IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 29 November 2023, accepted 27 December 2023, date of publication 3 January 2024, date of current version 10 January 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3349475

RESEARCH ARTICLE

Code-Division Space-Time Fountain Code for Plasma Sheath Communication

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This work was supported in part by the National Natural Science Foundation of China under Grant 62101591.

ABSTRACT Influenced by the special physical characteristics of the plasma sheath and the parameters of the aircraft's attitude, the channel containing the plasma sheath can be regarded as a special kind of discontinuous channel. A code-division space-time fountain code form is proposed that is suitable for the spatial characteristics of the plasma sheath channel. Simulation results show that the use of code-division space-time fountain code maximizes the use of the airspace resources in the plasma sheath channel. The scheme proposed in this paper can be used to alleviate the "ionization blackout" problem faced by hypersonic vehicles in the reentry process.

INDEX TERMS Plasma sheath, spatial-domain resource, communication window, fountain code, interleaved code.

I. INTRODUCTION

The research of hypersonic vehicles has gained attention in recent years as the world's military powers continue to deepen their research on near space. As an important carrier for the development and utilization of near space, hypersonic vehicle has the advantages of fast flight speed, rapid orbit change and rapid global arrival. However, when the speed of the aircraft exceeds Mach 10, the "ionization blackout" problem it faces cannot be overlooked [1], [2], [3]. The "ionization blackout" problem is caused by the plasma sheath on the surface of the aircraft [1], [4]. The plasma sheath become an obstacle to the communications of the aircraft and the ground control station, seriously affecting the flight safety of the aircraft.

During the flight of the aircraft, there are windward and leeward sides. The difference in the degree of friction with the surrounding air leads to a large difference in the electron density distribution of the plasma sheath on the two surfaces, and the electron density of the plasma sheath on the leeward side is significantly lower than that on the windward side. The plasma sheath is a dynamic time-varying, dispersive and lossy medium [4], [5], [6]. Research has found that changes in the flight attitude and other parameters of the aircraft will lead to the exchange of the positions of the windward and leeward sides, which in turn causes the parameters of the plasma sheath to change dynamically at different frequencies. Figure 1 shows the curve of plasma electron density and signal amplitude over time, with the X-axis representing time. T_1– T_3 represent the time intervals where the electron density of the plasma on the surface is reduced due to the change of aircraft attitude, respectively. In these time periods, the effect of the plasma sheath on electromagnetic waves is weakened.Therefore, it can be considered that the change of aircraft attitude will cause some "communicable windows" to appear alternately on the windward and leeward sides.

The change of the flight attitude of hypersonic aircraft leads to the complex variability of the plasma sheath on its surface in both airspace and time domain. Literature [7] and Literature [8] designed "Adaptive Classification Fountain Code" and "Short-frame Fountain Code" in the time domain for the large-scale and meso-scale characteristics of the plasma sheath, respectively. However, the spatial variation of the plasma sheath will limit the performance of the time-domain adaptive communication method proposed in the above literatures. Using the combination of time-domain adaptive coding and spatial-domain coding, based on the conventional measurement and control communication method, this paper proposes a code-division space-time fountain code to make full use of the channel's spatial-domain resources and

The associate editor coordinating the review of this manuscript and approving it for publication was Jenny Mahoney.

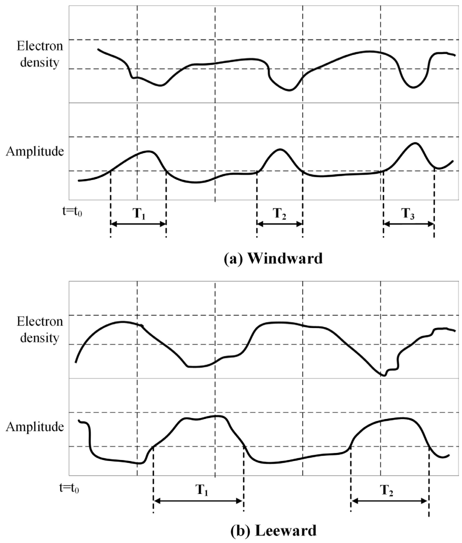

FIGURE 1. Relationship between plasma electron density and transmitted electromagnetic wave amplitude on windward and leeward sides.

alleviate the "communication difficulty" problem faced by hypersonic aircraft.

