Distortion Analysis of Underwater Acoustic Mobile Networks

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stract—The paper considers the average route distortion of mobile underwater acoustic networks. The network is composed of autonomous underwater vehicles (AUV's) that form multihop routes through the network. The mobility model is direction persistent. The average route distortion is evaluated in the context of an independent identically distributed (i.i.d.) Gaussian source and single description coding. Each AUV-to-AUV channel experiences frequency dependent path loss, Ricean fading, and interference. Numerical examples illustrate the distortion performance.

I. INTRODUCTION

There have recently been a number of studies of underwater acoustic networks [1]–[5]. The analysis, design and evaluation of multiaccess protocols for underwater acoustic networks has been considered in [6], [7]. An energy efficient multiaccess protocol for bursty data has been proposed in [8]. The throughput efficiency of linear networks has been considered in [9], while route selection for linear networks based on frequency selection and relay locations has been investigated in [10]. Localization based routing has been the focus of [11]. A survey of routing related issues and associated protocols can be found in [12].

These studies have been motivated in part by the need to perform sensing and surveying of underwater areas for a variety of reasons, including environmental, scientific, commercial, etc. The potential applications include general oceanographic needs, observations of marine biology and/or fisheries, environmental (pollution) monitoring, monitoring of off shore oil and gas fields, submarine detection etc. Networks consisting of AUV's that offer mobility may represent a particularly appealing choice in this regard [13].

Considering the sensing related tasks, that in addition to sensing, include computing, transmission, and reception, it is transmission that imposes the most significant strain on the energy consumption. In underwater acoustic communications, the attenuation (path loss) experienced by the transmitted signal depends not only on the transmitter-receiver distance, but also on the carrier operating frequency. The appropriate choice of the carrier operating frequency is crucial for efficient underwater communications. In addition, as underwater communication is based on the transmission of acoustic signals, the low speed at which sound propagates underwater results in significant transmission delays.

The paper considers the distortion performance of mobile underwater acoustic networks. An i.i.d. Gaussian source and a single description coder are considered. The focus is on the evaluation of the end-to-end distortion across a multihop route of AUV's. Each AUV-to-AUV link experiences frequency dependent path loss and independent Ricean fading. AUV's forward the packets using simple demodulate and forward relaying. The mobility model is direction persistent [14]. The multihop routing is facilitated by a modified version of the reserve listen and go transmission protocol. The modification is based on the introduction of a request to send (RTS) and clear to send (CTS) messages before the transmission phase, in order to alleviate the impact of interference from other network transmissions.

The organization of the paper is as follows. The model for underwater acoustic propagation is outlined in Section II. The average route distortion performance, in the context of the direction persistent mobility model, is discussed in Section III. Numerical examples are included in Section IV. Conclusion is given in Section V.

II. UNDERWATER ACOUSTIC PROPAGATION

Underwater acoustic communication experiences attenuation, i.e., path loss, for a signal transmitted on frequency *f*, that is characterized by, $A(d,f) = A_0 d^{\kappa} a(f)^{d}$, where A_0 is a unit-normalization constant that incorporates fixed losses, *d* is the distance between AUV's, κ is the spreading factor ($1 \leq \kappa \leq 2$), and $a(f)$ is the absorption coefficient, illustrated in Figure 1.

The overal ocean ambient noise is comprised of: turbulence, shipping, waves and thermal noise, described by Gaussian statistics and continuous power spectral densities (p.s.d.'s) in dB re μPa per Hz for the frequency in kHz [15]:

$$
\begin{aligned}
10 \log N_{\mathrm{t}}(f) &= 17 - 30 \log f, \\
10 \log N_{\mathrm{s}}(f) &= 40 + 20(s - 0.5) + 26 \log f \\
&\quad -60 \log(f + 0.03), \\
10 \log N_{\mathrm{w}}(f) &= 50 + 7.5\sqrt{w} + 20 \log f \\
&\quad -40 \log(f + 0.4), \\
10 \log N_{\mathrm{th}}(f) &= -15 + 20 \log f,
\end{aligned} \tag{1}
$$

Fig. 1. The absorption coefficient $a(f)$ given in dB/km for the signal frequency f in kHz: $10 \log a(f) = \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + \frac{2.75 f^2}{10^4} + 0.003$ [15].

where *s* is the shipping activity factor and *w* is the wind speed in m/s. The p.s.d. of the overall ocean ambient noise is simply $N(f) = N_{\mathrm{t}}(f) + N_{\mathrm{s}}(f) + N_{\mathrm{w}}(f) + N_{\mathrm{th}}(f)$.

