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An efficient method to measure reliability of underwater acoustic communication links

Roee Diamant[a,*], Yaakov Bucris[b], Arie Feuer[b]

[a] *Department of Marine Technology, University of Haifa, Haifa, Israel*
[b] *Department of Electrical Engineering, Technion, Haifa, Israel*

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Abstract

We consider the problem of evaluating the reliability of underwater acoustic communication (UWAC) systems. Reliability is a requirement for any communication system and is often defined as the probability to achieve a target bit error rate. Evaluation of system reliability is often performed empirically by conducting a large number of measurements. However, for UWAC, where experiments are expensive and time-consuming, not much data is available to perform such a reliability check. Based on the assumption that the long delay spread is the dominant characteristic of the underwater acoustic channel and for a given channel model, we offer a relaxed practical approach to evaluate the reliability of an UWAC system. As a test case, we show reliability results for the multiple input multiple output (MIMO) code division multiple access (CDMA) communication system.

Keywords: Underwater acoustic communication (UWAC); Reliability; Signal-to-interference-plus-noise ratio (SINR).

1. Introduction

The oceans with their diverse biology systems, vast energy resources, and climate and history records of our planet, have always attracted researchers and industries. In the last decade, ocean exploration has considerably increased through the use of ocean observation systems, autonomous underwater vehicles (AUVs), and fixed or mobile sensor networks. These submerged devices need to report the collective data back to base stations or to share information in the setting of a wireless communication network. Wireless communication underwater is usually established using acoustic transducers since radio frequency communication is only possible for very short distances underwater. Underwater acoustic communication (UWAC) can fulfill the needs of a multitude of underwater applications, including: oceanographic data collection, warning systems for natural disasters (e.g., seismic and tsunami monitoring), ecological applications (e.g., pollution, water quality and biological monitoring), military underwater surveillance, assisted navigation, industrial applications (offshore exploration), to name just a few [2]. For example, in offshore engineering applications, underwater sensors can measure and report parameters such as foundation strength and mooring tensions to monitor the structural health of deepwater mooring systems.

The fundamental key aspects of UWAC includes significant multipath interference, strong ambient noise, time-varying fading channel impulse response, and station-dependent power attenuation [1]. In terms of communication performance, these aspects reflect on *link reliability*. Reliability of communication reflect on the outage capacity of the communication link, and directly affect the probability of packet error. In the context of networks, link reliability is often referred to as availability and is the basic information required to obtain the network topology, which in turn determines the network energy consumption, throughput, and transmission delay [7]. For mobile AUVs and for drifting devices (e.g., boys) where nodes are in constant motion, achieving reliable

* Corresponding author.
E-mail address: roeed@univ.haifa.ac.il (R. Diamant).

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UWAC is especially difficult [6]. In fact, it was proven that reliable packet to surface stations is much more challenging than RF communication even in terrestrial networks t [3].

As reliability plays an important role in any communication system, many works considered ways to obtain reliable communication links. The available literature to increase reliability spans through almost all the network stack layers. This includes multiple-path channel coding [13], tradeoffs between re-transmissions and energy expenditure [9], link-dependent packet length and transmission rates [14], as well as dynamic hop-by-hop routing protocols to cope with the time-varying link availability [9] and acknowledgment management [3].

In the absence of proper definition for reliability in UWAC, the communication performance is usually measured in terms of the packet error probability for a given signal-to-interference-plus-noise ratio (SINR). While the error probability of individual communication links significantly affects the overall network performance [13], it only reflects an instantaneous notion of the link reliability. This is because, especially in the underwater acoustic channel, the error probability if fast time-varying. As a result, the error probability cannot reflect on target quality of service. Instead, motivated by the measure of outage capacity, we offer to measure reliability in terms of the probability to achieve a certain packet error rate in the link. Unfortunately, direct calculation of such quality measure requires a large amount of data collected from the channel, either from field trails or from numerical simulations. However, in UWAC, where sea trials are expensive and time consuming and simulators are often site specific, reliability evaluation is a complex task.

