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Dynamic Selection of Relay Node Based on Channel Fading Coefficient for Reentry Hypersonic Vehicles

Lei Shi*, **Jinxin Wei, Xiaoping Li, Bo Yao, and Bowen Bai**

Abstract—The development of near-space hypersonic vehicles is confronted with the "blackout" problem of the plasma sheath. As electronic density on the leeward surface is lower than that on the windward surface during the reentry process, a low Earth orbit (LEO) satellite may be used to mitigate this problem. In this study, the Iridium system, as a low-orbit relay satellite system, is utilized to evaluate the feasibility of using a LEO satellite. First, the incident angle of the electromagnetic waves radiating from the vehicles to various potential relay satellites is calculated by the STK software. Second, the transmission coefficient of the electromagnetic wave in the plasma is obtained by using the equivalent wave impedance method to present the attenuation effect of the plasma sheath channel. Finally, the attenuation coefficients of each channel between the aircraft and the potential satellite are used as a parameter to select the best relay in the reentry process of the vehicles. Simulation results show that the use of LEO satellites for relay can significantly reduce the communication interruption time during the reentry process by 32.6% for typical scenarios.

1. INTRODUCTION

Near-space hypersonic vehicles are capable of long-term and continuous flight in near-space for fast arrival. They have advantages in the areas of communication security and early warning, among others. However, the development of near-space hypersonic vehicles is confronted with the "blackout" problem caused by the plasma sheath during the reentry process [1, 2]. The plasma sheath is generated when air molecules and heat shield material are dissociated and ionized by the shock wave heating and heat shield abating when a spacecraft moves in the atmosphere at hypersonic speed. The plasma layer can strongly attenuate electromagnetic (EM) waves and cause communication interruption between vehicle and ground stations [3–5]. Many countermeasures have been proposed to improve the possibility of communication under the plasma sheath. Mitigation technologies are the most researched approaches to reduce the electron density of the plasma sheath through a physical or chemical method to weaken the influence of the plasma sheath on telemetry and communication signals. These physical and chemical methods include ion implantation, EM field drift aggregation, electrostatic collection, antenna cooling, optical communication, relay ejection, trajectory correction, magnetic fluid generator, electron beam modulation, Raman scattering, aerodynamic molding, magnetic window, and liquid quenching [6]. Three major technologies are currently favored: aerodynamic molding, liquid injection, and magnetic windows. Although the theoretical calculations or ground tests show that these methods are promising in weakening blackout, these mainstream mitigation techniques are limited in practical usage [7].

In the communication blackout mitigation adaptive technology, Dr. He Guolong proposed the following idea: "avoid large attenuation by high frequency transmission and slowing large dynamic by the reflected wave inversion" [8]. Thus, a new method of the plasma sheath channel estimation and prediction based on reflected wave inversion was introduced, and a communication scheme of

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* Corresponding author: Lei Shi (shilei2002yoda@163.com).
The authors are with the School of Aerospace Science and Technology, Xidian University, Xi'an 710071, China.

auxiliary carrier acquisition and adaptive transmission at the receiving end was developed to reduce the influence of plasma dynamic jitter on communication information transmission. A research team from Xidian University conducted an in-depth study on radio wave characteristics, signal characteristics, and channel characteristics under the dynamic plasma sheath [9–12]. Re-entry communication through a plasma sheath using standing wave detection and adaptive data rate control was suggested to shorten communication interruption time [13–16]. The experimental results showed that the communication rate could be adjusted at 250 bps–4 Mbps when the electron density increases by an order of magnitude. This method can be used in the vicinity of the interruption with a small channel capacity and play a certain role. However, it becomes powerless when the channel capacity continues to decline; therefore, the channel capacity still needs to be expanded. As the electronic density of plasma on the leeward side is lower than that on the windward side, the attenuation uplink to a space-based platform is less influenced by the plasma than the downlink to ground stations during the reentry process of hypersonic vehicles. Therefore, a low Earth orbit (LEO) satellite can act as a relay platform for signal transmission to effectively mitigate the effect of the plasma sheath. For general satellite relay systems, a fixed choice relay is currently the most popular strategy. The plasma sheath EM wave attenuation during the reentry process and the channel status of the entire link are time varying. Therefore, choosing an appropriate relay node at different times during the reentry process is important, and a suitable selection method needs to be proposed under a plasma environment.

