Applied Acoustics 177 (2021) 107911

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Optimizing the number of relays for energy efficient multi-hop covert underwater acoustic cooperative networks

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ARTICLE INFO

Article history:
Received 7 September 2020
Received in revised form 4 December 2020
Accepted 6 January 2021
Available online 1 February 2021

Keywords:
Underwater acoustic
Covert cooperative communication
Energy consumption
Probability of detection

ABSTRACT

Multi-hop underwater acoustic (UWA) cooperative networks can effectively reduce the energy consumption of the system, yet the covertness of communication is also greatly reduced since a spatial diversity gain can be obtained by both the intended receiver and the intercept detector. In this paper, we investigate how to select the optimal number of relays for multi-hop UWA cooperative networks, by considering both the low probability of detection (P_D) and energy consumption. We derive the relationship between P_D and the number of relays and then analyze the relationship between energy consumption and the number of relays for the system. To address the joint P_D and energy consumption optimal problem, we define the energy consumption rate for multi-hop UWA systems by normalizing the energy consumed in single-hop UWA systems at the same source-to-destination distance. Then, we derive the range number of relays under the given P_D and energy consumption rate. Moreover, we construct the objective function and derive the optimal number of relays by jointly addressing P_D and the energy consumption rate. Finally, we simulate and analyze the impact of several parameters on P_D and energy consumption, including the signal-to-noise ratio, working distance, position angle of interceptor and data length. The simulation results show that the number of relays for multi-hop covert UWA cooperative networks can take the value between 2 and 6 under a given condition, which can meet the covert communication requirement with a $P_D < 0.5$, while the system energy consumption is relatively low.

1. Introduction

In recent years, multi-hop underwater acoustic (UWA) cooperative communication technology has become very appealing because of the large area coverage, the improving data transmission rate, high energy efficiency and other advantages [1–3] which is especially true with the development of internet of underwater things [4–6]. Meanwhile, due to special application scenarios, such as military UWA command, control and communication, coastal monitoring and submarine operations, the demands for covert communication of multi-hop UWA networks have increased accordingly [7–10]. However, unfortunately, as indicated in [11] the relays in multi-hop UWA systems provide spatial diversity not only to the intended receiver but also to the intercept detector, which reduces the covertness significantly. Therefore, delicately balancing between covertness and multi-hop cooperation is a challenging task.

A primary concern in adopting multi-hop cooperation for UWA networks is saving the energy consumption for underwater equipment that is usually battery powered and expensive to replace in the ocean. The use of a multi-hop scheme can reduce the total power required for transmission, since the transmission loss, related to the distance, causes an exponential reduction in received power [12]. According to the results in [13] a significant amount of power can be saved in the multi-hop UWA networks compared with the direct single-hop long-distance UWA transmission. As the transmission loss in UWA channels is severely affected by signal frequency and transmission distance, in [14] a study on the joint optimization of node placement and carrier frequency selection is presented to minimize the power consumption in multi-hop UWA networks, showing that the use of different frequencies has an impact on the optimal relay placement. This work provides the basis for the selection of signal frequencies according to different distances caused by the relay placement in multi-hop UWA networks. A power based cost function is proposed in [15] for

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https://doi.org/10.1016/j.apacoust.2021.107911
0003-682X/

multi-hop UWA networks, which can minimize the number of hops/relays to optimize the transmission power of the entire link. Further, we investigate the trade-offs between the number of hops and the energy consumption, the end-to-end delay, for multi-hop UWA cooperative networks in [16]. Moreover, the authors in [17] focus on the optimum choice of the number of hops, retransmissions, code rate, and signal-to-noise ratio (SNR), in terms of energy efficiency for multi-hop UWA networks. This study indicates that optimizing the number of hops/relays is fundamental to minimize the energy consumption for medium to long links, while increasing the number of allowed transmission trials has a smaller impact. This is an interesting result, meaning that from the energy savings perspective, we should pay more attention to the number of hops/ relays during the design of multi-hop UWA networks. However, *none* of the works cited above consider the *covertness of communication* for multi-hop UWA networks.

For the stealth operations in most military underwater activities, UWA communication systems are required to remain undetected, and the data transmission is made with low probability of detection (LPD) [18].

As of now, most research on covert communication has been done for wireless electromagnetic channels [19,20]. For the UWA channels, the study on covert communications in the existing work is usually for single-hop transmissions. A pair of energy detectors that are insensitive to the phase fluctuations are presented in [21] and the focus is on long code sequences for the purpose of obtaining a high processing gain at the expense of a low data rate, so that communications can be performed at a low input SNR to minimize the probability of detection (P_D) by an interceptor. In [22] a direct-sequence spread-spectrum (DSSS) scheme based on a spreading waveform is investigated for covert UWA communications. Under the condition of a log-normal fading UWA channel, the covert performance of DSSS communication is investigated in [23]. Meanwhile, the directional transducers have been also adopted to enhance the concealment of UWA communications in [24]. A new covert underwater acoustic communication scheme based on ship-radiated noise and chaos signal has been proposed in [25] and the validity of this method is verified by sea experiments. In addition, orthogonal frequency-division multiplexing (OFDM), and multi-carrier spread spectrum (MC-SS) techniques have also been applied to covert UWA communication by many researchers [26–28]. Yet the signal waveforms used in the above schemes are easily distinguished by trained sonar operators due to their obvious features. Furthermore, in [29–31] the authors demonstrate that biological mimicry method can provide covert UWA communications by using intrinsic dolphin sounds. In covert UWA communications, performance greatly depends on the inter symbol interference (ISI) caused by the channel impulse response (CIR) and on the ability of the receiver to estimate CIR. To compensate for these channel distortions, two methods are analyzed in [32] to improve the LPD capabilities, both using a time-updated channel impulse-response estimate as a matched filter to mitigate the multipath-induced interference. However, these existing covert UWA communication schemes have not considered the multi-hop transmission scenario. Recently, the authors in [11] consider two performance metrics for LPD in multi-hop UWA cooperative networks. The results show that multi-hop cooperative networks exhibit worse LPD performance than single-hop systems, because it is more likely to be detected by the interceptor if more relay nodes are used in a cooperative network.

In general, the case with fewer relays is better for a multi-hop UWA system with respect to concealment; yet the case with more relays is better for that with respect to energy savings. Hence it is a challenging task to select the optimal number of relays for a multi-hop UWA system, by considering both LPD and energy consumption. The preliminary results of our work on this topic have been partly presented in [33] and further theoretical derivation and extensive numerical analysis will be reported in this paper.

The main contributions of this work are as follows:

1) We first establish the relationship between P_D and the number of relays based on the multi-hop UWA cooperative network, and then establish the relationship between energy consumption and the number of relays for the system. Note that the work in [11] did not consider energy consumption, and the work in [33] has not given the joint optimal objective function and its solution, although they are the multi-hop covert UWA communication issues.
2) Since the value of P_D is between 0 and 1, to compare P_D and energy consumption on the same scale, we define the energy consumption rate η as the total energy consumed in a multi-hop scheme divided by that consumed in a single-hop transmission scheme for the same UWA system, addressing the joint P_D and energy consumption optimal problem. Then, the value of the η is also between 0 and 1, where a small energy consumption rate value indicates that more energy is saved in multi-hop UWA system compared with a single-hop UWA system. Then, we derive the range number of relays under the given P_D and η. More importantly, we construct the objective function and derive the optimal number of relays by jointly addressing the P_D and η and then present the numerical solutions of the optimal number of relays.

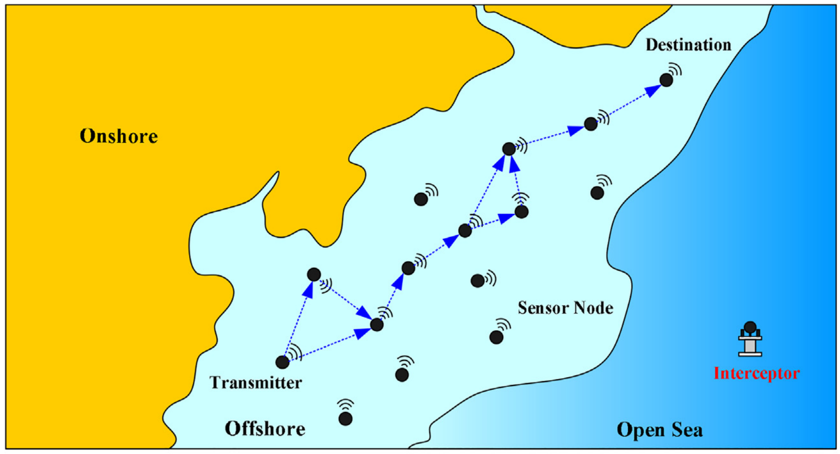
Note that the work in [11,33] has not introduced the concept of energy consumption rate η, and has not constructed the objective function considering the given P_D and η for the optimization problem.

