Performance analysis of NR Polar Codes at short information blocks for control channels

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Abstract One important innovation in information and coding theory is polar code, which delivers capacity attaining error correction performance varying code rates and block lengths. In recent times, polar codes are preferred to offer channel coding in the physical control channels of the 5G (5th Generation) wireless standard by 3GPP (Third Generation Partnership Project) New Radio (NR) group. Being a part of the physical layer, Channel coding plays key role in deciding latency and reliability of a communication system. However, the error correction performance degrades with decreased message lengths. 5G NR requires channel codes with low rates, very low error floors with short message lengths and low latency in coding process. In this work, Distributed Cyclic Redundancy Check Aided polar (DCA-polar) code along with Cyclic Redundancy Check Aided polar (CA-polar) code, the two variant of polar codes have been proposed which provide significant error-correction performance in the regime of short block lengths and enable early termination of decoding processes. While CRC bits improve the performance of SCL (successive cancellation list) decoding by increasing distance properties, distributed CRC bits permit path trimming and early-termination of the decoding process. The design can reduce the decoding latency and energy consumption of hardware, which is crucial for mobile applications like 5G. The work also considers the performance analysis of NR polar codes over AWGN (Additive White Gaussian Noise) for short information block lengths at low code rates in the uplink and downlink control channels using SNR (Signal to Noise Ratio) and FAR (False Alarm Rate) as the performance measures. Simulation results illustrate different trade-offs between error-correction and detection performances comparing proposed NR polar coding schemes.

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1 Introduction

The accelerative usage of wireless devices with better Quality of Service (QoS), along with the need for reliable and low latency web connectivity for practical Internet of Things (IoT) applications have been seen in recent times. The rapidly growing requirement for high throughput data, video and messaging traffic was steered the 4th Generation (4G) of mobile communication systems towards the advancement of the 5th Generation New Radio (5G NR) standard. Future mobile communication systems are expected to confront remarkable progress in the connectivity, traffic capacity and range of usage states [2] beyond 2020. This need draws a significant challenge, which involves a sustainable advancement of enhanced system competences, for example spectral energy, system operative and cost efficiencies [2], [3]. The classifications of 5G NR into three subtypes are mentioned in Table 1.

Channel coding enables error detection and correction in presence of noise, fading and interference. Channel coding of sender data and control information, both are measured separately as per 3GPP NR specification. LDPC codes are chosen for the data channels, whereas polar codes are preferred for the control channels of NR, substituting the turbo and tail-bit convolutional codes (TBCC) of 4G, correspondingly. Polar codes are capacity attaining channel coding scheme and expected to support the best error correction at short block lengths for control information [4], [5]. The observations on these two prospective channel coding methods for NR are presented in Table 2.

TS 38.212 [6] provides technical description of the polar and the LDPC encoder in the data and control channels, correspondingly. But the respecting polar and LDPC decoding processes are not stated in detail for 5G NR. The LDPC and polar codes for 5G NR are mentioned in [7]. But it does not detail all polar coding components and decoding operations. Further advances of NR polar codes are specified in [8]–[11]. [9] proposes hash-polar codes to improve performance over Parity Check (PC)-polar codes under specific False Alarm Rate (FAR). Moreover, an enhanced blind detection architecture is offered for PDCCH (Physical Downlink Control Channel) in [10]. A logarithmic stack polar decoding with low complexity has been suggested for 5G URLLC in [11]. Though none of these works deliver systematic explanation of the polar coding components and decoding for NR control channels.

In this work, a new polar coding method exploiting Distributed Cyclic Redundancy Check Aided Polar (DCA-polar) coding algorithm for the NR control channels is proposed and applied along with Cyclic Redundancy Check Aided Polar (CA-polar) codes. In contrast to the previous publications, the main contribution of this work is to deliver the operation and error performance (SNR and FAR) analysis of the polar codes at short block lengths for the NR control chan-
nels (specifically in uplink and downlink control channels). Simulation results are presented in graphs and performance analysis is done in detail. All the work has been performed as per new 5G standard specifications set by 3GPP NR group [6]. The explanation of the design of the NR polar codes (illustrated in Figure 1) and the future improvement prospects are also provided.

The rest of this paper is arranged in the given fashion. The uplink and downlink physical channels of 5G NR, applications, supported polar coding, information block lengths and encoded block lengths are detailed in sect. 2. The design schemes of DCA-polar codes are discussed in Sect. 3. Next, the operation of polar coding components in 5G NR physical channels is explained in Sect. 4. Complexed theoretical proofs and equations are omitted and possible references are given for in detail study. Simulation outcomes are displayed to compare the error correction and detection performances of different polar code combinations for various NR control channels in Sect. 5. Lastly, the conclusion is drawn in Sect. 6.

