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Joint Channel and Power Assignment for Underwater Cognitive Acoustic Networks on Marine Mammal-Friendly

Libin Xue and Chunjie Cao *

School of Cyberspace Security, Hainan University, Haikou 570228, China; xuelibin@hainanu.edu.cn
* Correspondence: caochunjie@hainanu.edu.cn

Abstract: When marine animals and underwater acoustic sensor networks (UASNs) share spectrum resources, problems such as serious harm caused to marine animals by underwater acoustic systems and scarcity of underwater spectrum resources are encountered. To address these issues, a mammal-friendly underwater acoustic sensor network channel power allocation algorithm is proposed. Firstly, marine animals are treated as authorized users and sensor nodes as unauthorized users. Considering the interference level of sensor nodes on authorized users, this approach improves network service quality and achieves a mammal-friendly underwater communication mechanism. Secondly, to maximize the utility of unauthorized users, the algorithm incorporates a network interference level and node remaining energy into a game-theoretical framework. Using channel allocation and power control, a game model is constructed with a unique Nash equilibrium point. Finally, through simulation, it can be found that the proposed algorithm can obtain a stable optimal power value, and with the increase of network load, the system capacity of the proposed algorithm is significantly improved than that of the traditional cognitive radio technology and the common spectrum allocation algorithm, and the transmitted power of nodes can be controlled according to the size of the residual energy, so as to comprehensively improve the overall performance of the network.

Keywords: underwater acoustic networks; channel allocation; power control; mammal-friendly

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1. Introduction

Underwater acoustic sensor networks (UASNs) [1,2], have drawn significant attention in marine commerce, military operations, and underwater environment exploration and become new research frontiers [3]. However, most existing research tends to overlook the impact of underwater acoustic sensor networks on marine mammal life and the resultant interference among nodes. Therefore, it is necessary to not only achieve mammal-friendly underwater communication but also address issues like severe node interference in underwater cognitive networks to enhance network performance.

The available spectrum in underwater acoustic channels often falls between tens to hundreds of kilohertz, while the frequencies primarily utilized by UASNs are concentrated in the range of 1 kHz to 40 kHz. Frequencies used by marine mammals for communication are primarily within 30 Hz to 150 kHz, leading to a spectral overlap. Research reveals that underwater sonar systems can severely impact the communication signals and normal behavior of marine mammals, causing significant harm to their survival. Moreover, underwater communication conditions are harsh due to limited energy supply, strong time variability, significant inter-node communication interference, and challenges in centralized control. Therefore, it is crucial to address the coexistence of marine life and underwater nodes' frequency spectrum while improving the overall performance of underwater acoustic networks.

In the literature [4], the concept of an underwater acoustic cognitive network was proposed for the first time, it senses the environment around the underwater acoustic network and adjusts the transmission power to improve the spectrum utilization. The literature [5,6] applied the cognitive underwater acoustic network technology, but did not consider the impact of underwater acoustic communication networks on the survival of marine mammals.

To tackle the aforementioned challenges, this paper proposes a game-theoretical and mammal-friendly underwater network channel power allocation algorithm. It treats marine mammals as primary users and underwater sensor nodes as secondary users. The algorithm aims to maximize the capacity and performance of secondary users by establishing a utility function. By incorporating network interference levels and node remaining energy into the game-theoretical framework, the algorithm allocates channels and adjusts the transmission power of underwater communication nodes. This design aims to achieve a mammal-friendly and system-performance-optimized underwater acoustic communication network.

The rest of this paper is organized as follows: In Section 2, we will mainly introduce the current research on channel allocation and power control. In Section 3, we will introduce the new mammal-friendly power control (MFPC) algorithm in detail. Then, we will compare the results through simulation experiments in Section 4 to verify the superiority of the new MFPC algorithm, and finally make a prospect and summary in Section 5.

2. Related Work

The Power and Spectrum Allocation Technique is one of the key technologies in cognitive radio technology. Reference [7] proposed a spectrum allocation scheme considering cognitive user mobility. In the same environment, cognitive users were able to access more spectrums when mobile, achieving good results in practical commercial applications. However, fairness among nodes was not extensively addressed.

