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An Innovative Modeling and Evaluating Bit Error Probability in Asynchronous DS-CDMA Systems with Rayleigh-Distributed Multiple Access Interference

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Abstract

Recent developments in cellular mobile systems indicate substantial capacity issues for densely populated urban areas. Emerging wireless systems require increased data rates and flexibility to exceed capacity constraints. Traditional multiple access methods like Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) allow users to share fixed-spectrum resources with one another. Yet these techniques come to a halt when their channels or time slots are exhausted. Code Division Multiple Access (CDMA) was originally created for secure communication and anti-jamming purposes but has even higher capacity and better multipath interference resistance. Multiple Access Interference (MAI) is an important limitation on CDMA performance. Here we study the effect of MAI on the Bit Error Probability (BEP) of asynchronous Direct Sequence CDMA (DS-CDMA) systems. Standard Gaussian Approximation (SGA), Improved Gaussian Approximation (IGA), and simplified IGA as three examples in architecture, depend on the Central Limit Theorem which models MAI as a zero-mean Gaussian distribution. Theoretical Framework: The contribution of MAI for BEP estimation is made more meaningful based on modeling of MAI as a Rayleigh-distributed random variable (RDRV). Comparative analysis highlights the performance of our method using SGA, which we observe results with nonzero mean, which highlights the weaknesses of the existing approaches, as well as suggests new direction for better accuracy in predicting CDMA performance.

Keywords: Code Division Multiple Access (CDMA); Bit Error Probability (BEP); Multiple Access Interference (MAI); Rayleigh Distribution; Asynchronous Systems

1. Introduction

Mobile communications have grown to be a huge part of our daily life and changing the way we connect and interact. Mobile is used for personal, professional and industrial use cases and the need for improved and scalable wireless systems has become more urgent. Conventional mobile communication systems, including the AMPS and GSM, that leverage the traditional multiple access method such as Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) or hybrid arrangements suffer a clear impact on the simultaneous usage process [1]. The bottlenecks are more prominent in densely populated urban areas as they show up as spectral congestion, which increases this bottleneck in performance. Similar congestion effects in CDMA-based cellular systems have been researched comprehensively [2]. The rapid development of cellular technologies capable of utilizing spectrum has now emerged as a pressing challenge due to the increasing number of spectral and interconnectivity requirements [3]. Developing spread spectrum (SS) communication techniques are one of the most transformative responses to these challenges. Originally conceptualized in the 1950s for secure and interference-resistant communication systems, SS systems were intended to prevent malicious access, jamming, and interference [4]. The spread spectrum approach propagates over a bandwidth much larger than is needed minimally, thus increasing interference resistance and allowing multiple users to share the same spectral resources in the same spectrum [5]. Code Division Multiple Access (CDMA), a popular SS-based approach, allowed multiple users to share spreading codes simultaneously. This approach

