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Potential application of X-ray communication through a plasma sheath encountered during spacecraft reentry into earth's atmosphere

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Rapid progress in exploiting X-ray science has fueled its potential application in communication networks as a carrier wave for transmitting information through a plasma sheath during spacecraft reentry into earth's atmosphere. In this study, we addressed the physical transmission process of X-rays in the reentry plasma sheath and near-earth space theoretically. The interactions between the X-rays and reentry plasma sheath were investigated through the theoretical Wentzel–Kramers–Brillouin method, and the Monte Carlo simulation was employed to explore the transmission properties of X-rays in the near-earth space. The simulation results indicated that X-ray transmission was not influenced by the reentry plasma sheath compared with regular RF signals, and adopting various X-ray energies according to different spacecraft reentry altitudes is imperative when using X-ray uplink communication especially in the near-earth space. Additionally, the performance of the X-ray communication system was evaluated by applying the additive white Gaussian noise, Rayleigh fading channel, and plasma sheath channel. The Doppler shift, as a result of spacecraft velocity changes, was also calculated through the Matlab Simulink simulation, and various plasma sheath environments have no significant influence on X-ray communication owing to its exceedingly high carrier frequency. *Published by AIP Publishing.*
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I. INTRODUCTION

A supersonic spacecraft entering the Earth's atmosphere at altitudes ranging from 20 km to 100 km is surrounded by a plasma sheath because of the tremendous heat generated by air compression and ablation around the craft. In this case, the spacecraft may undergo a critical period of time called "communication blackout" in which regular RF signals between the reentry vehicle and the ground stations will cease.[1,2]

Thus far, considerable efforts have been made to solve the problem connected with plasma sheath during reentry,[3–7] which includes the use of aerodynamic shapes,[3] injection of electrophilic materials,[4] use of standing wave detection and adaptive data rate control[5] or static magnetic field,[6] and transmission at higher frequencies.[7] However, aerodynamic shaping may have a reduced payload capability and increased aerodynamic heating problems. Injection of electrophiles reduces the concentration of electrons but leads to complexity in storage and insertion of coolants in the proper direction.[8] Moreover, the use of electromagnetic fields is an impractical technique because it will require extra weight. Although increasing the frequency generally reduces attenuation, higher frequencies are more subject to atmospheric and rain influence, and 10 GHz is often suggested as an upper limit for the RF signal, but the signal is difficult to penetrate the plasma sheath.[7] In the meantime, the advance of free-space optical communication[9–11] may be suitable for data transmission during spacecraft reentry into earth's atmosphere. Poddar and Sharma indicated that the communication link between the spacecraft and control station can be established through a self-focusing property laser beam, but this process needs much more demanding power of the laser source.[12]

Since 2007, the concept of X-ray communication (XCOM), which was first proposed by Dr. Keith Gendreau, was known as one of the most promising revolutionary concepts by NASA.[13] He had demonstrated the world's first XCOM system using a modulated X-ray source, with the hope of increasing the system's data rate of 50 kbps to 1 Mbps. However, it was only a ground experimental system using the facility's 600-m vacuum beamline. The exceedingly higher X-ray carrier frequency could provide high-rate, deep-space, low transmission power, and highly physically secure data links.[14] Similar to those of other optical, microwave, laser, and RF communications, information signals in XCOM are transformed into waveforms which are compatible with the nature of the communication channel by digital modulation schemes, for example, using a constant amplitude and phase or frequency variations to carry information. Fig. 1 shows the XCOM experimental concept of NASA, which is the X-ray link from the spacecraft to the International Space Station (ISS) and then the RF link from the ISS to the ground station. Kealhofer *et al.* illustrated ultrafast laser-triggered X-ray emission from hafnium carbide tips for space-based communications.[15] China's researchers proposed a novel space communication technology based on a grid-controlled X-ray source

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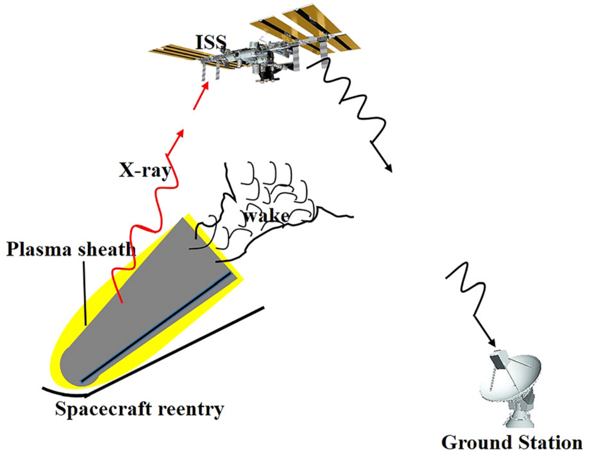

FIG. 1. Scheme of the X-ray communication (XCOM) Link System with the transmission process of X-rays being in the range of 25–1000 km, where the yellow region represents the plasma sheath in the spacecraft surface during reentry into earth's atmosphere. X-ray link from the Spacecraft (transmitter) to the ISS (receiver) and then transfer data to the Ground Station.

and realized a transmission speed with 64 kbps, and it was also a ground experimental system.[16] XCOM is analogous to wireless optical communication, but it enables high rate deep-space, low transmission power, smaller SWaP (size, weight, and power) than RF and laser communication, highly physically secure data links, and exceedingly high carrier frequency, which means significantly larger bandwidths for information transmission if technologies for modulating X-rays are further developed. Porter found that the data transfer rate of each X-ray link, which operates in the 3.0×10^{10} GHz range, could reach 40 Petabits/s by using on-off keying (OOK) modulation.[17] Furthermore, it enables communication with hypersonic vehicles reentering the atmosphere during communication blackout period arising from the plasma sheath.