Reference [8] proposed a dynamic spectrum allocation algorithm that achieves on-demand allocation of spectrum resources, significantly improving fairness. However, this algorithm did not consider the issue of channel power interference in strong interference environments, making it suitable only for professional wireless radio systems with higher transmission rates. Reference [9] employed a Cournot game model that optimized the spectrum allocation for licensed users, demonstrating that reducing spectrum similarity would decrease the amount of spectrum leased by primary users. However, this algorithm treated all secondary users as a collective entity and did not deeply consider the issue of mutual interference among secondary users in terms of transmission power. Reference [10] introduced a bandwidth allocation scheme based on false alarm, determining perception cycles based on the Nash equilibrium, and allocating a spectrum bandwidth based on false alarm performance, effectively reducing energy consumption. Reference [11] proposes a multiuser OFDM subcarrier, bit, and power allocation algorithm to minimize the total transmit power. This is achieved by assigning each user a set of subcarriers and by determining the number of bits and the transmit power level for each subcarrier. However, this algorithm is only applicable to terrestrial wireless networks. Thus, it can be seen that spectrum allocation and power control are key technologies in cognitive radio (CR) to enhance spectrum utilization.

The underwater acoustic cognitive network is proposed based on the above cognitive radio technology. CR technology based on spectrum allocation and power control is still an effective means to improve the utilization of spectrum, but due to the complexity of the underwater environment, the above technology needs to be improved before it can be applied. Based on game theory and OFDM modulation technology, literature [12] proposes a distributed power distribution algorithm to maximize the performance of each user through a non-cooperative game. However, because this algorithm does not provide channel state and node exchange information, it can not improve the performance and reliability. Literature [13] divides a channel into different cells and obtains a more accurate CSI based on the channel state information feedback by time-varying channels through self-learning. However, this algorithm can only achieve a higher throughput than traditional frequency multiplexing without considering propagation delay and resource allocation, which has great limitations. Based on the theory of a non-cooperative game, literature [14] proposes a CSI acquisition scheme with an instantaneous adaptive power allocation strategy. The forgetting factor is introduced into the power allocation algorithm, thus, improving the adaptive power allocation performance of multi-user communication in underwater acoustic channels. However, this algorithm does not consider the impact of sensor networks on marine mammals. Literature [15] proposed an environmentally-friendly channel allocation scheme. On the basis of locating marine mammals, transmit power and available channels were jointly allocated to competing users, which avoided the interference of artificial sensors on marine mammals and improved the network capacity. However, there was no further study on related issues such as channel transmission rate. In the case of marine mammals and transmission constraints, literature [16] proposed an environmentally friendly underwater acoustic sensor network protocol based on channel allocation, which improved the throughput and energy efficiency of underwater acoustic networks. However, this protocol failed to find a matching mac protocol in practical applications, and there are certain limitations. Literature [17] proposes an angle-aware user cooperation (AAUC) scheme, which avoids direct transmission to the attacked user and relies on other users for cooperative relaying. Simulation results showed that the proposed algorithm achieves higher security than direct transmission, but it did not consider the harm of the sensors to the animals. Therefore, in order to make full use of scarce underwater spectrum resources, it is necessary to combine cognitive underwater acoustic communication technology and a power control algorithm on the basis of realizing biofriendliness and to improve the communication performance and spectrum utilization of a cognitive underwater acoustic network while avoiding the interference of a natural acoustic system.

3. System Model

3.1. Mammal-Friendly Communication Mechanism

In the marine environment, artificial acoustic systems and marine mammals share spectrum resources ranging from tens to hundreds of kilohertz, as shown in Figure 1. Within the communication frequency range of 1 kHz to 40 kHz, significant overlap exists between the frequency bands used by artificial underwater sensors and various marine protected animals such as dolphins and whales. The impact of artificial noise sources, like ships, sonar, and underwater sensors on marine mammals, primarily manifests in hearing impairment, abnormal behavior, and organ damage [18,19]. For instance, Reference [20] analyzed the naval sonar military exercises held in Spain in 2002, which resulted in chronic tissue damage to beaked whales near the Canary Islands. Relevant evidence was provided, indicating that the cause of the disease was the formation of bubbles within their bodies due to interference from naval sonar signals.

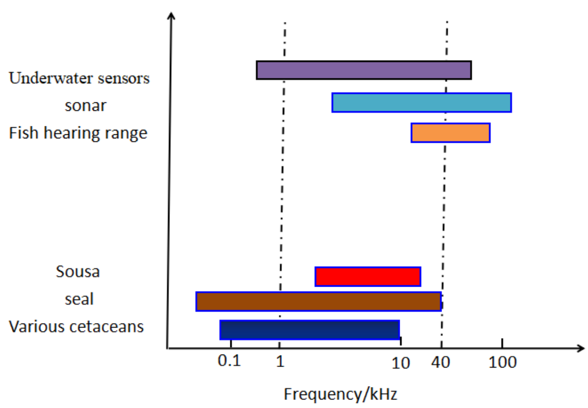

Figure 1. Diagram of signal overlapping frequency bands.

