Optik - International Journal for Light and Electron Optics 199 (2019) 163521

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Original research article

Power budget and performance analysis of X-ray communication during the Earth re-entry of spacecraft

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ARTICLE INFO

Keywords:
X-ray communication
Link model
Power budget
Reentry blackout

ABSTRACT

X-ray communication (XCOM) is a novel method that exploits X-rays as a carrier for data transmission. The high penetration of X-rays enables XCOM to avoid radio blackout during the atmospheric re-entry into Earth. To guarantee stable and robust XCOM, this study provides a power budget for XCOM. The Monte Carlo method was used to evaluate the transmission properties of X-ray beams in near-earth space, and a link model in the re-entry blackout region were established. Moreover, we established a noise model for the X-ray detector and evaluated the mathematical relationship between the transmitting power, and the bit-error-rate (BER). Results indicated that the X-rays with energies of 30–50 keV are highly suitable at an altitude of 35 km, and that robust communication performance could be obtained by using soft X-rays in the upper atmosphere. Adopting optimal X-ray energies according to different altitudes of spacecraft re-entry is, thus, of great significance. We calculated the minimum transmitting power of the X-ray source for a targeted BER and found that, when the link distance is 295 km and the X-ray energy is 50 keV, the power consumption of the X-ray source must be 140 W to achieve BER of less than 10^{-6} level.

1. Introduction

The radio frequency (RF) communication between a spacecraft and the ground station is interrupted during atmospheric re-entry into Earth. This phenomenon is commonly called reentry blackout. According to Radio Attenuation Measurement experiments conducted by NASA in the 1970s, reentry blackout generally occurs at altitudes between 35 and 80 km [1]. During this blackout, the plasma sheath surrounding the re-entry spacecraft surface generated by high-speed flight causes the absorption and reflection of electromagnetic waves, and the ground station loses control of the spacecraft, which greatly threatens the safety of the vehicle. Various methods have been suggested to solve the problem of communication blackout during re-entry, and approaches including aerodynamic shaping, use of magnetic fields, and the high- frequency method have been introduced [2–6]. X-ray communication (XCOM) is a method that aims to avoid the blackout phenomenon by using communication frequencies higher than those of plasma. Previous studies [7–9] demonstrated that X-rays could penetrate the plasma sheath without attenuation, and that using X-rays as a communication carrier may be feasible to eliminate reentry blackout. Moreover, XCOM can offer size and, weight advantages over RF communication due to its shorter wavelength. Compared with other optical bands, X-rays can provide a larger bandwidth, lower divergence, and higher directivity.

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https://doi.org/10.1016/j.ijleo.2019.163521
Received 26 June 2019; Accepted 1 October 2019

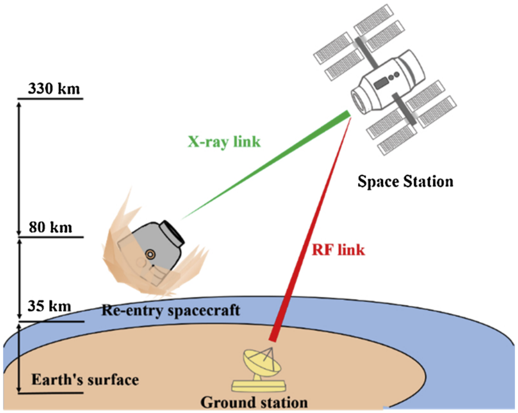

Fig. 1. Scheme of XCOM in the reentry blackout region.

Extensive research on the key devices of space XCOM have been reported [10–14], but transmission theory of the method in the RF blackout region has not been fully studied. Therefore, investigating the transmission process of XCOM and establishing its link model are necessary. The rest of this paper is organized as follows: The XCOM system and power budget equation are explained in Section 2. In Section 3, the influences of X-ray detectors, modulation schemes, and transmitting power on XCOM are evaluated. Finally, conclusions are given in Section 4.