1.1. Key idea

We offer an analytical relaxation to evaluate the system reliability. Our method for evaluating the system reliability is offered due to the lack of sufficient database for packet error rate in the underwater acoustic channel. Rather than collecting statistical information, we offer to evaluate link reliability based on the distribution of the underwater acoustic channel's dominant factor, namely, the multipath. For underwater acoustic communication, the multipath is observed in terms of the SINR. The SINR is determined by channel and system characteristics, e.g., signal bandwidth, channel noise level, channel impulse response, modulation type, etc. (Chapter 13 in [5]). Assuming time-invariant transmission power, it is common practice to relate changes in the SINR to time-varying channel path loss (Chapter 9 in [11]). Hence, we associate system reliability with the temporal and spatial fluctuations of the channel. Consequently, we formulate the system reliability as the connection between the SINR and the error probability, and suggest a relaxation to evaluate this relation analytically.

Using our method, it is no longer required to measure the channel parameters such as the delay spread, power attenuation, disparity, etc., nor it is required to measure the packet error rate. Both objectives require great efforts. Instead, only the distribution parameters of the SINR are required. As the latter can be estimated theoretically (e.g., using a bathymetric map and a numerical attenuation model such as the Bellhop [10]), the advantage in our approach is that it provides an efficient tool to pre-assess the expected link reliability. To show this effectiveness, we demonstrate the use of our method to evaluate the link reliability of the complex binary shift keying (BPSK) modulation scheme with a multiple input multiple output (MIMO) code division multiple access (CDMA) communication system.

1.2. Scope

Our work is analytical by nature. As such, it is independent of specific channel environments but rather builds on top of an estimate of the channel characteristics, and specifically on the distribution parameters of the SINR. This allows us to calculate the link reliability exactly without the need for simulations. The advantage is in using the suggested measure for different kinds of channel configurations. We therefore confine the scope of the paper to analytical analysis and avoid the use of emulated or measured channels.

The remainder of this paper is organized as follows. In Section 2, we formalize system reliability and demonstrate the model for BSPK-CDMA MIMO communication system. In Section 3, we present and demonstrate our approach. Finally, conclusions are offered in Section 4.

2. System reliability

2.1. Formalization of system reliability

Denote $P_{\text{error, req}}$ as the target error probability of the communication system and $P_{\text{error,act}}$ as the actual one. We define reliability as

$$P_{\text{reliab}} = P_{\text{r}}(P_{\text{error,act}} \leq P_{\text{error,req}}), \quad (1)$$

namely, the probability that the actual performance is better or identical to the desired performance. By (1), the cumulative density function (CDF) of $P_{\text{error,act}}$ is needed in order to calculate reliability. However, the evaluation of such CDF requires large amount of measurements which for UWAC are hard to acquire.

Under the assumption that the SINR is the dominant factor in the determination of the error probability, we model

$$P_{\text{error,act}} = f(\text{SINR}), \quad (2)$$

where $f(\cdot)$ is a monotonically decreasing function, determined by the structure off the transmitter and the receiver. We consider the SINR as a random variable which depends on the channel coefficients. Then, (1) is expressed as

$$P_{\text{reliab}} = P_r(\text{SINR} \geq T_{\text{h}}), \quad (3)$$

where $T_{\text{h}} = f^{-1}(P_{\text{error,req}})$. We note that (3) assumes time-invariant SINR. In cases where the SINR is time-varying (i.e., the channel is time-varying during one communication session), P_{reliab} in (3) is also time varying and reliability should be determined as $E[P_{\text{reliab}}]$.

In the following, we develop expression for the system reliability. As a test case, we consider a BPSK-MIMO communication system.

2.2. Reliability measure for BPSK-MIMO

Consider a BPSK communication system and define $s(t)$, $d(i)$, $h(t)$ and $e(t)$ as the transmitted signal (assumed to be zero outside the interval $[0, T_s))$, the ith information bit, the channel impulse response, and the channel ambient noise, respectively. The received signal is expressed by $r(t) = \sum_n d_n s(t - nT_s) * h(t) + e(t)$, where $*$ is the convolution operator. At the output of the matched filter, we have $I(t) = s(-t) * \left(\sum_n d_n s(t - nT_s) * h(t) + e(t)\right)$. After sampling,