To sum up, the impact on Marine life should be considered in underwater acoustic communication. Therefore, this paper proposes an MFPC algorithm. By controlling the power and energy of sensor nodes, the algorithm can avoid the interference of marine mammals and improve the utilization rate of the spectrum.

The flow chart of the algorithm in this paper is shown in Figure 2. The steps of the algorithm are as follows:

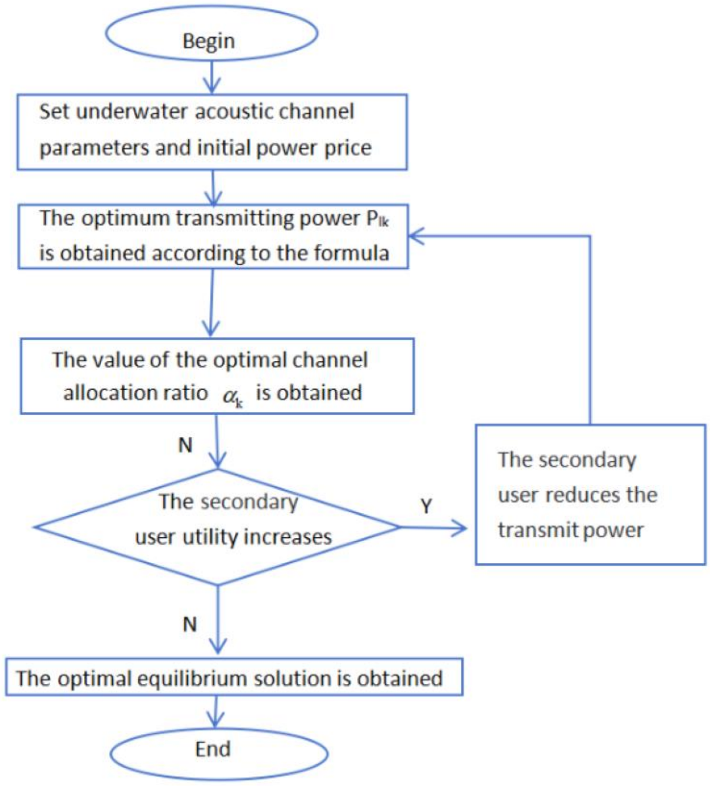

Figure 2. Algorithm flow.

1. Set underwater acoustic channel parameters.
2. The optimal power P_{lk} of the secondary user is obtained.
3. The channel allocation ratio a_k is obtained.
4. Determine whether the benefit of the secondary user continues to increase. If so, the secondary user reduces its power according to the step λ, returns to Step 2, and starts the algorithm process again until the utility function of the secondary user no longer increases.
5. The optimal Nash equilibrium solution is obtained and the algorithm is terminated.

3.2. Joint Channel and Power Assignment

In this study, the algorithm aims to achieve biologically friendly communication. It first obtains the positions and channel state information of marine organisms through perception. Then, using a game-theoretic approach, it allocates system power to enhance the communication quality while maximizing the system capacity.

Assume that there are L sub-channels in the underwater acoustic channel, Subuser $k \in [1, K]$, one of the sub-channels $l \in [1, L]$, and assuming that the other interfering user is m, then the interfering user $m \in [1, M]$, a_{lk} indicates whether channel l is assigned to user k, specifically defined as:

$$\alpha = \begin{cases} 1, & k \ occupies \ l \\ 0, & otherwise \end{cases} \tag{1}$$

Compared with the signal-to-noise ratio, the Signal-to-Interference-plus-Noise-Ratio (*SINR*) can better reflect the communication quality of the communication system, which is defined as:

$$SINR = \frac{P_{lk}h_{lk}}{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}} \tag{2}$$

Among them, P_{lk} is the transmitting power of cognitive user k on channel l, P_m is the transmitting power of other interfering node m, L_0 represents the power spectral density of noise, B represents the bandwidth of a sub-channel, and h_{lk} represents the channel gain of the cognitive user k communicating on the sub-channel l. The channel gain can be obtained by sending the pilot signal from the receiving node.

