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Research Article

A Novel Design of Downlink Control Information Encoding and Decoding Based on Polar Codes

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In legacy long term evolution (LTE) networks, multiple transmission modes are defined to cater to diverse wireless environment and improve the spectrum utilization. However, constrained by user equipment (UE) processing capability on blind detection of downlink control information (DCI), two transmission modes are allowed to be configured to UE simultaneously. In recent 5G standardization, the polar codes have supplanted the tail biting convolution codes (TBCC), becoming the channel coding scheme for downlink control information (DCI). Motivated by its successive decoding property, a novel design of DCI encoding and decoding is proposed in this paper. The proposed scheme could support dynamic configuration of transmission modes with decreasing the complexity of blind detection. Evaluation results from link level simulations show that the performance loss compared to conventional encoding/decoding scheme is generally negligible and the proposed scheme can comply with the false alarm rate (FAR) target of 5G standardization.

1. Introduction

In the long term evolution (LTE) system, transmitter, and receiver communicate with each other by different transmission scheme. Each transmission scheme is corresponding to a transmission mode (TM) [1]. In the LTE, the multiple TMs are defined to cater to diverse wireless environment and improve the spectrum utilization. The LTE system supports nine TMs; the difference among those is the special structure of the antenna mapping, the reference signal of demodulation, and the feedback type [2].

The downlink control information (DCI) transited by base station to users can be used to schedule the downlink/uplink data transmission and convey essential configurations [3]. Specifically, the different DCI formats correspond to the different transmission modes. The length of DCI format will be adjusted with the different system configuration. Constrained by UE processing capability of blind detection of DCI [4], two transmission modes are allowed to be configured to a UE simultaneously.

The polar codes have been adopted as the channel coding scheme of the control channel in the next-generation communication networks [5]. It is based on the polarization theory and can achieve the capacity of arbitrary binary-input discrete memoryless channel (B-DMC) [6]. Furthermore, the complexity of polar codes is low with some optimized decoding algorithms, such as low-complexity list successive cancellation (LCLSC) decoding algorithm [7]. Blind detection of polar codes has been researched in [8]; that work focuses on fitting within the 5G parameters. A low-complexity blind-detection algorithm for polar-encoded frames is proposed in [9]. That scheme decreased the complexity of polar decoding in blind detection. Our scheme decreased the complexity of the process of blind detection.

Being different from the tail biting convolution code (TBCC) which is the coding scheme in LTE, all the existing decoders of polar codes are based on successive cancellation (SC) decoder [10], which allows the encoded bits to be decoded in given order. Taking advantage of successive property of polar decoders, decoding process can be paused after the first several bits being decoded and continued accordingly based on the value of first several bits. Based on the successive property of polar decoders, a novel design on DCI encoding and decoding is proposed in this paper. The proposed scheme could support dynamic configuration of transmission modes with decreasing the complexity of blind detection.

The rest of this paper is organized as follows. In Section 2 we introduce the foundation of proposed scheme. The scheme of DCI design is proposed in Section 3. In Section 4, we analyze the complexity, and simulation results are given. Finally, Section 5 concludes the paper.

2. Preliminary

In this section, we introduce polar codes and DCI design of the LTE system briefly; these are the foundation of the proposed scheme.

2.1. Polar Codes. Polar codes are based on channel polarization theory which is described as follows.

Theorem 1. *For any B-DMC W, the channels $W_N^{(i)}$ polarize in the sense that, for any fixed $\delta \in (0,1)$, as N goes to infinity through powers of two, the fraction of indices $i \in \{1,\ldots,N\}$ for which $I(W_N^{(i)}) \in (1-\delta,1]$ goes to $I(W)$ and the fraction for which $I(W_N^{(i)}) \in [0,\delta)$ goes to $1-I(W)$, where N is the length of code word which is equal to the length of polarized subchannels, $W_N^{(i)}$ denotes the ith subchannel of N subchannels, and I denotes the channel capacity.*

According to Theorem 1, we set the information bits in the subchannel set in which $I(W_N^{(i)}) \in (1-\delta,1]$ and set the frozen bits in the other subchannels to construct the information block u. Before setting the information bits and frozen bits, we should calculate the reliability of N subchannels and decide which subchannels are good to be set as information bits. The common algorithms to calculate the reliability include algorithm based on Bhattacharyya parameters [11], density evolution (DE) [12], and Gaussian approximation (GA) [13]. And then send u into polar encoder to be encoded. The polar encoding is denoted as $x_1^N = u_1^N \mathbf{G}_N$, where $x_1^N = x_1, x_2, \ldots, x_N$ is the code word, $u_1^N = u_1, u_2, \ldots, u_N$ is the information block, and $\mathbf{G}_N$ is the generator matrix of order N. The recursive definition of G_N is given by

$$G_N = B_N F_2^{\otimes n}, \quad F_2 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}, \tag{1}$$

where B_N is a permutation matrix.

