Low Collision Random Access in Underwater Acoustic Sensor Network for Harbor Surveillance

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***Abstract*—This paper proposes a low collision random access method that statistically determines the participation in random access for multiple sub-channels in harbor surveillance. The proposed method estimates a distance between a sensor node (SN) and an enemy unmanned undersea vehicle (UUV), and calculates the number of SNs who may detect the UUV, and statistically selects sub-channels with a larger channel gain while keeping a low collision probability. The proposed method reduces the collision and increases channel utilization and throughput. Computer simulations show that the channel utilization and the throughput of the proposed method are greater than those of conventional method.**

Keywords—Underwater acoustic wireless sensor network, Harbor surveillance system, Random access

I. Introduction

Harbor surveillance system (HSS) monitors enemy submarines or unmanned undersea vehicles (UUVs) who infiltrates the harbor through underwater [1,2]. In order to detect the enemies, the passive sonar array and underwater acoustic-wireless sensor network (UWA-WSN) schemes were developed [1-5].

For the UWA-WSN, the sensor nodes (SNs) of the UWA-WSN detect these UUVs and report the UUV location and infiltration information to a fusion center (FC). In general, these SNs are arranged in line to maximize a detection coverage. When the UUV infiltrates into the harbor, many SNs may detect the UUV and simultaneously transmit the detection results to the FC. In this case, the collision at the FC occurs and the infiltration information may not be successfully transferred or be delayed to the FC. For collision avoidance, a time domain random back-off and an orthogonal code have been researched in the UWA-WSN [6-8].

The random back-off scheme in time, however, causes a time delay to transfer the infiltration information, which may not be adequate to the surveillance system since the UWA-WSN immediately reports the infiltration information of the UUV. The orthogonal code method utilizes long orthogonal sequences to preserve orthogonality among SNs. However, the narrow bandwidth of the UWA-WSN restricts the enough number of orthogonal codes of the SNs [9]. In addition, the infiltration information with the location and the velocity of the UUV is needed to be transmitted to the FC. Thus, a little bit large data rate is required. When large spread codes are utilized to keep the orthogonality of many SNs, the data rate or the throughput of the UWA-WSN becomes lower.

Therefore, this paper proposes a low collision random access method in multiple sub-channels which selects better sub-channels and statistically determines the participation in the random access. The proposed scheme can immediately transmit the infiltration information and reduces the collision probability at the FC. For the statistical participation in the random access, the proposed method measures the underwater radiated noise (URN) of the UUV, and estimates the number of detection SNs based on the sound pressure level (SPL) of the URN, and calculates the probability of the participation in the random access to reduce the collision probability. Since the proposed method utilizes better channels between the FC and SNs, the throughput also increases. Computer simulations demonstrate that the proposed method has greater channel utilization and throughput than a conventional random access method that randomly accesses the sub-channels.

II. Surveillance Environments

For the UWA-WSN, the SNs are linearly located to cover the harbor and each SN sends the UUV detection data to the FC by a single-hop. When the UUV is coming to the harbor, several SNs may simultaneously detect the UUV and immediately send the infiltration information to the FC. Assume that all SNs know their locations and transmit the infiltration information. This HSS configuration is depicted in Fig. 1.

Since SNs immediately send the data to the FC, the collision at the FC occurs, which may miss the infiltration information. In the next section, the proposed method that statistically selects sub-channels and obtains the large channel utilization and throughput, is described.