According to Shannon's theory, the channel capacity C_k of the K_{th} cognitive user can be expressed as follows:

$$C_k = \sum_{l=1}^{N} a_{lk} B log_2 \left(1 + \frac{P_{lk}h_{lk}}{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}} \right) \tag{3}$$

Therefore, the capacity of the multi-user underwater acoustic channel can be expressed as follows:

$$C_k = \sum_{k=1}^{K} \sum_{l=1}^{N} a_{lk} B log_2 \left(1 + \frac{P_{lk}h_{lk}}{L_0 B a_{lk} + \sum\limits_{m \neq k, m=1}^{M} P_m h_{mk}} \right) \tag{4}$$

To achieve biologically friendly communication, the transmission power of underwater sensor nodes acting as secondary users need to be restricted by the auditory threshold of marine mammals. The National Marine Fisheries Service (NMFS) stipulates [21] that when the auditory threshold of marine mammals reaches a threshold value of 180 dB, it is classified as permanent injury Level A. When the auditory threshold reaches a threshold value of 160 dB, it is classified as Level B, indicating behavioral effects. To ensure that the life of marine mammals is not affected, the upper limit of the transmission power of underwater sensor nodes is calculated as follows:

$$P_{lim} = A(D_{min}^{k}, f_n) \cdot 10^{[0.1(\delta - 170.77)]} \tag{5}$$

where f_n is the central frequency used by marine mammals to communicate in the channel, and d_k is the distance between cognitive user nodes that communicate with each other. After the variable a_{lk} is scaled to a continuous variable from 0 to 1, it can be regarded as a coefficient. Then, in Formula (4), we can solve the expression of a_{lk} by taking the partial derivative of a_{lk} and making its derivative equal to 0, as shown in Equation (6):

$$\frac{\partial C_k}{\partial a_{lk}} = 0 \Rightarrow ln(\frac{P_{lk}h_{lk}}{a_{lk}}) - \frac{P_{lk}h_{lk}}{a_{lk}} = \varepsilon \tag{6}$$

where ε is a constant, and if $\frac{P_{lk}h_{lk}}{a_{lk}}$ in Equation (6) is taken as a global variable u, Equation (6) can be simplified to:

$$lnu - u = \varepsilon \Rightarrow a_{lk} = \frac{P_{lk}h_{lk}}{e^{\varepsilon + u}} \tag{7}$$

The channel allocation ratio is represented by a_{lk}, and a user with the maximum a_{lk} value is selected to join a channel each time, which is as follows:

$$a_{max} = max(\frac{P_{lk}h_{lk}}{e^{\varepsilon + u}}) \tag{8}$$

The cyclic execution of Formula (8) enables cognitive users to select the optimal channel access in turn.

After solving the channel allocation problem, we continue to analyze how to avoid node interference in the underwater acoustic channel through power control by a non-cooperative game. Two different cognitive users, k and m, can be taken as two rational and selfish individuals. User k hopes to increase the transmission power to increase his own utility, but the increase in the transmission power will cause interference to the other user m, which not only reduces the transmission performance of the whole system, but also increases the cost of his own participation in the competition. Therefore, only when the transmitted power of different users achieves a Nash equilibrium in the competition of the game can each user fairly obtain the maximum benefit.

In addition, the mutual interference between nodes and the continuous loss of underwater battery energy can be regarded as the costs paid by users in the game, and this part of the costs must be removed to calculate the benefits of users. Therefore, the utility function of cognitive users can be expressed as follows:

$$\begin{aligned} &let\ E_k = \tfrac{E-E_c}{E} \Rightarrow \\ &U_k(P_{lk}) = \sum_{k=1}^{K}\sum_{l=1}^{N} a_{lk} Blog_2\left(1+\frac{P_{lk}h_{lk}}{L_0 Ba_{lk}+\sum\limits_{m\neq k,\ m=1}^{M} P_m h_{mk}}\right) \\ &\quad -\left(L_0 Ba_{lk}+\sum_{m\neq k,\ m=1}^{M} P_m h_{mk}+\sum_{k=1}^{K} P_{lk}h_{km}\right)-\frac{1}{E_k} \end{aligned} \tag{9}$$

In the above formula, $\sum\limits_{k=1}^{K} P_{lk}h_{km}$ means that user k interferes with other nodes. $\sum\limits_{m\neq k,\ m=1}^{M} P_m h_{mk}$ means that other nodes interfere with user k. $L_0 Ba_{lk}$ represents the disturbance by marine noise, including marine mammals. $\frac{1}{E_k}$ represents the increase or decrease in the final yield resulting from the amount of residual energy. The residual energy can be obtained by the detection of the transmitting node.

