DISTORTION PERFORMANCE OF UNDERWATER ACOUSTIC MIMO MOBILE NETWORKS

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Abstract. *The paper considers the distortion performance of underwater acoustic MIMO mobile networks for an independent identically distributed (i.i.d.) Gaussian source. Such networks are appealing due to the need to perform sensing and surveying of underwater areas. Underwater acoustic communication is subject to attenuation, or path loss, that depends not only on the distance between the transmitter and the receiver, but also on the operating carrier frequency. Each transmission experiences frequency dependent path loss and fading. The information is conveyed across the network by transmitting it from one mobile to another across the multihop route. The mobility is based on the direction persistent mobility model. Numerical examples are presented to illustrate the distortion performance of the underwater acoustic MIMO mobile network.*

Keywords: *underwater acoustic, mobility fading, distortion*

1. INTRODUCTION

The field of underwater acoustic networks has been the focus of a number of studies recently [1–4]. The motivation for these studies has been the need to perform sensing and surveying of underwater areas. The reasons are varied and include environmental, scientific and commercial needs. In particular, there are general oceanographic needs [5], observations of marine biology and/or fisheries [6], environmental, including pollution monitoring [7], monitoring of off shore oil and gas fields [8], submarine detection, and so on. Underwater mobile networks represent an appealing choice in this context [9]. Related to the sensing task are additional tasks, such as, computing, transmission and reception of information. The transmission task is in particular strenuous since underwater acoustic communication experiences attenuation, or path loss, that depends not only on the distance between the transmitter and the receiver, but also on the operating carrier frequency [10]. This means that the careful choice of the operating carrier frequency is of great importance for efficient underwater communications. In addition, as the attenuation increases with the increase in the carrier frequency, it effectively limits the range of choices for the operating carrier frequencies. Moreover, as underwater communication is established by the transmission of acoustic signals, the low speed with which sound propagates underwater introduces transmission delays.

The paper focuses on the average distortion performance of underwater acoustic MIMO mobile networks. The multihop routing is done by utilizing a modified version of the reserve listen and go transmission protocol [11] which includes request-to-send (RTS) and clear-to-send (CTS) messages [12]. The mobility model is direction persistent. Each mobile-to-mobile transmission is subject to frequency dependent path loss and independent Ricean fading.

The paper is organized as follows. The underwater acoustic propagation is highlighted in Section 2. The average distortion performance of a multihop route for the MIMO mobile underwater acoustic network is evaluated in Section 3. Section 4 presents numerical examples. Section 5 concludes the paper.

2. UNDERWATER ACOUSTIC PROPAGATION

Underwater acoustic transmission is subject to attenuation, that is, path loss. For a signal that is transmitted on a frequency, f, the attenuation is [10]

$$A(d,f) = A_0 d^k a(f)^d \qquad (1)$$

where A_0 is a unit-normalizing constant that includes fixed losses, d is the distance between the transmitter and the receiver, $a(f)$ is the absorption coefficient, and k is the spreading factor. For practical spreading $k = 1.5$,

$(1 \leq k \leq 2)$. The absorption coefficient is given by Thorp's formula that provides $a(f)$ in dB/km for f in kHz as [10]

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

This formula, appropriate for frequencies above few hundred Hz, is illustrated in Figure 1.

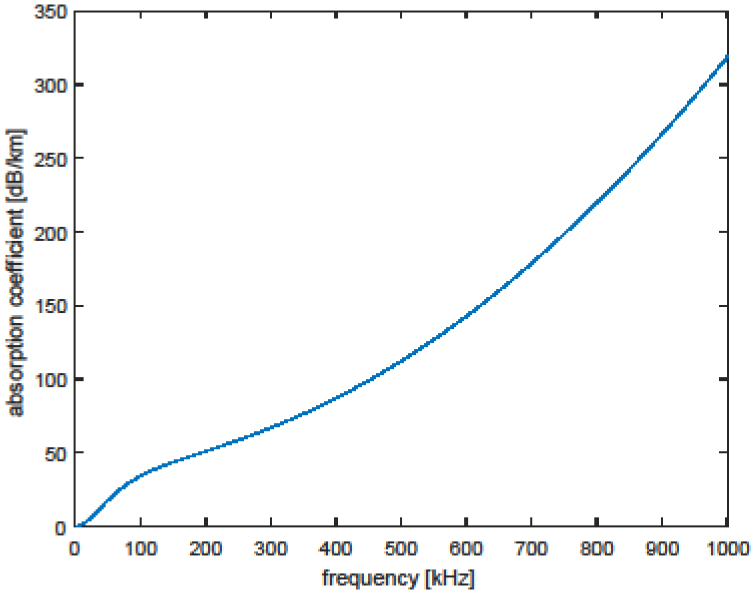

Figure 1 The absorption coefficient a(f)

