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PERFORMANCE ANALYSIS OF HYBRID FSO / RF COMMUNICATION SYSTEM WITH RECEIVE DIVERSITY IN THE PRESENCE OF CHI-SQUARE/GAMMA TURBULENCE AND RICIAN FADING

ХИ-КВАДРАТ/ГАММА СИГНАЛЫНЫҢ ТАРАЛУЫ ЖӘНЕ РИЦИАНДЫҚ ЫДЫРАУ ЖАҒДАЙЫНДА ҚАБЫЛДАУ ӘРТҮРЛІЛІГІМЕН FSO/RF ГИБРИДТІ БАЙЛАНЫС ЖҮЙЕСІНІҢ ТИІМДІЛІГІН ТАЛДАУ

АНАЛИЗ ЭФФЕКТИВНОСТИ ГИБРИДНОЙ КОММУНИКАЦИОННОЙ СИСТЕМЫ FSO/RF ПРИЕМНЫМ РАЗНООБРАЗИЕМ В УСЛОВИЯХ РАСПРОСТРАНЕНИЯ СИГНАЛА ХИ-КВАДРАТ/ГАММА РАСПРЕДЕЛЕНИЯ И РИЦИАНОВСКОГО ЗАТУХАНИЯ

Abstract. *Within mobile communication systems, the inherent limitations of mobile devices necessitate a considerable portion of signal processing to occur at the base station. The technique of multiple access at the base station, entailing the amalgamation of diverse received signals, plays a pivotal role in the reconstruction of the original signal. This investigation introduces an innovative hybrid FSO/RF system that operates via a single-hop transfer, adeptly incorporating the concept of receive diversity to effectively counteract the challenges posed by saturated atmospheric turbulence. It is important to note that the FSO channel is observed under the Gamma/Chi-Square turbulence model, while the RF channel adheres to the Rician fading model. Notably, the study also yields a closed-form expression for the outage probability of the system. The results underscore significant enhancements in comparison to conventional FSO and RF systems. Despite the demand for an advanced receiver, the proposed hybrid architecture presents substantial improvements that significantly impact the performance of the communication system. It's noteworthy that at the reception, the Switch and Stay (SSC) combining technique along with Selection Combining diversity (SC) strategies are being observed. This holistic approach not only addresses the challenges posed by atmospheric conditions but also harnesses the benefits of diversity techniques to enhance the overall reliability and performance of the communication system.*
Keywords: *Hybrid RF/FSO, diversity combining, Gamma/Chi-Square turbulence model, outage probability.*

Аңдатпа. *Ұялы байланыс жүйелері аясында мобильді құрылғылардың ішкі шектеулері базалық станцияда сигналды өңдеудің едәуір бөлігін қажет етеді. Бастапқы сигналды қалпына келтіруде әртүрлі қабылданған сигналдарды біріктіруді қамтитын базалық станциядағы бірнеше қол жеткізу әдісі шешуші рөл атқарады. Бұл зерттеу қаныққан атмосфералық турбуленттіліктен туындаған қиындықтарды тиімді жеңу үшін Бұл зерттеу қаныққан атмосфералық* *турбуленттіліктен туындаған қиындықтарды тиімді жеңу үшін қабылдау әртүрлілігі тұжырымдамасын шебер біріктіре отырып, бір реттік беру арқылы жұмыс істейтін инновациялық гибридті FSO/RF жүйесін ұсынады. Маңыздысы, FSO арнасы Гамма/хи-квадрат турбуленттілік моделіне сәйкес қарастырылады, ал RF арнасы рициан моделіне сәйкес келеді. Зерттеу сонымен қатар жүйенің істен шығу ықтималдығы үшін аналитикалық өрнек береді. Нәтижелер дәстүрлі FSO және RF жүйелерімен салыстырғанда айтарлықтай жақсаруды көрсетеді. Жетілдірілген қабылдағыштың қажеттілігіне қарамастан, ұсынылған гибридті архитектура байланыс жүйесінің жұмысына әсер ететін айтарлықтай жақсартуды білдіреді. Қабылдау кезінде таңдау стратегияларының (SC) әртүрлілігімен біріктірілген "ауыстыру және қалдыру" (SSC) біріктіру әдісі бар екенін атап өткен жөн. Бұл кешенді тәсіл атмосфералық жағдайлардан туындаған мәселелерді шешіп қана қоймайды, сонымен қатар байланыс жүйесінің жалпы сенімділігі мен өнімділігін жақсарту үшін әртүрлілік әдістерінің артықшылықтарын пайдаланады.*

