

Enhancing Speech Quality in Scintillating Satellite Communications: A Rician Fading Modeling Approach

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Abstract— Ionospheric scintillation causes rapid signal fluctuations that degrade satellite voice communications. While radio wave propagation under scintillation is well studied, its impact on speech signals is less understood. This work introduces a speech modeling framework using variable K-factor Rician fading to simulate scintillation effects. We propose two enhancement methods: a lightweight RNN for real-time use and a score-driven diffusion model for high-fidelity restoration. Both are trained on augmented datasets generated by our proposed scintillated speech model and joint optimization framework. Compared to the Cornell scintillation toolkit, our approach yields consistently better speech quality. This work contributes a practical solution for enhancing speech quality in satellite aviation communications.

Keywords— Ionospheric Scintillation, Rician Fading, Speech Signal Degradation, Speech Enhancement

I. INTRODUCTION

Satellite and space-based tactical communication systems are highly susceptible to propagation impairments caused by atmospheric disturbances, which can significantly degrade signal quality and reliability [1]. Among these impairments, ionospheric scintillation is particularly detrimental, introducing rapid and stochastic fluctuations in signal amplitude and phase due to irregularities in the ionosphere and troposphere [2]. Such effects lead to severe time-varying and frequency-selective fading, which is especially disruptive for speech transmission in dynamic and high-mobility satellite links.

The Rician fading model is widely adopted to characterize such channels, as it effectively represents scenarios with a dominant line-of-sight (LoS) component combined with multiple scattered paths [3]. This makes it suitable for modeling satellite links where partial LoS is often preserved under scintillation conditions. Despite substantial research on radio wave propagation under scintillation, there has been limited focus on its impact on speech signals and on practical mitigation strategies for satellite voice

communications.

This paper addresses this gap by presenting a novel simulation framework that models scintillated speech using varying K-factor Rician fading envelopes to replicate realistic propagation conditions. We further propose two speech enhancement methods that jointly optimize signal equalization and denoising: (i) a lightweight recurrent neural network (RNN) for real-time applications and (ii) a score-driven diffusion model targeting high-fidelity speech restoration. Both models are trained on an augmented speech corpus generated with the proposed scintillation model and joint optimization scheme.

We benchmark our Rician-based framework against the widely used Cornell scintillation simulation toolkit [18] and evaluate the performance of the enhancement models through objective and subjective measures. Experimental results demonstrate that the proposed methods consistently outperform conventional approaches and those trained on signals simulated with existing tools. The proposed framework lays a foundation for deploying robust speech enhancement solutions in practical satellite aviation communications, with planned trials in Singapore.

The remainder of the paper is structured as follows: Section 2 will discuss the background of scintillation and speech enhancement in fading channels. Section 3 will discuss the methodology, Section 4 will discuss the experimental setup, Section 5 will present the results, and Section 6 will offer a discussion of the findings.

II. BACKGROUND

In satellite communication systems, transmitted signals are frequently subjected to multipath propagation due to interactions with physical obstructions and reflective surfaces. This results in the signal arriving at the receiver via multiple paths, each exhibiting distinct delays, amplitudes, and phase shifts. As a result, the received signal experiences fading, which can severely impair the integrity and intelligibility of speech transmission, particularly under dynamic channel conditions influenced by environmental and atmospheric factors.

2.1) Scintillation and Its Impact on Speech

Scintillation is a frequent impairment in satellite and high-frequency radio communications, caused by environmental factors such as atmospheric turbulence, ionospheric irregularities, and surface-induced multipath reflections [5]. These disturbances produce rapid, random fluctuations in signal amplitude and phase, which can severely degrade speech transmission. In speech communication systems, scintillation induces dynamic amplitude modulation and temporal distortion, which smear phonetic elements and reduce spectral resolution. These effects collectively diminish speech intelligibility, particularly under low signal-to-noise ratio (SNR) conditions, where the impact of rapid signal fluctuations is most pronounced. Conventional enhancement methods, which assume stationary noise and linear signal behavior, often fail under such conditions. Therefore, accurate modeling of scintillation is essential for developing robust speech enhancement algorithms that preserve intelligibility and perceptual quality in challenging propagation environments.