This study mainly discusses the optimal relay selection method according to the state information of the channel when multiple satellites can act as relay nodes. Section 2 presents the method of relay node selection based on the channel fading coefficient. The calculation method of each channel coefficient between an aircraft and a possible communication satellite is given in Section 3. Section 4 simulates and analyzes communication interruption to evaluate the feasibility of a LEO satellite relay.

2. DYNAMIC SELECTION SCHEME OF RELAY NODES BASED ON A CHANNEL FADING COEFFICIENT

In the traditional communication satellite relay system, a terrestrial communication terminal moves slowly or even stops at a standstill relative to the satellite. Usually, sufficiently long communication tasks can be completed in a single satellite coverage, and then the channel state becomes relatively fixed. Reentry hypersonic aircraft may exceed the coverage of one relay satellite because of high-speed flight, and the situation in which several satellites can be accessed at the same time may also ensue. Additionally, the plasma sheath may result in a time variance of the channel state. Therefore, channel state variation and satellite handoff may occur in the reentry vehicle relay process. How to effectively select the relay access satellite is the main issue. Given that plasma attenuation is dominant and time varying, this study presents a method to optimize the relay satellite based on a channel fading coefficient.

A dynamic selection method based on the attenuation coefficient of the time-varying plasma should be determined. Currently, three mainstream relay selection methods are adopted, namely, those that are based on the relay location information, the average SNR ratio of the target user receives, and the channel instantaneous state information. In the selection method based on the channel instantaneous information, the relay node is selected according to the state information of the current channel. In view of the complexity and particularity of the plasma sheath channel, alleviating the blackout phenomenon for hypersonic reentry vehicles affected by the plasma sheath is effective.

In the method based on channel instantaneous information, the node with the best channel state is chosen as the relay node. As shown in Figure 1, n satellites can be used as relay nodes, and i denotes the satellite number of any potential relay. The vehicle calculates the uplink and downlink channel information with respect to each potential relay satellite, that is, the uplink instantaneous channel fading coefficient h_{vsi} between it and the vehicle and the downlink instantaneous channel fading coefficient h_{sig} between the satellite and the ground station. Then, the entire link channel corresponding to parameter h_i of each relay is evaluated by Equation (1). The EM wave attenuation caused by the plasma sheath is sometimes serious. Communication may be interrupted in deep fading when the EM wave attenuation in the plasma sheath exceeds 30 dB (the attenuation coefficient in the plasma sheath is less than 0.001). Therefore, the optimal relay strategy is set to Equations (1)–(2) [17, 18], and k is the number selected as the best satellite.

$$\begin{aligned} h_i &= \min\left(|h_{vs_i}|,\ |h_{s_i g}|\right) \qquad (1) \\ h_i &\geq 0.001 \\ k &= \arg\max\left(h_i\right) \qquad (2) \end{aligned}$$

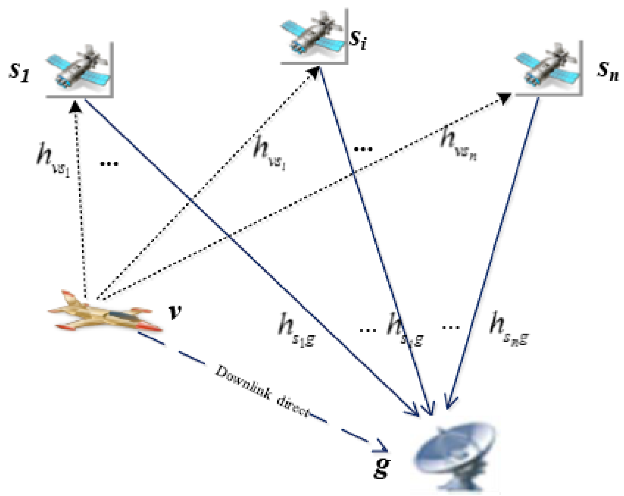


Figure 1. Schematic diagram of a LEO relay communication for hypersonic vehicles versus downlink direct communication.