2.2. Successive Cancellation Decoder. All the existing decoders of polar codes are based on successive cancellation (SC) decoder. After receiving y_1^N, the SC decoder generates its decision u_1^N by computing

$$\widehat{u}_i \triangleq \begin{cases} 0 & \text{if } i \in \mathscr{A}^c \\ h_i\left(y_1^N, \widehat{u}_1^{i-1}\right) & \text{if } i \in \mathscr{A}, \end{cases} \tag{2}$$

where

$$h_i\left(y_1^N, \widehat{u}_1^{i-1}\right) \triangleq \begin{cases} 0, & \text{if } \dfrac{W\left(0 \mid \widehat{u}_1^{i-1}, y_1^N\right)}{W\left(1 \mid \widehat{u}_1^{i-1}, y_1^N\right)} \geq 1 \\ 1, & \text{otherwise} \end{cases} \tag{3}$$

and $y_1^N = \mathbf{h} x_1^N + \mathbf{n}$ denotes the received message, $\mathbf{h}$ is the channel matrix, and $\mathbf{n}$ denotes the noise of channel.

Through the above formula, we can see that the polar decoder decodes the information bit by bit from u_1 to u_N. When we need to decode the ith bit u_i, it is decided as zero if u_i is frozen bit; otherwise u_i is decided by (2) with the prior information of $u_1, u_2, \ldots, u_{i-1}$ and $y_1, y_2, \ldots, y_N$. This property of polar decoder is defined as successive property which makes it is possible to suspend the process of decoding when $u_1, u_2, \ldots, u_{i-1}$ have been decoded.

2.3. DCI Design. According to the latest MIMO-related progress in the 3rd-generation partnership project (3GPP), only one code word (CW) is transmitted for 1 to 4 layers and two CWs are transmitted for 5 to 8 layers. Thus, the actual number of transmission layers could implicitly indicate the number of CWs. Moreover, compared to 1-CW case, 2 CWs would add an additional block of bit fields to DCI, possibly containing MCS/RV/NDI and CBGTI/CBGFI if CBG-based transmission is configured, as shown in Figure 1. This is where the difference between DCI payload sizes mainly rises. Consequently, DCI formats with 1- to 4-layer transmission could strive to have the same DCI payload size and so are the DCI formats with 5- to 8-layer transmission. Different transport layers corresponded to different DCI formats. UE does not know which DCI format of information is selected by base station; therefore blind detection is needed. Constrained by UE processing capability on blind detection of DCI, two DCI formats are allowed to be configured to UE simultaneously. UE attempted to decode the information with one DCI format, if it can not perform decoding correctly, UE will attempt to decode the information with the other DCI format.

3. Proposed Scheme

Based on the above discussion, a potential design is to add an explicit rank indicator (RI) field in DCI and utilize this field to implicitly indicate DCI payload size during decoding process. Specifically, the RI with fixed length could be decoded firstly, and then the number of CWs and possibly DCI payload size (this depends on the detailed DCI content) could be implicitly identified.

This design is feasible from technical perspective as polar codes have been adopted for PDCCH [1]. Based on the successive property of polar decoder, the number of RI can be decoded first before decoding of the CWs. Motivated by this property, the number of CWs could be informed dynamically by RI. If the number of transmission layer exceeds a threshold (e.g., 4-layer transmission based on current agreements), the decoder would continue the decoding process based on a long bit length, otherwise based on a short bit length. It is evident that such DCI format and decoding design are feasible with decreasing the blind decoding complexity at UE side.

In this section, the proposed scheme is described in detail. The encoding and decoding of polar codes are adjusted as the proposed scheme.

