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Adaptive Classification Fountain Codes for Reentry Communication

HAOJIE ZHANG, WEIMIN BAO, MIN YANG, XIAOPING LI, AND YANMING LIU
School of Aerospace Science and Technology, Xidian University, Xi'an 710071, China

Corresponding author: Min Yang (myang@xidian.edu.cn)

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ABSTRACT Radio blackout due to a plasma sheath during reentry has attracted much attention over several decades. However, radio blackout has long puzzled the aerospace industry and has not yet been completely resolved. A communication method based on adaptive classification fountain code is proposed to improve the transmission reliability of important information during a spacecraft's reentry. According to the deterioration of the plasma sheath channel, the classification parameters of the source information are adjusted to protect the most important information. This method allows the reliable transmission of the most important information. The deterioration of the communication quality of the plasma sheath channel is detected from the voltage standing wave ratio of the transmitting antenna in real time. The simulation results show that the transmission reliability of important information almost doubles when using the transmission method of adaptive classification fountain code. In contrast to the traditional communication method, the proposed method can be applied to TT&C (telemetry, tracking, and command) and communication of reentry vehicles and near-space hypersonic vehicles in the future, reducing the interruption time of communication blackout.

INDEX TERMS Fountain codes, classification, plasma sheath, voltage standing wave ratio, bit error rate.

I. INTRODUCTION

A layer of plasma surrounds a reentry vehicle when it travels at a speed of more than Mach 10 in near space (i.e., altitudes of 20–100 km). This is due to the tremendous heat generated by air compressing around the aircraft. Communication is seriously deteriorated by the electromagnetic shielding effect of the plasma sheath, and the communication link is thus interrupted by the plasma sheath in what is called radio blackout [1].

Scholars have conducted much research to solve the problem of radio blackout. Early studies mainly focused on manipulating the distribution or physical characteristics of the plasma sheath, including employing aerodynamic shaping [2], liquid quenchant injection [3], resonant transmission [4], an inflatable aeroshell [5], and electromagnetic windowing [6]; see [8] for a good summary. In recent years, some researchers began to focus on the changes of communication mode in plasma sheath, such as X-ray [9] communication and Terahertz communication [10]. Many related studies show that increasing the communication frequency is an effective way to improve the reliability of information transmission [11], but higher frequencies are more subject to atmospheric and rain influence.

Recent studies indicated that different communication methods based on channel state information are effective. One study [12] proposed a method of adaptively adjusting the data rate according to information of the channel state. The voltage standing wave ratio (VSWR) of the antenna can provide real-time feedback of the channel state [12]. On the basis of changes in the channel state, the spread spectrum gain is improved by reducing the transmission rate; however, a lower transmission rate leads to a waste of the channel. The time-varying transmission rate and information classification coding technology can improve the transmission reliability of high-priority data.

The original communication system assumes that the coded information symbols are equally important. However, some source symbols are more important than others owing to different information update rates or importance factors in

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many applications. Additionally, these source symbols need to be recovered prior to the rest. Unequal error protection (UEP) designs are attractive solutions for such source transmissions. The fountain code can be used for the UEP of data. Rahnavard proposed a weighted UEP Luby transform (LT) code [13], but the code is only weighted to protect different levels of data and an improvement in the degree distribution function is not thoroughly considered, which seriously increases the quantity of code in the implementation. The expanded window fountain code [14] uses a degree distribution function in the same window instead of various degree distribution functions. This code seriously deteriorates the transmission performance of low-priority information. Literature [15] proposes a scheme of real-time adjustment of the degree distribution function by channel feedback. This method can effectively improve the gain of communication system, but this method is not suitable for unidirectional link such as plasma sheath. Moreover, this scheme only uses the robust soliton distribution function, which may have some problems when the channel environment is deep fading.

The present paper proposes a method of adaptive classification fountain codes that combines Information classification, Mixed degree distribution and Extended window (i.e., the IMW). At its core, our encoder implements UEP for source information through mixed degree distribution and extended window that is dynamically adjusted based on estimated channel capacity of plasma sheath. Figure 1 depicts a schematic of our three-step encoder. The change in the channel state of the plasma sheath is first detected through the antenna's VSWR, the fountain code classification strategy and the parameters of mixed degree distribution are then adjusted automatically. By adjusting the weight of the important information in the classification strategy, the important information is obtained with an additional encoding gain to overcome the attenuation due to the plasma sheath. This method improves the transmission reliability of important information.

The remainder of the paper is organized as follows. Section II illustrates the overall framework of the proposed method, including the theoretical analysis of the real-time estimation of the state of the plasma channel and the adaptive information classification coding technology. Section III presents a simulation that verifies the feasibility of the proposed method. A detailed discussion, conclusion, and possible extensions are presented in Section IV.

