Effectiveness of handshake strategy in 3D underwater acoustic networks

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Abstract. Underwater acoustic networks (UWANs) have emerged as a promising technology to accomplish Internet of Underwater Thing (IoUT). Handshake-based protocols have been used in UWANs to resolve various problems for different protocol layers. However, the effectiveness of handshake is seriously influenced by interference as the underwater channel has lower spreading loss factor and absorption attenuation. In this paper, we derive effectiveness of handshake strategy for 3D UWAN and analyse it with various parameters.

1. Introduction
Underwater acoustic networks (UWANs) attract much researches with the development of acoustic modem in recent years [1]. UWANs have been a major concerned for Internet of Underwater Thing (IoUT) because of its flexibility and expansibility [1,2]. A great deal of networking protocols has been proposed to solve various problems in different underwater scenarios. Among these protocols, the handshake-based protocol plays a major role in UWANs.

Handshake-based strategy has been used in different protocol layers. MAC protocols use RTS/CTS handshake strategy to establish negotiation between each communication pair to resolve the hidden problem [3,4]. Routing protocols exploit Ping/Pong handshake to accomplish opportunistic forwarding [5,6]. Handshake strategy can resolve the hidden problem, however, the communication can still be interfered by nodes located outside of transmission range.

In UWANs, the effectiveness of handshake is seriously influenced by multi-hop interference due to the lower spreading loss factor and absorption attenuation. Xu et al. have defined and derived the effectiveness of RTS/CTS in IEEE802.11 based ad hoc networks in [7]. Ye et al introduce spatial reuse index to evaluate the efficiency of MAC protocol for IEEE802.11 [8]. In UWANs, Partan et al. have extended this work and derived the effectiveness of RTS/CTS MAC protocols in UWANs [9]. However, these works are only valid for 2-dimension (2D) scenarios while 3-dimension (3D) scenarios are common in UWANs. Thus, we extend these work and derive effectiveness of handshake strategy for 3D UWANs in the following sections.

2. System Model
Xu et al. define the effectiveness of handshake ($E_{hs}$) in 2D wireless network which is furtherly used to analyse similar scenarios in underwater [7,9]. As defined, $E_{hs}$ is the fraction of the interference region that are covered by handshake packets. On this basis, we extend $E_{hs}$ to 3D network deployment as below:
Fig.1 Three scenarios for different relations between transmission range $R_{tx}$ and interference range $R_i$.

Scenario I: Fig.1(a) is the scenario where $R_i$ is smaller or equal than $R_{tx}$. Interference regions covered by handshake zone contains two zones marked with I and II. The interference nodes in zone I can overhear RTS and CTS from sender S and receiver R, respectively. In zone II, interference nodes can only overhear CTS from receiver R. Thus, $E_{hs}$ equals with 1 as all of the potential interference nodes can overhear handshake packet.

Scenario II: Fig.1(b) depicts the scenario where $R_i$ is larger than $R_{tx}$ but smaller than $(R_{tx} + d)$. where $d$ is the distance between sender S and receiver D. In this case, the sender may cover zones outside of interference region. There are three zones in interference area marked with I, II, III. Zone I is the region where the node can overhear RTS and CTS. Zone II represents the region where only RTS or CTS can be overheard. In zone III, Both RTS and CTS cannot be received correctly as this zone is out of transmission range of sender S and receiver R.

Scenario III: Fig.1(c) is the scenario where $R_i$ is larger or equal than $(R_{tx} + d)$. All the nodes in the transmission range of sender S and receiver R are covered in the interference region. This scenario has the worst case of $E_{hs}$ since more interferences cannot be avoided by handshake strategy.

3. Derive effectiveness of handshake strategy

Considering definition of $E_{hs}$ in last section, we start to calculate the volume of each region in these scenarios. We only need to derive $E_{hs}$ for latter two scenarios since $E_{hs}$ is obvious equal with 1 in the first scenario. In all scenarios, the volume of interference region is $V_i = \frac{4}{3} \pi R_i^3$. Meanwhile, the volume of handshake region $V_{hs}$ can be expressed as follows.

$$V_{hs} = V_S + V_R - V_{S \cap R} = 2V_S - V_{S \cap R}$$
(a) The relationship among $V_{hs}$, volumes of RTS region and CTS region

(b) The relationship among volumes $V_0$, $V_{hs}$ and $V_i$

Fig. 2 The relationship among the regions in scenario II.

