Combination of Multiple PBCH Blocks in 5G NR Systems

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Abstract. Physical broadcast channel (PBCH) in 5G new radio (NR) systems transmits system informations required for the user equipment (UE) to access the cell. In the long term evolution (LTE) system, multiple PBCHs are usually combined to improve demodulation performances in the case of poor channel conditions. However, in 5G NR systems, the payload of PBCH includes the system frame number and the payloads of multiple frames are not exactly consistent. Hence, it is impossible to adopt the same combination approach as that in LTE. In this paper, there proposes a method to solve the problem of combining multiple PBCH blocks in 5G NR systems. The main idea is to convert log likelihood ratios (LLRs) of all transmitted PBCH blocks into that of the first block and accumulate all LLRs at the receiving end. Then, an improved combination algorithm is considered to reduce the complexity. The simulation results show that the proposed combination algorithm can correctly combine multiple PBCH blocks. Besides, the improved combination algorithm with sort can also reduce the complexity.

Keywords: New radio · Physical broadcast channel · Combination

1 Introduction

For the user equipment (UE), efficient decoding of physical broadcast channel (PBCH) is of great importance, even for UEs in low signal conditions. Right decoding of PBCH can help to improve the device performance in terms of faster cell selection and lower power consumption [1]. So in low signal conditions, it is necessary to combine PBCH blocks to improve demodulation performances. In long term evolution (LTE), the content of continuous frames mapping is the same [2], PBCH blocks in the 40 ms can be soft combined and decoded [3]. That

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is, log likelihood ratios (LLRs) of multiple transmissions can be added at the receiving end.

In 5G new radio (NR) systems, SS/PBCH block (SSB) is always transmitted at the interval of 80 ms [4]. In the 80 ms, the maximum number of retransmissions depends on the SSB reception periodicity. For initial cell selection, a UE may assume that half frames with SSBs occur with a periodicity of 2 frames [5]. So this paper mainly takes the periodicity of 20 ms as an example. When the channel condition is poor, there needs to combine multiple PBCH blocks. The master information block (MIB) generated by the higher layer does not change within 80 ms. But the composition of PBCH includes system frame number (SFN), the payloads of multiple frames are different. In the existing combination solutions, such as equal gain combining and maximum ratio combining [6], the combination can only be performed in the case where the same data is transmitted multiple times. Therefore, soft-combination cannot be performed directly as in LTE.

For solving the above problem, there are already some studies. Ref. [7] proposes a Polar code design that explicitly transmits the time information on PBCH. The time-index-associated transformation is applied on information bit vector. The transformation is that multiplying the information bit vector by a constant matrix $\mathbf{T_u}$ according to SSB index. In Ref. [8], Sequans Communications proposes a scrambling design for SFN indication. At the receiving end, as for different blocks, use different scrambling sequences to descramble and then accumulate LLR from different blocks. After traversing all the scrambling sequence possibilities, choose the maximal power among the accumulated LLRs. But with the advancement of the 3GPP protocol, Polar code and scrambling [4] are finally determined. Under the premise of not changing the coding design and scrambling, the above methods are no longer applicable. So a novel and effective combination approach is needed.

In this paper, we propose an algorithm to combine multiple PBCH blocks. Due to the operations such as the cyclic redundancy check (CRC) and polar coding are linear, the LLRs sequence of multiple PBCH blocks all can be converted into that of the first block, and then LLRs of all PBCH blocks can be accumulated. When UEs initially access the cell, they can not know the SFN. So the SFN needs to be assumed during the combination process and there needs to traverse multiple SFN assumptions. Then, an improved combination algorithm is proposed to reduce the complexity of combination. In this paper, the sum of absolute values of the LLR sequences is used as the sort criterion. The larger the sum of absolute values is, the more reliable the SFN hypothesis is considered. The simulation results show that the improved combination method proposed in this paper can correctly combine multiple PBCH blocks and reduce the complexity.