Space XCOM is based on the principle that the transmission of X-rays is almost 100% when their photon energy is more than 10 keV ($\lambda < 0.1$ nm) and atmospheric pressure is lower than 10^{-1} Pa,[18] which means that X-rays have no attenuation for transmission in space. Although the advantage of X-rays is used in the communication blackout during spacecraft reentry into earth's atmosphere, the atmospheric environment still exists in these altitudes. In addition, the Doppler shift generated by a hypersonic speed of the reentry spacecraft as well as the high frequency of X-rays is an important factor. However, theoretical analysis of XCOM during the reentry plasma sheath has not been reported in the existing literatures, including using optimal X-ray energy under different reentry altitudes and the XCOM system performance through considering the time-varying plasma sheath channel. Therefore, it is necessary to investigate more details regarding the above physical process in order to have a good understanding of XCOM.

In this paper, the Wentzel–Kramers–Brillouin (WKB) approximation method was used to investigate X-ray transmission properties in a plasma sheath environment. In addition, we employed the general-purpose Monte Carlo (MC) simulation to explore the transmission process of X-rays in the atmospheric model corresponding to the authentic atmospheric environment. Additionally, an effective Matlab Simulink's Communication System Toolbox was used to evaluate the properties of the XCOM system through calculating the probability of the Bit Error Rate (BER) versus Signal to Noise Ratio (SNR) under wireless channel models, namely, Additive White Gaussian Noise (AWGN), Rayleigh fading, and plasma sheath channel models.

II. THEORIES AND METHODS

A. Theoretical study of the interaction between the X-rays and plasma sheath

The theoretical WKB approximation method[19] was used to analyze the interaction between the X-rays and plasma sheath and to investigate X-ray transmission properties in plasma density gradients. In fact, the reentry plasma sheath is non-uniformly distributed and can be characterized by two important parameters, namely, electron density and collision frequency. The electron density of the plasma sheath is strongly correlated with the spacecraft's shape, velocity, trajectory, angle of attack, and altitude. Its distribution outward from the spacecraft surface would be expressed by a double Gaussian function[20] as follows:

$$N_e(z) = \begin{cases} N_{emax}\exp(a_1(z-z_0)^2) & (0 \le z \le z_0) \\ N_{emax}\exp(-a_2(z-z_0)^2) & (z_0 \le z \le z_1), \end{cases} \tag{1}$$

where N_{emax} is the peak value of the plasma electron density, z_1 is the thickness of the plasma sheath, z_0 is the location of the boundary layer, and a_1 and a_2 represent normal distribution's shape. According to the typical values of the reentry plasma sheath generated by the NASA Langley Research Center,[7,21] we set the parameters of $a_1 = 1$, $a_2 = 0.5$, $z_0 = 0.05$ m, and $z_1 = 0.15$ m in the following work. Plasma densities ranging from 10^{16} to $10^{19}\,\mathrm{m}^{-3}$ were measured over an altitude in the range of 90 km–25 km,[20] and collision frequency was in the range of 0.01 GHz–10 GHz. The plasma frequency (w_p) depends on the electron density and is given as[22]

$$w_p = \sqrt{\frac{N_e(z)e^2}{\varepsilon_0 m_e}}, \tag{2}$$

where e is the electron charge (1.6×10^{-19} C), ε_0 is the permittivity of free space (8.854×10^{-12} F/m), and m_e is the mass of the electron (9.1×10^{-31} kg). The ion mass is about four orders of magnitude larger than the electron mass. Thus, the ion plasma frequency can be ignored. Actually, the effective dielectric coefficient of the plasma sheath is not a constant, which is given by the following:[22]

$$\varepsilon = \left(1 - \frac{w_p^2}{w^2+v^2} - j\frac{v}{w}\frac{w_p^2}{w^2+v^2}\right)\varepsilon_0, \tag{3}$$

where v is the collision frequency and w is the angular frequency of X-rays, and propagation vector k can be expressed as[22]

TABLE I. Density as a function of geometric altitude from *U.S. Standard Atmosphere*, 1976 for each of the main atmospheric layer.[24]

Altitude (km)	15	20	25	32	37	47	48	51	61
Density (kg/m^3)	1.9476×10^{-1}	8.8910×10^{-2}	4.0084×10^{-2}	1.3555×10^{-2}	6.2355×10^{-3}	1.4187×10^{-3}	1.3167×10^{-3}	9.0690×10^{-4}	2.7321×10^{-4}
Altitude (km)	71	86	92	100	120	150	200	300	1000
Density (kg/m^3)	7.1966×10^{-5}	6.9580×10^{-6}	2.3930×10^{-6}	5.6040×10^{-7}	2.2220×10^{-8}	2.0760×10^{-9}	2.5410×10^{-10}	1.9160×10^{-11}	3.5610×10^{-15}

$$k = \frac{w}{c}\sqrt{\varepsilon_r} = \frac{w}{c}\sqrt{\frac{\varepsilon}{\varepsilon_0}}. \tag{4}$$

