Maximal Ratio Combining Diversity Analysis of Underwater Acoustic Communications Subject to $\kappa$–$\mu$ Shadowed Fading Channels

Ehab Salahat, Member, IEEE, Ali Hakam, Member, IEEE
{ehab.salahat,ali.hakam}@ieee.org

Abstract—In this paper, a novel unified analytical expression for average bit error rates (ABER) and average channel capacity (ACC) is presented for the $\kappa$–$\mu$ shadowed fading model. This model has recently shown to be suitable for underwater acoustic wireless channel modeling using the measurements conducted by the Naval Research Laboratory [1], and is not so well covered in the public literature. Deploying the maximal ratio combining diversity (MRC) receiver, a new simple analytical expression for the probability density function of the receiver’s output signal-to-noise ratio (SNR) is presented. Based on this new PDF, a novel unified ABER and ACC expression is derived. Furthermore, to generalize the ABER analysis, the additive white generalized Gaussian noise model is assumed which models different noise environments. The new unified expression is accurate, simple and generic, and is suitable for MRC analysis in this generalized shadowed fading and noise environment. Numerical techniques and published results from the literature prove the accuracy of our analysis and the generality of the derived unified expression.

Keywords—Underwater Acoustic Channel; Additive White Generalized Gaussian Noise; $\kappa$–$\mu$ shadowed; Rician Shadowed.

I. INTRODUCTION

Wireless communications is an active research area and its applications seems limitless. Previously restricted to outdoor environments, they have soon reached indoor environments and recently aquatic ones [2] [3]. Underwater acoustic communications systems have attracted research interest with promising applications, e.g. scientific exploration, commercial exploitation, pollution monitoring, tactical surveillance, submarines and unmanned underwater vehicles, etc. They have evolved from analog to digital and from incoherent to coherent [4].

However, underwater acoustic wireless communications is recognized to be one of the most difficult communication types in use today due to waves, internal turbulence, surface and seabed reflections, high signal attenuations, and other small-scale phenomena contributing to signal variations [5]. Statistical distributions are generally used to characterize on the effects that degrade the signal during its propagation, namely shadowing and multipath fading. The awareness to develop standardized statistical distributions and models for underwater acoustic communications continues to increase; however, still addressed to a limited extent. Statistical models will provide tools for predicting the oceanic system’s performance prior to deployment, and are also essential for aqueous research [6].

The Rician shadowed fading model, proposed in [7], is a shadowed fading distribution that assumes Rician distribution for its line-of-sight component and Nakagami-$m$ shadowing. This model has been successfully employed to land-mobile satellite (LMS) channels modelling and recently for modelling underwater acoustic channels [8]. The Rician shadowed fading distribution is a generalized distribution that encloses many distributions as special cases e.g. the Rayleigh and the Nakagami-$m$ fading models. The performance analysis of maximal ratio combining (MRC) for Rician shadowed fading channels was also studied in [9].

The $\kappa$–$\mu$ shadowed fading model, introduced very recently in [1], is a new shadowed fading model that assumes Nakagami-$m$ shadowing and $\kappa$–$\mu$ fading [10]. This shadowed fading model has a clear physical interpretation and good analytical properties. It encloses the Rayleigh, the Nakagami-$m$, the Rician, the one-side Gaussian, the $\kappa$–$\mu$, and the Rician shadowed fading models as special cases. This generalized model was shown to provide rather better fitting for the underwater acoustic channel (UAC) measurements conducted by the Naval Research Laboratory, as compared to the Rician shadowed [1] [11], as shown in Fig. 1. The new generalized shadowed fading distribution has an analytically traceable statistical characterization with remarkable flexibility given in closed-form without complicated special functions.