The remainder of this paper is organized as follows. Section 2 mainly describes the system model, and Sect. 3 elaborates the algorithm of combination. Section 4 introduces the main process of the receiver, including combination process and sorting algorithm. Section 5 shows the simulation results and analyzes the performance of the proposed algorithm by comparison. And finally Sect. 6 concludes this paper.

Notations: $\oplus$ is used to denote the XOR operator. The j-th entry of a matrix $\mathbf{X}$ is denoted as $\mathbf{X}(j)$. And $\mathbb{N}^{m\times n}$ denotes a set of natural number with m rows and n columns.

2 System Model

The payload in 5G NR PBCH denoted as $\mathbf{x} \in \mathbb{N}^{1\times 32}$ consists of MIB and some time-dependent bits, where the size of MIB is 24. The 24 bits of MIB denoted as $\mathbf{x}(0)$, $\mathbf{x}(1)$, $\ldots$, $\mathbf{x}(23)$, are the same in the 80 ms period, i.e., TTI. Then, an 8-bit time-dependent PBCH payload bit is added, where $\mathbf{x}(24), \mathbf{x}(25), \mathbf{x}(26), \mathbf{x}(27)$ are the least significant bits of the SFN, $\mathbf{x}(28)$ refers to the half radio frame bit and this bit will not change in the TTI. As for $\mathbf{x}(29), \mathbf{x}(30), \mathbf{x}(31)$, when the number of SSBs in a half radio frame is larger than 64, they mean the indexes of SSB [2]. They has not been determined when the number of SSB is smaller than 64, so it is assumed that these three bits are random and do not change during the TTI. An example of the payload composition under 4 GHz carrier frequency is illustrated in Fig. 1.

Information bit	LSBs of the SFN	Half frame bit	MSB of subcarrier offset	Reserved bits	CRC
24bit	4bit	1bit	1bit	2bit	24bit

Fig. 1. The composition of the payload in 5G NR PBCH.

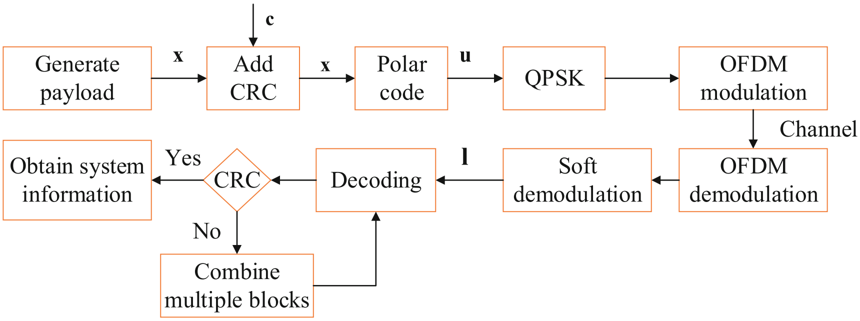


Fig. 2. The general process of PBCH

The general process of PBCH is shown in Fig. 2. In Fig. 2, the algorithm of combining multiple blocks is described in detail in Sect. 3. According to the agreements of 3GPP, the initial cell selection takes 20 ms as the SSB transmission period [5], so this paper mainly simulates the case of sending PBCH four times at most in the TTI. According to Fig. 1, the different parts in multiple PBCH payloads are the middle two bits between the four least significant bits of SFN, that is $\mathbf{x}(25), \mathbf{x}(26)$. There sets that when $\mathbf{x}(25), \mathbf{x}(26)$ changes from 00 to 11, correspondingly, i changes from 0 to 3 and multiple payload sequences of retransmission are denoted as $\mathbf{x_i}$. Then, we can get that,

$$\begin{aligned} &\mathbf{x_i} = \mathbf{x_0} \oplus \mathbf{d_i}, \\ &i = 1 \sim 3, \end{aligned} \tag{1}$$

where $\mathbf{d_i} = [0, 0, 0 \ldots 0, 0]_{1 \times 32}$, and $[\mathbf{d_i}(25), \mathbf{d_i}(26)] = [\mathbf{x_i}(25), \mathbf{x_i}(26)]$ are part of the SFN, i.e., $\mathbf{d_i}$ is a difference sequence which represents the difference between payloads.

