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Characterization of A2G UAV communication channels under rician fading conditions

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ABSTRACT

The variation in the k-factor value significantly influences the performance of unmanned aerial vehicle (UAV) air-to-ground point-to-point line of sight (A2G PTP LOS) communications over a Rician channel at 1,800 MHz using quadrature phase shift keying (QPSK) modulation and orthogonal frequency division multiplexing (OFDM) techniques. The research emphasizes the impact of the k-factor, which quantifies the dominance of the line-of-sight component over multipath scattering. The variation in the k-factor significantly influences UAV A2G PTP LOS communication performance for the empirical model (EM), as it involves precise measurements of the received power level in dBm from UAV to ground control station (GCS) across varying distances and altitudes. We introduce a method to compute the k-factor by assessing the ratio of the line-of-sight signal power to the multipath signal power, thereby enhancing channel modeling accuracy. Empirical analysis shows a strong correlation between bit error rate (BER) and signal-to-noise ratio (SNR) with differing k-factor values; a higher k-factor of 16.3 markedly improves performance, virtually eliminating errors at a 10 dB SNR, while a lower k-factor of 2.39 still shows significant errors at a 30 dB SNR. These results highlight the necessity of optimizing the k-factor in UAV A2G PTP LOS systems to ensure stable and reliable communication under diverse operational conditions.

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1. INTRODUCTION

In unmanned aerial vehicle (UAV) communications, understanding the impact of various physical phenomena such as reflection, diffraction, and scattering is pivotal for enhancing communication reliability and efficiency [1]. These phenomena contribute to the complexity of the propagation environment by introducing multipath components, which can lead to temporal dispersion and frequency selectivity [2]. Additionally, the Doppler effect further complicates the channel by inducing time-variant changes. In this context, the Rician K-factor, which quantifies the ratio of the dominant line-of-sight (LOS) component to multipath components, serves as a crucial metric in assessing the small-scale fading behavior of the communication channel [3].

The focus is on air-to-ground (A2G) communication to ensure robust connectivity between UAVs and ground control stations (GCS). These systems rely on the accurate characterization of the channel to meet the demands of UAV operations, which include maintaining high throughput and extended operational ranges [4], [5]. While traditional UAV communications have primarily utilized single-input single-output (SISO) technologies, there is a progressive shift towards employing more sophisticated configurations such as multiple-input multiple-output (MIMO) systems. Despite their advantages, these advanced technologies are susceptible to selective frequency fading, which can degrade communication quality [6]-[9]. Integrating orthogonal frequency-division multiplexing (OFDM) aims to mitigate these drawbacks by using multiple carrier frequencies to distribute the signal, thus improving resistance to channel impairments [10]-[12].

Despite considerable advancements, developing accurate and realistic A2G UAV communication channel models remains a significant challenge. These models are essential for devising effective modulation techniques and resource allocation strategies to optimize channel utilization and enhance data rates [13]. The difference between channel models for satellite communications or high-altitude platforms (HAP) and those required for low-altitude platforms (LAP) like UAVs is due to their differing operational altitudes and conditions.

Identifying research gaps in the A2G UAV communication channel model [14], [15] is critical in the scientific process, ensuring that new studies contribute meaningfully to existing knowledge. One effective method for this purpose is bibliometrics, also known as scientometrics. This approach allows for analyzing the novelty of research by systematically evaluating existing literature [16]. Bibliometrics facilitates a comprehensive quantitative analysis of related publications, thus offering a clear view of potential areas for new investigation. Search parameters encompassed the article title, abstract, and keyword sections of Scopus, spanning 2017 to 2024. The document types included articles and conference papers, as depicted in Figure 1, reveal considerable opportunities in UAV A2G communication research, particularly in areas like empirical models (EM), Rician channels, and video applications. Despite the growth in publications related to communication and LOS, indicating a competitive and evolving landscape, there is still a notable potential for more in-depth exploration. However, EM and Rician channels have received less attention, signifying a wide-open field for academic contributions to enhance our grasp of UAV A2G communication.

