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A third-party efficient PDCCH blind detection method based on the selection of polar decoding metrics

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Abstract: To investigate and design an efficient blind detection method for third-party scenarios, a third-party efficient physical downlink control channel (PDCCH) blind detection method was proposed based on polar decoding metric selection. This method comprised two main components: the study of the polar decoding algorithm, which introduced a polar decoding metric based on downlink control information (DCI) length and proposed an improved third-party blind detection method based on polar decoding metric selection; and the investigation of the PDCCH blind detection algorithm, which introduced a reordering blind detection algorithm. The enhanced polar decoding algorithm and reordering blind detection algorithm were organically combined to present an efficient PDCCH blind detection method for third-party scenarios. The proposed method was validated and analyzed using a 5G PDCCH blind detection simulation link on the MATLAB platform. The results show that the proposed method effectively reduces the number of PDCCH blind detections and the count of DCI candidates while enhancing blind detection efficiency and ensuring target capture accuracy.

Key words: polar decoding; physical downlink control channel (PDCCH); blind detection; downlink control information (DCI)

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The detection efficiency and power consumption of channel blind detection have been popular topics in physical layer research. Particularly because of the advent of the 5G era, the time requirement for controlling channel blind detection has decreased from 16 to 4 μs. The study of blind detection algorithms for PDCCHs in mobile communication terminal devices has substantial practical importance.

The PDCCH in 5G facilitates the transmission of downlink control information (DCI) from the base station to the user equipment. Different radio network temporary identifiers (RNTIs) are employed to scramble DCIs for resource allocation and link control indications within a cell. Compared with LTE, 5G PDCCH transmission method differs considerably. Unlike LTE, 5G eliminates the use of the physical control format indicator channel and instead relies on blind detection by terminals to reduce data transmission overhead and enhance spectrum resource use. Once a terminal establishes a radio resource control connection with the base station, it continuously monitors and decodes the PDCCH sent by the network on the time-frequency resources allocated by the base station, a process referred to as blind detection.

The 5G technology uses a wider range of transmission bandwidths and a more flexible orthogonal frequency division multiplexing (OFDM) scheme. Given the various scenarios for blind detection of PDCCH, 3GPP TS 38.211 introduces the concept of the control resource set (CORESET) in addition to LTE's search space (SS) to reduce the complexity of blind detection for terminal devices[1]. CORESET defines the frequency domain resources and the number of time-domain OFDM symbols that the PDCCH may occupy within the corresponding bandwidth part (BWP). In contrast, the SS defines the starting OFDM symbol index and the detection period for blind detection of PDCCH in the corresponding CORESET. These two configuration parameters impose limitations on the PDCCH search space in terms of frequency and time.

In addition, blind detection algorithms have fewer limitations than conventional communication scenarios, resulting in diverse research directions and abundant research achievements. However, research on blind detection algorithms for third-party scenarios is limited by more constraints and higher research difficulty. Therefore, designing an efficient blind detection method complies with the 5G communication protocol standard and is suitable for third-party blind detection scenarios is highly important.

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1 Research Content and Methods

1.1 Research approach

The technical approach of this research method involves starting from two perspectives: the polar decoding algorithm[2-3] and the PDCCH blind detection algorithm. This study aims to enhance the efficiency of PDCCH blind detection while addressing the accuracy of DCI blind detection. An improved third-party efficient PDCCH blind detection method is proposed based on the selection of polar decoding metrics[4-5]. The research ideas and main content are as follows:

1) Research the polar decoding blind detection algorithm, introduce a polar decoding metric based on the length of the DCI, and propose an improved third-party blind detection method based on the polar decoding metric, effectively reducing the number of candidate lengths for the DCI.

2) Research the PDCCH blind detection algorithm to introduce a reordering blind detection algorithm, effectively reducing the number of blind detection attempts for PDCCH.

3) Combine the improved polar decoding algorithm with the reordering blind detection algorithm to propose a third-party efficient PDCCH blind detection method based on the polar decoding metric, which substantially improves the blind detection efficiency while considering the accuracy of target capture.

