A Dynamic Spectrum Decision Algorithm for Underwater Cognitive Acoustic Networks

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ABSTRACT

Cognitive acoustic (CA) is emerging as a promising technique for spectrum-efficient Underwater Acoustic Networks (UANs). Due to the unique features of UANs, especially the long propagation delay, the busy terminal problem and large interference range, traditional spectrum decision methods used for radio networks need an overhaul to work efficiently in underwater environment. In this paper, we propose a dynamic spectrum decision algorithm called Receiver-viewed Dynamic Borrowing (RvDB) algorithm for Underwater Cognitive Acoustic Networks (UCANs) to improve the efficiency of spectrum utilization. RvDB algorithm is with the following features. Firstly, the spectrum resource is decided by receiver. Secondly, the receivers can borrow the idle spectrum resource from neighbouring nodes dynamically. Finally, the spectrum sensing is completed by control packets on control channel which is separated from data channels. Simulation results show that RvDB algorithm can greatly improve the performance on spectrum efficiency.

CCS Concepts

•Computer systems organization → Computer-Communication Networks; *Network Architecture and Design;*

Keywords

underwater cognitive acoustic networks, dynamic spectrum decision, long propagation delay

1. INTRODUCTION

Underwater Acoustic Networks (UANs) have attracted extensive attention in the last couples of years [1, 2] due to its widespread applications including oceanographic data collection, field monitoring and disaster prevention. Compared with the terrestrial counterpart, available communications frequencies in underwater are quite limited, usually from hounds of hertz to tens of kilohertz due to the severe frequency-depended attenuation.

To improve the efficiency of spectrum utilization in UANs, Cognitive Acoustic (CA) is advocated as a promising technique to achieve spectrum-efficient transmissions over acoustic channel [3, 4]. Specifically, the framework of Underwater Cognitive Acoustic Networks (UCANs) composed of the spectrum sensing, the dynamic power control and the spectrum management has been proposed, among which, the spectrum decision is a key part in spectrum management. Compared with Cognitive Radio (CR), the spectrum decision algorithm in CA faces three challenges including the long propagation delay, the terminal busy problem and the large interference range.

The authors in [5] explore how dynamic spectrum sharing concepts can be used for spectrum management to achieve integrated communication and navigation in integrated underwater acoustic systems. In [6], the authors propose the spectrum signaling protocol to inform neighbouring nodes of the channel allocation. A spectrum allocation approach is proposed in [7] to improve the channel capacity among users. In [8], the authors propose a receiver-initiated spectrum management (RISM) system to significantly improve the performance of UANs through a collaboration of the physical layer and medium access control layer.

In this paper, we focus on the three challenges aforementioned and propose a dynamic spectrum decision algorithm named Receiver-viewed Dynamic Borrowing (RvDB) for UCANs to improve the spectrum utilization efficiency. RvDB algorithm has the following features. Firstly, spectrum decision method is based on the viewpoint of receiver, which can efficiently avoid collision at receiver ending. Secondly, the receivers borrow dynamically the idle spectrum resource from the neighbouring nodes after they sense the environment. The strategy of sensing first and borrowing later guarantees that the CA users can maximize the utilization of the spectrum resource. Finally, to solve the busy terminal problem, the spectrum sensing is completed by control packet on control channel which is separated from data channels.

The remainder of this paper is organized as follows. In Section II, network model for environment surveillance is introduced and the hypotheses of the algorithm are presented. Then we describe RvDB algorithm in Section III. In Section IV, we evaluate the performance of the algorithm in OPNET software with underwater acoustic channel. Section V concludes the paper.

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2. NETWORK MODEL

Consider UCANs used for environment surveillance. Numerous sensor nodes (SNs) are evenly distributed in a sea area to monitor the physical quantities. The SNs in the surveyed sea region are organized as the form of virtual clusters, in which there are a cluster head (CH) and several SNs. The sensor readings of each SN are fused at the Fusion Center (FC). In this study, the CHs are referred as CA users in UCANs.