III. DISTORTION ANALYSIS

The section analyzes the average route distortion, in the context of the direction persistent mobility model, for an i.i.d.

Gaussian source and a single description coder.

A. Mobility Model

It is assumed that N AUV's are deployed over a network with circular area A. The density of AUV's is $\rho = \frac{N}{A}$ and it remains constant meaning that AUV's do not enter and do not leave the network. This could be a model for a network of AUV's surveying a given area.

The direction persistent mobility model assumes that the direction and the speed of AUV's are constant for the duration of the packet. Note that route's links are independent considering the AUV's mobility. That is, AUV's mobility status at packet reception is independent from the mobility status at packet transmission on the next hop of the route.

The AUV's mobility is described by its speed and direction angle. The distance between AUV's at time t is d, as illustrated in Figure 2. AUV a is moving with speed v_a at an angle θ_a (the angle between v_a and the horizontal axis). AUV b is moving with speed v_b at an angle θ_b.

At time $t+T$, as illustrated in Figure 3, the distance between

$$d_e = \sqrt{d^2 + T^2 u_1 - 2T^2 u_2 + 2dTu_3} \tag{2}$$

where

$$u_1 = v_a^2 + v_b^2, \; u_2 = v_a v_b \cos(\theta_a - \theta_b)$$
$$u_3 = v_a \cos(\theta_a) - v_b \cos(\theta_b). \tag{3}$$

AUV's a and b is [14]

v,

T ,

d

Fig. 2. The AUV's: time = *t*.

The time interval T is the sum of the packet duration and packet propagation time, i.e., $T = \frac{L}{R_b} + \frac{d}{c}$, where L is the number of bits per packet, R_b is the bit rate, and c = 1500 m/s is the speed of sound underwater. The average distance between AUV's a and b is $\overline{d} = \frac{d+d_e}{2}$.

B. Average Route Distortion

The AUV's utilize a simple demodulate and forward relaying strategy. The route frame error probability (FEP) is $\mathrm{FEP}_{\mathrm{route}} = 1 - \prod_{i=1}^{n_h} (1 - p_{b_i})^L$, where p_b is the bit error probability (BEP) for an AUV-to-AUV channel and n_h is the number of hops in the multihop route. The route distortion is [16]

$$D_{\mathrm{route}} = (1 - \mathrm{FEP}_{\mathrm{route}})D + \mathrm{FEP}_{\mathrm{route}}\sigma^2, \quad (4)$$

where $D = \sigma^2 2^{-2R}$ is the distortion for a sequence of i.i.d. Gausian random variables with variance σ^2, encoded at bit rate R by an optimal source coder [17]. Considering a large number of realizations over (v,θ), the ensemble average route distortion is

$$\overline{D}_{\mathrm{route}} = \frac{\sum_{m=1}^{M} D_{\mathrm{route}}}{M} \quad (5)$$

which can be evaluated through Monte Carlo simulation. Note that a multihop route with an average number of hops $n_h = \sqrt{\frac{N}{\pi}}$ is considered [14].

C. Transmission Protocol

The tranmission protocol along the multihop route from the source to the destination is based on the reserve listen and go transmission protocol [14]. The AUV first senses the channel.

It begins the transmission only if the channel is idle. If the channel is busy, it delays the transmission. Nonetheless, a detailed graphical study in [14] found that the protocol in its original format is still vulnerable to interference for a range of interferers at different distances to the destination. Therefore, we propose a modified version of the reserve listen and go protocol that includes an exchange of request to send (RTS) and clear to send (CTS) messages before the packet transmission phase. In other words, the AUV waits for a CTS message from the destination before transmitting the packet. This reduces the possibility of interference from neighboring AUV's. Of course, the transmission may still be vulnerable to interference, especially from AUV's whose distance to the destination is greater than the source-destination distance. Under the assumption of a constant p.s.d. S for all transmitting AUV's, the overall interference is

$$I(f) \approx \frac{cS}{A(d_{\mathrm{I}}, f)} \qquad (6)$$

where d_I is the distance between the destination and the interferers and c is a constant that indicates how many AUV's contribute to the interference. Without the loss of generality, we let $c = 6$. Given that there are a number of AUV's that contribute to the interference, a Gaussian interference with p.s.d. $I(f)$, is assumed. Figure 4 illustrates the signal to interference plus noise ratio (SINR) when the sourcedestination distance is $d = 1$ km and the transmit power spectral density is $S = 155$ dB re μPa per kHz. We observe a decrease in the SINR, as the distance to the interferers reduces from $d_I = 2d$, to $d_I = 1.75d$, and $d_I = 1.5d$.