Then, considering the problem of mammal-friendliness, it is necessary to limit the transmitted power in Formula (9), which is expressed as follows:

$$\begin{cases} U_k(P_{lk}) & = \sum\limits_{k=1}^{K}\sum\limits_{l=1}^{N} a_{lk} Blog_2\left(1+\dfrac{P_{lk}h_{lk}}{L_0 Ba_{lk}+\sum\limits_{m\neq k,\ m=1}^{M} P_m h_{mk}}\right) \\ & \quad -\left(L_0 Ba_{lk}+\sum\limits_{m\neq k,\ m=1}^{M} P_m h_{mk}+\sum\limits_{k=1}^{K} P_{lk}h_{km}\right)-\frac{1}{E_k} \\ C_1: & P_k \le P_{lim1}, P_m \le P_{lim1} \quad b \le n \le c \\ C_2: & P_k \le P_{lim2}, P_m \le P_{lim2} \quad a \le n \le b,\ c \le n \le N \end{cases} \tag{10}$$

The optimal power P_{lk} in Equation (10) is the Nash equilibrium result of the above game process so the equation can be expressed as a conditional extreme value problem. Then, Formula (10) can be reduced to:

$$\begin{aligned} U(P_k, P_m) &= \sum_{k=1}^{K}\sum_{l=1}^{N} a_{lk} B log_2\left(1 + \frac{P_k h_{lk}}{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}\right) \\ &- \left(L_0 B a_{lk} + \sum_{m \neq k,\ m=1}^{M} P_m h_{mk} + \sum_{k=1}^{K} P_k h_{km}\right) - \frac{1}{E_k} \\ &+ \sum_{k=1}^{K} \alpha_k (P_{nuc} - P_k) + \sum_{m=1}^{K} \beta_k (P_{nuc} - P_m) \\ &+ \sum_{k=1}^{K} \gamma_k (P_{nus} - P_k) + \sum_{m=1}^{K} \delta (P_{nus} - P_m) \end{aligned} \tag{11}$$

From formula (11), the following can be obtained:

$$\alpha_k (P_{nuc} - P_k) = 0 \tag{12}$$

$$\gamma_k (P_{nus} - P_k) = 0 \tag{13}$$

$$\begin{aligned} &\frac{\partial U(P_k, P_m)}{\partial P_k} = 0 \Rightarrow \\ &\begin{cases} \dfrac{a_{lk} B h_{lk}}{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk} + P_{lk} h_{lk}} - \alpha_k = 0 \\ b \leq n \leq c \\ \dfrac{a_{lk} B h_{lk}}{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk} + P_{lk} h_{lk}} - \gamma_k = 0 \\ a \leq n \leq b,\ c \leq n \leq N \end{cases} \end{aligned} \tag{14}$$

$$P_{lk} = \begin{cases} \dfrac{B}{\alpha_k} - \dfrac{L_0 B + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}{h_{lk}} \\ \qquad b \leq n \leq c \\ \dfrac{B}{\gamma_k} - \dfrac{L_0 B + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}{h_{lk}} \\ \quad a \leq n \leq b,\ c \leq n \leq N \end{cases} \tag{15}$$

In Equation (15), $\sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}$ means that other nodes interfere with user k. Its value can be detected when it is received by user k. So, it can be taken as a constant. It can be seen from the formula that when the power (P_m) of the interference node increases, the value of the user's transmitting power (P_{lk}) will decrease, thus improving the revenue of the whole network in the game. Then, the maximum value of power P_{lk} can be calculated. When t = 0 and $b \leq n \leq c$, the user's initial power $P_{lk}(0)$ = 0, and let t = t + 1, then:

$$P_{lk}(t) = BR(P_{lk}(t-1)); \tag{16}$$

After Formula (16) is calculated iteratively, once the result $P_{lk}(t_1)$ = $P_{lk}(t_1 - 1)$ is obtained in a calculation, then t_1 is the moment when the Nash equilibrium is achieved. Similarly, in the non-central frequency band $a \leq n \leq b$, $c \leq n \leq N$, the Nash equilibrium time (t_2) of this frequency band can be obtained. In Formula (15), In order to achieve bio-friendliness, the user's transmitting power (P_{lk}) cannot be greater than the limited power. When the cognitive user is located on the channel of the central frequency band, the optimal power of P_{lk} increases with the decrease in the interference power P_m. When $t \geq t_1$, the value of P_{lk} will increase to greater than the limited power (P_{lim1}), in which case, P_{lk} = P_{lim1} can only be taken. When the cognitive user is located on a channel in a non-central frequency band, it can be seen that when $t \geq t_2$, the P_k value will increase to greater than the limited power (P_{lim2}), and only P_{lk} = P_{lim2} can be taken at this time. In summary, the power P_k of cognitive users can finally be further optimized to:

$$P_{lk} = \begin{cases} \frac{B}{\alpha_k} - \frac{L_0 B + \sum\limits_{m \neq k,\ m=1}^{K} P_m h_{mk}}{h_{lk}} & ,\quad t < t_1 \\ P_{lim1} & ,\quad t \geq t_1 \\ \frac{B}{\gamma_k} - \frac{L_0 B + \sum\limits_{m \neq k,\ m=1}^{K} P_m h_{mk}}{h_{lk}} & ,\quad t < t_2 \\ P_{lim2} & ,\quad t \geq t_2 \end{cases} \tag{17}$$

