XLIII Simpozijum o novim tehnologijama u poštanskom i telekomunikacionom saobraćaju – PosTel 2025, Beograd, 16-17. decembar 2025.

https://doi.org/10.37528/FTTE/9788673955056/POSTEL.2025.25

AGENTIC AI FOR NETWORK MANAGEMENT: RELAY SIGNAL PERFORMANCE UNDER NAKAGAMI-M FADING

Miloš Milašinović[1], Nemanja Zdravković[1], Suad Suljović[2], Nenad Petrović[3]
[1]Faculty of Information Technology, Belgrade Metropolitan University,
milos.milasinovic@metropolitan.ac.rs, nemanja.zdravkovic@metropolitan.ac.rs
[2]MB Univerzitet, suadsada@gmail.com
[3]Faculty of Electronic Engineering, University of Niš, nenad.petrovic@elfak.ni.ac.rs

Abstract: *This paper investigates signal transmission over a relay link using the Amplify-and-Forward (AF) technique under Nakagami-m fading conditions. The system outage probability (Pout) at the receiver is analyzed through the der-ivation of the probability density and cumulative distribution functions of the instantaneous signal-to-noise ratio (SNR). The results show that the receiver sensitivity threshold has a key impact on system performance, while the reduction of relay transmit power has a much smaller effect. The study also includes a graphical representation of the outage probability (P_{out}) for different parameter values, providing insights into the reliability of AF relay systems and guidance for optimizing system design in fading environments. In the second part, we introduce an agentic AI workflow for network management, utilizing the outage probability expression and channel parameters derived in the case study*.

Keywords*: Nakagami-m fading, Outage probability, signal-to-noise ratio (SNR), Agentic AI*

1. Introduction

In wireless communication systems, variations in the received signal caused by multi-path fading and shadowing are key factors leading to performance degradation. These phenomena are typically modeled in theoretical and experimental analyses using sta-tistical distributions such as Rayleigh, Rician, Nakagami-m, and Weibull, with the choice of distribution depending on the characteristics of the propagation environment and the communication scenario [1], [2]. Among these, the Nakagami-m distribution is particularly important due to its flexibility in representing different fading severities through the parameter mmm [3]. Relay transmission is an effective technique for improving the coverage, capacity, and reliability of wireless networks. Multi-hop transmission allows signal delivery via one or more relay nodes when the direct link between the source and destination experiences severe impairments [4]. This ap proach is also advantageous in ad hoc networks, as it facilitates communication with-out central infrastructure and mitigates channel impairments through diversity [5]. Relay systems are generally classified into regenerative (Decode-and-Forward, DF) and non-regenerative (Amplify-and-Forward, AF) types. AF relays can operate with either fixed or adaptive gain based on channel state information (CSI), which contrib-utes to performance optimization [3], [6]. Analyzing relay systems under Nakagami-m fading conditions provides a more accurate assessment of reliability, which is cru-cial for the efficient design of modern wireless networks. Performance evaluation typically focuses on metrics such as average Signal-to-Noise Ratio (SNR) and outage probability (Pout), the latter being essential for determining system coverage and man-aging co-channel interference (CCI) in accordance with Quality of Service (QoS) and Grade of Service (GoS) requirements [7], [8].

In this paper, we analyze the outage probability at the receiver in a relay transmission system using the Amplify-and-Forward (AF) technique over channels modeled by the Nakagami-m distribution. Special attention is given to the impact of transmission parameters on system performance under varying propagation conditions. Afterward, we examine the potential of OpenAI's o1 family of Large Language Models (LLMs), which are distinguished by their advanced reasoning and planning capabilities. The proposed approach leverages previously computed outage probability values to sup-port the maintenance of Quality of Service (QoS) in mobile networks. To demonstrate this concept, we developed a proof-of-concept AI agent implemented in Python.