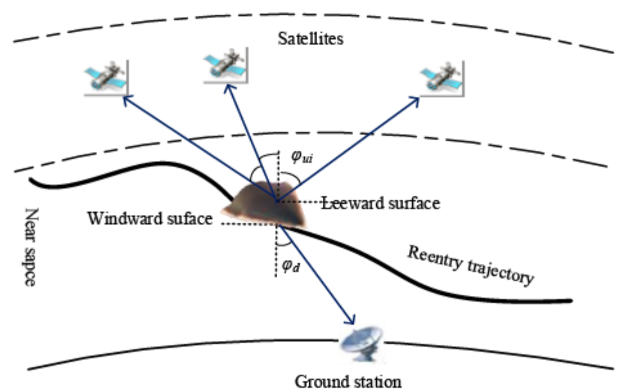


Figure 2. Schematic diagram of the EM wave incidence.

3. CALCULATION OF THE ATTENUATION COEFFICIENT OF THE PLASMA SHEATH CHANNEL

The above relay strategy is based on the uplink and downlink channel information; therefore, the calculation of the uplink and downlink attenuation caused by the plasma sheath must be solved first. The relative position between the aircraft and the satellite is variable. To obtain accurate attenuation, we must acquire the radio wave incident angle information of the uplink and then use the oblique incident plasma wave calculation method to gain the attenuation of the uplink channel coefficient. The downlink channel coefficient is determined by the satellite situation.

3.1. Incident Angle of the EM Wave on the Plasma Surface

To obtain the uplink attenuation coefficient from the vehicle to the satellite, the transmission coefficient of the EM wave on the plasma surface should be calculated. The EM wave is generally obliquely incident to the plasma, and thus the EM wave incident angle on the plasma surface needs to be calculated first. The schematic diagram of the EM wave incidence with respect to each potential satellite is illustrated in Figure 2.

Given the longitude, latitude, and altitude of the vehicle and each potential satellite at t moment and $t + \Delta t$ ($\Delta t > 0$ and $\Delta t \to 0$) moment, the elevation angle and distance of the satellite and the vehicle at t moment as well as the incident angle of the EM wave on the plasma surface from the vehicle to the ith satellite can be calculated by Equation (3). The downlink incident angle φ_d can be obtained analogously.

$$\varphi_{ui} = 90 - \sin^{-1}\frac{\left|m\left(x_0 - x_1\right) + n\left(y_0 - y_1\right) + z_0 - z_1\right|}{r\sqrt{m^2 + n^2 + 1}}, \qquad (3)$$

where

$$m = \frac{(z_2 - z_1)(x_1 z_2 - x_2 z_1) - (y_2 - y_1)(x_2 y_1 - x_1 y_2)}{(y_2 - y_1)(y_2 z_1 - y_1 z_2) - (x_2 - x_1)(x_1 z_2 - x_2 z_1)},$$
$$n = \frac{(x_2 - x_1)(x_2 y_1 - x_1 y_2) - (z_2 - z_1)(y_2 z_1 - y_1 z_2)}{(y_2 - y_1)(y_2 z_1 - y_1 z_2) - (x_2 - x_1)(x_1 z_2 - x_2 z_1)} \tag{4}$$

r is the distance between the satellite and the vehicle, (x_0, y_0, z_0) the coordinate of the satellite, (x_1, y_1, z_1) the coordinate of the vehicles at t moment, and (x_2, y_2, z_2) the coordinate of the vehicles at $t + \Delta t$ moment. By obtaining the incidence angle between the vehicle and the potential relay satellites, the attenuation coefficient of the EM wave in the plasma can be calculated by the equivalent wave impedance method.

