Eksplorium *p*-ISSN 0854-1418
Volume 46 No. 1, May 2025: 1566–1578 *e*-ISSN 2503-426X

Relay Selection in Cooperative Communication using Log-Likelihood Ratio over a Two-State Markov Fading Channel

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Article Received: 22 Feb 2025, Revised: 25 April 2025, Accepted: 04 May 2025

Abstract: - The demand for higher data rates and seamless coverage in real-time applications is a primary driving force behind the rapid evolution of wireless communication technologies. A critical challenge in the development of advanced communication systems is ensuring both reliability and spectral efficiency. One of the promising solutions to this challenge is the implementation of Multiple-Input Multiple-Output (MIMO) systems, which significantly enhance performance. Cooperative relaying, in particular, extends the benefits of MIMO technology to devices equipped with only a single antenna. By enabling resource sharing in environments where some users may be inactive, cooperative relaying introduces cooperative diversity, enhancing overall system performance. The adaptability of cooperative communication protocols allows them to be effectively utilized in various applications, such as sensor networks and Mobile Ad-hoc Networks (MANETs). This paper proposes a novel method based on the log-likelihood ratio for selecting relays, and models the dynamic, time-varying wireless channel as a two-state Markov process, incorporating both Rayleigh and Rician fading models. The proposed approach's effectiveness is demonstrated through extensive simulation results, which showcase notable performance improvements in terms of reliability and data throughput. The findings suggest that this method can play a crucial role in optimizing cooperative communication systems.

Keywords: Cooperative Communication, Cooperative diversity, Log-Likelihood ratio, Markov channel, Relay Selection, Wireless Communication

1. INTRODUCTION

Cooperative diversity leverages distributed single-antenna devices to form a virtual antenna array [1, 2], offering an effective approach to mitigate multipath fading and enhance Quality of Service (QoS) in communication systems. The reliability of signal reception is improved in cooperative diversity systems through the exploitation of multiple independently faded copies of the transmitted signal at the receiver, achieving diversity gain. This technique contrasts with traditional spatial diversity, which necessitates multiple antennas at the transmitter or receiver, leading to increased hardware complexity [1, 2].

In mobile communication, multipath propagation and shadowing induce signal attenuation and distortion. Flat fading further exacerbates this by subjecting the transmitted signal to narrowband Additive White Gaussian Noise (AWGN), resulting in fluctuations in received power and an increased probability of burst errors. Finite-state channel models, based on Markov chain processes, provide a means to characterize the correlation structure of fading channels, offering a valuable tool for analysis [3].

Diversity enhancement techniques, such as the beam-forming approach proposed by Sendonaris et al. [4, 5], have been explored to improve communication system performance. However, beam-forming often requires prior channel knowledge and modifications to radio resources, increasing system complexity. Alternative cooperative diversity schemes, including fixed, incremental, and selective relaying, have been analyzed by Laneman et al. [1, 2]. Furthermore, distributed space-time block coding and coded cooperation represent other methods to achieve cooperative diversity [6, 7, 8, 9].

Cooperative diversity offers improved spectral efficiency, but the simultaneous operation of relay nodes necessitates orthogonal channels to avoid interference, leading to increased bandwidth requirements [10, 11, 12, 13]. Consequently, effective relay selection mechanisms are crucial to optimize bit error rate (BER) performance and spectral efficiency. Research in this area has explored various relay selection strategies, including those based on instantaneous channel conditions [10, 11], threshold selection [12], optimized user selection [13], and signal strength [15]. Additionally, signal-to-noise ratio (SNR) based selection and adaptive on-demand relay selection schemes have been investigated to enhance energy efficiency and reduce spectrum requirements [16, 17, 18].

The log-likelihood ratio (LLR) has emerged as a significant metric for enhancing communication system performance, with studies demonstrating its effectiveness in improving cooperative diversity systems. LLR-based relay selection methods have been proposed to minimize bit error probability and optimize relay selection in decode-and-forward relaying [23, 24, 25]. Moreover, recognizing the time-varying nature of wireless channels, researchers have employed finite-state Markov channels (FSMC) to model fading environments accurately [27, 28, 29].