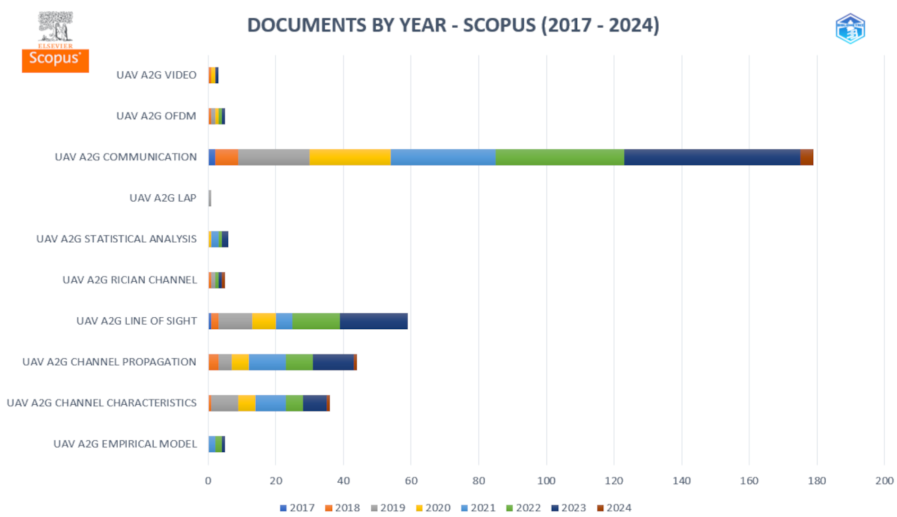

Figure 1. Visualization of research areas

This paper contributes to the field by presenting an empirical study that quantitatively evaluates the impact of the Rician k-factor on UAV A2G PTP LOS communications. This study enhances channel modeling accuracy by employing a method of moments approach to measure the LOS power ratio to multipath components. Our findings reveal a significant correlation between the bit error rate (BER) and signal-to-noise ratio (SNR) across varying k-factor values, with higher k-factors showing substantially better performance. These results underscore the critical role of optimizing the k-factor in ensuring dependable UAV communication under varying operational conditions. Table 1 details a comparative analysis and current research.

Table 1. Comparative analysis of previous UAV communication studies UAV A2G

Aspect	Current research	Paper [17]	Paper [18]	Paper [19]	Paper [20]	Paper [21]
Research focus	Comprehensive analysis including Rician k-factor and various heights and radii	A similar focus on measuring received power for Rician k-factor	Focuses on path loss model	UAV-aided localization of a ground RF emitter using a received signal strength indicator (RSSI)	Characterization of the A2G communication channel using field measurements	Investigate channel characteristics between UAV through ray-tracing simulation in an urban environment
Vehicle used	LAP	HAP	LAP	LAP	LAP	LAP
Frequency	1,800 MHz	1,200 MHz, 2,400 MHz	446 MHz	865 MHz, 2,400 MHz	3,500 MHz	2,200 MHz
Methodology	Empirical data collection in suburban areas measuring received power at various heights and radii; analyzing Histogram PDF, K-factor Rician distribution	Empirical data collection: measuring received power; HAP has a fixed height	Empirical data collection: measuring pathloss, only various altitudes	Collection of RSSI measurements	Using a smartphone for data collection, field measurements with UAV flights at various heights in a suburban area	Ray-tracing simulation (RT) using a high-performance computing
Performance tests	quadrature phase shift keying (QPSK)	DQPSK	Analysis of pathloss	Analysis of estimating the transmitter location	Focuses on measuring network quality parameters like RSSI and SINR to characterize path loss and shadowing effects	The study does not specify modulation technique directly but focuses on path loss modeling

2. METHOD

This research uses the Rician distribution for the EM, focusing on measuring the received power level (dBm) from the UAV to the GCS. The UAV executes circular flight patterns at varying heights (10m, 20m, 30m) and radii (10m, 20m, 30m) at 1,800 MHz above suburban areas to systematically evaluate different k-factor values, as in Figure 2. The UAV uses a DJI Phantom 4 Quadcopter with payload Adalm Pluto software-defined radio (SDR), transmitting cosine signals with a bandwidth of 2.5 MHz over an A2G PTP LOS connection.

The UAV and the GCS feature vertically mounted antennas, which optimize the reception and transmission of signals. At the GCS station, the Signal Hound BB60C equipment captures cosine signals from the UAV. These statistical analyses are crucial for a comprehensive understanding of channel characteristics, including the histogram probability density function (PDF) for the Rician distribution and an evaluation of the Rician k-factor. Performance tests using MATLAB to validate the accuracy of the EM, employing QPSK modulation within OFDM to analyze the BER and SNR. Table 2 shows the specifications of the parameters of the UAV.