3.2. Oblique EM Wave Propagation Calculation Method in the Plasma Sheath

The plasma can be considered a dispersive lossy medium. For uniform plasma, the relative dielectric constant is [19–21]

$$\tilde{\varepsilon}_r = 1 - \frac{\omega_p^2}{\omega_0^2 + v_e^2} - j\frac{v_e}{\omega_0}\frac{\omega_p^2}{\omega_0^2 + v_e^2}, \tag{5}$$

$$\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}, \tag{6}$$

where ω_0 is the frequency of the EM wave, v_e the collision frequency of the plasma, ω_p the characteristic frequency of the plasma, n_e the electron density of the plasma, ε_0 the dielectric constant of the vacuum, and e and m_e are the electron charge and electron mass, respectively.

The propagation coefficient of the plasma k can be written as

$$k = \beta - j\alpha = \omega_0\sqrt{\mu_0 \varepsilon_0 \tilde{\varepsilon}_r}, \tag{7}$$

where μ_0 is the permeability in vacuum, and α and β are the attenuation coefficient and phase shift coefficient, respectively.

$$\alpha = \frac{\omega}{\sqrt{2}c}\sqrt{\frac{\omega_p^2}{\omega^2 + v^2} - 1 + \sqrt{\left(1 - \frac{\omega_p^2}{\omega^2 + v^2}\right)^2 + \left(\frac{v}{\omega}\frac{\omega_p^2}{\omega^2 + v^2}\right)^2}}. \tag{8}$$

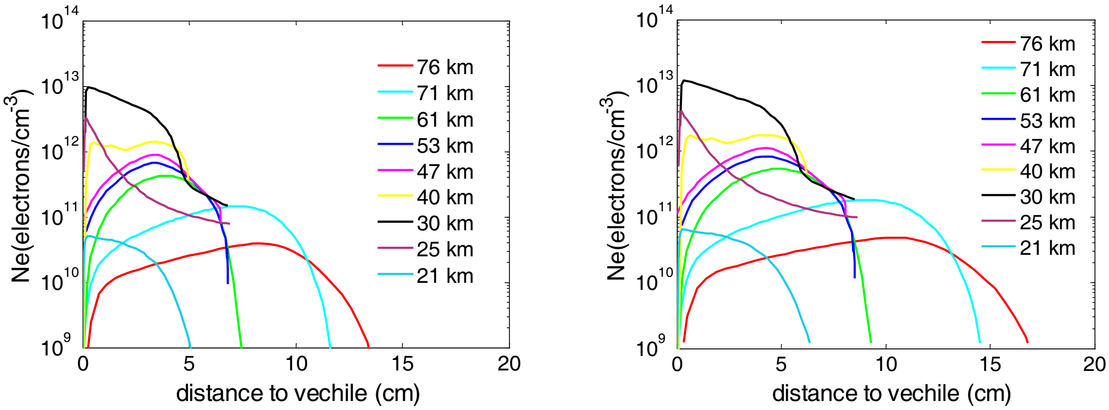
$$\beta = \frac{\omega}{\sqrt{2}c}\sqrt{1 - \frac{\omega_p^2}{\omega^2 + v^2} + \sqrt{\left(1 - \frac{\omega_p^2}{\omega^2 + v^2}\right)^2 + \left(\frac{v}{\omega}\frac{\omega_p^2}{\omega^2 + v^2}\right)^2}}. \tag{9}$$

The EM wave in the uniform plasma can be expressed by Equation (10):

$$\overrightarrow{E} = E_0 \exp\left(j\left(\omega t - k \cdot z\right)\right)\overrightarrow{e_z}. \tag{10}$$

However, the reentry plasma sheath is nonuniform and can be characterized by two parameters, namely, electron density and collision frequency. That is, plasma density and collision frequency are always subject to a certain distribution. We define the uplink plasma density as the plasma density on the leeward side and the downlink plasma density as the plasma density on the windward side of the vehicle. The uplink and downlink plasma densities are obtained with reference to RAM-C III vehicles, as shown in Figure 3. Overall, the peak electron density value of the downlink is larger than that of the uplink, and the thickness is wider.