Based on the network model mentioned above, the CA user firstly collects sensor readings in the cluster and then forwards the data to FC through multi-hop communication between the neighbouring CA users. In this network model, how to share severe spectrum resource efficiently is a key problem for all CA users. The proposed RvDB algorithm is based on the following hypotheses:

- OFDM is applied to data transmission at physical layer. The frequency available can be divided into multiple groups referred as data channels of UCANs according to different sub-carriers in OFDM. In this study, the sub-carriers in OFDM are divided into 13 groups, that is there are 13 data channels in UCANs.
- M-ary chirp spread spectrum modulation (MCSS) [9] is employed as modulation technique of control packets, which occupy the whole frequency band available. Compared with OFDM system, MCSS is with much lower bit rate so as to guarantee the transmission reliability.
- The whole network has a unified clock. The transmissions of data and control packets are arranged in two successive different processes.
- There are N neighbouring CA users for each CA user. In this study, we consider N is 8, which is a severe condition for sparse distributed UCANs. The IDs and coordinates of these neighbors are available.

3. ALGORITHM DESCRIPTON

3.1 Interference Constraint Condition

Similar to terrestrial network, the transmission range denoted by R_d is defined as the maximum distance between the transmission pairs. As for a receiving node, its neighbouring nodes are the ones within its transmission range. However, not only the neighbouring nodes but also the nodes beyond the transmission range will interfere with the transmission when they use the same frequency bands. We call these nodes beyond transmission range as the interference nodes. So the interference range denoted by R_i can be defined as the maximum distance away from the interference node. For a receiving node, the received signal can be illustrated by the signal-to-interference-plus-noise ratio (SINR) when interference nodes are existing:

$$SINR(dB) = 10\lg \frac{P_t/A(R_d, f)}{P_t/A(R_i, f) + \sigma_n^2} \tag{1}$$

where P_t is the power of transmitted signal, $A(R_d, f)$ and $A(R_i, f)$ are the attenuation of the desired signal and interference signal at frequency f, respectively, σ_n^2 is the power of ambient noise.

Attenuation of a signal with frequency f and propagation distance R in underwater acoustic channel is given by [10]

$$A(R, f) = R^k \cdot \alpha(f)^R \tag{2}$$

where k is the spreading factor and $\alpha(f)$ is the absorption coefficient.

The ambient noise power spectral density (p.s.d) expressed as $N(f)$ is also frequency dependent and its empirical formulate can be found in [10]. Then σ_n^2 in (1) can be expressed as:

$$\sigma_n^2 = N(f) \cdot \Delta f \tag{3}$$

where Δf is the noise bandwidth.

According to (2) and (3), we can get an optimal frequency in which there are the minimum sum of path loss and ambient noise at a special transmission distance. In this paper, OFDM is used to be the modulation technique and the frequency bandwidth of sub-channel is $500Hz$ in physical layer. And then we suppose $SINR$ is more than $9dB$ according to our several sea experiments. So we can get the interference range by solving the following equation at an optimal frequency.

$$10\lg \frac{P_t/A(R_d, f)}{P_t/A(R_i, f) + N(f) \cdot \Delta f} \geq 9 \tag{4}$$

Substituting $\Delta f = 500$ into (4), we can get $R_i \geq 2R_d$ when the transmission range is more than $6km$. In other words, the interference nodes have almost no negative effect on receiving nodes when R_i is two times of R_d. Then we define hop distance and interference constraint condition as followed.

Definition 1 *Hop Distance $d(u, v)$: The hop distance is the number of the reachable paths between two nodes u and v, which is normalized by transmission range. For example, the hop distance between neighbouring nodes is 1.*

Let f_u be the spectrum resource mapping with subset of available channel number set $\{0, 1, 2, \cdots, 12\}$ for CA user u. The mapping is denoted as:

$$f_u \to CH_u^n = \left\{ch_u^1, ch_u^2, \cdots, ch_u^n\right\}, n \leq 13 \tag{5}$$

Definition 2 *Interference Constraint Condition: For any two nodes u and v, the following condition should be satisfied,*

$$|ch_u^i - ch_v^j| : \begin{cases} \geq 2 & if\ d(u, v) = 1 \\ \geq 1 & if\ d(u, v) = 2 \\ \forall & otherwise \end{cases} \tag{6}$$

where $1 \leq i \leq m, 1 \leq j \leq n$.

