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Research Article

Design of the NCI Signal for BeiDou System Based on CCSK

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Currently, BeiDou Navigation Satellite System (BDS) has been a mature satellite navigation system. However, the transmission rate of the navigation signal is low. A novel Navigation and Communication Integrated (NCI) signal had been proposed in our previous work, its transmission rate was improved compared with the traditional navigation signal. In addition, an optimization algorithm was proposed to avoid cross-correlation interference between the navigation signal and the communication signal. Based on the above theoretical system, this paper gives a specific design for the BDS. The communication signal used in BDS is selected basing on the optimization algorithm, and the original BDS signal is used as the navigation signal. In addition, the error correction coding and interleaving technique in BDS are applied to the NCI signal to further improve the compatibility between the signal and BDS. The simulation results verify the superiority of the optimization algorithm. It illustrates each communication signal selected is suitable for the navigation signal of each satellite in BDS.

1. Introduction

With the development of navigation positioning technology, the four major satellite navigation systems are becoming mature [1–3]. For example, satellites can be connected to the space-air-ground integrated networks [4] and play a key role in target recognition [5, 6]. Among them, BeiDou Navigation Satellite System (BDS) has the short message communication function. It is introduced that the D1 navigation message rate is 50 bps in Interface Control Document (ICD) of BDS [7]. And it is modulated with secondary coding at a rate of 1 kbps [8–11]. Several acquisition methods for the navigation signal with secondary coding are introduced in [8–11]. Even if the signal modulated with secondary coding was influenced by the symbol conversion, it still can be received correctly in normal condition. Although the signal of BDS is modulated with secondary coding with a rate of 1 kbps, its rate is still low. For how to improve the signal rate, the Cyclic Code Shift Keying (CCSK) [12–16] technology has been proposed, i.e., the spreading code of the communication signal is cyclically shifted. The CCSK technology is introduced in [12, 13]. The information is transmitted by the cyclic shift number of spreading code sequences, thereby the transmission rate of the CCSK signal is improved. The performance of the CCSK signal is analyzed theoretically in [14], and the upper limit of symbol error rate is given. The performance of the CCSK signal transmitted on different channels is analyzed in [15, 16]. It is verified that the CCSK signal still has good performance and its rate can be improved.

A novel Navigation and Communication Integrated (NCI) signal is proposed in [17]. The navigation signal refers to the D1 navigation message in BDS. The communication signal uses CCSK signal. Compared with the traditional navigation signal, the rate of the NCI signal is greatly improved. Therefore, the NCI signal can be applied to BDS to improve the signal rate and reduce the Time to First Fix (TTFF).

The NCI signal proposed in [17] is applied to BDS in this paper. The signal in BDS is used as the navigation signal. The communication signal which is most suitable for each navigation signal is selected basing on optimization algorithm. Compared with the traditional navigation signal in BDS, the NCI signal has a higher transmission rate. Section 2 introduces some related works. Section 3 describes the signal design for BDS. In section 4, simulation results and theoretical analysis are given. Finally, the thesis is summarized.

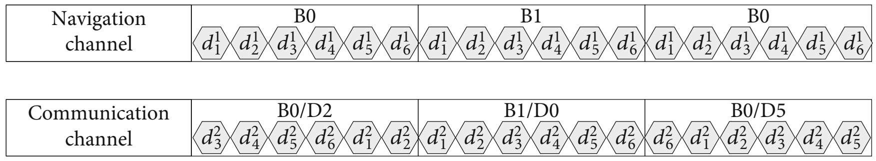

Figure 1: The NCI signal. B0 and B1 represent navigation data 0 and 1, respectively. D2, D0 and D5 denote cyclic shift number 2, 0 and 5. d denotes chip, where superscripts represent different ranging codes and subscripts represent different chips.

2. Related Work

2.1. Signal Structure. The NCI signal used in this paper can refer to [17]. The specific signal structure is shown in Figure 1. The navigation signal adopts the traditional BDS signal, it provides synchronization ability for the communication signal. The traditional receiver in service can be used without large-scale improvement, which saves the construction cost. As the communication signal, the CCSK signal improves the transmission rate and enhances the communication ability of the navigation system. They are transmitted synchronously at the same frequency and phase to achieve the effect of mutual enhancement.