1.2 Polar decoding blind detection algorithm based on metric selection

Because polar codes were identified as the coding scheme for the 5G control channel, they have served as the basis for research on blind detection algorithms by numerous experts and scholars. There is a design based on the decoding blind detection framework[6-7], while there are adaptive improvements concerning the decoding path metric (PM)[8-9].

During PDCCH transmission, the different lengths of DCI bits and different aggregation levels can affect the size of the original information sequence for polar decoding, thus influencing the distribution of information bit sets and frozen bit sets. In Refs. [10 – 11], a PM based on the length of the DCI is proposed. The original PM only considers the probability of the correct decoding of information bits. By improving the PM to simultaneously consider the probability of the correct DCI length, we can obtain

$$P(\hat{\boldsymbol{u}}_1^N, \boldsymbol{A}_K \mid \boldsymbol{y}_1^N) = \frac{P(\hat{\boldsymbol{u}}_1^N = \boldsymbol{v}_1^N, \boldsymbol{y}_1^N) P(\boldsymbol{v}_1^N \in \boldsymbol{A}_K)}{P(\boldsymbol{y}_1^N)} = P(\hat{\boldsymbol{u}}_1^N = \boldsymbol{v}_1^N \mid \boldsymbol{y}_1^N) P(\boldsymbol{v}_1^N \in \boldsymbol{A}_K) \quad (1)$$

where $\hat{\boldsymbol{u}}_1^N$ is the sequence of input bits; N is the code length; $\boldsymbol{A}_K$ is a set of effective DCI sequences with K bits, where K is the DCI length; $\boldsymbol{y}_1^N$ is the channel output sequence; $\boldsymbol{v}_1^N$ is the transmitted sequence; $P(\hat{\boldsymbol{u}}_1^N = \boldsymbol{v}_1^N \mid \boldsymbol{y}_1^N)$ is the probability of decoding correctly; and $P(\boldsymbol{v}_1^N \in \boldsymbol{A}_K)$ is the probability of the correct DCI length.

Because the information bits are uniformly distributed in {0, 1}, $P(\boldsymbol{v}_1^N \in \boldsymbol{A}_K)$ is calculated by

$$P(\boldsymbol{v}_1^N \in \boldsymbol{A}_K) = \frac{1}{2^K} \quad (2)$$

Combining Eqs. (1) and (2), the DCI-based metric (DM) for path measurements based on the DCI length can be obtained

$$\varphi = -\ln[P(\hat{\boldsymbol{u}}_1^N, \boldsymbol{A}_K \mid \boldsymbol{y}_1^N)] = \sum_{i=1}^{N} \ln\{1 + \exp[-(1 - 2\hat{u}_i) L_N^{(i)}]\} + K\ln 2 \quad (3)$$

where φ is the DCI metric in the logarithmic domain; $\hat{u}_i$ is the i-th sequence of coded bits ; $L_N^{(i)}$ is the log-likelihood ratio of $\hat{u}_i$.

In the optimized DM, the DCI length K is introduced as a penalty factor for the decoding result, increasing the dimensionality of the PM. A smaller DM value leads to a higher accuracy for the size and content of DCI.

1.3 Improvement method in the third-party scenario

In Refs. [10 – 11], the decision to enter DM sorting and the second-stage decoding relies mainly on the CRC check results. However, the CRC-based two-stage blind detection framework is unsuitable for third-party blind detection scenarios. In addition, the design scenario is for regular communication, where the PDCCH candidate positions and quantities can be known a priori from the PDCCH configuration, and the process is relatively simple. However, it does not discuss the blind detection situation when the number of candidates is large, which is the focus of research in third-party blind detection scenarios.

Therefore, further improvements and redesigns are necessary on the basis of these considerations. In the scenario of third-party blind detection, most PDCCH candidates are invalid signals. From a third-party perspective, considering the validity of candidate signals, further discussion on the measurement DM based on the length of DCI is needed.

1) Valid candidate signals. Because of the introduction of the dimension of DCI length in DM, valid candidate signals have the highest accuracy and minimum DM value only when the length of the information sequence is K, which is the decoding path.

