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High penetration X-ray communication under physical shielding

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Abstract.
BACKGROUND: Modern industrial facilities urgently need effective wireless communication technology to monitor instruments and equipment, but electromagnetic interference and physical shielding often exist in these fields, thereby preventing traditional communication methods from working correctly.
OBJECTIVE: As a special wireless optical communication technology, X-ray communication (XCOM) is expected to solve the problem of signal transmission under this extreme condition. Our goal was to prove the feasibility of XCOM for signal transmission under metal barrier condition.
METHODS: The Monte Carlo method was used to simulate the transmission characteristics of X-ray beam under metal barrier conditions, and the communication performance of XCOM was evaluated. Moreover, the experimental demonstration system of XCOM was developed to test the penetration and communication performance of XCOM under metal shield.
RESULTS: X-ray with energy above 150 keV could achieve a bit error rate of less than 10^{-4} after passing through a 20 mm iron, whereas X-ray with energy above 250 keV could maintain excellent communication performance after passing through a 30 mm iron. The experimental test results were consistent with the theoretical calculation.
CONCLUSIONS: As a new wireless optical communication technology, X-ray communication is expected to solve the problem of signal transmission under physical shielding conditions.

Keywords: X-ray communication, physical shielding, transmission characteristics of X-ray, communication performance

1. Introduction

In large industrial facilities, reliable and effective wireless communication technology is urgently needed to monitor, protect, and control equipment and instruments [1]. However, in some application scenarios such as modern warship construction [2], aircraft manufacturing or high-voltage power grid deployment [3], serious electromagnetic (EM) interference will occur, due to the extensive use of EM waves in various frequency bands and the blocking, interception, transmission, reflection and scattering

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effects of multiple metal devices around them. Serious EM interference prevents the conventional radiofrequency (RF) communication systems from working correctly, thereby failing in equipment monitoring and data transmission. Moreover, on the battlefield or other extreme cases, RF system is not allowed for the purpose of preventing eavesdropping [4].

New communication methods, such as free-space-optical communication [5] and ultrasonic communication, have been proposed to eliminate EM interference. However, these methods have limitations during implementation. For example, wireless optical communication technology uses light as a carrier to transmit information, which has the advantage of being immune to EM interference and capable of communicating in a complex EM environment. However, optical photon has no penetration. Complex mechanical structures are often present in large industrial facilities; thus, constructing a completely unobstructed optical communication link is difficult. Many researchers have proposed communication method by using ultrasound [6, 7]. Although ultrasonic waves can penetrate metal walls without EM interference, the severe total reflection of ultrasonic waves at the interface between the metal and air will cause severe signal attenuation. Therefore, ultrasonic communication requires the transceivers to be in intimate contact with the metal wall, significantly limiting its application.

In 2007, Dr. Keith Gendreau, an astrophysicist at the NASA Goddard Space Flight Center, first proposed the concept of space X-ray communication (XCOM) [8]. X-ray is an EM wave with short-wavelength (0.01 - 10 nm) and high-frequency (3×10^{16} Hz - 3×10^{19} Hz). By modulating XCOM on its amplitude, phase, or frequency, the information can be transmitted by an XCOM link. In comparison with the traditional communication method, XCOM has the advantages of high theoretical data rate [9], small size, weight, and power, immunity to EM interference, and high penetration. At present, researchers in China [10-13] and the United States [14, 15] have developed the XCOM prototype and conducted experimental verification.

In comparison with the traditional communication carrier, X-ray can penetrate the metal shield, and its transmission process will not be affected by EM interference. Therefore, we innovatively propose a communication method that uses an X-ray beam as a communication carrier and penetrates a metal wall for data transmission. The schematic of XCOM in metal wall data transmission is shown in Fig. 1. In our scheme, the information to be transmitted is loaded on the X-ray carrier; the modulated X-ray beam carrying the information is free to propagate in the air; after passing through the metal shield, it is received by an X-ray receiver; and the transmitted data can be obtained by demodulation.