II. THEORETICAL ANALYSIS

Considering the particularity of reentry communication, this paper proposes a channel estimation method that realizes adaptive communication with IMW parameters that are adjusted in real time according to the real-time estimation results of the channel state. Figure 2 shows the adaptive channel classification coding system. The new system has two main improvements compared with the traditional communication system: the real-time channel estimation module based on real-time VSWR monitoring (involving a directional coupler, VSWR measurement, and channel capacity estimation) and IMW modular.

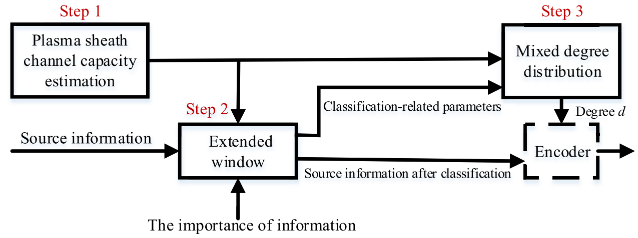

FIGURE 1. Three steps of adaptive classification coding for fountain codes.

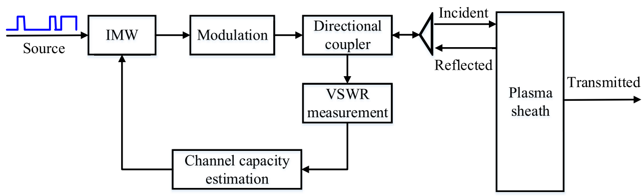

FIGURE 2. Overall block diagram of the adaptive channel classification coding system.

First, the VSWR of the antenna is measured in real time and the channel capacity is then estimated in real time according to the correlation between the VSWR and channel capacity. Second, the channel is classified into one of three grades according to the channel capacity: excellent, good or poor. Third, IMW modular is dynamically adjusted at different channel levels to ensure the transmission reliability of important information. The two improved modules of the system are introduced in the following sections.

A. REAL-TIME CHANNEL ESTIMATION

Plasma is neutral ionization gas composited by positive ions, free electrons and neutral atoms and can be viewed as a dispersing medium in radiowave propagation. The relative dielectric constant of plasma is expressed as [16]

$$\varepsilon_r = 1 - \frac{w_p^2}{w_0^2 + v_{en}^2} - j\frac{v_{en}}{w_0}\frac{w_p^2}{w_o^2 + v_{en}^2} \tag{1}$$

where w_p is the plasma frequency, w_0 is the carrier wave frequency, and v_{en} is the collision frequency.

The plasma frequency w_p is a function of the electron density in the plasma [17], [18]

$$w_p = \sqrt{\frac{n_e q_e^2}{\varepsilon_0 m_e}} \tag{2}$$

where n_e is the electron density, q_e is the electron charge, ε_0 is the dielectric constant for a vacuum, and m_e is the electron mass.

The propagation vector can be expressed as [12]

$$k = \frac{w_0}{c}\sqrt{\varepsilon_r} = \beta - j\alpha. \tag{3}$$

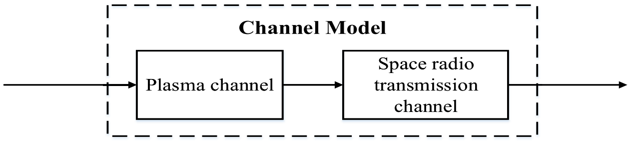

FIGURE 3. **Channel model of the reentry channel.**

In the case of nonmagnetic plasma, the attenuation coefficient (α) and phase-shift coefficient (β) can be simplified as [12] (4) and (5), as shown at the bottom of the this page.

The above equations show that compared with the case for traditional channels, the plasma sheath can introduce an extra amplitude attenuation and phase shift to the electromagnetic wave, which is directly related to the electron density distribution of the plasma sheath. For the purpose of analysis, the reentry channel can be divided into two parts, namely a plasma channel and space radio transmission channel [24], as shown in Figure 3.

Suppose that a plane electromagnetic wave is incident on an infinite uniform plasma plane with thickness d. The difference in wave impedance between the different media likely leads to the reflection and transmission of the electromagnetic wave.

The reflection coefficient Γ is directly related to the VSWR [9]

$$VSWR = \frac{1+\Gamma}{1-\Gamma} \tag{6}$$

According to Shannon's theorem and the description of channel capacity C in the literature [18], the relationship between C and the transmission coefficient T can be expressed as

$$C = B\log_2\left(1+\frac{TP_t-\tau}{BN_0}\right) \tag{7}$$

where N_0 is the power spectrum of the additive white Gaussian noise, P_t is the power of the transmitter, B is the bandwidth of the additive white Gaussian noise, and τ is the energy loss of free space.

The literature [12] points out that there is negative correlation between Γ and T. According to formulas (6) and (7), we use typical telemetry link parameters in the literature [24] to simulate the correlation between C and $VSWR$. Simulation results are shown in Figure 4. C decreases as $VSWR$ increases. For example, when $VSWR$ is 1.84, the corresponding C is 625 Kbps, and when $VSWR$ is increased to 3.14, C is reduced to 312 Kbps.