2) Invalid candidate signals. Invalid candidate signals can be considered random sequences of 0/1 with a length of N. When decoding is performed using the successive

cancellation (SC) algorithm with an information sequence length of K, it can be hypothesized that there is a reliable channel transmission of a subsequence with a length of K in the mother sequence of total length N. Therefore, as the value of K increases, the reliability of the transmission of N increases, and the accuracy probability of the received end for decoding the information sequence length and content also increases, resulting in a smaller DM value. Thus, when the decoding value K chosen for the invalid candidate signal is substantially different from the actual length of the valid DCI signal, the difference in DM becomes larger, making it easier to distinguish between the two. Therefore, based on the above analysis and inference, the design of the polar decoding blind detection method in the third-party scenario can be conducted, as shown in Fig. 1.

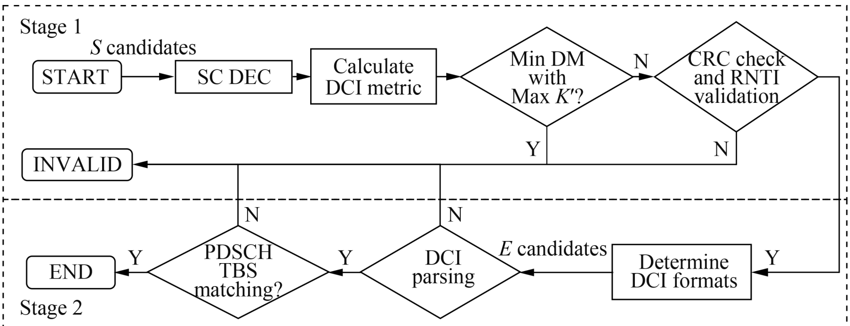

Fig. 1 Two-stage blind detection of polar decoding in a third-party scenario

The specific procedure is as follows:

1) Set the candidate DCI length collection as $\{K_1, K_2, \ldots, K_Y, K'\}$ when decoding, where $K_i (1 \leqslant i \leqslant Y)$ is the candidate DCI length (DCI 1_0, DCI 1_1) obtained by a third-party device based on higher-level signaling decoding, Y is the number of DCI candidate formats, and K' is the information sequence decoding length set greater than K_i to distinguish invalid signals.

2) Decode all the S PDCCH candidates with different information sequence lengths for SC decoding and calculate the corresponding DM concurrently. Sort and find the information sequence length K corresponding to the minimum DM value of the current PDCCH candidate in each decoding path.

3) Identify the candidate with the minimum DM under K' as an invalid candidate signal and exclude it. Determine the valid DCI format length for the surviving candidates based on the DM.

4) Proceed with the RNTI validity verification, DCI content parsing, and data length matching process for the remaining E surviving candidates one by one until the target PDCCH that meets the requirements is found.

The above approach complies with a two-stage blind detection architecture. In the first stage, this approach eliminates some invalid candidates and determines the length of the DCI information sequence, while in the second stage, it performs DCI parsing and length matching to determine DCI content and target capture.

1.4 Research on the PDCCH blind detection algorithm based on reordering

The mobile terminals obtain the PDCCH candidate space by parsing higher-layer signaling to retrieve the CORESET and SS configuration parameters, including the maximum number of PDCCH candidates and the indices of control channel element (CCE) positions for each PDCCH candidate[12].

In the blind detection process at the receiver end, a traditional exhaustive blind detection algorithm is used to extract the PDCCH candidates. This algorithm extracts candidate signals from the PDCCH candidate space in ascending order of aggregation level and performs blind detection sequentially. However, in the third-party blind detection scenario, the detection device cannot calculate the CCE position index of the candidate signals. Therefore, it can only traverse the entire CORESET resource space. It can be determined that the starting CCE position index should be a multiple of the aggregation level.

On the basis of the channel quality indication (CQI) and device capability uploaded by the terminal, combined with the current modulation and coding scheme (MCS) specification, the base station selects the appropriate aggregation level for different formats and lengths of DCI, which also corresponds to the signal's channel encoding and rate matching scheme. Therefore, the receiving end can rank the possibility of aggregation levels used by the base station for PDCCH on the basis of the current channel quality and MCS specification and prioritize the blind detection of the aggregation level with the highest possibility for the corresponding PDCCH candidate. This method has been adopted in Ref. [13] and has achieved good simulation results.