2.2. BeiDou Signal. The ranging code used for the B1I signal in BDS is Gold sequence. The code length is 2046 and the code rate is 2.046 Mcps. In order to improve the reliability, the data code of the navigation message adopts the error correction coding and interleaving technique. The error-correcting code is BCH (15,11,1) code. Every two groups of BCH (15,11,1) code are converted in parallel-serial conversion and the interleaving is performed by bit interleaving. The specific process can refer to [7].

3. Signal Design

3.1. Optimal Cyclic Shift Set. An optimization algorithm is proposed in [17] to avoid the cross-correlation interference between the navigation signal and the communication signal. By optimizing the cyclic shift number of the communication signal, the value which is larger than the optimal threshold of the cross-correlation function overlies fitly on the self-correlation peak. Where the cross-correlation function is obtained by correlation between the NCI signal and the local signal. The optimal cyclic shift numbers constitute the Optimal Cyclic Shift Set (OCSS).

The parameter is represented by binary in BDS. While the communication signal transmits information through its cyclic shift number. The number of elements in the OCSS i.e., M is 2^n by designing the optimal threshold, where n is a positive integer. However, there are a large number of the same values in the cross-correlation function, it is impossible to make $M=2^n$ by adjusting an optimal threshold. So two optimal thresholds i.e., K_1 and K_2 need to be set to design two OCSSs i.e., $\mathbf{Q}_1$ and $\mathbf{Q}_2$. K_1 should meet the requirement that the number of elements in $\mathbf{Q}_1$ i.e., M_1 is less than 2^n and M_1 is the number closest to 2^n. K_2 should meet the requirement that the number of elements in $\mathbf{Q}_2$ i.e., M_2 is more than the 2^n and M_2 is the number closest to 2^n. M_2-2^n elements are deleted from $\mathbf{Q}_2$ because $\mathbf{Q}_1 \subseteq \mathbf{Q}_2$.

Table 1: Mapping relationship between optimal cyclic shift number and binary number.

Optimal cyclic shift number	Mapping number	7-bit data
41	0	0000000
47	1	0000001
52	2	0000010
65	3	0000011
90	4	0000100
...	...	...
2004	127	1111111

Above method can further achieve the compatibility between the NCI signal and BDS. Since the length of the ranging code is 2046, n cannot exceed 10. If n is too large, the superiority of the optimization algorithm is limited. If n is too small, the improvement of communication signal rate is not obvious. Therefore, the range of n can be appropriately set as $6 \sim 8$. n is selected as 7 in this paper. In this way, the cyclic shift number of the communication signal can be directly converted to binary number by mapping without additional coding. The specific mapping method is shown in Table 1.

3.2. Generation of Navigation Signal and Communication Signal. The navigation signal and the communication signal suitable for each satellite need to be generated before applying the NCI signal to BDS. The following describes this process.

Firstly, the spreading code used for the navigation signal i.e., the navigation code refers to the C_{B1I} code in BDS. The specific generation process can refer to [7]. The generation process of the spreading code used for the communication signal i.e., the communication code is similar to that of the navigation code. When the communication code is generated, the different taps of the shift register used for generating the G2 sequence perform modular sum to realize the different offsets of the G2 sequence phase. It uses one-tap, three-taps, four-taps etc. Two-taps is excluded because two-taps is already used when the navigation code is generated. We can get $\sum_{k=1, k\neq 2}^{11} C_{11}^k$ i.e., 1992 code sequences, where C_{11}^k denotes combination number formula. Besides, the code sequences need to meet the condition of balanced code. This selects out 495 suitable code sequences. Finally, 37 code sequences are selected from the 495 code sequences as communication codes of 37 satellites. The selection principle bases on the optimization algorithm to avoid better the