2. The outage probability analysis of relay systems

Figure 1 shows the transmission model of an Amplify-and-Forward (AF) relay sys-tem, where the S–R and R–D links experience Nakagami-*m* fading with average power γ_1 and γ_2. The relay applies a fixed gain G, amplifying both signal and noise (c = 1). The outage probability (Pout) is evaluated assuming $\gamma_1 = \gamma_2 = \gamma$, $m_1 = m_2 = m$, $w_1 = w_2 = w$, and no diversity reception.

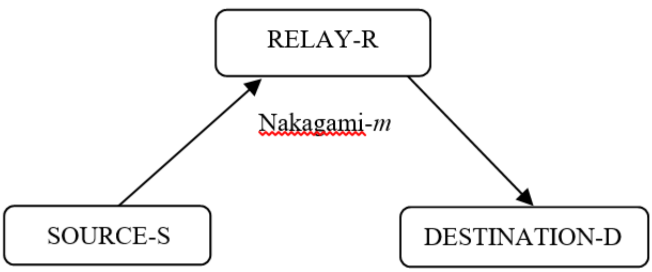

Figure 1. Relay transmission model under Nakagami-m fading on both links

For an accurate performance analysis of the relay system, it is essential to determine the statistical characteristics of the received signal, particularly the Probability Densi ty Function (PDF) and the Cumulative Distribution Function (CDF). These functions describe the behavior of the signal over the source–relay (S–R) and relay–

destination (R–D) links, where the propagation environment is modeled by the Nakagami-m distribution. The PDF of the amplitude values of the received signal x, subject to Nakagami-*m* fading on the considered link, is given in [9]:

$$p_x\left(x\right)=\frac{2}{\Gamma\left(m\right)}\left(\frac{m}{\Omega}\right)^m x^{2m-1}e^{-\frac{n}{\Omega}x^2}\ , \tag{1}$$

where Ω is the mean value of the signal power x, $\Gamma\left(\cdot\right)$ is the Gamma function, and m is the Nakagami fading parameter, which describes the fading severity (m > 0.5). As the parameter m increases, the fading severity decreases.

Introducing the notation γ for the value of the probability density of the signal-to-noise
ratio (SNR), i.e., the instantaneous SNR per symbol, we obtain the expression

$$x^2=\frac{\gamma}{w}\Omega, x=\sqrt{\frac{\gamma}{w}\Omega}\,,\left|J\right|=\frac{\partial x}{\partial\gamma}=\frac{dx}{d\gamma}=\frac{d}{d\gamma}\left(\sqrt{\frac{\gamma}{w}\Omega}\right)=\frac{1}{2\sqrt{\gamma}}\sqrt{\frac{\Omega}{w}}\,, \tag{2}$$

where *J* is the Jacobian of the variable transformation and *w* is the average SNR. Using expression [10, 2.3], the PDF of the instantaneous SNR is:

$$p_\gamma\left(\gamma\right)=\left|J\right|p_X\left(x\right)=\frac{1}{2\sqrt{\gamma}}\sqrt{\frac{\Omega}{w}}p_X\left(\sqrt{\frac{\gamma\Omega}{w}}\right)=\frac{\gamma^{m-1}}{\Gamma\left(m\right)}\left(\frac{m}{w}\right)^m e^{-\frac{m}{w}\gamma} \tag{3}$$

Using expression (3), the CDF of the instantaneous SNR [11] is:

$$F_\gamma\left(\gamma\right)=\int_0^\gamma p\left(t\right)dt=\frac{1}{\Gamma\left(m\right)}\left(\frac{m}{w}\right)^m\int_0^\gamma t^{m-1}e^{-\frac{m}{w}\gamma}dt \tag{4}$$

The integral in expression (4) is solved using the mathematical identity [12, 11.1.9]:

$$\int_0^c x^{b-1}e^{-x}dx=\gamma\left(b,c\right) \tag{5}$$

where $\gamma\left(b,\ c\right)$ is the lower Gamma function, and it can be expressed as [11]:

$$\gamma\left(n,x\right)=\Gamma\left(n\right)e^{-x}\sum_{k=0}^{n-1}\frac{x^k}{k!} \tag{6}$$