Table 2. A2G parameters UAV

Variable	Value
Payload (SDR+Raspberry Pi)	460 grams
Antenna gain transmit 1,800 MHz	2 dBi
Heights (h)	h1=10m, h2=20m, h3=30m
Radii (r)	r1=10m, r2=20m, r3=30m
Cosine signal Bandwidth (TX)	2.5 MHz

(a) (b)

Figure 2. Flight equipment and configuration, (a) UAV payload configuration and (b) UAV flight pattern

UAV communication involves three main components: the transmitter (TX), the receiver (RX), and the UAV channel [15], [22]. Signals transmitted (TX) and received (RX) may follow a direct path or reflect off surfaces like the ground, buildings, and moving vehicles, altering the wave's magnitude and phase based on reflection coefficients, trajectory, and incidence angle. The channel model often used in this analysis is formulated for direct and multipath signal components. To model the communication between a UAV and a GCS, the received signal y(f) is a function of frequency (f), where H(f) is the channel's transfer function, incorporating all effects of the transmission path. The transmitted signal is denoted by x(f), and n(f) represents the noise within the system. Therefore, mathematically express the relationship as (1).

$$y(f) = H(f) \cdot x(f) + n(f) \tag{1}$$

The equation H(f) characterizes how the signal interacts during transmission between the transmitted signal and the environment. It includes aspects such as the signal's attenuation, phase shift, and dispersion for accurately modeling and understanding the communication channel's behavior.

The Rician distribution is particularly relevant for modeling LOS conditions with a predominant direct signal path accompanied by multiple smaller reflected paths. The mathematical expression for the Rician distribution, which describes the PDF of the received signal amplitude in such a scenario, is given by (2).

$$p(R) = \frac{R}{\sigma^2} \exp\left(-\frac{R^2 + A^2}{2\sigma^2}\right) I_0\left(\frac{RA}{\sigma^2}\right) \quad \text{for } R \geq 0 \tag{2}$$

The amplitude of the received signal, denoted by R, includes contributions from paths other than the direct LOS path. A represents the signal level through the LOS path, σ is the standard deviation of the multipath component, and I_0 is the modified Bessel function of the first order. A critical measure in this context is the k-factor, or K, which quantifies the ratio between the power of the LOS signal and the power of the multipath signals. Express the k-factor formula as follows [23].

$$K = \frac{A^2}{2\sigma^2} \tag{3}$$

Data was collected empirically by measuring the received power level (R) in dBm at 1,800 MHz using BB60C equipment. The system collected 64 data samples for each frequency over 90 seconds, totaling 5,000 data points for each measurement parameter. The UAV was flown in circular patterns at heights of 10, 20, and 30 meters, with a corresponding radii of 10, 20, and 30 meters, to ensure data collection from various angles. To facilitate analysis, the data, initially in dBm units, were converted to volts. This conversion is critical for plotting histograms to observe signal distribution patterns. The transformation from dBm to mW, and subsequently to volts, is performed using the (4) and (5).

$$P_{\text{mW}} = 10^{\frac{P_{\text{dBm}}}{10}} \tag{4}$$

$$V = \sqrt{P_{\text{mW}} \times R} \tag{5}$$

P_{mW} is the dBm value in mW, and V is the dBm value converted to voltages with an R-value of 50 Ω. Normally distributed signal indicates a high k-factor, while deviations from normality suggest a lower k-factor. The k-factor, which is a measure of the ratio between the LOS signal power and the multipath signal power, can be deduced from the data using the method of moments, as described by [24], [25].

$$E[R^n] = (2\sigma^2)^{n/2}\Gamma\left(\frac{n}{2}+1\right)e^{-K}\,{}_1F_1\left(\frac{n}{2}+1;1;K\right) \tag{6}$$

Where n is the moment order, Γ is the gamma function, and ${}_1F_1$ is the confluent hypergeometric function. For the first and second moments ($n = 1$ and $n = 2$), the first moment ($n = 1$) is expressed as (7).

$$E[R] = (2\sigma^2)^{\frac{1}{2}}\Gamma\left(\frac{1}{2}+1\right)e^{-K}\,{}_1F_1\left(\frac{1}{2}+1;1;K\right) \tag{7}$$

Second moment (n=2) expressed as (8).

$$E[R^2] = \left(2\sigma^2\right)\Gamma(2)e^{-K}{}_1F_1\left(2;1;K\right) = \frac{A^2+2\sigma^2}{2} = \sigma^2(K+1) \tag{8}$$

The ratio of the first moment to the square root of the second moment can be analyzed to determine the k-factor:

$$\frac{E[R]}{\sqrt{E[R^2]}} = \frac{\left(2\sigma^2\right)^{\frac{1}{2}}\Gamma\left(\frac{3}{2}\right)e^{-K}{}_1F_1\left(\frac{3}{2};1;K\right)}{\sqrt{\sigma^2(K+1)}} \tag{9}$$

Deriving the identity from the hypergeometric function to bessel functions, the confluent hypergeometric function ${}_1F_1(a;b;z)$ can be expressed in terms of modified Bessel functions in certain cases. For ${}_1F_1\left(\frac{3}{2};1;K\right)$, the following identity is used:

$${}_1F_1\left(\frac{3}{2};1;K\right) = e^{\frac{K}{2}}\left[(K+1)I_0\left(\frac{K}{2}\right)+KI_1\left(\frac{K}{2}\right)\right] \tag{10}$$