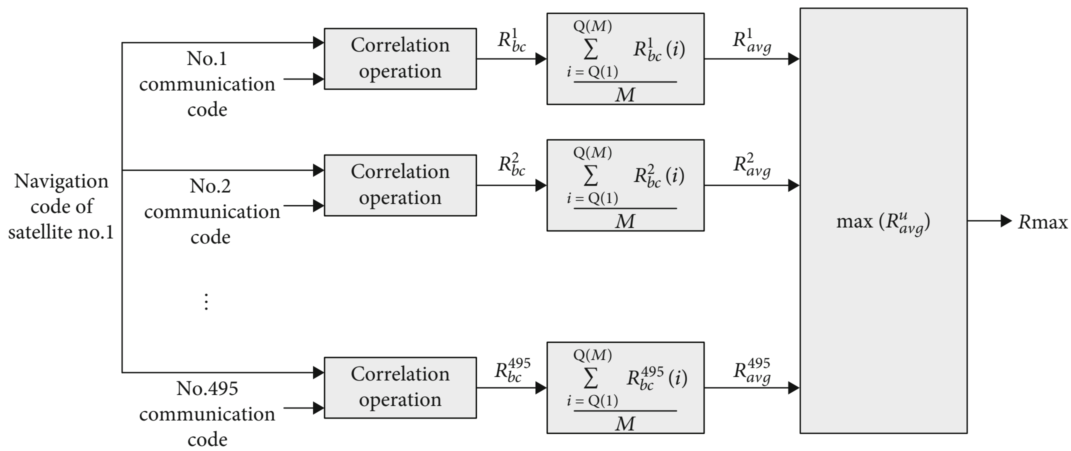

Figure 2: The flowchart of selecting communication code.

Table 2: The optimal cyclic shift for No.1 satellite.

Satellite's ID	OCSS
1	47, 52, 65, 90, 129, 159, 169, 178, 208, 218, 230, 250, 253, 261, 310, 368, 382, 404, 417, 427, 451, 462, 469, 517, 536, 543, 560, 568, 578, 599, 606, 661, 672, 709, 717, 738, 742, 749, 752, 813, 818, 843, 848, 866, 868, 880, 893, 902, 911, 929, 932, 945, 990, 998, 1020, 1069, 1074, 1076, 1153, 1156, 1193, 1203, 1218, 1219, 1244, 1252, 1254, 1275, 1280, 1294, 1301, 1312, 1325, 1335, 1341, 1344, 1355, 1381, 1382, 1389, 1391, 1393, 1399, 1419, 1428, 1448, 1454, 1460, 1468, 1492, 1499, 1500, 1508, 1520, 1533, 1570, 1600, 1612, 1617, 1625, 1637, 1644, 1649, 1661, 1668, 1687, 1702, 1712, 1724, 1735, 1737, 1748, 1801, 1823, 1851, 1856, 1864, 1868, 1874, 1875, 1880, 1915, 1952, 1961, 1972, 1986, 2004

cross-correlation interference between the navigation signal and the communication signal.

Taking the navigation code of satellite No.1 as an example, the most suitable communication code and the corresponding OCSS for this satellite need to be selected by this principle: to maximize the correlation peak between the NCI signal and the local signal by using the communication code, that is, the cross-correlation values that overlie on the self-correlation peaks are guaranteed to be statistical largest. Taking No.1 communication code as an example, the navigation code and the communication code perform the cross-correlation operation. We obtain the average value of M cross-correlation values that are all larger than the optimal threshold, i.e.,

$$R_{\text{avg}}^1 = \frac{\sum_{i=\mathbf{Q}(1)}^{\mathbf{Q}(M)} R_{bc}^1(i)}{M} \tag{1}$$

where $\mathbf{Q}$ denotes the OCSS, i is the optimal cyclic shift number, R_{bc}^1 is the cross-correlation function between the navigation code and the communication code. $R_{bc}^1(i)$ is larger than the optimal threshold. Other communication codes are similar with No.1 communication code, so 495 values are obtained. Finally, the maximum of 495 average values i.e.,

$$R_{\max} = \max\left(R_{\text{avg}}^u\right), u = 1, 2, \cdots, 495 \tag{2}$$

corresponding communication code is selected as the most suitable communication code for navigation code of satellite No.1. The specific selection process is shown in Figure 2.