The parameters α_k and γ_k in Formula (17) can be calculated according to Formulas (12) and (13), and the calculation results are as follows:

$$\alpha_k = \frac{BN_k}{P_{lim1} + \sum\limits_{n=1}^{N} \frac{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{K} P_m h_{mk}}{h_{lk}}} \tag{18}$$

$$\gamma_k = \frac{BN_k}{P_{lim2} + \sum\limits_{n=1}^{N} \frac{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{K} P_m h_{mk}}{h_{lk}}} \tag{19}$$

where N_k is the number of channels that user k accesses. Put Equations (18) and (19) into P_{lk} to get the final value of P_{lk}, which is as follows:

$$P_{lk} = \begin{cases} \frac{P_{lim1} + \sum\limits_{n=1}^{N} \frac{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}{h_{lk}}}{N_k} - \frac{L_0 B + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}{h_{lk}}, & t < t_1 \\ P_{lim1}, & t \geq t_1 \\ \frac{P_{lim2} + \sum\limits_{n=1}^{N} \frac{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}{h_{lk}}}{N_k} - \frac{L_0 B + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}{h_{lk}}, & t < t_2 \\ P_{lim2}, & t \geq t_2 \end{cases} \tag{20}$$

Replace the complex polynomial in this Formula (20) with the following:

$$\begin{aligned} P_1 &= \frac{P_{lim1} + \sum\limits_{n=1}^{N} \frac{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}{h_{lk}}}{N_k} - \frac{L_0 B + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}{h_{lk}} \\ P_2 &= \frac{P_{lim2} + \sum\limits_{n=1}^{N} \frac{L_0 B a_{lk} + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}{h_{lk}}}{N_k} - \frac{L_0 B + \sum\limits_{m \neq k,\ m=1}^{M} P_m h_{mk}}{h_{lk}} \end{aligned} \tag{21}$$

In Formula (20), P_{lk} is simply written as P_k. Then, Formula (20) can be simplified as:

$$P_k = \begin{cases} P_1 & , \quad t < t_1 \\ P_{lim1} & , \quad t \geq t_1 \\ P_2 & , \quad t < t_2 \\ P_{lim2} & , \quad t \geq t_2 \end{cases} \tag{22}$$

3.3. Existence Proof of Nash Equilibrium

Then, we prove the existence of the Nash equilibrium using lemma. The conditions for the existence of the Nash equilibrium are as follows:

1. P_k is a non-empty, closed, finitely convex set of Euclidean space R_N.
2. $U(P_k)$ is continuous on P, and quasi-concave on P_k.

Proof. P_k is the node's transmitted power, so P_k is positive. Then, the first condition is obviously satisfied. For condition (2), $U(P_k)$ is a continuous function on P and only needs to be quasi-concave on P_k. From Equation (14), the first derivative of $U(P_k)$ with respect to P_k is:

$$\frac{\partial U(P_k)}{\partial P_k} = \frac{a_{lk} B h_{lk}}{L_0 B a_{lk} + \sum\limits_{m \neq k,\, m=1}^{M} P_m h_{mk} + P_k h_{lk}} - \alpha_k \tag{23}$$

The second derivative of P_k with Equation (21) is:

$$\frac{\partial^2 U(P_k)}{\partial P_k^2} = -\frac{a_{lk} B h_{lk}^2}{\left(L_0 B a_{lk} + \sum\limits_{m \neq k,\, m=1}^{M} P_m h_{mk} + P_k h_{lk}\right)^2} < 0 \tag{24}$$

From Equation (24), we can see that the second derivative of the utility function with respect to P_k is less than 0, and $U(P_k)$ is quasi-concave on P_k, which means the second condition is also satisfied. So, there is a Nash equilibrium in the game of this algorithm. □

4. Discussion

In order to prove the effectiveness of the above algorithm, we conduct simulation experiments on the algorithm. The setting of the simulation scene is shown in Figure 3. The network is distributed in a 4 × 4 × 4 three-dimensional space, with cognitive users and marine mammals randomly distributed in these sub-regions, and the initial location of the marine mammals is random. Among them, two pairs of marine mammals are located in the innermost layer near the xoz plane in cyberspace, and the nodes from the inside to the outside are S1, S2, S3, and S4 in spatial order.