Table 1 Classifications of 5G NR based upon expected applications

| Generation | Technologies | Expected Applications | Characteristics |
|------------|--------------|-----------------------|-----------------|
| 5G NR      | massive MIMO communication in mmWave, Hybrid beamforming, Novel coding schemes (LDPC and Polar coding), OFDM (Orthogonal Frequency Division Multiplexing) | cMBB (Enhanced Mobile Broadband): high-capacity and faster mobile communications, 3D / Ultra-HD videos, virtual and augmented reality. URLLC (Ultra-Reliable Low Latency Communication): V2V(vehicle-to-vehicle) and V2I(vehicle-to-infrastructure) communications, autonomous driving. mMTC (Massive Machine-Type Communications): consumer and industrial IoT, MC-M2M (mission-critical machine-to-machine) communication. | Extreme broadband, higher throughput of 20 Gbps, ultra-low latency. |

Table 2 Annotations on channel coding methods for 5G NR

| Parameter | LDPC | Polar Code |
|-----------|------|------------|
| Latency   | Parallelised LDPC decoders can be implemented to decrease latency. | Several design methods are employed to decrease latency but polar codes are not highly parallelisable. |
| Complexity| Widely employed in commercial hardware to support throughput in Gbps, lesser size and energy efficiency, but have concerns for NR. | These codes have no existing commercial implementations but they are implementable and have some concerns for NR. |
| Applicability | Well established but more technical specifications are needed for NR requirements. | Newly introduced, Less well established and need additional effort for the NR requirements. |
| Flexibility | All prospective channel coding methods are believed to deliver acceptable flexibility. | |
NR Physical Control Channels

The NR physical layer includes several uplink and downlink control channels, as presented in Table 3. The physical channels are categorized as data channels to transmit user data, or control channels to transmit control information [14]. The uplink channels transport information from MS (Mobile handset) to BS (Base station) and the BS transmits to the MS in the downlink channel [12]. In 5G NR, PUCCH (Physical Uplink Control CHannel) and PUSCH (Physical Uplink Shared CHannel) are used for transmitting control information. Also, PDCCH (Physical Downlink Control CHannel) and PDSCH (Physical Downlink Shared CHannel) are used for receiving control information. PBCH (Physical Broadcast CHannel) is used for broadcasting control information to many MS connected to the BS. The control channels are transmitting control information to synchronize all MS connected with BS to manage transmission in data channels and assist preliminary connections to BS [13]. The lengths of information and encoded blocks in polar coding for NR physical uplink and downlink control channels are described in Table 4.

To reduce polar decoding complexity to extend MS battery life, early termination [16] is maintained in polar coding for PDCCH channel and CRC bits are dispersed through the information bits by interleaving. Instead of recovering the CRC bits simply at the end of the polar decoding, the CRC bits are recovered by DCA-polar decoding during the decoding process and decoding is stopped if the CRC fails [17], [18]. Moreover for the downlink control channels, DCA-polar shows better FAR performance gain with compare to CA-polar (CRC-Aided polar) decoding [16]. This gain is realized by using the CRC interleaver and it transfer the CRC bits to proper positions. Each MS implements blind decoding, where it attempts the decoding of numerous hypothesised blocks with combinations of A (information block length), E (encoded block length), DCI (Downlink Control Information) type and location within the PDCCH channel.
Table 3 | NR Physical control channels (used in this work)

| Physical Channel                          | Channel Coding          | Applications                                                                 |
|------------------------------------------|-------------------------|------------------------------------------------------------------------------|
| PUCCH (Physical Uplink Control CHannel)  | Polar code or Short Block code | conveys UCI (Uplink Control Information), CQI (Channel Quality Indicator) information and HARQ (Hybrid Automatic Repeat Request) information. |
| PDCCH (Physical Downlink Control CHannel)| Polar code              | conveys DCI (Downlink Control Information) including scheduling grants for PUSCH (Physical Uplink Shared CHannel) and scheduling decisions for PDSCH (Physical Downlink Shared CHannel). |