However, published study has no theoretical analysis or experimental research on XCOM in physical shielding. Therefore, a detailed study on this issue is necessary. In the present study, the performance of the XCOM link under metal shielding conditions is evaluated using the theoretical method. The transmission characteristics of the X-ray beam are simulated, and the XCOM verification system is developed to demonstrate the effectiveness of XCOM under physical shielding.

2. Transmission properties of X-ray in through-metal-wall communication

In the case of XCOM through the metal shield, X-ray signals need to pass through air and metal media. Therefore, we evaluated the signal intensity decay and beam divergence in the case of X-ray penetrating air and iron metal shield, and the overall transmission characteristics of X-ray in this communication scenario were obtained.

2.1. Simulation method

The Monte Carlo particle transfer program GEANT4 [16] was used to calculate the transmission characteristics of X-ray in air and metal shields. Initially, the X-ray source was set to the point that

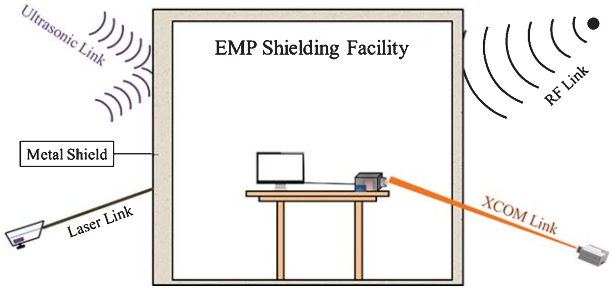

Fig. 1. Schematic of XCOM in metal wall data transmission.

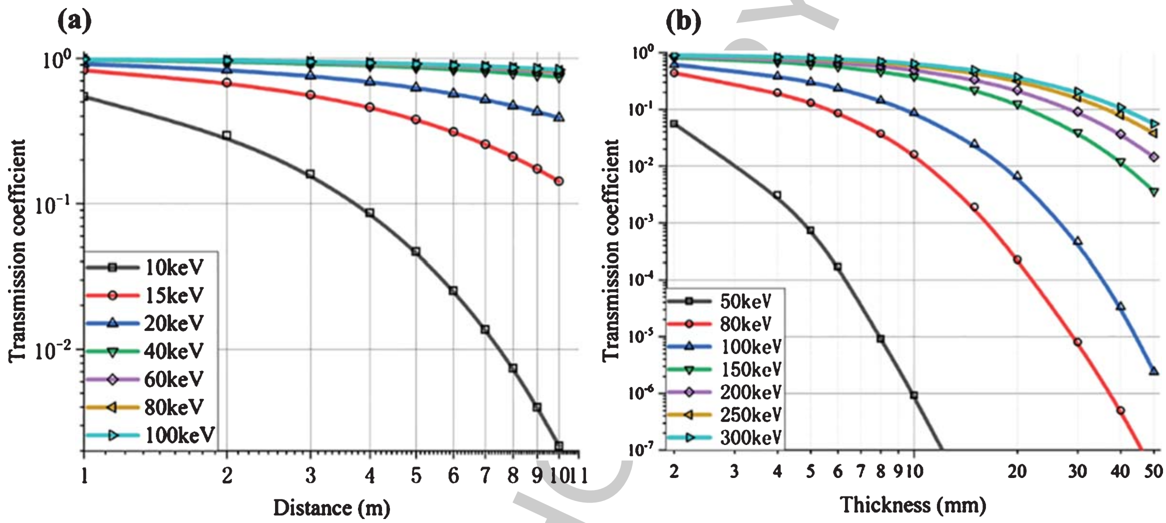

Fig. 2. Transmittance of X-ray beam after passing through the air (a) and iron metal (b).

emitted X-ray in a single direction. Then, the X-ray beam passed through a channel model consisting of air or iron metal and was recorded by the receiver. The transmission characteristics of the X-ray beam with energy from 10 keV to 300 keV were calculated. In all simulations, the number of simulated source particles was set to 1×10^8 to ensure effectiveness.