$$I[i] = I(iT_s) = \left(\sum_{n=0}^{n=N-1} d_i s(-t) * s(t - nT_s) * h(t)\right)_{t=iT_s} + (s(-t) * e(t))_{t=iT_s}, \quad (4)$$

where N is the number of received paths due to the reflections from the channel surfaces [5]. The elements in (4) for which $n > 0$ are ISI, and we express (4) as

$$I[i] = d_i \cdot \varepsilon + n_{\mathrm{ISI}}[i] + n_{\mathrm{noise}}[i], \quad (5)$$

where

$$\varepsilon = \int_0^{T_s} (s(t))^2 dt$$

is the symbol energy,

$$n_{\mathrm{noise}}[i] = (s(-t) * e(t))_{t=iT_s}$$

is the noise contribution and $n_{\mathrm{ISI}}[i]$ is the ISI, which for simplicity is assumed to be i.i.d Gaussian variable.

We consider maximum likelihood (ML) decoder for the estimation of d_i. Then, assuming $d_i = \pm 1$ with equal probabilities, the error probability is upper bounded by (Chapter 5 in [11])

$$P_{\mathrm{error,act}} \le P_r(\varepsilon + n_{\mathrm{ISI}}[i] + n_{\mathrm{noise}}[i] < 0 | d_i = 1) = Q\left(\sqrt{\frac{\varepsilon}{N_0/2 + N_{\mathrm{ISI}}}}\right), \quad (6)$$

where $Q(\cdot)$ is the tail probability of the standard normal distribution (Chapter 5 in [11]), and $N_0/2$ and N_{ISI} are the power spectral densities of the channel noise and the variance of n_{ISI}, respectively. Since

$$\frac{\varepsilon}{N_0/2 + N_{\mathrm{ISI}}} = \mathrm{SINR},$$

we have

$$f(\mathrm{SINR}) = Q(\mathrm{SINR}).$$

Moreover, we evaluate T_h by expressing

$$P_{\mathrm{error,req}} = Q(\sqrt{T_h}). \quad (7)$$

In order to express reliability (1), we still need to evaluate the CDF of n_{ISI}, or alternatively, that of N_{ISI}. For complex systems, evaluating the CDF for N_{ISI} remains a formidable task. Instead, we next present a relaxation of the problem.

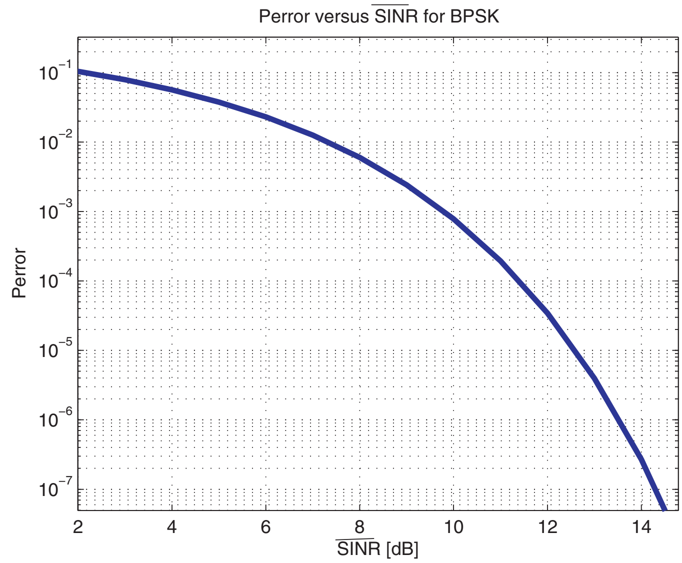

Fig. 1. $P_{\mathrm{error,act}}$ vs. $\hat{\mathrm{SINR}}$.