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departs from FDMA and TDMA's fixed resource allocation schemes and applies the soft capacity [6][7] model where system throughput is gracefully decreased under load rather than abruptly limited. Thus CDMA has underpinned 2G, 3G as well as hybrid 4G systems, where frequency reuse and dynamic resource allocation allows it to scale and achieve spectral efficiency [8]. Other than capacity enhancement, CDMA systems substantially improve the quality of digital communication through increased voice fidelity, improved facilitation of handoff, and extended cell coverage [9]. The resulting improvements help to establish the foundation of cutting-edge mobile systems for applications in streaming, IoT, and high-throughput devices [10]. However, one of the main limitations of CDMA systems is the vulnerability to Multiple Access Interference (MAI). The phenomenon of MAI occurs when codes from other users are transmitted, especially in non-ideal or asynchronous synchronization situations, and it leads to less signal-transparency and higher bit error [11]. The consequences of multi-access interference in a network configuration of commercial CDMA are proved in [12]. This behavior is amplified in high-density networks, when code orthogonality is challenged, and the cross-user interference becomes more pronounced [13]. Given that the design of CDMA has been extended since its initialization into modern architectures such as massive MIMO and reconfigurable intelligent surfaces (RIS), reducing the MAI problem is a fundamental concern [14][15]. To assess CDMA performances in the presence of MAI, we usually have to evaluate Bit Error Probability (BEP) particularly when using AWGN. One of the most popular is the Standard Gaussian Approximation (SGA), which believes that MAI contributions are independently and identically distributed, and predicts their cumulative effect as a zero-mean Gaussian process given CLT [16][17]. Although SGA provides an analytical ease, it has significant accuracy degradation when dealing with low-user-count or multiple systems that have differing power on users. Various alternative models for MAI modeling (Poisson and Binomial interference, for example,) are covered in [18]. Under such scenario, the Gaussian assumption exaggerates the performance, ignoring the distorted and unpredictable nature of real MAI [19]. To this end, various refactoring methods namely IGA and SIGA have been introduced by utilizing the above higher-order statistics and improved in the fit of the empirical distributions of the interference [20]. From this point of view, an alternative modeling approach is proposed for MAI, not as Gaussian but as an (RDRV), as the user interference in realistic asynchronous DS-CDMA system is dynamic, bursty, and fading susceptible. Rayleigh modelling is recognised for describing envelope fluctuation of multipath fading signals in wireless applications, and particularly for mobile data with no dominant line-of-sight component [12][21]. The same statistical patterns are observed in radar systems and stochastic channel modeling [14], and its use is also consistent with these observations. Also, this work brings back the traditional SGA method to the practical deployment scenario with a non-zero mean term that describes the skewness shown in all MAI distributions [11]. This composite approach allows us to compare Gaussian-based approximations, improved statistical methods and the Rayleigh model through a range of operating conditions, user densities and signal-to-noise ratios. The study also seeks to bring together the theoretical performance study and realistic system design. So as to obtain a more representative MAI characterization from the Rayleigh model in comparison to the other models and changed SGA, this paper extends the scope of system architects to design adaptive resource allocation and interference suppression approaches. This is of paramount importance for emergent architectures such as NOMA and 6G systems, for which spectral coexistence becomes a challenge [8][15][20]. Lastly, in a wider perspective of DS-CDMA performance, besides the primary MAI characterization, AWGN and slow fading channel conditions are also covered by the framework. This treatment is complete enough to allow the model to be generalized in the future for chaos based CDMA models and also considers RIS-assisted architectures and massive connectivity models due to its growing dependence on next-generation networks [8][19]. The arrangement of this paper is as follows: In Section 2, we outline the mathematical paradigm underlying the MAI as an RDRV. The numerical findings are reported in Section 3 alongside a comprehensive interpretation of the performance analysis. Finally, section 4 explains the central contribution of this work.

2. Modeling MAI Using a Rayleigh Distribution

Thus the Rayleigh distribution is mostly used for modeling mobile radio channels, as it allows precise measurement of time-dependent variation in amplitude corresponding to flat-fading signals, or the individual components within multipath propagation. More specifically, the Rayleigh distribution is used for the envelope from the sum between both orthogonal Gaussian signals. Also, this statistical model gives guidance on the changing characteristics of radar target detection processes. This section aims at deducing the BEP assuming that MAI acts as an RDRV defined by a certain probability density function (pdf):

$$f_{\psi_m}(\psi_m) = \frac{\psi_m}{\alpha^2} e^{-\psi_m^2/2\alpha^2} \qquad \psi_m \geq 0 \qquad (1)$$

where ψ_m represents the interference introduced by the m^{th} user. The interference level will depend on the condition for each user given channel conditions and system parameters. The CF of this distribution should be determined as part of the computation of BEP, thus to this mathematical study. The characteristic function (CF) of this probability density function (pdf) is described as follows:

$$F_{\psi_m}(\omega) \;=\; \int_{-\infty}^{\infty} f_{\psi_m}(\psi_m)\, e^{-j\omega\psi_m} d\psi_m \qquad (2)$$

$$F_{\psi_m}(\omega) \;=\; \int_{0}^{\infty} \frac{\psi_m}{\alpha^2} e^{-\psi_m^2/2\alpha^2} e^{-j\omega\psi_m} d\psi_m \qquad (3)$$

$$F_{\psi_m}(\omega) = \int_0^{\infty} \frac{\psi_m}{\alpha^2} e^{-\psi_m^2/2\alpha^2} \cos \psi_m\omega \;\; d\psi_m - j\int_0^{\infty} \frac{\psi_m}{\alpha^2} e^{-\psi_m^2/2\alpha^2} \sin\; \psi_m\omega \;\; d\psi_m \qquad (4)$$

The evaluation of the second term can be obtained through the following integration:

$$\int_0^{\infty} \frac{\psi_m}{\alpha^2} e^{-\psi_m^2/2\alpha^2} \sin\; \psi_m\omega\, d\psi_m = \sqrt{\frac{\pi}{2}}\alpha\omega e^{-\omega^2\alpha^2/2} \qquad (5)$$