2.2) Rician Fading Model

The Rician fading model has been extensively validated in the wireless communication literature, particularly for scenarios involving a dominant line-of-sight (LoS) component superimposed on multipath scattering [2], [3]. Its statistical flexibility and physical relevance make it a preferred choice for modeling satellite and high-frequency channels [6]. The model is characterized by the Rician K-factor, defined as the ratio of the power in the direct path to the power in the scattered paths:

$$K = \frac{P_{LOS}}{P_{NLOS}} \quad (1)$$

where, P_{LOS} is the power of the direct (LoS) path and P_{NLOS} is the power of the scattered (Rayleigh) components.

The Rician fading envelope is constructed by combining a constant-amplitude LoS signal with a Rayleigh multipath component, which is typically simulated using the sum-of-sinusoids method based on the Jakes model [7]. The Rician envelope $r(t)$ is defined in this formula:

$$r(t) = \left| \sqrt{\frac{K}{K+1}} + \sqrt{\frac{K}{K+1}} \cdot \sum_{n=1}^N \cos(2\pi f_d \cos(\theta_n) t + \phi_n) \right| \quad (2)$$

where,

K: Rician K-factor (in linear scale)

f_d : Maximum Doppler frequency

N: Number of sinusoids

θ_n, ϕ_n : Random angles and phases

The envelope is expressed as the magnitude of the sum of these components, scaled by the K-factor. This model introduces realistic amplitude fluctuations and Doppler effects,

making it well suited for simulating scintillated speech in satellite communication environments.

2.3) Speech Enhancement in Fading Channels

Speech enhancement for demodulated signals involves restoring the intelligibility and perceptual quality of speech that has been transmitted through wireless or satellite communication channels and subsequently subjected to demodulation. Post-demodulation, the speech signal often exhibits non-linear distortions, spectral smearing, and temporal energy fluctuations, which can severely impair the effectiveness of conventional enhancement algorithms. Traditional speech enhancement techniques are primarily designed to suppress additive stationary noise and generally assume linearity and time-invariance in the signal model, which limits their applicability in scenarios involving complex channel-induced distortions. The noisy signal is typically modeled as:

$$S_{noisy}(t) = S_{clean}(t) + noise(t) \quad (3)$$

In contrast, demodulated signals are affected by multiplicative fading, non-Gaussian amplitude variations, phase distortions, and time-varying spectral envelopes [8], all of which are inherently non-stationary and channel-dependent. Aniruddha Chandra [9] discusses how Rician fading introduces multiplicative amplitude distortion, directly impacting AM demodulation performance.

In amplitude modulation (AM), the speech signal modulates the amplitude of the carrier. The transmitted AM signal is given by:

$$s(t) = [1 + m(t)] \cos 2\pi f_c t \quad (4)$$

where $m(t)$ is the speech signal and f_c is the carrier frequency. The received signal $R(t)$ can be modeled as:

$$R(t) = h(t) \cdot s(t) + n(t) \quad (5)$$

where $h(t)$ is the complex channel gain due to Rician fading, $n(t)$ is additive noise. The channel gain $h(t)$ is modeled as:

$$h(t) = Ae^{j\theta} + g(t) \quad (6)$$

where $Ae^{j\theta}$ is the deterministic line-of-sight (LoS) component, $g(t)$ is a complex Gaussian process representing multipath.

During envelope detection, the output is proportional to the product of the original signal and the fading envelope [10]. The demodulated signal can be approximated as:

$$\hat{m}(t) \approx |R(t)| \approx |h(t)| \cdot [1 + m(t)] + n(t) \quad (7)$$

This observation confirms that the statistical properties of Rician fading coexistence of a dominant line-of-sight (LoS) component and scattered multipath signals in the demodulated signal.

Effective enhancement of demodulated speech therefore requires channel-aware approaches, such as envelope tracking and fading profile estimation [11], or deep learning models trained on synthetically generated fading conditions [12][13]. These methods can reconstruct clean speech from severely degraded inputs by explicitly modelling the underlying non-linear and time-varying properties of the transmission channel.

III. METHODOLOGY

This chapter outlines the methodologies employed for data simulation, describes the speech enhancement techniques applied, and details the custom loss function used during model training.