The ambient ocean noise consists of: turbulence, shipping, waves and thermal noise. It can be described by Gaussian statistics and continuous power spectral density (p.s.d.). The overall p.s.d. of the ocean ambient noise is [10]

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f). \tag{3}$$

3. DISTORTION PERFORMANCE

3.1 Transmission Protocol

The transmission protocol that facilitates the transmission of information along the multihop route from the source mobile to the receiving mobile [11–16] is based on the modified version of the reserve listen and go protocol [12]. According to the reserve listen and go protocol, the source mobile first senses the channel, and starts the transmission only if the channel is idle. If the channel is busy, the transmission is delayed. A careful graphical study, nonetheless, showed that the reserve listen and go protocol is still vulnerable to interference for a range of different distances between the interferers and the receiving mobile [11]. The reserve listen and go protocol has therefore been modified to include an exchange of request to send (RTS) and clear to send (CTS) messages before the start of the transmission [12]. The transmission may still be subject to interference if the distance from the interferers to the receiving mobile is greater than the distance between the source mobile and the receiving mobile [11–16]. Assuming constant p.s.d. S for all interferers, the interference can be described by

$$I(f) \approx \frac{cS}{A(d_I,f)} \tag{4}$$

where d_I is the distance between the receiving mobile and the interferers and c is a constant indicating the number of interferers (we let, $c = 6$). Due to the multiple interferers, the interference is modeled as Gaussian with p.s.d. $I(f)$.

3.2 Mobility Model

We consider N mobiles within a network with a circular area $\mathcal{A}$. The density of mobiles is $\rho = N/\mathcal{A}$. The mobiles do not enter or leave the network. The network density is therefore constant. The mobility is described by the mobile speeds and the direction angles. The direction persistent mobility model considers that the direction and the speed of the mobiles are constant for a certain duration, T, and vary independently from one hop to another [11]. In other words, the mobiles mobility status at packet reception is independent from the mobility status at packet transmission on the next hop along the route. Without the loss of generality, we consider the scenario where the distance between the mobiles at time t is d as illustrated in Figure 2. Mobile a moves with speed v_a at an angle θ_a. Mobile b moves with speed v_b at an angle θ_b. At time $t + T$, as illustrated in Figure 3, the distance between the mobiles is [11]

$$d_e = \sqrt{d^2 + T^2(v_a^2 + v_b^2) - 2T^2 v_a v_b \cos(\theta_a - \theta_b) + 2dT[v_a \cos(\theta_a) - v_b \cos(\theta_b)]} \tag{5}$$

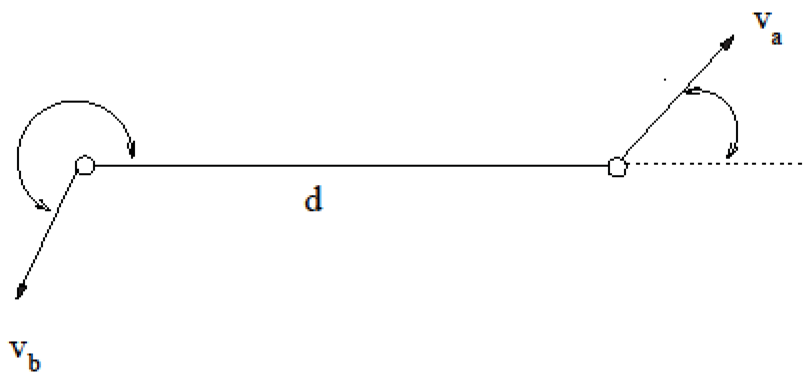

Figure 2 Mobiles: time = t

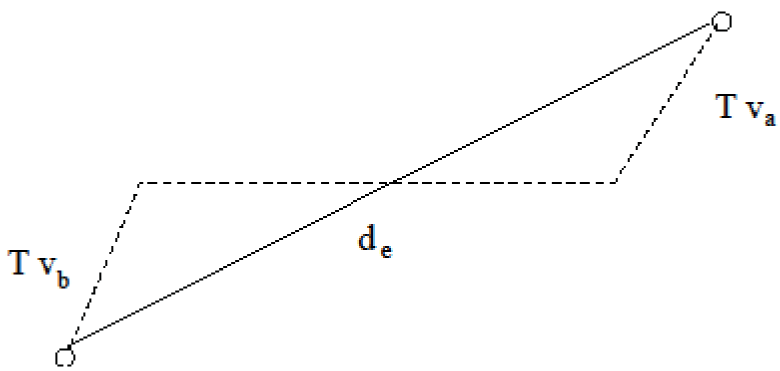

Figure 3 Mobiles: time = t + T

Note that $T = L/R_b + d/c$, where L is the number of bits per packet, R_b is the bit rate in bits per second, and $c = 1500$ m/s is the speed of sound underwater. The average distance between mobiles is $\bar{d} = (d + d_e)/2$.