However, the above discussions are based on conventional communication scenarios. Next, the application of this method in third-party blind detection scenarios will be analyzed. When the third-party device receives cell information, it can also obtain the CQI through signal-to-interference plus noise ratio values and set the possibility ranking of aggregation levels for each CQI value. Assuming that the current CORESET comprises 20 CCEs, the application effect of the reordering blind detection algorithm in third-party blind detection is shown in Table 1.

Table 1 Optimization effect of the maximum number of blind detections at different aggregation levels

Aggregation level	Exhaustive	Reordering	Optimization effect/%
1	20	20	0
2	60	20	66.67
4	80	15	81.25
8	81	6	92.59
16	84	3	96.43

According to Table 1, the blind reordering algorithm achieves remarkable efficiency improvements under third-party blind detection, particularly in cases of poor channel transmission quality, substantially reducing the maximum number of blind detection attempts for PDCCH [14]. The CORESET implemented here comprises only 20 CCEs and only considers the case of a single CORESET. However, practical scenarios can have up to 12 CORESETs and 40 SSs within a cell. Therefore, considering all possible scenarios, the blind reordering algorithm should achieve even better optimization effects, which would greatly assist third-party detection devices in capturing target DCI in complex environments.

1.5 An efficient third-party PDCCH blind detection method based on polar decoding metric selection

A review of the previous content shows that the improved polar decoding blind detection method achieves important results in eliminating invalid candidates and capturing target candidates when decoding PDCCH candidate signals. However, further research reveals that this method still has certain limitations. When decoding all candidate signals using SC decoding, it neglects the influence of different channel coding lengths N and coding rates on the configuration and decision results of the SC decoder. During the processing of actual PDCCH candidate signals, the base station selects different channel coding and rate matching schemes according to the MCS regulations for DCIs of different lengths and aggregation levels.

To address these issues and incorporate previous research on blind detection algorithms for reordering, this paper proposes a third-party efficient PDCCH blind detection method based on polar decoding metric selection, as illustrated in Fig. 2.

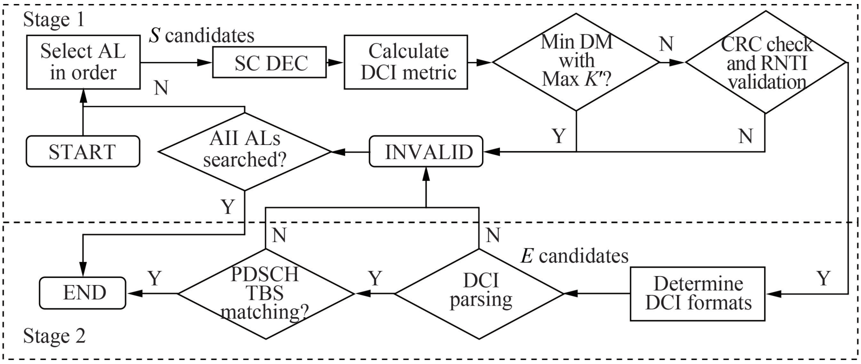

Fig. 2 Third-party efficient PDCCH blind detection method based on polar decoding metric selection

The specific procedure is as follows:

1) Set the corresponding aggregation level blind detection order according to the CQI threshold value, and sequentially select the PDCCH candidate signals corresponding to each aggregation level in this order.

2) As described earlier, perform SC decoding, DM sorting, invalid candidate exclusion, and RNTI validity verification operations on the candidate signals one by one. The difference here is that all PDCCH candidates have the same aggregation level, and their channel coding mother code length is identical to the coding rate.

3) If candidates are valid, proceed to Stage 2; otherwise, return to selecting the PDCCH candidates corresponding to the next aggregation level and reenter the process. If all aggregation levels have completed blind detection, the process ends.

4) Determine the DCI format for the surviving candidate signals based on the DM sorting and RNTI validity verification results.

5) Perform content parsing and data length matching on the candidate signals according to the DCI format. If the requirements are met, successfully capture the target terminal's DCI andcell RNTI (C-RNTI). Otherwise, deem the candidate invalid and return to selecting the PDCCH candidates corresponding to the next aggregation level to reenter the process. If all aggregation levels have completed blind detection, the process ends.