Where $V_S$ is the volume of the region covered by sender $S$, which can be calculated by $V_S = \frac{4}{3} \pi R_{tx}^3$.

$V_R$ is the volume of the region covered by receiver $R$, which is equal with $V_S$. $V_{S\cap R}$ is the intersection of these two regions as shown in Fig. 2 (a). Refer [10], $V_{S\cap R}$ can be divided into two spherical cap and can be calculated as follows:

$$V_{S\cap R} = 2\pi l_{oc}^2 (R_{tx} - \frac{l_{oc}}{3})$$

Where $l_{oc}$ is the height of spherical cap that can be calculated by $l_{oc} = R_{tx} - \frac{d}{2}$. Thus, we derive $V_{hs}$ as below.

$$V_{hs} = \frac{4}{3} \pi R_{tx}^3 + \pi R_{tx}^2 d - \frac{1}{12} \pi d^3$$

In scenario III, $V_{i\cap hs}$ is equal with $V_{hs}$ since the handshake region is covered by interference region. Thus, we calculate $V_{i\cap hs}$ in scenario II as below.

$$V_{i\cap hs} = V_{hs} - V_0$$

As shown in Fig. 2(b), $V_0$ is the volume where covered by sender $S$ but outside of interference region of receiver $R$ calculated by $V_0 = V_{S, cap} - V_{I, cap}$. In order to calculating $V_0$, we derive the volumes of spherical cap $V_{S, cap}$ and $V_{I, cap}$ as follows.

$$\begin{align*}
V_{S, cap} &= \pi l_{ac}^2 (R_{tx} - \frac{l_{ac}}{3}) \\
V_{I, cap} &= \pi l_{ab}^2 (R_i - \frac{l_{ab}}{3})
\end{align*}$$

Where $l_{ac}$ and $l_{ab}$ can be calculated as:

$$\begin{align*}
l_{ac} &= R_{tx} - (R_i \cos(\theta) - d) \\
l_{ab} &= R_i (1 - \cos(\theta))
\end{align*}$$

Thus, we can derive $V_0$ as:
\[ V_0 = \frac{\pi}{3} \left[ (R_n - R_i \cos(\theta) + d)^2 (6R_n + R_i \cos(\theta) - d) - R_i^2 (1 - \cos(\theta))^2 (2 + \cos(\theta)) \right] \] (8)

As considered in [9], the interference distance \( R_i \) can be written as \( R_i = \gamma d \), where \( \gamma \) is spatial reuse factor. In addition, we use normalized node separation \( \lambda = d/R_i \) to simplify formula as follows.

\[
V_0 = \frac{\pi d^3}{3} \left[ (1/\lambda - \gamma \cos(\theta) + 1)^2 (2/\lambda + \gamma \cos(\theta) - 1) - \gamma^3 (1 - \cos(\theta))^2 (2 + \cos(\theta)) \right]
\] (9)

Finally, we use formulas (1), (4) and (5) to derive the expression of \( E_{hs} \) for each scenarios as below.

\[
E_{hs} = \begin{cases} 
1, & 0 < \lambda \leq \frac{1}{\gamma} \\
\frac{4\gamma^3}{(4\lambda^3 + 3\lambda^2 - 1/4) + \gamma^3 (1 - \cos(\theta))^2 (2 + \cos(\theta))} & 1/\gamma < \lambda < 1/\gamma - 1 \\
\frac{4\gamma^3}{(1/\lambda - \gamma \cos(\theta) + 1)^2 (2/\lambda + \gamma \cos(\theta) - 1) - 1/\gamma < \lambda \leq 1} \\
\frac{4\gamma^3 (4\lambda^3 + 3\lambda^2 - 1/4)}{1/\gamma - 1} & \lambda \leq 1 
\end{cases}
\] (10)

Where, angle \( \theta \) can be calculated as:

\[
\theta = \arccos \left( \frac{1 + \gamma^2 - 1/\lambda^2}{2\gamma} \right)
\] (11)

When considering absorption and ambient noise, \( \gamma \) is no longer a constant value. In UWANs, \( \gamma(f, d) \) is a function of frequency \( f \) and source-receiver separation \( d \). We use spatial reuse factor \( \gamma(f, d) \) derived in paper [9] as below.

\[
\gamma^{-k} (A(f, d))^{-1} = \frac{P_s}{P_T} - \frac{\sigma_N(f)}{P_s A(f, d)}
\] (12)