Түйін сөздер: *Гибридті FSO/RF, әртүрлілікті біріктіру, гамма / хи-квадрат турбуленттілік моделі, бас тарту ықтималдығы.*

Аннотация. *В рамках систем мобильной связи, внутренние ограничения мобильных устройств требуют значительной части обработки сигнала на базовой станции. Техника множественного доступа на базовой станции, включающая объединение различных принятых сигналов, играет ключевую роль в восстановлении исходного сигнала. В данном исследовании представлена инновационная гибридная система FSO/RF, которая работает через однократную передачу, искусно интегрируя концепцию приемного разнообразия для эффективного преодоления вызванных насыщенной атмосферной турбулентностью трудностей. Важно отметить, что канал FSO рассматривается в соответствии с моделью турбулентности Гамма/Хи-квадрат, в то время как RF-канал соответствует рициановской модели. Исследование также дает аналитическое выражение для вероятности отказа в работе системы. Результаты подчеркивают значительное улучшение по сравнению с традиционными системами FSO И RF. Несмотря на потребность в продвинутом приемнике, предложенная гибридная архитектура представляет собой существенное улучшение, которое влияет на производительность коммуникационной системы. Следует отметить, что на приеме наблюдается метод комбинирования «Переключение и оставление» (SSC) в сочетании с разнообразием стратегий выбора (SC). Этот комплексный подход не только решает проблемы, вызванные атмосферными условиями, но также использует преимущества техник разнообразия для улучшения общей надежности и производительности коммуникационной системы.*

Ключевые слова: *Гибридная FSO/RF, комбинирование разнообразия, модель турбулентности Гамма/Хи-квадрат, вероятность отказа.*

Introduction. In the realm of contemporary communication systems, the quest for escalated data rates, heightened security, and refined network efficiency remains an incessant pursuit. Within this context, the emergence of Free-Space Optical (FSO) communication stands as a transformative technology poised to reshape data transmission paradigms. FSO, also referred to as optical wireless communication, harnesses the potential of visible or infrared light waves to convey data through the atmosphere. This innovative methodology presents a multitude of captivating advantages in contrast to conventional Radio Frequency (RF) communication methodologies, holding promise for addressing pivotal challenges within the domain. FSO communication bears the capacity to furnish data rates several magnitudes greater than those achievable through RF communication. By employing high-frequency light waves, FSO systems can achieve data rates reaching multi-gigabits per second, effectively satiating the voracious data appetite pervasive in today's data-centric landscape [1]. Unlike RF systems confined within limited and often congested spectrums, FSO harnesses the vast expanse of the optical spectrum. This intrinsic trait renders FSO communication impervious to electromagnetic interference, ensuring steadfast and dependable communication even in environments prone to RF disruptions [2]. The security prowess of FSO communication stems from its focused optical beams. Characterized by their narrow and directed trajectory, these beams create formidable challenges for unauthorized interception unless positioned precisely within the line of sight.

