential interference STA which can not be warned by RTS and CTS, but is able to interfere with the receiver. That is, the interfering STA is located within IR of the receiver. By Eq. (9), IR changes with P_t^S, P_t^I, D_{SR} and f. In general, D_{SR} and f are not changeable. Consequently, the simplest solution to ULIRC problem is to figure out the ratio of $\frac{P_t^I}{P_t^S}$, appropriate power levels for the sender and the interfering STA, to resist the possible interference. On the other hand, if the transmission power is adjustable such that the signal of the interfering STA can not reach the receiver, the CDC problem can also be avoided.

As a result, the basic idea of TLPC is to cover the IR by the CTS transmission. In other words, the main idea of TLPC is to adjust the transmission power such that the induced IR can be limited to D_{SR}. Thus, the exchanges of RTS and CTS can also warn the interfering STAs within the IR from transmission. Therefore, how to adapt the transmission power is introduced as follows.

B. Power Estimation

As mentioned above, the concept of TLPC is to cover IR by the transmissions of RTS and CTS. Thus, if IR can be reduced to D_{SR}, CDC and ULIRC problems can be avoided. In other words, in Eq. (9), IR is replaced by D_{SR} and we can have

$$D_{SR} = \frac{W(\frac{P_t^I}{P_t^S} * D_{SR} * \alpha(f)^{D_{SR}} * SNR_{th} * \ln\alpha(f))}{\ln\alpha(f)}. \tag{10}$$

In order to obtain P_t^I/P_t^S, let $D_{SR} * \ln\alpha(f)$ as constant a and let the others in Lambert W function as constant b. Therefore, we obtain

$$a = W(\frac{P_t^I}{P_t^S} * b). \tag{11}$$

According to Eq. (8) (Lambert W function), P_t^I/P_t^S can be obtained as below.

$$\frac{P_t^I}{P_t^S} = \frac{ae^a}{b}. \tag{12}$$

Replacing a and b by their original content to Eq. (12), we can obtain $P_t^I = 0.1 * P_t^S$. That is, if the sender transmits with P_t^S, the interfering STA I only needs to use 0.1 times the signal strength of the sender and the induced IR will be smaller than D_{SR}. Moreover, STAs in IR of R will be prohibited from transmission and the collision will not happen.

Therefore, if the sender and the interfering STA respectively use the maximum transmission power (P_{max}) to transmit DATA and $0.1 * P_{max}$ to transmit RTS, the IR of the receiver will be smaller than the TR of CTS. Therefore, the ULIRC problem can be prevent from happening.

C. Transmission Range Estimation

In this section, we will discuss the impact of the reduced power level on transmission range. By **C2** and Eq. (2), we can have

$$\frac{P_t}{A(D_{SR}, f)} \geq P_{th}. \tag{13}$$

By Eqs. (3) and (13), we can obtain

$$D_{SR} * \alpha(f)^{D_{SR}} \leq \frac{P_t}{P_{th}}. \tag{14}$$

In Eq. (14), D_{SR} is TR when $D_{SR} * \alpha(f)^{D_{SR}}$ equals $\frac{P_t}{P_{th}}$. According to Lambert W function, TR can be formulated as follows.

$$TR = \frac{W(\frac{P_t}{P_{th}} * \alpha(f))}{\ln\alpha(f)}. \tag{15}$$

If $P_t = P_{max}$, by Eq. (15), the maximum TR is about 1127.3m. Here, if a STA transmits with $0.1 * P_{max}$, the TR is reduced to 867.2m. The ratio of TR with and without power control is reduced approximately to 77%.

D. The TLPC MAC Protocol

In TLPC, STAs transmit by two levels of power. The transmission of RTS, CTS, and ACK use a low power to transmit and DATA is transmitted with the maximum transmission power, P_{max}. The details of TLPC protocol is described as follows by means of an example shown in Figs. 7 and 8.