Substitution and simplification:

$$\frac{E[R]}{\sqrt{E[R^2]}} = \frac{\sqrt{2\pi}}{2}\cdot\frac{e^{-K}}{\sqrt{K+1}}\cdot{}_1F_1\left(\frac{3}{2};1;K\right) \tag{11}$$

Replace ${}_1F_1\left(\frac{3}{2};1;K\right)$ with its expression in terms of Bessel functions:

$$\frac{E[R]}{\sqrt{E[R^2]}} = \sqrt{\frac{\pi}{2}}\cdot\frac{e^{-K}\cdot e^{K/2}\left[(K+1)I_0\left(\frac{K}{2}\right)+KI_1\left(\frac{K}{2}\right)\right]}{\sqrt{K+1}} \tag{12}$$

The final equation becomes:

$$\frac{E[R]}{\sqrt{E[R^2]}} = \sqrt{\frac{\pi}{2}}\cdot\frac{e^{-K/2}}{\sqrt{K+1}}\left[(K+1)I_0\left(\frac{K}{2}\right)+KI_1\left(\frac{K}{2}\right)\right] \tag{13}$$

I_0 and I_1 are modified zeroth-order Bessel functions of the first kind. The $\frac{E[R]}{\sqrt{E[R^2]}}$ value is from measurements and by applying the matching function method from mathematical (13), to calculate the K value.

3. RESULTS AND DISCUSSION

This phase focuses on the statistical analysis of empirical data obtained from field testing. After calculating the k-factor value, the next step is to test the performance using the basic OFDM method [15]. Random data sources are used in the transmission process and then modified using QPSK. The signal was transformed from the transmitter using the inverse fast fourier transform (IFFT) following modulation. Subsequently, the signal is transmitted through a Rician channel model, where the k-factor value is employed to determine the intensity of the direct signal relative to the reflected signal. Additive white gaussian noise (AWGN) is used to simulate noise. The receiver is processed through the FFT and then demodulated to analyze the BER relative to the SNR.

The RSSI data presented in Figure 3 shows variations in the signal strength at different flying heights (h) and radii (r) across frequencies 1,800 MHz. The RSSI data obtained from the measurements, as shown in Figure 3, exhibits significant fluctuations in the received signal strength, with values ranging from -99 dBm to around -74 dBm. Lower RSSI values, approaching -99 dBm, are typically caused by the increased distance between the UAV and the receiver or obstacles obstructing the LOS path. In comparison, higher RSSI values, approaching -74 dBm, indicate conditions where the LOS path is dominant.

In this context, linking the measurement results to the Rician propagation model is very beneficial, where areas with higher RSSI values indicate the dominance of the LOS path with a higher k-factor. In comparison, areas with lower RSSI values indicate the dominance of the multipath path with a lower K-Factor. Furthermore, it is crucial to calculate the link budget to support the channel characteristics of the UAV A2G PTP communication link, which includes all gain and loss components in the transmission path [26].