Substituting expressions (5) and (6) into (4), the SNR CDF becomes:

$$F_{\gamma}\left(\gamma\right)=1-e^{-\frac{m}{w}\gamma}\sum_{j_1=0}^{m-1}\frac{1}{j_1!}\left(\frac{m}{w}\gamma\right)^{j_1} \tag{7}$$

The system outage probability represents the probability that the observed SNR at the receiver falls below a predefined threshold γ_{th}, defined in accordance with the Quality of Service (QoS) standards and the Grade of Service (GoS) [13]:

$$P_{out}=F_{\gamma_{eq}}\left(\gamma_{th}\right)=1-\int_{0}^{\infty}C_{\gamma_1}\left[\gamma_{th}+\frac{\gamma_{th}^2+c\gamma_{th}}{t}\right]p_{\gamma_2}\left[\gamma_{th}+t\right]dt\ , \tag{8}$$

where $C_{\gamma_i}\left(\cdot\right)$ is the complementary CDF of γ_i, given by:

$$C_{\gamma_i}\left(\cdot\right)=\left|1-F_{\gamma_i}\left(\cdot\right)\right| \tag{9}$$

Substituting (7) into (9) gives the complementary CDF of γ_i at R:

$$C_{\gamma_1}\left(\gamma_{th}+\frac{\gamma_{th}^2+c\gamma_{th}}{t}\right)=e^{-\frac{m}{w}\left(\gamma_{th}+\frac{\gamma_{th}^2+c\gamma_{th}}{t}\right)}\sum_{j_i=0}^{m-1}\frac{1}{j_1!}\left(\frac{m}{w}\left(\gamma_{th}+\frac{\gamma_{th}^2+c\gamma_{th}}{t}\right)\right)^{j_i} \tag{10}$$

where the parameter *c* is 0 or 1, and γ_{th} is the threshold. Using expressions (3), the PDF of the SNR for the S-R-D link at the receiver is:

$$p_{\gamma_2}\left(\gamma_{th}+t\right)=\frac{\left(\gamma_{th}+t\right)^{m-1}}{\Gamma\left(m\right)}\left(\frac{m}{w}\right)^{m}e^{-\frac{m}{w}\left(\gamma_{th}+t\right)} \tag{11}$$

By substituting (10) and (11) into expression (8), the P_{out} for the S-R-D portion during signal transmission in the presence of Nakagami-m fading at the receiver is:

$$P_{out}=1-\frac{e^{-2\frac{m}{w}\gamma_{th}}}{\Gamma\left(m\right)}\sum_{j_1=0}^{m-1}\frac{\gamma_{th}}{j_1!}\left(\frac{m}{w}\right)^{j_1+m}\times\int_{0}^{\infty}\left(\gamma_{th}+t\right)^{m-1}\left(\frac{\gamma_{th}+c+t}{t}\right)^{j_1}e^{-\frac{m}{w}t}e^{-\frac{m\gamma_{th}\left(\gamma_{th}+c\right)}{w}\left(\frac{1}{t}\right)}dt \tag{12}$$

Using the binomial formula [14, 1.111]:

$$\left(a+x\right)^{n}=\sum_{k=0}^{n}\binom{n}{k}a^{n-k}x^{k} \tag{13}$$

In expression (12), the P_{out} can be written in the following form:

$$P_{out}=1-\frac{1}{\Gamma(m)}e^{-2\frac{m}{w}\gamma_{th}}\sum_{j_1=0}^{m-1}\sum_{j_2=0}^{m-1}\sum_{j_3=0}^{j_1}\binom{j_1}{j_3}\binom{m-1}{j_2}\left(\frac{m}{w}\right)^{j_1+m}$$
$$\times\frac{\gamma_{th}^{j_1-j_2+m-1}\left(\gamma_{th}+c\right)^{j_1-j_3}}{j_1!}\int_0^{\infty}t^{j_2+j_3-j_1}e^{-\frac{m}{w}t}e^{-\frac{m\gamma_{th}(\gamma_{th}+c+t)}{w}\left(\frac{1}{t}\right)}dt \tag{14}$$

