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Performance Analysis of MIMO Mobile Underwater Acoustic Networks

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Abstract—**The paper considers the average frame error probability (FEP) of mobile underwater acoustic networks consisting of autonomous underwater vehicles (AUV's) with multiple transmitters and receivers (MIMO). The MIMO AUV's utilize multihop transmissions to route the information through the network. It is based on a modified version of the reserve listen and go transmission protocol that incorporates request to send (RTS) and clear to send (CTS) messages before the transmission with the aim of reducing the impact of network interference. The mobility model is direction persistent. Each channel experiences frequency dependent path loss, Ricean fading and interference. Numerical examples illustrate the average route FEP performance.**

Keywords—**underwater acoustic networks, mobility, MIMO, frame error probability.**

I. Introduction

There have recently been a number of studies of underwater networks [1–6]. These have been motivated in part by the need to perform sensing and surveying of underwater areas with numerous potential applications such as general oceanographic needs [7], monitoring of marine biology and/or oil and gas fields, detection of submarines etc. Networks consisting of AUV's that offer mobility and are equipped with multiple transmitters and receivers in order to improve the link reliability may represent a particularly appealing choice in this regard.

The paper studies the average FEP performance of mobile underwater acoustic networks. The AUV's have multiple transmitters and receivers. The FEP is evaluated across a multihop route of MIMO AUV's. The multihop routing is done by utilizing a modified version of the reserve listen and go transmission protocol. The modification includes request-to-send (RTS) and clear-to-send (CTS) messages before the transmission takes place with the aim of reducing the impact of interference from other transmissions in the network. The mobility model is direction persistent. Each transmission link experiences frequency dependent path loss and independent Ricean fading.

The organization of the paper is as follows. The model for underwater acoustic propagation is outlined in Section II. The average FEP of a multihop route across the mobile underwater acoustic network is evaluated in Section III. Section IV illustrates the FEP performance of the mobile underwater acoustic network with MIMO AUV's through numerical examples. Conclusion is given in Section V.

II. Underwater Acoustic Propagation

Underwater acoustic propagation undergoes a path loss given by

$$A(d,f) = A_0 d^{\kappa} a(f)^d \qquad (1)$$

where A_0 is a unit-normalizing constant that incorporates fixed losses, d is the transmission distance, f is the frequency of the transmission, $a(f)$ is the absorption coefficient and κ is the spreading factor ($1 \le \kappa \le 2$). The absorption coefficient $a(f)$ given in dB/km is [8]

$$10\log a(f) = \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + \frac{2.75 f^2}{10^4} + 0.003 \qquad (2)$$

where f is in kHz. The validity of the formula extends to frequencies above few hundred Hz.

The ambient noise in the ocean can be modeled as consisting of turbulence, shipping, waves and thermal noise, described by Gaussian statistics and continuous power spectral densities (p.s.d.'s). The noise components have formulae that give their p.s.d.'s in dB re µPa per Hz as a function of frequency in kHz [8]:

$$\begin{aligned}
10\log N_{\mathrm{t}}(f) &= 17 - 30\log f\,,\\
10\log N_{\mathrm{s}}(f) &= 40 + 20(s-0.5) + 26\log f\\
&\quad -60\log(f+0.03)\,,\\
10\log N_{\mathrm{w}}(f) &= 50 + 7.5\sqrt{w} + 20\log f\\
&\quad -40\log(f+0.4)\,,\\
10\log N_{\mathrm{th}}(f) &= -15 + 20\log f\,, \qquad (3)
\end{aligned}$$

where s is the shipping activity factor and w is the wind speed in m/s. The total p.s.d. of the ambient noise is

$$N(f) = N_{\mathrm{t}}(f) + N_{\mathrm{s}}(f) + N_{\mathrm{w}}(f) + N_{\mathrm{th}}(f). \qquad (4)$$

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III. Mobile Network Setup

The section describes the transmission protocol and the mobility model utilized by the mobile underwater acoustic network consisting of MIMO AUV's. It evaluates the average route FEP through the network.

A. *Transmission Protocol*

It is assumed that the network utilizes a reserve listen and go transmission protocol along the multihop route from the source to the destination [9]. The transmitter first senses the channel. It only begins the transmission if the channel is idle. If the channel is busy, it delays the transmission. A careful study in [9] found that the protocol is still vulnerable to interference for various distances between the transmitter and the interferers. Therefore, we consider a modification based on the inclusion of request to send (RTS) and clear to send (CTS) messages before the transmission phase. That is to say, the transmitter awaits the reception of the CTS message before commencing with packet transmission. This reduces the possibility of interference from other network transmissions. Nonetheless, interference may still occur. The interferers whose distance to the destination is greater than the distance between the source and the destination may contribute to the interference. Assuming constant p.s.d. S for all interferers, the interference can be described by