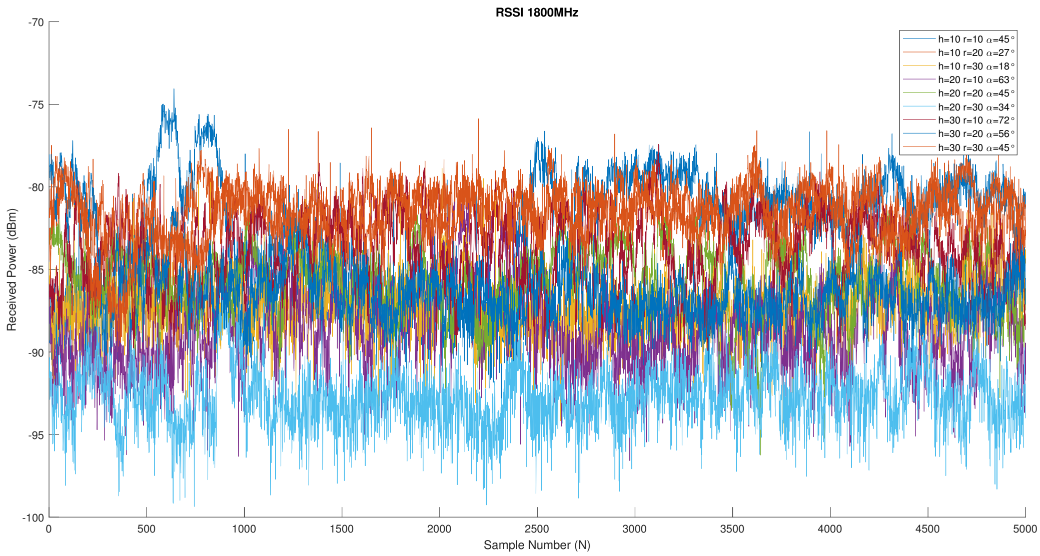

Figure 3. RSSI Data A2G - 1,800 MHz

The histogram generated from this simulation is designed to display the frequency distribution of data across various intervals visually. The primary purpose of this representation is to provide a deep understanding of the observed data's shape and distribution. In Figure 4, the horizontal axis depicts the received signal voltage, measured in volts, while the vertical axis shows the probability density associated with these voltage values. The red curve on the graph illustrates the alignment between the theoretical normal distribution and the observed data. The histogram beneath the curve highlights the data distribution in a bar format, clearly showing how closely the data conforms to a normal distribution. The closer the data fits the normal distribution, the higher the 'k' value assigned to each frequency.

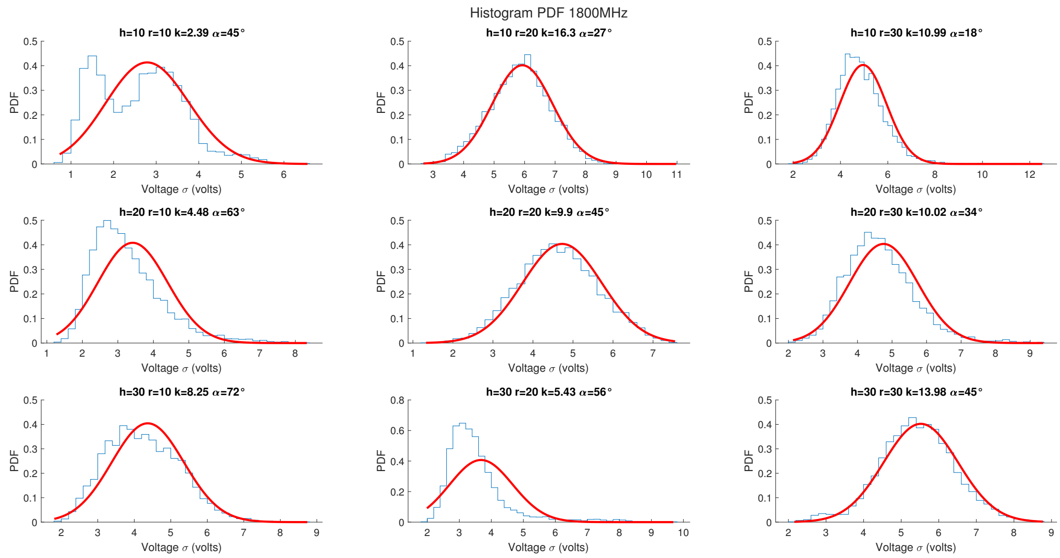

Figure 4. Histogram data A2G - 1,800 MHz

The histogram reveals that a higher k-factor, specifically $k = 16.3$ at the height of h=10 meter and r=20 meter with an angle of $\alpha = 27°$, results in a more centralized voltage distribution with lower variance, indicating better signal stability and minimal scattering effects. Conversely, with a lower k-factor, specifically $k = 2.39$ at the same heights of h=10 meter but with r=10 meter and an angle of $\alpha = 45°$, the distribution appears more spread out. This condition signifies an increase in multipath effects and a decrease in signal stability. Analyzing the PDF in channel propagation studies, especially for Rician channels, is crucial for analyzing the statistical characteristics of the received signals [27].

To facilitate understanding of the distribution of the k-factor based on empirical data collection, Figure 5 presents a two-dimensional (2D) visual representation of the k-factor distribution. This graph displays variations in the k-factor based on frequency, height, and radius. It can be observed from the graph that the darker the color displayed, the higher the k-factor represented, and vice versa.