According to this method, the most suitable communication codes for other navigation codes can be obtained. However, one communication code may be the most suitable one for different navigation satellites. Then, $R_{\max}$ which corresponds to the conflicting navigation codes need to be compared. The satellite with a larger $R_{\max}$, occupies this communication code. The most suitable communication codes for the conflicting satellites need to be re-selected. The second maximum of the average values i.e.,

$$\max_{R_{\text{avg}}^u \neq R_{\max}} \left(R_{\text{avg}}^u\right), u = 1, 2, \cdots, 495 \tag{3}$$

corresponding communication code is selected. Thus, the most suitable communication codes for the 37 navigation codes and their corresponding OCSSs can be obtained. Taking No.1 satellite as an example, its corresponding OCSS is shown in Table 2.

3.3. Structure Arrangement of the Navigation Message. As the data rate is greatly improved, the time for broadcasting the navigation message parameters is reduced. The navigation message parameters can be inserted into some time slots of the communication signal and broadcasted periodically. In order to further reduce the communication resources occupied by the navigation message parameters, some parameters unrelated to positioning can be deleted. Some parameters with less information can also be encapsulated together. Three types of frame are organized according to the different repetition periods of navigation message parameters, which are used to broadcast different types of

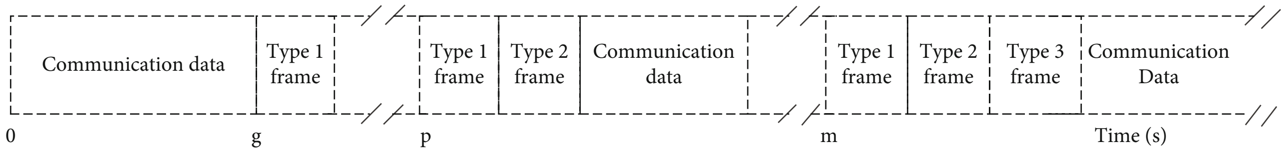

FIGURE 3: Frame structure format.

parameters. The repetition periods of three types of frame are set as g second, p second, and m second, respectively. Referring to the repetition periods of the navigation message parameters in ICD, g, p, and m can be set to 6, 30, and 720, respectively. If the repetition periods are too small, frequent broadcasting will take up more communication resources. If the repetition periods are too large and the broadcasting is not frequent, the TTFF will be extended. The positioning speed can be improved by inserting these frames into the head of the sub-frame. The specific frame structure is shown in Figure 3.

3.4. Encoding and Verification. In order to further improve the compatibility between the NCI signal and BDS, the error correction coding used in BDS is applied to the integration signal.

Firstly, the error correction coding and interleaving process are consistent with that in [7]. As shown in Figure 4, after the error correction coding and interleaving are applied to the navigation data, they are read out in every group of 7-bits. The 7-bits data are converted into decimal numbers and mapped to the optimal cyclic shift number in OCSS. The communication signal transmits information through the cyclic shift number. Thus, a period communication signal is modulated by CCSK technique with the corresponding optimal cyclic shift number. Every two groups of BCH code are encoded into 30-bit interleaved code in BDS. Thus, the remaining data are filled with zero if the data length cannot be divided by 7.

The receiver will calculate the cyclic shift number of the communication signal through the position of the correlation peak. And the cyclic shift number will be inversely mapped to a binary number of 7-bit, then the error correction decoding will be performed.

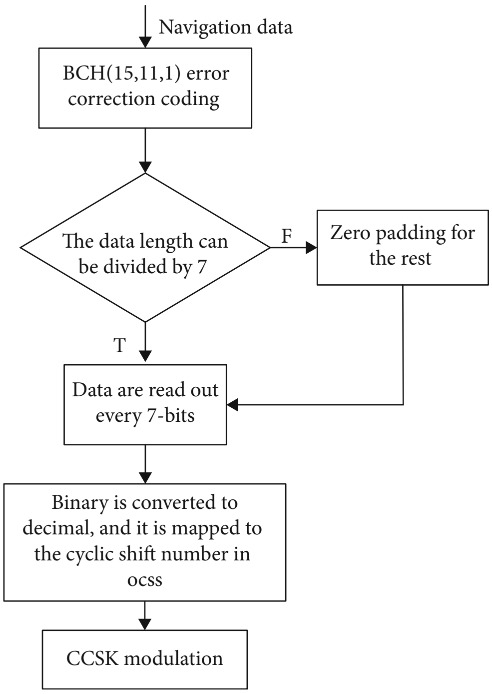

FIGURE 4: Schematic diagram of error correction coding of navigation message.