3.1. Encoding. Since each scheduled transmission may contain 1 or 2 CWs, we define two DCI formats with different

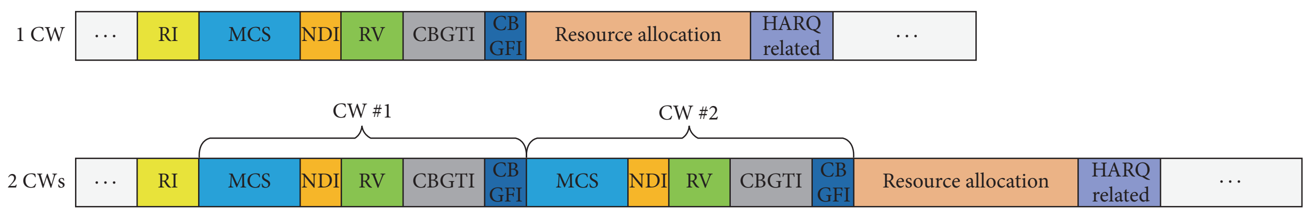
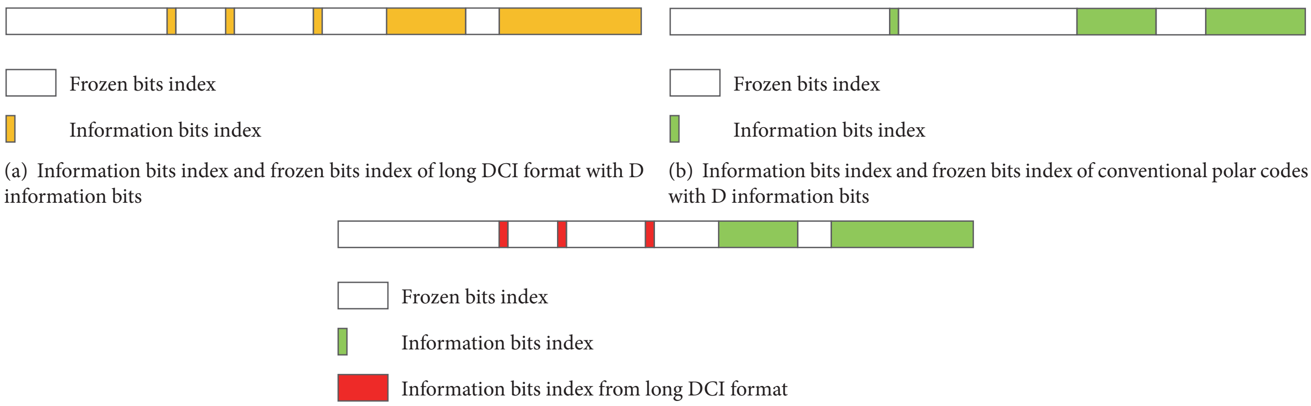


FIGURE 1: An illustrative DCI format for 1 CW and 2 CWs.



(a) Information bits index and frozen bits index of long DCI format with D information bits

(b) Information bits index and frozen bits index of conventional polar codes with D information bits

(c) Information bits index and frozen bits index of short DCI format with S information bits

FIGURE 2: The information bits index and the frozen bites index.

lengths. Assume that the long DCI format is D bits and the short DCI format is S bits. Both the DCI formats are encoded to an N-bit code words for PDCCH. The RI field in DCI is utilized to implicitly indicate the DCI payload size. The base station sets a threshold T for RI. If RI exceeds the threshold, the base station shall transmit the short DCI format or, otherwise, transmit the long DCI format. The encoding procedure for two DCI formats is illustrated as follows, respectively.

Long DCI Format. The base station knows which DCI format should be transmitted and encode the DCI format for different length. Step 1: the reliability of N-bit polarized subchannels is calculated. Transmitter selects the $(D+I)$ most reliable subchannels which are noted as $A_{(D+I)} = [A_1, A_2, \ldots, A_{(D+I)}]$. Step 2: the transmitter maps the $(D+I)$-bit information on the selected $A_{(D+I)}$; the first I bits of $(D+I)$-bit information are the RI field and the remaining D bits are the control information. Step 3: the transmitter maps the frozen bits (usually all being zero sequence) on the other $N-(D+I)$ subchannels to construct an N-bit sequence u. Last, input the sequence u into the polar encoder.