2. Link model of XCOM in the reentry blackout region

2.1. XCOM system

XCOM in the RF blackout region uses RF and X-ray relay communication. Fig. 1 shows the relay communication scheme; here, the X-ray link extends from the spacecraft to the space station and then the RF link from the space station to the ground station.

A typical XCOM system consists of a modulated X-ray source, an X-ray modulator, an X-ray detector module, an X-ray collimating optical system, an X-ray focusing optical system, and an electronic module (Fig. 2). Data are loaded onto the switch of the modulated X-ray source by the modulator, and the on-off of the switch corresponds to the binary signal “0” or “1.” The modulated X-ray beams are then collimated, transmitted in the blackout environment, detected and collected by the detector module, and restored to the data by the X-ray demodulator.

2.2. XCOM link model and power equation

The potential signal attenuation of X-ray links in the blackout environment can be divided into three parts: plasma attenuation, atmospheric attenuation, and geometric attenuation. Previous works [7] have proven that attenuation of X-rays in the plasma sheath can be neglected and that the transmission coefficient is close to 1 due to the high frequency of X-ray. In this section, the propagation process of X-ray beams in the atmosphere are simulated based on MCNP5 code. Based on the US Standard Atmosphere 1976 [15], the atmospheric model was divided into several layers considering different densities at various reentry altitudes. In addition, X-ray photons with energies in the range of 10–100 keV were used to simulate the transmission process, and the number of simulated particles was set to 10^7. The calculation error of all results was less than 0.1%.

The transmission coefficients of X-ray links with different energies as a function of altitude are shown in Fig. 3. Results indicate that X-ray attenuation is severe below 35 km due to the high atmosphere density, and that the 15 keV X-ray beam has a transmission coefficient of 0.01%. Here, 50 keV X-ray beams provide transmission coefficients of 28% and 95% at altitudes of 35 and 60 km, respectively, in the reentry blackout region. At altitudes above 80 km, a transmission coefficient of 90% is obtained even if 10 keV soft X-rays are used as a communication carrier. Thus, increasing the energy of X-ray beams can help improve atmospheric

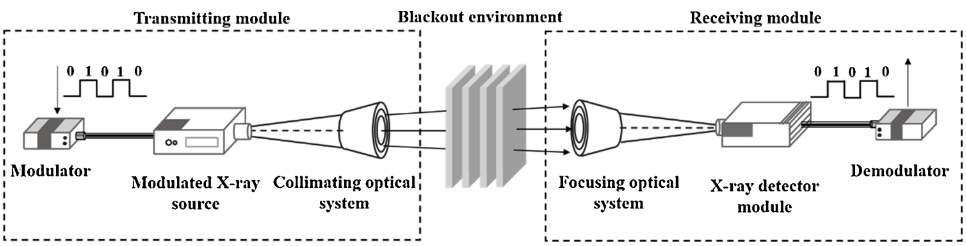

Fig. 2. System of XCOM in the reentry blackout region.

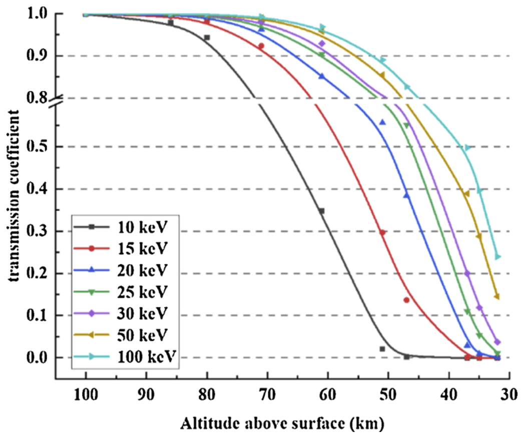

Fig. 3. Transmission coefficient of different X-ray energies in the uplink from 32 km to 330 km.

transmittance.

Fig. 4 depicts a line-of-sight (LOS) communication link model between the X-ray emitter and the X-ray detector. The distance between the emitter and detector is denoted by L, while the divergence angle and effective collection area of the detector are represented by ω and A_r, respectively.