The remainder of the paper is organized as follows. Section II analyzes the overall design idea of code-division space-time fountain code. Sections III establishes a transmission model of code-division space-time fountain code in the dynamic plasma sheath channel, and verifies the feasibility of the proposed method through simulation. Discussions and conclusions are presented in Section IV.

II. THEORETICAL ANALYSIS

Channels containing plasma sheath (short for plasma sheath channel) can be considered as a special type of transmission link. First of all, different from Additive White Gaussian Noise (AWGN) channel, the plasma sheath channel brings the double parasitic modulation on the amplitude and phase to the signal. The degree of modulation is related to the electron density, collision frequency and sheath thickness of the plasma sheath [6], [9], [10]. Secondly, the plasma sheath channel is not a continuous channel due to the random change of the "communication windows" in the spatial domain. In addition, the deep fading and large delay effect of the plasma sheath on electromagnetic wave make it difficult for the plasma sheath channel to establish an effective feedback loop (the plasma sheath channel can be approximately considered as an unidirectional transmission link). Therefore, the traditional adaptive communication methods based on channel feedback cannot be directly applied to plasma sheath channel.

Summarizing the above three particularities of the plasma sheath channel, it can be considered that the plasma sheath channel is a discontinuous unidirectional transmission link. In order to further improve the communication reliability of the system by making better use of the plasma sheath channel's spatial-domain resources, the code-division space-time fountain code coding scheme shown in Figure 2 is designed in this paper.

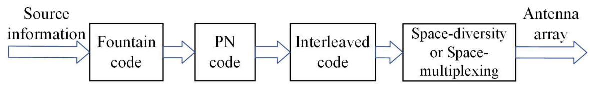

FIGURE 2. The overall coding scheme of code-division space-time fountain code.

The overall structure of code-division space-time fountain code includes space-time coding, interleaving coding, spread spectrum coding and fountain code. Fountain code is a rateless code [11], [12], [13], and its forward error-correction capability can reduce the bit error rate of the system, which can effectively deal with the problem of channel discontinuity; Interleaving coding [14], [15], [16] can maximize the use of discrete channel resources such as the "communication windows" shown in Figure 1 to transmit fragments of encoded packets, which will help improve the decoding rate of fountain codes; Although space-time coding [17] itself does not have error correction capability, it can introduce additional diversity gain or multiplexing gain, which can effectively utilize the weak leeward area of the plasma sheath for information transmission. The addition of space-time coding can effectively improve the transmission capacity of the plasma sheath channel by making full use of the airspace channel resources without increasing the spectrum resources; Spread spectrum coding [18], [19], [20] can solve the problem of no feedback loop in one-way channel transmission through code division, and it will also bring additional spread spectrum gain to the entire system.

Figure 3 shows the 4×4 channel transmission model based on code-division space-time fountain code, that is, the number of transmitting antennas and receiving antennas are both four. The transmission link mainly includes five parts: Channel sensing part, Fountain code part, Interleaving code part, Spatial code part and Pseudo code part. The position of the antenna is arranged reasonably on the windward and leeward sides based on the characteristics of the aircraft. The spatial coding part adopts the hybrid mode of spatial diversity coding and spatial multiplexing coding according to the communication conditions at different transmitting antennas, and the communication state perception adopts the Channel capacity estimation method based on VSWR [21]. This spatial hybrid encoding mode can simultaneously bring diversity gain and multiplexing gain to the link, improving the transmission reliability and channel utilization of the link.