In contrast, the first integration term can be expressed as:

$$\int_0^{\infty} \frac{\psi_m}{\alpha^2} e^{-\frac{\psi_m^2}{2\alpha^2}} \cos \psi_m\omega\, d\psi_m = 1 - (\omega\alpha)^2 + \frac{(\omega\alpha)^4}{3} - \frac{(\omega\alpha)^6}{3\,.5} + \frac{(\omega\alpha)^8}{3\,.5\,.7} - \ldots \approx e^{-(\omega\alpha)^2} \qquad (6)$$

Then, Equation (4) can be expressed as:

$$F_{\psi_m}(\omega) \approx e^{-(\omega\alpha)^2} - j\sqrt{\frac{\pi}{2}}\alpha\omega \;\; e^{-\omega^2\alpha^2/2} \qquad (7)$$

The BEP can be calculated directly from:

$$P_e = \frac{1}{2}\int_{I_0}^{\infty} p_{\psi}(\psi) d\psi \qquad (8)$$

where $p_{\psi}(\psi)$ represents the joint pdf associated with the (U−1) users. Its corresponding expression in the ω -domain can be written as:

$$P_{\psi}(\omega) \;=\; F_{\psi_1}(\omega) F_{\psi_2}(\omega) \cdots F_{\psi_{U-1}}(\omega) \qquad (9)$$

Assuming that the interference generated by the (U −1) users is independent and identically distributed (i.i.d.), the preceding expression can be simplified as

$$P_{\psi}(\omega) \;=\; \left[F_{\psi}(\omega)\right]^{U-1} \qquad (10)$$

By substituting Equation (7) into Equation (10), the expression for $P_{\psi}(\omega)$ can be obtained as follows:

$$P_{\psi}(\omega) \;=\; \left[e^{-(\omega\alpha)^2} - j\sqrt{\frac{\pi}{2}}\alpha\omega \;\; e^{-\omega^2\alpha^2/2}\right]^{U-1} = \sum_{\ell=0}^{U-1} \binom{U-1}{\ell} \left(\sqrt{\frac{\pi}{2}}\alpha\right)^{\ell} (-1)^{\ell} (j\omega)^{\ell} \left(e^{-\omega^2\alpha^2}\right)^{U-1-\frac{\ell}{2}} \qquad (11)$$

Concerning the Fourier transform (FT):

$$(j\omega)^{\ell} G(\omega) \Leftrightarrow \frac{d^{\ell}}{d\psi^{\ell}}(g(\psi)) \qquad (12)$$

Let $G(\omega) = \left(e^{-\omega^2\alpha^2}\right)^{U-1-\frac{\ell}{2}}$ then:

$$g(\psi) = \frac{1}{\alpha\sqrt{4\pi\left(U-1-\frac{\ell}{2}\right)}} e^{-\psi^2/4\alpha^2\left(U-1-\frac{\ell}{2}\right)} \qquad (13)$$

If Equation (13) is substituted into Equation (12), the Inverse Fourier Transform (IFT) of Equation (11) can be derived as ℓ th derivative of $g(\psi)$ with respect to ψ. Equally,

$$\frac{d^\ell}{d\psi^\ell}(g(\psi)) = \frac{d^\ell}{d\psi^\ell}\left(\frac{1}{\alpha\sqrt{4\pi\left(U-1-\frac{\ell}{2}\right)}} e^{-\psi^2/4\alpha^2\left(U-1-\frac{\ell}{2}\right)}\right) \qquad (14)$$

The reduction of the resultant expression mainly utilizes the Hermite polynomial and its definition:

$$H_\ell(x) = (-1)^\ell e^{x^2} \frac{d^\ell}{dx^\ell}\left(e^{-x^2}\right) \qquad (15)$$

$H_\ell(x)$ which is the Hermite polynomial. Rewriting the equation, we get:

$$\frac{d^\ell}{dx^\ell}\left(e^{-x^2}\right) = (-1)^{-\ell} e^{-x^2} H_\ell(x) \qquad (16)$$

Now, let $x = \frac{\psi}{2\alpha\sqrt{U-\frac{\ell}{2}}}$

The using of the developed polynomial in Equation (14) makes it as:

$$\frac{d^\ell}{d\psi^\ell}\left(e^{-\psi^2/4\alpha^2\left(U-1-\frac{\ell}{2}\right)}\right) = (-1)^{-\ell}\left(\frac{1}{2\alpha\sqrt{k-1-\frac{\ell}{2}}}\right)^\ell e^{-\psi^2/4\alpha^2\left(U-1-\frac{\ell}{2}\right)} H_\ell\left(\frac{\psi}{2\alpha\sqrt{U-1-\frac{\ell}{2}}}\right) \qquad (17)$$