3) From the view of LPD, in the process of calculating distance ratio for the overall multi-hop covert UWA system, we use the triangular area approximation method to derive statistical expectation geometrically, which can easily express the distance ratio in the multi-hop covert UWA system and better derive the upper bound of the optimal number of relays. From the view of energy consumption, we clarify the confusing transformation between radiated acoustic power P_t^{aco} and electrical power P_T^{el} of [3,17,34] through detailed mathematical derivation. All these have not been involved in [11,33].
4) We analyze the impact of several parameters on P_D and energy consumption, including the target SNR, working distance, position angle of the interceptor and data length, which is more abundant than the existing work in [11,33]. The simulation results validate the above theoretical analysis, and show that the number of relays for the multi-hop covert UWA cooperative networks can be between 2 and 6 under given conditions, which can meet the covert communication requirement with a $P_D < 0.5$, while the system energy consumption is relatively low.

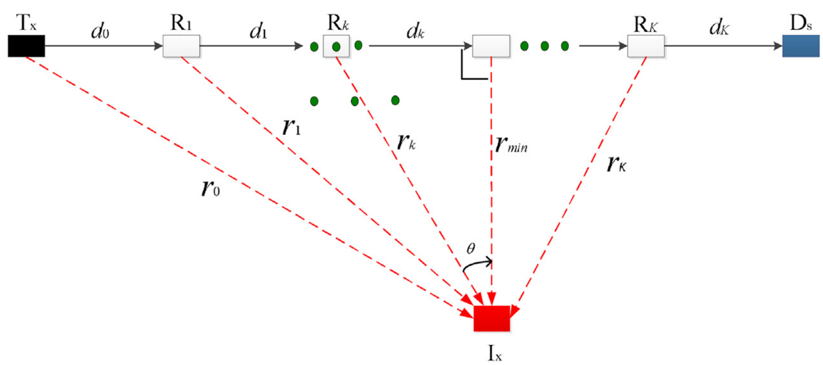
The remainder of this paper is organized as follows. Section 2 presents the system model and the calculation of P_D. The energy consumption is detailed in Section 3, while Section 4 presents a theoretical analysis of the optimum number of relays in terms of P_D and energy consumption. The numerical results are presented and discussed in Section 5, and Section 6 concludes the paper.

2. System model and the probability of detection

Fig. 1(a) depicts a typical application of multi-hop covert UWA cooperative networks, where the UWA sensors are deployed in the



(a)



(b)

Fig. 1. Multi-hop covert UWA cooperative networks: (a) Application scenario; (b) Network model (K is even as an example).

offshore area for monitoring acoustic data transmission, and the interceptor is deployed in the open sea. As shown in Fig. 1(b), we consider a simplified multi-hop UWA network with K relay nodes (R_k, k = 0, 1, 2,. . ., K, when k is zero, the relay node is the source node) between the source node (Transmitter, T_x) and the intended destination node (D_s). For simplicity, all the nodes are aligned perfectly in a straight line [11]. The interceptor/eavesdropper (I_x) is strategically placed at the perpendicular bisector of the T_x-R_k-D_s line.

We assume that each relay node (R_k) can correctly receive the signal from the previous relay node (R_{k-1}) and then amplify and forward it to the next relay node (R_{k+1}), which can be ensured by controlling the transmitting power and other measures.

In each hop, as shown in Fig. 1(b), the distance ratio is defined as follows [11]:

$$\gamma_k = \frac{r_k}{d_k}, \quad k = 0, 1, 2, \cdots, K \tag{1}$$

where r_k and d_k are the ranges at which I_x and R_k can successfully detect/receive the signals from T_x. In general, a smaller distance ratio means better covertness of the communication system, because the I_x has to be closer to the T_x to detect the communication signal. In an ideal case, where d_k is an equal distance for all k, the average intercept range for the relay network is the smallest when the I_x is placed at an equal distance from both ends of the T_x-D_s line [11] as shown in Fig. 1, thus we have,

$$d_k = \frac{d_c}{k+1}, \quad k = 0, 1, 2, \cdots, K \tag{2}$$

where d_c represents the distance between T_x and D_s.

2.1. The P_D for single-hop covert UWA communication

To obtain the P_D of a multi-hop UWA covertness communication system, we first calculate the P_D of the single-hop system.

The assumption is that the same bandwidth Gaussian noise UWA channel is experienced by both the D_s and the I_x, which has a two-sided spectral density equal to $N_0/2$. The signal energy detected at I_x is E_i, the signal energy required at D_s to correctly receive the data is E_s, and the distance ratio of the single-hop system is γ. Then, according to the energy consumption relationship between the transmitted signal and the received signal, we can obtain [11]

$$E_i = \lambda\phi E_s \gamma^{-n} \tag{3}$$

where λ is the gain difference between the communication receiver and the general wideband energy detector, and φ is a coefficient representing the existence of the signal of interest in the received signal, which is related to the signal design; n denotes the path loss exponent depending on the frequency band, relating to the sound waves' transmission method and transmission path in the water. According to different UWA propagation conditions, n takes different values. For example, n = 2 for spherical spreading, and n = 1 for cylindrical spreading. In a practical UWA communication system, we usually take the value of n = 1.5.

Using hypothesis testing [11] given the probability of a false alarm (P_{FA}), we can plug (3) into the relative formulas in [11] then the P_D of the single-hop system can be derived as follows:

$$P_D = \frac{1}{2}\mathrm{erfc}\left[\mathrm{erf}^{-1}(1-2P_{FA}) - \frac{E_s}{N_0}\cdot\frac{\lambda\phi}{\sqrt{2T_iW}}\cdot\gamma^{-n}\right], T_iW >> 1 \tag{4}$$

where T_i represents the integration time of I_x, W denotes the operating bandwidth of I_x, erf and erfc are the error function and complementary error function, respectively. E_s/N_0 represents the SNR when D_s can receive the signal correctly. Then, the quantity $SNR_{is} = \frac{E_s}{N_0}\cdot\frac{\lambda\phi}{\sqrt{2T_iW}}$ can be defined as the normalized SNR between the I_x and D_s. When n = 1.5, P_{FA} = 0.02, Fig. 2 shows the relationship between the P_D and γ, and the area of P_D < 0.5 is the area of LPD. As shown in Fig. 2, the P_D decreases rapidly as the γ increases. The smaller the SNR_{is}, the smaller the γ is, meaning that the covertness of communication system is better because the I_x needs to be closer to the T_x to intercept the signal.

In general, the complexity of the UWA channels will result in different SNR at the receiver. Eq. (14) in the following shows the relationship between the SNR and the transmission loss caused by the time–space-frequency varying UWA channels and the noise at the receiver. Therefore, E_s/N_0 in (4) indicates that the P_D of covert communication will be affected by the complex underwater environments

2.2. The P_D for multi-hop UWA cooperative covert communication networks

For the communication case with K relays (R_k), due to the different detection ranges of the UWA data transmission (r_k) for each hop, the authors in [11] propose two methods to calculate the detection range r of the overall multi-hop system. One is to take the minimum range, that is r_{min} = min(r_k), k = 0,1, 2,...,K. The second is to take the average, that is r_c = E[r_k], where E[ ] represents the statistical expectation for all r_k. We use the second method in this paper to calculate r, i.e., r = $r_c(K)$. Thus, the distance ratio for the case with K relays can be expressed as follows [11]:

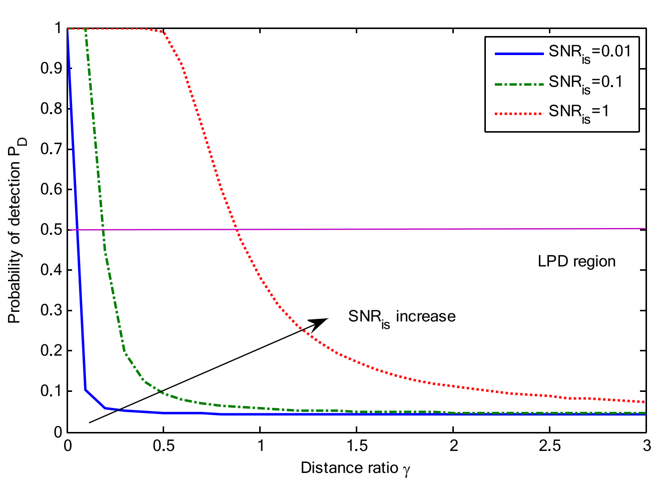


Fig. 2. The relationship between the probability of detection and detection distance.

$$\gamma_c(K) = \frac{r_c(K)}{d_c} \tag{5}$$

Taking $\gamma = \gamma_c$ and substituting (5) into (4), we obtain the P_D of the multi-hop UWA cooperative network with K relays, as follows:

$$P_D(K) = \frac{1}{2}\mathrm{erfc}\left[\mathrm{erf}^{-1}(1-2P_{FA}) - \frac{E_s}{N_0}\cdot\frac{\lambda\phi}{\sqrt{2T_{iW}}}\cdot\frac{1}{d_c^{-n}}\cdot r_c^{-n}(K)\right] \tag{6}$$

Next, according to different values of K, we will calculate $r_c(K)$ by the geometric relationship shown in Fig. 1.