Considering the plasma sheath under X-rays incident vertically, the transmission coefficient (T) and attenuation coefficient (Att) can be given by[23]

$$T = \exp\left(-2\mathrm{Im}\left(\int_0^{z_1} kdz\right)\right), \tag{5}$$

$$Att = -10\lg T = 8.686\mathrm{Im}\left(\int_0^{z_1} kdz\right). \tag{6}$$

The values of T and Att are calculated to assess the transmission properties of X-rays (10^{17}–10^{18} Hz analyzed) in the plasma sheath and then explain the advantage of X-ray communication in radio blackout.

B. X-ray transmission in the near-earth space

The general-purpose Monte Carlo N-Particle Transport Code (MCNP5) was used to simulate the transmission process of X-rays in the atmospheric model corresponding to the authentic atmospheric environment[24] from the plasma sheath existing between altitudes of 90 km and down to 25 km to the International Space Station (ISS), which maintains an orbit with an altitude of between 330 km and 435 km. The atmosphere density of different geometric altitudes is summarized in Table I.

As shown in Fig. 2, the atmospheric model was divided into several layers considering the density of different geometric altitudes. X-ray emission with energies in the range of 15 keV–200 keV was chosen to simulate the transmission process in this simulated geometry, and the number of particles crossing each surface of interest was calculated using MCNP5 tally F1. In addition, the number of simulated source particles was set to 1×10^9 in all simulations to make the statistical uncertainty below 2% for the photon transmission.

C. X-ray communication performance simulation

The simple XCOM system was simulated with the Matlab Simulink's Communication System Toolbox, and its performance was evaluated by calculating the probability of BER versus SNR under wireless channel models, namely, AWGN, Rayleigh fading, and plasma sheath channel models. The BER is the number of bit errors divided by the total number of transferred bits during a particular time arrival, and the SNR is the ratio of the received signal strength over the noise strength in the frequency range of the operation, and both of them are indicators used for assessing the quality of a communication link. Digital signals are transformed into waveforms compatible with the nature of the communication channels by digital modulation schemes, and there are three categories which use a constant amplitude and phase or frequency variations to carry information.

An on-off keying (OOK) modulation was employed to realize X-ray communication in the ground system whose transmission speed reaches 64 kilobits per second in Ref. 16. Although an OOK intensity modulated based wireless link is widely adopted, it requires an adaptive threshold to perform optimally in atmospheric turbulence conditions.[25] In this paper, the Binary Phase Shift Keying (BPSK) scheme was employed for the whole system. BPSK is a common form of phase modulation that conveys information by changing the phase of the carrier wave, and the BER of BPSK has a least

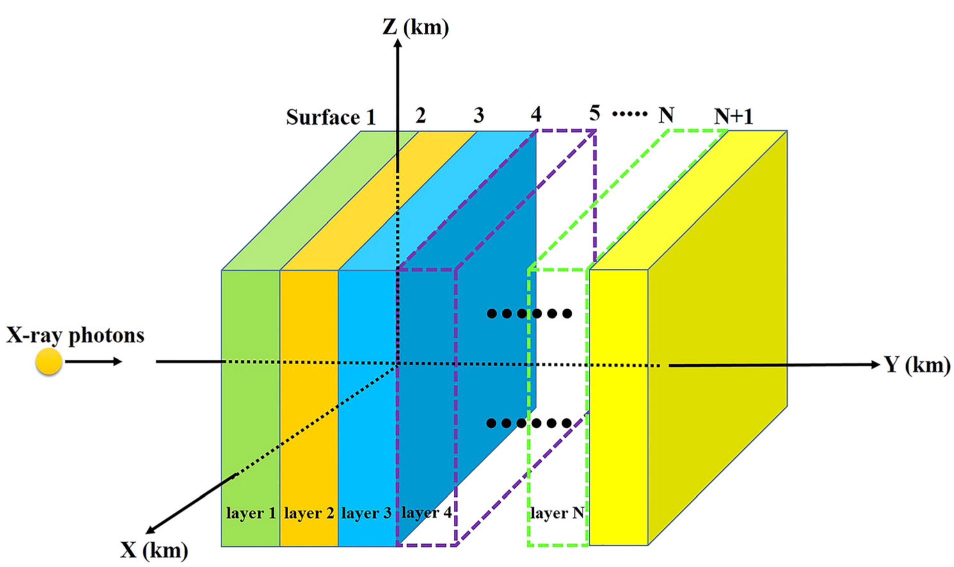

FIG. 2. Schematic illustration of transmission properties between the X-rays and atmospheric model which is divided into several layers according to different densities at various reentry altitudes. Three reentry altitudes (86 km, 61 km, and 32 km) to the ISS are considered in Monte Carlo simulation according to Table I, with index N being a variable and representing different layer numbers.