This distinctive characteristic bolsters data confidentiality and security, positioning FSO as an apt choice for applications necessitating stringent protection measures [3]. In contrast to RF systems, FSO platforms exhibit diminished latency. This reduced time lag holds paramount significance in scenarios demanding real-time interactions, such as online gaming and video conferencing, where minimal delay is pivotal for an uninterrupted user experience [4]. FSO communication functions within the unlicensed optical spectrum, negating the requirement for regulatory endorsements and the accompanying expenses. This attribute expedites deployment and scalability, endowing FSO with feasibility in contexts such as last-mile connectivity and disaster recovery operations [5]. The optical spectrum proffers substantial bandwidth, empowering FSO setups to accommodate the burgeoning demand for high-definition video streaming, cloud services, and nascent applications like Virtual Reality (VR) and Augmented Reality (AR) [6]. Concurrently, FSO communication embraces inherent energy efficiency and environmental compatibility. By leveraging light as the medium of transmission, FSO systems engender minimal power consumption and generate no electromagnetic radiation, aligning harmoniously with sustainability imperatives and attenuating their impact on the electromagnetic ecosystem**.**

FSO communication exhibits a myriad of advantageous traits; however, it is not impervious to challenges, notably its sensitivity to atmospheric phenomena such as turbulence, fog, and precipitation. To address these challenges, researchers have turned to the exploration of hybrid systems amalgamating the merits of FSO and RF technologies. Hybrid RF/FSO communication systems capitalize on the inherent strengths of each technology to counterbalance their respective constraints, culminating in a more resilient and versatile communication paradigm [8]. Such hybrid architectures proffer augmented reliability through seamless transition between RF and FSO channels, contingent on prevailing conditions. This adaptability ensures uninterrupted communication continuity, even in the face of varying atmospheric dynamics or meteorological perturbations. While FSO communication is constrained by prerequisites for unobstructed line-of-sight, the inclusion of RF elements within hybrid frameworks affords extended coverage, facilitating communication beyond direct visual connections. The synergy of RF and FSO components within hybrids holds the potential to mitigate the detriments of atmospheric hindrances like fog or rain, which can hamper FSO performance [9]. In this context, the RF link functions as a contingency during adverse weather circumstances. Additionally, hybrids furnish operational elasticity, empowering the system to dynamically apportion resources based on the accessibility of FSO and RF conduits. This adaptability optimizes communication efficacy in real-time scenarios, augmenting system performance. The hybrid paradigm avails judicious resource utilization, optimizing bandwidth allocation and load equilibrium across FSO and RF avenues. This culminates in elevated network capacity and holistic system efficiency. Furthermore, hybrids bear economic promise by capitalizing on pre-existing RF infrastructure while harnessing the elevated data rates and security perks intrinsic to FSO [10]. This strategy engenders cost efficiencies in comparison to exclusively FSO-reliant solutions. Through the amalgamation of two disparate technologies, hybrid systems unveil a robust and forward-looking solution poised to accommodate evolving communication requisites, technological advancements, and regulatory shifts. Hybrid FSO/RF systems can assume single-hop [11-12], dual-hop [13] or multi-hop [14] structures. The single-hop structure is preferred for short distances, where data is transmitted via two parallel FSO and RF links or by using switches. The switch technique necessitates constant activation, unlike simultaneous transmission, which requires no feedback.

Numerous models have been put forth to characterize channel behavior within FSO systems operating amid the influence of atmospheric turbulence. Distinct channel distribution functions have been devised to portray varying degrees of atmospheric turbulence. Among these, notable distributions encompass Gamma-Gamma, Negative Exponential, Log-Normal, Rayleigh, Ricean, Chi-square, K-distribution, I-K distribution, IG distribution, Double-Weibull, Exponentiated Weibull, and Double Generalized distribution [15]-[16]. The work presented in [17] delves into analytical formulations encapsulating the Probability Density Function (PDF) of the receiver's irradiance and the instantaneous Signal-to-Noise Ratio (SNR) under the aegis of the Gamma/Chi-square model. This analytical treatment accommodates both atmospheric turbulence and pointing error, effectively consolidating prior models within its framework. Notably, the model's versatility allows it to be transformed into these antecedent models through parameter manipulation to assume specific configurations.

Diversity combining is a widely employed technique for enhancing communication system performance. In wireless communication systems, receive diversity is practical because mobile transmitters have limitations in terms of energy consumption and processing complexity [18]. This technique involves collecting distinct copies of the transmitted signal on the receiver side (base station) to counteract the diversity of channel fading. Combining these copies aids in reconstructing the transmitted signal. Well-known combiners include the Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), Switch-and-Stay Combining (SSC) and Selective Combining (SC).