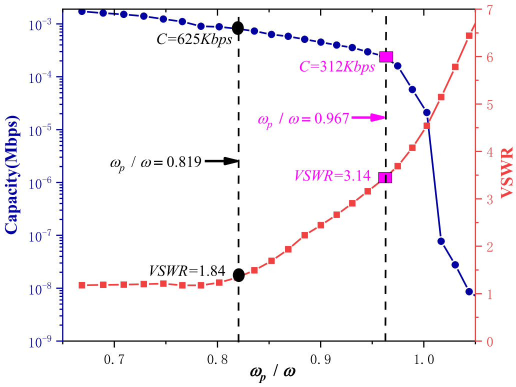

FIGURE 4. **Correlation between the channel capacity and VSWR under different ω_p/ω.**

Simulation results show that $VSWR$ has a negative correlation with C. Therefore, C can be estimated in real time by measuring the changes in $VSWR$ without increasing additional feedback channels in advance.

B. ADAPTIVE CLASSIFICATION ENCODING

The channel real-time estimation module provides a priori knowledge for adaptive classification coding. We can adjust variables of the fountain coding strategy, such as the number of information priorities and the ratio of each degree distribution function in the mixed degree distribution function, according to the channel estimation result. The overall framework of the model is shown in Figure 5.

First, according to the transmitting antenna's real-time VSWR, the communication quality of the plasma channel can be divided into several levels. Considering the feasibility and practicality under the plasma sheath channel environment, we suggest that the communication quality of the plasma channel can be divided into three levels: excellent, good and poor.

Second, for different channel levels (i.e., different levels of communication quality), the source information is divided into several priorities according to its importance. For example, the source information content is transmitted at a single priority when the channel level is excellent, two priorities when the channel level is good, and three priorities when the channel level is poor. The number of information priorities is dynamically adjusted according to the channel level estimated from the VSWR of the transmitting antenna.

$$\alpha = \frac{w_0}{\sqrt{2}c}\sqrt{\frac{w_p^2}{w_0^2+v_{en}^2}-1+\sqrt{\left(1-\frac{w_p^2}{w_0^2+v_{en}^2}\right)+\left(\frac{v_{en}}{w_0}\frac{w_p^2}{w_0^2+v_{en}^2}\right)^2}} \tag{4}$$

$$\beta = \frac{w_0}{\sqrt{2}c}\sqrt{1-\frac{w_p^2}{w_0^2+v_{en}^2}+\sqrt{\left(1-\frac{w_p^2}{w_0^2+v_{en}^2}\right)+\left(\frac{v_{en}}{w_0}\frac{w_p^2}{w_0^2+v_{en}^2}\right)^2}} \tag{5}$$

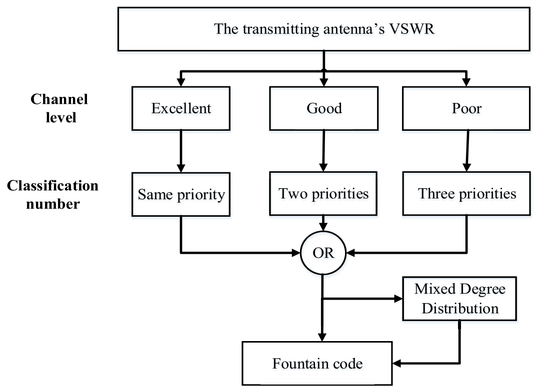

FIGURE 5. Diagram of adaptive classification encoding.

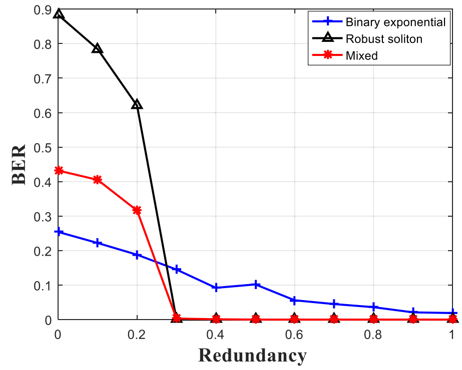

FIGURE 6. BER versus redundancy for different degree distribution functions (a=0.4, b=0.6).

Third, the parameters of the mixed degree distribution and fountain code are dynamically adjusted according to the prioritization of source information, and the source information is then encoded using LT code.

1) MIXED DEGREE DISTRIBUTION

The attenuation and phase shift of the electromagnetic wave generated by the plasma sheath will lead to errors of information snippets in the transmission process, thus reducing the overall transmission reliability. Fountain code can effectively solve this problem. Fountain code is record-breaking sparse-graph code for channels with erasures and has strong robustness. An encoding package is the smallest unit of fountain code. At the transmitter, the encoder generates many encoding packages according to the degree distribution function. At the receiver, all source information can be decoded as long as any $k(1 + \varepsilon)$ encoding packages are received, where ε is the decoding cost and k is the amount of source information.