The communication link equation determines the relationship between the received signal power and the transmitting power. The LOS X-ray link model describes the attenuation caused by the plasma sheath, the near-earth atmosphere, and the free- space divergence. The relationship between the received X-ray optical power P_r and the transmitted optical power P_t can be represented by [16,17]:

$$P_r = \frac{P_t \eta_{atm} \eta_p \eta_c^2 A_r}{\pi (D_t + \tan(0.5\omega) L)^2} \tag{1}$$

where η_{atm} and η_p are the attenuation coefficients of the atmosphere and plasma sheath, respectively, η_c is the efficiency of the X-ray focusing/collimating optical system, and D_t is the aperture radius of the emitter.

2.3. Noise model

The X-ray signal photons received by the detector after long-distance transmission are few, and identification of the noise sources at the X-ray detector is crucial. Therefore, noise sources in the reentry blackout XCOM link are key factors determining communication performance. The noise sources at the receiver input mainly consist of the shot noise from the received photocurrent and the thermal noise from the receiver electronics. The shot noise (including background noise σ_{bg} and dark current noise σ_d) can be expressed as [18]:

$$\sigma_{bg}^2 = 2M^2 q^2 \left(\eta_d B F_u A_r + \frac{P_r \eta_d B}{(h\nu)} \right) \tag{2}$$

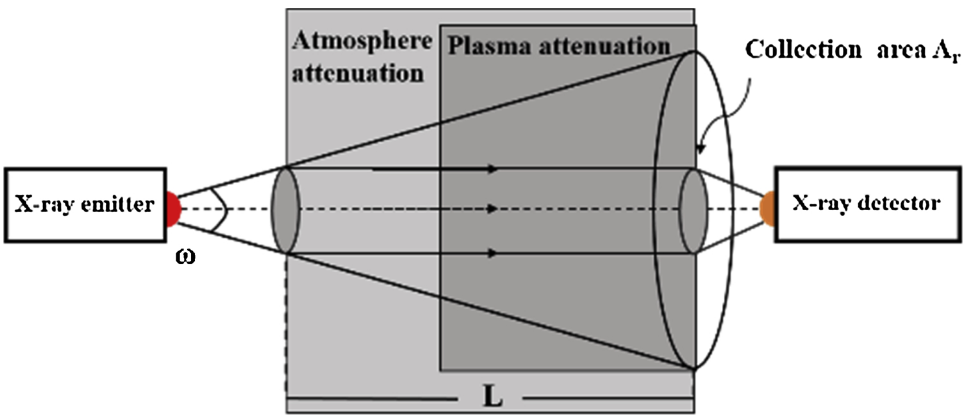

Fig. 4. Line-of-sight (LOS) XCOM link model.

$$\sigma_d^2 = 2qI_dBM^2 \tag{3}$$

The electronic noise (thermal noise σ_{th}) can be expressed as:

$$\sigma_{th}^2 = \frac{4KTB}{R_l} \tag{4}$$

where q is electron charge, B is the bandwidth, η_d is the quantum efficiency of the detector, F_u is the background noise photon flow per unit area, ν is the X-ray frequency, I_d is the dark current, K is the Boltzmann constant, T is the noise temperature, M is the gain of the detector, and R_l is the equivalent impedance of detector. The signal-to-noise ratio (SNR) at the receiver, which is a vital parameter for evaluating the quality of the communication link, can be determined by [19]:

$$S = (\gamma P_r)^2 \tag{5}$$

$$N = \sigma_{bg}^2 + \sigma_{th}^2 + \sigma_d^2 \tag{6}$$

$$\gamma = \frac{\eta_d q}{h\nu} \tag{7}$$

$$SNR = \frac{S}{N} = \frac{(\gamma P_r)^2}{\sigma_{bg}^2 + \sigma_{th}^2 + \sigma_d^2} \tag{8}$$

Following from Eqs. (1) and (8), the SNR per bit can be expressed as [20]:

$$SNR = \frac{E_b}{N_0} = \frac{(\gamma P_r)^2}{\sigma_{bg}^2 + \sigma_{th}^2 + \sigma_d^2}\frac{B}{R} \tag{9}$$

where R is the bits per second (bps), and E_b/N_O is the bit energy per noise-spectral-density. Therefore, the relationship between core parameters, such as transmitting power, communication rate, detector system, and SNR could be obtained, and the minimum transmitting power required to achieve a target SNR could be estimated.

