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An Integrated Ray Tracing and Variable-Step Fourier Transform-Based Split-Step Parabolic Equation Modeling Approach for UAV-Assisted Channel Characterization in Mountainous Environments

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ABSTRACT: To enhance communication performance in mountainous environments, unmanned aerial vehicle (UAV)-assisted communication systems have emerged as a mainstream solution. Channel modeling for UAV-assisted communication is a critical research focus, confronting prominent challenges, including balancing computational efficiency and modeling accuracy. This paper proposes a hybrid modeling approach that combines ray tracing (RT) and the variable-step Fourier transform-based Split-Step Parabolic Equation (V-FSSPE) to address the issue. The proposed method fully leverages the strengths of RT in accurately calculating direct, reflected, and diffracted propagation paths, as well as the advantages of V-FSSPE in efficiently modeling long-distance and large-scale areas. A hierarchical model suitable for low-altitude UAV communication is thereby established. Simulation results demonstrate that, compared with traditional modeling methods, the proposed method in this study effectively balances accuracy and efficiency in terrain-dominated air-to-ground channels, making it suitable for millimeter wave (mmWave) communication and emergency communication network planning in terrain-dominated propagation environments. Since factors such as vegetation and atmospheric effects have not yet been incorporated, practical deployment requires case-specific corrections based on the actual environment. Nonetheless, this framework is expected to provide important theoretical references and foundational support for the design and optimization of communication systems in related fields.

1. INTRODUCTION

With the rapid development of sixth-generation (6G) networks and unmanned aerial vehicle (UAV) technologies, UAV communication networks are gaining increasing significance in both military and civilian applications. In particular, in the context of the integration of space-air-ground integrated networks, UAV serves as a crucial component, providing robust support for achieving global seamless coverage and ubiquitous connectivity [1]. Millimeter wave communication technology, with its abundant spectrum resources and high data transmission rates, has emerged as one of the most promising cutting-edge technologies in the field of UAV communications [2]. In complex terrains, such as mountainous regions and border areas, UAV-assisted communication has demonstrated great potential for application. However, accurate channel modeling has become a key challenge in system design and performance optimization. The irregular undulations of mountainous terrain, vegetation coverage, and dynamic motion of UAVs lead to significant spatial non-uniformity and temporal variability in communication channels, which traditional modeling methods struggle to accurately characterize.

To address this challenge, a hybrid modeling method that integrates ray tracing (RT) and the variable-step Fourier transform-based Split-Step Parabolic Equation (V-FSSPE) is proposed in this study. The RT method can precisely capture deterministic paths, such as line-of-sight (LoS) propagation and specular reflection, which feature computational efficiency and physical intuitiveness. In contrast, the V-FSSPE can efficiently simulate diffraction and scattering effects in complex terrains using adaptive step-size adjustment and Fourier transform techniques. Most existing studies focus on individual modeling methods that do not fully exploit the complementary strengths of the two techniques. While RT excels in LoS propagation scenarios, it falls short in handling non-line-of-sight (NLoS) environments. Conversely, although the V-FSSPE can accurately capture phase and field strength variations, it suffers from computational redundancy in simple scenarios. By combining their strengths, RT is suitable for detailed and precise modeling, whereas the V-FSSPE is appropriate for large-scale path analysis. The integration of these two methods not only enhances the modeling accuracy but also maintains computational efficiency, thus providing an efficient and precise solution for UAV communication channel modeling in complex terrains.

Numerous studies have provided essential references and insights into the development of UAV communication channel characteristics. Zhang et al. [3] investigated the channel characteristics of 6G UAV-assisted emergency communications in complex mountainous scenarios by combining ray-tracing simulations with field measurements. This study provides criti-

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cal data and theoretical support for the design and optimization of UAV communication systems within integrated space-air-ground networks. To address the issue of phase error sensitivity in traditional phased arrays, Galvan-Tejada et al. [4] employed a baseband mixed array scheme for compensation, which resulted in improved noise performance for UAV signal tracking. Zhu et al. [5] proposed a new path loss model for UAV-to-ground millimeter-wave communication and provided a detailed analysis of path loss data under different scenarios and UAV flight altitudes, offering new perspectives and methods for millimeter-wave channel research. Guan et al. [6] presented an ultra-compact self-decoupled multiple-input multiple-output (MIMO) antenna that leverages common-mode/differential-mode current cancellation. Without any additional decoupling structures, it achieves high isolation and high efficiency for 5G communications in space-constrained UAV scenarios, offering a core antenna engine for future integrated air-space-ground networks, which is smaller, more powerful, and faster to deploy. Akram et al. [7] analyzed the path loss, delay spread, and Ricean K-factor of UAV air-to-ground channels through field measurements in hilly, open terrain, and suburban environments, and proposed an empirical channel model tailored to the characteristics of the South Asian region. For UAV communications in short-range, low-altitude, and obstruction-free environments, Salman et al. [8] proposed a modified two-ray propagation model and revealed that the distortion of the antenna radiation pattern by the device's printed circuit board is a critical factor leading to signal strength fluctuations. He et al. [9] analyzed large and small-scale channel characteristics at flight altitudes of 300 and 400 m, respectively, in rural scenarios using measurement data and established corresponding mathematical models, providing important references for future UAV-assisted communication channel modeling in complex environments.