Assuming that the shortest distance between I_x and relay nodes (R_k) is r_{min}, and for any r_k(k = 0,1,2,...,K), it is occurring with equal probability, therefore, for an odd K,

$$r_c(K) = \frac{r_{min}}{K+1}\sum_{k=0}^{K}\sqrt{\left(\frac{K+1}{2}-k\right)^2\cdot\tan^2\theta+1} \tag{7}$$

and for an even K,

$$r_c(K) = \frac{r_{min}}{K+1}\sum_{k=0}^{K}\sqrt{\left[\left(\frac{K}{2}-k+\frac{1}{2}\right)^2-\frac{1}{4}\right]\cdot\tan^2\theta+1}, \tag{8}$$

where $\tan\theta = \frac{d_k}{r_{min}}$,and the angle θ is the position parameter of I_x, which represents the distance relationship between the I_x and the T_x-R_k-D_s line. Substituting (7) and (8) into (6), we obtain the $P_D(K)$ for the multi-hop UWA cooperative network with K relays.

3. The calculation of energy consumption

In each hop, the minimum SNR required by the receiver to correctly receive signals is defined as the target SNR and marked as SNR_0. The energy consumed at the transmitter can be obtained by calculating the transmission loss under the given target SNR_0 at the receiver. The details will be presented next.

3.1. Transmission loss and noise

The energy attenuation of the transmitted signal in a UWA link is related to transmission distance, including the spreading loss and the absorption loss. Then, the path attenuation over distance d_k for the signal of frequency f in the k-th hop is as follows [35]:

$$A(d_k, f) = (1000\cdot d_k)^n[\alpha(f)]^{d_k} \tag{9}$$

where n is the spreading factor, $\alpha(f)$ is the coefficient of absorption loss. Expressed in dB re μPa, the path attenuation is defined as the transmission loss (TL),

$$\begin{aligned} TL &= 10\log_{10}A(d_k, f) \\ &= n\cdot 10\log_{10}(1000\cdot d_k) + d_k\cdot 10\log_{10}\alpha(f) \end{aligned} \tag{10}$$

where the absorption coefficient given in dB re μPa /km for f in kHz can be obtained from Thorp's formula as follows [21]:

$$10\log_{10}\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + \frac{2.75f^2}{10^4} + 0.003 \tag{11}$$

The ambient noise in the ocean can be modeled by Gaussian statistics and a continuous power spectral density (p.s.d.). The total noise p.s.d., denoted as $N_0(f)$, is a function of frequency f in kHz. The calculation can refer to the Wenz Noise model in [35] usually including four different noise sources: turbulence, shipping, wind-driven waves, and thermal noise. The approximation, in dB re μPa /Hz, may be useful [35]:

$$10\log_{10}N_0(f) \approx 50 - 18\log_{10}f \tag{12}$$

Let the source power of the transmit node be $P_t(d_k, f)$, and the total noise be $N(f)$, we can calculate the average SNR at the receiver as follows [35]:

$$\bar{\Lambda}_{SNR}(d_k, f) = \frac{P_t(d_k, f)}{A(d_k, f)N(f)} \tag{13}$$

Expressed in dB re μPa, as follows:

$$\begin{aligned} SNR &= 10\log_{10}\bar{\Lambda}_{SNR}(d_k, f) \\ &= \underbrace{10\log_{10}P_t(d_k, f)}_{:=SL} - \underbrace{10\log_{10}A(d_k, f)}_{:=TL} - \underbrace{W \cdot 10\log_{10}N_0(f)}_{:=NL} \end{aligned} \tag{14}$$

where SL and NL, in dB re μPa, are the source level and noise level, respectively, and W is the bandwidth of receiver, in Hz.

In (13), for a given distance, choosing the optimal frequency can make the product of $A(d_k, f)$ and $N(f)$ smaller, which can minimize the energy consumption under the same average SNR condition [35]. According to [14] for each hop, the relationship between the optimal working frequency $f_{opt}(d_k)$ and working distance d_k can be modeled as follows:

$$f_{opt}(d_k) = a(d_k) \cdot d_k^{-b(d_k)} \tag{15}$$

where

$$\begin{aligned} &a = 23.33, b = 0.16449, d_k \in (0, 1) \\ &a = 20.421, b = 0.54012, d_k \in [1, 10) \\ &a = 53.197, b = 0.86133, d_k \in [10, 100] \end{aligned} \tag{16}$$

In (15), the optimal frequency f_{opt} is expressed in kHz, and the working distance d_k is in km.

3.2. Acoustic transmit power

From (14), we know that, given the target SNR_0 at the receiver, TL, and NL, it is possible to obtain the SL and then the source power $P_t(d_k, f)$, which is expressed as follows:

$$P_t(d_k, f) = 10^{\frac{SNR_0 + TL + NL}{10}} \tag{17}$$

Now there is a question regarding the unit of $P_t(d_k, f)$. The authors in [17] indicate that it is in μPa, yet the authors in [3,34] reason that it is in dB re μPa, detailing the following:

$$P_T^{el}(d_k, f) = P_t(d_k, f) \cdot \frac{10^{-17.2}}{\varphi} \tag{18}$$

where $10^{-17.2}$ is the conversion factor from acoustic power in dB re μPa to electrical power $P_T^{el}(d_k, f)$ in watts, and ϕ is the overall efficiency of the power amplifier and transducer [3,34]. However, many people may question why the unit of acoustic power is in μPa, the sound pressure unit, instead of in watts, the power unit.

We argue that the descriptions regarding the unit of $P_t(d_k, f)$ and the conversion between acoustic power and electrical power in [3,17,34] are not rigorous enough. We present the detailed reasoning as follows.

The reference intensity in underwater sound [36] is usually the intensity of a plane wave having an rms pressure equal to 1 μPa, denoted as $I_{ref} \approx 0.667 \times 10^{-18}$ W/m^2. At a large distance d, in m, let the intensity of the sound emitted by the projector be I_d. For a nondirectional projector, this intensity corresponds to a radiated acoustic power output of $P_t^{aco} = 4\pi d^2 I_d$, in watts. Combine these according to the definition of SL as follows [36]:

$$SL = 10\log_{10}\frac{I_d}{I_{ref}} \tag{19}$$

Algorithm 1 The calculation of total energy consumption for multi-hop UWA cooperative networks

1: **for** each hop (k = 0,1,2,...,K) **do**

Stage 1: Parameter input and the basic calculation

2: Given the transmission distance d_k

3: Calculate the optimal frequency $f_{opt}(d_k)$ using (15) and (16), the 3-dB bandwidth W given by (26)

4: Calculate the absorption coefficient given by (11), under the $f_{opt}(d_k)$

Stage 2: Acoustic parameter calculation

5: Calculate the transmission loss TL given by (10)

6: Calculate the ambient noise using (12), and convert it into noise level NL

7: Given the target SNR_0

8: Calculate the source level SL given by (14), plugging the TL and NL

9: Convert SL into acoustic power P_t^{aco} using (20), and electrical power P_T^{el} using (21)

Stage 3: Energy consumption calculation

10: Given the data length and transmission rate, calculate the duration of data transmission T_L

11: Calculate the energy consumption of transmitter $E_{tr}(k)$ using (22), and the energy consumption of receiver $E_{rr}(k)$ using (23)

12: **end for**

13: Calculate the total energy consumption $E_{sys}(K)$ using (24)

then we have the radiated acoustic power P_t^{aco} and electrical power P_T^{el} as follows:

$$P_t^{aco}\big|_{d=1} = \underbrace{4\pi I_{ref} d^2}_{10^{-17.2}} \cdot \underbrace{10^{\frac{SL}{10}}}_{:=P_t}\Bigg|_{d=1} \tag{20}$$

$$P_T^{el} = \frac{P_t^{aco}}{\varphi} \tag{21}$$

where we can clearly find that the conversion factor $10^{-17.2}$ is in the unit of watts, and the P_t is in the unit of 1.