Motivated by the above discussion, the goal of this paper is to provide a rigorous analysis for $\kappa$–$\mu$ shadowed fading model that fits underwater acoustic propagation. In parallel, we also aim to develop efficient unified analytical expression that describes the underwater acoustic communications fading channel in the different noise and fading environments. The additive white generalized Gaussian noise environment is assumed in this work, which encloses the Gaussian, the Laplacian, and other noise models as special cases. We derive...
simple closed-form expression for the probability density function and cumulative density function for the MRC output SNR with independent and identically distributed (i.i.d.) channels. In addition, we used the approximation in [3] of the generalized $Q$--function in our AWGN modelling and derive a novel unified and generic expression for the ABER and ACC expression to study and analyze underwater wireless acoustic communications channels. It should be also noted that the mathematical analysis can be directly extended to other wireless environments, but the emphasis here is given to UAC.

The remaining part of this paper is structured as follows. In section II, the $\kappa - \mu$ shadowed fading model is visited, and the new simplified PDF and CDF expressions for the MRC output SNR are derived, with a quick revision to the generalized $Q$--function and its approximation. Next, the new unified ACC and ABER for MRC in AWGN and $\kappa - \mu$ shadowed fading environment is presented in section III. Following to that, in section IV, the analysis and the results of the many test cases are presented, which are also corroborated by the numerical evaluation and compared to the published results from the technical literature. Finally, the paper contributions are then summarized in section V.

II. MRC Statistical Derivations

A. $\kappa - \mu$ Shadowed Fading Model -- An Overview

The $\kappa - \mu$ shadowed fading model relies on a generalization of the physical model of the $\kappa - \mu$ model [2] [10] [12]. Assuming a non-homogeneous environment propagation, the multipath waves are assumed to have scattered waves with the same power and an arbitrary power for the dominant component. In contrast with the $\kappa - \mu$ distribution that assumes a deterministic dominant component within each cluster, the $\kappa - \mu$ shadowed model assumes that the dominant components of the clusters can change randomly due to shadowing. Since the $\kappa -\mu$ distribution includes the Rician distribution as a special case [10], a natural generalization of the $\kappa - \mu$ fading distribution can be obtained by an LOS shadow fading model with the same multipath/shadowing scheme used in the Rician shadowed model [1]. Assuming that shadowing follows Nakagami-$m$, then, the probability density function and the cumulative density function of the $\kappa - \mu$ shadowed fading are given respectively as [1]:

$$f_\gamma(y) = \frac{\mu^m m^m (1+\kappa)^m}{\Gamma(m)(\kappa m)^m} y^{\mu-1} e^{-\frac{(\mu+1)y}{\kappa}} I_1(m; \mu; \frac{\mu^2 (1+\kappa)}{(1+\kappa)m}) y, \quad (1)$$

$$F_\gamma(y) = \frac{\mu^m m^m (1+\kappa)^m}{\Gamma(m)(\kappa m)^m} \Phi_2\left(\mu - m; m; \mu + 1; \frac{\mu (1+\kappa)}{\kappa}, \frac{\mu - m}{\kappa}\right), \quad (2)$$

where $\kappa$, $\mu$ and $m$ account for the ratio between the total power of the dominant components and the total power of the scattered waves, the number of the multipath clusters, and the Nakagami-$m$ shadowing parameter, respectively [1] [10], and the functions $I_1$ and $\Phi_2$, defined in [13], denote the confluent hypergeometric function and bivariate confluent hypergeometric function, respectively. The model includes the $\kappa - \mu$, the Nakagami-$m$, the Rician shadowed, the Rician, the Rayleigh and the one-sided Gaussian as special cases. These distributions can be obtained from (1) as shown in and summarized in table I for brevity.

| Fading Distribution | $\kappa$ | $\mu$ | $m$ |
|---------------------|---------|-------|-----|
| Nakagami-$m$        | $\mu = m$ | $\kappa = 0$ | $m ightarrow \infty$ |
| Rician shadowed     | $\mu = 1$ | $\kappa = K$ | $m = m$ |
| Rician              | $\mu = 1$ | $\kappa = K$ | $m = m$ |
| Rayleigh            | $\mu = 1$ | $\kappa = 0$ | $m ightarrow \infty$ |
| One-Sided Gaussian  | $\mu = 0.5$ | $\kappa = 0$ | $m ightarrow \infty$ |

