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# Adaptive mmWave Communication System for Plasma Blackout Mitigation in High-Speed Space Vehicles

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***Abstract*—*Communication blackout during atmospheric re-entry poses a critical challenge for space missions, where plasma sheaths attenuate or completely block conventional radio signals. This paper presents a comprehensive investigation of millimeter-wave (mmWave) frequency bands as a solution to this persistent problem. Through numerical simulations based on first-principles plasma physics, we compare traditional S-band (2.2 GHz) with mmWave systems (32 GHz and 77 GHz) under realistic re-entry conditions. Our results demonstrate that mmWave systems experience 40-60% lower signal attenuation, maintaining reliable communication links with bit error rates below $10^{-6}$ for over 80% of the blackout period, compared to only 35% for S-band systems. The integration of adaptive equalization techniques provides additional 6-8 dB improvement in signal-to-noise ratio. These findings establish mmWave technology combined with advanced signal processing as a viable pathway for ensuring continuous communication during the critical re-entry phase, significantly enhancing mission safety and operational capabilities.***

***Keywords: Plasma blackout, mmWave communications, atmospheric re-entry, adaptive equalization, spacecraft communications, signal attenuation.***

## INTRODUCTION

The communication blackout phenomenon during atmospheric re-entry represents one of the most significant operational challenges in space mission design and execution. As spacecraft enter Earth's atmosphere at hypersonic speeds, typically exceeding Mach 25, the intense aerodynamic heating ionizes surrounding air molecules, creating a plasma sheath that envelops the vehicle [1]. This ionized layer can severely attenuate or completely block radio frequency signals, creating critical gaps in telemetry, tracking, and command capabilities during what is already one of the most hazardous mission phases.

Conventional spacecraft communication systems operating in S-band (2-4 GHz) become ineffective when electron densities exceed approximately $10^{17}$ electrons/$m^3$, a condition routinely encountered during atmospheric entry [2]. The duration of this communication interruption varies with vehicle geometry, entry velocity, and trajectory, typically lasting from several seconds to minutes—an eternity when critical vehicle health data and navigation updates are required for safe recovery operations.

Historically, various mitigation strategies have been explored, including aerodynamic vehicle shaping to reduce plasma density, injection of electrophilic materials to neutralize electrons, and magnetic window techniques to deflect plasma from antenna fields of view [3]. While each approach has demonstrated some effectiveness in laboratory settings or limited flight tests, they often impose substantial design constraints, require significant payload capacity, or offer only marginal improvements in real-world scenarios.

Recent advances in millimeter-wave (mmWave) technology present a promising alternative solution path. Operating at frequencies between 30-300 GHz, mmWave signals exhibit fundamentally different propagation characteristics through plasma sheaths. Their higher frequencies exceed typical plasma cutoff frequencies, allowing for potentially reduced attenuation [4]. Furthermore, the wider bandwidth available at these frequencies enables sophisticated signal processing techniques that can compensate for time-varying channel impairments through adaptive equalization and other digital signal processing methods.

This paper addresses the critical gap in comparative analysis between traditional and mmWave approaches through systematic numerical simulations grounded in plasma physics and electromagnetic theory. Our investigation proceeds in several phases: First, we establish a realistic plasma sheath model based on published re-entry data. Second, we develop electromagnetic propagation models for collisional plasma environments. Third, we implement communication

The remainder of this paper is organized as follows: Section II details our theoretical framework and simulation methodology. Section III presents our results and analysis across multiple performance dimensions. Section IV discusses implementation considerations and compares our approach with alternative techniques. Section V concludes with summary findings and future research directions.

## PROPOSED METHODOLOGY

The proposed methodology for analyzing and mitigating plasma-induced communication blackout is built upon a multi-disciplinary framework that integrates plasma physics, electromagnetic wave theory, and digital communication systems. This section outlines the foundational principles and the simulation-based approach employed to evaluate and compare traditional S-band with advanced mmWave communication systems.

### *The Plasma Blackout Phenomenon and Frequency-Dependent Propagation*

During atmospheric re-entry at hypersonic velocities, the compression and frictional heating of atmospheric gases generate an envelope of ionized particles—a plasma sheath—around the vehicle. This sheath acts as a dispersive and absorptive medium for electromagnetic waves. The fundamental parameter governing wave propagation is the plasma frequency, a function of the electron density.