Table 4 | The block lengths used in polar coding for NR physical channels

| NR Physical channels | Information Block lengths | Encoded Block lengths | Supported polar coding |
|---------------------|---------------------------|-----------------------|------------------------|
| PUCCH               | A ∈ [12, 1706]            | E [A + 9, 8192] if A ∈ [12, 19] or [A + 11, 8192] if A ∈ [20, 359] or [A + 11, 16385] if A ∈ [1013, 1706] or [2[A/2]+22, 16385] if A ∈ [360, 1012] or [A + 11, 16385] if A ∈ [360, 1012] or [2[A/2]+22, 16385] if A ∈ [1013, 1706] | CA-polar with 11 CRC bits |
| PDCCH               | A ∈ [12, 140]             | E [A + 24, 8192], practically E [108, 216, 432, 864, 1728] | DCA-polar with 24 CRC bits |

3 Distributed CRC-Aided Polar (DCA-Polar) codes in 5G NR

Polar codes can asymptotically achieve channel capacity in low-complexity SC (successive cancellation) decoding [19]. However, SC decoding supports mediocre error-correction performance at finite code length and suffers from low error correction capability in wireless channels [21]. [20] proposes SCL (successive cancellation list) decoding which improves SC by using L candidate codewords throughout the decoding to produce improved BLER (block error rate) performance with a higher complexity. The list size L of SCL decoding extents the number of SC decoding executed in parallel [20]-[25], [31]-[32]. [22] introduces CA-SCL (CRC-aided SCL) decoding where CRC (cyclic redundancy check) code is added to SCL decoder to further enhance the BLER. The selection of the optimal CRC is of utmost need to boost the error correction of CA-SCL [26]. Figure 2 depicts SCL decoding algorithm with CRC bits whereas Figure 3 depicts CA-SCL polar encoding and decoding process.

Polar code is selected as a preferred 5G-NR coding scheme for UCI and DCI (uplink and downlink control information) [6]. In 5G-NR for DCI, polar codes are aided with distributed CRC and input bit interleaver is facilitated for PBCH payloads and PDCCH DCIs. Distributed CRC bits are acquired by bit interleaving between the CRC encoder and the polar encoder. Also, the CRC bit is positioned after the last bit required for calculation [27]. Thus, the decoding complexity is diminished by early terminating the decoding as soon as improper check is encountered [6],[28]-[29], or else error-correction is enhanced by trimming the decoding tree as Parity-Check(PC) polar codes [30]. The interleaver allocates the CRC bits equally inside the information bits whereas CRC remainder bit are come across after appropriate information bits during the decoding process. Thus, Distributed
CA (DCA) polar decoder eases the decoding complexity applying early termination of the decoding process if each path is meeting an incorrect check. Furthermore, the distributed CRC bits are used to trim the SCL decoding tree and enhance the decoder error-correction performance [30]. Figure 4 depicts the DCA polar code design scheme in 5G-NR.

4 Polar Coding Component Operation in 5G NR

The operation of polar coding components in 5G NR physical channels is mentioned in this section. During encoding and decoding long blocks, code block segmentation is applied in PUCCH/PUSCH channel as mentioned in [6]. As the
information block lengths are restricted to $A \in [12, 140]$ for PDCCH channel, code block segmentation is not applied. Code block segmentation permits the polar code core length restricted to $N = 1024$ bits while the largest $A = 1706$ bits. This declining of the polar code core complexity upsurges with $N \log N$. Also, code block segmentation permits up to $E = 2048$ bits for $N = 1024$, deprived of depend on repetition, which worsens the error correction performance. During decoding, code block segmentation is complemented by concatenating the number of decoded
information block segments and removing the padding bit if used in encoding.

CRC calculation and attachment are mentioned in [6]. In the course of polar encoding, redundant CRC bits are added with each information block segment to achieve error detection and correction in the decoder [17]. CRC checks are performed by the polar decoder to decide if a codeword is free of errors and the codeword is selected from a list of decoding candidates. The numbers of CRC bits necessary for error detection is mentioned as \([-\log_2(FAR)]\) [6]. CA-SCL polar decoding with a list size of \(L = 8\) shows a great trade-off between error correction and decoding complexity. Hence, \(\log_2(L) = 3\) CRC bits is offered to maintain the CA-SCL decoding. For best FAR results, the 11 and 24-bit CRC generator polynomials are chosen for the PUCCH and PDCCH control channels as shown in Table-5. In polar decoding, a CRC check is done inputting decoded information bits to a CRC generator and matching the resultant P CRC bits with the P decoded CRC bits. If both are equal, then no errors are sensed and a successful CRC check is counted. Else, the decoded information sequence and CRC bits are inputted in the CRC generator attaining P-bit syndrome. If the syndrome has P zero-valued bits, then no errors are identified and the CRC check is successful.