2 Simulation Results

2.1 Simulation of the blind detection algorithm based on metric selection

Table 2 summarizes the parameters used in the simulation. In the proposed passive terminal detection scheme, the third-party device detects only two lengths of DCI, DCI 1_0 and DCI 1_1. To investigate the detection performance of this method on different DCI lengths and enhance the comparability of experimental results, three DCI candidate lengths, including the added 24-bit CRC checksum, were set as controls in the simulation.

Table 2 Simulation parameters of the polar decoding blind detection algorithm

Parameter type	Parameter setting
Encoding length N	1 024
Encoding structure	$G_N = F^{\otimes n}$
Channel	AWGN
Modulation	BPSK
CRC check	CRC_{24C}
Set of valid candidate DCI lengths/bits	[44, 54, 64]
Invalid candidate filter length K'	100

2.1.1 Feasibility verification of an ineffective candidate signal filtering scheme based on DM sorting

Fig. 3 shows the results of the DM sorting filtering on three groups of valid signals with different DCI lengths and one group of invalid signals. The simulation results show that the DM-based scheme can achieve good filtering effects on invalid candidate signals. Under low signal-to-noise ratio (SNR) conditions, the probability of missing detection of valid signals is less than 20%, while the exclusion rate of invalid candidate signals is above 90%. Under good channel conditions, the scheme can achieve an exclusion rate near 100% for invalid signals and a false alarm rate near 0 for valid signals. The decrease in accuracy under low SNR is due to the channel conditions affecting the signal transmission quality, reducing the decoding performance of the SC algorithm and causing measurement result errors. Through this filtering mechanism, most invalid candidates can be excluded in the decoding stage, thereby avoiding subsequent workflows such as C-RNTI validity verification, DCI parsing, and length matching.

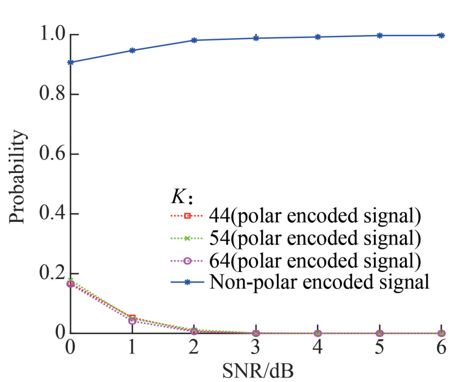

Fig. 3 Exclusion effect of DM sorting on invalid candidate signals

2.1.2 Simulation and analysis of the accuracy of DCI length recognition for this algorithm

The simulated results of DCI length recognition using the PM in the context of third-party blind detection are shown in Fig. 4. This figure compares the performances of the improved metric DM and the conventional metric PM in terms of different SNRs and information bit lengths K for decoding. The results indicate that the improved metric outperforms the conventional metric in terms of DCI length recognition, particularly in low SNRs where the DCI length recognition rate substantially improves. In high SNRs, it achieves a recognition hit rate near 100% without any loss in accuracy compared with traditional algorithms.

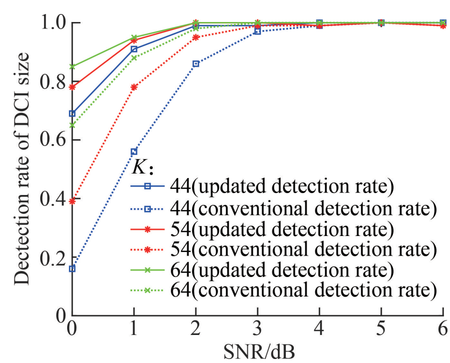

Fig. 4 Comparison of the length recognition rates of two measurements under different DCI lengths

2.1.3 Algorithm simulation and analysis of the DCI

Fig. 5 shows the simulation results of DCI length detection accuracy and DCI content detection accuracy. Because this algorithm determines the DCI sequence length and content in separate stages, the DCI length detection accuracy is always higher than the DCI content detection accuracy. The final DCI recognition result depends on the accuracy of the DCI length detection and the decoding performance of the SC algorithm under different SNRs. Therefore, a certain loss in the recognition rate occurs under low SNR.