Semkin et al. [10] reviewed a UAV-based millimeter-wave measurement system and presented preliminary experimental results obtained in an open-air venue at 28 GHz, setting a technical benchmark for high-frequency aerial channel research and providing a replicable technical approach for subsequent studies. Thakur et al. [11] proposed a miniature dual-port MIMO antenna that integrated a T-shaped patch with a defected ground structure. Without any extra decoupling elements, it simultaneously delivers high isolation, low correlation, and high radiation efficiency at 28 and 38 GHz millimeter-wave bands, offering a minimalist yet high-performance antenna solution for 5G terminals. Kohli et al. [12] focused on the propagation characteristics from outdoor to indoor environments in a dense urban setting at 28 GHz, establishing a path loss model through large-scale measurement activities and evaluating the impact of different environmental factors on signal propagation, further enriching the content of mm-wave channel research. To date, researchers have extensively studied millimeter-wave channels in various scenarios, including indoor [13, 14], urban [15, 16], suburban [17], and sea-surface [18] environments, achieving a series of results. However, mountainous areas, which are one of the critical scenarios for UAV communication, require accurate channel modeling for the design of UAV communication systems, especially in applications such as mountain rescue and forest fire detection [19, 20].

Therefore, this study proposes a high-precision channel modeling method for UAV-assisted communication in complex mountainous environments, based on the integration of RT and V-FSSPE. It fully exploits the precision of RT for computing the direct, reflected, and diffracted paths, along with the efficiency of the V-FSSPE in modeling large-scale, long-distance propagation, thereby delivering an efficient and reliable millimeter-wave channel model for complex mountainous terrains.

2. THEORETICAL ANALYSIS OF THE HYBRID METHOD

Gao et al. [21] employed the Parabolic Equation (PE) method in their study. By assuming wave propagation in the $+x$ direction and performing factorization, they obtained the forward parabolic equation from the Helmholtz equation. Subsequently, employing the Feit-Fleck approximation method, they derived a wide-angle parabolic equation. Finally, the parabolic equation is solved using the Split-Step Fourier Transform (SSFT) method, yielding the final solution as

$$u(x+\Delta x, z)=e^{ik(n-2)\Delta x}\mathcal{F}^{-1}\left\{e^{i\Delta x\left(\sqrt{k^2-p^2}-k\right)}\mathcal{F}[u(x_0,z)]\right\}, \quad (1)$$

where $\mathcal{F}$ and $\mathcal{F}^{-1}$ represent the Fourier and inverse Fourier transforms, respectively; p denotes the frequency-domain variable; $e^{ik(n-2)\Delta x}$ is the refractive index; $e^{i\Delta x\left(\sqrt{k^2-p^2}-k\right)}$ is the diffraction factor; Δx denotes a step-size adaptive function, as shown in Figure 1.

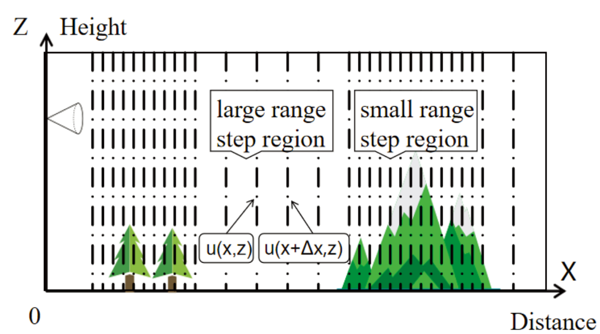

FIGURE 1. Schematic diagram of regional decomposition in complex mountainous environments.

The step-size adaptive function Δx can be written as

$$\Delta x = \min\left(\Delta x_{\max}, \max\left(\Delta x_{\min}, \frac{\lambda}{10\cdot\|\nabla n\|}\right)\right), \quad (2)$$

where $|\nabla n\|$ is the magnitude of the gradient vector, and λ is the wavelength of the electromagnetic wave in free space. In the V-FSSPE, the step size depends on the terrain complexity and can be selected based on the following judgments

$$N_{\text{steps}} = \begin{cases} \max\left(6, \min\left(15, \frac{d}{20}\right)\right) & C < 30 \\ \max\left(16, \min\left(25, \frac{d}{10}\right)\right) & 30 \le C < 60 \\ \max\left(26, \min\left(50, \frac{d}{3}\right)\right) & C \ge 60 \end{cases}, \quad (3)$$

where d represents the horizontal propagation distance from the transmitter to the receiver, and C denotes the relative steepness of the terrain, which can be obtained as follows:

$$C = 100 \times \frac{G(x, y) - G_{\text{min}}}{G_{\text{max}} - G_{\text{min}}}, \tag{4}$$

where $G(x, y)$ represents the topographic gradient magnitude, with G_{min} being the global minimum and G_{max} being the global maximum gradient values across the entire domain. The general classifications of terrain complexity are listed in Table 1.

TABLE 1. Complexity classification and step-size strategy.