By applying the formula [14, 3.471]:

$$\int_0^{\infty}x^{v-1}e^{-\frac{\beta}{x}-\gamma x}dx=2\left(\frac{\beta}{\gamma}\right)^{\frac{v}{2}}K_v\left(2\sqrt{\beta\gamma}\right) \tag{15}$$

for the solution of the integral in expression (14), where $K_v(x)$ is the second-order Bessel function, the P_{out} at the receiver can be written in the following form:

$$P_{out}=1-\frac{2}{\Gamma(m)}e^{-2\frac{m}{w}\gamma_{th}}\sum_{j_1=0}^{m-1}\sum_{j_2=0}^{m-1}\sum_{j_3=0}^{j_1}\frac{\gamma_{th}^{\frac{j_1+j_3-j_2+2m-1}{2}}}{j_1!(w/m)^{j_1+m}}\binom{m-1}{j_2}$$
$$\times\left(\gamma_{th}+c\right)^{\frac{j_1+j_2-j_3+1}{2}}\binom{j_1}{j_3}K_{j_2+j_3-j_1+1}\left(2\frac{m}{w}\sqrt{\gamma_{th}\left(\gamma_{th}+c\right)}\right) \tag{16}$$

The following chapter presents the outage probability P_{out} of the average signal-to-noise ratio [dB] for different values of the parameters m and γ_{th}, obtained based on expression (16) using the software packages Origin and Mathematica.

2.1. Graphical representation of system outage probability results

Figure 2 shows the receiver outage probability P_{out} from expression (16) as a function of average SNR for different values of *m* and γ_{th}.

From Figure 2, it can be observed that as the parameter m increases, the system outage probability decreases, indicating an improvement in system performance. Conversely, as the threshold parameter γ_{th} increases, the system outage probability rises, reflecting a degradation in system performance. This behavior highlights the significant impact of the Nakagami-m fading parameter and the SNR threshold on the reliability and efficiency of the communication system.

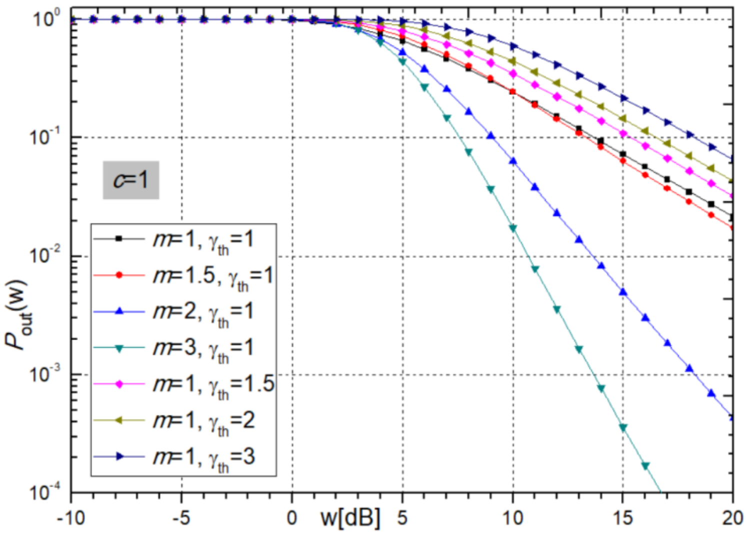

Figure 2. System outage probability for varying values of m and γ_{th}

3. Network management using agent-based artificial intelligence

In large-scale 5G deployments, where user density and operating conditions fluctuate dynamically, ensuring consistent Quality of Service (QoS) over extended periods is critical for maintaining user satisfaction. Artificial Intelligence (AI) has emerged as a key enabler of intelligent network automation and long-term QoS assurance [15]. To address these challenges, we propose a novel agent-based AI framework for network management, built on OpenAI's latest generation of large language models (LLMs). While LLMs have demonstrated strong proficiency in natural language tasks such as summarization and content generation, their direct application to numerically inten-sive or strategic planning problems has traditionally been limited. To overcome this limitation, OpenAI introduced the o1 model family [16], an advancement of the GPT- 4 architecture. These models integrate reinforcement learning into the training pro-cess, thereby strengthening their ability to reason through and navigate complex, mul-ti-step scenarios.