In Fig. 2, the CRC sequence of $\mathbf{x}$ is $\mathbf{c}$. 3GPP specifies that the parity bits of PBCH are generated by [4], CRC is linear and CRC code matrix is set as $\mathbf{C}$. So the CRC sequence $\mathbf{c}$ can be calculated as

$$\mathbf{c} = \mathbf{x}\mathbf{C}, \tag{2}$$

Correspondingly, the sequence after CRC added of $\mathbf{x}$ is denoted as $\widetilde{\mathbf{x}}$. In 5G NR systems, PBCH uses Polar code at the transmitting end, and the generator matrix of Polar code is set as $\mathbf{G_N}$. As shown in Fig. 2, the sequence after Polar encoding is denoted as $\mathbf{u}$. And the output sequence of soft demodulation of $\mathbf{u}$ is $\mathbf{l}$.

3 Algorithm of Combination

In this section, it is theoretically analyzed why multiple PBCH blocks can be combined when their payloads are different. Firstly, according to (2), CRC output sequences $\mathbf{c_i}$ of $\mathbf{x_i}$ are calucated as

$$\begin{aligned} &\mathbf{c_{d_i}} = \mathbf{d_i}\mathbf{C}, \\ &\mathbf{c_0} = \mathbf{x_0}\mathbf{C}, \end{aligned} \tag{3}$$

$$\begin{aligned} \mathbf{c_i} &= \mathbf{x_i}\mathbf{C} = (\mathbf{x_0} \oplus \mathbf{d_i})\,\mathbf{C} \\ &= (\mathbf{x_0}\mathbf{C}) \oplus (\mathbf{d_i}\mathbf{C}) \\ &= \mathbf{c_0} \oplus \mathbf{c_{d_i}}, \end{aligned} \tag{4}$$

where $i\ = 1–3$ and $\mathbf{c_{d_i}}$ is the output bit sequence to CRC of $\mathbf{d_i}$. Then the output after encoding of $\mathbf{x_i}$ can be obtained as

$$\begin{aligned} \mathbf{u_i} &= [\mathbf{x_i}, \mathbf{c_i}]\,\mathbf{G_N} = [\mathbf{x_0} \oplus \mathbf{d_i}, \mathbf{c_0} \oplus \mathbf{c_{d_i}}]\,\mathbf{G_N} \\ &= ([\mathbf{x_0}, \mathbf{c_0}] \oplus [\mathbf{d_i}, \mathbf{c_{d_i}}])\,\mathbf{G_N} \\ &= ([\mathbf{x_0}, \mathbf{c_0}]\,\mathbf{G_N}) \oplus ([\mathbf{d_i}, \mathbf{c_{d_i}}]\,\mathbf{G_N}), \end{aligned} \tag{5}$$

Set $\mathbf{f_i} = [\mathbf{d_i}, \mathbf{c_{d_i}}]\,\mathbf{G_N}$, then

$$\mathbf{u_i} = \mathbf{u_0} \oplus \mathbf{f_i}. \tag{6}$$

So when the SFN changes, the relationship between LLRs with different SFNs can be deduced. At the receiving end, $\mathbf{l_i}$ can be given as

$$\begin{aligned} &\mathbf{l_0}\left(j\right) = \log\left(\tfrac{P(\mathbf{y}|\mathbf{u_0}(j)=1)}{P(\mathbf{y}|\mathbf{u_0}(j)=0)}\right), \\ &j = 0, 1, ..., J-1, \end{aligned} \tag{7}$$