Based on this result, the pdf of ψ can be evaluated as:

$$p_\psi(\psi) = \sum_{\ell=0}^{U-1}\binom{U-1}{\ell}\left(\sqrt{\frac{\pi}{2}}\alpha\right)^\ell (-1)^\ell \frac{1}{\alpha\sqrt{4\pi\left(U-1-\frac{\ell}{2}\right)}}(-1)^{-\ell}$$

$$\times\left(\frac{1}{2\alpha\sqrt{U-1-\frac{\ell}{2}}}\right)^\ell e^{-\psi^2/4\alpha^2\left(U-1-\frac{\ell}{2}\right)} H_\ell\left(\frac{\psi}{2\alpha\sqrt{U-1-\frac{\ell}{2}}}\right) \qquad (18)$$

Substituting Equation (18) into Equation (8) yields the average BEP as:

$$P_e = \sum_{\ell=0}^{U-1}\binom{U-1}{\ell}\frac{1}{\alpha\sqrt{16\pi\left(U-1-\frac{\ell}{2}\right)}}\left(\sqrt{\frac{\pi}{2}}\alpha\right)^\ell\left(\frac{1}{2\alpha\sqrt{U-1-\frac{\ell}{2}}}\right)^\ell \times\int_{I_0}^{\infty} e^{-\psi^2/4\alpha^2\left(U-1-\frac{\ell}{2}\right)} H_\ell\left(\frac{\psi}{2\alpha\sqrt{U-1-\frac{\ell}{2}}}\right)d\psi \qquad (19)$$

Because the above integral equation does not admit a closed-form solution, numerical evaluation is performed.

3. Numerical Results

In this section we present validation of the proposed model by matching the analytical results with the numerical tests. The numerical analysis is performed with emphasis on the important parameter α^2. This value is written as $\alpha^2 = \frac{\sigma_\varsigma^2}{2-\frac{\pi}{2}}$, where:

$$\sigma_\varsigma^2 = \frac{NT_c^2}{6}\sum_{m=1}^{U-1} P_m \qquad (20)$$

$T_c = 1$ and $P_0 = P_1 = P_{U-1} = 2$.

The BEP change as a function of the number of users (U) is shown in Fig. 1. The Spreading gain N parameterizes the plotted curves, highlighting its impact on system performance. When the spreading gain increases, the BEP is reduced.

This results in a relatively bigger spreading gain helping the system resist interference more effectively, leading to a lower BEP than that given by smaller spreading gain. Figure 1 illustrates this assertion.

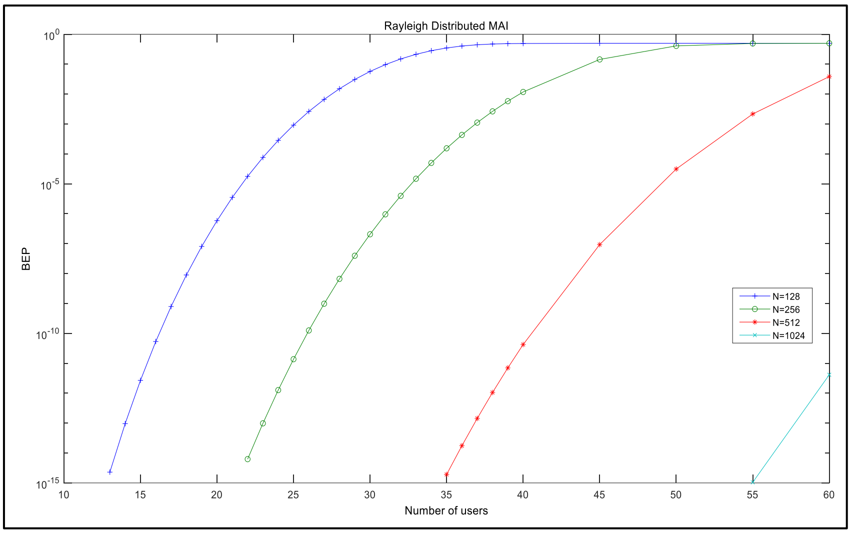


Figure 1 BEP with total number of users at different spreading gains and assuming that the MAI is Rayleigh-distributed with $\alpha^2 = \sigma_\varsigma^2/10\left(2-\frac{\pi}{2}\right)$