Complexity Range	Terrain Category	Step-size Strategy
$C < 30$	Flat terrain	Large step size ($\frac{d}{20}$)
$30 \leq C < 60$	Moderate relief	Medium step size ($\frac{d}{10}$)
$C \geq 60$	Complex terrain	Small step size ($\frac{d}{3}$)

A decision function is then employed to integrate the RT and V-FSSPE, and the decision condition is given by

$$M(d, C) = \mathbb{I}(d \leq d_{th} \vee C \leq C_{th}), \tag{5}$$

where d_{th} denotes the distance threshold, and C_{th} denotes the terrain-complexity threshold which is

$$C_{th} = 100 \times \frac{\theta_c}{\theta_{\text{max},terrain}}, \tag{6}$$

where θ_c is the maximum applicable slope for the V-FSSPE, and $\theta_{\text{max},terrain}$ is the maximum physical slope within the region. Based on the computational complexity balance model and the total computational cost of the two methods, it can be concluded that

$$\alpha \cdot (d_{\text{th}})^{\gamma} \cdot N_{\text{rays}} \cdot (1 + \langle n_{\text{ref}} \rangle) = \beta \cdot K_{\text{flat}} \cdot N_z \cdot \log N_z, \tag{7}$$

$$d_{\text{th}} = \left(\frac{\beta \cdot K_{\text{flat}} \cdot N_z \cdot \log N_z}{\alpha \cdot N_{\text{rays}} \cdot (1 + \langle n_{\text{ref}} \rangle)} \right)^{\frac{1}{\gamma}}, \tag{8}$$

where α denotes the unit computational cost coefficient for RT; γ represents the computational complexity growth exponent for RT; N_{rays} is the number of initial rays; $\langle n_{\text{ref}} \rangle$ is the average number of effective interactions; β corresponds to the single-step computational cost coefficient for V-FSSPE; K_{flat} indicates the total number of steps over flat terrain; N_z is the number of grid points in the vertical dimension; and $\log N_z$ reflects the FFT computation factor.

Terrain attenuation and free-space path loss (FSPL) are two critical factors when modeling channels in mountainous environments. For constructing the channel model, this study strictly adheres to the relevant calculation standards published by the International Telecommunication Union (ITU) [22, 23], to ensure the accuracy and reliability of the model. In accordance with the published standards, all geometrical parameters in the terrain attenuation model are combined in a single dimensionless parameter normally denoted by

$$v = h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1} + \frac{1}{d_2}\right)}, \tag{9}$$

where h is the height of the top of the obstacle above the straight line connecting the two ends of the path. If the height is below this line, h is negative and vice versa. d_1 and d_2 are the distances between the two ends of the path from the top of the obstacle. The formula is then applied to the single-knife-edge diffraction field amplitude model:

$$J(v) = -20\log\left(\frac{\sqrt{[1 - C(v) - vS(v)]^2 + [C(v) - S(v)]^2}}{2}\right), \tag{10}$$

where $C(v)$ and $S(v)$ are the real and imaginary parts of the complex Fresnel integral $F(v)$, which is defined as

$$F(v) = \int_0^v \exp\left(j\frac{\pi s^2}{2}\right) ds = C(v) + jS(v), \tag{11}$$

where j is the complex operator equal to $\sqrt{-1}$, and $C(v)$ and $S(v)$ are the Fresnel cosine and sine integrals, respectively, defined by

$$C(v) = \int_0^v \cos\left(\frac{\pi s^2}{2}\right) ds, \tag{12}$$

$$S(v) = \int_0^v \sin\left(\frac{\pi s^2}{2}\right) ds. \tag{13}$$

For v greater than -0.78, an approximate value can be obtained from the expression

$$J(v) = 6.9 + 20\log\left(\sqrt{(v - 0.1)^2 + 1} + v - 0.1\right) \text{ dB}. \tag{14}$$

After analyzing diffraction losses in complex terrain environments, a comprehensive evaluation of the total attenuation in UAV communication channels necessitates considering the fundamental path loss under unobstructed free-space propagation conditions (FSPL). FSPL refers to the signal attenuation caused by beam spreading as electromagnetic waves propagate through free space (an obstacle-free environment). It is a fundamental concept in wireless communication, radar, and satellite systems, and is primarily used to estimate the power attenuation of signals in an ideal vacuum or unobstructed line-of-sight propagation environment. In this study, the altitude of the UAV was set to 300 m. At this height, the unobstructed propagation distance between the UAV and the ground is relatively long, and thus the signal attenuation in free space has a significant impact on the analysis of experimental results. To accurately assess this part of the signal attenuation, this study introduces the FSPL model and elaborates on its calculation method as follows:

$$\text{FSPL} = -10\log_{10}\left(\frac{1}{4\pi d^2} \times \frac{\lambda^2}{4\pi}\right) = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \text{ dB}, \tag{15}$$

where d is the distance; λ is the wavelength; d and λ are expressed in the same unit. Following the incorporation of the FSPL model as a foundational element of propagation attenuation, the assessment of the overall communication link loss