To improve the spectrum utilization efficiency, more channels should be selected by CA users. We formulate the spectrum decision problem as the following optimization problem which satisfies (6).

Prob 1

$$f^* = \arg\max_f \sum_u size(CH_u) \tag{7}$$

In this study, we propose RvDB algorithm to solve Prob.1 in the following subsection.

3.2 Transmission Scheduling

Fig.1 illustrates the transmission scheduling. We suppose the transmission pairs have been set up. So the task of the transmission pairs is to select suitable channels and then transmit data on the selected channels. The time is organized as frame including Channel Selection (CS) process and Data Transmission (DT) process. The spectrum resource is divided into 13 data channels, while control packets occupy the whole spectrum band.

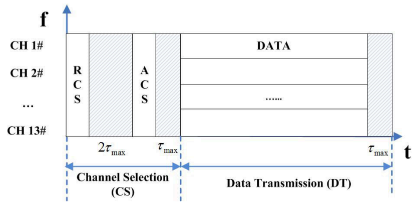

Figure 1: Synchronized transmission scheduling

The sending CA user sends out Request Channel Selection (RCS) packet to its destination to start a CS process before it transmits data. Here the RCS message includes some useful information such as ID and coordinate information of the source and destination nodes, which are the key references for destination to select channel set. The invited receiver who has successfully received RCS packet will respond with Answer Channel Selection (ACS) packet. The ACS message includes the information of selected channel set. The sending CA user who successful received the ACS packet will start data transmission on the selected channel set in DT process. $\tau_{\max}$ is defined as the transmitting duration within transmission range in Fig.1.

The RCS/ACS handshaking provides the necessary information for RvDB algorithm. How to avoid or reduce collisions among control packets is essential. However, in CS process, no other prior information except a unified clock can be available, that is, the transmissions of RCS and ACS are in a distributed network. A time-slotted scheduling is presented in the paper. Fig.2 illustrates the transmission scheduling for RCS control packets.

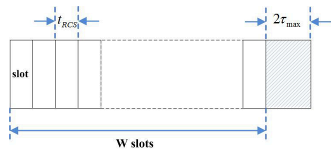

Figure 2: Transmission scheduling of RCS packets

As shown in Fig.2, there are W slots followed by $2\tau_{\max}$ in the transmission duration. The duration guarantees that the interference node's transmission could be received. The length of a slot denoted as t_{RCS} is equal to the duration of RCS packet. The intended sender will select one randomly from W slots and then send RCS packets at the selected slot. The receiver maybe receive the RCS packets from the senders within interference range. The larger W is, the less the probability of collision. According to [11], W reaches 250 when the average number of the neighbouring nodes is 4. For t_{RCS} is small (e.g. $0.1s$), the duration of the transmission for RCS packets is reasonable though W is large.

The transmission scheduling for ACS packets is similar to the one for RCS packets. Compared with the transmission of RCS packets, the sender just need receives ACS packets from the receiver within the transmission range. So the transmission process is followed by the duration of $\tau_{\max}$.

3.3 Spectrum Decision Algorithm

We assume that each CA user has been arranged a unique ID and coordinate. Furthermore, it can get the information of the neighbouring nodes. For convenience, a regular rectangle network is adopted in this study but this is not necessary.

Assume there are 8 neighbouring nodes for node u with coordinate (x, y) . The IDs and coordinates of these neighbouring nodes are available for node u . The spectrum decision algorithm is divided into two stages, namely, initial decision stage and dynamic borrowing stage. In initial decision stage, node u is arranged a specific channel, which is expressed in (8):

$$f_u(x,y) : \begin{cases} x \cdot a + y \cdot (3a+b) \pmod N \\ N = 5a + 3b \end{cases} \tag{8}$$

From the interference constraint condition described in Definition 2, the parameters in (8) are set as $a = 2, b = 1$ and we can get the following spectrum decision strategy in the initial decision stage:

$$f_u(x,y) = 2x + 7y \pmod{13} \tag{9}$$

where (x, y) is the coordinate of u.