where J is the length of the sequence $\mathbf{l_i}$. Then,

$$\mathbf{l_i}\left(j\right) = \log\left(\frac{P\left(\mathbf{y}|\mathbf{u_i}\left(j\right)=1\right)}{P\left(\mathbf{y}|\mathbf{u_i}\left(j\right)=0\right)}\right) = \log\left(\frac{P\left(\mathbf{y}|\mathbf{u}_0\left(j\right)\oplus\mathbf{f_i}(j)=1\right)}{P\left(\mathbf{y}|\mathbf{u}_0\left(j\right)\oplus\mathbf{f_i}(j)=0\right)}\right). \tag{8}$$

So we can get that

$$\begin{aligned} &\mathbf{f_i}(j) = 0 \rightarrow \mathbf{l_i}(j) = \mathbf{l_0}(j) \\ &\mathbf{f_i}(j) = 1 \rightarrow \mathbf{l_i}(j) = -\mathbf{l_0}(j) \end{aligned}. \tag{9}$$

The relationship between $\mathbf{l_0}$ and $\mathbf{l_i}$ can be concluded that,

$$\mathbf{l_i}\left(j\right) = \mathbf{l_0}(j) \cdot (-1)^{\mathbf{f_i}(j)}. \tag{10}$$

From (10), when the payloads of multiple PBCH transmissions are different in SFN, LLRs of $\mathbf{x_i}, i = 1, 2, 3$, can be reversed after soft demodulation to LLRs of $\mathbf{x_0}$. And then accumulate LLRs to combine multiple PBCH blocks. Therefore, difference sequences, i.e., $\mathbf{f_i}$ can be stored at the transmitting end. When the SFN is 11, i.e., $i = 3$, $\mathbf{f_3}$ can be obtained as

$$\begin{aligned} \mathbf{f_3} &= \left[\mathbf{d_3}, \mathbf{c_{d_3}}\right]\mathbf{G_N} = \left[\mathbf{d_1} \oplus \mathbf{d_2}, \mathbf{c_{d_1}} \oplus \mathbf{c_{d_2}}\right]\mathbf{G_N} \\ &= \left[\mathbf{d_1}, \mathbf{c_{d_1}}\right]\mathbf{G_N} \oplus \left[\mathbf{d_2}, \mathbf{c_{d_2}}\right]\mathbf{G_N} \\ &= \mathbf{f_1} \oplus \mathbf{f_2}. \end{aligned} \tag{11}$$

Therefore, in order to reduce the number of stored difference sequences, there only holds the difference sequences $\mathbf{f_1}$ and $\mathbf{f_2}$. So when combination is needed, LLRs of $\mathbf{x_i}$ are converted into LLRs of $\mathbf{x_0}$. For example, when combining two PBCH blocks, the payload sequences are denoted as $\mathbf{x_0}$ and $\mathbf{x_1}$ respectively. At this time, only $\mathbf{l_1}$, LLRs of $\mathbf{x_1}$, need to be reversed, according to the difference sequence $\mathbf{f_1}$. According to (10), when $\mathbf{f_1}\left(j\right)$ is 1, reverse $\mathbf{l_1}\left(j\right)$, or $\mathbf{l_1}\left(j\right)$ stay the same otherwise. Then accumulate $\mathbf{l_0}$ and $\mathbf{l_1}$. Finally, decode the accumulated LLRs sequence.

Considering the initial cell selection assumption, UEs do not know the SFN, so various assumptions are made on the SFN at the receiving end during the combination process. Compared with the same payloads that can be combined directly, the complexity of proposed combination method is higher. And if there are more PBCH blocks to combine, there are more than assumptions, which makes the complexity even higher. So multiple SFN assumptions should be sorted and then choose the most reliable assumption to traverse first.