In the calculations, the gain of the detector was 1, the effective receiver area was 0.3 m^2, and the bandwidth was 10^6 Hz. The beam divergence for the link from the spacecraft to the space station was set to 0.5 mrad.

2.4. Modulation scheme

Intensity modulation/ direct detection (IM/DD) are the main modulation methods for XCOM. The digital modulation technologies commonly used include the on-off keying scheme (OOK), pulse position modulation (L-PPM) and pulse interval modulation (DPIM). Table 1 summarizes the methods for determining the bandwidth requirements and BER of these three modulation schemes [21].

3. Results and discussion

3.1. Influence of the detector

A silicon drift detector (SDD) is a type of semiconductor that has become one of the core components of space XCOM systems [5]. This detector presents the advantages of high SNR and fast responses. The SDD detector has a quantum efficiency peak at an X-ray energy of 10 keV [22,23]. Therefore, this detector was chosen as the receiver of the proposed XCOM system. The SNR and BER performance of the XCOM link was calculated under a transmitting power of 100 W and OOK modulation scheme.

The SNR and BER value of X-ray links with different energies as a function of the altitude are shown in Fig. 5. The results indicate that, when the altitude is 35–40 km, a high SNR can be obtained by using an X-ray energy of 30 keV. Moreover, the quantum efficiency and receivable X-ray photons of the SDD detector decreased gradually with increasing X-ray energy, leading to a decrease in SNR and increase in BER in the communication system. Using 10 keV X-rays could provide an optimal performance at an altitude of 65 km. Therefore, under certain conditions, optimal communication performance can be obtained by choosing the appropriate X-ray beam energy. X-ray links with energies of 30–50 keV are suitable for reentry blackout XCOM.

In order to further improve the SNR of the 30–50 keV energy range, a cadmium zinc telluride (CZT) detector was selected as the

Table 1
Methods for determining BER and bandwidth requirements.

Modulation scheme	BER	Bandwidth requirement
OOK	$\frac{1}{2}\mathrm{erfc}(\frac{1}{2\sqrt{2}}\sqrt{SNR})$	R
PPM	$\frac{1}{2}\mathrm{erfc}(\frac{1}{2\sqrt{2}}\sqrt{SNR\frac{L}{2}\log_2 L})$	$R\frac{L}{\log_2 L}$
DPIM	$\frac{1}{2}\mathrm{erfc}(\frac{1}{2\sqrt{2}}\sqrt{SNR\frac{L+3}{4}\log_2 L})$	$R\frac{L+3}{2\log_2 L}$