3.1) Speech Signal Preparation

A clean speech signal is selected from the publicly available TIMIT corpus [14] and preprocessed to ensure suitability for fading simulation and enhancement. The signal is sampled at 16 kHz to retain high-frequency details, normalized to maintain consistent amplitude levels, and segmented into 20 ms frames with 50% overlap to facilitate time-frequency analysis. This preprocessing pipeline ensures that the signal is well-conditioned for subsequent modeling and enhancement tasks.

3.2) Rician Fading Envelope Generation

To simulate the effects of scintillation on speech signals, a Rician fading envelope is generated and applied to the clean waveform. The Rician model is chosen for its suitability in representing wireless channels with a dominant line-of-sight (LoS) component and multiple scattered paths, closely resembling the propagation conditions in satellite communication systems affected by ionospheric disturbances. The Rician envelope $r(t)$ is defined in Equation (2). By varying the K-factor, different fading conditions can be simulated:

- $K = 0$: Pure Rayleigh fading (no LoS).
- $K > 0$: Rician fading with increasing dominance of the LoS component.
- $K \rightarrow \infty$: Approaches an AWGN channel with negligible fading.

To reflect realistic channel behavior, the envelope is generated with temporal correlation. This is achieved by filtering white Gaussian noise through a Doppler spectrum shaping filter, typically modeled using the Jakes spectrum or a Gaussian-shaped Doppler profile. The Doppler frequency f_d

is determined by the relative velocity between the transmitter and receiver and the carrier frequency:

$$f_d = \frac{v}{c} f_c \quad (8)$$

where, v is the relative velocity, c is the speed of light, and f_c is the carrier frequency. This introduces time-varying fading effects that mimic the scintillation observed in satellite links.

3.4) Speech Enhancement Techniques

Recent advances in deep learning have significantly transformed the field of speech enhancement by enabling models to learn complex non-linear relationships between degraded and clean speech signals. In scenarios involving Rician fading-induced scintillation—characterized by multiplicative and non-stationary distortions, conventional denoising techniques often show limited effectiveness. Deep learning architectures, particularly those optimized for real-time processing and high-resolution restoration, offer promising alternatives. This section presents two representative approaches: an RNN-based model and a diffusion-based denoising model. RNNNoise [15], due to its lightweight and recurrent structure, is well suited for real-time enhancement, whereas StoRM diffusion models [16], with their iterative refinement capabilities, are appropriate for offline post-processing and archival restoration of speech degraded by severe scintillation.

A. RNNNoise

RNNNoise is a lightweight, real-time speech enhancement model developed by Jean-Marc Valin [15]. It combines traditional signal processing with a recurrent neural network (RNN) to perform noise suppression. To adapt for Rician Fading, RNNNoise retrained on speech data corrupted by simulated Rician fading with varying K-factors and Doppler frequency. The fading envelope is treated as a form of non-stationary noise. The model learns to suppress fading-induced amplitude fluctuations while retaining speech intelligibility.

B. StoRM (Diffusion Denoising Models)

Diffusion models represent a cutting-edge approach to generative modeling and have recently been adapted for speech enhancement [17]. This model work by iteratively refining a speech data corrupted by simulated Rician fading through a learned denoising process. The model learns to disentangle fading effects from speech content, effectively reconstructing clean speech from severely distorted inputs.

C. Training Objective

To ensure both fidelity and perceptual quality in the enhanced speech signal, we employ a custom loss function that

penalizes both spectral distortion (for denoising), and envelope deviation from expected fading profile (for de-fading). The joint loss is defined in this formula:

$$L_{joint} = \|\hat{S}(f, t) - S(f, t)\|_2^2 + \lambda \cdot \|\hat{e}(t) - e_{target}(t)\|_2^2 \quad (9)$$

where,

$\hat{S}(f, t)$ is enhanced speech spectrogram,

$S(f, t)$ is clean reference spectrogram,

$\hat{e}(t)$ is an estimated envelope of the enhanced signal,

$e_{target}(t)$ is expected envelope from a fading model,

λ is the weighting factor to balance the two loss components,

$\|\cdot\|_2$ refers to the L_2 norm.

The first term, spectral distortion loss ensures that the enhanced signal matches the clean reference in the frequency domain. Second term, envelope deviation loss penalizes deviations from the expected fading envelope, encouraging the model to correct fading-induced amplitude fluctuations. The weight λ allows tuning the emphasis between denoising and de-fading.