3. Relaxation for evaluating system reliability

3.1. Estimating the CDF of N_{ISI}

Our approach is based on the observation that the P_{error} does not depend on the information sequence $\{d_i\}$. Hence, for each experiment we may choose the same sequence $d_i = 1, \ \forall i$. By doing so, we get a time-invariant ISI, i.e., $n_{\mathrm{ISI}}[i] = n_{\mathrm{ISI}}$ (which still differs from experiment to experiment). While multipath can improve system performance in some scenarios, we consider it to be an undesirable interference. Thus, assuming the CDF of $\mathrm{n}_{\mathrm{noise}}$ to be a time and spatial invariant, (5) and (6) can be rewritten as

$$P_{\mathrm{error,act}} = Prob(\varepsilon - |\mathrm{n}_{ISI}| + n_{\mathrm{noise}}[i] < 0) = Q\left(\sqrt{\frac{\varepsilon - |n_{\mathrm{ISI}}|}{N_0/2}}\right), \quad (8)$$

with $\mathrm{n}_{\mathrm{ISI}}$ being a channel dependent random variable. By (8), we simplify the SINR to be

$$\hat{\mathrm{SINR}} = \frac{\varepsilon - |n_{\mathrm{ISI}}|}{N_0/2}.$$

Then, for

$$Q\left(\sqrt{\hat{\mathrm{T}}_h}\right) = P_{\mathrm{error,req}}$$

(1) is rewritten as

$$P_{\mathrm{reliab}} = P_r(\hat{\mathrm{SINR}} \ge \hat{\mathrm{T}}_h), \quad (9)$$

which is also the CDF of $\hat{\mathrm{SINR}}$. For BPSK communication, we show $P_{\mathrm{error,act}}$ as a function of $\hat{\mathrm{SINR}}$ in Fig. 1.

Assuming $\mathrm{n}_{\mathrm{ISI}}$ is an i.i.d Gaussian random variable, the CDF of $\hat{\mathrm{SINR}}$ is

$$P_{\mathrm{reliab}} = P_r\left(|n_{\mathrm{ISI}}| \le \varepsilon - \frac{\hat{\mathrm{T}}_h}{\cdot} N_0 2\right)$$

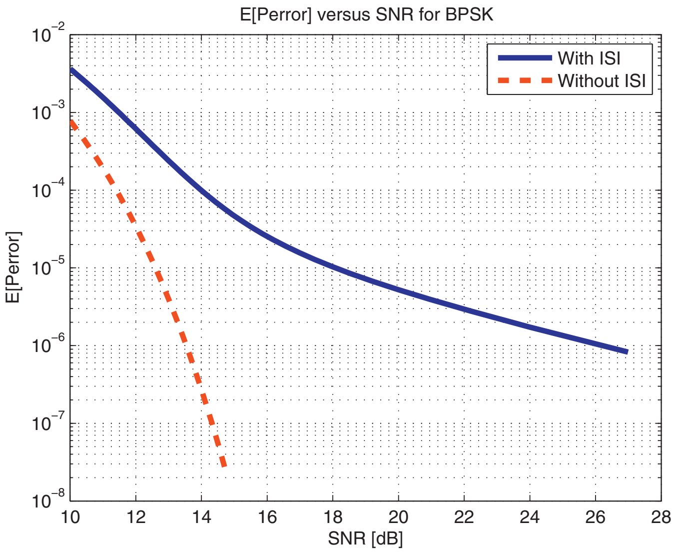

Fig. 2. $P_{\text{error, act}}$ vs. SNR for ISI channel with $N_{\text{ISI}} = 50$ and $\mu_{n_{\text{ISI}}} = 0$ and for AWGN channel.

$$= \int_0^{\varepsilon - \frac{\hat{T}_h \cdot N_0}{2}} \frac{2}{\sqrt{2\pi N_{\text{ISI}}}} e^{-\frac{(x-\mu_{n_{\text{ISI}}})^2}{2N_{\text{ISI}}}} dx$$
$$= 1 - 2Q\left(\frac{\varepsilon - \mu_{n_{\text{ISI}}} - \frac{\hat{T}_h \cdot N_0}{2}}{N_{\text{ISI}}}\right), \tag{10}$$

where $\mu_{n_{\text{ISI}}}$ is the first moment of n_{ISI}. By (10), we observe that reliability decreases with $\hat{T}_h$. In this sense, $\hat{T}_h$ can be considered as a *reliability parameter*, determined by the system modulation scheme and $P_{\text{error,req}}$.