TABLE 3: Simulation parameters.

Specific parameters	Specific values
Carrier frequency	4.092 MHz
Sampling frequency	16.368 MHz
Spreading code length	2046
Code period	1 ms

4. Simulation and Analysis

The simulation results and performance analysis are given in this section. As shown in Table 3, the parameters used in the simulation refer to ICD.

In the simulation, the navigation code of satellite No.1 is used as the spreading code for the navigation signal, and the corresponding communication code is used as the spreading code for the communication signal.

4.1. Detection Performance Analysis. In order to verify the detection performance of the optimization algorithm, the detection probability (P_d) is simulated when the optimization algorithm is applied. Moreover, no communication signal and random cyclic shift of communication signal are included for compare. The P_d of the navigation signal is shown in Figure 5.

It can be known form Figure 5, the P_d increases with Signal-to-Noise Ratio (SNR), which is consistent with the theory. When OCSS is used, the P_d is significantly better than the other two cases. It is increased by about 9.3% when the BDS works at the minimum signal strength, i.e., the SNR is -27 dB. The side lobe of the correlation function is almost unchanged when the optimization algorithm is applied, but the correlation peak slightly increases. Thus, the signal's P_d is greatly improved.

The same simulation of communication signal is performed, as shown in Figure 6.

Similar to the P_d of the navigation signal, the P_d of the communication signal is obviously better than the other two cases when the optimization algorithm is used. The P_d

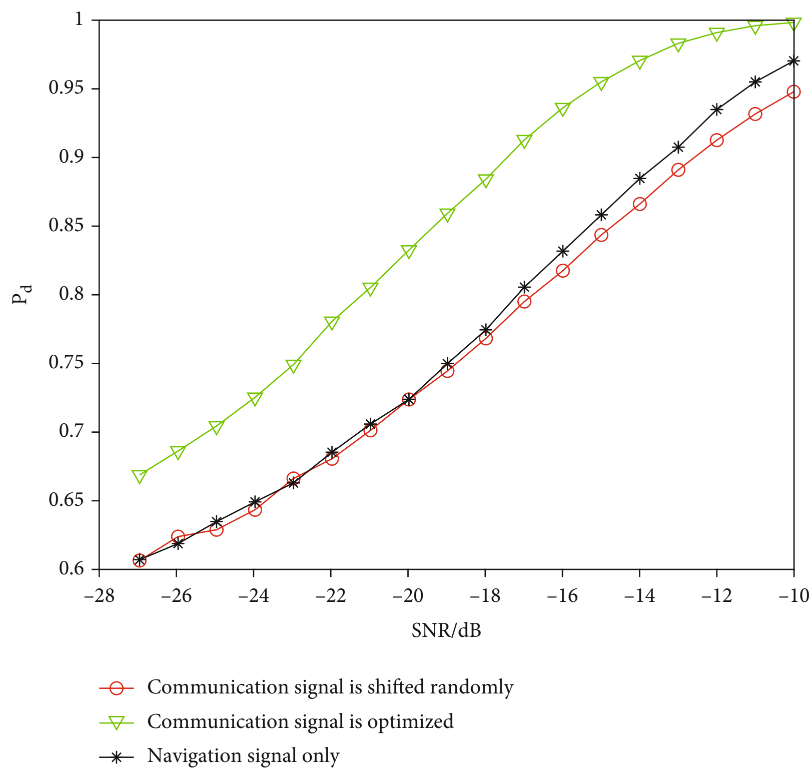

Figure 5: The P_d of the navigation signal.