Plasma is generated by friction between air and vehicle surface. That is, air temperature increases to some degree, and it causes air molecules to be dissociated and ionized. Therefore, plasma collision frequency is closely related to air density and temperature of the sheath. The collision frequency distribution is difficult to measure, and thus an approximation value is usually required. Figure 4 shows the typical collision frequency of a RAM-C III vehicle with altitudes and temperatures [11, 22]. The



(a) (b)

Figure 3. Plasma density with altitude: (a) uplink; (b) downlink.

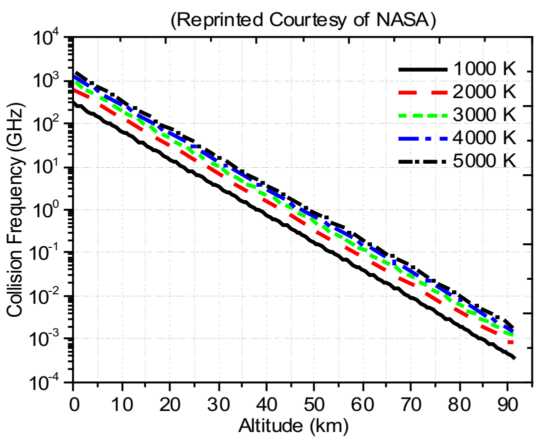


Figure 4. Collision frequency with altitude and temperature.

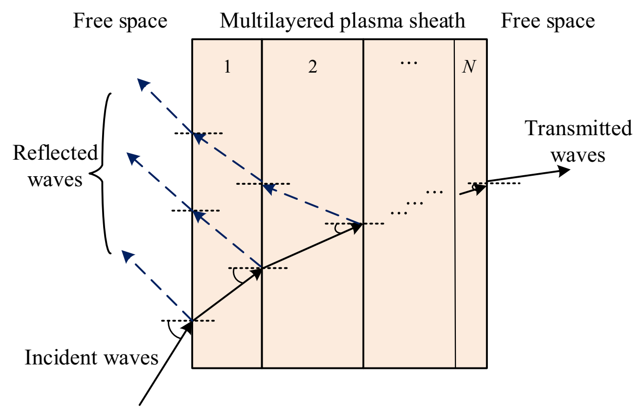


Figure 5. Multilayered plasma model of EM waves propagating in a nonuniform plasma sheath.

typical temperature of 2000 K is adopted to obtain the typical collision frequency. The peak collision frequency varies from 7 MHz at 76 km to the extreme 24 GHz at 21 km.

Generally, obtaining rigorous analytical solutions for EM waves propagating in the nonuniform plasma is quite difficult. However, the plasma sheath can be approximately modeled by several adjacent homogeneous thin plasma slabs according to the electron density distribution profile [22]. To achieve excellent computation accuracy and prevent a superabundant calculated amount, the electron density discrepancy between adjacent thin plasma slabs is limited $< 10\%$ [23]. The nonuniform plasma sheath is divided into N layers, and the incident waves pass through the multilayered plasma and undergo multiple reflections and transmission processes, as shown in Figure 5. The complex dielectric coefficient of the nth plasma slab can be determined by Equation (5). The thickness of each layer is non-uniformly divided according to the distribution of electron density and may differ largely according to the electron density gradient. The more the stratification numbers are and the thinner the slab width is, the larger the gradient (electron density changes drastically); otherwise, the slab width becomes thick with a few stratification numbers [22]. The EM waves propagating in the N-layered plasma along the z-axis can be equivalent to the cascade of the transmission lines with different impedances, and the transmission coefficients of the N-layered plasma model can be determined by the transmission line analogy method. The specific oblique incident calculation method is based on the literature [21, 23].