The plotted family of curves provides the values for $\alpha^2 = \frac{\sigma_\varsigma^2}{2-\frac{\pi}{2}}$, $\alpha^2 = \frac{\sigma_\varsigma^2}{10\left(2-\frac{\pi}{2}\right)}$, and $\alpha^2 = \frac{\sigma_\varsigma^2}{20\left(2-\frac{\pi}{2}\right)}$ that we can interpret. In order to better describe how the effect of α^2 on BEP behavior changes there are adjusted curves shown in Figure 2 for smaller values α^2 and in Figure 3 for larger values of α^2. This means that the parameter α^2 has a significant impact on the BEP with respect to the number of users. The BEP similarly correlates with lower $\alpha^2$and subsequently lowers. The underlying theory is that a smaller α^2means that the variance of MAI is smaller. The BEP will have larger values for BEP as α^2increases. With more users, the BEP increases: the MAI has a stronger effect on the reference user. BEP is directly affected by the variance of the MAI. In figure 4, we can see this relationship is in the form of plotting the BEP given the number of users U at different variance values. This figure shows a general trend in the family of curves, but when the variance is greater, the beginning of the one curve follows another curve with U-values of higher numbers. The asymptotic BEP approaches about 50% for all instances. An effective technique is to increase the spreading gain to alleviate the negative effects of this variance. This effect is shown in Figure 5.

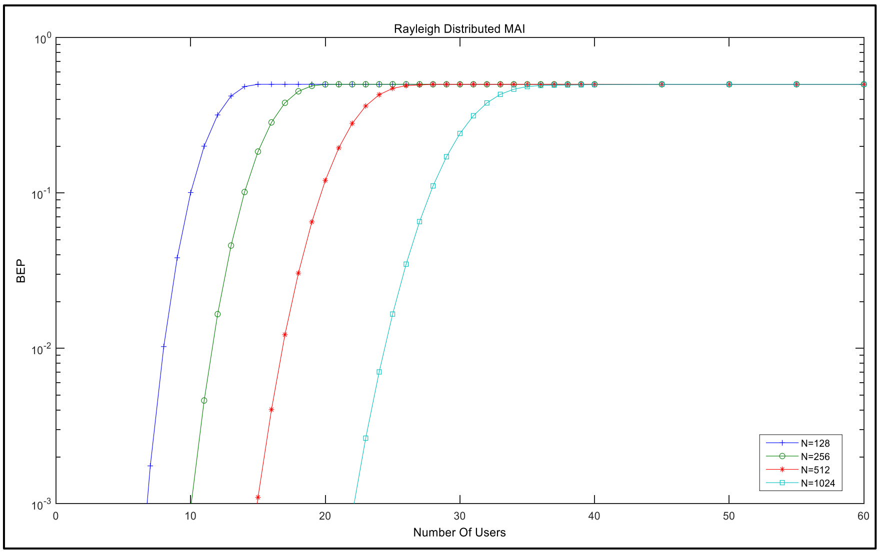


Figure 2 BEP with total number of users at different spreading gains and assuming that the MAI is Rayleigh-distributed with $\alpha^2 = \sigma_\varsigma^2/\left(2-\frac{\pi}{2}\right)$

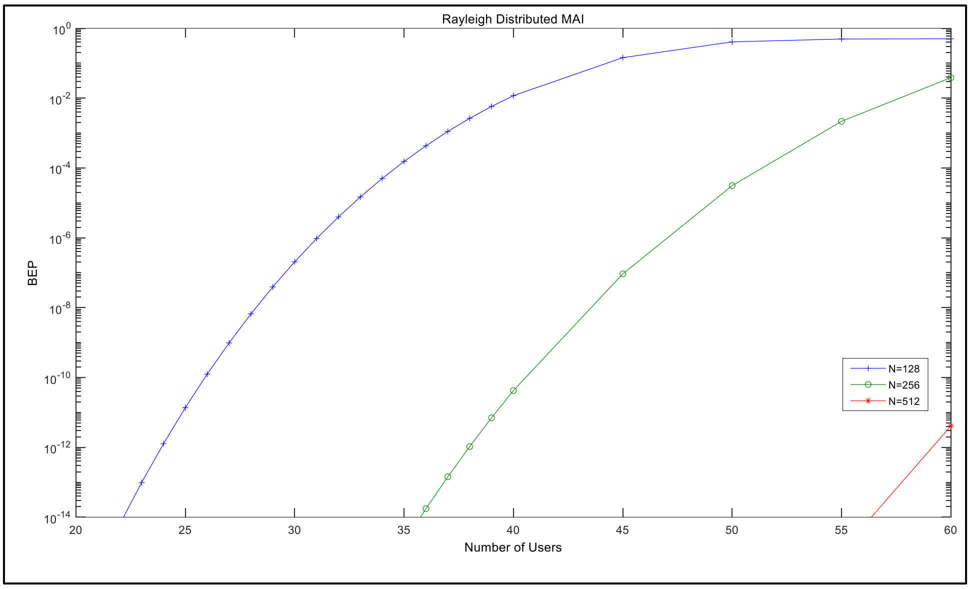


Figure 3 BEP with total number of users at different spreading gains and assuming that the MAI is Rayleigh-distributed with $\boldsymbol{\alpha^2 = \sigma_\varsigma^2/20\left(2-\frac{\pi}{2}\right)}$

We compare the presented model with previous authors of the previous papers for BEP and computed several BEP values by using our method and those computed already described as methods. The related results are shown in Figure 6(a) for N = 128 and $\alpha^2 = \sigma_\varsigma^2/\left(2-\frac{\pi}{2}\right)10$.