Shot DCI Format. Step 1 for short DCI format is the same as that for long DCI format. In step 2, instead of selecting the most reliable $(S+I)$ subchannels from the set, the transmitter selects the first I elements from the set $A_{(D+I)}$ as RI field which is the same as the long DCI format. Then select the most reliable S subchannels from the remaining sets as the information set A_S. Then the information bits of short DCI format are mapped on selected S subchannels and the frozen bits are mapped on the other $N-(S+I)$ subchannels.

The construction of sequence u is shown as in Figure 2. Figure 2(a) denotes the sequence u of long DCI format. Figure 2(b) denotes the sequence u of conventional polar codes with S information bits. And Figure 2(c) denotes the sequence u of short DCI formats. The black blocks are information bits which are selected by the reliability of subchannels, the white blocks are the frozen bits, and the red blocks are the information bits selected by the long DCI format.

The selection of thresholds T and I is not fixed, that is, depended on the practical situation. When the channel condition is good, two CWs can be transmitted in one block, and the small value of T and I can be set; otherwise set a large value of T and I.

3.2. Decoding. The proposed decoding process is generally based on the SCL decoder with adding a step called pause-and-judge (PJ). The detail of the PJ step is described as follows.

Based on successive decoding property, the polar decoder can decode the information from u_1 to u_N bit by bit. That is, the polar decoder can pause when $u_1, u_2, \ldots, u_I$ have been decoded and proceed with other operations.

In the proposed scheme, user receives message from the base station without the knowledge of DCI format used. The difference between coded information of long DCI format and that of the short DCI format is selection of information bits set, but the first I elements of RI field are the same. The