Cooperative strategies offer enhanced robustness and efficiency, as evidenced by a DSTC-OFDM scheme achieving significant anti-jamming gains [30] and optimized relay selection in FANETs improving network performance in disaster scenarios [31]. Furthermore, deep reinforcement learning presents a promising avenue for efficient relay selection in collaborative networks with limited channel knowledge [32].

This paper develops a simulation framework for cooperative diversity systems that use an LLR-based relay selection scheme. The framework models transitions between Rayleigh and Rician fading by utilizing a two-state FSMC model. Performance evaluation of the proposed scheme is conducted using metrics such as channel capacity, bit error rate, and outage probability. This evaluation provides insights into the scheme's effectiveness under dynamic channel conditions.

2. RELAY-ASSISTED COMMUNICATION MODEL

A cooperative diversity scenario is analyzed, featuring a source node, a destination node, and several single-antenna relay nodes. Communication is structured in two phases: broadcast and relay, with all channels operating in a half-duplex manner. The source broadcasts its signal to the destination and relays. The relay phase employs LLR-based relay selection (following the method in [23]) to choose the relay that exhibits the maximum LLR value (which corresponds to the minimum probability of error) to assist the source in forwarding the information, as visually depicted in Figure 1.

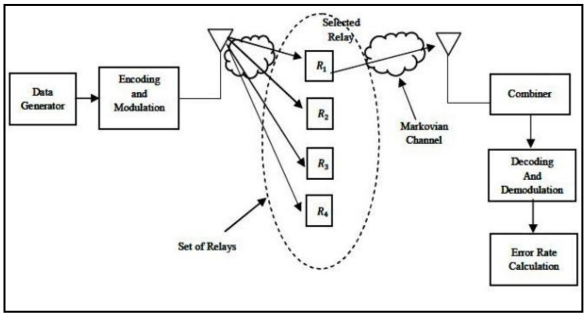

Figure 1: Cooperative Communication System Block Diagram

Consider a constellation data symbol that is M-Point and is valued complexly, denoted as $S \in \mathbb{C}^{1\times N}$, which is a product of the M-array phase shift keying (MPSK) modulation technique. Data accepted at the i[th] no. of relay, represented by $y_{SR_i} \in \mathbb{C}^{1\times N}$, is a function of the complex channel coefficients, $H_{sr_i}, H_{r_iD} \in \mathbb{C}^{1\times N}$and Additive White Gaussian Noise (AWGN). This noise has mean of zero and a variance of $n_{sr_i}, n_{r_iD} \in \mathbb{C}^{1\times N}$, and it affects the links among the source - i[th] relay - destination. For both the source-2-relay and relay-2-destination connections, the channel coefficients are modeled using a two-state Markov process. This model captures the transitions occurring between communication environments characterized by Rayleigh and Rician fading (as illustrated in Figure 2). It shows the probabilities of these transitions within the two-state Finite-State Markov Channel (FSMC). Specifically, P_{AB}, indicates the probability of a shift from the fading state of Rayleigh to fading state of Rician, while P_{BA}, indicates the probability of a shift from the Rician fading state to the Rayleigh fading state.

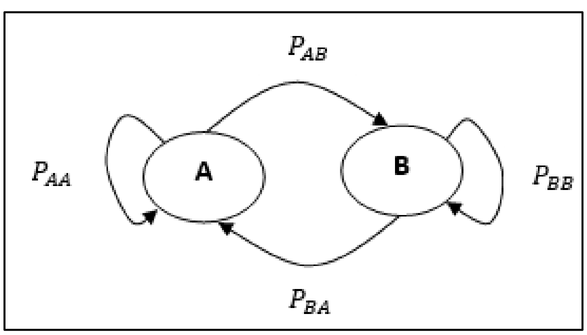

Figure 2: 2-state Markov channel representing Rayleigh fading state (A) and Rician fading state (B)

Considering the premise that explicit communication amid source-destination terminals is not dependable, The source transmits data to the destination through an intermediate relay in a two-step process: initial transmission to the relay, and subsequent forwarding to the destination. The total power available for transmission is denoted by P, and noise power spectral density is represented by N_0.