B. Maximum Ratio Combining Analyses

By deploying maximal ratio combiner (MRC) reception, and emphasizing the fact that MRC provides the highest average output SNR a diversity scheme can attain [14], we start this section by introducing the following theorem:

**Theorem:** Assuming that signals are transmitted over $L$ independently and identically distributed (i.i.d.) shadowed $\kappa - \mu$ fading branches with MRC diversity, the corresponding PDF of the output SNR is then given by

$$f_{Y_{MRC}}(y) = \frac{\mu^L m^L (1+\kappa)^L}{\Gamma(L)(\kappa m)^L} y^{\mu-1} e^{-\frac{(\mu+1)y}{\kappa}} I_L(m; \mu; \frac{\mu^2 (1+\kappa)}{(1+\kappa)m}) y, \quad (3)$$

where $\mu = L \mu$, $m = L m$, $\eta = Ly$, and $L$ denoting the number of diversity branches used.

**Proof:** following the previous assumptions, the instantaneous SNR of the MRC combiner output is given by [15]:

$$\gamma = \sum_{i=1}^{L} \gamma_i. \quad (4)$$

If the moment generating function (MGF) for any branch is given in [1] by:

$$M_{\gamma}(s) = \frac{(-\mu)^m m^m (1+\kappa)^m}{\Gamma(m)(\kappa m)^m} \left[\frac{\mu^2 (1+\kappa)}{\kappa} \right]^{m-\mu} \frac{1}{\Gamma(m) \mu^m m^m} \Phi_2\left(\mu, m; m+1; \frac{\mu (1+\kappa)}{\kappa}, \frac{\mu}{\kappa}\right), \quad (5)$$

and assuming that the average SNR for all $L$ branches to be the same, i.e. $\bar{\gamma} = \bar{\gamma}_1 = \bar{\gamma}_2 = \cdots = \bar{\gamma}_L$, the MGF of the MRC output is then given as:

$$M_{Y_{MRC}}(s) = \prod_{i=1}^{L} M_{\gamma}(s) = \frac{(-\mu)^m m^m (1+\kappa)^m}{\Gamma(m)(\kappa m)^m} \left[\frac{\mu^2 (1+\kappa)}{\kappa} \right]^{m-\mu} \frac{1}{\Gamma(m) \mu^m m^m} \Phi_2\left(\mu, m; m+1; \frac{\mu (1+\kappa)}{\kappa}, \frac{\mu}{\kappa}\right), \quad (6)$$

and if we define $\bar{\mu} = L \mu$, $\bar{m} = L m$, and $\eta = Ly$, so $m = \bar{m}/L$ and $\mu = \bar{\mu}/L$, then (6) can be rewritten as:

$$M_{Y_{MRC}}(s) = \frac{(-\mu)^L m^L (1+\kappa)^L}{\Gamma(L)(\kappa m)^L} \left[\frac{\mu^2 (1+\kappa)}{\kappa} \right]^{Lm-\bar{\mu}} \frac{1}{\Gamma(m) \mu^m m^m} \Phi_2\left(\mu, L m; L m+1; \frac{\mu (1+\kappa)}{\kappa}, \frac{\mu}{\kappa}\right), \quad (7)$$