$$I(f) \approx \frac{cS}{A(d_{\mathrm{I}},f)} \tag{5}$$

where d_{I} is the distance between the destination and the interferers and c is a constant indicating the number of interferers (we let, $c = 6$). As there are multiple interferers, a Gaussian interference with p.s.d. $I(f)$, is considered. The signal to interference plus noise ratio (SINR) is shown in Figure 1 and Figure 2, when the distance between the source and the destination is $d = 1$ km and $d = 2$ km, respectively. The transmit p.s.d. is $S = 105$ dB re μPa per kHz. It can be seen that in both cases the SINR decreases as the distance to the interferers decreases from $d_{\mathrm{I}} = 2d$, to $d_{\mathrm{I}} = 1.75d$, and $d_{\mathrm{I}} = 1.5d$. In addition, it can be observed that the preferred operating frequency $f_o(d)$ is lower when the source and the destination are farther apart, and that it depends on the amount of interference.

B. *Mobility Model*

It is assumed that N AUV's are deployed over a network with circular area $\mathcal{A}$. The density of AUV's is $\rho = N/\mathcal{A}$. It is assumed that the network density is constant which means that AUV's neither enter nor leave the network. This could be a model for a network of AUV's surveying a specific area for environmental, scientific, and/or commercial objectives [10,11].

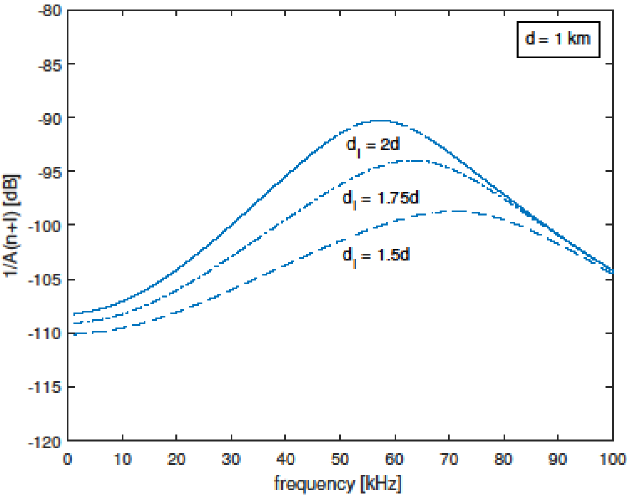

Fig. 1. SINR for $d = 1$ km.

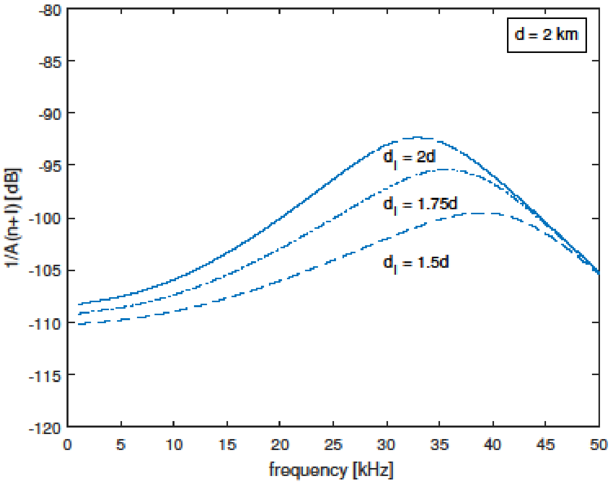

Fig. 2. SINR for $d = 2$ km.

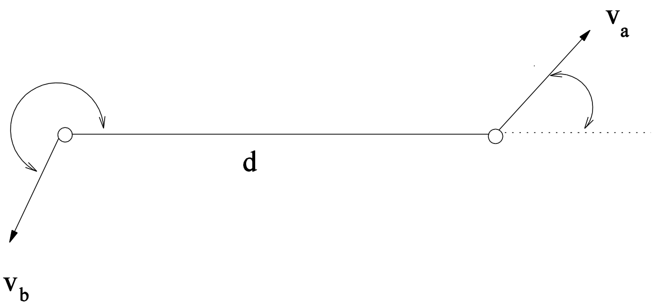

Fig. 3. AUV's: time $= t$.

As the direction persistent mobility model is considered, the direction and the speed of the AUV's are constant for the duration of the packet. The route's links are assumed to be independent with respect to the AUV's mobility. The AUV's mobility status at packet reception is independent from the mobility status at packet transmission on the route's next hop.