The selection of the degree distribution function is a critical factor in the encoding progress of fountain code. A good degree distribution function can realize efficient and reliable information transmission with lower data redundancy.

The binary exponential degree distribution function $A(d)$ [19] and robust soliton distribution function $B(d)$ [20] are traditional degree distribution functions, which can be expressed as:

$$A(d) = \begin{cases} 1/k & d = 1 \\ 1/d(d-1) & d = 2, 3, \cdots, k \end{cases} \tag{8}$$

$$B(d) = \frac{A(d) + \tau(d)}{\sum_d A(d) + \tau(d)} \tag{9}$$

$$\tau(d) = \begin{cases} \frac{s}{k}\frac{1}{d} & d = 1, 2 \cdots (k/s) - 1 \\ \frac{s}{k}\log(s/\delta) & d = k/s \\ 0 & d > k/s \end{cases} \tag{10}$$

$$s = c \ln\left(\frac{k}{\delta}\right)\sqrt{k} \tag{11}$$

where k is the number of source information, d is the degree of each encoding package, c and δ are the two adjustment parameters of the robust soliton distribution function.

The advantage of the binary exponential degree distribution function is that the degrees of encoding packages are relatively low and the decoding process is not easy to interrupt but the disadvantage is that the encoding packages are not strong enough to cover all the data and abundant redundant data are needed to complete the whole decoding process. The advantage of the robust soliton distribution function is that the degrees of the encoding packages are relatively high and the source information is covered as much as possible in the coding process but the disadvantage is that there are fewer encoding packages with a smaller degree and the decoding process is easily interrupted because of the lack of small encoding packages. On this basis, we propose a weighted mixed degree distribution function ($\mu(d)$) based on the advantages and disadvantages of the two distribution functions mentioned above [21], [22]:

$$\mu(d) = aA(d) + bB(d) \tag{12}$$

where a and b are the proportions of the binary exponential degree distribution function and the robust soliton distribution function in the mixed degree distribution function, respectively.

We compared the performances of the binary exponential distribution function, robust soliton distribution function and mixed degree distribution function, as shown in Figure 6. The binary exponential degree distribution function can start the decoding process with a small amount of data redundancy, but abundant redundant data are needed to complete the whole decoding process. The robust soliton distribution function requires less data redundancy to complete the whole decoding process, but the decoding process is not easy to start. The mixed degree distribution function mainly uses the binary exponential distribution function in the first half, which ensures the decoding process starts quickly, and then mainly uses the robust soliton distribution function, which reduces the data redundancy.

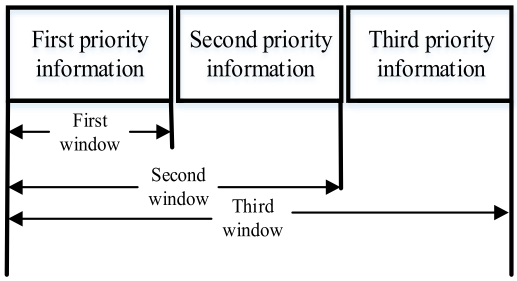

FIGURE 7. **Window-type distribution function.**

The communication link becomes no longer reliable as the channel level decreases. Many encoding packages are lost in the communication process. We should increase the proportion of $A(d)$ in $\mu(d)$ to ensure that the decoder can receive enough correct encoding packages with a relatively small degree and thus start the decoding smoothly and quickly.

The communication quality of the communication link improves with an increase in the channel level. To reduce the communication redundancy, we should increase the proportion of $B(d)$ in $\mu(d)$.

2) CLASSIFICATION CODING

The original design of the standard communication system assumes that coded information symbols are equally important. The coding gain is thus the same for all information. However, the deep fading due to the plasma sheath and a variety of complex noise makes that the traditional means of communication cannot guarantee the reliable transmission of all information. Compared with the traditional means of communication, the use of fountain code achieves a certain improvement in performance but it still needs to receive enough correct encoding packages to complete the decoding of the original information. This is difficult, especially when the electron density of the plasma sheath is high. However, the requirement of the bandwidth is greatly reduced if we only focus on important information. The present paper proposes a classification transmission method on this basis. The transmission information over the plasma channel can be divided into several priorities, and the unequal error protection is implemented for different priorities using a window function, as shown in Figure 7. The number of windows is equal to the number of priority levels, and the size of the window is equal to the sum of the information of the current priority and all previous priorities.

The communication link becomes no longer reliable as the channel level decreases. We should increase the number of information priority levels and reduce the amount of first-priority information, and then adjust the relevant parameters of the window-type distribution function to match. This is done to improve the communication reliability of the high-priority information by sacrificing the communication reliability of the low-priority information.