2.2. X-ray intensity decay

Figure 2 shows the calculated transmittance of X-ray after penetrating air (a) and metal (b). X-ray intensity decreases exponentially with the increase in the medium thickness. As the energy of X-ray increases, the attenuation of X-ray beams decreases gradually. As shown in Fig. 2(a), X-ray beam has a strong penetration performance in the air. The transmission coefficient of X-ray with energy above 10 keV exceeds 90% with a communication distance of 2 m. Furthermore, the X-ray beam of over 40 keV can provide a transmittance of more than 50% with a communication distance of 10 m. Figure 2(b) shows that the energy required for XCOM is high in penetrating metallic iron. X-ray with energy below 50 keV attenuates more than 40 dB after penetrating 1 cm barrier, and the communication link cannot be established. X-ray with energy above 100 keV attenuates less than 10 dB after penetrating 3 cm barrier. X-ray with energy above 200 keV can ensure that attenuation remains less than 10 dB after penetrating 3 cm barrier.

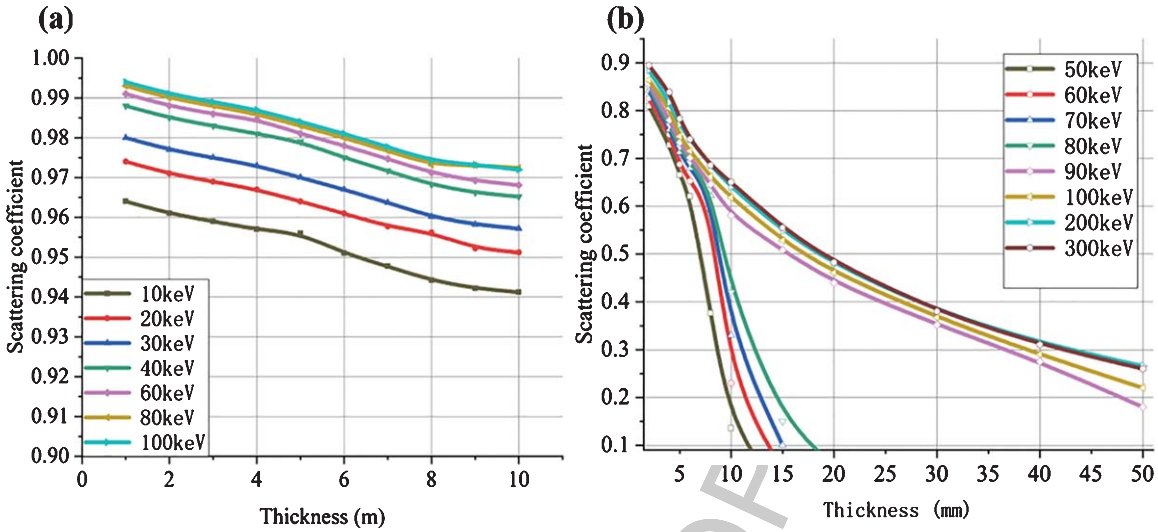

Fig. 3. Parallel X-ray beam divergence after passing through the air (a) and metal (b).

2.3. X-ray beam divergence

XCOM is a point-to-point communication mode that requires both ends of the communication link to be aligned. During transmission, the X-ray beam deposits its energy into the medium through photoelectric, Compton, or electronic pair effect. The direction of the X-ray beam may be deflected due to these interactions, resulting in signal loss. The following paragraph will discuss the divergence of the X-ray beam along the transmission path.

Figure 3 shows the divergence of the X-ray beams after passing through air (a) and metal barrier (b). The scattering coefficient in the figure means the ratio of the number of particles in the original direction to the total number of particles after the parallel X-ray beam passes through the metal barrier, which is used to indicate the degree of beam divergence. Figure 3(a) illustrates that the X-ray beam has an excellent forward property in the air. Even if the energy of X-ray is as low as 10 keV, the forward property remains over 90% after 10 m transmission, indicating that the X-ray beam can almost maintain its original path. Figure 3(b) shows the scattering of the X-ray beam through the iron barrier. After passing through the iron barrier, the direction of the X-ray beam propagating forward significantly changes. When penetrating the barrier with a thickness below 5 mm, the X-ray keeps an excellent forward property. With the increase in thickness of the barrier, the X-ray divergence becomes increasingly serious. The forwardness of the X-ray beam with energy below 100 keV decreases linearly with the increasing thickness, but it decreases exponentially with an energy of X-ray above 100 keV. The X-ray with an energy above 100 keV penetrates the 2 cm barrier and maintains the forward directional characteristics at around 50%, and it can still exceed 20% after penetrating the 5 cm iron barrier.