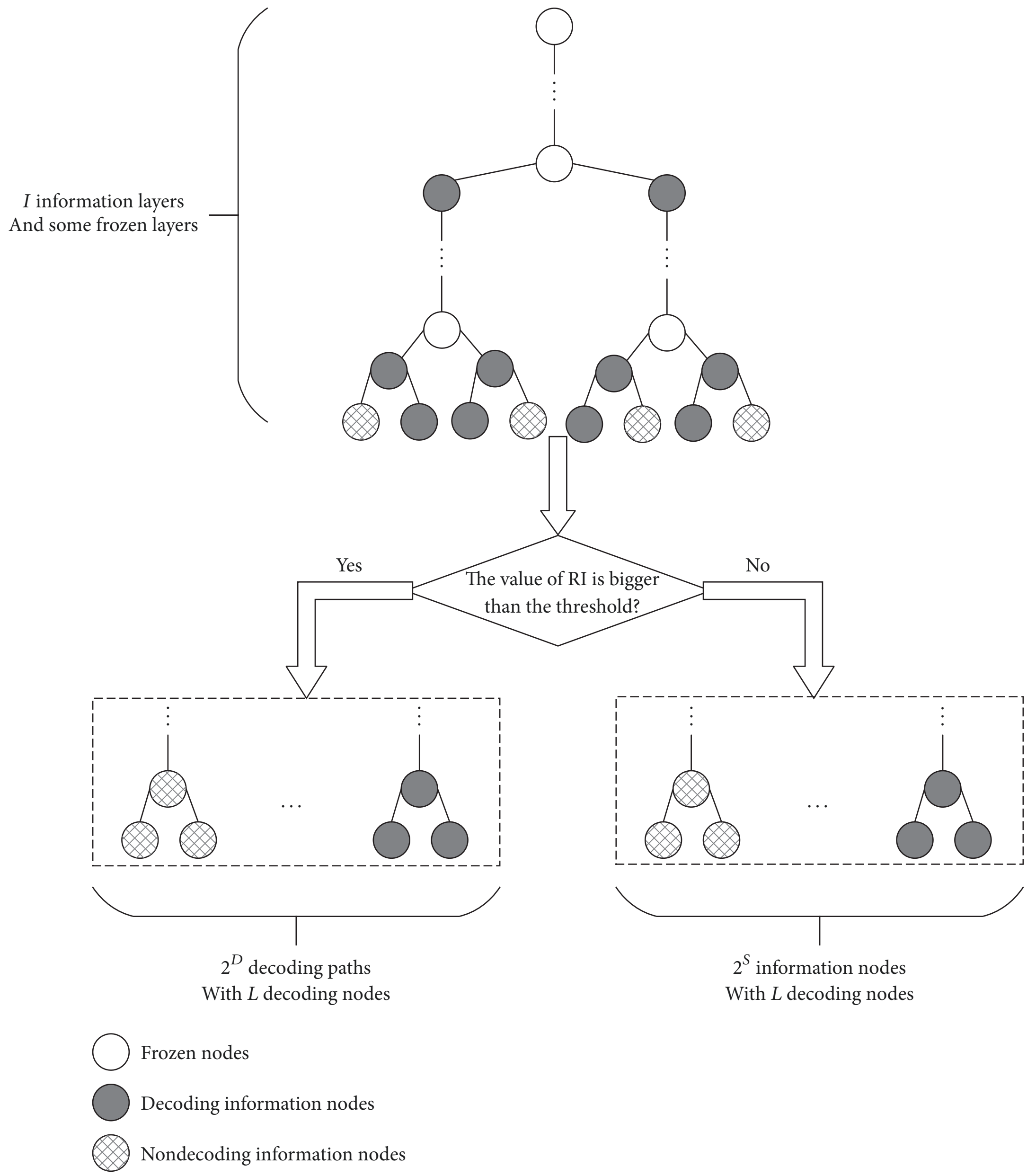


Figure 3: The proposed SCL decoding with L decoding paths.

user decodes information from u_1 with the SCL algorithm, when u_1 to u_I have been decoded, the decoding proceeding is paused and user selects the most reliability path to decode $u_1, u_2, \dots, u_I$ and judges the value of $u_1, u_2, \dots, u_I$. If it is bigger than threshold T, user continues decoding according to the long information set $A_{(D+I)}$. Otherwise, user continues decoding according to the short information set A_S. The decoding process is shown as in Figure 3.

4. Analysis and Simulation Results

4.1. Complexity of Blind Detection. In the LTE system, the blind detection of PDCCH can be divided into two parts, detection of search space and detection of DCI format. The DCI can be placed in various valid locations which form the so-called search space. There are 22 candidate search spaces. And two DCI formats are allowed to be configured to UE simultaneously. UE does not know which search space and DCI format are transmitted. Therefore, the most amount of blind detection of PDCCH is $22 * 2 = 44$ times. Our work saves the complexity of blind detection which is used to determine DCI format, the most amount of blind detection of PDCCH is decreased to 22 times.

With proposed scheme, before the blind detection, we can decide which DCI format base station uses by the dynamic configuration of DCI format. That is, we can save up to 50% for complexity of blind detection.

4.2. Block Error Rate (BLER). In this section we provide numerical examples to illustrate that the proposed scheme

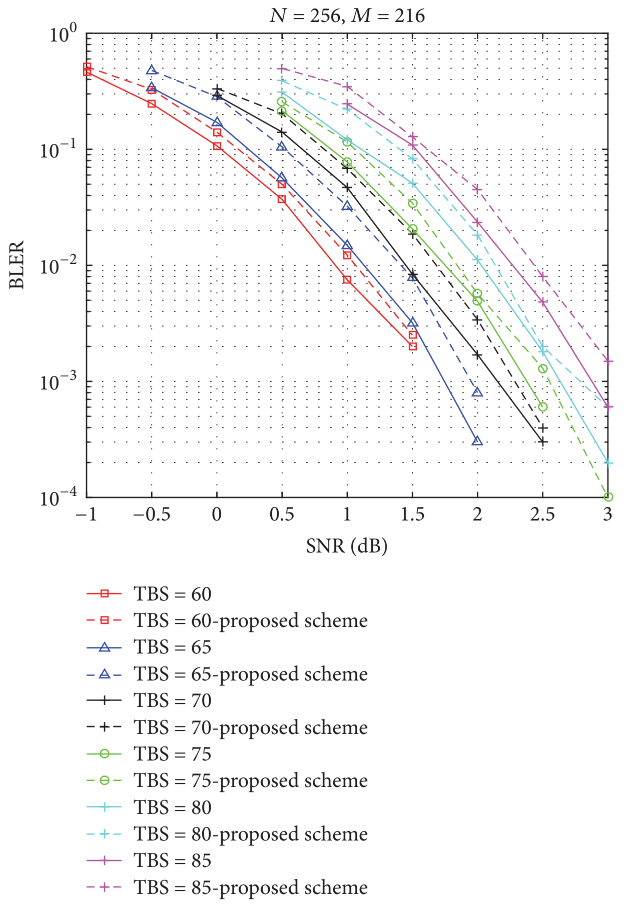


Figure 4: The BLER performance for proposed scheme with $N = 256$, $M = 216$, and various TBS.