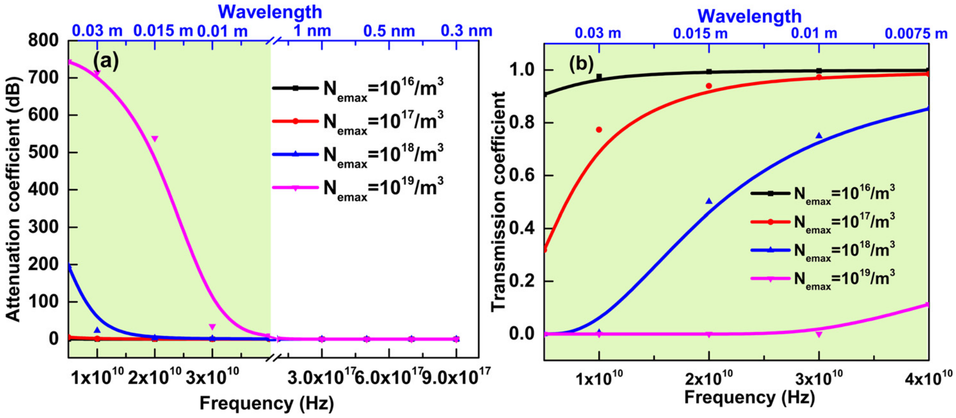

FIG. 3. (a) Attenuation coefficient (*Att*) at different carrier frequencies ranging from RF signals (5.0×10^9–4.0×10^{10} Hz) to X-rays (1.0×10^{17}–1.0×10^{18} Hz) under various plasma peak electron densities (10^{16}–$10^{19}/m^3$) with the fixed collision frequency at 1 GHz and (b) transmission coefficient (*T*) of RF signals with carrier frequencies lower than 4.0×10^{10} Hz.

minimum which means that it is one of the most robust modulation methods as compared to other techniques such as OOK, Quadrature Phase Shift Keying (QPSK), and so on; therefore, it will give an excellent result in fading channels.[25] The performance of BPSK was presented with coherent detection. In addition, the performance of the XCOM system was also compared with that of AWGN and Rayleigh channels to provide more insights about the plasma sheath channel.

III. RESULTS AND DISCUSSION

A. Transmission of X-rays in the plasma sheath

In this section, the WKB approximation method was employed to investigate X-ray transmission properties in the plasma sheath. We focused mainly on the relationship between different carriers and plasma sheath's electron densities and collision frequencies. The *Att* and *T* were calculated, to some extent, which could reflect the transmission properties of X-rays in the plasma sheath.

On the one hand, we fixed the collision frequency of the plasma sheath $v = 1$ GHz and identified the relationship between the *Att* and *T* at different carrier frequencies ranging from RF signals (5.0×10^9–4.0×10^{10} Hz) to X-rays (10^{17}–10^{18} Hz) under various plasma peak electron densities at 10^{16}–$10^{19}/m^3$. For comparison, the same analyses were made for RF signals with frequencies lower than 4.0×10^{10} Hz. As illustrated in Fig. 3, the RF carrier with a frequency lower than 1.0×10^{10} Hz hardly penetrates the plasma sheath, which is similar in the maximum electron density with the highest frequencies. Conversely, the *Att* of the X-ray carrier can be totally ignored and the *T* is almost close to 1 even in the maximum electron density, which are attributed to its exceedingly high carrier frequency.

To better understand the relationship between the *Att* and *T* at different carrier frequencies with various plasma collision frequencies in the range of 0.01–10 GHz, the peak electron densities were fixed at $10^{19}/m^3$. The same analyses were also made for RF signals with frequencies lower than 4.0×10^{10} Hz for comparison. Fig. 4 shows little dependence of X-ray transmission in the plasma sheath on the collision frequency, and the *Att* of the RF carrier decreases with the increase in the carrier frequency. It is clear that the *T* of carrier frequency lower than 1.0×10^{10} Hz is nearly close to 0. Thus, communication blackout occurs when using the RF carrier during the spacecraft reentry into earth's atmosphere, and the *Att* of X-rays is so small that it can be neglected and the *T* of them is close to 1 as well. Therefore, X-rays can transmit information in the plasma sheath as a communication carrier, which is better than the regular RF communication.

B. Transmission of X-rays in the near-earth space

It is universally acknowledged that X-rays have no physical attenuation for transmission in space. However, the attenuation in the atmospheric environment cannot be ignored. According to the discussion in Subsection III A, X-rays can penetrate the plasma sheath to transmit information owing to their extremely high frequencies, but the thin