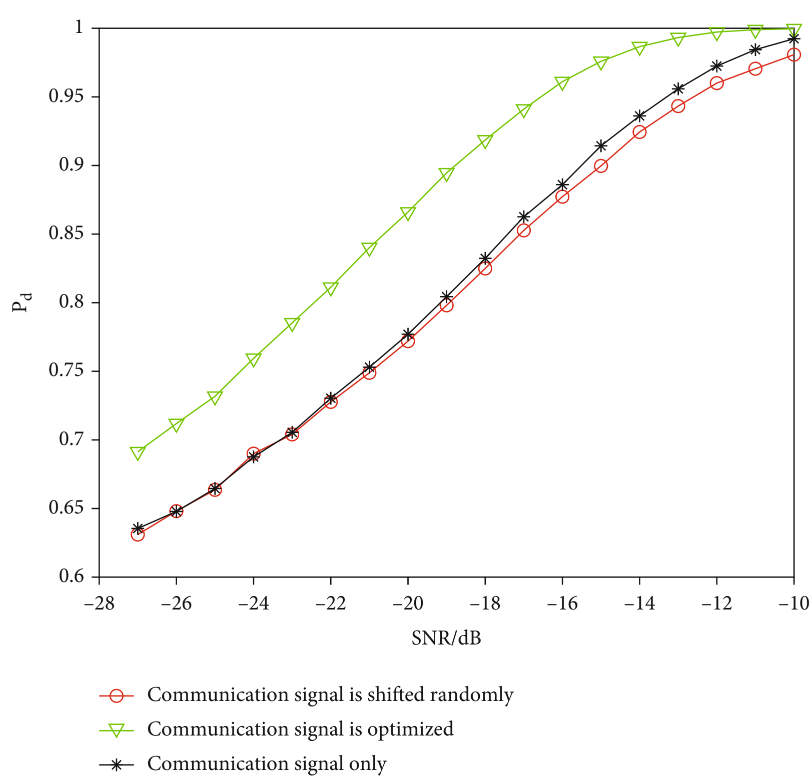

Figure 6: The P_d of the communication signal.

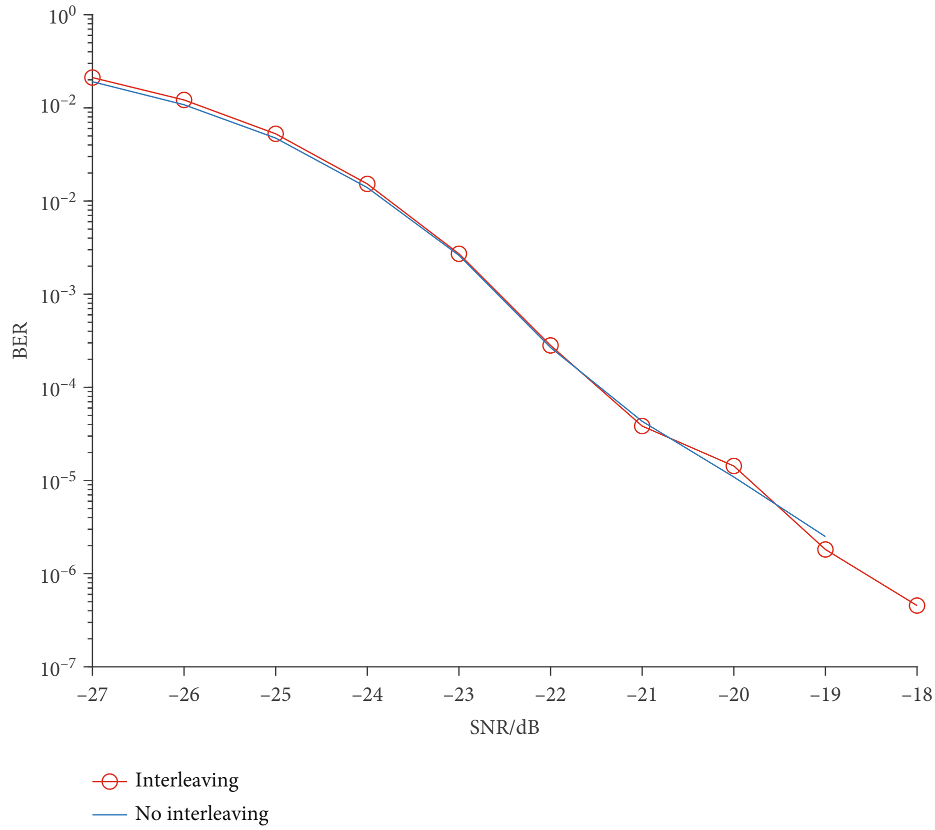

Figure 7: BER of the navigation signal.

of the communication signal is increased by about 8% when the SNR is -27 dB. Since the principle of the optimization algorithm is all the same. The only difference is that the local sequence is the navigation code or the communication code.