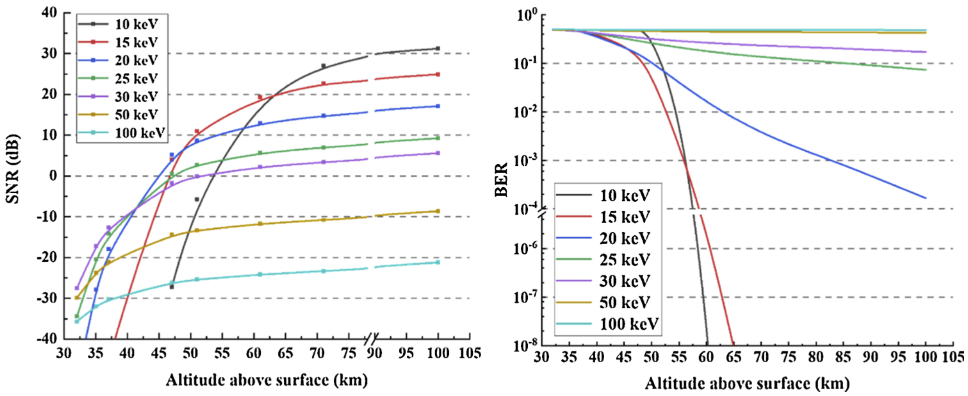

Fig. 5. (a) SNR and (b) BER of XCOM links as a function of the spacecraft altitude with varied X-ray energies.

detector for the reentry blackout XCOM system. Compared with the SDD detector, the CZT detector has higher detection efficiency in the 20–100 keV energy range. The photoelectric detection efficiency of the CZT detector for 50 keV X-rays can exceed 90%, while that of the SDD detector for the same energy is less than 10% [24,25]. Thus, the SNR and BER performance of the XCOM link was calculated, as shown in Fig. 6.

The results demonstrate that improvements in detective quantum efficiency yield considerable SNR at altitudes of 35–40 km. Furthermore, 50 keV is the most suitable energy of X-rays for the reentry blackout XCOM system. As illustrated in Fig. 6, the energy of a 10 keV X-ray is chosen to obtain the maximum SNR when the spacecraft reentry altitude is over 67.5 km. Here, X-ray beams with 30–50 keV and a CZT detector with high quantum efficiency could effectively improve communication performance in the lower atmosphere. Moreover, low-energy X-rays and the SDD detector system are highly suitable at altitudes above 60 km. Thus, the X-ray energy and type of detector system should be chosen according to the required communication altitude.

3.2. Analysis of different IM/DD schemes

To achieve low-error-rate communication, the SNR requirement is discussed based on the relationship between SNR and BER in Table 1.

As shown in Fig. 7, compared with OOK and DPIM modulation, PPM modulation requires a lower SNR to achieve the same error performance. Furthermore, at higher modulation levels of L, the SNR required by PPM modulation to achieve a targeted BER is significantly reduced. Hence, an appropriate modulation scheme could effectively reduce the SNR requirement of the communication system, and reduce the power requirement of the communication link. The relationship between altitude and BER in the OOK, DPIM and PPM modulation schemes could be obtained according to the BER calculation formula and the link equation.

Fig. 8 shows that the BER of the XCOM system gradually increases with decreasing altitudes. Such a result demonstrates that the performance of the communication system decreases with decreasing altitude. At the same altitude in the reentry blackout region, the BER performance of PPM modulation was much better than that of OOK modulation. Using a 50 keV X-ray energy in the low altitude area (32–37 km) can effectively reduce the BER and improve communication performance. At altitudes above 37 km, a 30 keV X-ray can be used to achieve communication performance higher than those obtained from 50 and 100 keV X-rays. Moreover, compared with the OOK and DPIM modulations, PPM modulation require less optical power to achieve the same BER performance. Therefore, PPM modulation with a high peak-to-average power ratio is the optimal choice for a reentry blackout XCOM system.