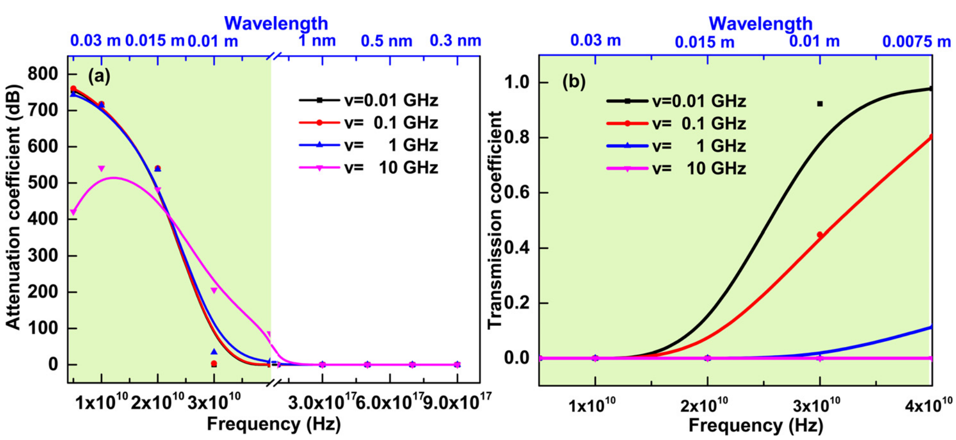

FIG. 4. (a) Attenuation coefficient (*Att*) at different carrier frequencies ranging from RF signals (5.0×10^9–4.0×10^{10} Hz) to X-rays (1.0×10^{17}–1.0×10^{18} Hz) under various plasma collision frequencies with the fixed peak electron densities at $10^{19}/m^3$ and (b) transmission coefficient (*T*) of RF signals with carrier frequencies lower than 4.0×10^{10} Hz.

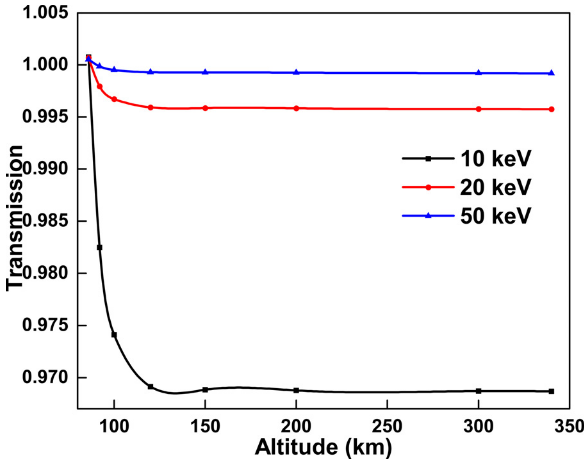

FIG. 5. Transmission of X-rays at an altitude above 86 km, with photon energies being 10 keV, 20 keV, and 50 keV, respectively.

atmosphere in communication blackout altitude still exists. To give a detailed description of X-ray transmission properties in communication blackout, the MC simulation was employed to study X-ray transmission during spacecraft reentry into the atmosphere process. The whole atmospheric model is in the range of the X-ray emitter altitude (32 km, 61 km, and 86 km considered) to the receiver in the ISS (300–340 km).

As shown in Fig. 5, considering the communication blackout altitude at 86 km, the penetration ability of various X-ray photon energies decreases with increasing thin atmosphere altitude; even 10 keV soft X-rays still have extremely high transmission (>95%) after hundreds of kilometers. Moreover, the transmission in the thin atmosphere will be further improved if X-ray energies advance. X-ray uplink communication was an effective and feasible method when the spacecraft reentry altitude was over 86 km even using the soft X-ray carrier, let alone hard X-rays.

However, as illustrated in Fig. 6, the X-ray attenuation from communication blackout altitude occurring at 61 km and 32 km to the ISS is more severe than that at 86 km owing to the high density in the low atmosphere. Depending on the increasing X-ray energy, the transmission of 50 keV X-rays reaches 96% after hundreds of kilometers, while for 20 keV X-rays emitted from 32 km, the transmission is almost close to 0, and the transmission of 500 keV X-rays reaches 80%. Therefore, the higher the X-ray energy is, the better its transmission property is in the low atmosphere as a communication carrier. Thus, we should use a high-energy X-ray emitter in the low atmosphere to provide a stable and robust X-ray communication.

Increasing X-ray energies contributes to their transmission in different reentry altitudes, but not all the X-ray photons will be received by a detector especially over a long-distance transmission, and only those receiving enough X-ray photons can guarantee stable and robust X-ray communication. Therefore, the effective acquisition of X-ray signals is an important issue[26,27] especially for X-ray detectors' advancement.

C. X-ray communication property in the reentry plasma sheath

1. Influence of the Doppler shift caused by reentry flight

The Doppler shift is the change in the frequency of a wave for a moving observer relative to its source. For space communications, the high-speed relative radical velocity v_d between the transmitter and receiver generates a very large Doppler shift f_d on the carrier frequency, and the XCOM system is no exception, then the f_d is given by the following:

$$f_d = \frac{v_d}{c} f_c, \tag{7}$$

where $c = 3 \times 10^8$ m/s is the speed of light and f_c is the carrier frequency. The final signal frequency of the receiver is $f_c \pm f_d$, which seriously affects the receiving signal ability of the receiver.

In the simulation, we only considered the reentry velocity at an altitude of communication blackout, 7.619 km/s (83.82 km) and 5.120 km/s (24.3 km), according to the RAM C-III vehicle.[7] The Doppler shift value for relative speed 7.619 km/s would be ~9142.8 GHz for X-ray carrier frequency $f_c = 10^8$ GHz. Therefore, it is necessary to consider the influence of the Doppler shift because of the reentry flight. As shown in Fig. 7, the Multipath Rayleigh fading channel with AWGN has been chosen to describe the influence of the reentry high-speed vehicle on XCOM at Simulink multipath fading box in which the corresponding calculated Doppler shift has been inserted. We have simulated the proposed scheme for XCOM system specifications.