The above approach to calculate the CDF of n_{ISI} also allows us to evaluate the mean value of $P_{\text{error,act}}$,

$$E\left\{P_{\text{error,act}}\right\} = \int_{-\infty}^{0} \frac{2 \cdot Q\left(\sqrt{\frac{\varepsilon - x}{N_0/2}}\right)}{\sqrt{2\pi N_{\text{ISI}}}} e^{-\frac{(x-\mu_{n_{\text{ISI}}})^2}{2N_{\text{ISI}}}} dx. \tag{11}$$

By (11), we observe that $E\left\{P_{\text{error,act}}\right\}$ depends on both the SINR and the signal-to-noise-ratio (SNR), $\frac{\varepsilon}{N_0/2}$. In Fig. 2, we show $E\left\{P_{\text{error,act}}\right\}$ as a function of the signal-to-noise ratio (SNR) for an additive Gaussian noise channel (AWGN) channel with multipath contributing to ISI. From the figure, we readily observe that for SNR > 16 dB, the ISI is the dominant factor in determining $P_{\text{error,act}}$.

3.2. Example for MIMO CDMA

We now derive an expression for reliability, P_{reliab}, as a function of $\hat{T}_h$ for a MIMO CDMA communication system with M_{Tx} transmitters and M_{Rx} receivers. In such a system, each transmitter in the MIMO array modulates its transmitted symbols using a different pseudo random (PN) sequence of $L_c = \frac{T_s}{T_{\text{chip}}}$ chips, $a_{j,k} \in \{\pm 1\}$, where T_{chip} is the duration of the chip [8]. To formalize this, denote

$$g^{T_{chip}}(t) = \begin{Bmatrix} 1 & |t| \le \frac{T_{\text{chip}}}{2} \\ 0 & else \end{Bmatrix}.$$

The transmitted signal from the kth element is

$$s_k(t) = \sum_{j=0}^{L_c - 1} a_{j,k} g^{T_{\text{chip}}}(t - jT_{\text{chip}})), \quad 0 < t \le T_s. \tag{12}$$

We model the channel impulse response for the kth transmitter and the lth receiver as a tap delay line with a path loss α, such that [12]

$$h_{k,l}(t) = \alpha \cdot \delta(t) + \sum_{p=2}^{N_{\text{path}}} c_{p,k,l} \cdot \delta(t - \tau_{p,k,l}), \tag{13}$$

where N_{path} is the number of taps, $c_{p,k,l}$ is the complex received power of the pth path, and $\tau_{p,k,l}$ is the path delay. We model $\tau_{p,k,l}$ as a random variable uniformly distributed between T_{chip} and the impulse response length, T_{m}. We assume that $c_{p,k,l}$ is Rician distributed [4] with uniformly distributed phase, such that

$$c_{p,k,l} = \sqrt{x_{p,k,l}^2 + y_{p,k,l}^2} \cdot e^{j\theta_{p,k,l}}, \tag{14}$$

where $x_{p,k,l} \sim N(\mu_x, \sigma_c^2)$, $y_{p,k,l} \sim N(\mu_y, \sigma_c^2)$ and $\theta_{p,k,l} \sim U[0, 2\pi]$. For simplicity, we assume the direct path is the strongest path.

3.2.1. Formalizing the ISI

The received signal is matched filtered and re-sampled at a rate of $\frac{1}{T_s}$. Assuming for $k \neq k'$,

$$\int_0^{T_s} s_k(t) s_{k'}(t) dt = 0,$$

the ith sample of the matched filter output is

$$g[iT_s] = \alpha \sum_{j=1}^{M_{\text{Tx}}} \sum_{k=1}^{M_{\text{Rx}}} \sum_{m,l=1}^{L_c - 1} a_{j,m} a_{j,l} \xi[iT_s - T_{\text{chip}}(m-l)]$$
$$+ \sum_{j=1}^{M_{\text{Tx}}} \sum_{k=1}^{M_{\text{Rx}}} \sum_{p=2}^{N_{\text{path}}} \sum_{m,l=1}^{L_c - 1} a_{j,m} a_{j,l} c_{j,k,p}$$
$$\cdot \xi[iT_s - T_{\text{chip}}(m-l) - \tau_{j,k,p}] + n_{\text{noise}}[iT_s], \tag{15}$$