Fig. 4. SINR for $d = 1$ km.

Under the assumption of perfect channel state information at the receiving AUV and flat Ricean fading for the channel between two AUV's [18], [19], the BEP is [20]

$$p_b \leq \left(\frac{1+\mathcal{K}}{1+\mathcal{K}+\gamma(\bar{d},f)}\right)\exp\left(-\frac{\mathcal{K}\gamma(\bar{d},f)}{1+\mathcal{K}+\gamma(\bar{d},f)}\right) \quad (7)$$

where γ is the SINR. The SINR evaluated at $f_o(d)$ is

$$\gamma(\bar{d},f_o) = \frac{P}{A(\bar{d},f_o)(N(f_o)+I(f_o))B} \quad (8)$$

where P is the transmission power and B is the bandwidth in kHz. For OFDM systems [21], this could be the sub-band of a carrier. The performance on that carrier would be indicated

by $f_o(d)$. The performance on the other carriers would depend on their respective operating frequency.

IV. NUMERICAL RESULTS

Numerical examples are presented that illustrate the distortion performance of a mobile underwater acoustic network. The focus is on the end-to-end distortion of a multihop route with an average number of hops. It is averaged over $M = 1000$ realizations. The circular network area is A = 1000 km^2. The variance of the i.i.d. Gaussian random variables is $\sigma^2 = 1$. Independent Ricean fading for each AUV-to-AUV channel with K = 10 is assumed. 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. The AUV's move at a speed of $v = 1$ m/s. Note that $\kappa = 1.5$, $s = 0.5$ and $w = 0$ m/s.

Figure 5 presents the average route distortion when there is interference from other AUV's in the network. The transmission power is $P = 145$ dB re μPa. The rate is $R = 2$ bits per description, hence $D = 6.25 \times 10^{-2}$. We observe that when the interferers are at a distance $d_I = 2d$, the route distortion is close to optimum, $D = 6.25 \times 10^{-2}$. As the distance to the interferers reduces to $d_I = 1.75d$, the route distortion still remains close to optimum. There is, nonetheless, some loss in performance and the impact of interference is more pronounced as the number of AUV's in the network increases. However, as the distance to the interferers reduces further to $d_I = 1.5d$, the interference has a deleterious impact on the route distortion.

0 A = 1000 km², P = 145 dB re μPa, B = 4 kHz

Fig. 5. Distortion for $R = 2$ bits per description.

Similarly, Figure 6 presents the average route distortion in the presence of interference from other AUV's in the network. In this case, the rate is $R = 4$ bits per description, hence $D = 3.9 \times 10^{-3}$. The transmission power is $P = 155$ dB re μPa. When the distance to the interferers is $d_I = 2d$, the route distortion is close to optimum, $D = 3.9 \times 10^{-3}$. When the distance to the interferers reduces to $d_I = 1.75d$, we observe a graceful degradation in the route distortion. The degradation in the route distortion is greater as the number of AUV's in the network increases, as that is when the interference impact becomes more pronounced. Further reduction in the distance to the interferers to $d_I = 1.5d$, has a detrimental impact as the route distortion performance deteriorates by an order of magnitude.

0 A = 1000 km², P = 155 dB re μPa, B = 4 kHz

Fig. 6. Distortion for $R = 4$ bits per description.

V. CONCLUSIONS

The paper analyzed the distortion of mobile underwater acoustic networks for the case of an independent identically distributed (i.i.d.) Gaussian source and single description coding. The direction persistent mobility model was considered. The AUV's utilized a simple demodulate and forward relaying strategy. The average route distortion was investigated in the context of the modified reserve listen and go transmission protocol that included an exchange of RTS/CTS messages before transmission. The modification was introduced in order to alleviate the impact of network interference. Numerical examples illustrated that the interference impact strongly depends on distance between the destination and the interferers.

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