2.4. Total X-ray transmission characteristics through a metal wall

The signal transmission characteristics of X-ray beam in metal wall were evaluated. Figure 4(a) shows the transmission coefficients of XCOM links after passing 2 m air with different energies as a function of thickness, and Fig. 4(b) presents the total transmission coefficients of XCOM links after continuous penetration of two metal shields. Figure 4 illustrates that the attenuation coefficient of 50 keV X-ray exceeds 30 dB when the metal occlusion is over 5 mm. However, 200 keV X-ray can penetrate 20 mm metal occlusion and provide an attenuation coefficient less than 10 dB. In this case,

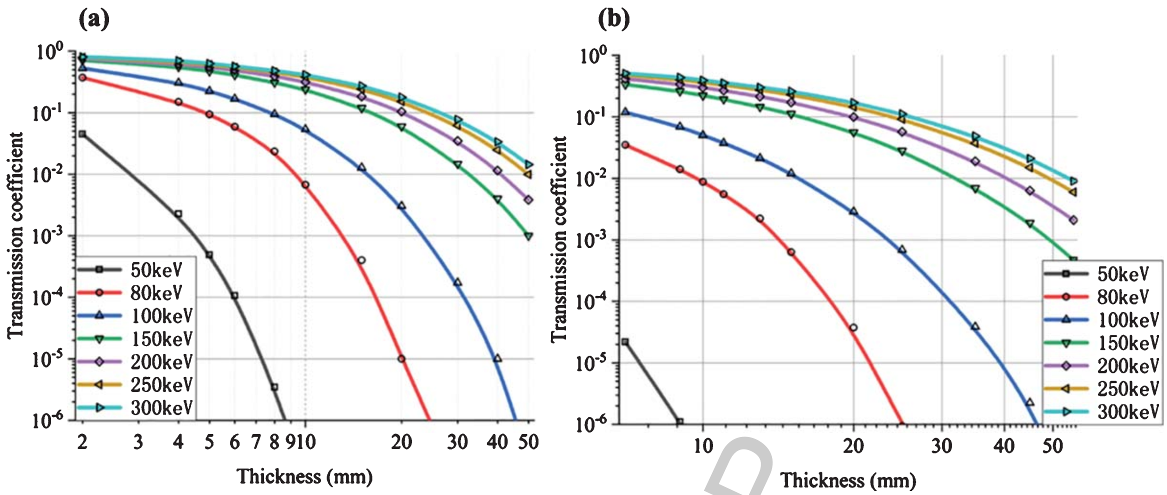

Fig. 4. (a) Total signal transmission characteristics of XCOM during metal wall transmission; (b) Total transmission coefficients of XCOM links after continuous penetration of two metal shields.

an X-ray link can be established. During penetration of the metal wall, the absorption caused by the interaction with the barrier is the main cause of the X-ray beam's intensity decay.

3. Communication performance evaluation

3.1. Evaluation method

Due to the limitations of existing X-ray generation methods, XCOM cannot be modulated with frequency and phase. Therefore, intensity modulation direct detection (IM/DD) is the main modulation method of XCOM. In the existing X-ray communication system, the binary signal "0" or "1" is loaded into the gate potential of the X-ray tube through the modulator, and the ON/OFF of the electron beam in the X-ray tube is controlled by the level of the gate potential. The resulting pulsed electron beam is targeted to generate a pulsed X-ray beam with information; at the receiving end, the X-ray detector receives the X-ray and converts the detected X-ray pulse signal into an electrical pulse signal. The information transmitted is obtained after demodulation.

In this section, the communication performance of XCOM under metal shielding was evaluated based on intensity modulation/direct detection (IM/DD) communication system and on-off keying (OOK) modulation method.