Source *S* sequentially broadcasts its signal to M relays during Phase I, resulting in the following formulation for the data received at the i[th] relay as:

$$Y_{sr_i} = \sqrt{\frac{P}{N_0}} * H_{sr_i} * S + n_{sr_i} \forall i = 1, \ldots, M \qquad (1)$$

In this context, H_{sr_i} represents the channel gain bounded by the i[th] relay node and source, S being the modulated signal with $+\sqrt{E_s}$ or $-\sqrt{E_s}$ magnitudes that are equally probable, n_{sr_i} is additive white Gaussian noise (AWGN) with mean being zero and a per-dimension divergence of $I_0/2$.

Following this, the present study utilizes a relay selection approach grounded in the log-likelihood ratio (LLR), as detailed in the optimal antenna selection strategy presented in [23]. The relays involved in the cooperative communication then compute the magnitude of the LLR, which is expressed as:

$$\Delta_i = ln \frac{P\left(x = +\sqrt{E_s} | H_{sr_i}, y_i\right)}{P\left(x = -\sqrt{E_s} | H_{sr_i}, y_i\right)} = \frac{4\sqrt{E_s}}{I_0} Re\left\{H^*_{sr_i} y_i\right\} = \left|H_{sr_i}\right|^2 x + Re\{H^*_{sr_i}, n_{sr_i}\} \qquad (2)$$

The absolute value of the LLR, as shown in Equation (2), serves as an indicator of the confidence in the binary decision, whereas its algebraic sign determines the value of that decision. Moreover, the probability of a bit error at the i[th] relay, symbolized by P_{e_i}, is associated with the magnitude of the LLR, Δ_i, according to the following relationship:

$$P_{e_i} = \frac{1}{1 + e^{|\Delta_i|}} \qquad (3)$$

As evidenced by Equation (3), the likelihood of error at the i[th] relay exhibits an inverse relationship with the absolute LLR value, $|\Delta_i|$. Consequently, the most effective approach to reduce the error probability is to choose the relay that offers the maximum LLR magnitude. The minimal error probability achievable through this selection process is then expressed as:

$$P_{e,opt} = E_{\Delta_{max}} \left[\frac{1}{1 + e^{\Delta_{max}}}\right] \qquad (4)$$

Here, $\Delta_{max} = \max_{1 \le i < M} |\Delta_i|$

According to Equation (4), the two relays with the highest LLR magnitudes are chosen in second phase, i.e., the relaying phase. This chosen couple of relays then applies an amplification factor β to the received signal and transmits it towards the destination terminal. The signal received at the destination node can be represented as:

$$y_{r_i,d} = \sqrt{\frac{P}{N_0}} * h_{r_id} * \beta * Y_{sr_i} + \eta_{r_id} \forall i = 1,2 \quad (5)$$

In this context, β represents the amplification factor, which is determined by the gain of the channel linking the source to the i[th] relay, and its value is expressed as:

$$\beta = \sqrt{\frac{1}{\left|h_{sr_i}\right|^2 * P + N_0, sr_i}} \quad (6)$$

The combined signal obtained through maximal ratio combining (MRC) at the receiver is expressed as:

$$\tilde{S} = h^*_{r_1D} y_{r_1,d} + h^*_{r_2D} y_{r_2,d} = \left\{\left(\left|h_{r_1D}\right|^2 + \left|h_{r_2D}\right|^2\right) * Y_{sr_i} + h^*_{r_1D} n_{r_1D} + h_{r_2D} n^*_{r_2D}\right\} \quad (7)$$

3. ERROR PROBABILITY ANALYSIS

The average SER for coherent MPSK modulation scheme is given by Equation 8 as:

$$P_b(E) = \frac{1}{\pi} \int_0^{\pi-(\pi/M)} \phi_\gamma \left(\frac{g_{mpsk}}{\sin^2\theta}\right) d\theta \quad (8)$$