This work focuses on the hybrid FSO/RF system with a single-hop transfer and parallel simultaneous transmission. This configuration is an exceptional case where diversity technique with a single-hop transfer is applied to a hybrid FSO/RF communication system. The system's behavior is evaluated in conditions of saturated atmospheric turbulence. Both RF links with Rayleigh fading and FSO links under the influence of atmospheric turbulence, modeled as Gamma/Chi-square model, are considered. Standard performance criterion at the SSC and SC output, outage probability (OP) has been derived in closed form and analyzed in the function of observed system parameters

System model. It has been presented in [17] that PDF for the SNR of introduced Gamma/Chi-square FSO model can be presented as follows:

$$f_{\gamma_{FSO}}\left(\gamma_{FSO}\right)=\sum_{m=0}^{\infty}\frac{K_1{}^m\,\mathrm{e}^{-K_1}}{\Gamma(\alpha)\Gamma(m+1)m!}\left(\frac{\alpha\left(1+K_1\right)}{\sqrt{\mu_a}}\right)^{\frac{\alpha+m+1}{2}}\gamma_{FSO}{}^{\frac{\alpha+m-3}{4}}K_{\alpha-m-1}\left(2\sqrt{\alpha\left(1+K_1\right)\sqrt{\frac{\gamma_{FSO}}{\mu_a}}}\right) \tag{1}$$

where $K_\upsilon(\cdot)$ is υth-order modified Bessel function of the second kind [19, Eq. 8.432]. Parameter μ_a represents the average electrical SNR, parameter K_1 denotes the ratio of the power of the LOS component to the average power of the scattered components, while parameter α is the effective numbers of small-scale eddies of the scattering environment. This is parameter of the atmospheric turbulence that for propagation of plane waves and zero inner scale can be expressed in the terms of Rytov variance, as a function of index of refraction which is a measure of the turbulence strength, optical wave number and distance between the transmitter and the receiver, i.e. the length of the optical signal propagation [17].

Similarly, it can be shown that CDF for the SNR of introduced Gamma/Chi-square FSO model can be presented as follows, after applying the relation [19, Eq. 9.31.5] to transform Meijer G function:

$$F_{\gamma_{FSO}}\left(\gamma_{FSO}\right)=\int_0^{\gamma_{FSO}} f_{\gamma_{FSO}}\left(t\right)dt$$
$$=\sum_{m=0}^{\infty}\frac{K_1{}^m\,\mathrm{e}^{-K_1}}{\Gamma(\alpha)\Gamma(m+1)m!}\left(\frac{\alpha(1+K_1)}{\sqrt{\mu_a}}\right)^{\frac{\alpha+m+1}{2}}\gamma_{FSO}{}^{\frac{\alpha+m+1}{2}}G_{1,3}^{2,1}\left(\alpha(1+K_1)\gamma_{FSO}\left|\begin{matrix}1-\frac{\alpha+m+1}{2}\\ \frac{\alpha+m-1}{2},-\frac{\alpha+m+1}{2},\frac{1-\alpha-m}{2}\end{matrix}\right.\right) \tag{2}$$

According to [18] PDF of Ricean distributed SNR per symbol of the channel RF is distributed as:

$$f_{\gamma_{RF}}\left(\gamma_{RF}\right)=\frac{1+K_2}{\Omega_P}\mathrm{e}^{-K_2-\frac{(1+K_2)\gamma_{RF}}{\Omega_P}}I_0\left(2\sqrt{\frac{K_2\left(1+K_2\right)}{\Omega_P}\gamma_{RF}}\right),\quad \gamma_{RF}>0 \tag{3}$$

where K_2 is the ratio of the power of the RF LOS component to the average power of the RF scattered component, Ω_P is total received signal power, while $I_\upsilon(\cdot)$ is υth-order modified Bessel function of the first kind [19, Eq. 8.431].