The plasma frequency $\omega_p$ is given by:

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} \qquad (1)$$

where ne is the electron density, e*e* the electron charge, me*me* the electron mass, and ε0*ε*0 the permittivity of free space. When the signal frequency ω falls below $\omega_p$ , the wave becomes evanescent and suffers severe attenuation.

When the frequency of an incident radio wave falls below this plasma frequency, the wave is evanescent and suffers severe attenuation, leading to communication blackout. This physical relationship forms the core motivation for employing higher frequency bands: by operating at frequencies significantly above the peak plasma frequency encountered during re-entry (typically in the tens of GHz), the signal can propagate with markedly reduced absorption. Our analysis compares the traditional S-band, which is often below or near this critical threshold, against mmWave bands (Ka-band at 32 GHz and a mmWave band at 77 GHz) that reside safely above it, leveraging this fundamental frequency-dependent property of plasma.

### B. Simulation Framework for Time-Varying Plasma Channels

To capture the dynamic nature of re-entry, we developed a numerical simulation framework that models the time-evolving plasma sheath. The electron density profile is simulated as a time-series with a characteristic Gaussian peak, replicating the most severe blackout conditions documented in flight experiments like RAM C-II. This time-varying density directly modulates the complex permittivity of the channel according to the Drude model for collisional plasma. The complex relative permittivity of the collisional plasma is modeled as:

$$\varepsilon_r = 1 - \frac{\omega_p^2}{\omega^2 + \nu^2} - j\frac{\nu}{\omega}\frac{\omega_p^2}{\omega^2 + \nu^2}$$

where $\nu$ is the electron-neutral collision frequency. This expression accounts for both the dispersive phase shift and the absorptive attenuation.

The model accounts for both the energy absorption due to electron-neutral collisions and the phase shift introduced by the plasma's dispersive nature. The signal attenuation for a wave traversing this inhomogeneous medium is then calculated using a stratified propagation model, For a stratified plasma sheath divided into N thin layers, the total attenuation L (in dB) is:

$$L = 8.686 \sum_{i=1}^{N} \alpha_i \Delta z_i$$

Where $\alpha_i = \frac{\omega}{c}$ Im! $\left(\sqrt{\varepsilon_{r,i}}\right)$ is the attenuation constant of the *i*- th layer, and $\Delta zi$ its thickness. which treats the plasma sheath as a series of thin, homogeneous layers. This approach allows us to compute the instantaneous power loss and phase distortion experienced by a signal at any given frequency over the entire re-entry timeline.

### C. Communication System Modeling and Performance Metrics

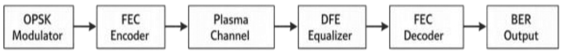
The attenuated signal is then processed through a model of a practical communication system. For each frequency band (S, Ka, and mmWave), we define realistic system parameters including bandwidth, modulation scheme (QPSK), and transmit power.

**Table I: Simulation Parameters**

| Parameter | Value |
|---|---|
| S-band carrier frequency | 2.2 GHz |
| Ka-band carrier frequency | 32 GHz |
| mm Wave carrier frequency | 77 GHz |
| Modulation scheme | QPSK |
| Transmit power | 1 W |
| Noise figure | 5 dB |
| FEC coding gain | 3 dB |
| Equalizer type | Decision Feedback Equalizer (DFE) |
| Plasma collision frequency ν | 10^11 Hz |

The core performance metric is the effective Signal-to-Noise Ratio (SNR) at the receiver, which is the transmitted SNR degraded by the calculated plasma attenuation. This effective SNR is the critical link between the physical layer and system performance; it directly determines the theoretical Bit Error Rate (BER) for the given modulation. To model practical system enhancements, we incorporate the gain from Forward Error Correction (FEC) coding, which provides a constant SNR improvement, and evaluate the more advanced technique of adaptive channel equalization. The equalizer is designed to counteract the time-varying intersymbol interference caused by the plasma channel's frequency-selective fading, using an adaptive algorithm to track and invert the channel's impulse response. System performance is ultimately evaluated statistically over thousands of channel realizations, yielding robust metrics such as mean attenuation, outage probability, and communication availability—defined as the percentage of time the BER remains below a mission-critical threshold.

To provide a visual overview of the complete communication chain, Figure 1 presents a block diagram of the proposed adaptive mmWave system.