3.3 Average Route Distortion

The mobiles use a decode and forward relaying strategy. The route frame error probability (FEP) is $\text{FEP}_{\text{route}} = 1 - \prod_{i=1}^{n_h}\left(1 - p_{b_i}\right)^L$, where p_b is the bit error probability (BEP) for a mobile-to-mobile link and n_h is the number of hops in the multihop route. For a large number of realizations over (v, θ), the ensemble average route frame error probability which can be evaluated via Monte Carlo simulation is $\overline{\text{FEP}}_{\text{route}} = \frac{1}{M}\sum_{m=1}^{M} \text{FEP}_{\text{route}}$. The route distortion is

$$D_{\text{route}} = (1 - \overline{\text{FEP}}_{\text{route}})D + \overline{\text{FEP}}_{\text{route}}\sigma^2 \quad (6)$$

where $D = \sigma^2 2^{-2R}$ is the distortion for a sequence of i.i.d. Gaussian random variables with variance σ^2 encoded at a bit rate R by an optimal source coder [17]. The multihop route has an average number of hops $\bar{n}_h = \sqrt{N/\pi}$ [11].

Given perfect channel state information at the receiving mobile and flat Ricean fading for the mobile-to-mobile channel [18], the BEP is [19, 20]

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

where γ is the signal to interference plus noise ratio (SINR). The Ricean fading parameter $\mathcal{K}$ is the same for all mobile-to-mobile links. The achieved transmit diversity gain is t and the achieved receive diversity gain is r. The attenuation and noise are considered to be constant over the operational bandwidth, therefore for transmit power P and bandwidth B in kHz, the SINR is

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

4. NUMERICAL EXAMPLES

We consider numerical examples that illustrate the average distortion performance of a multihop route with an average number of hops. It is assumed that the variance of the i.i.d. Gaussian random variables is $\sigma^2 = 1$. The distortion is averaged over $M = 1000$ realizations. The network area is $\mathcal{A} = 1000\ \text{km}^2$. Independent Ricean fading for each MIMO mobile-to-mobile link with $\mathcal{K} = 10$ is assumed. The bandwidth is $B = 4$ kHz. The frame size is $L = 1000$ bits. The bit rate is $R_b = 1$ kbps. The mobiles move at a speed of $v = 1\ \text{m/s}$ and operate with the same transmit power level. It is also assumed that given the number of transmitters and receivers, full transmit and receive diversity in the MIMO mobile-to-mobile channel is achieved. Fixed losses are neglected. The spreading factor is $\kappa = 1.5$, the shipping activity factor is $s = 0.5$, and the wind speed is $w = 0$.

Figure 4 presents the average route distortion for 2×2 MIMO mobile-to-mobile link. The transmit power is $P = 110$ dB re μPa. The rate is $R = 4$ bits per description, that is, $D = 6.25 \times 10^{-2}$. In the case when the interferers are at a distance $d_\text{I} = 2d$, the average route distortion is close to optimum. When the distance to the interferers decreases to $d_\text{I} = 1.75d$, there is a graceful degradation in the average route distortion performance. As the distance to the interferers decreases to $d_\text{I} = 1.5d$, there is a significant degradation in the average route distortion performance.

Figure 5 similarly illustrates the average route distortion for 3×3 MIMO mobile-to-mobile link. The transmit power is reduced to $P = 100$ dB re μPa due to the higher degree of diversity. The rate is still $R = 4$ bits per description, that is, $D = 6.25 \times 10^{-2}$. In the case when the interferers are at a distance $d_\text{I} = 2d$, the average route distortion is close to optimum. When the distance to the interferers decreases to $d_\text{I} = 1.75d$, there is a graceful degradation in the average route distortion performance. As the distance to the interferers decreases to $d_\text{I} = 1.5d$, again a significant degradation in the average route distortion performance can be observed