Similarly, it can be shown that CDF for the SNR of introduced Rician RF model can be presented as follows:

$$F_{\gamma_{RF}}\left(\gamma_{RF}\right)=\int_0^{\gamma_{RF}} f_{\gamma_{RF}}\left(t\right)dt=\sum_{s=0}^{\infty}\frac{K_2{}^s\,\mathrm{e}^{-K_2}\,\Gamma\left(s+1,0,\frac{K_2+1}{\Omega_p}\gamma_{RF}\right)}{\Gamma(s+1)s!} \tag{4}$$

As mentioned, assuming independent RF and FSO links, SC diversity receiver selects and outputs the branch with highest instantaneous signal SNR value, i.e.:

$$\gamma=\gamma_{out}=\max\left(\gamma_{FSO},\gamma_{RF}\right) \tag{5}$$

PDF of the SNR random process at the output of SC can be written as:

$$f_\gamma(\gamma)=f_{\gamma_{FSO}}(\gamma)F_{\gamma_{RF}}(\gamma)+f_{\gamma_{RF}}(\gamma)F_{\gamma_{FSO}}(\gamma) \tag{6}$$

To circumvent the need for the simultaneous and continuous monitoring of all diversity channels, a strategy akin to switched combining, referred to as switch-and-stay combining (SSC), is frequently adopted. This method offers the least intricate approach to space diversity reception, compatible with diverse modulation schemes like coherent, non-coherent, and differentially coherent ones. Within SSC, the combining process is executed in a manner where a specific branch is chosen and outputted until its SNR descends beneath a predefined threshold. Subsequently, irrespective of the SNR of that branch, the combiner remains fixed on the selected branch [18]. The meticulous selection of this predetermined threshold stands as a crucial design consideration within SSC reception design. Let us represent the instantaneous SNR at the SSC output, and γ_T the predetermined switching threshold for the both input branches. Following [18], the PDF of SSC output is given by:

$$f_{SSC}(\gamma)=\begin{cases}\dfrac{F_{\gamma_{FSO}}(\gamma_T)F_{\gamma_{RF}}(\gamma_T)}{F_{\gamma_{FSO}}(\gamma_T)+F_{\gamma_{RF}}(\gamma_T)}(f_{\gamma_{FSO}}(\gamma)+f_{\gamma_{RF}}(\gamma)) & \gamma\le\gamma_T;\\ \dfrac{F_{\gamma_{FSO}}(\gamma_T)F_{\gamma_{RF}}(\gamma_T)}{F_{\gamma_{FSO}}(\gamma_T)+F_{\gamma_{RF}}(\gamma_T)}(f_{\gamma_{FSO}}(\gamma)+f_{\gamma_{RF}}(\gamma))+ & \\ +\dfrac{f_{\gamma_{FSO}}(\gamma)F_{\gamma_{RF}}(\gamma_T)+F_{\gamma_{FSO}}(\gamma_T)f_{\gamma_{RF}}(\gamma)}{F_{\gamma_{FSO}}(\gamma_T)+F_{R_2}(\gamma_T)}; & \gamma>\gamma_T;\end{cases} \tag{7}$$

CDF of SSC output SNR can be presented as [18]:

$$F_{SSC}(\gamma)=\begin{cases}\dfrac{F_{\gamma_{FSO}}(\gamma_T)F_{\gamma_{RF}}(\gamma_T)}{F_{\gamma_{FSO}}(R_T)+F_{\gamma_{RF}}(R_T)}(F_{\gamma_{FSO}}(\gamma)+F_{\gamma_{RF}}(\gamma)) & \gamma\le\gamma_T;\\ \dfrac{F_{\gamma_{FSO}}(\gamma_T)F_{\gamma_{RF}}(\gamma_T)}{F_{\gamma_{FSO}}(\gamma_T)+F_{\gamma_{RF}}(\gamma_T)}(F_{\gamma_{FSO}}(\gamma)+F_{\gamma_{RF}}(\gamma)-2)+ & \\ +\dfrac{F_{\gamma_{FSO}}(\gamma)F_{\gamma_{RF}}(\gamma_T)+F_{\gamma_{FSO}}(\gamma_T)F_{\gamma_{RF}}(\gamma)}{F_{\gamma_{FSO}}(\gamma_T)+F_{\gamma_{RF}}(\gamma_T)}; & \gamma>\gamma_T;\end{cases} \tag{8}$$