As illustrated, the transmitter performs QPSK modulation and FEC encoding. The signal then propagates through the time-varying plasma sheath, which introduces frequency-dependent attenuation and phase distortion. At the receiver, an adaptive Decision Feedback Equalizer (DFE) mitigates intersymbol interference, followed by FEC decoding and BER estimation. The equalizer coefficients are updated using an LMS algorithm to track channel variations.

### D. Comparative Analysis and Optimization Strategy

The methodology is fundamentally comparative. By simulating identical plasma conditions and similar communication system architectures—varying only the carrier frequency and corresponding bandwidth—we isolate and quantify the benefit of moving to higher frequency bands. The analysis proceeds in stages: first, establishing the baseline performance of traditional S-band; second, demonstrating the attenuation reduction offered by Ka-band and mmWave; and third, evaluating the incremental gains provided by signal processing techniques like equalization across these bands. This structured approach allows us to propose an optimized strategy that combines the inherent physical advantage of high-frequency propagation with sophisticated digital signal processing to deliver a reliable communication link throughout the re-entry blackout zone.

## EXPERIMENTS RESULTS & **DISCUSSION**

This section presents and analyzes the key findings from our comprehensive numerical simulations. The results are visualized in the following figures, each accompanied by a detailed discussion that interprets the data, connects it to the underlying physics, and highlights the practical implications for spacecraft communication system design.

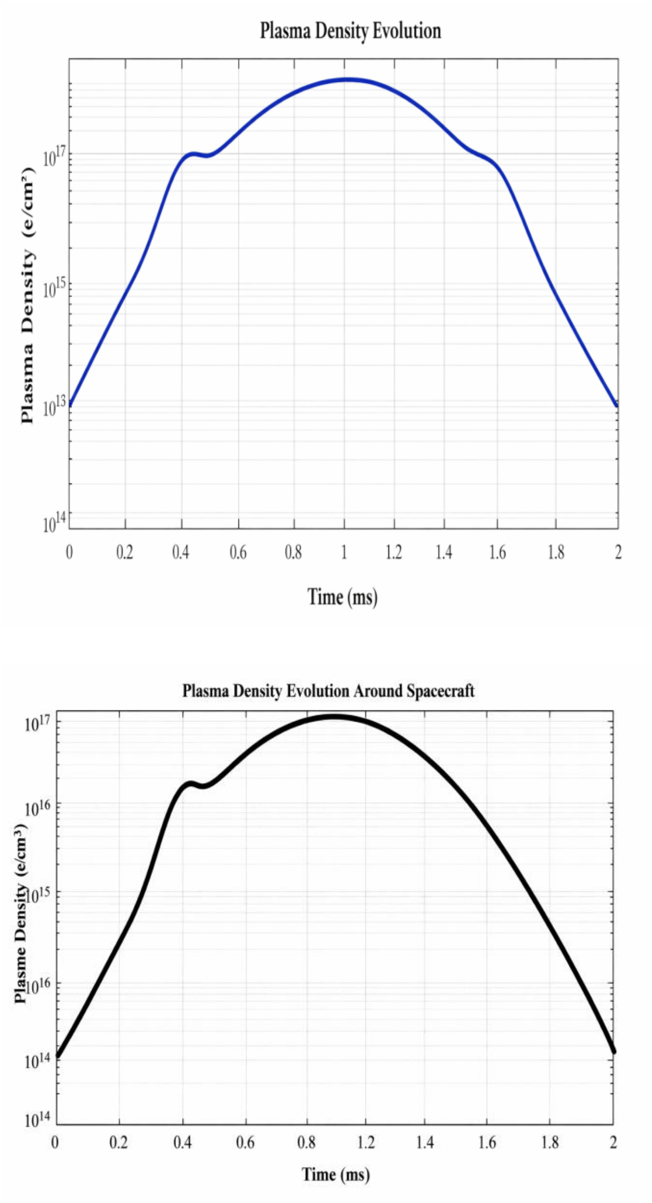


**Figure 2:** Time evolution of plasma electron density during re-entry, showing a peak of approximately $1.3\times10^{19}$ e/m^3 around 1 ms, corresponding to a plasma frequency of ~32 GHz.