Therefore, we argue that $10^{-17.2}$ is the conversion factor from acoustic power in 1 (corresponding to source level in dB re μPa) to acoustic power in watts, and ϕ is the conversion factor from acoustic power in watts to electrical power in watts, which indicates the overall efficiency of the power amplifier and transducer.

3.3. Total energy consumption

In each hop, the receiver can correctly decode the transmitting signal when the target SNR_0 is satisfied, which means there is no retransmission for this case; hence there is no extra energy consumption caused by retransmission for each transmitting node. We only consider the energy consumption of encoding and decoding in the source node, relay nodes and destination node, and assume that the energy required to correctly receive the signal is the same in every relay node or destination node. In the k-th hop, the energy consumption of the transmitter is as follows:

$$E_{tr}(d_k, f) = E_{enc}(d_k, f) + P_T^{el}(d_k, f) \cdot T_L \tag{22}$$

where E_{enc} represents the energy of encoding, P_T^{el} represents the electrical power of the power amplifier, and T_L is the duration of data transmission.

On the other hand, the energy consumption of the receiver in the k-th hop is as follows:

$$E_{rr}(d_k,f) = E_{dec}(d_k,f) + P_R(d_k,f)\cdot T_L \quad (23)$$

where E_{dec} is the energy required to decode the data, and P_R represents the electrical power of the receiver node to receive the signal, which can be set as [37] $P_R = \frac{1}{10}P_T^{el}$.

Thus, the overall energy consumption to transmit a signal for a multi-hop UWA cooperative network with K relay nodes is as follows:

$$E_{sys}(K) = \sum_{k=0}^{K}\left[E_{tr}(d_k,f) + E_{rr}(d_k,f)\right]\cdot \quad (24)$$

It is normally assumed that the energy consumption is the same for all the hops in the ideal equal distance case, and then we can rewrite (24) as follows:

$$E_{sys}(K) = (K+1)\cdot E_{tr} + (K+1)\cdot E_{rr} \quad (25)$$

Above all, we present the process for calculating the total energy consumption for multi-hop UWA cooperative networks, as shown in Algorithm 1.

We can use the 3-dB bandwidth around the optimum operating frequency as the operating bandwidth W. For simplicity, following the theoretical analysis in [2,3,21] the 3-dB bandwidth W, the source power P_t, and the electrical power P_T^{el} are function of the transmission distance under the given target SNR_0, respectively, which can be approximately expressed as follows:

$$W(d_k,f) = \omega\cdot d_k^{-\varpi} \quad (26)$$

$$P_t(d_k,f) = \delta\cdot d_k^{\chi} \quad (27)$$

$$P_T^{el}(d_k,f) = P_t(d_k,f)\cdot 10^{-17.2}/\varphi = \psi\cdot d_k^{\chi} \quad (28)$$

where ω, δ and ψ represent the corresponding spreading factors, and ψ is the factor related to the target SNR_0; ϖ and χ represent the corresponding exponent, which are positive values and can be readily calculated by first-order least-squares polynomial approximation on a logarithmic scale.

4. Selection of optimal number of relays

In this section, we derive the optimal number of relays based on the above modeling of probability of detection and energy consumption for the multi-hop covert UWA system. Taking the LPD as the constraint, the optimal number of relays K_{opt} is the solution of the objective function of minimum energy consumption, and it can be expressed as follows:

$$\begin{aligned} K_{opt} &= \arg\min_K E_{sys}(K) \\ &\text{s.t. } P_D(K) < 0.5 \end{aligned} \quad (29)$$

The following is the theoretical derivation of the optimal selection of relays K_{opt}.

4.1. From the view of energy optimization

Generally, substituting (22) and (23) into (25), and taking $E_{enc} = E_{dec} = \rho\cdot P_T^{el}\cdot T_L$ and $P_R = \sigma\cdot P_T^{el}$, we have

$$\begin{aligned} E_{sys}(K) &= (K+1)\cdot\left(E_{enc} + P_T^{el}\cdot T_L\right) + (K+1)\cdot\left(E_{dec} + P_R\cdot T_L\right) \\ &= (K+1)\cdot(\sigma+2\rho+1)\cdot P_T^{el}\cdot T_L \end{aligned} \quad (30)$$

where ρ is the difference between the power consumption of the encoding and that of the transmitting, and σ is the difference between power consumption of the receiver and that of the transmitter. Plugging (2) and (28) into (25), we have the following:

$$\begin{aligned} E_{sys}(K) &= (K+1)\cdot(\sigma+2\rho+1)\cdot\psi\cdot d_k^{\chi}\cdot T_L \\ &= \underbrace{(\sigma+2\rho+1)\cdot d_c^{\chi}\cdot\psi\cdot T_L}_{:=\Omega}\cdot(K+1)^{1-\chi} \\ &= \Omega\cdot(K+1)^{1-\chi} \end{aligned} \quad (31)$$

Taking the first-order derivative of $E_{sys}(K)$ with respect to K we obtain the following:

$$\frac{\partial E_{sys}(K)}{\partial K} = (1-\chi)\cdot\Omega\cdot(K+1)^{-\chi} \quad (32)$$

Because $\chi > 1$, thus $\partial E_{sys}(K)/\partial K < 0$, which means that the energy consumption rate decreases as the number of relays K increases. For a target energy consumption ε_0, to meet $E_{sys}(K) < \varepsilon_0$, plugging into (31) we have the following:

$$\Omega\cdot(K+1)^{1-\chi} < \varepsilon_0 \quad (33)$$

which obtains $K > \sqrt[1-\chi]{\frac{\varepsilon_0}{\Omega}} - 1$, and this is the solution of the number of relays from the energy consumption aspect. Taking $K_0 = \left\lceil \sqrt[1-\chi]{\frac{\varepsilon_0}{\Omega}} - 1\right\rceil$ as the upper bound value, $K \geq K_0$ is the number of relays that can meet the energy consumption target.

However, we need to consider both $E_{sys}(K)$ and $P_D(K)$, and $P_D(K)$ is a value between 0 and 1, therefore it is better to normalize $E_{sys}(K)$. We define the energy consumption rate of the K-hop system $\eta(K)$ as follows:

$$\eta(K) = \frac{E_{sys}(K)}{E_{sys,max}|_{K=0}} = (K+1)^{1-\chi}, \quad (34)$$

where $E_{sys,max}$ is the maximum energy consumption required and it is the case with no relay nodes, i.e., $E_{sys,max} = E_{sys}(0)$. Hence $\eta(K)$, taking a value between 0 and 1, represents the energy saving index of the multi-hop UWA system. The closer the energy consumption rate η is to 0, the better the multi-hop UWA system efficiency.

Similarly, we have $\partial\eta(K)/\partial K < 0$, which means that the energy consumption is decreasing as the number of relays K are increasing. For a given target energy consumption rate η_0, to meet $\eta < \eta_0$, plugging into (34) yields the following:

$$(K+1)^{1-\chi} < \eta_0 \quad (35)$$

Then, we find the solution is $K > \eta_0^{\frac{1}{1-\chi}} - 1$. Likewise, taking $K_0 = \left\lceil \eta_0^{\frac{1}{1-\chi}} - 1\right\rceil$ as the upper bound value, $K \geq K_0$ is the number of relays where the energy consumption rate can be less than the target energy consumption rate.

Comparing (31) with (34), we find that $\eta(K)$ loses the effect of the target SNR_0, indicated by ψ in (31), although it is better to use the normalized value $\eta(K)$ when comparing it with $P_D(K)$. We want to note that both the absolute value $E_{sys}(K)$ and the normalized value $\eta(K)$ are effective evaluation metrics, depending on the different profiled scenarios.