4 Receiver Process of PBCH in 5G NR Systems

The main process of the receiving end includes orthogonal frequency division multiplexing (OFDM) demodulation, channel estimation, channel equalization, soft demodulation, de-rate matching, and channel decoding, etc. If retransmission is required, it needs to be combined before soft demodulation. As described in Sect. 3, the main idea of combination in this paper is that, at the transmitting end, the changes in the multiple encoded sequences are recorded through the difference sequences, i.e., $\mathbf{f_1}$ and $\mathbf{f_2}$. Then reverse LLRs of received SSBs according to $\mathbf{f_1}$, $\mathbf{f_2}$ and the current SFN hypothesis.

4.1 Specific Steps for Combination

This subsection mainly describes the specific steps of combination at the receiving end.

Step 1: Firstly, receive first SSB and keep the LLRs. If CRC is passed, obtain the system information. Then repeat Step 1.

Step 2: Otherwise, receive second SSB after 20 ms. When SFN of the first received SSB is 00, 01, 10 or 11 respectively, combine according to the detailed process in Fig. 3. Four hypotheses are elaborated below.

- Hypothesis 1 (SFN of first received SSB is 00): Reverse the LLRs of the second SSB according to $\mathbf{f_1}$.
- Hypothesis 2 (SFN of first received SSB is 01): the LLRs of the two SSBs need to be reversed according to $\mathbf{f_1}$ and $\mathbf{f_2}$. And the two LLRs sequences after the reversal accumulate.
- Hypothesis 3 (SFN of first received SSB is 10): As is described in Hypothesis 2, the LLRs of the two blocks should be reversed.
- Hypothesis 4 (SFN of first received SSB is 11): At this time, SFN of the second SSB is 00. Obviously, they are in the different TTI. So payloads of the two SSBs are not only different in SFN. It is assumed that the two SSBs cannot be combined. In this case, only decode the second SSB.

The detailed process of Step 2 is shown in Fig. 3. Where SFN_SSB1 refers to SFN of the first SSB and then SFN of the next SSB adds one in turn. LLRs_SSB1 and LLRs_SSB2 refer to the received LLRs after soft demodulation of the first SSB and second SSB. Partial reversal in Fig. 3 means reversing the LLRs sequences by $\mathbf{f_1}$ and $\mathbf{f_2}$. LLR combination means accumulating the LLRs sequence after the reversion.

Step 3: If four hypotheses of Step 2 fail to pass, receive the third SSB after 20 ms. As shown in Step 2, there are also four SFN hypotheses. Combine three blocks respectively under four SFN hypotheses.

Step 4: If Step 3 cannot pass CRC, it is necessary to receive the fourth SSB after 20 ms. If one of the four hypotheses passes, the system information can be obtained. Otherwise, go to the Step 5.

Step 5: Drop the first SSB, receive the next SSB after 20 ms. Return to Step 4, and combine the last four SSBs.

4.2 Multiple SFN Hypotheses Sorting

In this paper, the times of traversing SFN hypotheses are taken as the measure of complexity. As can be seen from the above descriptions, in terms of complexity, it may be higher than combining same payloads with existing algorithms. According to this paper, it is necessary to make assumptions about SFN at the receiving end. Due to the maximum number of retransmissions in this paper is 4, there are up to 4 hypothetical situations at a time. However, there may be up to eight hypotheses under 5G NR PBCH in the TTI. This complexity may be a bit unacceptable. To reduce complexity, it is necessary to look for an indicator to characterize the reliability of each hypothesis. Then the four hypotheses can be sorted based on their reliability and a more reliable hypothesis can be traversed first to reduce the numbers of traversal.