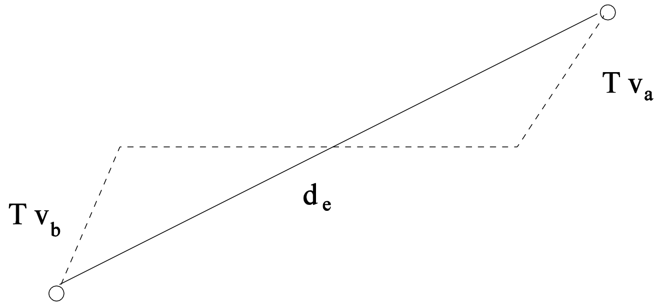

Fig. 4. AUV's: time $= t + T$.

The mobility of the AUV's is specified by the speed and the direction angle. The distance between AUV's at time t is d, as shown in Figure 3. AUV a moves with speed v_a at an angle θ_a (the angle between v_a and the horizontal axis). AUV b moves with speed v_b at an angle θ_b. At time $t + T$, as shown in Figure 4, the distance between the AUV's is [9]

$$d_e = (d^2 + T^2 u_1 - 2T^2 u_2 + 2dTu_3)^{1/2} \qquad (6)$$

where

$$\begin{aligned} u_1 &= v_a^2 + v_b^2, \\ u_2 &= v_a v_b \cos(\theta_a - \theta_b)\,, \\ u_3 &= v_a \cos(\theta_a) - v_b \cos(\theta_b)\,. \end{aligned} \qquad (7)$$

Note that $T = \frac{L}{R_b} + \frac{d}{c}$, where L is the number of bits per packet, R_b is the bit rate in bps, and $c = 1500$ m/s is the speed of sound underwater. The average distance between AUV's is given by $\bar{d} = \frac{d + d_e}{2}$.

C. *Average FEP Evaluation*

The AUV's use simple decode and forward relaying. The route FEP is

$$\mathrm{FEP}_{\mathrm{route}} = 1 - \prod_{i=1}^{n_h} \left(1 - p_{b_i}\right)^L \qquad (8)$$

where p_b denotes the bit error probability (BEP) for an AUV-to-AUV channel, and n_h denotes the number of hops of the multihop route.

Considering a large number of realizations over (v, θ), the ensemble averaged $\mathrm{FEP}_{\mathrm{route}}$ is

$$\overline{\mathrm{FEP}}_{\mathrm{route}} = \frac{\sum_{m=1}^{M} \mathrm{FEP}_{\mathrm{route}}}{M} \qquad (9)$$

which can be obtained by Monte Carlo simulation. In particular, the route FEP of a multihop route with an average number of hops, $\bar{n}_h = \sqrt{N/\pi}$ [9], is considered.

BPSK transmission is assumed [12]. Given Ricean fading model for the AUV-to-AUV channel [13,14], and perfect channel state information at the receiver, the BEP can be approximated as

$$p_b \lesssim \left(\frac{1+\mathcal{K}}{1+\mathcal{K}+\gamma(\bar{d},f)}\right)^{tr} \exp\left(-\frac{tr\mathcal{K}\gamma(\bar{d},f)}{1+\mathcal{K}+\gamma(\bar{d},f)}\right) \qquad (10)$$

where γ is the SINR. It is assumed that the Ricean fading parameter $\mathcal{K}$ is the same for all AUV-to-AUV links. It is assumed that the achieved transmit diversity gain is t and that the achieved receive diversity gain is r. The attenuation and noise are considered to be constant over the operational bandwidth, hence the SINR is

$$\gamma(\bar{d}, f_o) = \frac{P}{A(\bar{d}, f_o)\big(N(f_o) + I(f_o)\big)B}, \qquad (11)$$

where B is the bandwidth in kHz and P is the transmit power. This may approximate the narrow bandwidth performance or the sub-band performance of one carrier of an OFDM system.

IV. Numerical Results

We consider numerical examples that focus on the FEP of a multihop route with an average number of hops. The FEP is averaged over $M = 1000$ realizations. The area of the network is circular, where $\mathcal{A} = 1000\ \mathrm{km}^2$. Independent Ricean fading for each AUV-to-AUV link with $\mathcal{K} = 10$ is assumed. Fixed losses are neglected [4]. The bandwidth is $B = 4$ kHz. The frame size is $L = 1000$ bits. The bit rate is $R_b = 1$ kbps. It is assumed that all AUV's operate with the same transmit power level. All AUV's move at a speed of $v = 1$ m/s. Without the loss of generality, it is assumed that given the number of transmitters and receivers, full transmit and receive diversity in the MIMO AUV-to-AUV channel is achieved. The spreading factor is $\kappa = 1.5$, the shipping activity factor is $s = 0.5$, and the wind speed is $w = 0$.