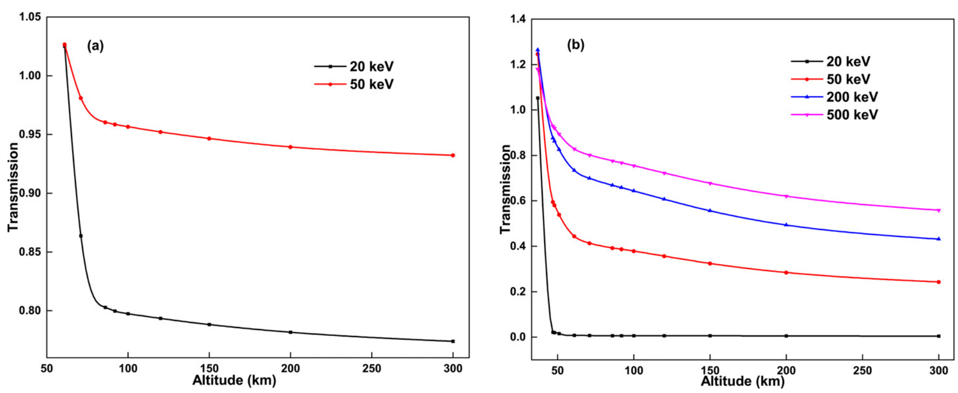

FIG. 6. Transmission of X-rays at the altitude above (a) 61 km and (b) 32 km, with photon energies being 20 keV, 50 keV, and 200 keV, respectively.

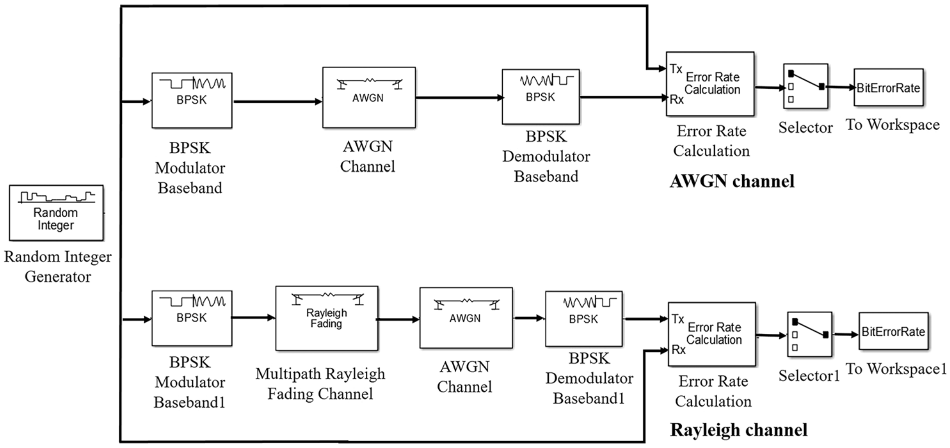

FIG. 7. Matlab Simulink model of the Additive White Gaussian Noise (AWGN) channel and Multipath Rayleigh fading channel.

The AWGN and Multipath Doppler shift channel models are used for testing.

Comparing all the schemes by measuring BER versus SNR with a setup as shown in Fig. 7, the performance of the XCOM system degrades rapidly by adding the Multipath Rayleigh fading channel as illustrated in Fig. 8. This finding reveals that the influence of the Doppler shift is an important factor because of the reentry of high-speed vehicles when high frequency X-rays are used as communication carriers, and increasing the SNR is not an effective method to reduce BER for mitigating the Doppler shift. It should be pointed out that this issue may also be addressed by an off-the-shelf Doppler shift compensation.[28] Also, the BER of relative velocity with 7.619 km/s is slightly higher than that of 5.120 km/s under the same SNR of a receiver. In addition, the vehicle speed has no significant influence on the performance of the AWGN channel, and the BER presents an obvious decrease as the SNR increases.

2. Influence of the plasma sheath channel because of reentry flight

Communication properties are degraded and distorted by the turbulent plasma reentry sheath around the hypersonic spacecraft during reentry into the atmosphere; thus, the plasma sheath is always treated as a time-varying communication channel.[1] Fig. 9 illustrates plasma sheath channels; the input X-ray carrier signal $x(t)$ transmits into the plasma sheath profile described as Equation (1) and get the baseband signal $\mathrm{y(t)}$ through BPSK modulation and coherent demodulation due to its minimum value of BER compared to other modulation methods.[25] The transmission properties of the X-ray carrier in the plasma sheath can be mathematically expressed as

$$\mathrm{y(t)} = T_P(w_p, t)x(t), \tag{8}$$

where $T_P(w_p, t)$ is the X-ray transmission coefficient in the plasma calculated on the basis of Equations (4) and (5), the real and imaginary parts of $T_P(w_p, t)$ represent the phase constant and transmission attenuation, and the typical spatial profiles of electron densities and collision frequency are adopted in Ref. 7. In this section, the BER versus SNR was calculated under various plasma sheaths by the Matlab Simulink simulation, and the relevant plasma sheath channel models have been reported.[29,30] We considered the combination between the plasma sheath and AWGN as a joint communication channel, in which the Matlab function module was used to describe the attenuation coefficient of X-rays according to the electron density and collision frequency of the plasma sheath.