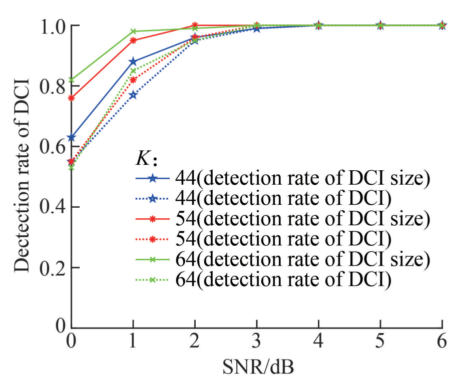

Fig. 5 Results of DCI's accuracy in length and accuracy in content

2.2 Simulation of the blind detection algorithm based on reordering

The simulation parameters are shown in Table 3.

Table 3 Simulation parameters of the PDCCH blind detection algorithm based on reordering

Parameter type	Parameter setting
CORESET frequency domain resources	120 RB
CORESET time-domain resources	1 symbol
SS type	USS
Subcarrier spacing/kHz	30
Channel	AWGN

The simulation results are shown in Figs. 6 and 7. These results indicate that by dynamically adjusting the blind detection order of the aggregation levels, particularly when the channel transmission quality is poor and the DCI aggregation level is high, the blind detection times of PDCCH can be considerably reduced under the condition that the correspondence between the SNR (or CQI) and the aggregation level is correct. As the SNR gradually increases, the PDCCH aggregation level decreases accordingly, and at this point, the average blind

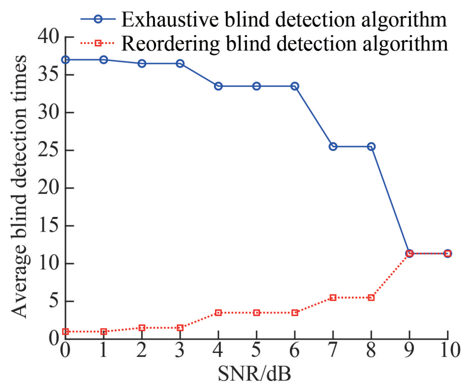

Fig. 6 Average blind detection times of PDCCH using third-party blind detection

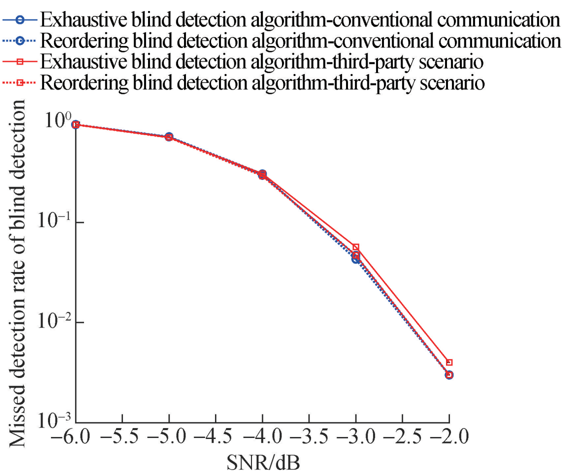

Fig. 7 Different scenarios and the probability of false negatives in blind detection algorithms

detection times of the exhaustive search blind detection algorithm and the reordering blind detection algorithm are similar.

The simulation results in Fig. 7, which show the missed detection probability of different scenarios with blind detection algorithms, demonstrate that the exhaustive search blind detection algorithm and the reordering blind detection algorithm have similar PDCCH detection accuracy and exhibit good blind detection performance. As both algorithms differ only in the blind detection order of aggregation levels and require traversing all PDCCH candidate signals, they have an unsubstantial impact on blind detection results and a low missed detection probability.

2.3 Simulation of a third-party efficient PDCCH blind detection method based on the polar decoding metric selection

Simulations were conducted on the MATLAB platform to build a 5G PDCCH blind detection simulation link and verify the effectiveness of the proposed improvement method. The simulation parameters are shown in Table 4.