In order to prove the effectiveness of the designed protocol, we conducted simulation experiments on the algorithm. In this paper, we used the Aqua-Sim simulation software based on NS2 to conduct simulation analysis. The process of transmitting data packets by underwater sensor nodes adopts Poisson distribution, and the parameter k represents the arrival rate of the nodes. The red triangle represents the mammal at the receiving end of the acoustic signal. The red squares represents the mammal at the transmitting end of the acoustic signal. The white triangle represents the sensor nodes at the receiving end of the acoustic signal. The white squares represents the sensor nodes at the transmitting end of the acoustic signal.

In reality, there are many sensors that can be applied to the above network model, such as the Type HOIT-UAC816WDN sensor.

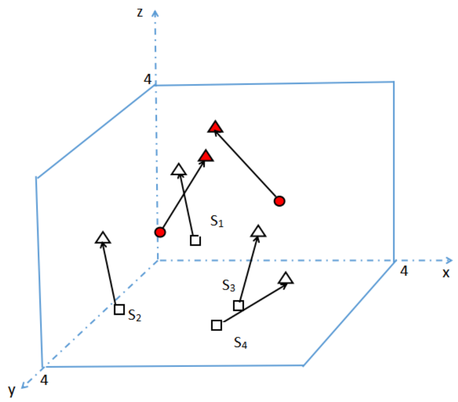

Figure 3. Mammal and sensor node distribution.

4.1. Node Transmitting Power

As shown in Figure 4, the initial power of the transmitting node was set to zero. With an increase in the number of iterations to the third iteration, the transmission powers of nodes S_1 and S_3 stabilized at fixed values of 8.9 W and 7.2 W, respectively. This is because node S_1 is located in the central frequency band, and its Nash equilibrium value of transmission power exceeds P_{lim1} due to the magnitude of its channel state information parameters. However, to protect marine mammals, the transmission power of S_1 can only be limited to the bio-friendly power upper limit P_{lim1}. Similarly, node S_3 is positioned in a non-central frequency band, and its Nash equilibrium value of transmission power exceeds P_{lim2}, causing its transmission power value to be limited to P_{lim2}.

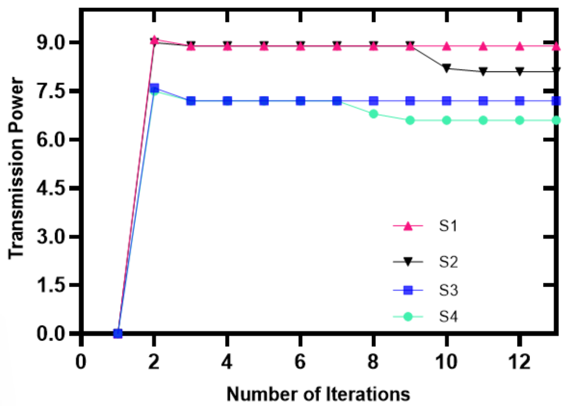

Figure 4. Convergence curve of node transmitting power.

The transmission power of node S_2 stabilized at 8.9W between the third and ninth iterations. This is due to Formula (22) in this paper's algorithm, where when $t < t_1$, the computed power (P_k) reaches a Nash equilibrium point, denoted as P_1. When $t \geq t_1$, the value of P_k continues to increase until it exceeds P_{lim1}. However, node S_2 is situated in the central frequency band where marine mammals vocalize. To avoid disrupting the normal life of marine mammals, the value of P_1 must be lower than the restricted power P_{lim1}. Consequently, the transmission power of node S_2 stabilizes at the size of P_{lim1}, which is 8.9 W. As the number of iterations increases to the tenth iteration, due to energy depletion and changes in channel state information, the value of the transmission power of P_k gradually decreases below P_{lim1}. At this point, the variable expression for P_k, denoted as P_1, remains the same. Similarly, when $t < t_2$, the value of P_k obtained from Formula (22) at that time is abbreviated as P_2. The transmission power of node S_4 stabilizes at the value of P_{lim2}, which is 7.2 W when $t \geq t_2$. As the number of iterations increases to the eighth iteration, the transmission power of node S_4 starts to decrease and stabilizes at the Nash equilibrium value P_2.

4.2. System Capacity

When the initial position of marine mammals is different, the system capacity of the underwater acoustic network is greatly different. However, the sensor of the underwater acoustic cognitive network adopted in this paper can sense the position information of marine mammals and calculate its own transmission power when sending data, so as to improve the system capacity.