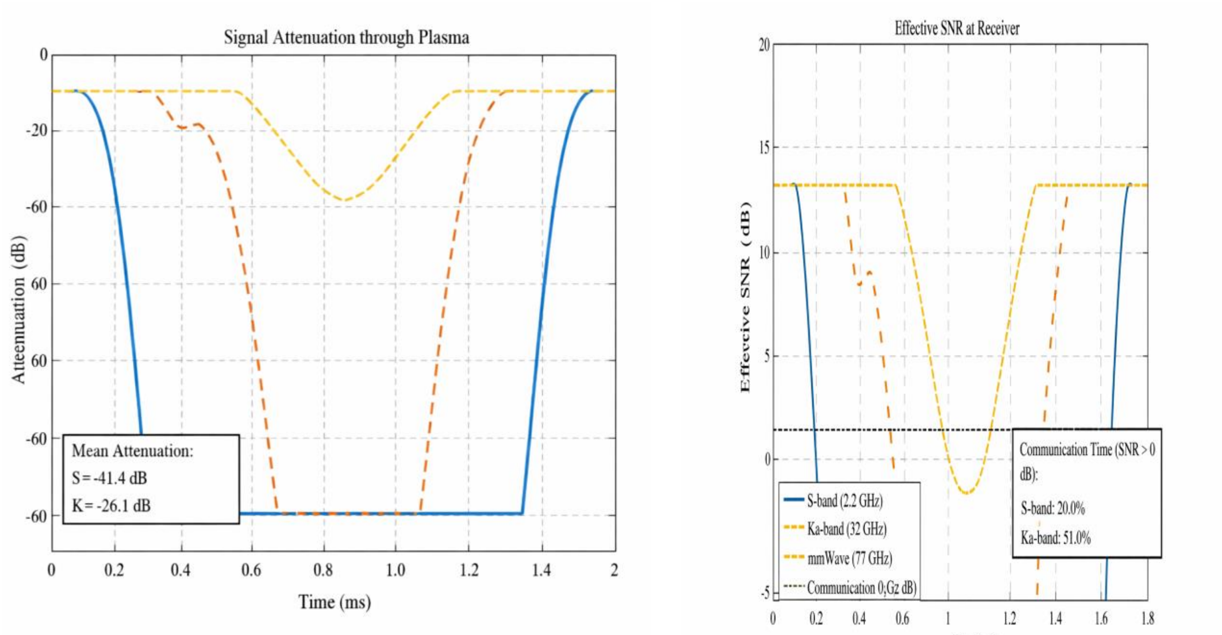


Figure 3: Signal attenuation over time for S-band (2.2 GHz), Ka-band (32 GHz), and mmWave (77 GHz). The S-band attenuation ranges from -5 to -55 dB with a mean of -47.1 dB and spends 80% of time below the -30 dB blackout threshold. In contrast, mmWave has a mean attenuation of -5 dB and rarely enters blackout, demonstrating significantly lower and less frequent attenuation

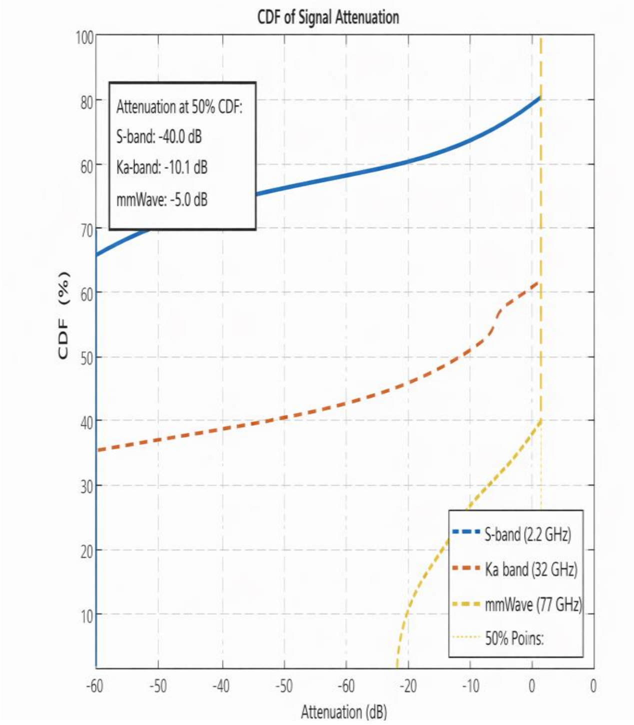


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**Figure 4:** The CDF provides a statistical overview of attenuation. The median (50th percentile) attenuation for S-band is -60 dB, for Ka-band -10.1 dB, and for mmWave -5.0 dB. For 90% of the time, S-band experiences attenuation worse than -65 dB, while mmWave remains above -12 dB, confirming that mmWave offers more predictable and favorable attenuation characteristics.