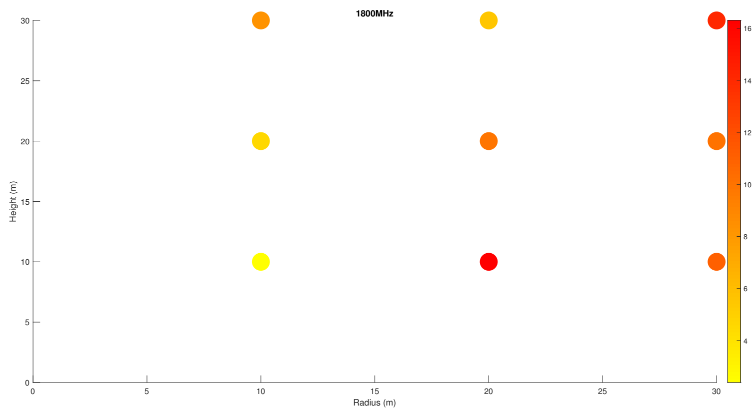

Figure 5. UAV k-factor distribution at frequencies 1,800

The next step is to perform a performance test through simulations using MATLAB software, version R2022a. In these simulations, the modulation technique employed is QPSK combined with the fundamental method of OFDM. The transmission block diagram includes generating random signals, modulation, and IFFT. The channel model used is the Rician model, complemented by AWGN. At the receive stage, the process involves only FFT and demodulation without synchronization and equalizer function blocks. The k-values previously obtained from measurements will be implemented in these simulations at 1,800 MHz frequencies. These simulations will be conducted over 1,000 iterations with an SNR range of up to 30. The primary metric to be analyzed is the BER relative to the SNR for each tested k-value. The MATLAB function code used for the Rician channel is as follows:

```
%RICIAN
mean = sqrt(k/(k+1)); %mean
sigma = sqrt(1/(2*(k+1))); %variance
Nr2 = randn(1,length(inChannel))*sigma+mean;
Ni2 = randn(1,length(inChannel))*sigma;
riciancoef = sqrt(Nr2.^2+Ni2.^2); %Rician fading
inChannel = inChannel.*riciancoef;
outChannel = awgn(inChannel, SNR, EbdB);
outChannel = outChannel./riciancoef;
```

The Rician distribution parameters are computed using k, where the mean (μ) of the in-phase or quadrature component is defined as $\sqrt{\frac{k}{k+1}}$, while the variance (σ) of each component is calculated as $\sqrt{\frac{1}{2(k+1)}}$. This results in a distribution that accounts for the variability in signal reception due to multipath effects. In the simulation, the in-phase and quadrature components of the Rician faded signal, represented as 'Nr2' and 'Ni2', are generated as gaussian random variables with the calculated mean and variance. The Rician fading coefficient, 'riciancoef', is then computed by taking the square root of the sum of the squares of the in-phase and quadrature components, following the Rician distribution. This process involves modifying the input signal 'inChannel' by multiplying it with 'riciancoef' to apply the Rician fading effect. Subsequently, the faded signal is processed by adding gaussian noise ('awgn') based on a specified SNR, resulting in the output signal 'outChannel'. The code line 'outChannel = outChannel./riciancoef' within the simulation is designed to compensate for the multipath effects induced by the Rician fading coefficient on the signal. The primary function of this code is to normalize or restore the signal to its original scale after undergoing the fading process. This compensation is critical to accurately reflect the original condition of the signal prior to the influence of fading. By normalizing the signal, the simulation ensures that fading effects accurately represent the signals. This step is crucial in maintaining the validity of further analyses, such as performance evaluations or signal quality assessments conducted on the simulated data. Performance evaluations confirmed the quality of UAV A2G PTP LOS communications over a Rician channel, focusing on the impact of k-factor variations determined through empirical data. Figure 6 illustrates the outcome of these evaluations at 1,800 MHz.

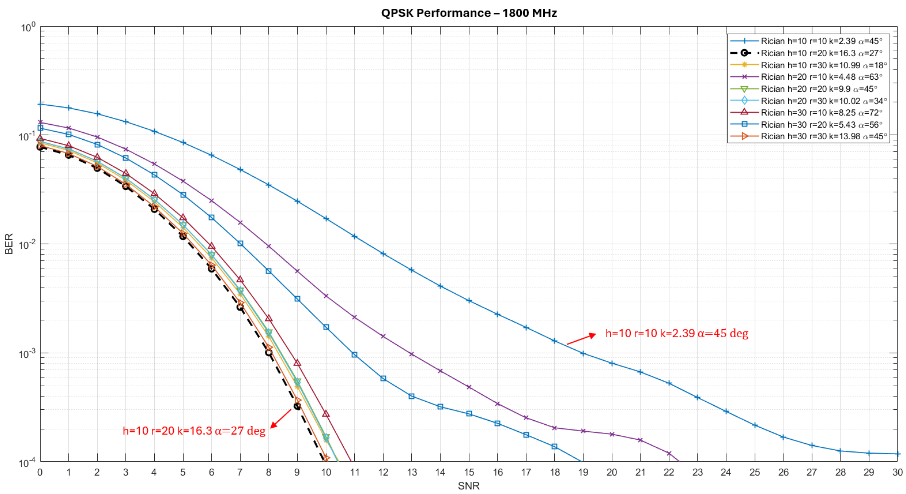

Figure 6. QPSK performance - 1,800 MHz

This analysis simulated two k-factor value scenarios, a high k-factor of 16.3 and a lower k-factor of 2.39. The results indicate good performance at a k-factor of 16.3, where, at an SNR of 10 dB, the BER reduces to nearly imperceptible levels. Conversely, low performance at a k-factor of 2.39, even at an elevated SNR of 30 dB. Additionally, the flight angle significantly influences the k-factor.