The signal attenuation of X-rays in the plasma sheath channel was time-varying because of plasma changing electron density. In this section, we analyzed BER versus SNR of XCOM system under four plasma electron densities ($10^{16}/\mathrm{m}^3$, $10^{17}/\mathrm{m}^3$, $10^{18}/\mathrm{m}^3$, and $10^{19}/\mathrm{m}^3$) with a fixed collision frequency of 10 GHz. As shown in Fig. 10, the higher plasma electron density results in relatively larger BER performance. Therefore, the SNR should be improved for the X-ray receiver to satisfy the robust communication performance.

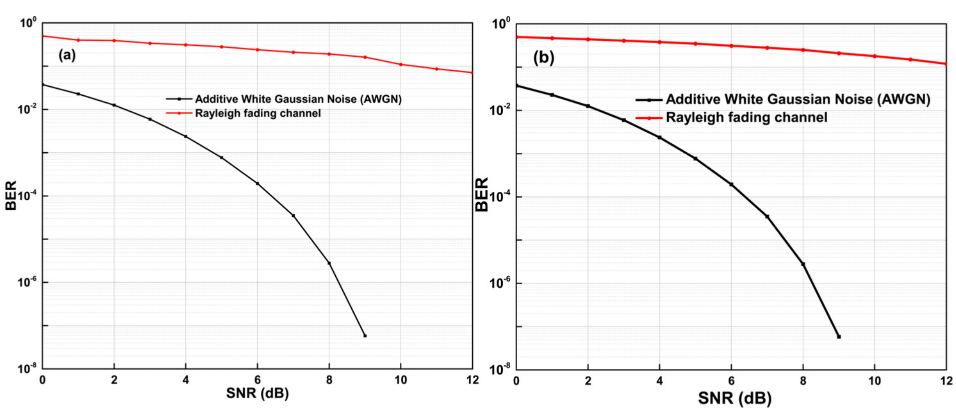

FIG. 8. Bit Error Rate (BER) versus Signal to Noise Ratio (SNR) under Additive White Gaussian Noise (AWGN) channel and Multipath Rayleigh fading channel with the high-speed relative velocity (a) 7.619 km/s and (b) 5.120 km/s between the transmitter and receiver.

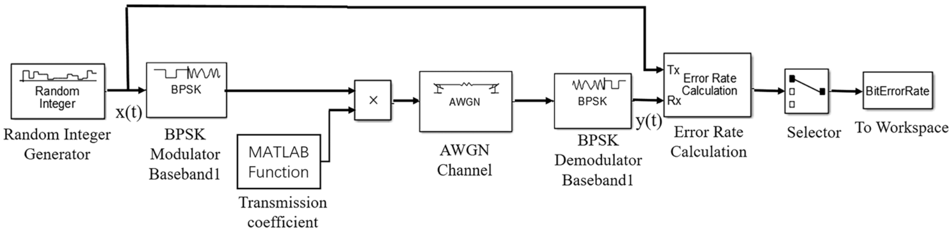

FIG. 9. Plasma sheath channel assessment of the X-ray communication (XCOM) system implemented in Simulink as Matlab functions.

Additionally, we can also ascertain that various plasma electron densities have no significant effect on the BER performance of XCOM under the same SNR of the receiver, mainly because X-rays have a high transmission coefficient of nearly 1 because of their extremely high frequencies. Therefore, XCOM is a potential application for maintaining real-time communication during spacecraft reentry into earth's atmosphere.

IV. CONCLUSION

This paper theoretically aims at investigating the potential application of current state-of-the-art XCOM in the plasma sheath encountered during spacecraft reentry into earth's atmosphere. First, we found that the attenuation coefficient of X-rays is extremely small and can thus be neglected, whereas the transmission coefficient is nearly 1 in the reentry plasma sheath. This finding indicates that X-ray transmission is not influenced by the severe reentry plasma sheath as compared with regular RF signals. Second, having simulated the transmission properties of X-rays, we discovered that adopting an X-ray source with different energies according to the different spacecraft reentry altitudes is imperative when using X-ray uplink communication, especially in the near-earth space. In addition, the performance of the robust XCOM system has been evaluated, considering the effects of the severe plasma sheath channel and Doppler shift caused by high-speed spacecraft. It should be pointed out that the Doppler shift is an important factor, and its influence may be addressed by improving the SNR of a receiver or other Doppler shift compensation techniques. Although increasing the SNR of the receiver contributes to the reduction of the BER of the XCOM system, various reentry plasma sheath channels have no significant influence on its performance because of the high frequency of X-rays. Generally speaking, XCOM would be a potential application for maintaining real-time communication during the spacecraft reentry into earth's atmosphere.

These results may be helpful for understanding the advantages and some related physical processes of XCOM in the severe plasma sheath environment. However, this study is only a feasibility study of XCOM during spacecraft reentry into near-earth space, and further theoretical and experimental studies are to be carried out in our future works.