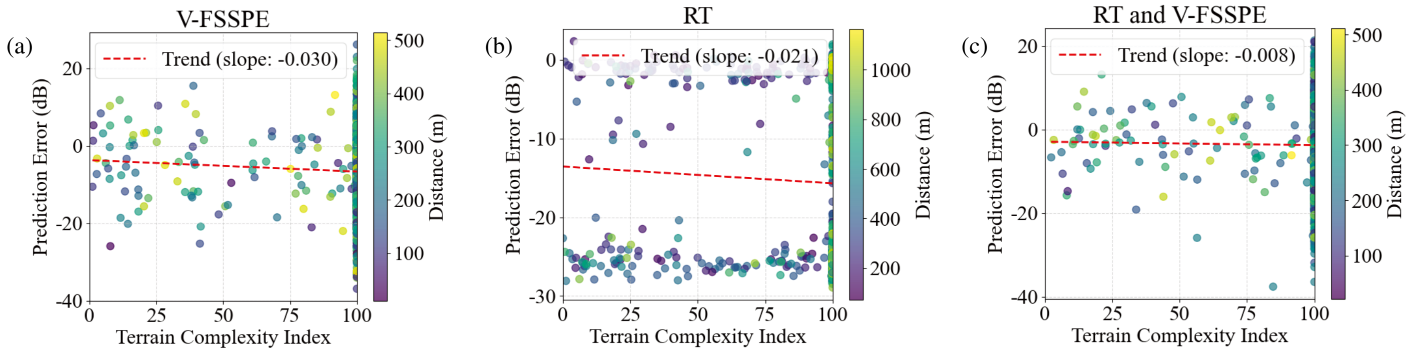

FIGURE 2. Slope estimation error by different methods in lofty mountains.

requires an extension to the estimation of the received power at the terminal. The received power is calculated using a typical model employed in wireless communications.

$$P_{rx} = P_{tx} - \text{FSPL} - L_{Dif} - L_{Shadow} - L_{Mul}. \quad (16)$$

where P_{tx} denotes the transmit power, L_{Dif} the diffraction loss incurred owing to terrain obstructions, L_{Shadow} the shadow fading, and L_{Mul} the multipath fading. Subsequently, the signal-to-noise ratio (SNR) is calculated based on the received power.

$$\text{SNR} = 10\log_{10}\left(\frac{P_{rx}}{P_n}\right) \quad \text{(dB)}, \quad (17)$$

P_n represents the noise power, and the average bit error rate (BER) is subsequently derived from the SNR.

$$\text{BER}_{avg} = \int_0^{\infty} \text{BER}(\text{SNR}) \cdot p(\text{SNR})\, d\text{SNR}. \quad (18)$$

To validate the performance of the hybrid modeling method, a mountainous area was simulated, and the average BER was obtained as follows 8.79×10^{-2} for RT, 9.22×10^{-3} for V-FSSPE, and as low as 3.79×10^{-4} for the combined RT and V-FSSPE method. These results demonstrate that the RT and V-FSSPE methods outperform all other comparative methods, achieving the lowest average BER. This indicates that the hybrid method maintains a low BER across different SNR conditions, exhibiting superior reception performance and significantly outperforming the other individual methods. It further validates the superiority and reliability of the RT and V-FSSPE method in complex environments, providing strong support for enhancing the performance of communication systems.

As illustrated in Figure 2, the relationship between the slope estimation error and terrain complexity was evaluated across three methods: the proposed RT, V-FSSPE, and their combined approach. A clear trend was observed for all methods, where the estimation error generally decreased as the terrain complexity increased, as indicated by the negative slope of the fitted trend lines. Among them, the proposed V-FSSPE method exhibited the most pronounced downward trend (slope $= -0.029$), suggesting a significant improvement in estimation accuracy in complex terrains. The stand-alone RT method showed a moderate trend (slope $= -0.021$), while the RT and V-FSSPE demonstrated the flattest trend and smallest absolute slope (slope $= -0.008$), indicating its superior robustness and consistently high performance across all levels of terrain complexity.

3. CHANNEL MODELING OF UAV AIR-TO-GROUND (AG) COMMUNICATION IN MOUNTAINOUS ENVIRONMENTS

In mountainous environments, the modeling of UAV AG communication channels is vital for the design and evaluation of future UAV communication systems. To construct an accurate and realistic UAV AG communication channel model in a mountainous scenario, the ArcMap tool was used to collect high-precision terrain data for a specific mountainous area. These detailed terrain data were then imported into the Python environment, where the Python programming language was used in conjunction with a Digital Elevation Model (DEM) to successfully create a highly accurate three-dimensional mountainous environment model.

3.1. Channel Simulation Model

RT integrates Geometrical Optics (GO) and Uniform Theory of Diffraction (UTD) to predict signal propagation paths in known electromagnetic environments. This modeling approach requires a substantial amount of data to accurately describe the real environment and is highly dependent on the accuracy of the data. Figure 3 illustrates the channel modeling results obtained using a UAV at an altitude of 300 meters. In this figure, the transmitter location is marked with a red star, and the points on the terrain surface represent the received signal strength at different locations. The color gradient from blue to red indicates the variation of received power from low to high, with a power range spanning from -130 dBm to -70 dBm. Through this three-dimensional visualization, the attenuation and distribution of the signal in space can be intuitively observed. In LoS propagation, RT is computationally efficient and physically intuitive, accurately predicting signal propagation paths and received power. However, in NLoS propagation, the prediction accuracy of RT degrades due to complex scattering, reflection, and diffraction effects, resulting in very low predicted received power values. It indicates that the applicability of RT

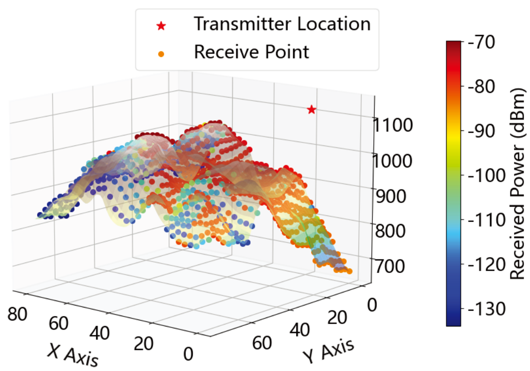

FIGURE 3. 3D RT simulation of wireless signal propagation in mountainous.

in complex mountainous environments is limited and needs to be combined with other methods to improve both the accuracy and efficiency of modeling.