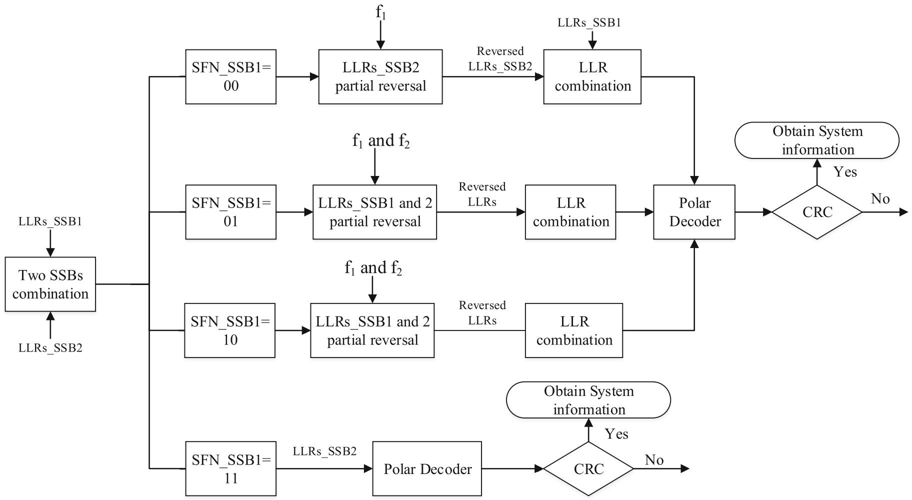


Fig. 3. Specific method of combining two SSBs

In Ref. [9], the author expounds the relationship between LLR and an estimation of the bit error rate (BER). From the author's description and theoretical deduction, the larger the absolute value of LLR is, the smaller the BER. And in Ref. [9], the author employs the calculated BER metric to perform a prediction on the reliability of the transmission. So in our paper, the reliability of the hypotheses is characterized with the sum of absolute values of the reversed LLR sequences. There are K hypotheses, numbered 1 to K. For hypothesis k, the reliability is calculated as shown in (12),

$$\begin{aligned} &\mathbf{s}(k) = \sum_{j=0}^{J-1} \mathbf{l}(j), \\ &k = 1, \ldots K, \\ &k = \arg\max\{\mathbf{s}(k)\}. \end{aligned} \tag{12}$$

From (12), it is assumed that the larger $\mathbf{s}(k)$ is, the hypothesis k more reliable. In the cases where combination cannot be performed, it is considered to give a weight to the sum of absolute values of the LLRs sequence, so that they can also participate in sort. Simulations are performed to determine the weight value, so that the complexity can be minimized. In this paper, the combination of two PBCH blocks are used as an example. Since it is unable to distinguish Hypothesis 1 and 3 in Sect. 4 through the combined LLRs, Hypothesis 3 is always put after Hypothesis 1 during the sorting.

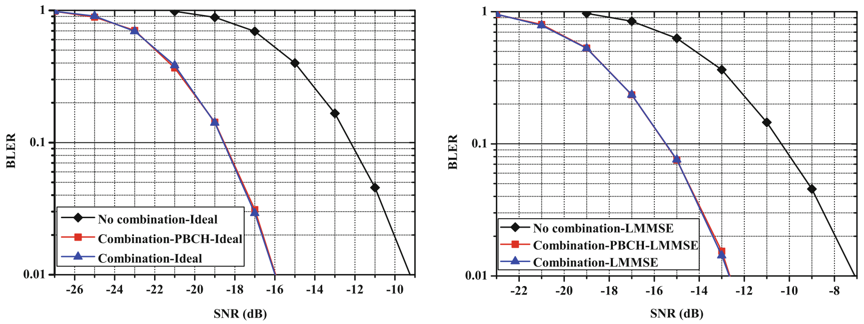
5 Simulation Results and Analysis

In this section, simulations are performed for comparison and analysis, including the combination performance and complexity of combination process. There mainly simulates the performance of ideal and linear minimum mean square error (LMMSE) channel estimation. Simulation parameters are shown in the Table 1.

Table 1. Simulation parameters of the PBCH [10].