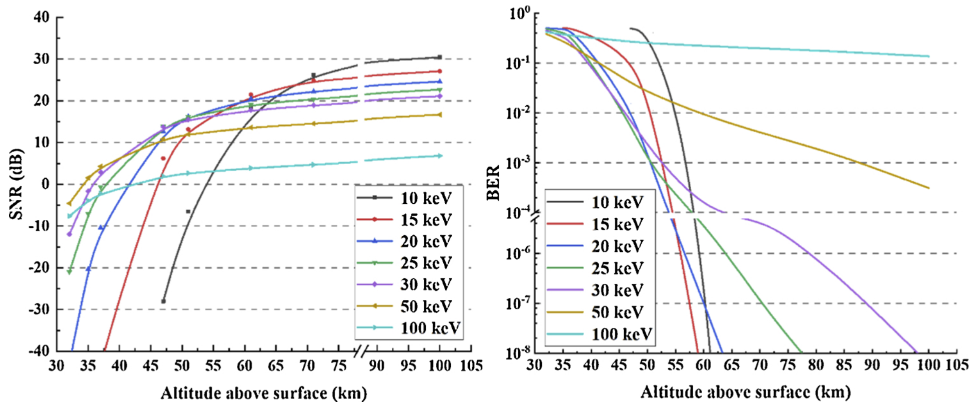

Fig. 6. (a) SNR and (b) BER of the XCOM links as a function of the spacecraft altitude with varied X-ray energies.

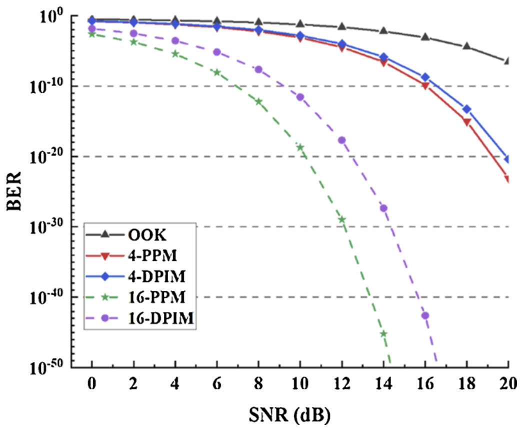

Fig. 7. BER of XCOM links as a function of SNR with different modulation methods.

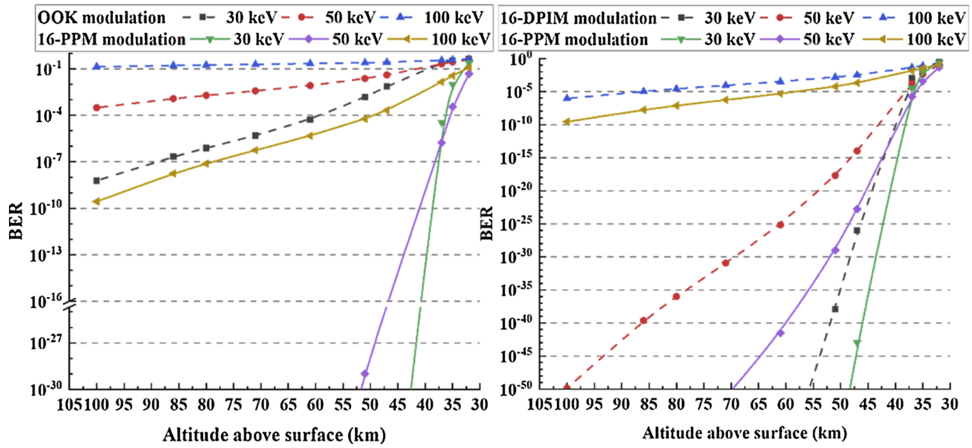

Fig. 8. BER of XCOM links as a function of altitude with varied X-ray energies under the OOK, 16-DPIM and 16-PPM modulation schemes.

3.3. Effect of transmitting power on communication performance

For a targeted BER of 10^{-6} [26], in addition to increasing the PPM modulation levels, increasing the transmitting power can also reduce the BER of reentry blackout XCOM link, as shown in Fig. 9(a). Moreover, as illustrated in Fig. 9(b), during spacecraft re-entry, when the altitude is 35 km, a communication BER of less than 10^{-6} can be achieved by using a 50 keV X-ray link with a transmitting power of 140 W.