**TABLE I: SPECIAL CASES OF THE $\kappa - \mu$ SHADOWED FADING.**

| Fading Distribution | $\kappa$ | $\mu$ | $m$ |
|---------------------|---------|-------|-----|
| Nakagami-$m$        | $\mu = m$ | $\kappa = 0$ | $m ightarrow \infty$ |
| Rician shadowed     | $\mu = 1$ | $\kappa = K$ | $m = m$ |
| Rician              | $\mu = 1$ | $\kappa = K$ | $m = m$ |
| Rayleigh            | $\mu = 1$ | $\kappa = 0$ | $m ightarrow \infty$ |
| One-Sided Gaussian  | $\mu = 0.5$ | $\kappa = 0$ | $m ightarrow \infty$ |
By comparing (5) and (7), it can be deduced that the PDF for the output SNR with \( L \) diversity branches MRC receiver is given by:

\[
f_{FMRC}(y) = \frac{\tilde{\mu}^{2}P_{n}^{2}(1+k)\tilde{x}^2}{\Gamma(\tilde{\mu})\tilde{\mu}^{2}P_{n}^{2}(1+k)\tilde{x}^2} e^{-\frac{\tilde{\mu}(1+k)\tilde{x}^2}{\tilde{\mu}}} I_{1}(\tilde{\mu};\tilde{x}^2) \left( \frac{\tilde{\mu}(1+k)\tilde{x}^2}{\tilde{\mu}} \right). \tag{8}
\]

This new PDF will be very useful, due to its simplicity as compared to eqn. (10) in [1], which utilizes the complicated confluent hypergeometric function [16]. For compactness, (8) is written as:

\[
f_{FMRC}(y) = \psi y^\frac{1}{\tilde{\mu}} e^{-\beta y} I_{1}(\tilde{\mu};\tilde{x}^2;\tilde{\mu} y), \tag{9}
\]

where \( \psi = \frac{\tilde{\mu}^{2}P_{n}^{2}(1+k)\tilde{x}^2}{\Gamma(\tilde{\mu})\tilde{\mu}^{2}P_{n}^{2}(1+k)\tilde{x}^2} \left( \frac{\tilde{\mu}(1+k)\tilde{x}^2}{\tilde{\mu}} \right) \), and \( \zeta = \left( \frac{\tilde{\mu}(1+k)\tilde{x}^2}{\tilde{\mu}} \right) \).

**Corollary:** It follows from (2) and (9) that the corresponding CDF of the MRC reception will be given as:

\[
f_{r}(y) = \frac{\psi y^{\frac{1}{\tilde{\mu}}}}{\Gamma(\tilde{\mu})\tilde{\mu}^{2}P_{n}^{2}(1+k)\tilde{x}^2} \phi_{1}(\tilde{\mu};\tilde{\mu} y;\tilde{x}^2), \tag{10}
\]

This new form of generalized PDF in (9) is generic and suitable for all the fading models presented in Table I with \( L \)-branches MRC reception. In section III, (9) will be used in the derivations of the unified ABER and ACC expression.

**C. The Generalized Q–Function Approximation**

Literature has extensively studied the Gaussian \( Q \)-function, being used in Gaussian noise related analysis. Wireless communication systems might be subject to other types of noise, e.g. the Laplacian, the Gamma and the impulsive noise. The additive white generalised Gaussian noise is a generalized noise that renders the aforementioned noise models as special cases. It’s formulated using the generalized \( Q \)-function. The generalized \( Q \)-function is given in [2] [3] [17] as:

\[
Q_{2A}(x) = \frac{1}{\pi} \int_{0}^{\infty} e^{-\lambda_{0} u^{2}} du = \frac{1}{\pi} \int_{0}^{\infty} e^{-\lambda_{0} u^{2}} du = \frac{\lambda_{0}^{1/2}}{\pi} \Gamma(1/2, \lambda_{0} x^2), \tag{11}
\]

where \( \lambda_{0} = \sqrt{(3\alpha)/\Gamma(1/2)} \), and \( \Gamma(\cdot) \) is the gamma function. Table II illustrates how the noise special models can be achieved from (11).