Communication performance was represented by two parameters, signal-to-noise ratio (SNR) and bit error rate (BER). SNR is the ratio of received signal strength to noise strength, and BER is the number of erroneous bits divided by the number of transmitted bits in a given time.

SNR and BER of XCOM links were calculated by considering attenuation of signal intensity and divergence caused by the atmosphere and metal shield. The SNR value can be determined by Equation (1) [17, 18]:

$$\mathrm{SNR} = \frac{M^2\,(\eta e/h\upsilon)^2\,P_R^2}{\langle i_{SN}^2\rangle + \langle i_{JN}^2\rangle} \cdot \frac{B}{V} \tag{1}$$

The BER under OOK modulation can be determined by Equation (2):

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\frac{\sqrt{\mathrm{SNR}}}{2\sqrt{2}}\right) \tag{2}$$

where M is the gain of the detector, e is the electronic charge, η is the detection efficiency of the detector, h is the Planck constant, ν is the carrier frequency, P_R is the receiving power, B is the bandwidth of the detector, V is the communication rate, $\langle i_{SN}^2\rangle$ is the excitation noise, and $\langle i_{JN}^2\rangle$ is the thermal noise.

The excitation and thermal noises can be determined by Equations (3)–(4) [19, 20]:

$$\langle i_{SN}^2\rangle = 2eFM^2(\eta e P_R/h\upsilon + i_D)B \tag{3}$$

$$\langle i_{JN}^2\rangle = 4kTB/R_L \tag{4}$$

where F is the noise figure, i_D is the dark current, T is the noise temperature, K is the Boltzmann constant, and R_L is the receiving impedance. Receiving power P_R can be determined by transmitting power P_T and transmission coefficient τ by Equation (5):

$$P_R = P_T\tau \tag{5}$$

In this simulation, the detector gain M is 1, bandwidth B is 10^6 Hz, η is 0.9, V is 1 Mbps, F is 0.9, i_D is 0.1 nA, and T is 300 K [21].

3.2. *Results and discussion*

Figure 5 displays the SNR and BER values of XCOM links through iron metal shields. The thickness of the metal shield that XCOM can penetrate increases with the increase in energy of X-ray while maintaining specific communication performance. When the energy is less than 50 keV, the SNR of XCOM is very low and XCOM is always in a high-BER state due to the attenuation of X-ray link by the metal shields, and the communication link cannot be established. After passing through 20 mm iron barrier, X-ray links with energies above 150 keV can achieve the BER below 10^{-4}. However, to penetrate a 30 mm metal wall, X-ray links with energies above 250 keV are necessary. Moreover, a BER valley of XCOM will exist with the increase in X-ray energy. This phenomenon is mainly caused by the link transmittance increases and detector detection efficiency decreases with the increase in link energy. With the increase in X-ray energy at the same transmitting power, the overall penetration capability of the X-ray beam is improved. However, the responsiveness of the detector and the number of useful photons in the communication link are reduced. The combination of these factors leads to the SNR rising and then decreasing as the X-ray energy increases, causing the BER to drop first and then rise, which leads to the change of communication performance. Thus, the optimal value of the carrier frequency required for XCOM can be found in a particular communication scenario.

4. XCOM experiment verification

4.1. *Construction of XCOM verification system*

An XCOM verification system was developed to verify the feasibility of XCOM under metal shielding conditions. The schematic diagram of the system is shown in Fig. 6. This system mainly included signal-sending and signal-receiving modules. The signal-sending module was composed of a radioisotope, signal loader, and driving circuit. The signal loader is a lead chopper driven by a stepping motor, which is used to load the digital signal onto the X-ray intensity. The radioisotope source generated a continuous X-ray beam, and the driving circuit controlled the motion of the signal loader in accordance with the modulated digital signal and loaded the digital signal onto the intensity of the X-ray.