We can take the opposite tack when the communication quality of the channel improves.

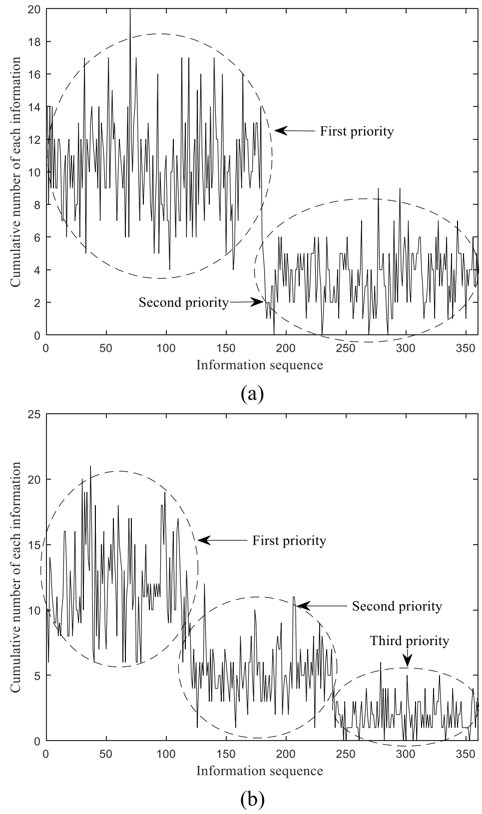

FIGURE 8. **Cumulative amounts of information of different priority in all encoding packages: (a) source information divided into two priorities and (b) source information divided into three priorities.**

During the specific implementation of classification coding, the UEP for different priority information is realized by adjusting the cumulative amount of information of each priority in all encoding packages. Figure 8 shows the cumulative amount of information of each priority in all encoding packages when the information is divided into two and three priorities. The cumulative amount of high-priority information is much more than that of low-priority information.

The cumulative amount of information for each priority affects the coding gain of each priority and the overall transmission rate, which are analyzed to evaluate the effect of adaptive transmission proposed in this paper.

a: THE CODING GAINS OF DIFFERENT PRIORITIES

The coding gain of the *nth* priority level can be expressed as:

$$G_{Ln} = P_r + P_b = 10\lg(xl_b/kl_r) + 10\lg(xP_{Ln}/xl_b/kl_r) = 10\lg(xl_b/kl_r) + 10\lg(kl_rP_{Ln}/l_b) \quad (13)$$

where P_r is the gain of information redundancy, P_b is the gain of the classification coding, x is the number of encoding packages, l_b is the length of each encoding package, k is the amount of source information, and l_r is the length of each source information. P_{Ln} is the average probability of the *nth* priority information in all encoding packages:

$$P_{Ln} = \sum_{m=n}^{m=i} \frac{1}{n} \left(\sum_{d=1}^{d=k_m} \mu(d) \times \frac{C_{k_m-1}^{d-1}}{C_{k_m}^{d}} \right) \quad (14)$$

where $\mu(d)$ is the degree distribution function used in the coding and i is the number of priority levels. Meanwhile,

$$k_n = \sum_{x=1}^{x=n} m_x \tag{15}$$

where m_x is the amount of xth priority information.

b: THE OVERALL TRANSMISSION RATE

Assuming that the original transmission rate is R, the equivalent transmission rate ($R_{equivalent}$) after classification transmission can be expressed as:

$$R_{\text{equivalent}} = \frac{R}{r+1} \times P_1 \tag{16}$$

where r is the transmission redundancy and P_1 is the proportion of the first priority information in all source information.

III. SIMULATION AND ANALYSIS

Employing the theory described above, this section evaluates the performance of adaptive classification fountain codes based on the block diagram in Figure 2.

The plasma sheath is a non-uniform and dispersive medium. Electron density is an important parameter expressing its character. In fact, the electron density of the plasma sheath is strongly correlated with the spacecraft's shape, velocity, trajectory, altitude, etc. Its distribution outward from the spacecraft surface would be expressed by a double Gaussian function[9], [26] as follows

$$Ne(z) = \begin{cases} N_{e(\max)} e^{-\alpha_1 (z-z_0)^2}, & 0 \leq z \leq z_0 \\ N_{e(\max)} e^{-\alpha_2 (z-z_0)^2}, & z_0 \leq z \leq z_2 \end{cases} \tag{17}$$

Here, z is the vertical distance from the surface of the aircraft, $N_{e(max)}$ is the peak electron density at the location of z_0, and α_1 and α_2 represent the curve's shape. According to the research results in the literature [12], we set the parameters of $\alpha_1 = 2000$, $\alpha_2 = 1700$, $z_0 = 0.035$ m, and $z_2 = 0.2$ m in the following work. The tendency of the change in the plasma sheath peak electron density is shown in Figure 9, with the range being 0.8×10^{18} to 1.7×10^{18} m^{-3}. The collision frequency of the plasma sheath is 1 GHz while the thickness of the plasma sheath is 20 cm.