Performance analysis. The outage probability (OP), denoted as Pout, emerges as a well-established performance metric to delineate the efficiency of diversity systems functioning within fading scenarios. This metric holds pivotal significance in aiding wireless communication system designers to effectively address the requisites of Quality of Service (QoS) and Grade of Service (GoS). In precise terms, OP is formulated based on the statistical characteristics of the received signal, quantifying the likelihood that the received Signal-to-Noise Ratio (SNR), γ, descends below a predefined outage threshold, often referred to as the protection ratio, denoted as γ_{th}. Should the cumulative distribution function (CDF) of γ be ascertainable beforehand, the computation of OP can be derived using the subsequent expression [18]:

$$P_{out}=\int_0^{\gamma_{th}} f_\gamma(t)\,dt=F_\gamma(\gamma_{th}); \tag{9}$$

The Average Bit Error Rate which depends on the SNR at the receiver for an optical signal transmitted by FSO system with the On-off keying (OOK) modulation scheme can be expressed as [20]:

$$P_e=\int_0^\infty \frac{1}{2}\operatorname{erfc}\left(\frac{\sqrt{\gamma}}{2}\right) f_\gamma(\gamma)\,d\gamma \tag{10}$$

where erfc(·) is a complementary error function [19, Eq. 8.250.4], and $f_\gamma(\gamma)$ represents PDF of instantaneous SNR of the received signal.

Numerical results. For numerical computations, the FSO system was investigated using a wavelength of λ = 1550 nm and a distance between the transmitter and receiver of L = 1 km. The study encompassed three distinct levels of atmospheric turbulence: weak, moderate, and strong, characterized by refractive index structure parameters of $C_n^2 = 6\cdot10^{-15}$ $m^{-2/3}$, $C_n^2 = 2\cdot10^{-14}$ $m^{-2/3}$, and $C_n^2 = 1.2\cdot10^{-13}$ $m^{-2/3}$, respectively. The overall received signal power was designated as Ω_P =1, while the detector's responsivity was set at R = 1 A/W, and the noise variance was represented by $\sigma_N = 10^{-7}$ A/Hz.

At Figure 1 we have depicted OP of observed hybrid RF/FSO system for applied SC at reception. It is visible from figure that OP values deteriorate with the increase of K_1 and K_2 parameter values. Namely, value of parameter K_2 determines whether RF branch would be selected in observed low turbulence case, and when its value reaches the corresponding value. switching between the branches is performed.

At Figure 2 we have depicted OP of observed hybrid RF/FSO system for applied SSC at reception. Moderate and strong turbulence case are observed and threshold is set at Ωp. It is visible from figure that OP values deteriorate with the increase of K_1 and K_2 parameter values. Namely, value of parameter K_1 determines whether FSO branch would be selected in observed low turbulence case, and when its value reaches the corresponding value. switching between the branches is performed.