4.2. From the view of probability of detection

From (4) and (6), we know that $P_D(K)$ can also be written as follows:

$$P_D(K) = \frac{1}{2}\mathrm{erfc}\left[\mathrm{erf}^{-1}(1-2P_{FA}) - \frac{E_s}{N_0}\cdot\frac{\lambda\phi}{\sqrt{2T_iW}}\cdot\gamma^{-n}(K)\right] \quad (36)$$

where $\gamma(K) = \frac{r_c(K)}{d_c} = \frac{\mathrm{E}[r_k(K)]}{d_c}$. For simplicity, we will calculate $\mathrm{E}[r_k(K)]$ in an approximate method according to Fig. 1(b) next. It can be seen from Fig. 1(b) that when K is close to infinity, the sum of $r_k(K)$ can be approximated as the area of a triangle; then $\mathrm{E}[r_k(K)]$ can be approximately expressed as follows:

$$\mathrm{E}[r_k(K)]|_{K\to\infty} = \frac{1}{K+1}\sum_{k=0}^{K} r_k(K)\Big|_{K\to\infty} \approx \frac{1}{K+1}\cdot\frac{1}{2}r_{\min}\cdot d_c \tag{37}$$

Actually, since the value of K cannot be infinity, the gain difference can be expressed as ς (apparently $\varsigma < 1$). Then, the exact value of $\mathrm{E}[r_k(K)]$ can be written as follows:

$$\mathrm{E}[r_k(K)] = \varsigma\cdot\mathrm{E}[r_k(K)]|_{K\to\infty} = \frac{1}{2}\cdot\frac{1}{K+1}\varsigma\cdot r_{\min}\cdot d_c \tag{38}$$

By $\tan\theta = \frac{d_k}{r_{\min}}$, we have $r_{\min} = \frac{d_k}{\tan\theta} = \frac{d_c}{(K+1)\cdot\tan\theta}$, therefore,

$$\gamma(K) = \frac{r_c(K)}{d_c} = \frac{\mathrm{E}[r_k(K)]}{d_c} = \frac{1}{2}\varsigma\cdot r_{\min} = \frac{\varsigma}{2\tan\theta}\cdot d_c\cdot\frac{1}{(K+1)^2} \tag{39}$$

Thus, plugging (39) into (36), we have the following:

$$\begin{aligned} P_{\mathrm{D}}(K) = &\ \tfrac{1}{2}\mathrm{erfc}\left[\underbrace{\mathrm{erf}^{-1}(1-2P_{\mathrm{FA}})}_{:=\beta} - \underbrace{\frac{E_s}{N_0}\cdot\frac{\lambda\phi}{\sqrt{2T_{\mathrm{i}}W}}\cdot\left(\frac{\varsigma}{2\tan\theta}\right)^{-n}\cdot d_c^{-n}}_{:=\psi\cdot\xi}\cdot(K+1)^{2n}\right] \\ = &\ \tfrac{1}{2}\mathrm{erfc}\left[\beta-\psi\cdot\xi\cdot(K+1)^{2n}\right] \end{aligned} \tag{40}$$

where we continue using ψ in (40), due to the effect of SNR, and the other effect can be synthetically expressed as ξ in (40). This is very important because the SNR is a reflection of the dynamic changes of marine environments at the receiver.

In the meantime, we have $\partial P_{\mathrm{D}}(K)/\partial K > 0$, which means that the probability of detection increases when decreasing the number of relays K. For a given probability of detection threshold P_{D0}, ($P_{\mathrm{D0}} = 0.5$ according to LPD), i.e., to meet $P_{\mathrm{D}}(K) < P_{\mathrm{D0}}$, we can adopt (40) to obtain the range of relays K, as follows:

$$K < \sqrt[2n]{\frac{1}{\psi\cdot\xi}[\beta - \mathrm{erfcinv}(2P_{\mathrm{D0}})]} - 1 \tag{41}$$

Taking $K_1 = \left\lfloor \sqrt[2n]{\frac{1}{\psi\cdot\xi}[\beta-\mathrm{erfcinv}(2P_{D0})]} - 1\right\rfloor$ as the lower bound value, $K \le K_1$ is the number of relays that meet the P_{D} less than the target threshold.

4.3. Analysis and discussion

From the discussion above, it can be found that $P_{\mathrm{D}}(K)$ and $E_{sys}(K)$ are the two curves showing opposite performance trends with increasing relay values once the system parameters are set and the target SNR is given.

In summary, to jointly consider probability of detection P_{D} and energy consumption ε, the range of number of relays K is as follows:

$$K_0 \leqslant K \leqslant K_1,\ \begin{cases} K_0 = \left\lceil \sqrt[1-\chi]{\frac{\varepsilon_0}{\Omega}} - 1\right\rceil \quad or \quad K_0 = \left\lceil \eta_0^{\frac{1}{1-\chi}} - 1\right\rceil \\ K_1 = \left\lfloor \sqrt[2n]{\frac{1}{\psi\cdot\xi}[\beta-\mathrm{erfcinv}(2P_{\mathrm{D0}})]} - 1\right\rfloor \end{cases} \tag{42}$$

where the value of K_0 and K_1 are related to the system parameter, target P_{D} threshold P_{D0}, target energy consumption ε_0 or target energy consumption rate η_0, and so on.

At this time, the range of the number of relays K for the optimal solution is determined. In the range of K, the exact value of K depends on the different needs, such as a lower probability of detection or lower power consumption.

Furthermore, to obtain the unique solution of (29), considering both indexes, P_{D} and η in (42), take value between 0 and 1, the optimal objective function can be constructed as the sum of $P_{\mathrm{D}}(K)$ and $\eta(K)$, that is as follows:

$$P_{\mathrm{D}}(K) + \eta(K) = C(K), K \in [K_0, K_1] \tag{43}$$

Then, (29) can be further expressed as follows:

$$\begin{aligned} &K_{\mathrm{opt}} = \arg\min_K C(K) \\ &\mathrm{s.t.}\ C(K) = P_{\mathrm{D}}(K) + \eta(K) \\ &\qquad K \in [K_0, K_1] \end{aligned} \tag{44}$$

Finally, taking the first-order derivative of C(K) with respect to K we obtain the following:

$$\begin{aligned} \frac{\partial C(K)}{\partial K} &= \frac{\partial P_{\mathrm{D}}(K)}{\partial K} + \frac{\partial \eta(K)}{\partial K} \\ &= \frac{1}{2}\frac{\partial}{\partial K}\left\{\mathrm{erfc}\left[\beta-\psi\cdot\xi\cdot(K+1)^{2n}\right]\right\} + \frac{\partial}{\partial K}\left[(K+1)^{1-\chi}\right] \\ &= -\frac{1}{\sqrt{\pi}}\cdot\frac{\partial}{\partial K}\left[\beta-\psi\cdot\xi\cdot(K+1)^{2n}\right]\cdot e^{-\left[\beta-\psi\cdot\xi\cdot(K+1)^{2n}\right]^2} \\ &+ (1-\chi)(K+1)^{-\chi} \\ &= \frac{2n\cdot\psi\cdot\xi}{\sqrt{\pi}}\cdot(K+1)^{2n-1}\cdot e^{-\left[\beta-\psi\cdot\xi\cdot(K+1)^{2n}\right]^2} + (1-\chi)(K+1)^{-\chi} \end{aligned} \tag{45}$$

As it is difficult to calculate the optimal solution by calculating $\partial C(K)/\partial K = 0$, we resort to numerical solutions to find K_{opt} for the given conditions using (45). Taking $P_{\mathrm{FA}} = 0.02$, $\beta = 1.1987$, $\psi = 10^{0.1SNR_0 - 4.9040}$, $\chi = 2.2047$, $\xi = 20$, and $SNR_0 = 10$ dB, the results are plotted in Fig. 3, indicating the relationship between the number of relays K and performances of $P_{\mathrm{D}}(K)$, $\eta(K)$ and $C(K)$, respectively.