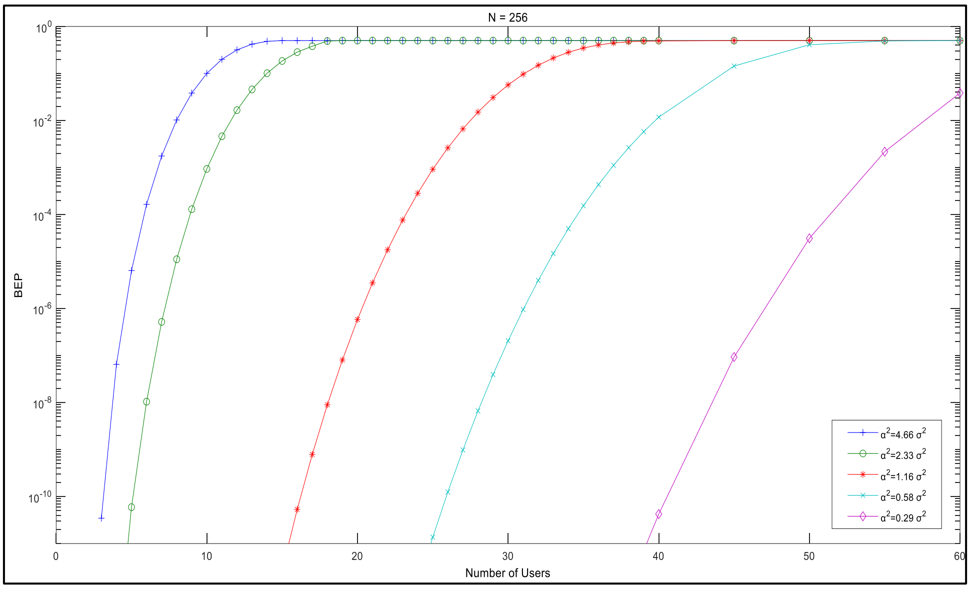


Figure 4 BEP versus the number of users U for various $\boldsymbol{\alpha^2}$ when N = 256

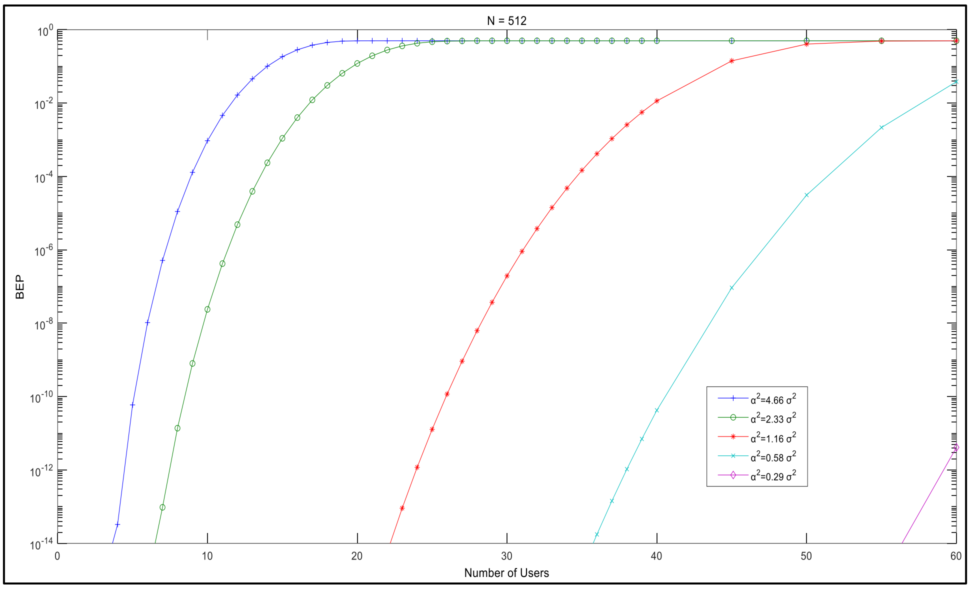
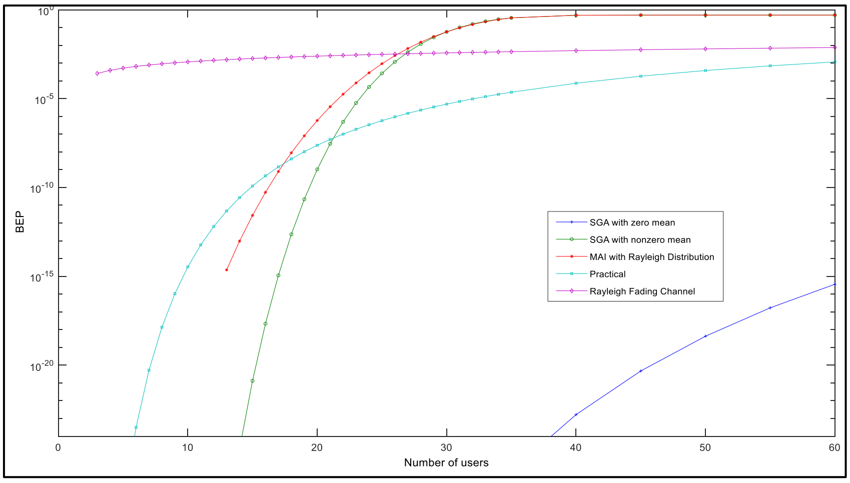