Here, $g_{mpsk} = \sin^2(\frac{\pi}{M})$

Above Equation can be re-written as:

$$P_b(E) = \frac{1}{\pi} \int_0^{\pi/2} \phi_\gamma \left(\frac{g_{mpsk}}{\sin^2\theta}\right) d\theta + \frac{1}{\pi} \int_{\pi/2}^{\pi-(\pi/M)} \phi_\gamma \left(\frac{g_{mpsk}}{\sin^2\theta}\right) d\theta \quad (9)$$

Let's consider

$f_1 = \frac{1}{\pi} \int_0^{\pi/2} \phi_\gamma \left(\frac{g_{mpsk}}{\sin^2\theta}\right) d\theta$ and

$$f_2 = \frac{1}{\pi}\int_{\pi/2}^{\pi-(\pi/M)} \phi_\gamma\left(\frac{g_{mpsk}}{\sin^2\theta}\right)d\theta$$

Let f_1 be solved by letting $t = \cos^2(\theta)$

Therefore, $t^{\frac{1}{2}} = \cos(\theta)$ and $(1-t)^{-\frac{1}{2}} = \sin(\theta)$

and, $dt = -2cos\theta sin\theta d\theta$

or $d\theta = -\frac{dt}{2cos\theta sin\theta}$

Also, $f_1 = \frac{1}{2\pi}\int_0^1 \left(\frac{msin^2\theta + g_{mpsk}\bar{\gamma}}{msin^2\theta}\right)^{-m}\frac{dt}{cos\theta sin\theta}$

On substituting above values, we get

$$f_1 = \frac{1}{2\pi}\int_0^1\left(\frac{m(1-t)+g_{mpsk}\bar{\gamma}}{m(1-t)}\right)^{-m}\frac{1}{(t\ldots} \quad (10)$$

Furthermore, f_2 be solved by letting $t = \frac{\cos^2\theta}{Cos^2(\pi/M)}$ then, $dt = \frac{-2cos\theta sin\theta}{cos^2(\pi/M)}d\theta$ or $d\theta = -\frac{cos^2\left(\frac{\pi}{M}\right)}{2cos\theta sin\theta}dt$.

Also let $\cos^2\theta = t\cos^2\left(\frac{\pi}{M}\right)$ or $cos\theta = t^{\frac{1}{2}}\cos(\pi/M)$ therefore, $\sin^2\theta = 1 - tcos^2(\pi/M)$

or $sin\theta = 1 - t^{\frac{1}{2}}\cos(\pi/M)$

Substituting these values in Eq. (9) we get,

$$P_b(E) = \frac{\frac{1}{2\pi}\int_0^1\left(\frac{m(1-t)+g_{mpsk}\bar{\gamma}}{m(1-t)}\right)^{-m} 1}{t^{\frac{1}{2}}}\frac{1}{(1-t)^{\frac{1}{2}}} + \frac{1}{\pi}\int_0^1\left(\frac{m\left(1-t\cos^2\left(\frac{\pi}{M}\right)\right)+g_{mpsk}\bar{\gamma}}{m\left(1-\cos^2\left(\frac{\pi}{M}\right)\right)}\right)^{-m}\frac{\cos\left(\frac{\pi}{M}\right)}{2(t)^{1/2}\cos\left(\frac{\pi}{M}\right)\left(1-t^{1/2}\cos\left(\frac{\pi}{M}\right)\right)}dt \quad (11)$$

Or

$$P_b(E) = \frac{1}{2\pi}\int_0^1\left(\frac{m(1-t)+g_{mpsk}\bar{\gamma}}{m(1-t)}\right)^{-m}\frac{1}{t^{\frac{1}{2}}}\frac{1}{(1-t)^{\frac{1}{2}}} + \frac{1}{\pi}\int_0^1\left(\frac{m\left(1-t\cos^2\left(\frac{\pi}{M}\right)\right)+g_{mpsk}\bar{\gamma}}{m\left(1-\cos^2\left(\frac{\pi}{M}\right)\right)}\right)^{-m}\frac{\cos\left(\frac{\pi}{M}\right)}{\left(2t\cos\left(\frac{\pi}{M}\right)-2(t)^{1/2}\right)}dt \quad (12)$$