A defining feature of the o1 models is their internal chain-of-thought (CoT) reason-ing, which allows them to decompose complex problems into a structured sequence of manageable steps during response generation. This capability enables o1 models to surpass conventional LLMs in tasks requiring deep analysis and strategic decision-making [16, 17]. Recent studies on the integration of agentic AI into telecommunica-tions further underscore this approach as a foundational enabler for next-generation mobile networks, with applications spanning autonomous network maintenance, self-healing functionalities, and improved user experience [18]. The proposed workflow is illustrated in Fig. 3.

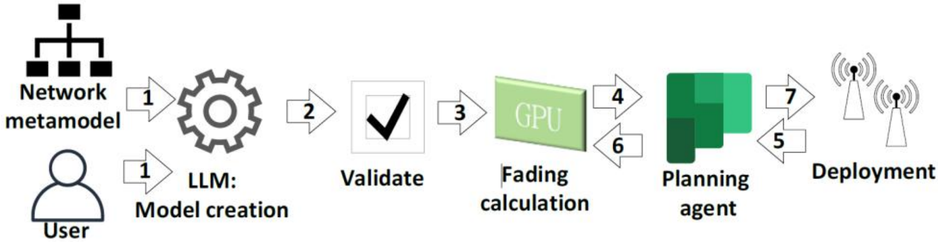

Figure 3. Workflow overview: (1) Define experiment; (2) Generate JSON schema; (3) Populate network experiment in JSON; (4) Apply rule-based validation; (5) Determine outage probability; (6) Monitor infrastructure; (7) Perform recalculations; (8) Issue planning and reconfiguration commands.

The workflow begins with the user submitting an unstructured textual description of a network scenario. This description may include details such as the assumed fading model, the type of co-channel interference, infrastructure parameters, and the ex-pected number of users. From this input, an experiment model is instantiated in JSON format, adhering to a metamodel (JSON schema) defined in our prior work [15]. The generated model is then subjected to rigorous validation against a predefined rule set to ensure both completeness and semantic accuracy, as outlined in [15].

Once validated, the finalized model is passed to a GPU-accelerated simulation engine [19], which efficiently computes Pout values. These results are subsequently utilized by a planning agent powered by a large language model (LLM), which devises an appropriate sequence of actions to maintain acceptable Quality of Service (QoS) lev-els for end users. The resulting action plan is then executed through NETCONF commands, enabling reconfiguration of the underlying network infrastructure.

To demonstrate this process, we employed the o4-mini model (a lightweight and re-source-efficient member of the o1 family). The complete prompt was formulated as follows: "Your objective is to manage a mobile network. Your responsibilities include analyzing telemetry data, calculating key performance indicators (KPIs), detecting underperforming cells, and recommending corrective actions such as adjusting trans-mission power or antenna azimuth. If the calculated outage probability exceeds a predefined threshold, the planner may initiate one or more of the following actions: (1) increase transmission power by 2 dB, or (2) modify antenna azimuth by 10°. The result should be a reconfiguration command submitted to a NETCONF service end-point. You are supported by an LLM agent capable of executing your plan using the following available functions: (1) read_snr(cell_id) – retrieves the latest signal-to-noise ratio (SNR) measurements via NETCONF; (2) calculate_pout(snr_values, threshold) – computes *P*out using SNR values below the specified threshold; (3) get_config(cell_id) – obtains the current transmission power and azimuth settings; (4) update(cell_id, new_tx_power, new_azimuth) – modifies the power and azimuth set-tings; (5) reconfig(cell_id, tx_power, azimuth) – applies new configuration values to the specified cell." To demonstrate the effectiveness of this agentic AI-driven work-flow, in Table I we present two illustrative experiments derived from use case of out-age probability and observations from Fig. 2.