4. SIMULATION RESULTS

To obtain the relay coverage performance, we set up a typical relay communication relay scenario, in which Iridium system is selected as the low-orbit relay satellite and the scene is generated by the STK software as shown in Figure 6. We assume the channel between the satellites and the ground station as the Rice fading channel, and the channel between the vehicle and the satellites are composed of the Rice fading channel superimposed on the attenuation of the plasma sheath. The channel attenuation coefficient of the plasma sheath is calculated according to Section 3.2. The relay selection method based on the channel fading coefficient in Section 2 is used to select the best relay.

The other parameters are set as follows: The Xi'an Station is set as the ground station, the vehicles are assumed to fly from Jiuquan to Lanzhou, the flight altitude is 20–81 km, and the carrier frequency is 2 GHz. The launch time for the flight task is 17:00 on December 12, 2016, and the end time is 17:02:55 on December 12, 2016. IR310, IR311, IR410, and IR411 can be used as the potential relay during this time period. By using the STK software, the position of the vehicle at each moment can be obtained and the incident angle of the EM wave between the plasma surface and each potential satellite can be calculated by Equation (3). The calculation results of the incident angles of the EM wave between the vehicle and IR310, IR311, IR410, and IR411 are shown in Figure 7. The incident angles of the EM wave between the vehicle and IR310 and IR410 are decreasing, and those of the EM wave between the vehicle and IR311 and IR411 are increasing.

According to the incident angle of the EM wave in the plasma obtained in Section 3.1, the typical plasma density, collision frequency, and attenuation coefficient of the EM wave through the plasma

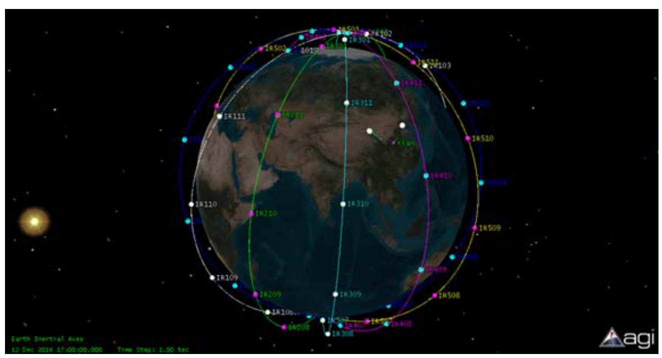


Figure 6. Iridium communication system generated by the STK software.

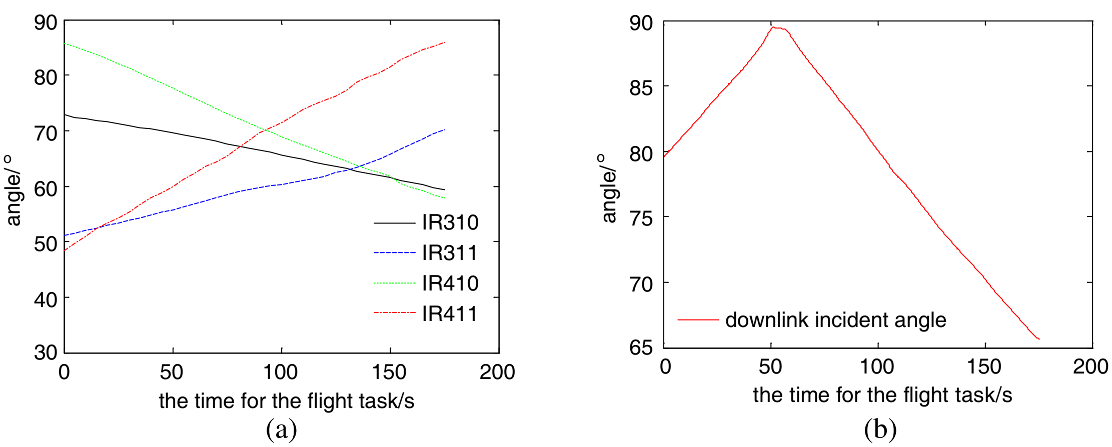


Figure 7. Incident angle of the EM wave: (a) between the vehicle and the potential satellites (uplink); (b) between the vehicle and the ground station (downlink).