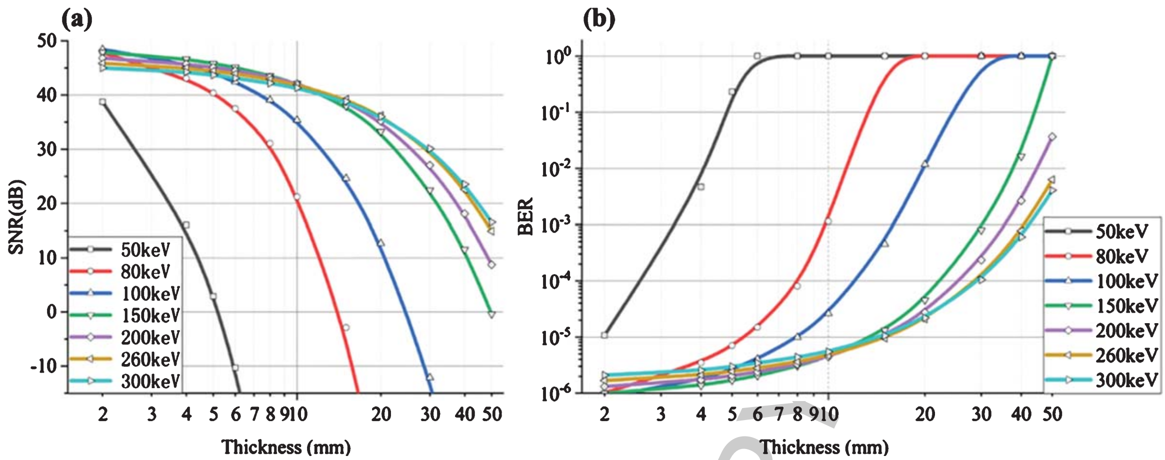

Fig. 5. SNR (a) and BER (b) of XCOM in metal wall data transmission.

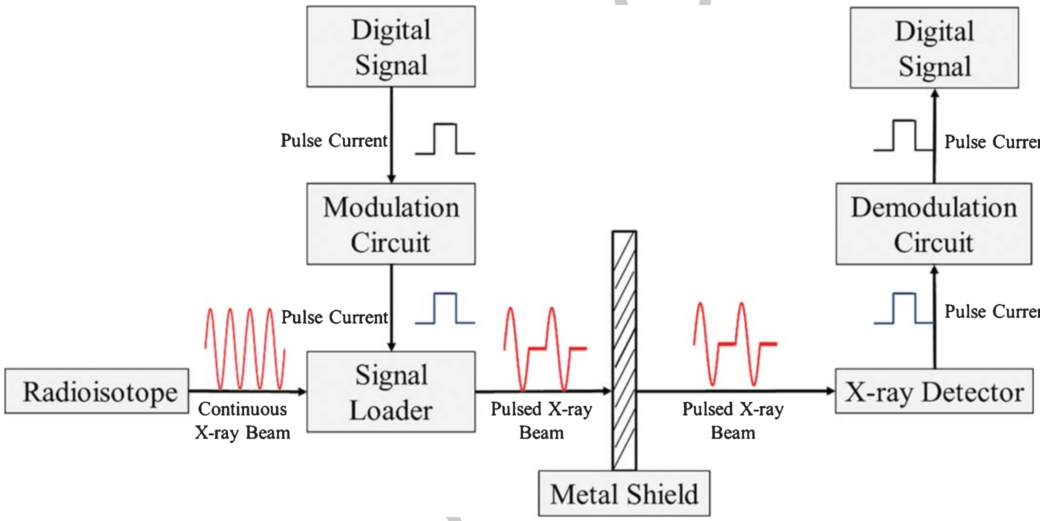

Fig. 6. Schematic of the XCOM verification system.

Therefore, a pulsed X-ray beam carrying information was generated, which passed through the metal shield and was received by the signal-receiving module. The signal-receiving module was composed of an X-ray detector (CZT detector) and a data acquisition circuit. The detector received the pulsed X-ray beams and converted them into an electrical pulse signal. The electrical pulse signal entered the data acquisition circuit and generated a digital signal after signal sampling and analog-to-digital conversion. The transmission information was then restored by signal demodulation.

The radioisotopes ^{241}Am and ^{57}Co were used to verify the X-ray penetration performance in the metal wall, and the BER value in different conditions was tested.

4.2. Experimental test of XCOM BER

The communication performance of XCOM was tested using the XCOM demonstration verification system, and the experimental and theoretical BER results are shown in Table 1.