**Table II: Relation Between \( Q_{2A}(x) \) and Special Noise Models.**

| Noise Dist. | Impulsive | Gamma | Laplacian | Gaussian | Uniform |
|------------|-----------|-------|-----------|----------|---------|
| \( \alpha \) | 0.0       | 0.5   | 1.0       | 2.0      | \( \infty \) |

Since the \( Q \)-function appears more in the form of \( Q_{2A}(\sqrt{\tau}) \) in the performance analysis, in addition to the fact that the square root will help reducing the fast decaying nature of this function, the following approximation for \( Q_{2A}(\sqrt{\tau}) \) was given and proposed in [3] as:

\[
Q_{2A}(\sqrt{\tau}) \approx \sum_{i=1}^{\infty} \delta_{i} e^{-\sigma_{i}^{2}}, \tag{12}
\]

where the fitting parameters, \( \delta_{i} \) and \( \sigma_{i} \) are obtained using nonlinear curve fitting, with sample fitting values for different cases of \( \alpha \) being presented in Table III [3]. Obtaining the \( Q_{2A}(\cdot) \) approximation is straightforward with a simple and direct variable transform.

**III. PERFORMANCE EVALUATION**

**A. Approximate Bit Error Rate Analysis**

It’s known that the average bit error rate (ABER) due to a fading channel can be evaluated by averaging the bit error rate of the noise channel using the fading PDF [18]. With the \( \kappa-\mu \) shadowed fading and AWGN environment, this averaging process can be expressed as:

\[
P_{e} = A \int_{0}^{\infty} f_{r}(y) Q_{2A}(\sqrt{By}) dy, \tag{13}
\]

where \( f_{r}(y) \) is the fading PDF, \( Q_{2A}(\cdot) \) is the AWGN, and \( A \) and \( B \) are modulation dependent, as shown in Table IV.

**Table III: Fitting Parameters of \( Q_{2A}(\sqrt{\tau}) \) Approximation.**

| \( \tau \) | \( a_{1} \) | \( b_{1} \) | \( c_{1} \) | \( d_{1} \) | \( e_{1} \) | \( f_{1} \) | \( g_{1} \) |
|----|----|----|----|----|----|----|----|
| 0.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Using (9), then (13) can be written as:

\[
P_{e} = A \int_{0}^{\infty} y^\frac{1}{\tilde{\mu}} e^{-\beta y} I_{1}(\tilde{\mu};\tilde{x}^2;\tilde{\mu} y) Q_{2A}(\sqrt{By}) dy. \tag{14}
\]

Utilizing the novel generalized \( Q_{2A}(\sqrt{\tau}) \) in (12), then (13) can then be written in the form:

\[
P_{e} = A \int_{0}^{\infty} y^\frac{1}{\tilde{\mu}} e^{-\beta y} I_{1}(\tilde{\mu};\tilde{x}^2;\tilde{\mu} y) Q_{2A}(\sqrt{By}) dy, \tag{15}
\]

with simple variable transform, as \( z = \gamma y \), (15) is evaluated in a simple closed form as:

\[
P_{e} = A \int_{0}^{\infty} \Psi_{2} F_{1}(\tilde{\mu} y;\tilde{x}^{2}) \left( \frac{\beta + \tilde{\mu} \gamma}{\tilde{\mu} \gamma} \right), \tag{16}
\]

with \( \tilde{\beta} = [\beta + \gamma \tilde{\beta}] / \tilde{\gamma} \) and \( \Psi = [\tilde{A} \tilde{A}_{1} \Gamma(\tilde{\mu})] / [\chi^{2} \tilde{\beta}] \).

This new expression in (16) is simpler than that in (1) in eqn. (21). It also generalizes the analysis of MRC reception to the special cases of the \( \kappa-\mu \) shadowed fading (such as the Rician shadowed, Nakagami-\( m \), etc.) in different noise environments.