Or

$$P_b(E) = \frac{1}{2\pi}\int_0^1 (t)^{-\frac{1}{2}}(1-t)^{-\frac{1}{2}}\left(\frac{m(1-t)+g_{mpsk}\bar{\gamma}}{m(1-t)}\right)^{-m}dt + \frac{1}{\pi}\int_0^1\left(\frac{m\left(\cos\left(\frac{\pi}{M}\right)-t\cos^3\left(\frac{\pi}{M}\right)\right)+g_{mpsk}\bar{\gamma}\cos\left(\frac{\pi}{M}\right)}{m\left(1-t\cos^2\left(\frac{\pi}{M}\right)\right)\left(2t\cos\left(\frac{\pi}{M}\right)-2(t)^{\frac{1}{2}}\right)}\right)^{-m} \quad (13)$$

Or

$$P_b(E)=\frac{1}{2\pi}\int_0^1 (t)^{-\frac{1}{2}}(1-t)^{-\frac{1}{2}}\left(\frac{m(1-t)+g_{mpsk}\bar{\gamma}}{m(1-t)}\right)^{-m}dt+\frac{1}{\pi}\cos\left(\frac{\pi}{M}\right)\int_0^1\left(\frac{m\left(1-t\cos^2\left(\frac{\pi}{M}\right)\right)+g_{mpsk}\bar{\gamma}}{m\left(1-t\cos^2\left(\frac{\pi}{M}\right)\right)\left(2t\cos\left(\frac{\pi}{M}\right)-2(t)^{\frac{1}{2}}\right)}\right)^{-m}dt \quad (14)$$

i.e,

$$P_b(E)=\frac{1}{2\pi}\int_0^1 (t)^{-\frac{1}{2}}(1-t)^{-\frac{1}{2}}\left(\frac{m(1-t)+g_{mpsk}\bar{\gamma}}{m(1-t)}\right)^{-m}dt + \frac{1}{\pi}cos\left(\frac{\pi}{M}\right)\int_0^1 (m + g_{mpsk}\bar{\gamma})^{-m}\left(\frac{1-\frac{tcos^2\left(\frac{\pi}{M}\right)}{(m+g_{mpsk}\bar{\gamma})}}{m\left(1-tcos^2\left(\frac{\pi}{M}\right)\right)\left(2tcos\left(\frac{\pi}{M}\right)-2(t)^{\frac{1}{2}}\right)}\right)dt \quad (15)$$

By performing the integration of Equation (15), the ultimate expression for the probability of error is derived as:

$$P_b(E)=\frac{\Phi_\gamma(g_{mpsk})\Gamma\left(m+\frac{1}{2}\right)}{2\sqrt{\pi}\Gamma(m+1)}\left[2\,{}_2F_1\left(m,\frac{1}{2}:m+1;\frac{1}{1+\frac{g_{mpsk}\bar{\gamma}}{m}}\right)\right] + \frac{1}{\pi}\cos\left(\frac{\pi}{M}\right)\Phi_\gamma(g_{mpsk})\left(F_1\left(\frac{1}{2},m,\frac{1}{2}-m;\frac{3}{2};\frac{cos^2\left(\frac{\pi}{M}\right)}{1+\frac{g_{mpsk}\bar{\gamma}}{m}},cos^2\left(\frac{\pi}{M}\right)\right)\right) \quad (16)$$

4. RESULTS AND DISCUSSION

This study evaluates the performance of an LLR-based relay selection scheme over a two-state Markov channel model. The simulations were conducted using MATLAB, modeling a system with a single-antenna source, destination, and multiple relay nodes. The simulation assumes no direct communication between the source and destination nodes, with data transmission occurring exclusively through relays. A Markov process with two states was utilized to model the communication channel. In this model, the initial state corresponds to a Rayleigh fading environment, while the subsequent state represents a Rician fading environment. The metrics used to evaluate performance included the performance metrics for the proposed system model include bit error rate (BER), channel capacity, and outage probability. The simulations explore the impact of varying transition probabilities within the Markov channel. In addition, a comparison is made between the suggested relay selection method and existing relay selection methods.