Table 1. Agentic AI-Based QoS maintenance experiments overview

Case	Constraints	Pout threshold	Outcome
$w = 10dB, \gamma_{th} = 1, m = 3$	$m > 1$ and $c = 1$	0.01	P_{out} > threshold ➔ update
$w = 15dB, \gamma_{th} = 1, m = 2$	$m > 1$ and $c = 1$		P_{out} < threshold ➔ no action

4. Conclusion

In this study, signal transmission over a relay path under Nakagami-m fading was analyzed using the Amplify-and-Forward (AF) method, without applying diversity techniques. The results show that the system outage probability mainly depends on the receiver sensitivity threshold, while the reduction of relay transmit power has a much smaller impact. Receiver sensitivity is thus identified as the key factor deter-mining overall system performance. Furthermore, we present a proof-of-concept implementation to illustrate the potential of employing state-of-the-art large language models (LLMs) with advanced reasoning and planning capabilities for automating network maintenance tasks. The initial findings indicate that this approach holds significant promise for enabling innovative applications and improving maintenance strategies in network management. Looking forward, future work will focus on extending the planning framework to incorporate additional considerations, particularly safety aspects such as the impact of electromagnetic radiation, buidling upon the work presented in [20].

Acknowledgments: This work has been supported in part by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia [Grant Number: 451-03-137/2025-03/200102] and [Grant Number: 451-03-137/2025-03/200148; Goal 9], and in part by the Blockchain Technology Laboratory at Belgrade Metropolitan University.

Literature

[1] W. C. Y. Lee, *Mobile Communications Engineering*, McGraw-Hill, 2001.
[2] M. Pätzold, *Mobile Fading Channels: Modelling, Analysis and Simulation*, Wiley, 2nd ed., 2005.
[3] M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels*, 2nd ed., Wiley, 2005.
[4] H. El-Sayed and O. A. Dobre, "Performance Analysis of Amplify-and-Forward Relaying over Nakagami-m Fading Channels," *IEEE Communications Letters*, vol. 17, no. 2, pp. 325–328, 2013.
[5] S. Mumtaz, J. Rodriguez, and L. Dai (Eds.), *5G Mobile Communications*, Wiley, 2016.
[6] N. Yang, Y. Zhong, and S. Zhang, "Outage Probability Analysis of Multi-hop AF Relay-ing over Nakagami-m Fading Channels," *IEEE Access*, vol. 6, pp. 12315–12324, 2018.
[7] J. Proakis, *Digital Communications*, 4th ed., McGraw-Hill, 2001.