Simulation parameters	Values
Antenna configuration	1Tx*4Rx
Bandwidth	20 MHz
Carrier frequency	4 GHz
Velocity	3 km/h
Cell ID	1
DCI	$32 + 24(\text{CRC}) = 56$bit
Encoding method	Polar
Channel estimation method	LMMSE/ ideal
Code rate	56/(24*9*2*2)
Channel model	CDL-C [11] 300 ns

In this part, the Signal to Noise Ratio (SNR) at 1% Block Error Ratio (BLER) is taken as a performance metric [10], and the performance gain between combination and without combination are compared. Besides, the performance of combining multiple PBCH blocks by the algorithm proposed in this paper and that of combining the same payloads are analysed. The simulation results are



(a) Ideal Channel Estimation (b) LMMSE Channel Estimation

Fig. 4. Simulation results with CDL-C 300 ns

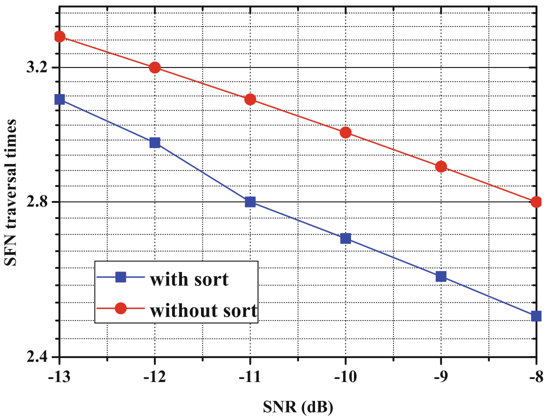


Fig. 5. Complexity with sort

shown below. Where no combination represents the performance of transmission only once within 20 ms, Combination denotes combining the same PBCHs and Combination-PBCH denotes combining multiple PBCH blocks in 5G NR systems.

Firstly the result of ideal channel estimation is shown as Fig. 4(a). As can be seen from Fig. 4(a), compared with the same PBCHs retransmitted four times, the performance of combining different PBCH blocks in 5G NR systems by proposed algorithm is the same on the whole. And when retransmitting up to 4 times, the performance gain is about 6.8 dB compared with no retransmission. Then, the performance with LMMSE channel estimation is presented in Fig. 4(b). In the case of real channel estimation, the SNR gain is about 5.6 dB. At this time, the channel estimation is considered to be not accurate, resulting in insufficient gain compared with ideal channel estimation.

In the combination process, the complexity is also statistically analyzed. The following is mainly the analysis on the process of combining two SSBs. The complexity is compared between the improved combination algorithm with sort and the combination algorithm without sort. Without sort refers to traversing in the order of SFN Hypothesis 1, 2, 3, 4 in Sect. 4. According to the simulation results, it is found that with the improved combination algorithm with sort, there is no effect on performance, e.g., BLER. Moreover, the average times of traversing SFN hypothesis decreases. From Fig. 5, it is seen that complexity decreases as the SNR increases. And even the SNR is higher, the complexity can also reduce up to 10%.

6 Conclusion

In order to solve the combination problem of PBCH in 5G NR systems, an algorithm is proposed in this paper. Although the payloads of multiple PBCH blocks in the 5G NR system are different, the difference only lies in two bits of the SFN, and it also shows the continuity. So we can use the proposed algorithm to convert LLRs of all transmitted PBCH blocks, and then accumulate them. The simulation results show that the algorithm in this paper can bring reasonable gains in BLER, compared with combining the same PBCHs.

In addition, in the proposed combination algorithm, the complexity is relatively high due to the need of making multiple assumptions about the SFN. Hence, an improved combination algorithm is proposed to reduce the complexity. The absolute value of LLRs after the combination is mainly used to determine the reliability of the SFN hypotheses. These hypotheses can be sorted based on their reliability. The simulation results indicate that the complexity can be reduced by about 10% in the case of combining two SSBs. The improved combination algorithm proposed in this paper plays a certain role in reducing the complexity, but there is room for improvement.

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