The above results show that the optimization algorithm can significantly improve the detection performance. It also verifies that the method proposed in Section 3.2 to select the most suitable communication code for each navigation code is effective.

4.2. Bit Error Performance Analysis. In order to verify the capability of the NCI signal to resist interference, the Bit Error Rate (BER) of the signal is simulated. There are two situations including BCH (15,11,1) coding and no error correction coding. The BER is shown in Figure 7.

It can be seen from Figure 7 that the BER of the signal is not improved although error correction coding and interleaving are applied to the integration signal. Because the cyclic shift number of the communication signal is inversely mapped to the 7-bits binary number. If a period signal is disturbed, the 7-bits binary number may have continuous errors. Therefore, the BER of the signal has not been further improved under the special interleaving mode in BDS.

4.3. Communication Rate Analysis. The information is carried by the cyclic shift number of the communication signal. Since the navigation signal is added for providing synchronization, it can be seen from Section 3.1 that a period communication signal can transmit 7 bits information. Thus, the signal rate is increased to 7 kbps. While the navigation message rate in BDS is 50 bps. It is 140 times higher than the original signal.

4.4. Positioning Speed Analysis. As the transmission rate of the signal is greatly improved, the navigation message parameters can be obtained faster. Therefore, the TTFF will reduce. Take the cold start mode of the receiver as an example, the valid satellite ephemeris and almanac is absent before positioning. The receiver need search all satellites one by one and demodulate the ephemeris parameters after capturing the signal. For the traditional navigation signal, a frame is divided into five sub-frames, each sub-frame lasts for 6 seconds, a total of 30 seconds. The ephemeris parameters of the first three sub-frames are required for positioning, so it takes at least 18 seconds to collect the ephemeris parameters. If other interference factors are considered, such as capture time and program loading time, the TTFF of cold start is generally about 60 seconds. It can be seen from section 4.3, after using the NCI signal to transmit information and adopting the optimization algorithm, the signal rate is increased to 7 kbps. So the time for broadcasting navigation message parameters is reduced. As shown in Figure 3, the ephemeris parameters required for positioning are inserted into the head of the sub-frame. It takes at least about 12 s to collect the ephemeris parameters, which is reduced by 6 seconds compared with the minimum TTFF of the traditional navigation signal. If other interference factors are considered, the TTFF is more than 12 seconds but less than 60 seconds.

4.5. Compatibility Analysis. The NCI signal have many similarities with the BDS signal, such as ranging code and carrier frequency. It preliminarily realizes the compatibility between the integration signal and BDS. The number of elements of the OCSS is 2^n. Thus, the cyclic shift number of the communication signal can be directly converted to binary by mapping. In this way, the compatibility between the integration signal and BDS is further realized. Therefore, some technologies including error correction coding and interleaving can be directly applied to the integration signal. It not only improves the reliability but also ensures the plug-and-play feature of this technology.

5. Conclusion

In this paper, a novel NCI signal is combined with BDS. And the navigation signal and communication signal suitable for BDS are generated basing on the optimization algorithm. The error correction coding and interleaving mode of BDS are also applied to the signal. The simulation results verify that the optimization algorithm can improve the detection performance. The detection probability of the navigation signal is increased by about 9.3% when the SNR is -27 dB. It further shows that method for selecting the communication signal basing on the optimization algorithm is effective. The addition of communication signal improves the transmission rate. It is increased by 140 times compared with that of the BDS signal, and the TTFF is also reduced. The deep integration of navigation positioning and communication is realized.

Data Availability

The data used to support this study are included within the paper or available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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