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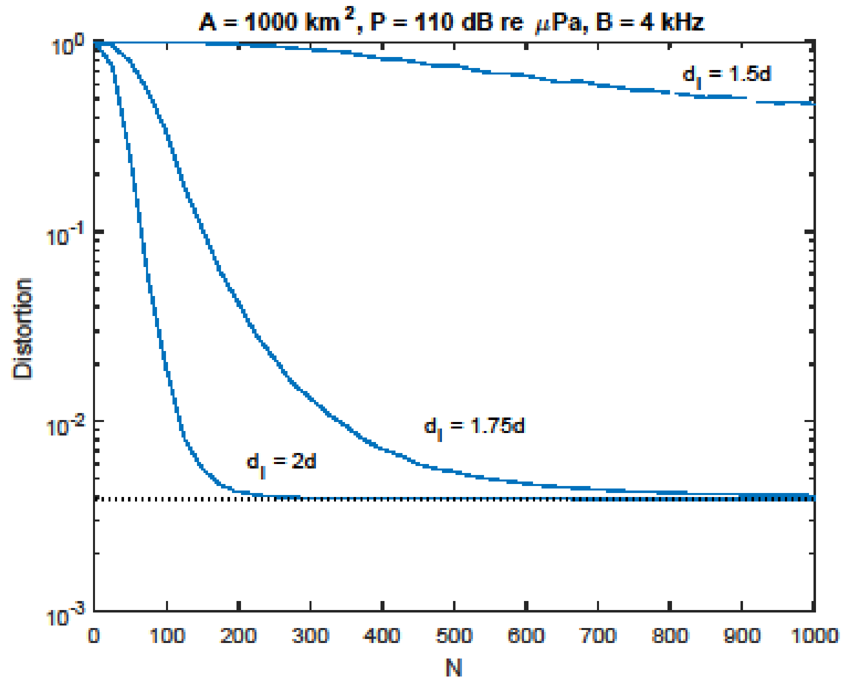

Figure 4 Distortion 2X2 MIMO mobile channels for R=4 bits per description

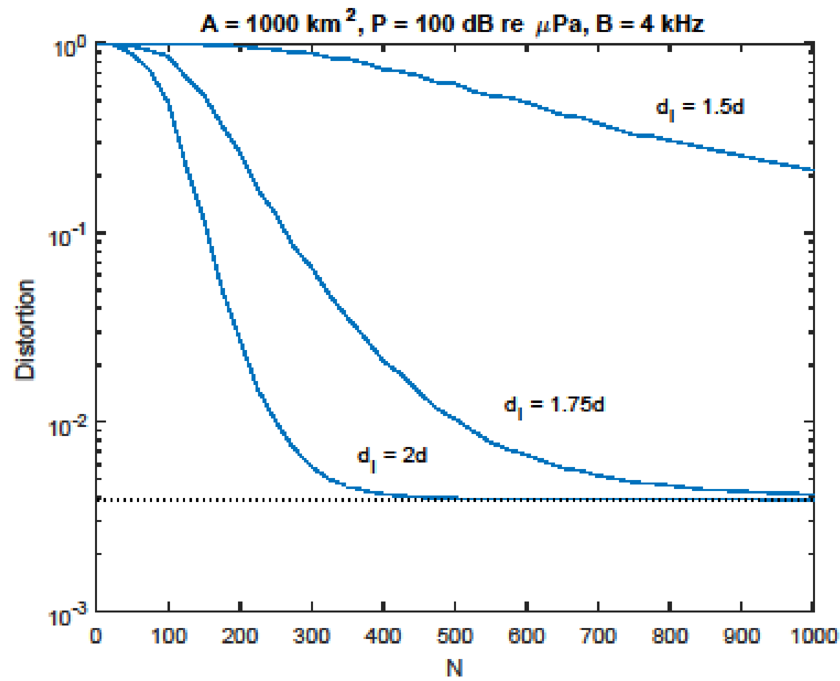

Figure 5 Distortion for 3X3 MIMO mobile channels for R=4 bits per description

5. CONCLUSION

The paper evaluated the average distortion performance of underwater acoustic MIMO mobile networks in the context of a direction persistent mobility model and the modified reserve listen and go transmission protocol that incorporated and exchange of RTS/CTS messages before the start of the transmission. The mobiles used decode and forward relaying. An i.i.d. Gaussian source was considered. The average distortion performance was illustrated through numerical examples. It was found that the impact of interference strongly depends on the distance between the receiving mobile and the interferers. The average route distortion performance deteriorates as the distance to the interferers decreases. On the other hand, the increase in the mobile's number of transmitters and receivers lead to performance improvements due to the increased diversity level.

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