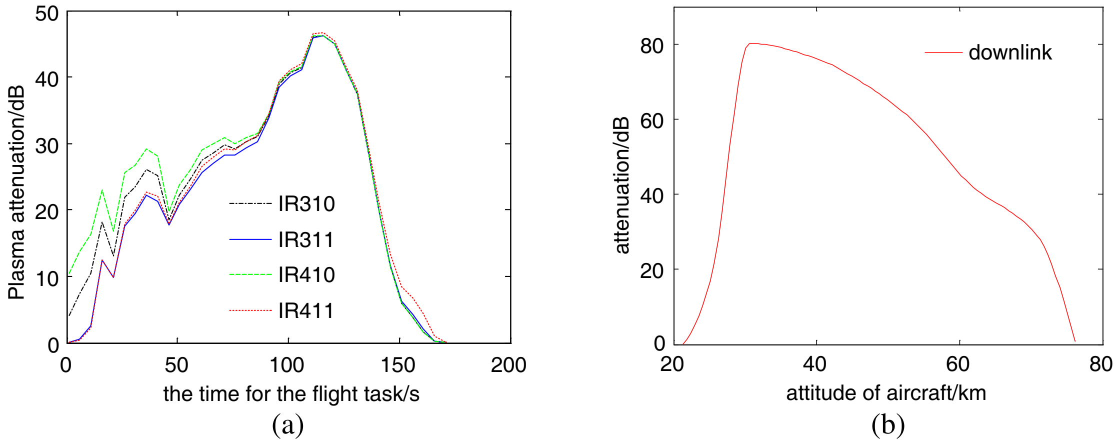


Figure 8. Plasma attenuation coefficients: (a) between the vehicle and the potential satellites (uplink); (b) between the vehicle and the ground station (downlink).

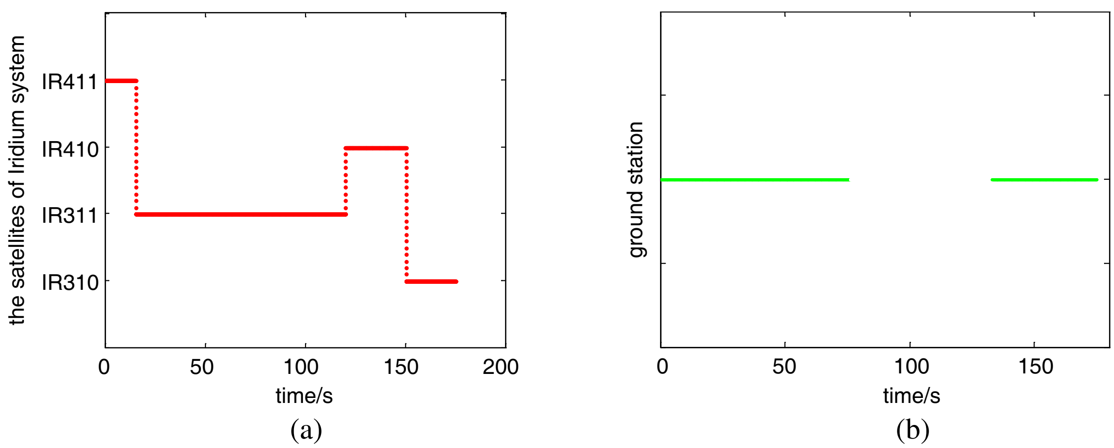


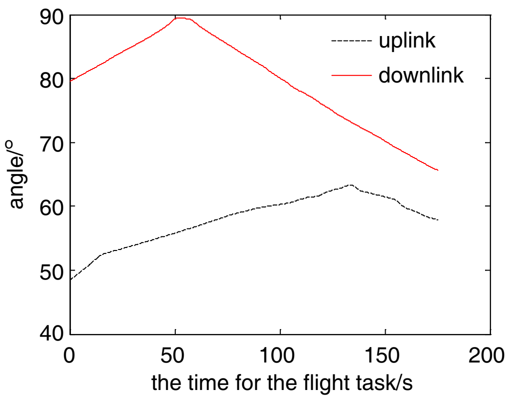
Figure 9. Coverage performance comparison: (a) proposed relay strategy with LEO; (b) direct communication with the ground station.

sheath can be obtained by the above oblique incident calculation method. The calculation results of the plasma attenuation coefficients between the vehicle and the potential satellites (IR310, IR311, IR410, and IR411) at 2 GHz are shown in Figure 8. At the beginning of the time of flight at 50 s, the attenuation coefficients of the various relay points are all different, with the difference becoming smaller with time.