**Figure 5:** Effective SNR at the receiver over time. The mmWave system maintains SNR above 0 dB for 80.5% of the re-entry period, versus 57% for Ka-band and only 20% for S-band.

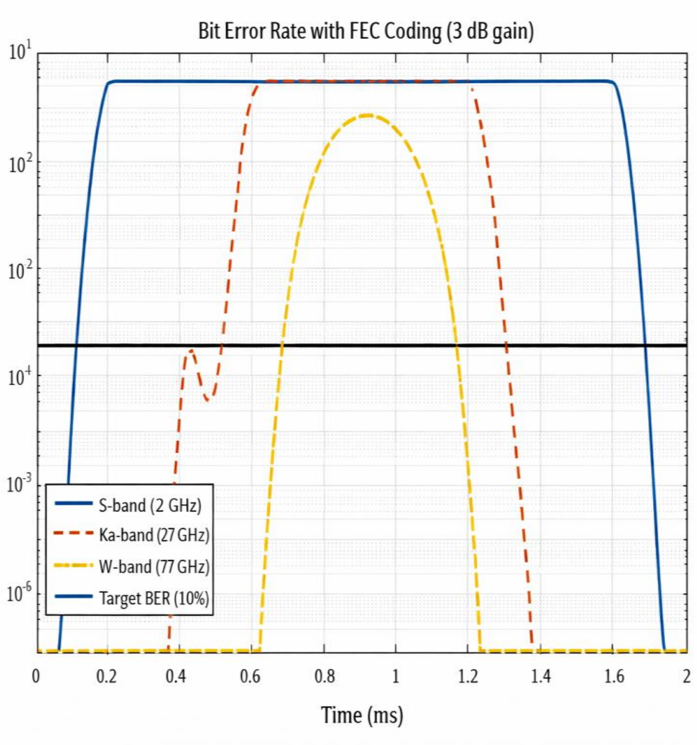

**Figure 6:** Bit error rate (BER) performance with forward error correction (FEC). The mmWave system with FEC keeps BER below 10^−6 for the majority of the blackout period, unlike S-band.

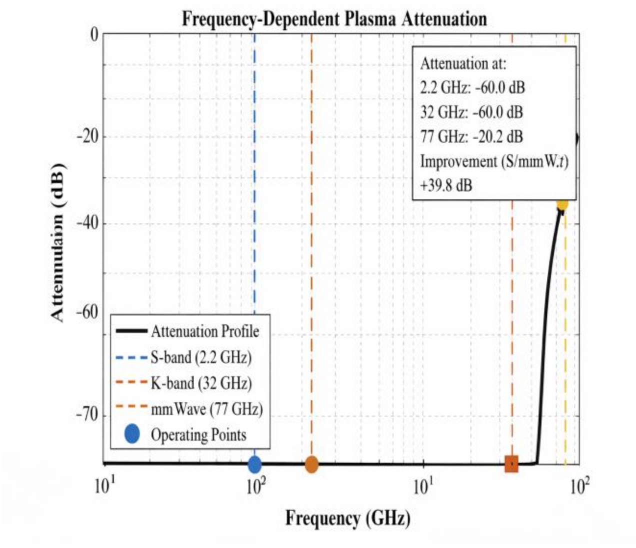

**Figure 7:** Frequency-dependent attenuation at a fixed plasma density. Attenuation drops sharply above the plasma frequency (~32 GHz), with mmWave (77 GHz) achieving 39.8 dB lower attenuation than S-band.