As shown in Fig. 7, suppose S and R is a transmission pair and I is a potential interfering STA. When S has data to send, it will transmit RTS to R with power of P_{low}, where $P_{low} = 0.1 * P_{max}$. After receiving RTS, R will reply CTS with P_{low} as well. When the exchange is successful, S starts to transmit DATA to R. DATA will be transmitted with P_{max}. Since I may not receive CTS yet, it can transmit RTS or CTS. Thus, CDC problem may happen. However, CDC will not happen, because I transmits RTS or CTS with a small power, P_{low}. The IR of R will be smaller than D_{SR}, as shown in Fig. 8. Therefore,

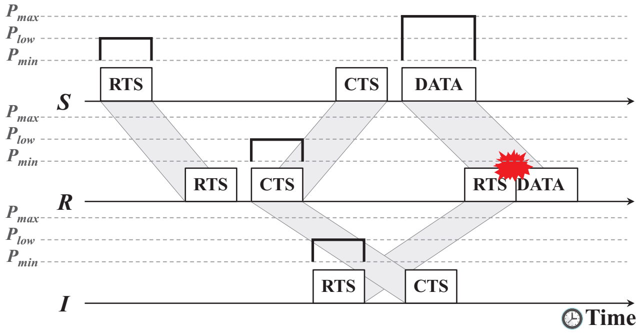


Fig. 7. An illustration of TLPC protocol in time domain.

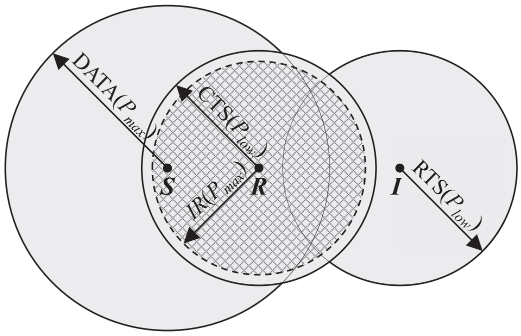


Fig. 8. An illustration of TLPC protocol in space domain.

since IR of R is smaller than D_{SR}, the potential interfering neighbors of S and R will be prohibited after receiving the control frames. Some neighbors of R may also be possible to transmit RTS or CTS. However, since these STAs are not located within the IR of R, the collision will not happen even if these STAs transmit frames. Consequently, TLPC can not only solve CDC and ULIRC problems, improve the four-way handshaking MAC protocol,but also can be directly applied to UANs.

V. Performance Evaluations

To verify the effectiveness of TLPC, Slotted FAMA [2], APCAP [3], and IEEE 802.11 DCF are simulated and compared by ns-2 simulator [14] in terms of network throughput and number of collisions. For ns-2 simulator to work in underwater environment, some modifications, such as signal attenuation, propagation and power consumption models, are made. The general simulation settings are shown in Table I.

As shown in Fig. 9, a grid topology is employed to observe CDC and ULIRC problems in each protocol. Nine STAs are deployed in the network. The distance between each other is 800m. In this topology, diagonal STAs will be located within the IR of the center STA.

Fig. 10 shows the comparison of TLPC, APCAP, and Slotted FAMA in terms of number of collisions per STA. APCAP can not prevent ULIRC problem. Therefore, the number of collisions in APCAP is the worst. Note that collisions at N_4 is the worst because the number of potential interfering STAs of N_4 is more than that of the other STAs. Therefore,

TABLE I
Simulation Parameters.

Parameter	Value
Simulator	ns2-2.31
Topology	Grid
Data rate	9600bps
Sound speed	1500m/s
Frequency	100kHz
SNR_{th}	10dB
Tx Range	1127.3m
Tx Range with power control	867.2m
Data packet size	1024Bytes
Simulation time	600s

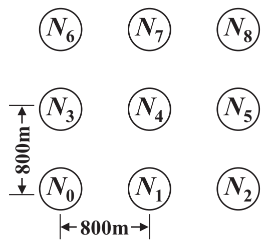


Fig. 9. The grid topology.

the reception of ACK is hardly successful. On the other hand, TLPC can not only prevent CDC problem, but also can avoid ULIRC problem. Therefore, TLPC performs better than APCAP. Although Slotted FAMA can prevent CDC problem, but it also can not prevent ULIRC problem. Moreover, in Slotted FAMA, one transmission needs to spend four time slots. That means Slotted FAMA has a little chance to transmit. In other words, it also has a little chance to collide. As a result, Slotted FAMA has the best performance in number of collisions.