Figure 5 BEP versus the number of users U for various α^2 when N = 512

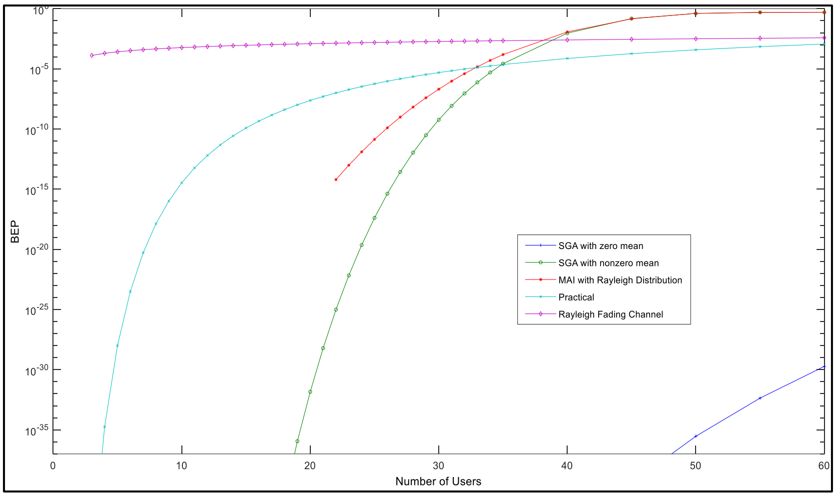
Figure 5 shows that the Rayleigh channel produces the highest BEP values when the user count is small. As U increases, the BEP also rises, with the growth rate depending on the employed detection approach. The reference model achieves superior performance up to U=17; beyond this point, the proposed scheme outperforms the SGA (non-zero mean). This trend persists up to U=28, where both techniques converge and the BEP value reaches identical level, which is significantly larger compared to the reference case and Rayleigh channel cases.

In contrast, the SGA (non-zero mean) produces lower BEP values. The proposed Rayleigh-based approach assumes a non-zero mean, making its closest equivalent the SGA (non-zero mean). For smaller U, the proposed model achieves lower BEP compared with the SGA (non-zero mean). As U increases, both techniques provide nearly the same BEP, consistent with the Central Limit Theorem (CLT), which states that the summation of independent random variables tends to form a Gaussian distribution.

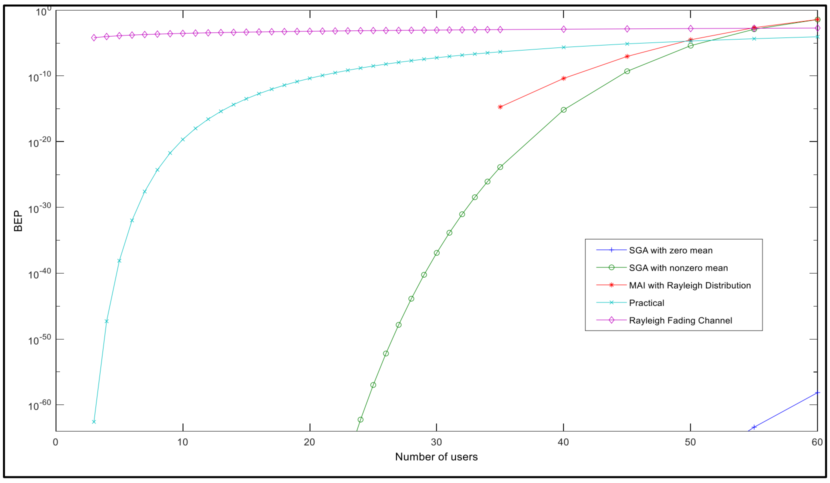
The curves in this figure are generated for fixed N and MAI variance. To highlight the influence of MAI variance, the simulation is repeated using a different α^2 value, as illustrated in Figure 6(b). In this case, the reference model maintains superior performance up to U = 28, after which the proposed method outperforms the SGA (non-zero mean). The advantage persists until U=40, beyond which both techniques yield identical BEP values, still exceeding those of the reference and Rayleigh channels.