III. Propoesd Low Collision Random Access Scheme

The UWA communication system utilizes a narrow bandwidth. Therefore, the number of sub-channels of the multicarrier modulation is small [10]. In the random access for multicarrier modulation, when the number of sub-channels is less than that of SNs, the collision probability increases. This paper proposes the low collision random access method that each SN estimates the number of SNs detecting the UUV and statistically determines the

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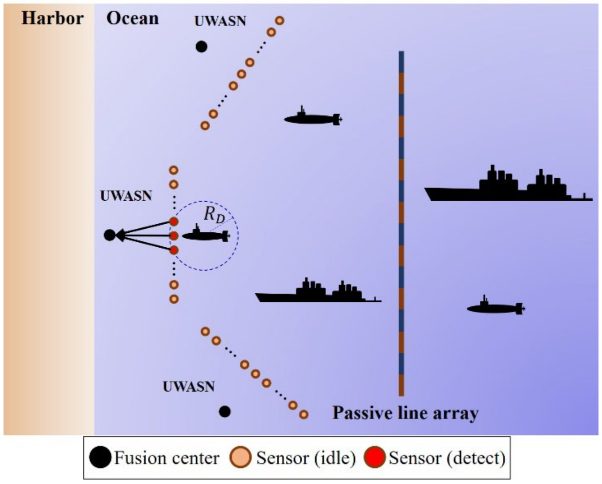

Fig. 1. Network configuration.

participation in the random access to reduce the collision probability.

To estimate the number of SNs who may detect the UUV, a distance between the SN and the UUV is measured by URN power difference for a short time duration, and the SPL at the UUV is estimated, and the number of SNs that are located within a detection distance from the UUV is counted.

Assume that the propeller of the UUV generates the URN whose SPL at an arbitrary time *t* is measured as *SL*(*t*) (in dB re μPa). The URN of the UUV is radiated through the underwater channel with a pathloss (*PL*(*t*)). A signal to noise power ratio (SNR) of the URN at the SN who has a distance (*d*(*t*)) from the UUV is measured as a received signal power including an environment noise (*NL*(*t*)). The measured SNR (*R*(*t*)) is calculated as following equation [11].

$$R(t) = SL(t) - PL(t) - NL(t) + DI, \qquad (1)$$

where *DI* denotes a directivity index at a hydrophone. Without loss of generality, the underwater environment is assumed as wide sense stationary, and then *NL*(*t*) is constant. *PL*(*t*) is given as [12]

$$PL(t) = 10k \, log_{10}\{d(t)\} + \alpha(f)d(t)\,, \qquad (2)$$

where *k* denotes a spreading factor and 1.5 is chosen in the paper. $\alpha(f)$ denotes an absorption coefficient (dB/km) and is expressed as the function of a transmitted signal frequency (*f*), which is given as [13]

$$\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 \times 10^{-4}f^2 + 0.003. \qquad (3)$$

Assume that *SL*(*t*) and *NL*(*t*) of *R*(*t*) are constant, *d*(*t*) in Eq. (2) can be estimated by the first and second order derivatives of *R*(*t*) with respect to a time. The first order derivative is calculated as

$$\frac{\partial R(t)}{\partial t} = -\frac{10k}{ln\,10}\frac{1}{d(t)}v - \alpha(f)v, \qquad (4)$$

where *v* denotes a speed of the UUV. Assume that *v* of the UUV is constant for a short time duration, the second derivative can be obtained as

$$\frac{\partial^2 R(t)}{\partial t^2} = \frac{10k}{ln\,10}v^2\left\{\frac{1}{d(t)}\right\}^2. \qquad (5)$$

Eqs. (4) and (5) can be rewritten as a matrix form as

$$\begin{bmatrix} \frac{\partial R(t)}{\partial t} \\ \sqrt{\frac{\partial^2 R(t)}{\partial t^2}} \end{bmatrix} = \begin{bmatrix} -\frac{10k}{ln\,10} & -\alpha(f) \\ (-1)^{(j+1)}\sqrt{\frac{10k}{ln\,10}} & 0 \end{bmatrix} \begin{bmatrix} \frac{v}{d(t)} \\ v \end{bmatrix} + \varepsilon, \qquad (6)$$

where ε denotes a measured noise and *j* is equal to zero when the UUV is coming in or to one when the UUV is far away. Using Eq. (6), the *d*(*t*) between a SN and the UUV is calculated by using a least square or Kalman filter. When the *d*(*t*) is estimated, the estimated SPL ($\widehat{SL}$) can be calculated by Eqs. (1) and (2). Then, the number of SNs who may detect the UUV is also estimated by counting the number of SNs within a detection circle calculated by the SPL of the UUV.