The coding redundancy of fountain code is 2 and the number of source information for each priority is the same. The transmission rate and sampling rate are 5*Mbit/s* and 40*MSa/s* respectively. The transmission of the modulation electromagnetic signal of the binary phase-shift keying (BPSK) at a carrier frequency of 12 GHz in the plasma sheath is simulated in the following.

With an increase in the peak electron density, the VSWR of the transmit antenna increases and the communication quality of the plasma channel worsens. The plasma sheath results in the amplitude attenuation and phase shift of the encoding packages [17], which will lead to error code. To improve the utilization of encoding packages, we use pseudo-noise (PN) code with a period of 31 as the error correcting code. The transmission redundancy caused by fountain code and PN code will reduce the transmission efficiency. we calculated the change of $R_{equivalent}$ according to the formula (16).

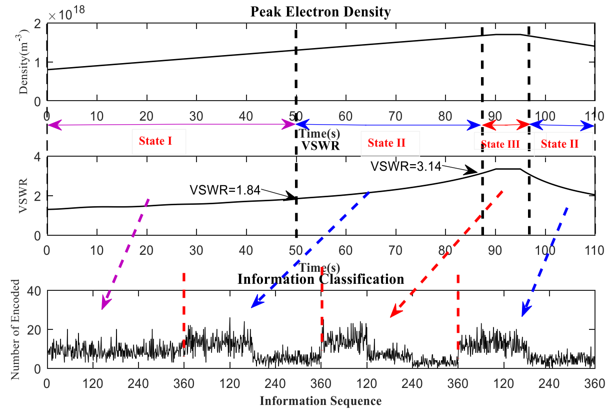

FIGURE 9. Relationship between the VSWR and information classification.

One priority:

$$R_{equivalent} = \frac{5Mbit/s}{(2+1) \times 8 \times 31} = 625Kbit/s \tag{18}$$

Two priorities:

$$R_{equivalent} = \frac{5Mbit/s}{(2+1) \times 8 \times 31} \times \frac{1}{2} = 312Kbit/s \tag{19}$$

Three priorities:

$$R_{equivalent} = \frac{5Mbit/s}{(2+1) \times 8 \times 31} \times \frac{1}{3} = 208Kbit/s \tag{20}$$

The $R_{equivalent}$ provides a reference for channel classification. According to Shannon's theorem and the simulation conditions in this paper, we can think that when the channel capacity is greater than 625Kbps, the channel level is excellent, and the source information content can be transmitted at a single priority; when the channel capacity is between 625Kbps and 312Kbps, the channel level is good, and the source information content can be transmitted at two priorities; when the channel capacity is less than 312Kbps, the channel level is poor, and the source information content can be transmitted at three priorities. In Figure 4, when the channel capacity is 625Kbps and 312Kbps, the $VSWR$ is 1.84 and 3.14, respectively. So we can set $VSWR = 1.84$ and $VSWR = 3.14$ as thresholds for separating the different channel levels.

Figure 9 shows the adaptive adjustment of the classification coding along with the change in the VSWR. With the increase of peak electron density, the reflection effect of plasma sheath on electromagnetic wave is gradually enhanced, resulting in the gradual increase of VSWR, the channel level from excellent (State I: $VSWR < 1.84$) to good (State II: $1.84 < VSWR < 3.14$), and the number of information priorities from one to two. As VSWR increases further, the channel level becomes poor (State III: $VSWR > 3.14$), and the source information is divided into three priorities.