The PE method is a technique for approximating the solution of the wave equation. It is assumed that the propagation of electromagnetic waves primarily occurs along the axis of a parabola and is concentrated within a conical region near the axis. Chen and Qin proposed a variable-step-size technique based on the Fourier Split-Step Parabolic Equation (FSSPE) for predicting radio-wave propagation over large-scale irregular terrain. The performances of fixed (50 m) and variable-step-size (50 m to 1000 m) methods were compared in their study, and the results concluded that the variable-step FSSPE (V-FSSPE) method demonstrates excellent computational efficiency and prediction accuracy in propagation forecasting over low-altitude irregular terrain [24]. Gao et al. introduced the Split-Step Fourier Transform (SSFT) algorithm, which effectively overcomes the issue of low computational efficiency associated with fixed-step-size methods and enhances the adaptability of the SSFT algorithm in various complex environments [21].

By analyzing the propagation factors under different environmental conditions and step sizes and comparing them with fixed-step-size solutions, the reliability and efficiency of the variable-step-size technique were verified. Moreover, without compromising computational accuracy, the variable-step-size method can further improve the efficiency of the parabolic equation. In the V-FSSPE algorithm, the fundamental principle of domain decomposition is as follows: large-step increments and coarse-grid discretization are employed in obstacle-free areas and regions with simple terrain structures; conversely, small-step increments and fine-grid discretization are used in areas with complex terrain structures where electromagnetic waves exhibit significant variations in all directions. The domain decomposition for the aforementioned complex mountainous environment is shown in Figure 3. The terrain complexity distribution and the V-FSSPE propagation paths in a mountainous scenario are described in the two parts of Figure 4. The left panel displays the distribution of terrain complexity, where color coding is used to represent the degree of complexity. The color bar ranges from blue to red. Variations in color across the figure depict the spatial distribution of terrain complexity, where blue areas indicate relatively flat terrain, and red areas indicate more complex terrain.

The terrain complexity calculation method is based on the classical terrain gradient theory. The steepness and undulation of the terrain ware accurately characterized by computing the composite magnitude of the partial derivatives of the elevation data in the east-west and north-south directions. This approach establishes an intuitive and reliable terrain influence evaluation system for wireless propagation modeling. The right panel shows the V-FSSPE propagation paths for the mountainous scenario. This three-dimensional visualization illustrates the propagation paths from the transmitter to various receivers. The red, orange, and blue lines indicate small, medium, and large steps, respectively. The differently-colored lines represent the signal paths through space, intuitively showing how the signals propagate in the mountainous environment and how the region is decomposed based on terrain complexity.

When modeling UAV air-to-ground channels in mountainous environments, factors such as terrain complexity, climate change, and multipath effects impose higher demands on the accuracy of channel modeling than in other environments. To enhance the accuracy of channel modeling while maintaining computational efficiency, this study employs a hierarchical model that integrates RT and V-FSSPE. In low-altitude complex terrains, the RT can finely simulate the details of signal propagation and accurately capture the LoS paths. In high-altitude or free-space propagation, the V-FSSPE provides efficient large-scale channel modeling, rapidly handles long-distance propagation and large-scale terrain variations. The modeling area was divided into different sub-regions based on environmental characteristics, such as mountainous areas, suburban areas, and open spaces. Each sub-region selects an appropriate modeling method according to its terrain and propagation characteristics, thereby achieving both efficiency and accuracy of the model.

The 3D propagation paths after the integration of RT and V-FSSPE are shown in Figure 5. In the figure, the red lines represent the propagation paths of the RT, whereas the blue lines represent those of the V-FSSPE. Through this three-dimensional visualization, one can intuitively observe the signal paths and processes from the transmitter to various receivers via the hierarchical model, which adaptively employs different methods according to the characteristics of each region of interest. The strengths of both RT and V-FSSPE are fully leveraged in this hybrid modeling method, providing an efficient and precise solution for UAV communication channel modeling in complex terrains.

4. ANALYSIS OF SIMULATION RESULTS

In this study, the statistical tool of Cumulative Probability was employed in conjunction with power to conduct an in-depth analysis of the impact of the high-precision channel modeling method integrating RT and V-FSSPE on channel modeling in mountainous environments. The cumulative probability reflects the probability that a random variable takes a value less than or equal to a specific value, providing an effective means of quantifying data distribution, conducting probabilistic esti-

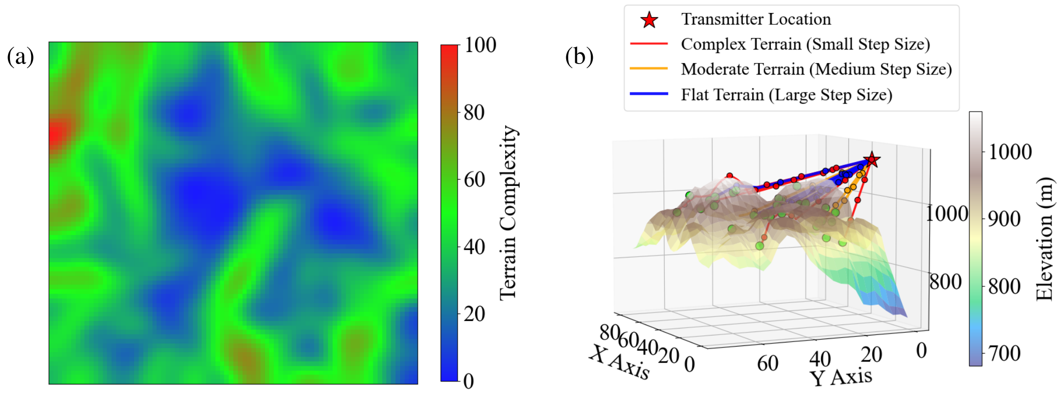

FIGURE 4. (a) Terrain complexity. (b) V-FSSPE paths in ordinary mountains.