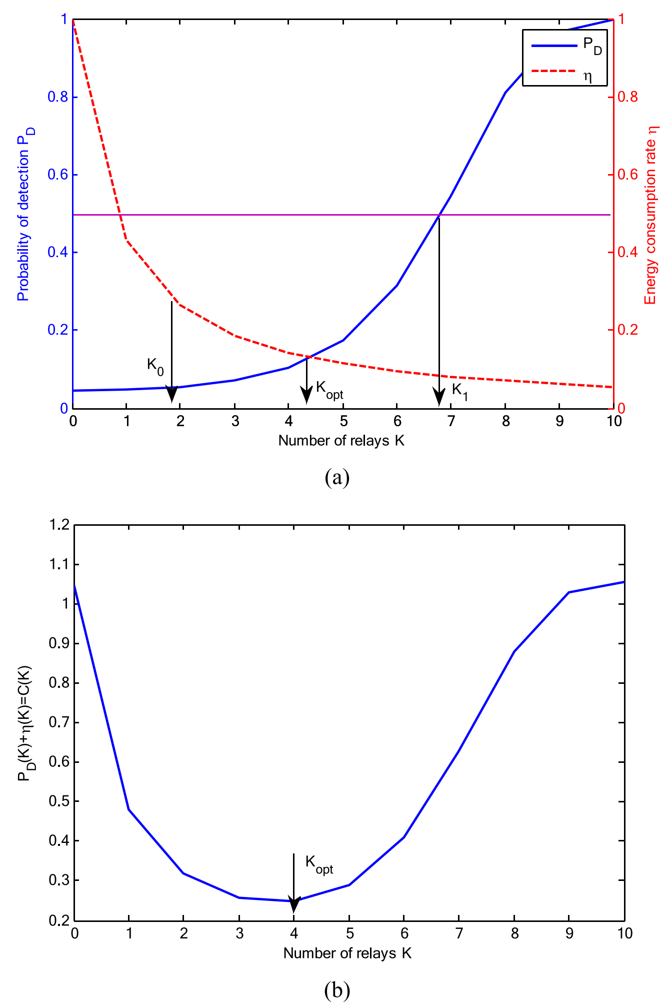


Fig. 3. Optimal number of relays for selection: (a) Probability of detection vs. number of relays and energy consumption rate vs. number of relays; (b) Optimal number of relays, the calculation result of the objective function.

From Fig. 3(a), if we set P_{D0} = 0.5 and η_0 = 0.3, then we have K_0 = 2, K_1 = 6, which means that the optimal range of the number of relays is $2 \le K \le 6$. Hence this plot shows that there may be no solution for certain with separately drawing the P_D and η. However, when adopting P_D and η as the joint optimal objective function, the unique solution of the optimal number of relays should be K_{opt} = 4 from Fig. 3(b). Therefore, as shown in Fig. 3(a), we can approximately define the number of relays according to the intersection of the two curves as the optimal number of relays K_{opt}, where the P_D is approximately equal to η, indicating that the two indexes are almost equal and there is no "favoritism" phenomenon.

5. Numerical analysis

In this section, we numerically evaluate the probability of detection/energy consumption as a function of the number of relays by adjusting different parameters, aiming at obtaining the optimal number of relays for multi-hop UWA networks.

Note that, according to (31) and (34), it can be found that the effects of factors, including target SNR, transmission distance, and transmission time, have disappeared during the calculation of the energy consumption rate. Therefore, to study the effects of the mentioned factors on energy consumption, we will take the absolute value of energy consumption in (31) instead of the normalized value of that in (34) in the following simulation.

5.1. Simulation parameters setup

The basic parameters for simulation are as follows: the distance between the source node and destination node is d_c = 50 km; the target SNR in each hop where the receiver can correctly receive a signal is SNR_0 = 10 dB; the position angle of I_x is $\theta = \pi/15$; the energy required for the transmitter to encode and that for receiver to decode are equal, which are set as 1% of the energy required for transmitting; the transmitted data length L_D is 256 bytes, and the transmission bit rate R_b is 160 bps, then the time required to transmit the data is $T_L = L/R_b$. Take the integration time of the I_x as $T_i = 1.2T_L$. The bandwidth of I_x is the same as that of the receiver, and the false alarm probability of I_x is P_{FA} = 0.02. The other parameters for calculating (26), (27) and (28) corresponding to the optimal frequency f_{opt} are $\omega = 10^{1.4291}$, $\psi = 10^{0.1SNR0-4.9040}$, ϖ=0.5392, χ = 2.2074, and ϕ = 0.25. The parameters will be adjusted according to different simulation purposes.

5.2. General covert UWA communications

First, given the distance of each hop d_k, the optimal operating frequency f_{opt} for each hop can be calculated by (15) and (16). Meanwhile, from (26), we can calculate the relationship between d_k and the available bandwidth W, as shown in Fig. 4. It can be seen that W is reduced with the increase of d_k. On the other hand, the relationship between d_k and the transmit power is shown in Fig. 5 calculated by (27) and (28) under different target SNR_0 values. From Fig. 4 and 5, it is clear that a shorter d_k will be better, which means more relays will consume less power and offer more available bandwidth, improving the transmission rate for multi-hop UWA networks.

Next, let the transmission distance be fixed at 50 km. Fig. 6 shows the relationship between P_D and γ under different target SNR_0 values for the single-hop UWA communication system. With the same P_D condition, it can be seen that the lower the target SNR_0, the smaller the distance ratio that is required, indicating that the covertness of the system is better. This simulation result is in accordance with the theoretical analysis in Section 2.

Considering both covertness and energy consumption, it can be observed from Figs. 5 and 6 that if the target SNR_0 decreases from 12 dB to 8 dB, the emission source power P_t will decrease from 166.4425 dB to 162.4425 dB, and the distance ratio γ will decrease from 0.875 to 0.5, aiming at P_D = 0.5 over a 50-km transmission distance. Therefore, designing a good transmitting signal to ensure the receiver can correctly decode with lower target SNR_0 is the key to achieve low-power consumption in covert UWA communications. In the meantime, since the complexity of uncertainty in oceanic turbulence on UWA channels will affect the target SNR_0, different UWA channel states usually need different target SNR_0. Hence it is very important to design the good UWA signal and decoding scheme to overcome the shortcomings of variable UWA channels and keep the performance of LPD at the same time in practice.

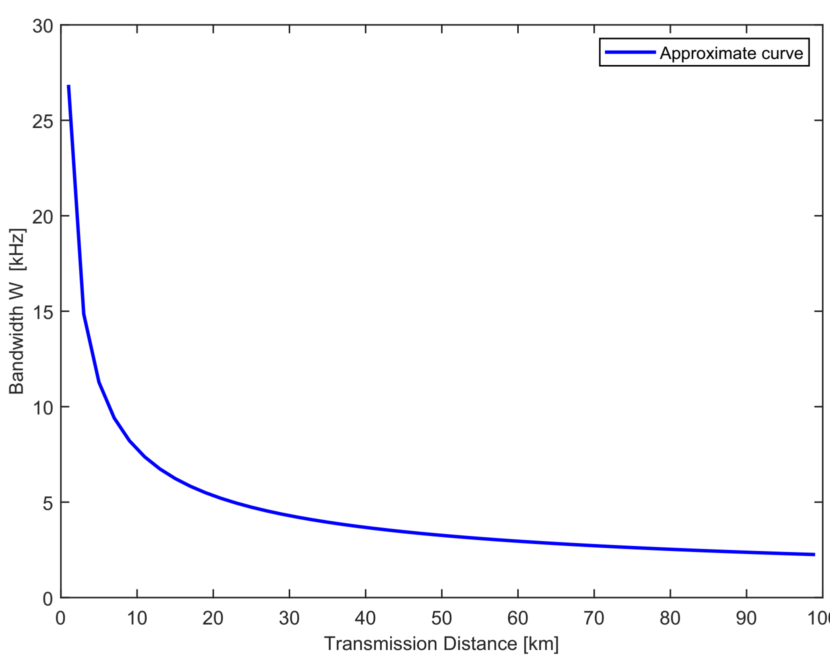


Fig. 4. The relationship between the available bandwidth and transmission distance of a single-hop UWA communication system.

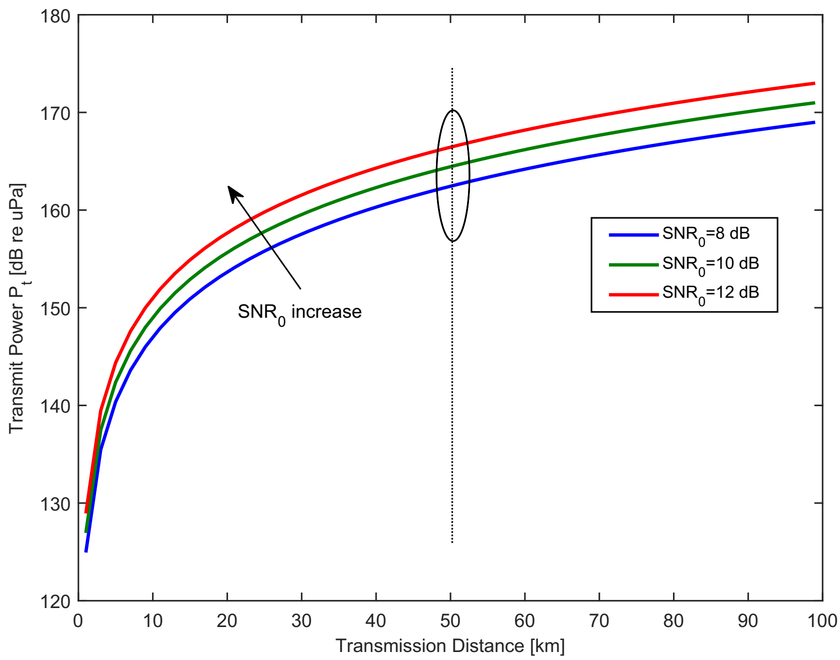


Fig. 5. The relationship between the transmit power and transmission distance for a single-hop UWA communication system.