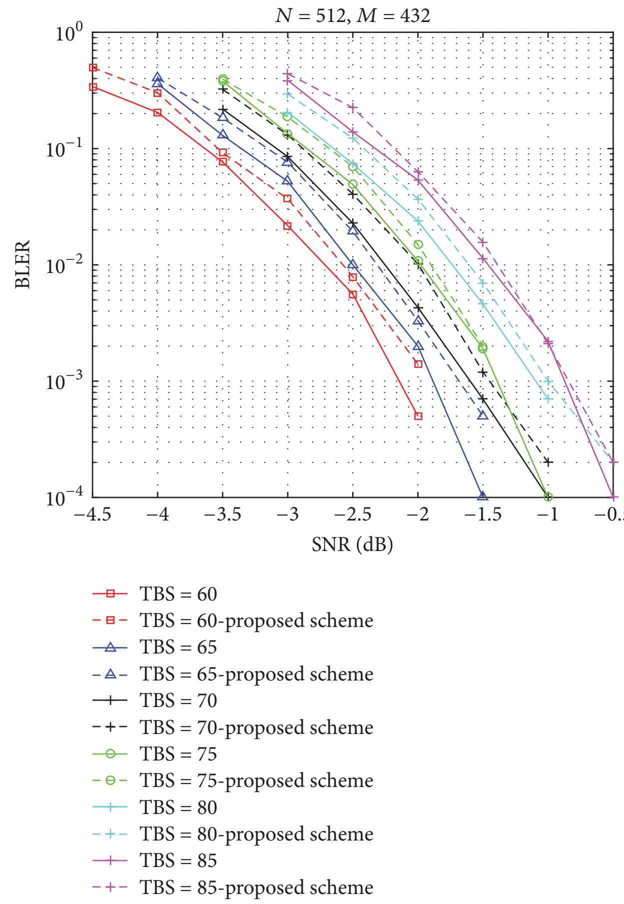


Figure 5: The BLER performance for proposed scheme with $N = 512$, $M = 432$, and various TBS.

has lower complexity and the degradation caused by dynamic indication of code word number is generally negligible. When DCI format uses long information set, the selection of information set of proposed scheme is the same as that of common polar codes; there is hardly any BLER performance loss. Therefore the BLER of short information set with I RI field is needed to be simulated.

We consider the 216-, 432-, and 864-bit DCI payload with the various length of the short information from 60 bits to 85 bits. Note that $M = 216/432/864$ corresponds to aggregation level 2/4/8 with 1/4 RS density per resource element group (REG), respectively. And the mother code lengths are $N = 256/512/1024$, respectively. The proposed scheme is compared with common polar codes. The simulation results are shown as in Figures 4–6. Figure 4 shows that, with a shorter DCI payload length ($M = 216$), a considerable performance degradation on BLER is caused by dynamic indication, less than 0.1 dB, when BLER is 10^{-2}. Figures 5 and 6 show that, with a longer encoded bit length ($N = 432/864$), the performance loss is generally negligible. It is obvious that a larger aggregation level would be more possibly used for a larger DCI payload size (e.g., DCI format with 2 CWs) to ensure the reliable reception of NR-PDCCH on UE side, under which the BLER performance is hardly impacted by dynamic indication.

4.3. False Alarm Rate (FAR). The false alarm ratio has been one of the most important measures of channel coding in 3GPP. The FAR is defined as $\mathrm{FAR} = N_u/N_t$, where N_u denotes the number of undetected erroneous packets and N_t denotes the number of total packets. Figures 7 and 8 show that the FAR for the proposed scheme over various (K, M) pairs can comply with the FAR target of $1.5 * 2^{-21}$.