IV. EXPERIMENTS

This section presents the experimental framework for simulating scintillation effects on speech using a Rician fading model, alongside synthetic data from the Cornell Scintillation Simulation Toolkit (CSST) [18]. A training corpus of 20,000 utterances was used to develop enhancement models. For evaluation, real-world ionospheric interference data from Singapore and Southeast Asia region were applied to clean speech to emulate realistic conditions. The study assesses fading-induced degradation and compares enhancement performance using RNNNoise and the diffusion-based StoRM model.

4.1) Simulation Setup

To evaluate the impact of scintillation on speech and test enhancement strategies, we simulate fading conditions using two complementary approaches:

A. Rician Fading Model

The Rician fading model simulates multipath propagation with a dominant line-of-sight (LoS) component. The fading envelope is generated as described in Equation (2). Rician fading was simulated with K-factors of 0 (pure Rayleigh), 2, 5, 7, and 10 to represent increasing LoS dominance, and maximum Doppler frequencies ranging from 70 Hz to 300 Hz. This setup enables controlled experimentation across a range of fading severities:

- Low K-factors (K = 0, 2): Severe amplitude fluctuations and spectral distortion, approximating Rayleigh fading.

- Moderate K-factors (K = 5, 7): Realistic scintillation effects with noticeable but recoverable degradation.
- High K-factor (K = 10): Minimal fading, preserving most speech structure.

To simulate realistic channel conditions, the synthetic amplitude fading envelope was applied multiplicatively to the speech waveform and combined with additive white Gaussian noise (AWGN) at varying signal-to-noise ratios (SNRs).

B. Cornell Scintillation Simulation Toolkit (CSST)

The CSST simulates ionospheric scintillation based on empirical models and historical measurement data. It uses parameters such as:

- S₄ Index: Measures the severity of amplitude scintillation (0 = no scintillation, >0.6 = strong scintillation).
- Decorrelation time (τ_0): Indicates the time scale of fading. Shorter τ_0 implies more rapid fading and higher Doppler frequency.

The fading envelope generated by CSST is resampled to match the speech signal's sampling rate and applied multiplicatively to the waveform, simulating real-world scintillation conditions. Higher S₄ index values correspond to lower K-factors in the equivalent Rician model.

Table 1: The testing datasets with collected scintillation amplitude data from the Singapore and Southeast Asia region.

Voice Sources	Number of files	Add scintillation (strong, moderate, weak)
ATC_SIN	400	400 x 3
ATC_SEA	500	500 x 3

C. Ionospheric Scintillation Dataset

In addition to synthetic models, we incorporated empirically collected scintillation amplitude data from the Singapore (ATC_SIN) and Southeast Asia region (ATC_SEA) to simulate realistic ionospheric fading conditions. Unlike the previous simulations, this approach applies actual recorded scintillation envelopes to Air Traffic Control (ATC) speech signals. Three distinct levels of scintillation severity (weak, moderate, strong) were selected and randomly applied to the speech samples to reflect diverse propagation scenarios. A summary of the testing dataset and its associated interference conditions is provided in Table 1.

V. RESULTS AND DISCUSSION

This section evaluates the performance of the proposed simulation and enhancement framework under realistic scintillation conditions. The framework integrates a novel Rician fading based speech signal generation method to

simulate a wide range of scintillation severities and a joint optimization approach for speech enhancement that directly addresses the unique characteristics of fading-induced distortions. For benchmarking, we compare the proposed simulation method with the Cornell Scintillation Simulation Toolkit (CSST).

Tables 2 and 3 show PESQ scores for speech signals enhanced using RNNNoise [15] and StoRM diffusion models [16], respectively, both trained under our proposed joint optimization scheme with the Rician-based scintillated speech dataset. A clear trend is observed: PESQ scores decrease as scintillation severity increases, confirming that stronger fading severely degrades speech intelligibility. This effect is more pronounced in the ATC_SIN dataset, which likely experiences more severe or variable ionospheric conditions compared to the ATC_SEA dataset.