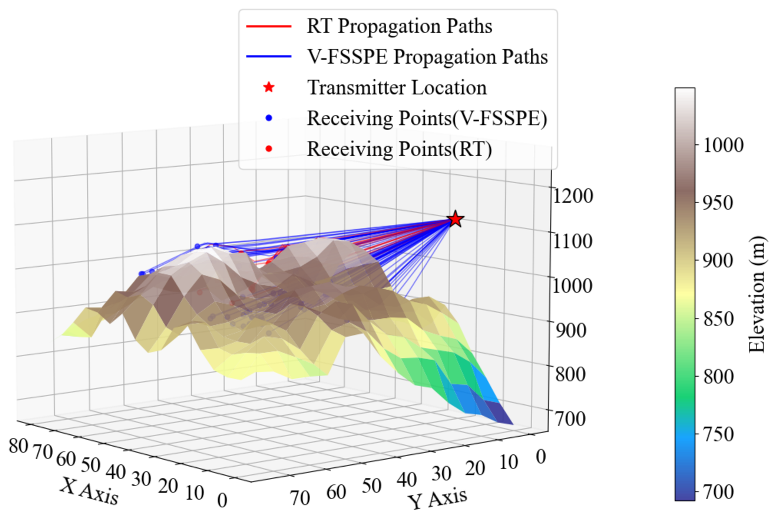

FIGURE 5. 3D RT and V-FSSPE simulation of wireless signal propagation in mountainous.

mation, and performing hypothesis testing. Power represents the energy transferred or consumed by the signal per unit time. It plays a significant role in various aspects of communication technology, permeating every link of signal transmission, network optimization, equipment design, and environmental protection. Power is an indispensable consideration in communication systems. The delay primarily quantifies the response speed of a system. Its core advantage lies in the precise evaluation of performance in real-time-demanding scenarios. By measuring the time loss in each link of signal transmission or data processing, the delay can directly reveal the bottlenecks in communication link quality, computational efficiency, and user experience. This provides a crucial basis for the design and optimization of network architecture, helping to achieve low-latency and highly reliable system objectives.

Figure 6 shows the cumulative distribution function (CDF) of the received power and average BER. It can be observed from the figure that the RT method performs the best in the medium power range of -85 to -70 dBm, with the probability of the received signal rising rapidly. However, when the power fell below -85 dBm, the performance of the RT method dropped significantly. This is mainly due to the complex variations of mountainous terrain, which increase the complexity of the NLoS paths and lead to a significant increase in path loss. The V-FSSPE method exhibits a significant increase in the probability of the received signal when the power is above -70 dBm, demonstrating its advantage at higher power levels. The combined RT and V-FSSPE method performs well at high power levels above -60 dBm. This indicates that the hybrid method can effectively enhance the probability of signal reception in high-power scenarios, fully leveraging the complementary strengths of both the methods. It provides a more accurate and efficient solution for channel modeling in complex mountainous environments.

As illustrated in Figure 7, a comprehensive performance evaluation of the three-channel modeling approaches was conducted using box-plot analysis. The box plot provides a detailed view of the received power distribution characteristics. The distributions of the V-FSSPE and hybrid methods are markedly more concentrated, whereas the RT method exhibits the widest distribution range and contains several outliers, further confirming its instability. These results indicate that although the high variability and broad distribution of the RT method make it suitable for scenarios requiring the capture of extreme signal fluctuations, the V-FSSPE method demonstrates superior performance in terms of stability and concentration, making it

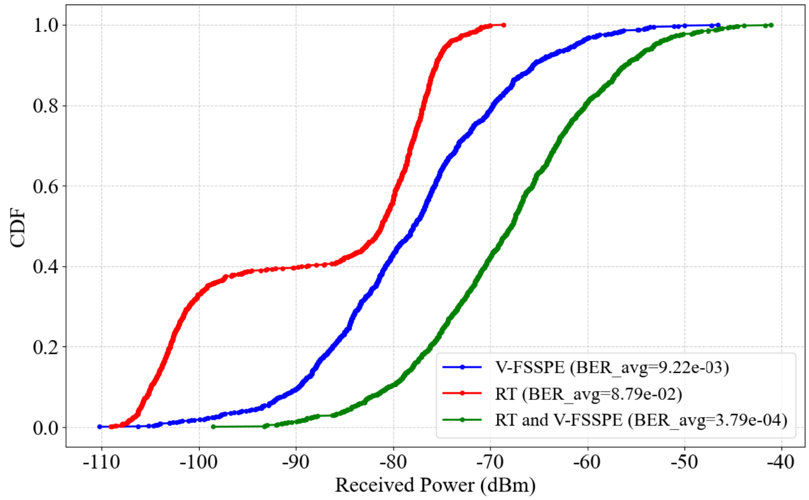

FIGURE 6. Received power CDF with average BER.