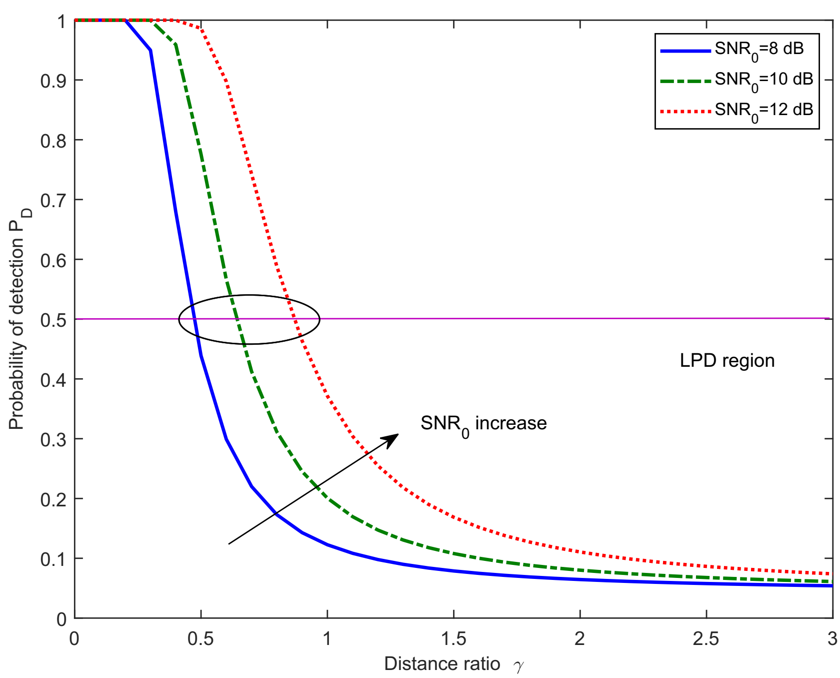


Fig. 6. The relationship between the probability of detection and distance ratio with different target SNRs for a single-hop UWA communication system.

5.3. The effect of different target SNR_0

To further discover the effect of the different target SNR_0 values on the covertness and energy efficiency for the multi-hop UWA networks, Fig. 7 shows the relationship between the probability of detection/energy consumption and the number of relays with different target SNR_0 values. Obviously, with the increase in the number of relays K, the energy consumption E_{sys} of the multi-hop UWA system decreases, while the probability of detection P_D increases. On the other hand, to keep the same P_D, the number of relays K must be reduced when the target SNR_0 is increasing. This is because the increased target SNR_0 leads to an increased instantaneous transmit power, which is more easily intercepted by I_x. For example, to maintain P_D = 0.42, the number of K must be reduced from 6 to 3 when the target SNR_0 increases from 8 dB to 12 dB, otherwise the signal is intercepted more easily.

Under the given basic simulation conditions, in the rectangular region of Fig. 7 (i.e., the LPD region), when the target SNR_0 is set at 8 dB, the number of relays K should be between 2 and 6 to satisfy the requirement of the LPD, i.e., P_D < 0.5. Meanwhile, the energy consumption is relatively low. If the target SNR_0 is 12 dB, the number of relays K can only be 2 or 3 when taking into account the

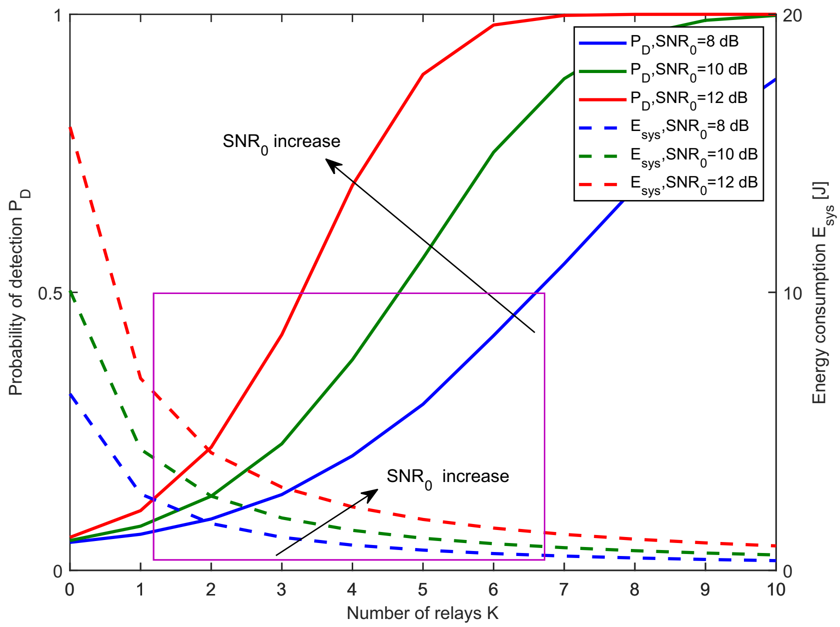


Fig. 7. The relationship between the number of relays and probability of detection, energy consumption, respectively, with different target SNR_0.

requirements of both LPD performance and low power consumption.

5.4. The effect of different transmission distances

Fig. 8 shows the effect of different transmission distances d_c on P_D and energy consumption. It is clear that the total energy consumption of the system is increasing as the total transmission distance increases, as shown in Fig. 8. Further, when the transmission distance is 20 km and the number of relays K is 3, we find that P_D = 0.3153 and the energy consumption is 0.2497 J. When the transmission distance is 80 km and the number of relays K is 3, we find that P_D = 0.1950 and the energy consumption is 5.3258 J. With the same number of relays K and the other conditions unchanged, the distance of each hop is also increasing as the total transmission distance increases, which is equivalent to reducing the risk of being intercepted by a multi-hop scheme, and thus reducing the overall P_D of the system. On the other hand, when the transmission distance is 80 km and the number of relays K is increased to 4, the P_D is only 0.3180, and the energy consumption is reduced to 4.0679 J. Even if the number of relays K is increased to 5, the P_D is only 0.4740, and still meets $P_D < 0.5$, i.e., the index of the LPD, while the energy consumption is reduced to 3.2641 J. This means that, over the 80-km transmission distance, when the number of relays K increases from 3 to 5, the energy consumption decreases from 5.3248 J to 3.2641 J, a decline of 38.7%, and it still meets the LPD requirements.

Therefore, based on the given basic simulation conditions, when the total transmission distance of the multi-hop UWA system is 80 km, the number of relays K can be set between 2 and 5, which meets the LPD requirement, i.e., $P_D < 0.5$, and the energy consumption is also relatively low. If the transmission distance reduces to

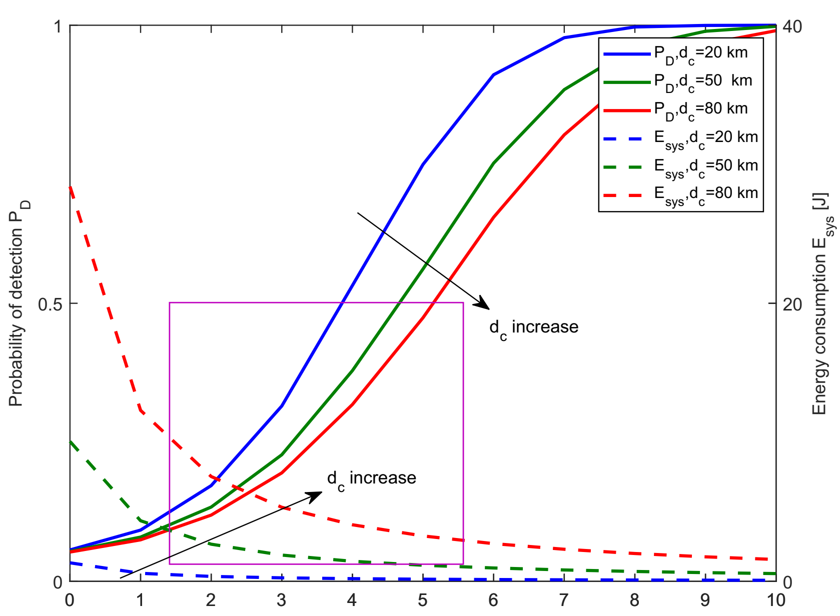


Fig. 8. The relationship between the number of relays and the probability of detection and energy consumption, individually, with different transmission distances.