Let V_{TH} be a detection threshold. The detection range (R_D) of the UUV is defined as

$$R_D = \arg\max_d\{d \in \mathbb{R} \mid PL \le \widehat{SL} - NL - V_{TH}\}, \qquad (7)$$

where $\mathbb{R}$ denotes a set of real number. Assume that d_{SN} is a distance between two SNs. The number (*K*) of the detection SNs can be calculated using the cross-section of the sensor line and a circle of R_D radius, which is given by

$$K = 1 + 2 \times \max\left\{k \in \mathbb{N} \mid k \le \sqrt{{R_D}^2 - d(t)^2}/d_{SN}\right\}, \qquad (8)$$

where $\mathbb{N}$ denotes a set of an integer number. When the number of SNs is greater than that of the sub-channels, the collision probability increases. To reduce the collision, this paper proposes that each SN statistically determines whether the SN transmits or not, based on the participation probability.

When multiple sub-channels are utilized, the participation probability needs to be derived from multi sub-channels. If better sub-channels are selected, a frequency selection diversity gain can be achieved and the throughput of WSN also increases. In UWA-WSN, the FC periodically broadcasts beacon signals that experience the underwater multipath channels [14,15], and the SN can select better sub-channels and utilize the frequency selection diversity. Unfortunately, since adjacent SNs who detect the UUV are closely located and the horizontally located adjacent SNs have the similar frequency response channel, the adjacent SNs try to select the same sub-channels among multiple sub-channels. This similar frequency channel responses also cause collisions in the sub-channels. Therefore, this paper proposes the statistical participation in multiple sub-channel random access to avoid the collision and to attain the frequency selection diversity.

Assume that the number of sub-channels is *L* and the sub-channel gains are measured regularly from the beacon. To obtain the frequency selection diversity, sub-channels who have a larger gain need to be sorted in descending order. If the l-th sub-channel is set as C_l, a descending ordered sub-channel vector ($\mathbf{C}$) is given as

$$\mathbf{C} = [C_1 \quad C_2 \quad \cdots \quad C_{L-1} \quad C_L]^T. \tag{9}$$

Note that C_1 has a sub-channel with the largest channel gain and C_L has the lowest one.

To increase the throughput or to decrease bit error rate (BER), the sub-channel is sequentially selected from a larger channel gain to a lower one. Since adjacent SNs tries to select better sub-channels, the collision probability increases. Therefore, to avoid the collision, this paper sequentially selects the best sub-channels with the probability of p and next better sub-channel with the probability of $p(1\text{-}p)$ and so on. Then, the selection probability (p_{SC}^l) of the l-th sub-channel is calculated as

$$p_{SC}^l = p \times (1-p)^{l-1}. \tag{10}$$

To reduce the collision probability at a sub-channel by multiple SNs, p needs to be determined by the number (K) of SNs. Since adjacent K SNs select the same sub-channel with a large probability, p needs to be selected to reduce the collision rate keeping the channel utilization, which is given as

$$p = \frac{1}{K}. \tag{11}$$

Using Eqs. (10) and (11), the collision for a sub-channel is reduced.

To reduce the collision probability, the proposed method calculates the distance between the SN and the UUV, and estimates the number of detection SNs, and statistically determines the participation in the random access. Therefore, this proposes scheme obtains the large channel utilization and throughput.

IV. Simulations

In this section, the channel utilization and throughput performances of the proposed random access method is compared with those of the conventional method that randomly accesses the sub-channels.