Figure 3 shows a communication transmission system containing plasma, with four transmitting and receiving antennas. If the system adopts a traditional fixed rate transmission method, the receiving end needs to be able to correctly receive all data from the four transmitting antennas. Otherwise, the transmitting end needs to resend, which is the Automatic Repeat Request (ARQ). Based on this communication method, when designing the link communication strategy, it is necessary to consider the layout of the four transmitting antennas comprehensively to ensure

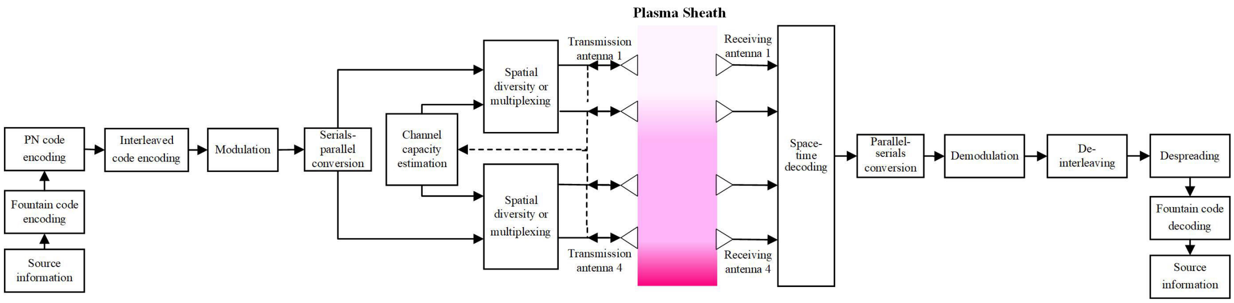

FIGURE 3. Design block diagram of Code-division space-time fountain code.

that all transmission information can be correctly received by the ground receiving end. There is a significant difference in electron density between the windward and leeward sides of the plasma sheath. On the windward side, the electron density of the plasma is relatively high, and the strong attenuation effect of the plasma on electromagnetic waves can easily cause the transmitting antenna here to not work properly. This will cause the feedback retransmission process to repeat many times, and the large delay characteristics of the plasma sheath channel lead to extremely low transmission efficiency of this feedback repeat request transmission method.

If forward error correction transmission mode is adopted, such as fountain code, the problem of low efficiency of feedback repeat request transmission method can be effectively solved. The $[x_1, x_2, x_3, x_4]$ ransmitted by the transmitting antenna correspond to the four encoded packets of the fountain code respectively. Since the receiver has no demand for the continuity of the encoded packets, the loss of any encoded packets will not affect the receiver's decoding, that is, code-division space-time fountain code can decode all information only through the encoded packets transmitted on the leeward side, without introducing a retransmission mechanism to retransmit the information on the windward side. This will improve the transmission efficiency and reliability of the plasma sheath channel, and the four transmitting antennas in Figure 3 can be designed in groups, that is, the code matrix and spatial transmission method can be designed separately for the channel characteristics of the windward and leeward sides.

III. NUMERICAL SIMULATION

This section simulates the transmission performance of code-division space-time fountain code in the plasma sheath channel through Matlab simulation software.

A. CHANNEL MODEL CONSTRUCTION

Based on the downlink communication link shown in Figure 3, we constructed the simulation model shown in Figure 4, which consists of 4 transmitting antennas and 4 receiving antennas, forming a total of 16 spatial communication channels.

Assuming that the fading between each antenna is uncorrelated, the channel transmission matrix $\mathbf{H}$ can be expressed as:

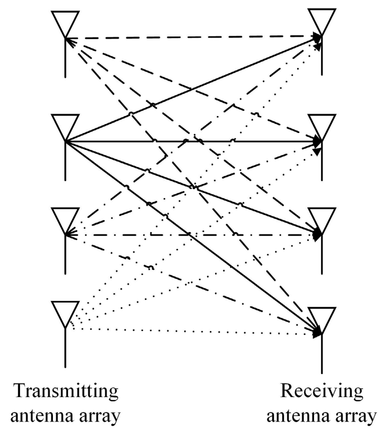

FIGURE 4. Downlink communication link of 4 × 4.

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \tag{1}$$

where h represents the fading coefficient of the channel.

According to the different characteristics of the windward and leeward sides of the aircraft, different plasma parameters are assigned to each spatial channel shown in Figure 4. The collision frequency of the plasma at the four transmitting antennas is 1 GHz, with a thickness of 80 mm and an electron density range of 1×10^{16} m^{-3}–6.7×10^{16} m^{-3}. The corresponding ratio of plasma frequency (w_p) to carrier frequency ($w = 2.5$ GHz) is 0.36–0.93. According to the theory of electromagnetic wave transmission in plasma, when w_p is approximately equal to w, most of the electromagnetic waves will be reflected on the surface of the plasma sheath, and communication transmission will be almost interrupted. Therefore, it can be considered that under this simulation condition, electron densities of 1×10^{16} m^{-3} ($w_p/w = 0.36$) and 6.7×10^{16} m^{-3} ($w_p/w = 0.93$) represent the good and poor communication states of the channel, respectively. The modulation method selected in this simulation is QPSK. The fountain code in the code-division space-time fountain code adopts LT encoding and BP decoding. The number of source information and encoded packets is 1000 and 3000, respectively, and the length of encoded packets is 130.