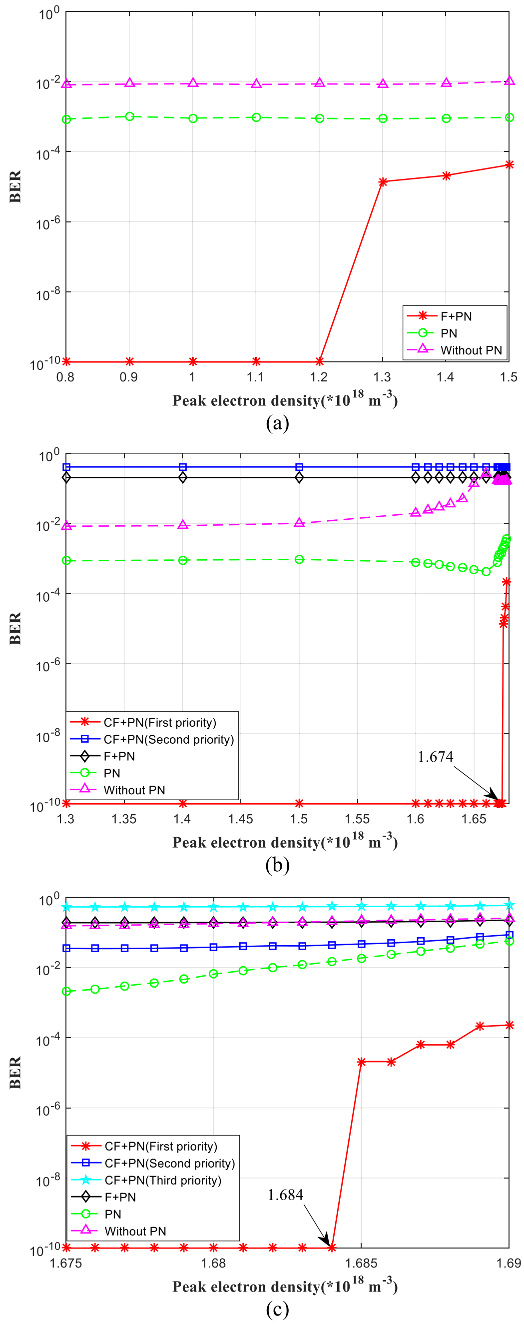

FIGURE 10. Relation between the BER and peak electron density of the plasma sheath. (a) State I. (b) State II. (c) State III.

Taking the classification transmission of 360 pieces of source information as an example, we compared the traditional equivalent transmission protocol and proposed transmission protocol for different peak electron densities.

Figure 10(a) shows that although the bit error rate (BER) remains high, the use of PN code as the error correcting code (PN) results in a BER lower than that without the PN code (Without PN). If we use fountain code on the basis of PN code (F+PN: Fountain code +PN code), the BER greatly improves and the communication link maintains continuous reliable communication when the electron density of plasma

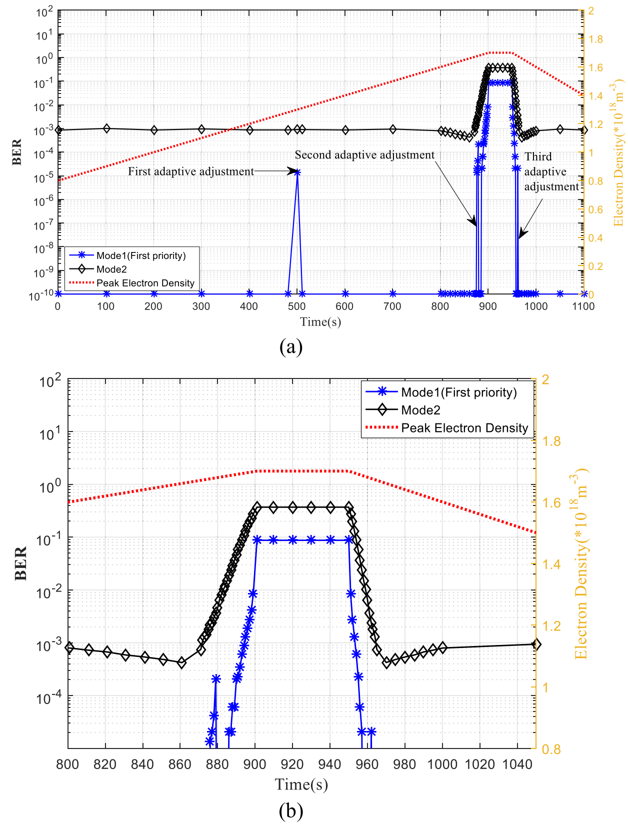

FIGURE 11. BERs of three transmission modes.

sheath is 1.2×10^{18} m^{-3}. In addition, according to the theory of the fountain code, after the encoded packet is transmitted through the plasma sheath, if the verification fails, the entire encoded packet will be thrown, which will cause an increase in the overall redundancy of the system, so the packet loss rate can directly reflect the transmission performance of the system. We counted the packet loss rate of this state. When the peak electron density is 1.2×10^{18} m^{-3}, the packet loss rate is 26.7%.

A further increase in electron density results in an increase in the packet loss rate, which does not guarantee the reliable transmission of all information. In this case, we need to consider how to ensure the reliable transmission of high-priority information, which is the idea behind information classification transmission proposed in this paper.

As illustrated in Figure 10(b), as the channel quality worsens, the source information is divided into two priorities. The UEP in the information classification method allows the reliable transmission of first-priority information even when the peak electron density of the plasma sheath is 1.674×10^{18} m^{-3} (CF+PN: Classification Fountain code+PN code). At this time, the packet loss rate is 46.7%.

Employing the theory described above, with an increase in peak electron density, we need to further refine the information classification parameters, increase the number of priorities to three and reduce the amount of information in the first priority, so that there is better UEP of the first-priority information. The simulation results in Figure 10(c) show that this method ensures continuous reliable transmission of the first-priority information even when the electron density of the plasma sheath is 1.684×10^{18} m^{-3} (CF+PN). Corresponding, the packet loss rate is 63.3%.