Figure 5 shows the change in network system capacity when the network load increases.

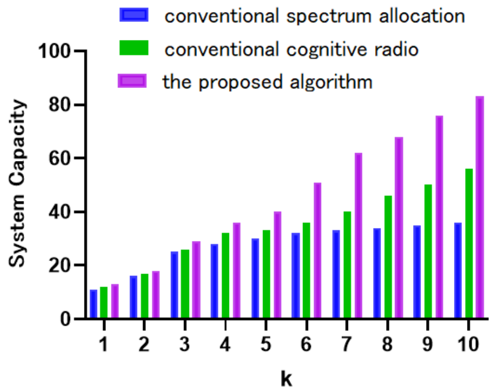

Figure 5. System capacity under different algorithms.

As can be seen from Figure 5, with the increase of network load, the system capacity of the three different algorithms increases continuously. When the network load is not large, the system capacity of the three algorithms has little difference. However, starting from $k = 6$, the system capacity obtained by applying this algorithm increases significantly compared with the other two algorithms. The system capacity of the proposed algorithm is 36.6% higher than that of conventional cognitive radio technology and 62.4% higher than that of the conventional spectrum allocation method.

4.3. Node Residual Energy

Next, we provide a detailed analysis of the energy optimization of cognitive nodes in this algorithm. As shown in Figure 6, nodes S_1 and S_2, when sufficiently energized, transmit at the optimal center frequency power of P_{lim1} in Formula (22). Nodes S_3 and S_4, when sufficiently energized, transmit at the optimal non-center frequency power of P_{lim2} in Formula (22). Node S_1, due to its greater distance from the receiving end of other nodes, experiences less interference from other nodes, allowing it to achieve a larger transmission power according to Formula (22). However, node S_4 is relatively close to the other receiving end of other nodes and experiences greater interference from other nodes, allowing it to achieve a smaller transmission power according to Formula (22). When the remaining energy of node S_4 reaches about 40%, as nodes S_1 and S_3 exit the game, the interference of node S_4 by other nodes decreases, and the transmitting power will suddenly increase.

In summary, during the initial period, nodes do not consume energy, and their remaining energy is 100%. The transmission power of all nodes reaches the Nash equilibrium point. As the remaining energy of nodes decreases, their transmission power gradually decreases. Formula (11) in this study shows that as energy (E) decreases, the price of unit power increases, and the user's transmission cost also increases. Therefore, according to this algorithm, users will reduce their transmission power, thereby increasing the total revenue $U(P_k)$ of nodes and saving energy. Thus, this algorithm can control the transmission power of nodes based on the remaining energy, ultimately enhancing the overall network performance.

With the increase in network load, the system capacity of the three algorithms increases continuously. When the network load is not high, the system capacity differences among the three algorithms are not significant.

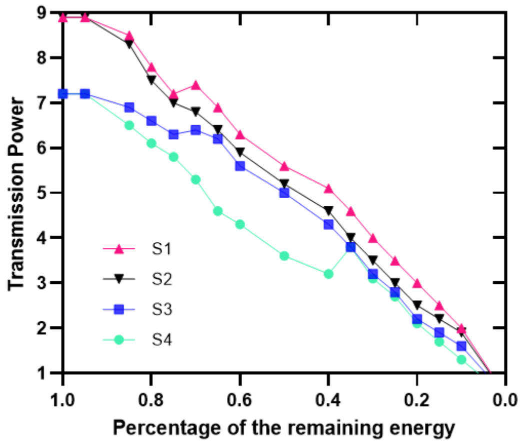

Figure 6. The change of node transmitting power with energy.

5. Conclusions

Aiming at the problems, such as the influence of sensor nodes on marine mammals in UASNs and the large interference between underwater network nodes, a channel power allocation algorithm, based on game theory and mammal-friendliness in an underwater acoustic network, is proposed. The algorithm aims to avoid the communication interference of sensor nodes in marine mammals, and further avoid the direct mutual interference of sensor nodes, so as to improve the communication quality of nodes while ensuring mammal-friendliness.

Firstly, with marine mammals as primary users and sensor nodes as secondary users, the system capacity of secondary users is maximized by a non-cooperative game without interfering with the communication of primary users. Secondly, the network interference level is introduced into the utility function, and then the transmitting power of the node is adjusted according to the income of the game. Simulation analysis shows that the proposed algorithm improves the communication quality and energy efficiency of UASNs while improving the capacity of the UASN system.

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