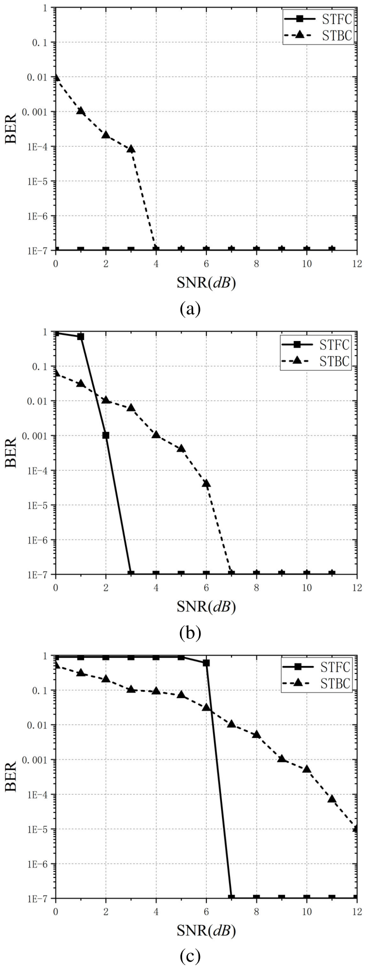

FIGURE 5. Comparison of transmission performance between STFC and STBC in plasma sheath environment: (a)Excellent channel state (b)Good channel state (c)Poor channel state.

B. SIMULATION RESULTS AND ANALYSIS

In the simulation part, we mainly simulated and compared the transmission performance of the coding methods among traditional space-time block code (STBC for short), space-time fountain code (STBC+Fountain code+Interlaced code, STFC for short) and code-division space-time fountain code (STBC+Fountain code+Interlaced code+PN code, CDSTFC for short) in the plasma sheath channel.

Figure 5 compared the transmission performance between space-time Fountain code and STBC when the four transmitting antennas are in different plasma densities. The electron densities of the plasma sheath at the four transmitting antennas in Figure 5 are:

(a) 1.0×10^{16} m^{-3}, 1.0×10^{16} m^{-3}, 1.0×10^{16} m^{-3}, 6.7×10^{16} m^{-3};

(b) 1.0×10^{16} m^{-3}, 6.7×10^{16} m^{-3}, 6.7×10^{16} m^{-3}, 6.7×10^{16} m^{-3};

(c) 6.7×10^{16} m^{-3}, 6.7×10^{16} m^{-3}, 6.7×10^{16} m^{-3}, 6.7×10^{16} m^{-3}.

The simulation results indicate that the improvement of communication conditions in each channel will increase the diversity gain of the system, thereby improving the transmission performance of the entire system. However, the performance of space-time fountain code is better than that of STBC on the whole. The use of space-time fountain code can reduce the requirements of the whole system on the signal-to-noise ratio (SNR). The simulation results in Figure 5 (b) show that the requirements of space-time fountain code on SNR are 4 dB less than those of STBC. This is mainly because the non rate characteristic of space-time fountain code can make full use of the information segments transmitted by the "communication windows" in each channel. In addition, when SNR is 0 dB, the bit error rate (BER) of space-time fountain code is higher than that of STBC. This is mainly because the number of coding packets transmitted through four channels is too small. According to the principle of BP decoding algorithm, fewer coding packets will lead to higher bit error rate.