**Table IV: \( A \) and \( B \) Values for Different Modulations.**

| Modulation Scheme | Average SER | \( A \) | \( B \) |
|------------------|------------|-------|-------|
| BFSK             | 0.00       | 0.00  | 0.00  |
| BPSK             | 0.00       | 0.00  | 0.00  |
| QPSK,4-QAM       | 0.00       | 0.00  | 0.00  |
| M-PAM            | 0.00       | 0.00  | 0.00  |
| M-PSK            | 0.00       | 0.00  | 0.00  |
| Rectangular M-QAM| 0.00       | 0.00  | 0.00  |
| Non-Rectangular M-QAM | 0.00 | 0.00  | 0.00  |
B. Average Channel Capacity

Channel capacity is defined as the maximum transmission rate of information over a channel with arbitrarily negligible. The average channel capacity (ACC) can be obtained by averaging the capacity of AWGN channel over the fading PDF [15], i.e.: 
\[ C = \int_0^\infty \log_2 (1 + \gamma) f_\gamma(\gamma) d\gamma, \]  
(17)

where C denotes the normalized channel capacity (bits/s/Hz). If the \( \log_2 (1 + \gamma) \) is exponentially approximated, just as \( Q (\sqrt{\gamma} \) ) was approximated in (12), i.e.
\[ \log_2 (1 + \gamma) \approx \sum_{i=1}^\infty \delta_i e^{-\sigma_i \gamma}, \]  
(18)

then the ACC expression for this shadowed fading model will be exactly the same as that of the ABER in (16), with the new fitting values given as \( \delta = [9.331, -2.635, -4.032, -2.388] \) and \( \sigma = [0.000, 0.037, 0.004, 0.274] \). Please refer to [3], Fig. 4. This expression is applicable for a reasonably large SNR range, the typical SNR range that is studied in the literature.

IV. RESULTS

This section illustrates the simulation results for sample test scenarios for our derived expression, and compares these results with numerically obtained ones as well as the results available in the technical literature for some of the special cases of the \( \kappa - \mu \) shadowed fading model.

Five test scenarios will be illustrated for the ABER here based on (16). The first test considers the general \( \kappa - \mu \) shadowed fading in AWGN, using different modulation schemes from Table IV of different constellation orders, namely 8-PSK, 16-PSK, 32-QAM and 256-QAM, using different values of model parameters and subject to different noise environments, specified by the value of \( a \), without diversity (i.e. \( L=1 \)). The

ABER curves of this case are shown in Fig. 3. One can clearly see that numerically integrated results (solid lines) match the results of (16) denoted by the overlaid dots, confirming its accuracy for the different test scenarios presented. The second test case, presented in Fig. 4, uses the same previous values of parameters subject to the same noise environments, but deploying MRC reception with three diversity branches (\( L=3 \)). It’s obvious that (16) gives very accurate results as the dots overlay the curves of the numerical integration.

As a third test case, we consider the special case of \( \kappa - \mu \) fading using BPSK in AWGN and selected the \( \kappa \) and \( \mu \) values to match those found in [2], to compare our generated results, shown in Fig. 5, with those in the technical literature. One can see a clear match between the ABER curves in Fig. 5 and those shown in [2]. As for the Average Channel Capacity (ACC), one test case is presented due to space limitations. The ACC of the \( \kappa - \mu \) shadowed fading is considered, and the generated results are shown in Fig. 8. Following on the discussion presented in section III.B, the ACC expression is exactly the same as that in (16) with changing the fitting parameters to the new ones specified there. The results of (16) agree with the curves of the numerical integration (solid lines) for the different tested cases. This proves that (16) is indeed unified for ABER and ACC analysis.

V. CONCLUSION

In this paper, we presented novel performance analysis of the new \( \kappa - \mu \) shadowed fading model, which was shown to be suitable for underwater acoustic communications channel modeling. Deploying the MRC reception, we derived a new PDF for the MRC output SNR. We also utilized the generalized Q-function approximation used to model the AWGN in our ABER analysis. Consequently, a novel unified ABER and ACC expression for the analysis of \( \kappa - \mu \)
shadowed fading in AWGGN conditions using L-branches MRC receiver. The unified expression was shown to be very accurate with a wide spectrum of promising applications due the generality of this expression.

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