The dynamic borrowing strategy is based on the viewpoint of the receiver, who will borrow idle channels from the neighbouring nodes through RCS/ACS handshake process. That is why we call the algorithm as RvDB. The idle channels are those which are different from the channels selected by the nodes within the interference range. After RCS transmission process, the receiver can get the activate states of not only the neighbouring nodes but also the ones within the interference range. The activate states are sending or receiving. But the selection processes are distributed and at the same time for all receivers. So how to select idle channels is the key issue in this stage. The selection principle of RvDB algorithm is to judge the idle channels which may be selected by other receivers within the interference range. There are three main steps as followed.

- At the beginning, the channels of the neighbouring nodes are all regarded as idle channels by the receiver. After that,some candidates will be subtracted according to the information of RCS packets sent by other nodes.
- The channels of the neighbouring sending and receiving nodes are subtracted firstly.
- Prejudge the idle channels selected by other receiver with higher priority. Then these idle channels will be subtracted from the candidates. The receiver with higher priority are the two kinds of nodes. Ones are the neighbouring receiving nodes with lower ID. The others are the nodes beyond the transmission range.

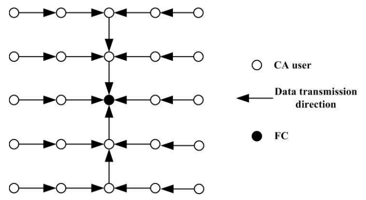

Figure 3: Simulation scenario

The spectrum decision algorithm is illustrated as Algorithm 1. For receiver u, we suppose its ID and the number of neighbouring nodes is iID and 8, respectively. The number of RCS packet received by u is denoted as K.

Algorithm 1

Initial decision stage:

Step 1: Calculate the channel number according to (9): $CH_u = \{ch_u\}$

Step 2: Calculate the channel number of the neighbouring nodes according to (9): $CH_{nb} = \left\{ch_{nb}^1, ch_{nb}^2, \cdots, ch_{nb}^8\right\}$

Dynamic borrowing stage:

Step 3: The channels available for node u: $CH_u = \{ch_u\} \cup \left\{ch_{nb}^1, ch_{nb}^2, \cdots, ch_{nb}^8\right\}$

Iterative Calculations according to K RCS message:

for $k = 1$ to K

Step 4: Denote the sender as s, if s is a neighbouring node, the channels owned by s should be subtracted from CH_u: $CH_u = CH_u - \{ch_s\}$

Step 5: Denote the corresponding receiver as r, if r is the neighbouring node, the channels owned by r should be subtracted from CH_u: $CH_u = CH_u - \{ch_r\}$

Step 6: Denote the ID of node r as rID. Calculate the probable channel set of node r: $CH_r = \left\{ch_r^1, ch_r^2, \cdots, ch_r^9\right\}$

Step 7: if $rID < iID$ or r is not the neighbouring node: $CH_u = CH_u - CH_u \cap CH_r$

End for

4. PERFORMANCE EVALUATION

In this section, we evaluate the performance of RvDB algorithm via simulations.

4.1 Simulation Settings

The simulations are based on OPNET14.5 software with modified pipeline stages which are coincident with underwater acoustic channel model. The propagation speed of the acoustic signal is $1500m/s$. DATA packets are modulated by OFDM with 390 sub-carriers. So each sub-channel is composed of 30 sub-carriers. The OFDM signal is with the spectrum band from $10kHz$ to $16kHz$ and lasts $60s$. While RCS and ACS control packets are modulated by MCSS with the same spectrum resource as DATA packets and last $1s$.

For convenience, a regular distributed network scenario is used in the simulations in spite of the assumption is not necessary. In the simulation network, 24 CA users collect and forward the sensor readings within the clusters to FC, which is the center of all CA users. The distance among neighbouring nodes is $6km$, which is also the maximum transmission range. According to the description in Section 3.2, the interference range is two times of the data transmission range. So the reachable distance of DATA and ACS packets is set as $6km$. While the reachable distance of RCS packets is set as $12km$ due to the RCS packets should be got by the nodes within the interference range. The duration of $\tau_{\max}$ is set as $4s$.

The network scenario is shown in Fig.3. The arrows in the figure direct the network route for each node.