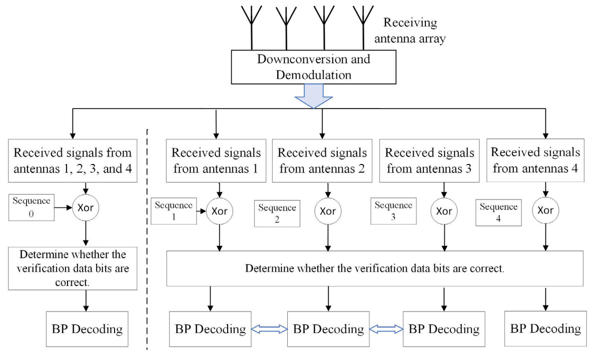

FIGURE 6. Schematic diagram of spatial transmission mode discrimination.

The code-division space-time fountain code contains PN code. When using spatial diversity or spatial multiplexing for transmission, the four transmission channels choose the same and different PN codes accordingly. By selecting the corresponding PN code at the receiving end, each channel can be decoded, as shown in Figure 6. The receiving end prioritizes using the PN code corresponding to spatial diversity for decoding. If decoding fails or data verification errors occur, the PN code corresponding to spatial multiplexing is used for decoding. Through this method, the receiving end can automatically recognize the transmission mode and decode. In addition, the addition of PN code will bring additional spread spectrum gain (G_{PN}) to the system. Figure 7 shows the transmission effect of the space-time fountain code superimposed on the PN code with chip period of 31 bits.It can be seen that the addition of PN code will further improve the transmission performance of the space-time fountain code in the plasma sheath channel.

$$G_{PN} = 10\lg(M) \tag{2}$$

where M is the chip period of the PN code.

However, PN code brings spread spectrum gain while reducing the transmission rate of information. Equation (3) represents the equivalent transmission rate (r_{eq}) of informa-

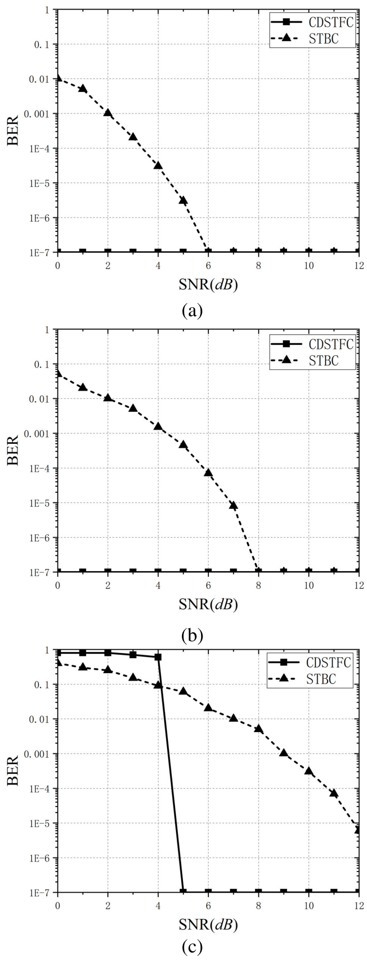

FIGURE 7. **Comparison of transmission performance between CDSTFC and STBC in plasma sheath environment: (a)Excellent channel state (b)Good channel state (c)Poor channel state.**

tion after adding PN code.

$$r_{eq} = \frac{R}{M} \tag{3}$$

where R is the original transmission rate of the system.

Although the addition of PN code will reduce the transmission rate of the whole code-division space-time fountain code, it can improve the transmission reliability of some key information, which can not be achieved only by traditional reduction of transmission rate. In Figure 7 (b), when SNR=2, if only STBC is used, BER ≈ 0.01, then the information received by the receiver is no longer available. If code-division space-time fountain code is adopted, although the transmission rate of information is reduced by 31 times, the BER of information is less than 10^{-7}, which means that the communication is uninterrupted. At this point, it is possible to consider using information classification to ensure reliable transmission of critical information at normal rates by sacrificing the transmission probability of unimportant information, which can effectively delay the arrival of the ''ionization blackout''.