5. Conclusion

In this paper, we proposed the dynamic configuration of DCI format based on polar codes. In the encoder of proposed scheme, the RI field is used to indicate the number of MCS fields and other related fields. Then the pause-and-judge step is added to the SCL scheme. Analysis and the simulation results illustrate that the proposed scheme can reduce the complexity of the blind detection and the degradation caused by dynamic indication of code word number is generally negligible.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

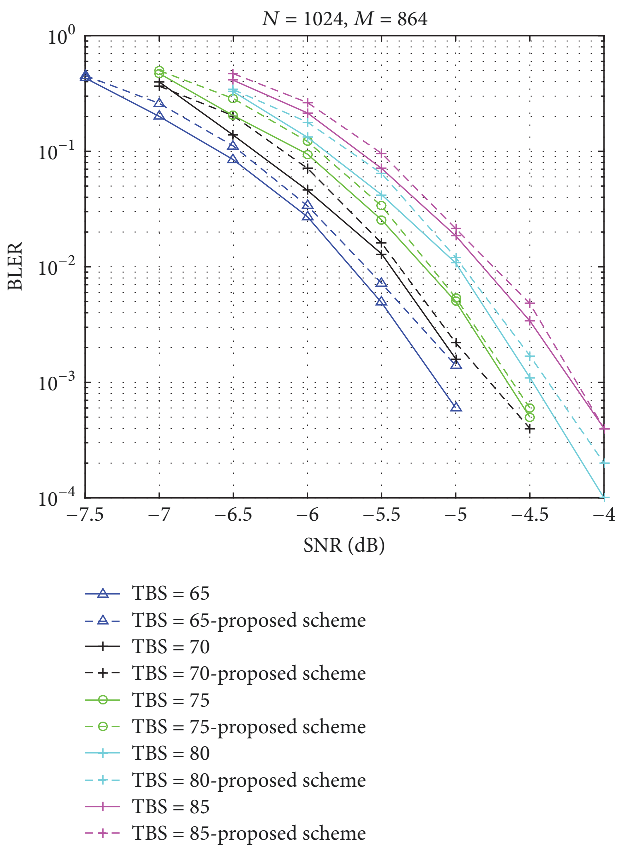


FIGURE 6: The BLER performance for proposed scheme with $N = 1024$, $M = 864$, and various TBS.

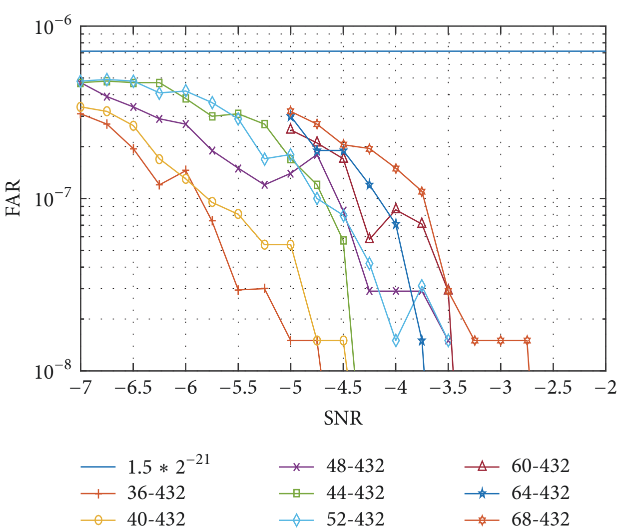


FIGURE 7: FAR evaluation results for $M = 432$.

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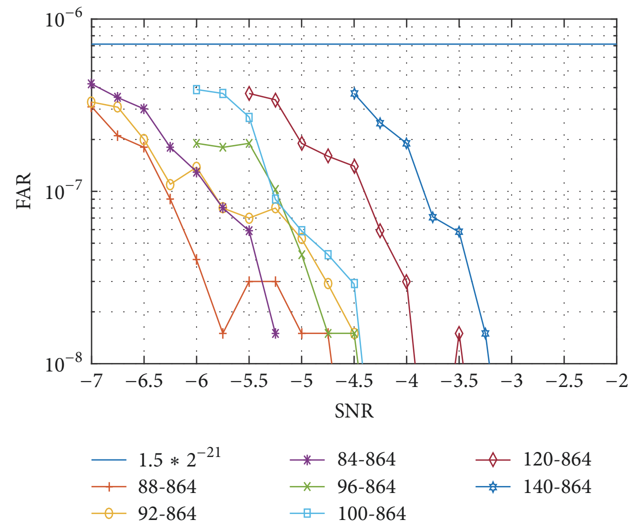

FIGURE 8: FAR evaluation results for $M = 864$.

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