CRC interleaving [6] is applied shuffling the order of the bits achieved following CRC attachment in PBCH encoding and following CRC scrambling during PDCCH encoding. NR polar code implements redundancy as frozen and PC bits in the information sequence and CRC bits to facilitate forward error correction, as mentioned in [6]. Bit positions regarding puncturing or shortening through rate matching are used for frozen bits. Frozen and PC bits are added to increase the length of the input bit sequence from K bits to the block length \(N = 32, 64, 128, 256, 512\) and 1024 as detailed in [6]. After embedding frozen and PC bits within the information and CRC bits, polar encoding is done by multiplying the row vector of \(N\) input bits \(u = [u_0, \ldots, u_{N-1}]\) by a Kronecker kernel matrix \(F_N\) obtaining a row vector of \(N\) encoded bits \(d = [d_0, \ldots, d_{N-1}]\) [18], to \(d = u F_N\). Here, \(F_N\) equals \(F_2^n\) is the nth Kronecker power of matrix \(F_2\), where \(n = \log_2(N)\) and \(F_2 = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}\).

Polar encoding is reversed by polar decoding in the receiver. Meanwhile, the decoding complexity of polar list decoders is as low as \(O(LN \log N)\), where \(N\) is the encoded block length and \(L\) is the list size. These features make polar code very attractive for applications like digital communications and storage. The detailed discussion of polar encoding and decoding process is mentioned in [31]-[32]. A distributed CRC is applied for PDCCH to allow early termination [17]-[18]. The rate matching process is decomposed in sub-block interleaving, bit selection and channel interleaving as detailed in [6]. The main error correction capability is provided by the polar coding, whereas the error correction capability of the polar code is improved by the sub-block interleaving and the burst errors are dispersed by the channel interleaver. But, the channel interleaving is applied only for PUCCH channel, whereas it is avoided for PDCCH channel and PBCH channel.
Table 5 CRC generator polynomials of 5G NR

| NR Physical channels | Information Block lengths | CRC bits | CRC generator polynomials | Polar coding used |
|----------------------|---------------------------|----------|---------------------------|-------------------|
| PUCCH                | A ϵ[20, 1706]            | P=11 bits| gCRC11(x) = [x11+x10+x9+x5+1] | CA-polar          |
| PDCCH                | A ϵ[12, 140]             | P=24 bits| gCRC24(x) = [x24+x23+x21+x20+x17+x15+x13+x12+x8+x4+x2+x+1] | DCA-polar         |

5 Error Detection and Correction of NR Polar Codes

For the polar codes of 5G NR, this section evaluates SNR and FAR to examine error performance. To attain a BLER of $10^{-3}$, the SNR necessary for the PUCCH and PDCCH channels is shown in Figures 5 and 6, respectively. In Figure 7, the graph of FAR vs. CRC bits is attained by decoding random Gaussian distributed LLRs whereas simulation is performed till 1000 false alarms or block errors are detected. However keeping the coding rate A/E unchanged, BLER and SNR of the polar codes increases upon incrementing A as displayed in Figure 6 to 7. Once A and E are small, BLER of the polar codes approaches near the capacity bound. Once the coding rate is less, NR polar decoding in PUCCH and PDCCH channels achieve error correction requirements of BLER = $10^{-3}$ at lower SNRs as shown in Figures 5 and 6. Advantage of NR polar codes at short block lengths can be seen clearly from the figures as error performance approaches near the capacity bound for short block lengths. Finally, FAR performance progresses upon incrementing the CRC length of NR polar codes for the PUCCH and PDCCH channel, as shown in Figure 7.

Fig. 5 Graph of SNR Es/No vs. A (information block length) for NR polar code in PUCCH control channel with BLER of 10^{-3}
6 Conclusion

This paper has provided the operation as well as error performance analysis of the polar codes for the 5G NR control channels (PUCCH and PDCCH). First, the PUCCH and PDCCH control channels of 5G NR are briefly studied with the encoding and decoding operation of NR polar coding. Then for 5G NR control channels, the error detection and correction performance of the polar codes are systematically examined using SNR and FAR analysis. With the conflicting metrics for example the coding-complexity, coding-delay, code-length, code-rate etc. and the complex design trade-offs, the idea of formulating the optimal polar codes rises. It is extremely promising and challenging forthcoming research interest is to design the optimum polar codes, subject to the particular practical application.

7 Declarations

7.1 Funding

Not Applicable.

7.2 Conflicts of interest/Competing interests

No potential conflicts of interest was reported by the authors.
7.3 Availability of data and material

Not Applicable.

7.4 Code availability

Not Applicable.

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