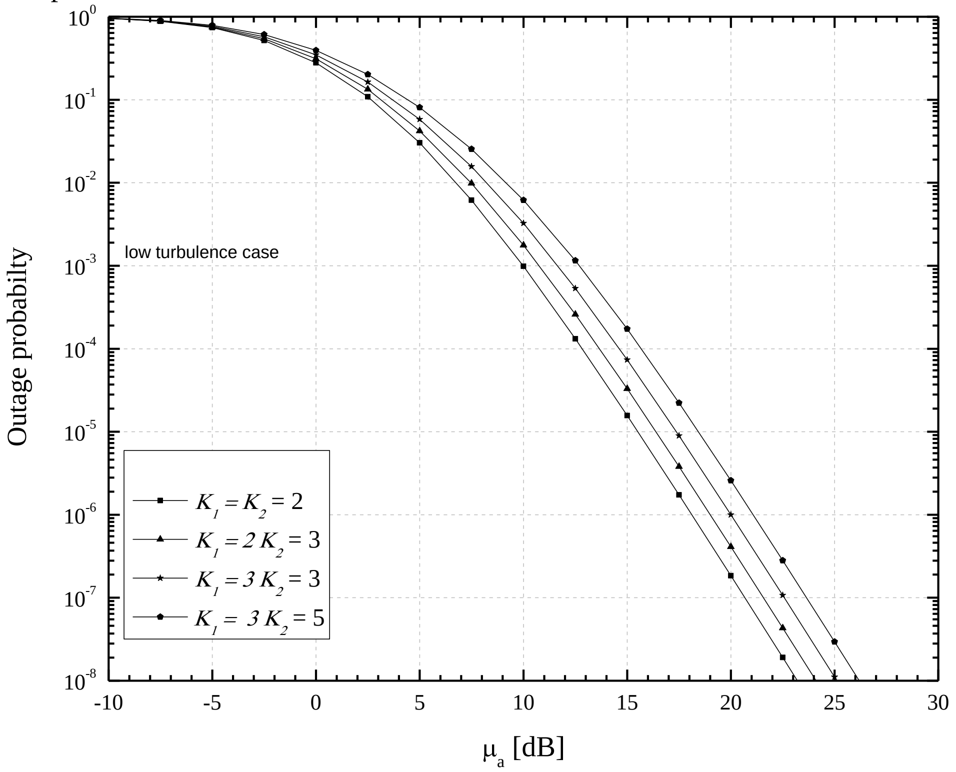

Figure 1. Outage probability of observed hybrid RF/FSO system for applied SC at reception

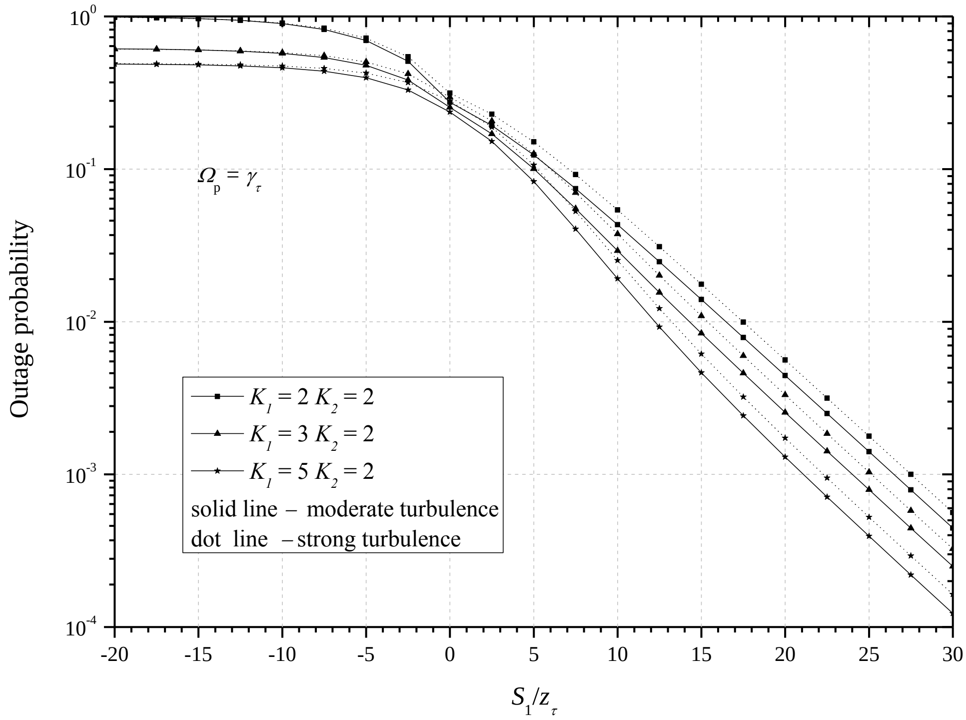

Figure 2. Outage probability of observed hybrid RF/FSO system for applied SC at reception