where $\xi[iT_s]$ is the iT_sth sample of $g^{T_{\text{chip}}}(t) * g^{T_{\text{chip}}}(-t)$, and $n_{\text{noise}} \sim N(0, \frac{N_0}{2} \cdot T_s)$. Since the desired signal is regarded as the output of the matched filter for the direct path, and ISI reflects the contribution to $g[iT_s]$ from multipath, for

$$\varepsilon = \alpha \cdot T_s \cdot M_{\text{Tx}} \cdot M_{\text{Rx}}, \tag{16}$$

we formalize the ISI as

$$n_{\text{ISI}} = \sum_{n=-1}^{\lfloor 1 + \frac{T_m}{T_s} \rfloor} y[n] - n_{\text{noise}}[n] - \varepsilon. \tag{17}$$

As assumed above (see Section 3), by low of large numbers and for large $\frac{T_m}{T_s}$, n_{ISI} is Gaussian.

Recall that for reliability evaluation we needed to formalize the CDF of each random variable in our system. By (17), we observe that ε is fixed and that n_{ISI} can be considered as an i.i.d Gaussian random variable. Thus, to calculate (10) and (11), we require only the first and second moments of n_{ISI}.

Since $\tau_{p,\,k,\,l}$ and $c_{p,\,k,\,l}$ in (13) are independent random variables and since $E\{c_{p,k,l}\} = 0$, we get

$$E\{n_{\rm ISI}\} = \mu_{n_{\rm ISI}} = 0. \tag{18}$$

The expression of the second moment of $n_{\rm ISI}$, $E[(Re\{n_{\rm ISI}\})^2]$, is provided next.

3.2.2. Calculation of $E[(Re\{n_{ISI}\})^2]$

Since $E[(Re\{n_{\rm ISI}\})] = 0$, $E[(Re\{n_{\rm ISI}\})^2]$ is the second moment of $n_{\rm ISI}$. Denote $\mu^2 = \mu_x^2 + \mu_y^2$, where μ_x and μ_y are the mean value of $x_{p,\,k,\,l}$ and $y_{p,\,k,\,l}$ from (14), respectively, and consider σ_c^2 to be the variance of both $x_{p,\,k,\,l}$ and $y_{p,\,k,\,l}$. Since $c_{p,\,k,\,l}$ is considered Rician distributed (Chapter 2 in [11]),

$$E[c_{i,k,p} c_{i',k',p'}] = (2\sigma_c^2 + \mu^2)\delta_{i-i'}\delta_{k-k'}\delta_{p-p'}.$$

Thus, denoting

$$\zeta(n, m, l, i, k, p) = \xi\left(nT_{\rm s} - T_{\rm chip}(m - l) - \tau_{i,k,p}\right),$$

we have

$$E[(Re\{{\rm n_{ISI}}\})^2] = \frac{1}{2} \sum_{i=1}^{M_{\rm Tx}} \sum_{k=1}^{M_{\rm Rx}} \sum_{p=2}^{N_{\rm path}} \sum_{\substack{m,m'=1\\ l,l'=1}}^{L_c-1} a_{i,m} a_{i,l'} a_{i,m'} a_{i,l} \cdot (2\sigma_c^2 + \mu^2) \cdot \sum_{\substack{n,n'=-1\\ n,n'\neq 0}}^{\lfloor 1+\frac{T_{\rm m}}{T_{\rm s}} \rfloor} E[\zeta(n, m, l, i, k, p)\zeta(n', m', l', i, k, p)]. \tag{19}$$