To obtain a data rate of 1 Mbps and BER of 10^{-6}, the mathematical relationship between the minimum transmitting power and

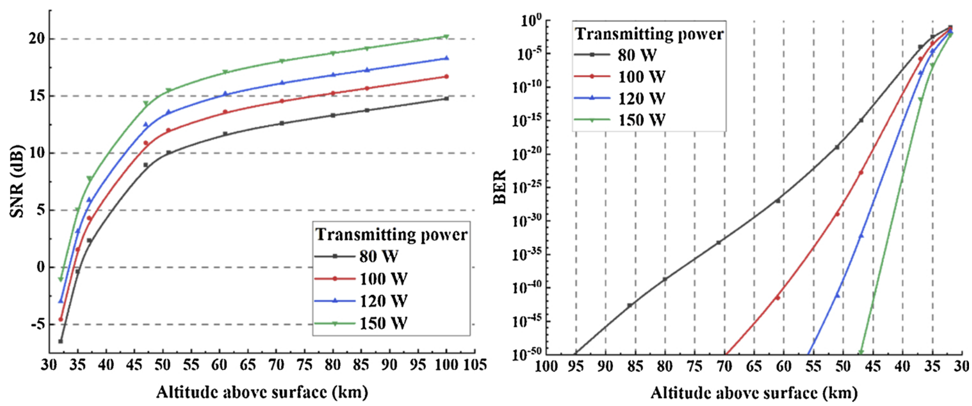

Fig. 9. (a) SNR and (b) BER of XCOM links as functions of altitude with varied transmitting powers.

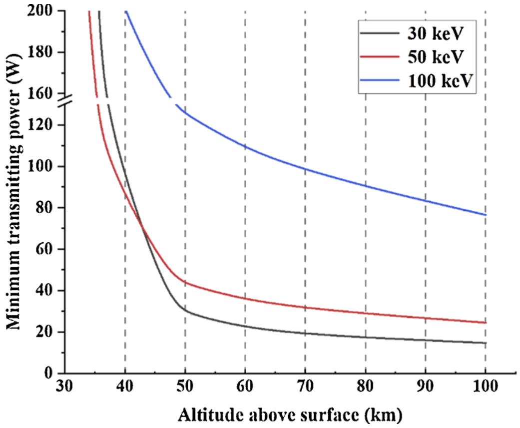

Fig. 10. Minimum transmitting powers of XCOM links as a function of altitude with varied X-ray energies.

altitude is evaluated, as shown in Fig. 10. The results demonstrate that the minimum transmitting power increases with the altitude. To achieve a data rate of 1 Mbps for a link distance of 295 km at an un-coded BER of 10^{-6}, X-ray links with energies of 30, 50, and 100 keV require transmitting powers of 203, 140, and 263 W, respectively.

4. Conclusion

As a special optical communication technology, XCOM is expected to overcome the problem of reentry blackout. This paper establishes an XCOM link model and provides a theoretical basis for the engineering of XCOM in the reentry blackout region. The transmission process of X-rays with different energies in the atmosphere were simulated by the Monte Carlo method, and a link power equation and noise model were established. The results showed that 30–50 keV is a suitable energy range for X-rays for blackout altitudes of 35–40 km and that using soft X-ray as a communication carrier in the upper atmospheric environment (over 67.5 km) could achieve a high SNR and low BER. Therefore, XCOM has optimal link energies for different blackout communication scenarios. The effect of transmitting power on communication performance was analyzed considering the types of detectors and modulation technologies available, and results indicated that PPM modulation is the optimal choice for the reentry blackout region. In addition, when the altitude is 35 km (transmission distance is 295 km), the optimal XCOM link is that with an energy of 50 keV. Under this condition, the XCOM link with a transmitting power of 140 W can achieve a data rate of 1 Mbps and BER of 10^{-6}.

Our results preliminarily provide a direction for the development of core components, such as modulation X-ray sources and X-ray detectors. However, as this study only presents a theoretical model, theoretical and experimental research must be carried out in future work.

Acknowledgements

This work was supported by the Fundamental Research Funds for the Central Universities [Grant No. NT2018017], the Special Foundation of China Postdoctoral Science Foundation [Grant No. 2018T110500], the Fundamental Research Funds for the Central Universities [Grant No. NP2018408], and the Foundation of Graduate Innovation Center in NUAA [Grant No. kfjj20180611].

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