Table 1
Theoretical and experimental BER of XCOM

Thickness /mm	59.5 keV X-ray		122 keV X-ray	
	Experimental BER level	Theoretical BER level	Experimental BER level	Theoretical BER level
2	3.75×10^{-4}	1.40×10^{-4}	2.00×10^{-4}	2.63×10^{-5}
3	4.30×10^{-3}	1.09×10^{-3}	2.25×10^{-4}	3.71×10^{-5}
4	1.83×10^{-2}	9.24×10^{-3}	3.50×10^{-4}	5.29×10^{-5}
5	9.52×10^{-2}	9.52×10^{-2}	3.75×10^{-4}	7.60×10^{-5}
6	2.16×10^{-1}	1.34×10^{-1}	4.00×10^{-4}	1.10×10^{-4}
7	3.72×10^{-1}	3.23×10^{-1}	6.00×10^{-4}	1.60×10^{-4}
8	4.93×10^{-1}	4.19×10^{-1}	9.50×10^{-4}	2.34×10^{-4}
9	5.02×10^{-1}	5.00×10^{-1}	1.00×10^{-3}	3.45×10^{-4}
10	5.00×10^{-1}	5.00×10^{-1}	2.03×10^{-3}	5.10×10^{-4}
11			3.10×10^{-3}	7.53×10^{-4}
12			4.78×10^{-3}	1.13×10^{-3}
13			6.03×10^{-3}	1.69×10^{-3}
14			9.58×10^{-3}	2.54×10^{-3}
15			1.50×10^{-2}	3.87×10^{-3}

Experimental results demonstrate that the BER level of the XCOM system is consistent with the theoretical calculation. The BER increases with the increase of the thickness of the shielding layer, and in the scope of this experiment, under the same experimental conditions, the BER of 122 keV X-ray is always lower than that of 59.5 keV X-ray. When the energy of the X-ray is 59.5 keV, due to the severe attenuation and divergence, the XCOM link can only maintain a high BER of the order of 10^{-4} to 10^{-1} when penetrating a thin metal shield. When the thickness of the barrier exceeds 3 mm, the BER of the XCOM exceeds 10^{-3}, so communication cannot be achieved. When the energy of the X-ray reaches 122 keV, the communication performance of the XCOM link is greatly improved, and the XCOM link can maintain a BER of about 10-3 when penetrating the 1 cm metal shield to meet the communication requirements.

The experimental results show that the BER of the XCOM system could be less than 10^{-4} by selecting X-ray with appropriate energy as a communication carrier under the specific thickness of the metal shield, which satisfies the basic communication requirements. The results demonstrate the potential application of XCOM through metal shields.

5. Discussion and conclusion

XCOM is a new communication mode, which is characterized by using X-ray as communication carrier to realize wireless communication under physical shielding. Compared with other communication methods, X-ray has good penetration and high theoretical communication rate, which is expected to provide a new and effective method for solving the problem of signal transmission under physical shielding.

This study preliminary demonstrated the feasibility of X-ray signal transmission under physical shielding conditions through simulation calculation and experimental verification. The Monte Carlo method was used to simulate the propagation of the X-ray beam under metal occlusion, and the transmittance of different X-ray energies was obtained. Moreover, the SNR and BER values of XCOM links were evaluated on the basis of the transmission characteristics of X-ray. Results indicated that

X-ray with energies above 150 keV could achieve a BER of less than 10^{-4} after passing through a 20 mm metal shield, whereas X-ray with energy above 250 keV could maintain excellent communication performance after passing through a 30 mm metal shield. An XCOM experimental demonstration system was developed to test the communication performance of 59.5 and 122 keV X-ray communication under metal occlusion. Experimental results were consistent with the theoretical calculation level, which confirmed the feasibility of XCOM for signal transmission under physical shielding conditions.

The results of this study provide a new method for achieving data transmission through the metal wall. However, this research is only a preliminary study of XCOM in through-metal-wall data transmission. Further theoretical and experimental studies will be conducted in our future work.

Acknowledgments

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