The plasma sheath has a strong attenuation effect on electromagnetic waves, and the strong random multiplicative interference introduced by the comprehensive channel of hypersonic aircraft can also lead to a decrease in the SNR of the received signal. In order to make full use of the spatial resources of the plasma channel, we need to adjust the parameters of the code-division space-time fountain code according to the change of SNR, and comprehensively consider the reliability and transmission rate of the channel. The code-division space-time fountain code used in this simulation is mainly divided into two coding forms: orthogonal code-division space-time fountain code (FP-STBC) and quasi orthogonal code-division space-time fountain code (FP-QSTBC)

FP-STBC:

$$X_4 = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & -x_2 \\ -x_4 & -x_3 & x_2 & x_1 \\ x_1^* & x_2^* & x_3^* & x_4^* \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & x_4^* & x_1^* & -x_2^* \\ -x_4^* & -x_3^* & x_2^* & x_1^* \end{bmatrix} \tag{4}$$

FP-QSTBC:

$$X_4 = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2^* & x_1^* & -x_4^* & x_3^* \end{bmatrix} \tag{5}$$

The transmission rates of FP-STBC and FP-QSTBC are:

$$R_{FP-STBC} = {}^{1}\!/_{2} \tag{6}$$

$$R_{FP-QSTBC} = 2 \tag{7}$$

Figure 8 mainly compares the performance of STBC, QSTBC, FP-STBC and FP-QSTBC in the plasma sheath transmission environment. It can be seen that the particularity of the plasma sheath channel leads to poor transmission performance of both STBC and QSTBC. STBC can communicate normally at SNR = 11 dB, while QSTBC needs to communicate normally at SNR = 12 dB. This is mainly because the orthogonality of STBC encoding method is better than QSTBC, which can obtain more diversity gain. The transmission performance of FP-STBC and FP-QSTBC is better than that of STBC and QSTBC, which indicates that code-division space-time fountain code can better utilize the spatial channel resources of the plasma sheath channel. When SNR<4 dB, FP-STBC can ensure the normal transmission of the link by virtue of more diversity gain and forward error correction capability of fountain code. FP-QSTBC sacrifices part of diversity gain due to weakening the orthogonality between channels, resulting in high bit error rate. Therefore, based on the performance of the four encoding forms STBC, QSTBC, FP-STBC, and FP-QSTBC in the plasma sheath transmission environment, it can be concluded that:

When SNR<4 dB, the code-division space-time fountain code can adopt the encoding form of FP-STBC, and the system ensures the reliability of link communication by maximizing diversity gain. When SNR≥4 dB, both FP-STBC and FP-QSTBC can ensure reliable information transmission.

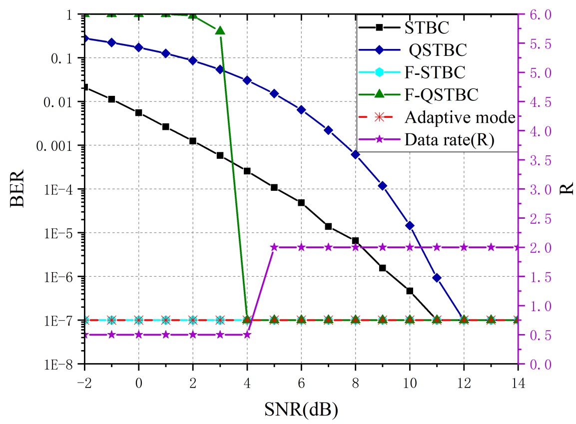

FIGURE 8. Performance Comparison of STBC, QSTBC, FP STBC, and FP QSTBC in Plasma Sheath Environment.

However, due to $R_{FP-QSTBC} > R_{FP-STBC}$, when SNR≥4 dB, F-QSTBC is chosen as the encoding form for code-division space-time fountain code. At this time, code-division space-time fountain code fight for the maximization of transmission rate while ensuring link communication reliability.

IV. CONCLUSION

The rate free characteristic of code-division space-time fountain code can better adapt to the random variation of ''communication windows'' in the plasma sheath channel; Secondly, the diversity gain and multiplexing gain provided by code-division space-time fountain code can give better consideration to the reliability and efficiency of plasma channel transmission; In addition, due to the large transmission delay of the plasma sheath channel and the inability to establish an effective feedback loop, the code-division space-time fountain code can realize the adaptive switching of diversity and multiplexing transmission modes in the one-way downlink transmission link through PN code. The code-division space-time fountain code makes full use of the ''communication windows'' of the plasma sheath channel in the space-time domain, which can effectively delay the arrival of ''ionization blackout'' in the plasma sheath channel.

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