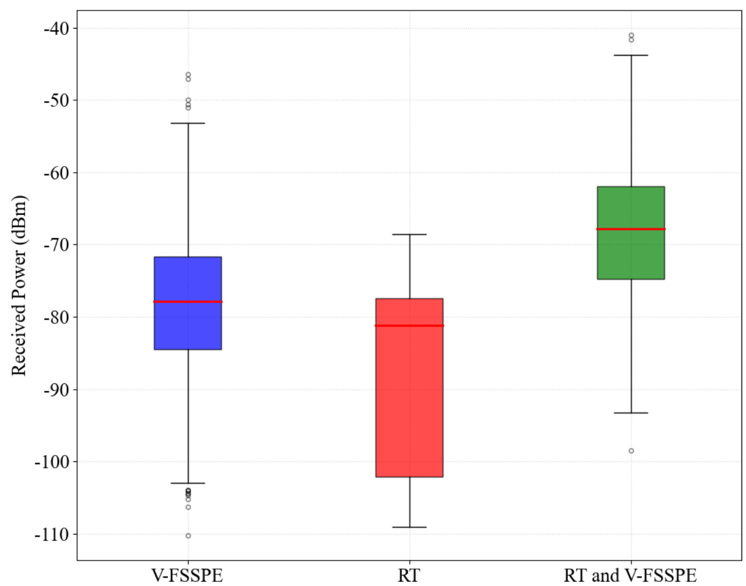

FIGURE 7. Received power box plot.

more appropriate for applications requiring reliable signal reception. The hybrid method effectively combines the strengths of both approaches.

The accuracy and applicability of the RT and V-FSSPE hybrid method were further validated using two additional representative mountainous scenarios characterized by highly complex topography, as illustrated in Figures 8 and 9. Both terrains exhibit pronounced surface undulations, irregular geomorphology, and substantial elevation differences, thereby providing rigorous test beds for evaluating the prediction precision and computational efficiency under realistic conditions. The simulation results for these two challenging environments are presented in Figures 2 and 10. It can be observed that the RT and V-FSSPE hybrid method maintains high accuracy in LOS regions while significantly improving the continuity of power prediction in NLOS areas. By compensating for the systematic negative bias inherent in the conventional RT caused by the absence of higher-order reflections or diffractions in complex mountainous settings, the proposed approach enhances overall modeling reliability and coverage assessment accuracy.

Table 2 presents the average BER for the three distinct mountainous terrain types. The hybrid RT and V-FSSPE methods demonstrated significantly superior adaptability to mountainous environments, achieving the lowest BER across all terrain categories. This advantage is particularly pronounced in rugged and towering mountainous terrain. Table 3 compares the average execution time of the three methods across different terrain types. The results indicate that, in all tested scenarios, the pure V-FSSPE method achieves the fastest computational speed, while the pure RT method exhibits the lowest computational efficiency. Notably, the hybrid method proposed in this study demonstrates execution efficiency between the two,

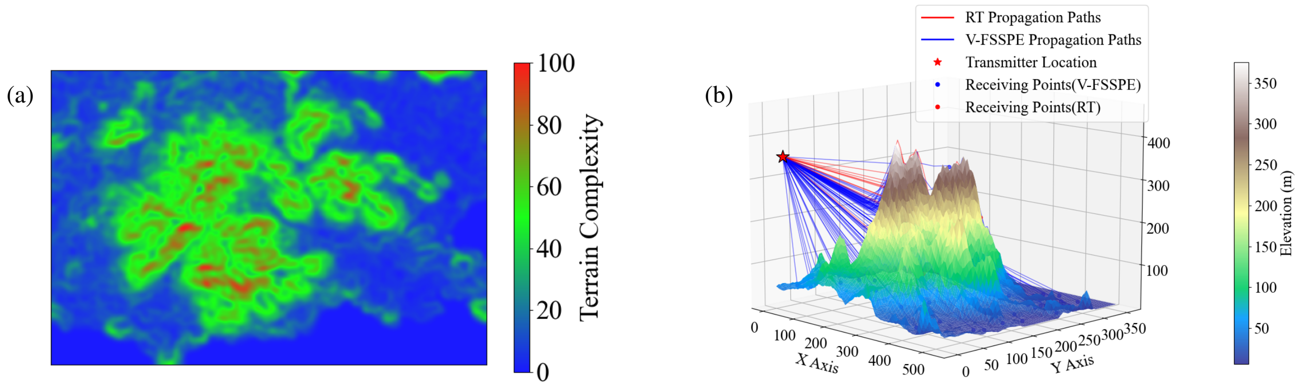

FIGURE 8. (a) Terrain complexity. (b) RT and V-FSSPE paths in rugged mountains.