5.1) Simulation Dataset Evaluation

To evaluate the fidelity and utility of the proposed scintillated speech signal generation, we conducted a comparative analysis between the statistical properties of the Rician fading envelopes and those generated by the CSST [18]. The Rician model, parameterized with controllable K-factors, effectively replicates diverse fading conditions from severe Rayleigh-like scenarios ($K \approx 0$) to near-AWGN conditions ($K = 10$). Notably, envelope variance and temporal decorrelation metrics align well with the empirical CSST profiles when Doppler parameters reflect realistic satellite motion dynamics.

Importantly, our controllable Rician-based simulation method allows scalable generation of large, fully annotated speech corpora with precisely adjustable fading conditions. This capability provides a significant advantage over fixed empirical datasets by enabling extensive training and robust generalization of enhancement models to a wider range of propagation scenarios.

5.2) Enhancement Strategy Evaluation

Our joint optimization strategy, combining spectral distortion and envelope deviation loss terms, proved effective for both RNNNoise and StoRM models. RNNNoise consistently improves PESQ scores, especially under weak and moderate fading, demonstrating that a lightweight RNN can adapt to non-stationary fading distortions when trained on properly simulated scintillated speech. However, its performance drops under strong scintillation, where rapid envelope fluctuations are more difficult to track in real time.

In contrast, the StoRM diffusion denoising model consistently outperforms RNNNoise across all evaluation scenarios on the same dataset, with particularly pronounced gains under severe scintillation conditions. This performance advantage highlights the effectiveness of combining a realistic

fading simulation with a loss function specifically designed to capture the non-linear and time-varying characteristics of scintillation-induced fading. Together, these elements contribute to enhanced model robustness and improved speech quality in challenging propagation environments.

Table 2: Comparison PESQ results using RNNNoise speech enhancement model trained on CSST and Rician fading simulation datasets.

Testsets		Original	CSST	Rician
ATC_SIN	weak	2.4579	3.093	2.9785
	moderate	2.4265	3.0402	3.0846
	strong	2.1206	2.5685	2.6346
ATC_SEA	weak	2.8354	3.1128	3.0268
	moderate	2.78	3.0176	3.1037
	strong	2.3813	2.6715	2.7198

Table 3: Comparison PESQ results using diffusion speech enhancement model trained on CSST and Rician fading simulation datasets.

Testsets		Original	CSST	Rician
ATC_SIN	weak	2.4579	3.274	3.3163
	moderat	2.4265	3.2796	3.3642
	strong	2.1206	3.1592	3.2177
ATC_SEA	weak	2.8354	3.4822	3.5021
	moderat	2.78	3.4814	3.4953
	strong	2.3813	3.4173	3.4475

In addition to evaluating speech quality, we assessed the computational efficiency of the enhancement models. Table 4 presents the average processing times. RNNNoise consistently achieves real-time performance, processing audio at under 50 milliseconds per second, making it well-suited for live satellite and tactical communication applications. In contrast, StoRM diffusion models deliver superior perceptual quality but incur significantly higher computational costs. This trade-off suggests a promising hybrid strategy: employing RNNNoise for low-latency pre-processing in real-time scenarios, while leveraging StoRM for high-fidelity offline restoration where computational resources and latency constraints are less critical.

Table 4: The processing of speech enhancement models when varying the number of reverse time steps (N). RTF is the average time to process one second of audio.

Models	N	RTF
RNNNoise	NA	< 50ms
StoRM diffusion denoising	50	> 1s
	30	0.564s
	15	0.385s

VI. CONCLUSION

This study introduced a comprehensive framework for simulating ionospheric scintillation effects on speech signals using a controllable Rician fading model, coupled with a joint optimization strategy for training speech enhancement models tailored to fading-impaired satellite channels. Compared to the widely adopted Cornell Scintillation Simulation Toolkit, the proposed approach enables the generation of large, parameter-rich datasets that better capture realistic fading profiles essential for robust model development. The integration of spectral distortion and envelope deviation losses in model training yielded consistent improvements in intelligibility and perceptual quality. RNNoise proved effective for real-time enhancement under mild fading, while StoRM diffusion models delivered superior restoration under severe conditions, albeit with increased computational demands. Collectively, the proposed simulation and optimization framework offers a scalable foundation for advancing resilient speech enhancement in satellite and tactical communication systems. Future work will explore real-time channel estimation, hybrid model cascades, and deployment in operational aviation and maritime contexts, particularly in regions such as Singapore where scintillation remains a persistent challenge.

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