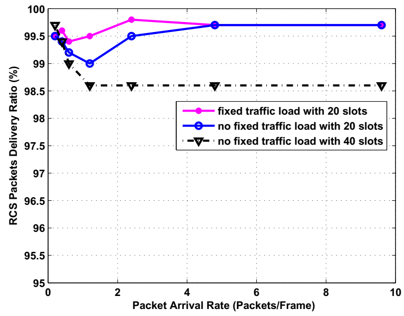

Figure 4: The delivery ratio of RCS packets

4.2 Simulation Results

We first evaluate the efficiency of RvDB algorithm in scenarios with and without fixed traffic load. Packet arrival rate and channel occupancy ratio are referred as traffic load and network efficiency, respectively. The former is defined as the number of data packets generated at each frame and the latter is defined as the number of sub-channels got at each negotiation of spectrum source decision. In the scenario with fixed traffic load, each node only generates 500 data packets in total. While in the scenario without fixed traffic load, each node will generate data packets according to the traffic distribution function all the time. According to the transmission scheduling described in Section 3.2, the transmission of control packets is not collision-free. The collision of control packets will lower the efficiency of RvDB algorithm. Fig.4 shows RCS delivery ratio with different scenarios and negotiation slots. The delivery ratio is the number of packets successfully received divided by the total number of packets transmitted.

As shown in Fig. 4, the delivery ratio is more than 98.5% no matter what kinds of situations. So the efficiency of RvDB algorithm is just lightly affected by the collision of control packets due to their relatively high delivery ratio.

Fig.5 illustrates the channel occupation ratio. According to RvDB algorithm, the upper bound is 69% due to each transmission pair can select 9 from 13 sub-channels at most. The channel occupancy ratio of FDMA is constant 8% due to one sub-channel is selected at each transmission. As shown in Fig.5, with the increase of packet arrival rate, the occupancy ratio is reduced and tends to be stable. Moreover, compared with the scenario without fixed traffic load, the occupancy ratio is higher at the same packet arrival rate in

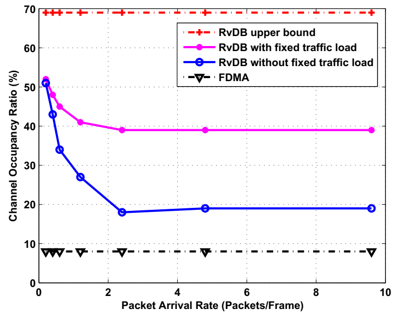

Figure 5: Channel occupation ratio in different scenarios

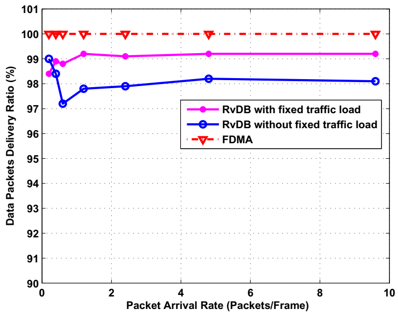

Figure 6: Data transmission success ratio

the scenario with fixed traffic. No matter what kinds of scenarios, it is easy to observe the significant improvement on the channel occupation ratio of RvDB algorithm ove FDMA at the same packet arrival rate.

Fig.6 shows that, FDMA is a kind of collision-free spectrum decision method and its delivery ratio is 100%. As for RvDB algorithm, no matter the packet arrival rate is high or low, over 97% transmitted DATA packets are successfully received by corresponding receivers. The collisions happen when more than one DATA packets with the same spectrum resource are transmitting beyond interference range. Compared with the scenario without fixed traffic load, the delivery ratio in the scenario with fixed traffic load is a litter higher at the same packet arrival rate similar to the channel occupancy ratio.

5. CONCLUSION

A dynamic spectrum decision algorithm named RvDB for UCANs is proposed in this paper. CA users borrow idle spectrum resource from their neighbouring nodes to improve spectrum utilization efficiency. Furthermore, the borrowing strategy is designed based on viewpoint of the receiver, which can efficiently avoid collision at receiver ending. Simulation results show that UCANs applying RvDB algorithm is with higher spectrum efficiency compared with static FDMA.

6. ACKNOWLEDGMENTS

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