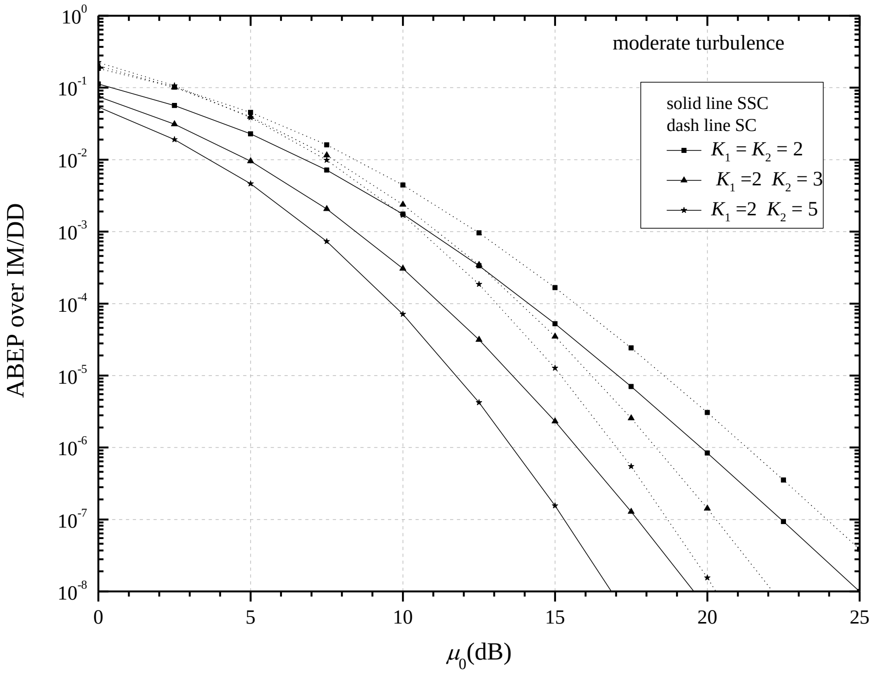

Figure 3. ABER of observed hybrid RF/FSO system for applied IM/DD modulation format

At Figure 3 is presented ABER of observed hybrid RF/FSO system for applied IM/DD modulation format for moderate turbulence case. As expected better performances are obtained for SC diversity case over SSC and increase of K_1 and K_2 parameter values leads to performance improvement.

Conclusion. In summary, the exploration of the innovative hybrid FSO/RF communication system has illuminated a promising path towards addressing the challenges posed by atmospheric turbulence within mobile communication systems. The convergence of Free-Space Optical (FSO) and Radio Frequency (RF) technologies in a single-hop transfer configuration, bolstered by the concept of receive diversity, has proven to be a strategic solution. The comprehensive study conducted under the Gamma/Chi-Square turbulence model for FSO and Rican fading model for RF has yielded profound insights into the system's behavior. The derived closed-form expression for the outage probability stands as a testament to the rigor of this investigation, shedding light on the performance under adverse atmospheric conditions. The results of this research underscore a significant leap forward in comparison to conventional FSO and RF systems. Despite the technical demands associated with an advanced receiver, the hybrid architecture's marked enhancements in reliability and performance are evident. Notably, the deployment of the SSC combining technique along with SC diversity strategies embodies a holistic approach that not only addresses the challenges posed by atmospheric dynamics but also harnesses diversity techniques for a more robust communication framework. This study, centered on the single-hop hybrid FSO/RF system, has provided a comprehensive examination of its operation in the presence of saturated atmospheric turbulence. By modeling both RF and FSO channels, the research has laid the groundwork for a deeper understanding of the system's behavior. The analytical formulation of the outage probability, coupled with the consideration of various system parameters, offers valuable insights for engineering robust and reliable communication systems in real-world scenarios. As the field of hybrid communication systems continues to evolve, the findings of this research pave the way for further innovations that could revolutionize the future of mobile communication, enhancing data rates, security, and network efficiency.

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