20 km, the number of relays K can only be 2 or 3 when considering the requirements of both LPD performance and low power consumption.

5.5. The effect of different position angles of the interceptor

Fig. 9 presents the effect of different position angle parameters of the interceptor on P_D and energy consumption. It can be seen from the figure, that under the same transmission distance, when increasing the position of angle interceptor, the interceptor is closer to the transmitter and can obtain a higher P_D. In particular, when the number of relays K is 3 and the angle of interceptor increases from $\pi/20$ to $\pi/10$, the P_D of the system is increased from 0.1418 to 0.4982. In addition, if we only change the position of the interceptor, it does not affect the energy consumption of the multi-hop UWA system. Thus, if the interceptor changes position, the system energy consumption remains unchanged.

Therefore, given the basic simulation conditions, when the position angle of the interceptor is $\theta = \pi/20$, the number of relays K can be between 2 and 6, which satisfies the requirement of the LPD, and the energy consumption stays relatively low. If the position angle of the interceptor is $\theta = \pi/10$, the number of relays can only be 2 or 3 when considering the LPD performance and low power requirement of the system.

5.6. The effect of different data lengths

Fig. 10 plots the effect of different data lengths L_D on P_D and energy consumption. We observe that, as the data length increases, the integration time of interceptor is also increasing, and thus the

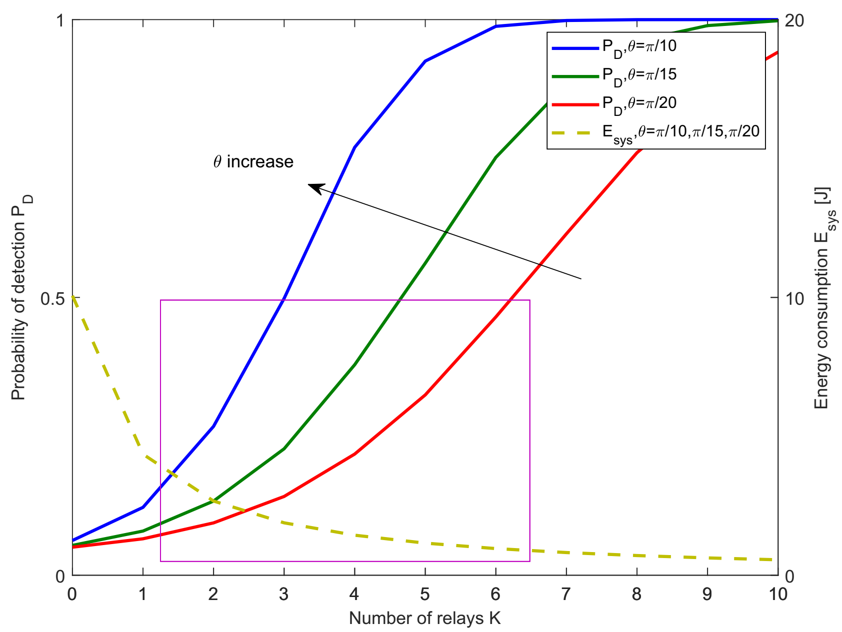


Fig. 9. The relationship between the number of relays and the probability of detection, energy consumption, individually, with the different position angles of the interceptor.

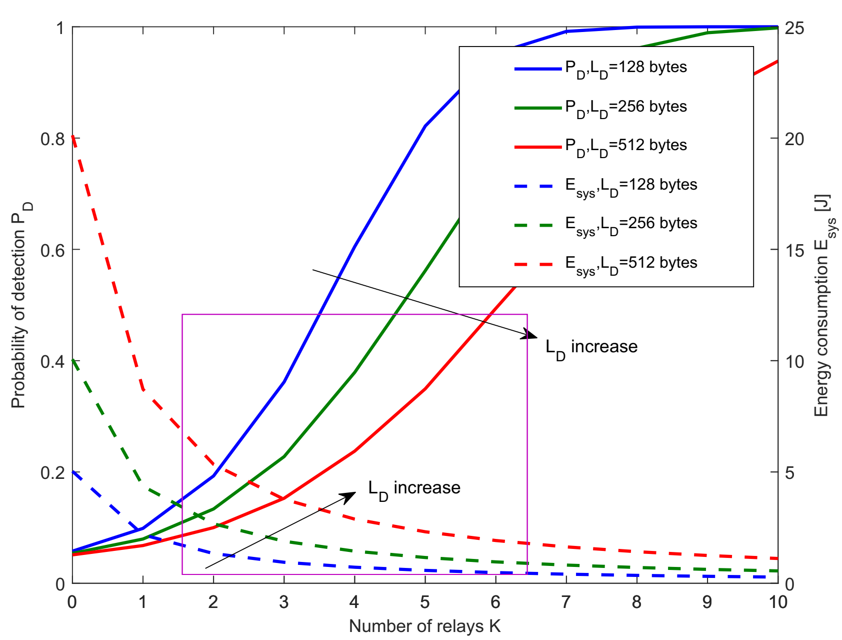


Fig. 10. The relationship between the number of relays and the probability of detection, energy consumption, individually, with different data lengths.

energy is dispersed in a longer time, reducing the instantaneous power, thereby further reducing the probability of being intercepted. It should be noted that although the total energy consumption increases as the data length increases, the increase rate is not enough to eliminate the energy dispersion due to the increase of the integration time. Thus, the instantaneous power is still reduced. Specifically, taking the number of relays K as 3, if the data length increases from 128 bytes to 512 bytes, the system energy consumption will increase from 0.9436 J to 3.7743 J, yet the P_D will decrease from 0.3617 to 0.1528.

In summary, under the given basic simulation conditions, when the data length is 512 bytes, the number of relays K can be set between 2 and 6, which satisfies the requirement of LPD performance, and the energy consumption is relatively low. If the data length is 128 bytes, the number of relays K can only be 2 or 3 when considering the requirements of both LPD performance and low power consumption.

6. Conclusion

We study the optimization of the number of relays for multi-hop UWA covert communication networks. By establishing the models for probability of detection and energy consumption for the multi-hop system, we theoretically derive the range of the number of relays both in terms of probability of detection and of energy consumption/energy consumption rate. Furthermore, we present the unique solution of the optimal number of relays by constructing an objective function as the sum of the probability of detection and the energy consumption rate. The impact of the target SNR, transmission distance, position angle of interceptor, and data length are investigated in detail by simulation, while optimizing the number of relays considering the above two conditions. The numerical results validate our theoretical analysis and show that the number of relays must be reduced to maintain the same detection probability as the target SNR increases. Under the same probability of detection, the number of relays should be increased appropriately to reduce the overall energy consumption of the multi-hop system. Under the given conditions, such as a total transmission distance of 50 km, data length of 256 bytes, target SNR_0 of 10 dB, and interceptor position angle of $\pi/15$, the number of relays can be between 2 and 6 to meet the requirements of covert communication, i.e., a probability of detection<0.5, while the energy consumption is relatively low.

Funding

This work was supported in part by the Basic Research Program of Science and Technology of Shenzhen, China under Grant JCYJ20190809161805508, in part by the National Key Research and Development Program of China under Grant 2016YFC1400200, and in part by the National Natural Science Foundation of China under Grant 41476026, Grant 41676024 and Grant 41976178, and Natural Science Foundation of Fujian Province of China under Grant 2018J05071.

CRediT authorship contribution statement

Yougan Chen: Conceptualization, Methodology, Writing - review & editing. **Yuying Tang:** Writing - original draft. **Junhui Liu:** Writing - original draft. **Xiaokang Zhang:** Software. **Xiaomei Xu:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to thank Mr. Jianming Wu, Mr. Shenqin Huang from Xiamen University for their contributions to the early discussions of this research. This work was supported in part by the Basic Research Program of Science and Technology of Shenzhen, China under Grant JCYJ20190809161805508, in part by the National Key Research and Development Program of China under Grant 2016YFC1400200, and in part by the National Natural Science Foundation of China under Grant 41476026, Grant 41676024 and Grant 41976178, and Natural Science Foundation of Fujian Province of China under Grant 2018J05071.

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