4. CONCLUSION

This research investigates the A2G PTP LOS communication channel, focusing on the effects of Rician fading on system performance via an EM. Employing QPSK modulation at 1,800 MHz, we systematically determined the relationship between BER and SNR to assess the impact of varying k-factor values under different flight configurations, including altitude, distance, and angle.

The simulation analysis results show a clear relationship between the k-factor value and the UAV A2G PTP LOS communication performance. A higher k factor, such as k=16.3, shows much better performance, evidenced by a nearly undetectable error rate at an SNR of 10 dB, compared to a lower k factor, such as k=2.39, where the error can still be observed even at an SNR of 30 dB, this indicates the existence of multipath scattering effects. Several factors contribute to the variation in the k-value, such as variations in heights, radius, and flight angle. These findings allow us to decide the optimal effective flight angles to enhance transmission quality. In future research, we propose to use a simulation technique that combines synchronization and equalization to improve the SNR quality using a more complex OFDM method to describe real conditions.

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REFERENCES

[1] O. S. Badarneh, M. K. Awad, S. Muhaidat, and F. S. Almehmadi, "Performance analysis of intelligent reflecting surface-aided decode-and-forward UAV communication systems," *IEEE Systems Journal*, vol. 17, no. 1, pp. 246–257, Mar. 2023, doi: 10.1109/JSYST.2022.3178327.

[2] R. Han, J. Ma, and L. Bai, "Trajectory planning for OTFS-based UAV communications," *China Communications*, vol. 20, no. 1, pp. 114–124, Jan. 2023, doi: 10.23919/JCC.2023.01.010.

[3] L. Rubio *et al.*, "Analysis of the Rician k-factor in a typical millimeter-wave office scenario," *IEEE Antennas and Wireless Propagation Letters*, vol. 23, no. 5, pp. 1553–1557, May 2024, doi: 10.1109/LAWP.2024.3362408.

[4] L. Tian, C. Shi, and Z. Xu, "Digital self-interference cancellation for full-duplex UAV communication system over time-varying channels," *Drones*, vol. 7, no. 3, p. 151, Feb. 2023, doi: 10.3390/drones7030151.

[5] X. Gu and G. Zhang, "A survey on UAV-assisted wireless communications: recent advances and future trends," *Computer Communications*, vol. 208, pp. 44–78, Aug. 2023, doi: 10.1016/j.comcom.2023.05.013.

[6] C. Ge, R. Zhang, D. Zhai, Y. Jiang, and B. Li, "UAV-correlated MIMO channels: 3-D geometrical-based polarized model and capacity analysis," *IEEE Internet of Things Journal*, vol. 10, no. 2, pp. 1446–1460, Jan. 2023, doi: 10.1109/JIOT.2022.3206424.

[7] H. Tang *et al.*, "A low-profile flexible dual-band antenna with quasi-isotropic radiation patterns for MIMO system on UAVs," *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 1, pp. 49–53, Jan. 2023, doi: 10.1109/LAWP.2022.3201492.

[8] I. Ahamed and M. Vijay, "Comparison of different diversity techniques in MIMO antennas," in *Proceedings of the 2nd International Conference on Communication and Electronics Systems*, ICCES 2017, Oct. 2017, vol. 2018-Janua, pp. 47–50.

[9] G. Femenias and F. Riera-Palou, "Cell-free massive MIMO-OFDM over spatially correlated doubly selective channels," *IEEE Access*, vol. 10, pp. 118438–118453, 2022, doi: 10.1109/ACCESS.2022.3220907.

[10] A. J. Al-Askery, C. C. Tsimenidis, S. Boussakta, and J. A. Chambers, "Performance analysis of coded massive MIMO-OFDM systems using effective matrix inversion," *IEEE Transactions on Communications*, vol. 65, no. 12, pp. 5244–5256, Dec. 2017, doi: 10.1109/TCOMM.2017.2749370.

[11] W. Zhang, H. Li, W. Kong, Y. Fan, and W. Cheng, "Structured compressive sensing based block-sparse channel estimation for MIMO-OFDM systems," *Wireless Personal Communications*, vol. 108, no. 4, pp. 2279–2309, 2019, doi: 10.1007/s11277-019-06522-8.

[12] Y. Guno *et al.*, "Initial development of real-time video link for UAV," in *AIP Conference Proceedings*, 2023, vol. 2941, no. 1, p. 020011, doi: 10.1063/5.0181525.

[13] L. Zhou, H. Ma, Z. Yang, S. Zhou, and W. Zhang, "Unmanned aerial vehicle communications: path-loss modeling and evaluation," *IEEE Vehicular Technology Magazine*, vol. 15, no. 2, pp. 121–128, Jun. 2020, doi: 10.1109/MVT.2019.2961608.