When the peak electron density increased from 1.2×10^{18} m^{-3} to 1.684×10^{18} m^{-3}, the packet loss rate increased from 26.7% to 63.3%. According to the theory of fountain code, we need to receive more than the number of source information to be able to decode all the information. As the packet loss rate increases, it will take longer to achieve this. It is not advisable in plasma communication. However, in this paper, we can achieve high-priority information decoding by only receiving a small number of encoding packets instead of all encoding packets, which can ensure the timeliness of decoding. Corresponding to the above simulation, we only need to receive 73.3%, 53.3%, 36.7% of the encoding package to ensure the correct transmission of all, half and one-third of the information, respectively.

The following sections focus on the performance of the adaptive classification fountain code (mode 1) and PN code (mode 2) in accordance with the electron density variation curve of Figure 9. The simulation results are shown in Figure 11(a). The figure shows that (a) the BER of mode 1 is lower than that of mode 2 overall. Furthermore, (b) mode 1 was adaptively adjusted three times. As a result, the first-priority information can be transmitted normally by mode 1 even when the peak electron density reaches 1.684×10^{18} m^{-3}.

To analyze the details of communication, Figure 11(b) presents the BERs of the two transmission modes near the cut-off frequency. The figure shows that (a) although the overall BER of mode 1 is lower than that of mode 2, the BERs of two modes both suddenly increase when w_p approaches the cut-off frequency. Furthermore, (b) analysis of the angle of the communication link interruption time reveals that the use of mode 1 delays the interruption time for almost 20 seconds if we assume that the interruption threshold is a BER less than 0.01.

IV. CONCLUSION

An adaptive transmission scheme for the plasma sheath was investigated. There is an obvious negative correlation between the VSWR and channel capacity. On this basis, the channel can be divided into different levels according to the VSWR, and the source information priority scheduling can be optimized in real time according to the channel level. The simulation results demonstrate the effectiveness of the proposed scheme, despite the use of three simple adaptive adjustment strategies. The advantages of the proposed scheme are summarized as follows.

a. The information transmission strategy can be adjusted automatically according to the channel level. When the channel condition is poor, the transmission reliability of low priority information is traded for the extra gain required to compensate for the attenuation of high-priority information by the plasma sheath; therefore, fewer data can be transmitted during reentry. Nevertheless, the method may guarantee the continuous transfer of small amounts of important information. When the channel state improves, the priority partition of source information can be automatically reduced to make full use of channel resources. This method enhances the adaptability of the communication system.

b. The electromagnetic wave energy is reflected or absorbed completely when w_p approaches the cut-off frequency. At present, w_p can be less than the cut-off frequency in a short period because of a physical means such as electromagnetic interference. In these circumstances, part of the radiowave energy can penetrate the plasma sheath but this information has a high BER, and the traditional means of communication are no longer applicable. This new method thus adopts the coding structure "PN code + Fountain code". Discrete encoding packages can be obtained by correcting the errors of PN codes, and fountain codes can then use these discrete encoding packages to decode part of the information correctly. This method effectively improves the tolerance of the communication process to the electron density and shortens the communication interruption time. Moreover, this method can cooperate with these physical means and realize the advantage complementation, which has wide application potential in the plasma communication field.

c. For the traditional transmission mode, the receiver needs to adjust accordingly as the transmission rate decreases. Although the transmission method of adaptive classification fountain code reduces the equivalent transmission rate, the channel transmission rate does not change, so the receiver does not need to make any adjustment.

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HAOJIE ZHANG was born in Shandong, China, in 1987. He received the B.S. and M.S. degrees in communication and information system from Air Force Engineering University, Xi'an, China, in 2009 and 2011, respectively. He is currently pursuing the Ph.D. degree with Xidian University, Xi'an. His current research interests include wireless channels and receivers.

WEIMIN BAO received the B.E. degree in electronic engineering from Xidian University, Xi'an, China, in 1982, where he is currently a Professor. His research interests include space launch vehicle and control engineering. He is a CAS Member of China.

MIN YANG received the B.S. and Ph.D. degrees from Xidian University, Xi'an, China, in 2009 and 2014, respectively.

He is currently an Associate Professor with the School of Aerospace Science and Technology, Xidian University. His current research interests include the wave propagation and the near-space vehicle's TT&C technology.

XIAOPING LI received the B.S., M.S., and Ph.D. degrees from Xidian University, Xi'an, China, in 1982, 1988, and 2004, respectively, where she is currently a Full Professor with the School of Aerospace Science and Technology. Her current research interests include the near-space vehicle's TT&C and communication technology.

YANMING LIU received the B.S., M.S., and Ph.D. degrees from Xidian University, Xi'an, China, in 1982, 1988, and 2004, respectively, where he is currently a Full Professor with the School of Aerospace Science and Technology. His current research interests include the near-space vehicle's TT&C and communication technology.