Table 4 Simulation parameters of the PDCCH blind detection method based on the polar decoding metric selection

Parameter type	Parameter setting
CORESET frequency domain resources	120 RB
CORESET time-domain resources	1 symbol
CCE-REG mapping	Non-interleaved
Subcarrier spacing/kHz	30
Channel	AWGN
Modulation	QPSK
SS type	USS
SS maximum candidate number	[6,6, 2, 2, 1]
Aggregation level	[1, 2, 4, 8, 16]
DCI format	DCI 1_0/DCI 1_1
DCI length/bit	64
RNTI type	C-RNTI

In this section, simulations were only performed for the scenario of PDCCH blind detection in 1 CORESET and 1 SS. The target DCI is scrambled using C-RNTI and has a length of 64 bits. To correspond to Table 1, the simulation set 20 CCE resources in the CORESET, occupying 120 RB in the frequency domain and 1 OFDM symbol in the time domain.

The simulation results are shown in Fig. 8 and validate the effectiveness of the proposed method. When a third-party device blindly detects the target DCI in the CORESET using the above-mentioned method, it achieves good capture performance for the target candidates, eliminating most of the invalid candidate signals in the first stage. The exclusion rates under different SNRs are near 90%.

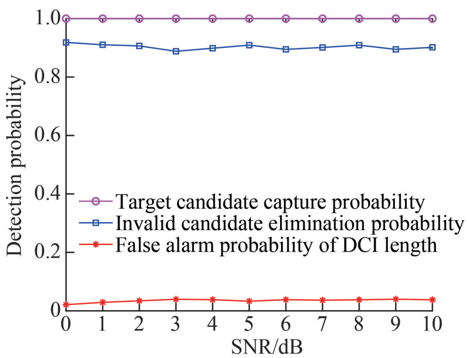

Fig. 8 Simulation results of a third-party efficient PDCCH blind detection method based on polar decoding metric selection

The simulation results of this case and the invalid candidates excluded in Section 2.1 differ because the invalid candidates obtained in the current simulation are not random signals unrelated to the target candidates. When selecting PDCCH candidates based on different aggregation levels, valid transmission data of some or all target DCIs may be included. Therefore, filtering invalid candidates has a certain impact, and some invalid candidates may be misjudged as DCI candidate signals of other lengths and enter the second stage. In simulations where the transmitting end uses larger aggregation levels to enhance PDCCH transmission efficiency under low SNR, the target candidate capture rate is improved.

3 Conclusions

1) Against the backdrop of a surge in demand for 5G terminal management, this study investigates and designs an efficient blind detection method for third-party scenarios to meet the high blind detection efficiency requirements of passive detection schemes.

2) This paper focuses on the research and improvement of the polar decoding blind detection algorithm and the PDCCH blind detection algorithm, proposing a third-party efficient PDCCH blind detection method based on polar decoding metric selection.

3) The 5G PDCCH blind detection simulation link is constructed using MATLAB for verification and analysis, and the results indicate that the proposed method can effectively reduce the number of PDCCH blind detections and the quantity of DCI candidate lengths while maintaining the accuracy of target detection, thereby enhancing the blind detection efficiency with practical application value.

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一种基于 Polar 译码度量选择的第三方高效 PDCCH 盲检方法

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摘要:为研究和设计面向第三方场景的高效盲检方法,提出了一种基于 Polar 译码度量选择的第三方高效 PDCCH 盲检方法,其技术路线包括 Polar 译码算法与物理的下行控制信道(PDCCH)盲检算法 2 个板块. 基于 Polar 译码盲检算法,引入一种基于下行控制信息(DCI)长度的 Polar 译码度量,提出了改进的基于 Polar 译码度量选择的第三方盲检方法. 基于 PDCCH 盲检算法,引入一种重排序盲检算法. 将改进的 Polar 译码算法与重排序盲检算法有机结合,提出面向第三方场景的高效 PDCCH 盲检方法. 基于 MATLAB 平台搭建 5G PDCCH 盲检仿真链路,对所提方法进行验证与分析. 结果表明,该方法能够同时有效减小 PDCCH 盲检次数与 DCI 候选长度数量,在保证目标捕获准确率的前提下提高盲检效率.

关键词: Polar 译码;物理的下行控制信道; 盲检;下行控制信息
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