[14] A. A. Khuwaja, Y. Chen, N. Zhao, M. S. Alouini, and P. Dobbins, "A survey of channel modeling for uav communications," *IEEE Communications Surveys and Tutorials*, vol. 20, no. 4, pp. 2804–2821, 2018, doi: 10.1109/COMST.2018.2856587.

[15] Z. Huang, J. Rodriguez-Pineiro, T. Dominguez-Bolano, X. Cai, and X. Yin, "Empirical dynamic modeling for low-altitude UAV propagation channels," *IEEE Transactions on Wireless Communications*, vol. 20, no. 8, pp. 5171–5185, Aug. 2021, doi: 10.1109/TWC.2021.3065959.

[16] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, and W. M. Lim, "How to conduct a bibliometric analysis: an overview and guidelines," *Journal of Business Research*, vol. 133, pp. 285–296, Sep. 2021, doi: 10.1016/j.jbusres.2021.04.070.

[17] Iskandar and S. Shimamoto, "The channel characterization and performance evaluation of mobile communication employing stratospheric platform," in *2005 IEEE/ACES International Conference on Wireless Communications and Applied Computational Electromagnetics*, 2005, vol. 2005, pp. 830–833, doi: 10.1109/WCACEM.2005.1469712.

[18] B. Ede, S. Yarkan, A. R. Ekti, T. Baykas, H. A. Cirpan, and A. Gorcin, "Measurement based statistical channel characterization of air-to-ground path loss model at 446 MHz for narrow-band signals in low altitude UAVs," in *IEEE Vehicular Technology Conference*, May 2020, vol. 2020-May, pp. 1–5, doi: 10.1109/VTC2020-Spring48590.2020.9128440.

[19] S. Moro, V. Teeda, D. Scazzoli, L. Reggiani, and M. Magarini, "Experimental UAV-Aided RSSI localization of a ground RF Emitter in 865 MHz and 2.4 GHz Bands," *IEEE Vehicular Technology Conference*, vol. 2022-June, 2022, doi: 10.1109/VTC2022-Spring54318.2022.9860875.

[20] L. Val-Terron, J. J. Escudero-Garzas, L. Perez-Roca, A. M. Vega-Viejo, and A. Alves-Gonzalez, "Air-to-ground channel characterization for unmanned aerial vehicles based on field measurements in 5G at 3.5 GHz," in *International Conference on Wireless and Mobile Computing, Networking and Communications*, Oct. 2022, vol. 2022-Octob, pp. 453–456, doi: 10.1109/WiMob55322.2022.9941634.

[21] L. Zhu, D. He, K. Guan, B. Ai, Z. Zhong, and D. Li, "Channel characterization and simulation for unmanned aerial vehicle communication," in *2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting, APSURSI 2019 - Proceedings*, Jul. 2019, pp. 2135–2136, doi: 10.1109/APUSNCURSINRSM.2019.8888656.

[22] X. Yin and X. Cheng, "Characterization of propagation channels," in *Propagation Channel Characterization, Parameter Estimation, and Modeling for Wireless Communications*, Wiley, 2018, pp. 15–40.

[23] D. L. Hall, M. J. Brandsema, and R. M. Narayanan, "Derivation of k-factor detection statistics to discriminate between LOS and NLOS scenarios," *IEEE Transactions on Wireless Communications*, vol. 21, no. 4, pp. 2668–2679, 2022, doi: 10.1109/TWC.2021.3114614. [24]

[24] K. K. Talukdar and W. D. Lawing, "Estimation of the parameters of the rice distribution," *The Journal of the Acoustical Society of America*, vol. 89, no. 3, pp. 1193–1197, 1991, doi: 10.1121/1.400532. [25]

[25] G. Azemi, B. Senadji, and B. Boashash, "Estimating the Ricean k-factor for mobile communication applications," in *Seventh International Symposium on Signal Processing and Its Applications, 2003. Proceedings*, 2003, vol. 2, pp. 311–314 vol. 2, doi: 10.1109/ISSPA.2003.1224876.

[26] Y. Guno *et al.*, "An analytical approach to uninterrupted UAV video communication: simulations and findings," in *Proceeding - 2023 International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications: Empowering Global Progress: Innovative Electronic and Telecommunication Solutions for a Sustainable Future, ICRAMET 2023*, Nov. 2023, pp. 51–56, doi: 10.1109/ICRAMET60171.2023.10366537.

[27] C. Stefanovic, S. Panic, V. Bhatia, and N. Kumar, "On second-order statistics of the composite channel models for UAV-to-ground communications with UAV selection," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 534–544, 2021, doi: 10.1109/OJCOMS.2021.3064873.

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