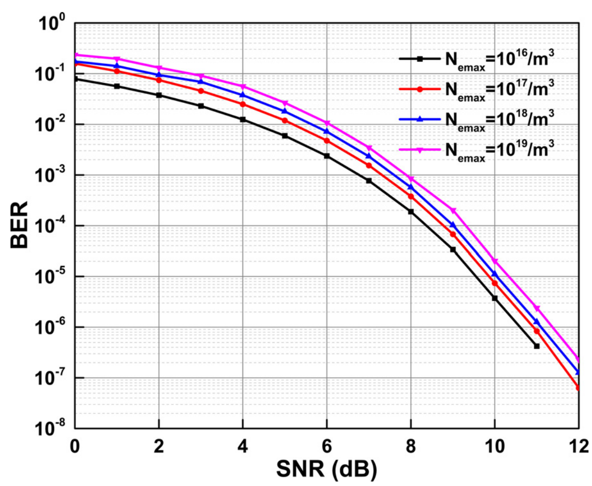

FIG. 10. Bit Error Rate (BER) versus Signal to Noise Ratio (SNR) of the X-ray communication (XCOM) system under four different plasma sheath electron densities in the range of 10^{16}–$10^{19}/m^3$.

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[1]R. P. Starkey, J. Spacecr. Rockets **52**(2), 426 (2015).
[2]J. T. Li and L. X. Guo, J. Electromagn. Waves Appl. **26**(13), 1767 (2012).
[3]I. F. Belov, V. Y. Borovoy, V. A. Gorelov *et al.*, J. Spacecr. Rockets **38**(2), 249 (2001).
[4]L. C. Schroeder and N. D. Akey, J. Spacecr. Rockets **10**(3), 170 (1973).
[5]K. Xie, M. Yang, B. Bai *et al.*, J. Appl. Phys. **119**(2), 023301 (2016).
[6]C. Thoma, D. V. Rose, C. L. Miller *et al.*, J. Appl. Phys. **106**(4), 043301 (2009).
[7]R. A. Hartunian, G. E. Stewart, S. D. Fergason *et al.*, Aerospace Report No. ATR-2007 (5309)-1, The Aerospace Corporation, EI Segundo, 2007, pp. 1–103.
[8]N. Mehra, R. K. Singh, and S. C. Bera, Prog. Electromagn. Res. **63**, 161 (2015).
[9]H. P. Lutz, ESA Bull. **91**, 25 (1997).
[10]T. Jono, Y. Takayama, K. Shiratama *et al.*, Lasers Appl. Sci. Eng. **6457**, 645702 (2007).
[11]D. E. Raible, B. R. Fast, D. Dinca *et al.*, in *International Conference on Space Optical Systems and Applications* (2011), p. 312.
[12]S. Poddar and D. Sharma, Optik **126**(24), 5899 (2015).
[13]NASA Technology Roadmaps, "Communication, navigation, and orbital debris tracking and characterization systems," Report No. TA5 (2015), pp. 12–13, see https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_5_communication_and_navigation_final.pdf.
[14]NASA, "Next-generation communications: 'Demonstrating the world's first x-ray communication system'," Report No. FS-2007-10-103-GSFC (TT#7), see https://gsfctechnology.gsfc.nasa.gov/TechSheets/XRAY_Goddard_Final.pdf.
[15]C. Kealhofer, S. M. Foreman, S. Gerlich *et al.*, Phys. Rev. B **86**(3), 035405 (2012).
[16]L. Sheng, B. Zhao, and Y. Liu, Proc. SPIE **9207**, 920716 (2014).
[17]G. Porter, *See Straight Through Data Center Bandwidth Limitations with X-Rays* (CiteSeer, 2013).
[18]B. L. Henke, E. M. Gullikson, and J. C. Davis, At. Data Nucl. Data Tables **54**(2), 181 (1993).
[19]P. Yeh, *Optical Waves in Layered Media* (Wiley-Interscience, 2005).

[20]R. Rawhouser, "Overview of the AF avionics laboratory reentry electromagnetics program," Technical Report No. 19710011627, NASA, Washington, DC, USA, 1970.
[21]E. D. Gillman, J. E. Foster, and I. M. Blankson, "Review of leading approaches for mitigating hypersonic vehicle communications blackout and a method of ceramic particulate injection via cathode spot arcs for blackout mitigation," Technical Report No. 20100008938, NASA, Washington, DC, USA, 2010.
[22]J. P. Rybak and R. J. Churchill, IEEE Trans. Aerosp. Electron. Syst. **AES-7**, 879 (1971).
[23]S. Liu, T. Zhou, X. He *et al.*, in *7th International Symposium on Antennas, Propagation & EM Theory* (IEEE, 2006), pp. 1–4.
[24]T. W. Schlatter, *Atmospheric Composition and Vertical Structure* (Earth System Research Laboratory, NOAA, Boulder, CO, USA, 2009).
[25]W. O. Popoola and Z. J. Ghassemlooy, Lightwave Technol. **27**(8), 967 (2009).
[26]T. Okajima, Y. Soong, E. R. Balsamo *et al.*, Proc. SPIE **9905**, 99054X-1 (2016).
[27]L. J. Wong, I. Kaminer, O. Ilic *et al.*, Nat. Photonics **10**(1), 46 (2016).
[28]A. E. Abdelkareem, B. S. Sharif, and C. C. Tsimenidis, Ad Hoc Networks **45**, 104 (2016).
[29]M. Yang, X. Li, Y. Liu *et al.*, in *10th International Symposium on Antennas, Propagation & EM Theory* (IEEE, 2012), pp. 575–578.
[30]X. Lyu, W. Feng, and N. Ge, in *8th International Conference on Wireless Communications & Signal Processing* (IEEE, 2016), pp. 1–5.