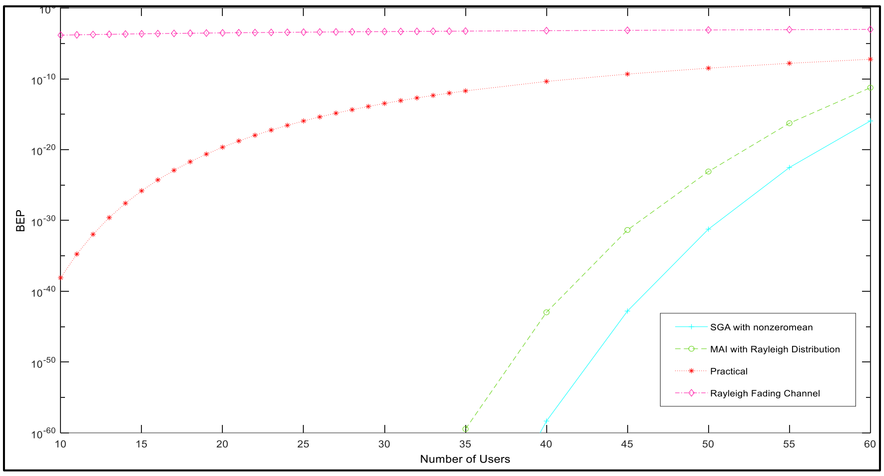
(a) N= 64



(b) N= 128



(c) N= 512



(d) N= 1024

Figure 6 Comparison of BEP curves for different calculation techniques with varying α^2 and spreading gain (N)

To further analyze the effect of the spreading gain, the curves are regenerated for different N values, as shown in Figure 6(c) and Figure 6(d). The results indicate that the SGA (non-zero mean) assumption is impractical, since the MAI mean is non-zero, which invalidates the SINR expression under that condition.

4. Conclusion

In this paper, we discuss the Rayleigh distribution, a new and more realistic distribution for Multiple Access Interference (MAI) in asynchronous DS-CDMA networks. In contrast to classical Gaussian approximations, the proposed approach compensates for the dynamic, bursty and fading-prone nature of the interference to the target user. The obtained analytical formulation is used as a basis for an accurate estimate of Bit Error Probability (BEP) and thus to give an accurate characterization of MAI in practical deployment situations. The novelty of this paper is an application of Rayleigh modelling to MAI, which has not been covered before in literature. Numerical findings establish the fit of the proposed model for systems with limited user number, where the standard Gaussian approximation will not achieve accurate results. The Central Limit Theorem (CLT) states that the overall interference distribution will tend toward the Gaussian distribution when the number of interfering users is high so that our proposed method is consistent with classical models in high-user conditions. BEP performance may be influenced by various parameters, as shown in its MAI variance and spreading gain. When increasing spreading gain, BEP reduces indicating an increased resistance to interference, but having a higher MAI variance will also lead to an increase in BEP. The numerical results for smaller user groups are close to the reference, indicating that the Rayleigh-based approach is superior over others.

Compliance with ethical standards

Disclosure of conflict of interest

The authors have declared that no competing interests exist.

Author contributions

Conceptualization, Methodology: Nasr Rashid, Mohamed B. El_Mashad, and Hussein A. Konber. Formal analysis, Investigation: Mohammed Albekairi, Khaled Kaaniche. Project administration: Mohamed B. El_Mashad, and Hussein A. Konber. Resources: Nasr Rashid. Supervision: Mohamed B. El_Mashad, and Hussein A. Konber . Validation: Nasr Rashid, Mohammed Albekairi, and Khaled Kaaniche. Visualization: Mohammed Albekairi, Khaled Kaaniche. Writing – original draft: Nasr Rashid. Writing – review & editing: Nasr Rashid.

Data availability statement

All data are in the manuscript and/or supporting information files.

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