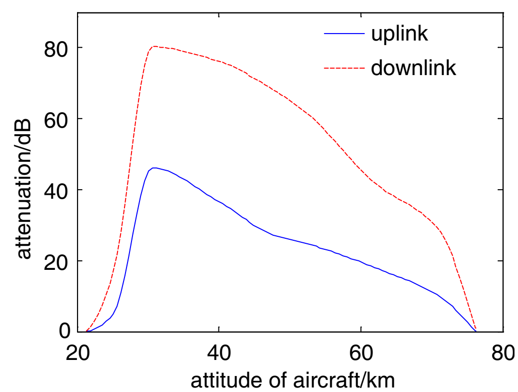
The coverage performance comparison is illustrated in Figure 9. Figure 9(a) shows the simulation results of the relay selection. The horizontal axis represents the flight time, and the vertical axis represents the different satellites selected as relay nodes. At the beginning, IR411 is selected as the access node for the channel fading coefficient between the vehicle and the satellite. IR411 is the smallest at 0–15 s, followed by IR311 at 15–120 s, IR410 at 120–150 s, and IR310 at 150 s until the end of the tasks. The relay strategy works effectively, although the channel condition of the vehicle and each satellite changes with time.

Figure 9(b) shows the communication between the vehicle and the ground station without LEO relay. The time of communication interruption is about 32.6%. That is, the use of low-orbit satellites to relay can improve the communication coverage time by 32.6%, and this finding proves that a LEO relay is feasible during the reentry process.

The above results can be intuitively observed through the comparison between the uplink attenuation after relay selection and downlink attenuation. Figure 10(a) presents the incident angle comparison of the uplink after relay selection with the downlink. The downlink incident angle increases



(a)



(b)

Figure 10. Comparison between the uplink and the downlink: (a) incident angle of EM wave; (b) attenuation.

from 79.5°, and it decreases when the time for the flight task is about 50 s. The incident angle of the uplink fluctuates continuously because different satellites are chosen as the relay at different times, and the uplink incident angle increases initially and then decreases slightly when the time for the flight task is 130 s. Figure 10(b) is the attenuation comparison between the uplink and the downlink. The uplink plasma attenuation is significantly less than the downlink plasma attenuation, and the most serious plasma attenuation occurs at the altitude of 30 km, at which the downlink plasma attenuation is much larger than the uplink plasma attenuation at about 35 dB.

5. CONCLUSION

In this study, a relay communication method is proposed based on a low-orbit satellite as the relay platform to alleviate the communication interruption caused by the deep fading of the plasma sheath. We take the Iridium system as the low-orbit relay satellite system and use the attenuation coefficient of each channel as a parameter to select the best relay in the reentry process for hypersonic vehicles. The EM incident angle between the vehicle and the satellite or ground station is calculated during the reentry process. Then, the oblique incident wave calculation method is used to obtain the uplink and downlink channel attenuation with a typical reentry electronic density distribution. The simulation results show that the use of low-orbit satellites to relay can significantly reduce the time of communication interruption in the reentry process.

The uplink relay scheme is promising in mitigating the plasma blackout problem through S-band analysis under a typical reentry environment. Studies have shown that mitigating the plasma can also reduce the plasma attenuation by increasing the frequency band to the Ka-band. In this case, the high-frequency band is subjected to greater spatial link attenuation, thus resulting in reduced relay effectiveness. In fact, this problem is easy to solve by adding a near-space floating platform as a new relay node between the satellite and the aircraft.

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