Simulation environments are shown in Table 1. Universal filtered multicarrier (UFMC) was utilized for a robust time synchronization among sub-channels [16]. The noise power level at the SNs was set as 90 dB re µPa and the SPL of the URN at the UUV was set as 120 dB re µPa. Assume that the UUV was moving toward to the SN. The detection threshold (V_{TH}) was set to be -5 dB re µPa and the detection distance (R_D) was calculated as 216 m using Eq. (7), and the number of detection SNs was calculated as 25 in this scenario. The number of filter taps was set as 70 for the delay spread of the UWA channels and the asynchronous of SNs.

TABLE I. Simulation conditions.

Parameters	**Values**
Distance between SNs	18 m
Minimum distance between SN and FC	5 km
Bandwidth	5 kHz
Modulation scheme	16QAM-UFMC
Filter length of UFMC	70
FFT size	1024
The number of sub-channels	4
Doppler shift	5Hz

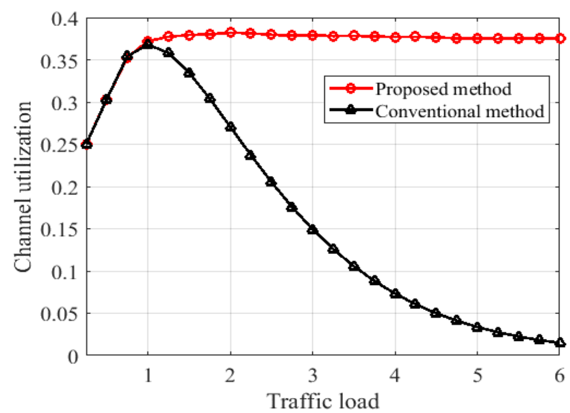

Fig. 2. Channel utilization according to traffic load.

As the UUV was coming closer, the number of detection SN increased up to 25, and a traffic load also increased. The channel utilization versus the traffic load for the proposed and the conventional random accesses is displayed in Fig. 2. As in Fig. 2, the channel utilization of the conventional random access showed the same as that of slotted-aloha. This is because multiple sub-channels can be considered as slots in time domain. The proposed method showed the same channel utilization when the traffic load is less than one. However, as the traffic load was larger than one, the channel utilization of the proposed method was larger than that of the slotted aloha because the proposed method statistically determined the participation in the random access by Eqs. (10) and (11).

The throughput versus the traffic load of the proposed and conventional schemes is shown in Fig. 3. The conventional scheme showed the same throughput as the slotted aloha since the conventional scheme did not select better sub-channel, while the proposed method showed larger throughput than the conventional scheme. In particular, when the traffic load was larger than one, the proposed scheme statistically determined the participation in the better sub-channel to reduce the collision probability and to increase the throughput.

Computer simulations showed that the proposed random access method provided better channel utilization and

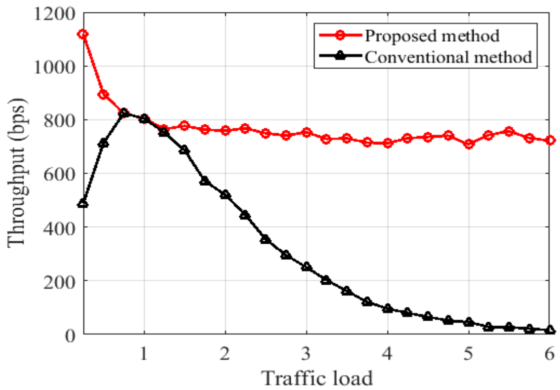

Fig 3. Network throughput according to traffic load.

throughput by statistically selecting the participation in the random access of UWA-WSN

V. Conculusioin

For UWA-WSN, this paper proposed the low collision random access scheme that selected better sub-channel and statistically determined the participation in the random access. To calculate the statistical participation probability, the proposed method measured the distance between the UUV and SN, and estimated the number of detection SNs. Computer simulations showed that the proposed method exhibited larger channel utilization and throughput than the conventional random access method.

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