The study, using the designed framework, investigates the relationship between distance and power allocation, and the resulting channel capacity, bit error rate and outage probability.

Figure 3 illustrates bit error rate performance comparison of the LLR-occupied relay-selection scheme for the two-state Markov channel under varying probabilities. The LLR relay selection scheme demonstrates optimal performance in the Rayleigh fading environment, achieving an error probability on the order of 10^{-5} dB. Beyond this point, the proposed approach exhibits a significantly reduced bit error rate.

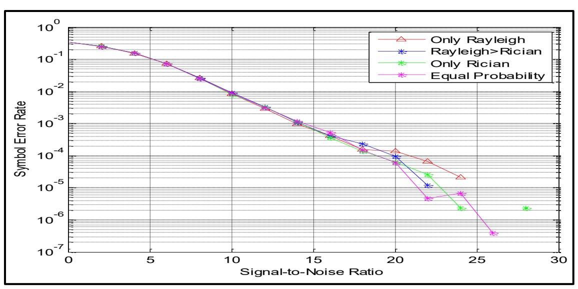

Figure 3: Performance Analysis of bit error rate for the suggested scheme under various channel transition probabilities

Figure 4 depicts a comparative analysis of the LLR-occupied relay selection strategy against traditional relay selection methods, including Max-Min, Random selection and Harmonic Mean. The Harmonic Mean and Max-Min relay-selection strategy reach a BER of 10^{-4} dB at SNR of 30 dB, while the proposed approach achieves the same BER at an SNR of 18 dB. Under Rayleigh fading conditions, the proposed scheme demonstrates a 12 dB SNR improvement.

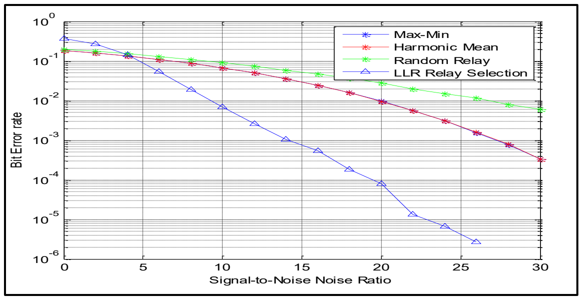

Figure 4: Analysis of bit error rate performance between conventional and proposed relay selection methods

Figure 5 depicts how the bit error rate (BER) changes with varying power distribution ratios between the initial and subsequent transmission stages of the presented system model. The optimal performance for this framework is observed when approximately 80% of overall available transmitted power is assigned to source node.

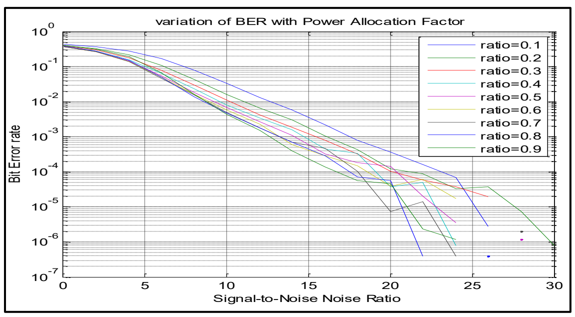

Figure 5: Influence of the power allocation factor on the bit error rate performance of the suggested scheme

We now examine channel capacity performance of the proposed cooperative scheme.

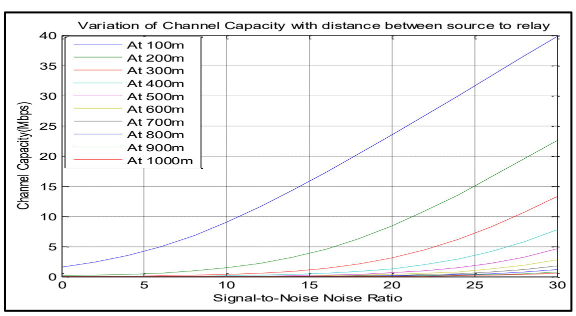

Figure 6: Impact of source-relay distance on channel capacity

Figure 6 depicts the impact of the separation between the source and relay on the calculated channel capacity. One can evidently see, as the distance separating the source-relay nodes grows, the channel capacity diminishes. Peak channel capacity attained is around 40 Mbps, given a bandwidth of 5 MHz with path loss exponent of 3.5.