Since $E[\zeta(n, m, l, i, k, p)\zeta(n', m', l', i, k, p)]$ is not effected by the choice of i, k and p, we can simplify it to be $E[\zeta(n, m, l)\zeta(n', m', l')]$. Furthermore, assuming

$$a_{i,m} a_{i,m'} a_{i,l} a_{i,l'} = a_{i',m} a_{i',m'} a_{i',l} a_{i',l'}, \ \ \forall i, i' = 1, \ldots, M_{\rm Tx},$$

we have [8]

$$E[(Re\{n_{\rm ISI}\})^2] = \frac{1}{2} M_{\rm Rx} M_{\rm Tx} (2\sigma_c^2 + \mu^2) \cdot (N_{\rm path} - 1) \sum_{\substack{n,n'=-1\\ n,n'\neq 0}}^{\lfloor 1+\frac{T_{\rm m}}{T_{\rm s}} \rfloor} \sum_{\substack{m,m'=1\\ l,l'=1}}^{L_c-1} a_m a_{m'} a_l a_{l'} E[\zeta(n, m, l)\zeta(n', m', l')]. \tag{20}$$

3.2.3. Numerical results

In Fig. 3, we show $P_{\rm reliab}$ as a function of $\hat{\rm T}_{\rm h}$ for $M_{\rm Tx} = 4$, $M_{\rm Rx} = 4$, $\lfloor \frac{T_{\rm m}}{T_{\rm s}} \rfloor = 10$, $T_{\rm s} = 62\,{\rm ms}$, $L_{\rm c} = 31$, $N_{\rm path} = 5$, $\mu_y = \mu_y = 2, \sigma_c = 1$ and $\alpha = 0.1$. For comparison, we also show reliability results for a SISO system, namely when $M_{\rm Rx} = M_{\rm Tx} = 1$. From the figure, as expected we observe that due to the spatial diversity applied in MIMO systems, it achieves a considerable reliability gain compared to the SISO system.

Finally, we wish to determine $\hat{\rm T}_{\rm h}$ using (7). Considering BSPK communication (see Section 2.2) and observing the results of Fig. 1, we conclude that for $P_{\rm error,req} = 10^{-4}$, SNR > 12 dB. Hence, we choose $\hat{\rm T}_{\rm h} = 12$ dB. Observing the results in Fig. 3, a reliability of 0.93 is achieved for such $\hat{\rm T}_h$. Namely, the probability that the system will achieve the desired error probability is greater than 0.93. This figure of merit means that if the SINR is below threshold $\hat{\rm T}_{\rm h}$, a reliability of 0.93 can only be achieved if ISI mitigation techniques are applied.

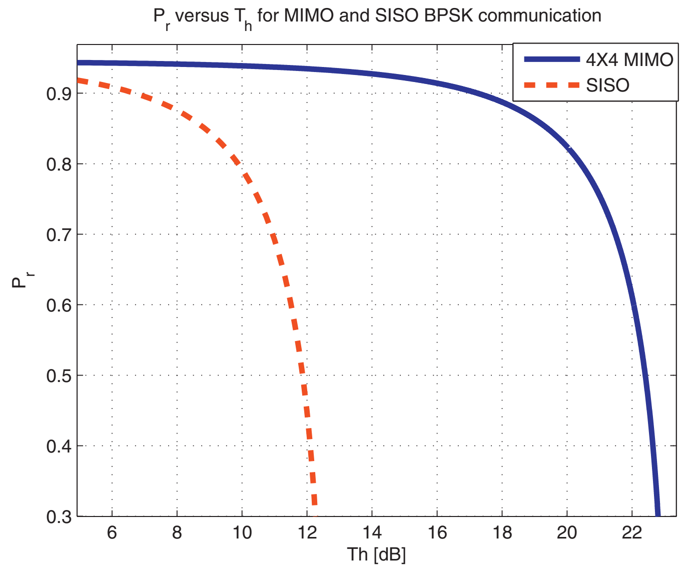

Fig. 3. $P_{\rm reliab}$ vs. $T_{\rm h}$.

4. Conclusion

In this paper, we presented the problem of determining the reliability of an UWAC system. We discussed the difficulty in statistical evaluation of the system reliability using large amount of acquired data. We showed the challenge in obtaining the reliability measure numerically via calculation of the CDF of the error probability. Considering these challenges, we suggested an alternative relaxed approach based on analyzing the CDF of the SINR. We demonstrated our approach for the relatively complex case of BPSK-MIMO CDMA communication system. Based on our method and for a given channel model, the reliability of any UWAC system can be analyzed. Future work would include a comparison between the analytical calculated link reliability and statistical measurements from real sea environments.

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