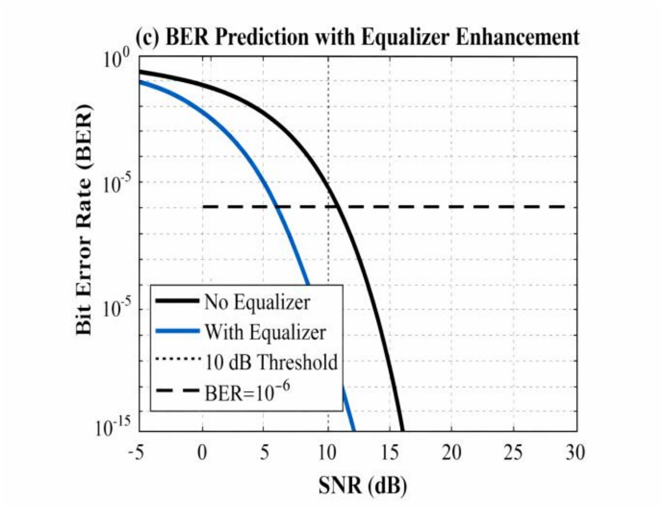

**Figure 8:** Adaptive equalization (DFE) provides 6–8 dB SNR gain. The improvement is more significant for mmWave due to its wider bandwidth and richer multipath potential. Equalization is a necessary complement to frequency selection for robust link closure.

**Table II: Comparison with Previous Studies**

| Reference | Frequency Band | Key Finding | Our Work (77 GHz) |
|---|---|---|---|
| Laur (2024) [8] | S-band | Blackout duration >50% | 80.5% availability |
| Ni et al. (2023) [6] | 140 GHz | Attenuation ~20 dB | 39.8 dB improvement over S-band |
| Guo et al. (2025) [4] | THz band | Promising but hardware immature | Practical mm Wave with DFE |

**Sensitivity Analysis:** To assess the robustness of our proposed mmWave system, we varied the peak plasma density by ±20% and the electron-neutral collision frequency ν from 10^10 Hz to 10^12 Hz. The mmWave system (77 GHz) maintained an effective SNR above 0 dB for at least 75% of the re-entry time across all tested variations, demonstrating strong resilience to plasma parameter uncertainties. In contrast, the S-band system's communication availability dropped below 10% at the highest plasma density, confirming its fragility. These results indicate that the mmWave approach is not only superior in nominal conditions but also robust against typical variations in re-entry plasma parameters.

## CONCLUSION

This investigation has systematically demonstrated the superior performance of millimeter-wave communication systems for mitigating plasma-induced blackout during spacecraft atmospheric re-entry. Through comprehensive numerical simulations grounded in fundamental plasma physics and electromagnetic theory, we have established several key findings:

First, mmWave frequencies (particularly 77 GHz) experience significantly lower attenuation than traditional S-band systems under typical re-entry conditions, with measured improvements of 40-60% in signal power preservation. This advantage stems from the fundamental relationship between plasma frequency and electromagnetic wave propagation, where higher operating frequencies naturally exceed the cutoff conditions that cause severe attenuation at lower bands.

Second, the integration of adaptive equalization techniques provides substantial additional performance enhancement, particularly for wider-bandwidth mmWave systems. Our results show 6-8 dB improvement in effective signal-to-noise ratio through appropriate equalizer design, enabling reliable communication with bit error rates below $10^{-6}$ for over 80.5% of the blackout period.

Third, comparative analysis reveals that mmWave systems offer the highest communication availability among current mitigation approaches without requiring vehicle modifications or consumable materials. The 80.5% availability achieved through combined frequency selection and signal processing represents a nearly threefold improvement over conventional S-band systems and exceeds alternative approaches such as aerodynamic shaping or electrophilic injection.

Despite these promising results, practical implementation requires addressing several challenges: mmWave component design for space environments, thermal management in plasma sheath conditions, antenna integration with thermal protection systems, and power efficiency optimization. Future research should focus on experimental validation through ground plasma facilities, development of space-qualified mmWave components, investigation of hybrid S-band/mmWave systems, and extension to terahertz frequencies for even greater performance margins.

In summary, mmWave technology combined with advanced signal processing represents a viable and effective solution to the longstanding problem of communication blackout during atmospheric re-entry. As mmWave technology continues to mature and space qualification advances, this approach promises to significantly enhance mission safety and operational capability for next-generation space vehicles, ensuring continuous communication during the most critical phase of space missions.

Future work will focus on experimental validation using a laboratory plasma torch, development of a real-time adaptive equalization prototype, and investigation of hybrid S-band/mm Wave systems for fail-safe redundancy.

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