Figure 3 shows the average route FEP when the AUV's have two transmitters and two receivers, in the presence of interference from other AUV's in the network. The transmit power is $P = 105$ dB re μPa. It can be observed that the route FEP strongly depends on the distance to the interferers. As the distance to the interferers decreases from $d_{\mathrm{I}} = 2d$ to $d_{\mathrm{I}} = 1.75d$, the average route FEP gets worse by approximately two orders of magnitude. For example, for $N = 700$, the $\overline{\mathrm{FEP}}_{\mathrm{route}} \approx 10^{-3}$ when the distance to the interferers is $d_{\mathrm{I}} = 2d$. However, when the distance to the interferers decreases to $d_{\mathrm{I}} = 1.75d$, the average route FEP increases to $\overline{\mathrm{FEP}}_{\mathrm{route}} \approx 10^{-1}$. Note that when the distance to the interferers is decreased further to $d_{\mathrm{I}} = 1.5d$, the network cannot achieve any decrease in the average route FEP, in the case of 2×2 MIMO full diversity links, for the given transmit power.

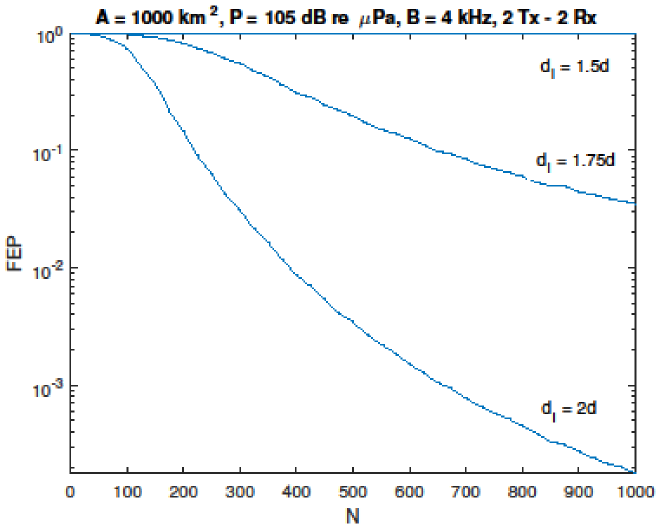

Fig. 5. Average route FEP for $\mathbf{2 \times 2}$ MIMO AUV-to-AUV links for various interferer distances.

Figure 4 depicts the average route FEP when the AUV's have three transmitters and three receivers, in the presence of interference from other AUV's in the network. The transmit power is $P = 105\,\mathrm{dB\ re\ \mu Pa}$. It can be observed that the trend is similar, that is, the average route FEP deteriorates as the distance to the interferers decreases. Of course, for each respective distance to the interferers, that is, $d_\mathrm{I} = 2d$, $d_\mathrm{I} = 1.75d$, and $d_\mathrm{I} = 1.5d$, the achieved average route FEP is significantly lower as compared to the 2×2 MIMO links, due to the increased diversity gain in the case of the 3×3 MIMO full diversity links.

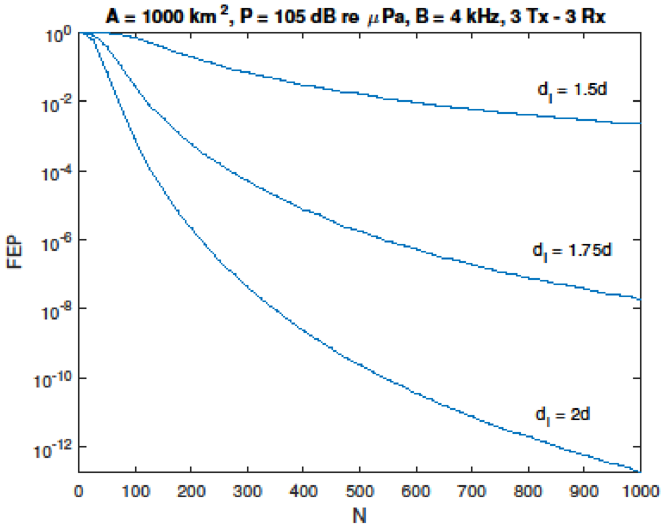

Fig. 6. Average route FEP for $\mathbf{3 \times 3}$ MIMO AUV-to-AUV links for various interferer distances.

V. Conclusions

The paper considered the average route FEP for mobile underwater acoustic networks consisting of AUV's with multiple transmitters and receivers. The direction persistent mobility model was considered. The multihop routes utilized the modified version of the reserve listen and go transmission protocol that included RTS and CTS messages before the transmission phase. Each MIMO AUV-to-AUV link was subject to frequency dependent path loss, independent Ricean fading and interference from other network transmissions. Numerical examples considered the average route FEP for different interferer distances and illustrated that the performance strongly depends on the distance to the interferers. An increase in the number of transmitters and receivers on each MIMO AUV-to-AUV link, that is, an increase in the diversity gain, resulted in an improved performance and an increased robustness to interference.

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