[8] S. A. Alshebeili, S. K. Sharma, and X. Wang, “Interference Management in 5G and Be-yond Networks: A Survey,” *IEEE Communications Surveys & Tutorials*, vol. 22, no. 1, pp. 70–93, 2020.
[9] S. Suljović, D. Krstić, D. Bandjur, S. Veljković, M. Stefanović, "Level Crossing Rate of Macro-diversity System in the Presence of Fading and Co-channel Interference", Revue Roumaine des Sciences Techniques, Publisher: Romanian Academy, ISSN: 0035-4066, Vol. 64, 1, pp. 63–68, Bucharest, 2019.
[10] S. Panić, M. Stefanović, J. Anastasov and P. Spalević: Fading and Interference Mitigation in Wireless Communications, Taylor & Francis Publishing group, CRC Press, New York, USA, ISBN 978-14665-0841-5, December 2013.
[11] S. Suljović and D. Milić, "Performance of Relay Signal Transmission by AF Technique Influenced by κ-μ Fading, 27th Telecommunications Forum (TELFOR)", 2019, DOI: 10.1109/TELFOR48224.2019.8971264
[12] J. Alan, D. Hui-Hui, Handbook of Mathematical Formulas and Integrals: 4th edition, San Diego, 2008.
[13] M. O. Hasna and M. S. Alouini, "End-to-end performance of transmission systems with relays over Rayleigh-fading channels", IEEE Transactions on Wireless Communications, ISSN: 1536-1276, Vol. 2, pp. 1126-1131, November 2003.
[14] I. S. Gradshteyn and I. M. Ryzhik, Tables of Integrals, Series and Products Academic: New York, 1980.
[15] D. Krstic, S. Suljovic, G. Djordjevic, N. Petrovic, and D. Milic, "MDE and LLM synergy for network experimentation: case analysis of wireless system performance in Beaulieu-Xie fading and κ-μ cochannel interference environment with diversity combining", Sen-sors, vol. 24, no. 10, p. 3037, 2024. https://doi.org/10.3390/s24103037
[16] OpenAI, "Introducing OpenAI o1", OpenAI, Sep. 2024. [Online]. Available: https://openai.com/o1/, last accessed: 24/04/2025.
[17] K. Wang, J. Li, N. P. Bhatt, Y. Xi, Q. Liu, U. Topcu, and Z. Wang, "On The Planning Abilities of OpenAI’s o1 Models: Feasibility, Optimality, and Generalizability", arXiv preprint arXiv:2409.19924, Sep. 2024. [Online]. Available: https://arxiv.org/abs/2409.19924
[18] Y. Xiao, G. Shi, and P. Zhang, "Towards Agentic AI Networking in 6G: A Generative Foundation Model-as-Agent Approach", arXiv, preprint, pp. 1-7, 2025. https://arxiv.org/pdf/2503.15764
[19] N. Petrović, S. Vasić, D. Milić, S. Suljović, S. Koničanin, "GPU-Supported Simulation for ABEP and QoS analysis of a Combined Macro Diversity System in a Gamma-Shadowed k-μ fading channel", Facta Universitatis: Electronics and Energetics Vol. 34, No 1, March 2021, pp. 89-104. https://doi.org/10.2298/FUEE2101089P
[20] N. Petrović, D. Milić, D. Javor, M. Jović, S. Škrbić and E. Suljović, "Llm-Based Emr Estimation: Channel Capacity in Mrc System Under κ−μ Fading for Wireless Signal Transmission Case Study," 2025 12th International Conference on Electrical, Electronic and Computing Engineering (IcETRAN), Cacak, Serbia, 2025, pp. 1-4, doi: 10.1109/IcETRAN66854.2025.11114218.N.

Rezime: *U ovom radu analiziraju se performanse prenosa signala preko relejne veze korišćenjem tehnike Amplify-and-Forward (AF) u uslovima Nakagami-m fedinga. Posebna pažnja posvećena je verovatnoći ozkaza sistema (Pout) na prijemnoj strani, koja je određena izvođenjem funkcija gustine verovatnoće i kumulativne funkcije raspodele trenutnog odnosa signal-šum (SNR). Dobijeni rezultati pokazuju da prag osetljivosti prijemnika ima presudan uticaj na ukupne performanse sistema, dok smanjenje izlazne snage releja ima znatno manji efekat. Dodatno, prikazana je grafička analiza verovatnoće prekida za različite vrednosti parametara, koja pruža dublji uvid u pouzdanost AF relejnih sistema i može poslužiti kao smernica za optimizaciju dizajna sistema u promenljivim kanalnim uslovima. U drugom delu rada predstavljen je agentni AI tok rada za upravljanje mrežom, koji koristi izraze za verovatnoću prekida i parametre kanala izvedene u studiji slučaja, čime se ukazuje na mogućnosti integracije agentnih AI modela u adaptivno mrežno upravljanje.*

Ključne reči: *Nakagami-m feding, verovatnoća otkaza, odnos signal-šum (SNR), Agentni AI*

AGENTNA VEŠTAČKA INTELIGENCIJA ZA UPRAVLJANJE MREŽAMA: PERFORMANSE RELEJNOG PRENOSA SIGNALA U USLOVIMA NAKAGAMI-M FEDINGA

Miloš Milašinović, Nemanja Zdravković, Suad Suljović, Nenad Petrović