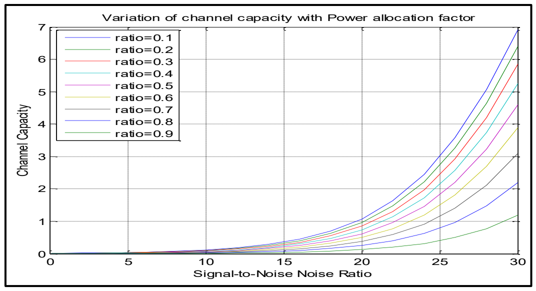

Figure 7: Influence of power allocation on channel capacity

Figure 7 displays the changes in channel capacity as the power allocation factor is varied. The findings suggest an inverse relationship, where channel capacity diminishes with an increasing power allocation factor.

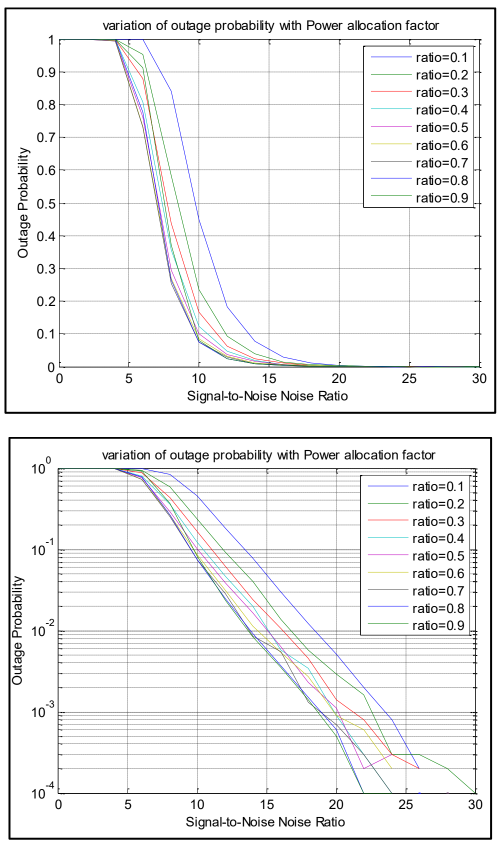

Figure 8: Outage probability vs. power allocation factor for the proposed system

The subsequent figures 8(a) and (b) present a comparative analysis of outage probability for the proposed system model as a function of the power allocation factor, with the outage threshold set to 10^{-4} dB.

Outage probability, a key measure of performance, indicates the chance that the quality of the received signal drops beneath a specified level, resulting in a breakdown of communication. The graphs illustrate that outage probability decreases as the power allocation factor increases, indicating improved system reliability with higher allocation factors.

5. CONCLUSION

Cooperative diversity methods present a viable approach to tackle the challenges of spectrum inefficiency in wireless communication networks. Various sophisticated communication frameworks, such as Wireless Sensor Networks (WSNs), Cognitive Radios (CRs), Mobile and Vehicular Ad-Hoc Networks (MANETs and VANETs), utilize cooperative leverage cooperative relaying to enhance system performance. However, cooperative relaying techniques present certain challenges, notably the selection of an optimal relaying strategy. Within this framework, the present study puts forth an optimized relay selection technique founded on the log-likelihood ratio (LLR) criterion. To simulate practical communication environments, a simulation platform based on a Markov channel was constructed to replicate the shifts between Rayleigh and Rician fading conditions. The assessment of performance, carried out using metrics such as bit error rate (BER), outage probability and channel capacity, reveals that the suggested scheme yields a 12 dB enhancement in SNR when matched with conventional relay selection approaches, with a peak channel capacity of approximately 40 Mbps attained at a bandwidth of 5 MHz. Moreover, the influence of changing channel conditions on the system's performance has been analyzed.

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