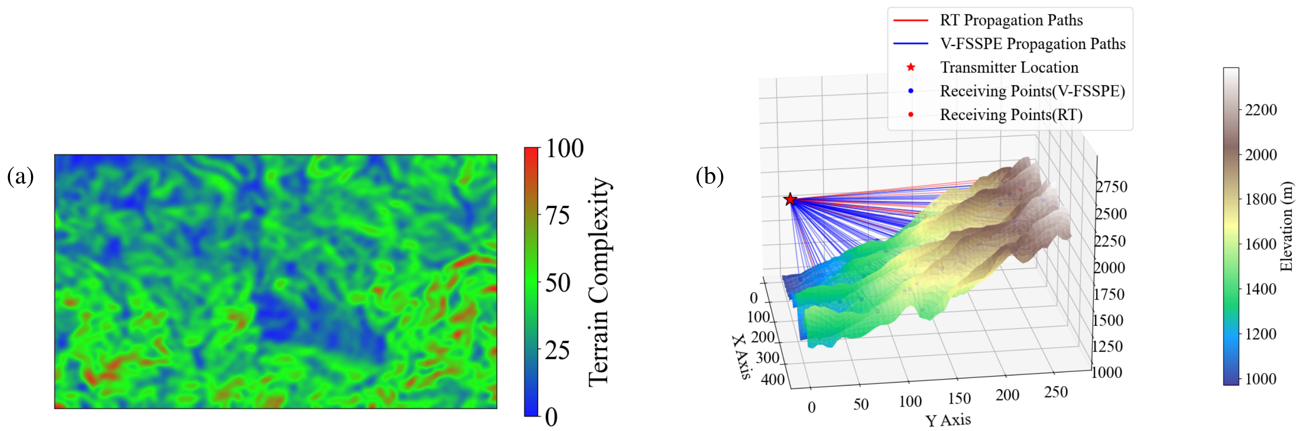

FIGURE 9. (a) Terrain complexity. (b) RT and V-FSSPE paths in lofty mountains.

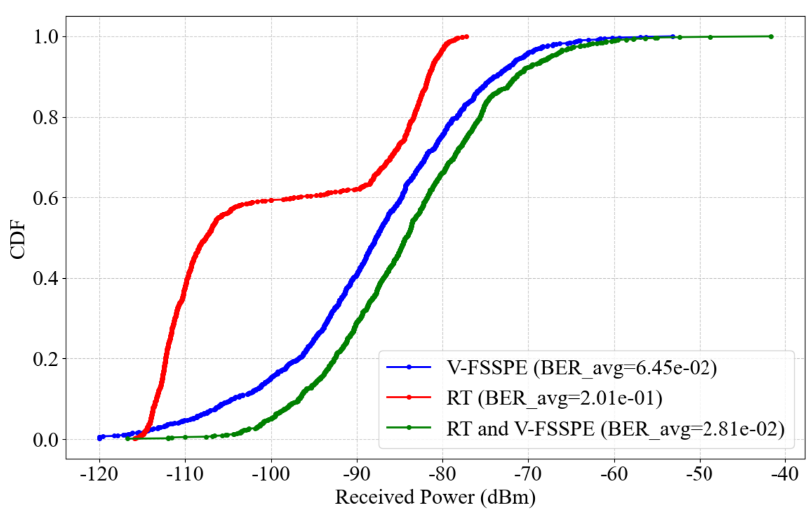

FIGURE 10. Received power CDF and average BER for rugged mountains.

yet significantly outperforms the pure RT method. This suggests that by incorporating V-FSSPE for coupling, the hybrid method effectively circumvents the computational bottlenecks faced by the pure RT method in topographically complex areas, thereby achieving a substantial improvement in overall computational efficiency while ensuring methodological reliability. In summary, in complex mountainous communication scenarios, a single propagation model often has inherent applicability limitations, whereas a hybrid modeling strategy that integrates the advantages of multiple methods can demonstrate enhanced reliability and environmental adaptability.

TABLE 2. Comparison of average bit error rate.

Terrain Type	Average BER		
	RT	V-FSSPE	RT & V-FSSPE
Ordinary mountains	8.79×10^{-2}	9.22×10^{-3}	3.79×10^{-4}
Rugged mountains	2.10×10^{-1}	6.45×10^{-2}	2.81×10^{-2}
Lofty mountains	2.07×10^{-1}	4.35×10^{-2}	2.50×10^{-2}

TABLE 3. Comparison of execution time.

Terrain Type	Average Execution Time		
	RT	V-FSSPE	RT & V-FSSPE
Ordinary mountains	1.37 s	0.43 s	1.16 s
Rugged mountains	5.14 s	1.29 s	1.59 s
Lofty mountains	4.29 s	1.56 s	1.65 s

5. CONCLUSION

This study addresses the challenging problem of channel modeling for UAV-assisted communications in complex mountainous terrain by proposing a hybrid approach that integrates RT with V-FSSPE. First, theoretical analyses were conducted to thoroughly investigate the impact of the RT and V-FSSPE hybrid method on the channel characteristics of UAV communications in mountainous environments. Subsequently, systematic comparative evaluations among RT, V-FSSPE, and the proposed hybrid scheme were conducted over three representative mountainous scenarios, clearly demonstrating the superiority of the mixed approach. The experimental results reveal that the proposed method achieves superior performance and higher stability compared with standalone RT or V-FSSPE in mountainous settings: the average BER is optimized to 3.79×10^{-4} in ordinary mountains, reduced to 2.81×10^{-2} in rugged mountains, and in lofty mountains, the slope value lowered to -0.008, resulting in a decrease in the average BER to 2.50×10^{-2}. Consequently, this study provides a high-accuracy and high-efficiency channel modeling solution for emergency communications in mountainous regions, offering significant engineering value for enhancing the reliability and applicability of UAV communications. Future work will introduce multiphysics correction factors to further incorporate factors such as vegetation, atmospheric effects, and artificial obstacles, gradually expanding the application scope of the model.

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