Where \( k \) is the spreading factor that describes the extended geometric shape (\( k = 2 \) for spherical spreading, \( k = 1 \) for cylindrical spreading). \( P_s \) and \( P_i \) are the transmit power of the sender and the interferer respectively (For simplicity, we consider a condition that \( P_s = P_i \) in this paper). \( \sigma_N(f) \) represents the ambient noise power, which can be calculated with p.s.d by using the shipping activity factor of 0.5 and wind speed of 6.5 m/s. \( S(d, k) = (d/d_0)^{-k} \) and \( A(f, d) = 10^{-\alpha(f)d/10} \) represent spreading loss and absorption attenuation, respectively. \( d_0 \) is a reference distance set to 1 m. \( \alpha(f) \) is the absorption coefficient in dB/km for carrier frequency \( f \) in kHz, which is given by Thorp’s formula in [11].

Because of no closed solution for \( \gamma(f, d) \), we use the data approximation method to get its asymptotic numerical solution in next section. We use a typical detection threshold of \( T = 10 \) dB and spreading loss of \( k = 1.75 \) to give better asymptotic of the real underwater scenario.

4. Simulation Results and Discussions

In this section, we firstly set \( f \) to 25 kHz and calculate \( \gamma(f, d) \) with various Source Level (SL) ranging from 150 dB to 180 dB. Meanwhile, we simulate effectiveness of handshake strategy in 3D scenarios and compare it with that in 2D scenarios. Secondly, we set transmission range to 1 km and
analyze $\gamma(f,d)$ in the case of typical acoustic communication frequencies ranging from 3 kHz to 80 kHz.

![Graph](image)

Fig.3 Spatial reuse factor $\gamma(f,d)$ and effectiveness of handshake $E_{hs}$ vary with different $\lambda$ for several SL values.

Fig.3(a) shows the relationship between $\gamma(f,d)$ and $\lambda$ for several SL values. The effectiveness of spatial reuse is improved with the increasing of SL. However, the improvement diminishes in higher SL. The increasing of $\lambda$ can significantly improve spatial reuse in the case of $\lambda \leq 0.74$, especially in higher SL. According to formulas (10) and (12), we obtain the curves of $E_{hs}$ for different SL with respect to $\lambda$. As shown in Fig.3(b), the $E_{hs}$ decreases with the increasing of $\lambda$. Furthermore, the optimal $\lambda$ for different scenarios have positive correlation with SL. Moreover, the performance of spatial reuse can be improved with the increasing of SL. When SL equals with 180 dB, $E_{hs}$ can reaches 100% under the condition that $\lambda$ is not larger than 0.74. Thus, we need to consider an appropriate transmit power for specific scenario to obtain perfect handshake efficiency.

![Graph](image)

Fig.4(a) shows the relationship between spatial reuse factor $\gamma(f,d)$ and distance $d$ for several frequencies. As expected, the $\gamma(f,d)$ is heavily influenced by frequency. $\gamma(f,d)$ is larger in lower frequencies and decreases with the increasing of frequency. On this basis, We analyze $E_{hs}$ for different frequencies with respect to $d$. As shown in Fig.4(b), the $E_{hs}$ decreases with the increasing of $d$ for different frequencies in both 2D and 3D scenarios. $E_{hs}$ of 3D scenario decrease sharply than that of 2D scenario, especially in the scenarios with lower frequency. $E_{hs}$ increases with the increasing of frequency for all scenarios. In order to give a comprehensive analysis, we also simulate the range for 80% handshake efficiency for different frequencies and find that the distance for $E_{hs} = 80\%$ is close to $R_s$ in higher $R_s$ with higher frequency. When choosing frequency with 80 kHz and $R_s$ with 3 km, we can ensure $E_{hs}$ larger than 80% within the limits of 2.67km. Thus, we need to choose modem with a relatively higher frequency to obtain perfect handshake efficiency.

5. Conclusion

In this paper, we derive effectiveness of handshake strategy for 3D UWANs. On this basis, we compare it with that in 2D scenarios with various parameters. The results show that handshake efficiency is subject to frequency and source level. The handshake strategy in higher frequencies have
better performance. Moreover, handshake efficiency can be improved by increasing SL to some extent. Furthermore, the handshake efficiency in 3D scenarios is obviously worse than that in 2D scenarios, since it naturally introduces more interferences.

![Spatial reuse factor and effectiveness of handshake](image_url)

**Fig.4 Spatial reuse factor** $\gamma(f,d)$ and effectiveness of handshake $E_{hs}$ vary with distance $d$ for several frequencies.

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