Fig. 11 shows the number of collisions in terms of different traffic loads. Since TLPC solves CDC and ULIRC problems, the number of collisions does not increase too much even if the traffic load increases. Slotted FAMA gets the minimum number of collisions due to its little transmission chance. However, Slotted FAMA does not take ULIRC problem into consideration, thus the network throughput of Slotted FAMA

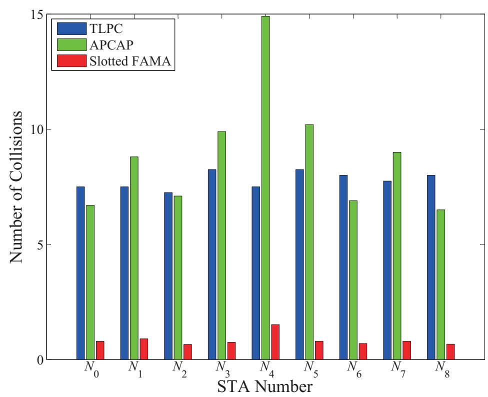


Fig. 10. The comparison of TLPC, APCAP, and Slotted FAMA in terms of number of collisions per STA. (Offered load=0.8)

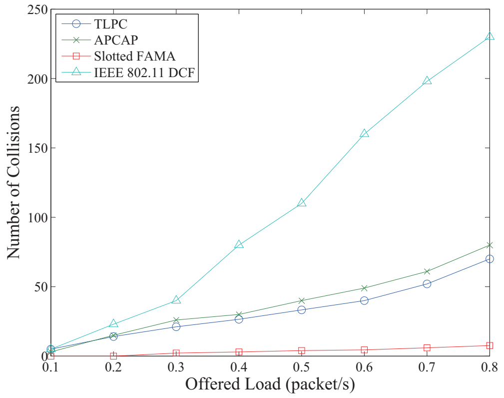


Fig. 11. The comparison of number of collisions of TLPC, APCAP, Slotted FAMA, and IEEE 802.11 DCF in terms of different traffic loads.

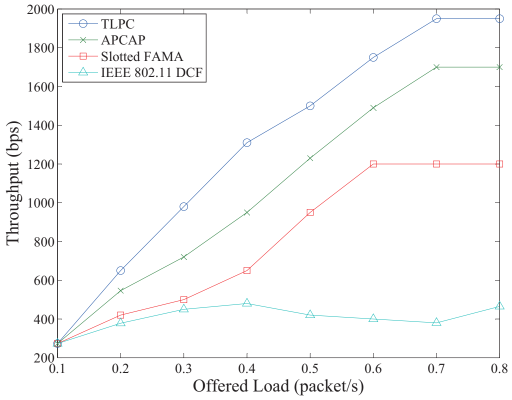


Fig. 12. The comparison of network throughput of TLPC, APCAP, Slotted FAMA, and IEEE 802.11 DCF in terms of different traffic loads.

is worse than TLPC, which will be shown in Fig. 12.

Fig. 12 shows the comparison of network throughput of TLPC, APCAP, Slotted FAMA, and IEEE 802.11 DCF in terms of different traffic loads. IEEE 802.11 DCF is designed for terrestrial networks and can not be directly applied to UANs. Thus, the performance of DCF is the worst. Slotted FAMA is able to prevent CDC problem. However, concurrent transmission cannot be achieved in Slotted FAMA and four slots are needed in a transmission. Furthermore, Slotted FAMA can not prevent ULIRC problem. Thus, the network throughput of Slotted FAMA is just only better than that of IEEE 802.11 DCF and gets saturated when the traffic load is about 0.6. APCAP can also avoid CDC problem and it is no need to wait for 4 slots. However, it can not prevent ULIRC problem. Therefore, the network throughput of APCAP is lower than that of TLPC. TLPC can prevent not only CDC problem, but also ULIRC problem. As a result, TLPC can achieve the best network throughput. Therefore, even though TLPC has a higher collisions than Slotted FAMA, TLPC has much better network throughput against Slotted FAMA.

VI. Conclusions

Due to the feature of acoustic wave, the hidden terminal problem can not be avoided even if the four-way handshaking mechanism is applied to UANs. Two collision problems, termed Control/DATA Collision (CDC) and Underwater Large Interference Range Collision (ULIRC) problems, are studied in this paper. As a result, a power control MAC protocol, named TLPC, is proposed to prevent CDC and ULIRC problems in UANs. TLPC adopts two levels of power to transmit such that the interference range can be limited to the distance between the sender and the receiver. Simulation results show that TLPC respectively outperforms Slotted FAMA and APCAP 63% and 14% in network throughput. Besides, TLPC outperforms 13% than APCAP and 70% than IEEE 802.11 DCF in number of collisions. Although TLPC has more collisions than Slotted FAMA, the network throughput of TLPC is much better than that of Slotted FAMA. Comprehensively speaking, TLPC is an effective and efficient MAC protocol in dealing with CDC and ULIRC problems in UANs.

Acknowledgement

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