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1 Introduction

In this contribution, we discuss the drawbacks of NR Short Block-Length codes (SBLC) and show the benefits of transmission of small payloads without DMRS. Moreover, we outline some areas of novel coding strategies with improved performance.

In the last meeting RAN1#125, although some discussions have taken place, no agreements have been reached regarding SBLC.

Agreement:	**RAN1#123**

- For the study of channel coding for small UCI with payload size of 3~11bits, at least considering:
  - 5G RM code
- Identify the justifiable drawbacks of 5G RM code, if exists, study potential solution(s).

RAN1 will continue to identify the justifiable drawbacks of 5G RM code and, if exists, study potential solution(s).

We argue that the main drawback of the 5G RM code is its subpar performance compared to non-coherent codes that do not require DMRS and are decoded via sequence correlation. The main improvements stem from the following three aspects:

1. No DMRS, i.e. DMRS resources can be used to encode payload
2. Optimized code for non-coherent detection, i.e. sequence correlation
3. Improvements of PAPR via optimized sequence design

As per chairman guidance, we try to decouple the channel coding aspect from the transmission aspect of UCI on PUCCH. Please refer to our contribution on sequence-based PUCCH in [2].

In summary, transmitting small payloads of up to 11 bits via transmit sequences generated from RM channel coding and DMRS is highly inefficient. The only benefit that this sequence-encoding offers, is the strong structure which can be decoded very efficiently (coherent detection). On the other hand, sequenced-based transmissions, where the sequences are designed for non-coherent detection, have enormous performance advantages.

Hence, we propose that the RM code is replaced by a code that is optimized for non-coherent detection.

The remainder of this contributions provides an in-depth analysis of 5G RM codes and potential enhancements.

2 Characteristics of 3GPP Short Block Length Codes

In 3GPP NR, the transmissions of small packets $B \leq 11$ usually employ sequence encoding if $B \leq 2$, e.g. in PUCCH Formats 0 and 1, or Reed-Muller (RM) coding $B > 2$, [1]. RM coding has been a part of the 3GPP specifications since 3G where the simple and efficient decoding via a Hadamard transform was very appealing. Later it was used in LTE Rel-8 (TS36.212 V8.2.0) to encode UCI carrying channel quality information (CQI). First a $(20, B)$ binary block code was specified which was extended in NR Rel-15 to a $(32, B)$ block code.

However, RM codes perform far from optimal and can be significantly improved upon. Hardware has improved tremendously in 25 years and low decoding complexity is no longer a strong argument to justify the mediocre performance of RM codes.

Alternatives exist, such as the orthogonal convolutional codes used in CDMA systems, or short block-length codes for phase-modulation (e.g. QPSK) [3]. The latter are simple binary or non-binary codes which are designed for non-coherent detection when the number of signaling dimensions do not allow for orthogonal transmission. More recently, novel strategies for short block-length transmission have been studied in the Rel-17 SI on coverage enhancements [4] in order to improve coverage of PUCCH (notably PUCCH Format 3). This so called DMRS-less designs showed significant performance gains but specification has been postponed due to lack of time and consensus.

Returning to the Short Block-Length Codes in NR. When appropriate permutations of the rows of the generator matrix of the $(32, B)$ code is applied, for $B \leq 6$, the code represents a bi-orthogonal code in 32 *real* dimensions. To see the bi-orthogonal nature, the codewords must be transformed using a Hadamard transform of order 32. For $B > 6$ the code is extended by adding cosets of the base bi-orthogonal code obtained from $B = 6$. For instance, consider $B = 7$, the code is extended by its coset obtained from the 7th column of the generator matrix. It is clearly no longer a bi-orthogonal code. A similar procedure is used for the remaining 4 codes (i.e. $B = 8,9,10,11$).

To characterize the performance of the current 3GPP short block-length code, we use the set of pair-wise correlations between the transmit vectors $\boldsymbol{x}$, namely

$$\rho(m, m') = \boldsymbol{x}_m^H \boldsymbol{x}_{m'} \quad , m \neq m'$$

where $m, m' = 0,1, \dots, 2^B - 1$ is the message index. In the case of the joint estimation-detection receiver, the probability of error of any coding scheme increases monotonically with $\rho_{\text{NC,max}} = \max_{m \neq m'} |\rho(m, m')|$.

As a comparison, in Table 1, we compute the asymptotic loss $1 - \rho_{\text{NC,max}}$ of the 9 short-block length codes used in 3GPP 5G NR compared to an orthogonal signal set. For $3 \leq B < 12$, these codes are built from a $(32, B)$ binary block code and modulated using QPSK modulation. Hence there are 16 QPSK symbols per codeword. For this evaluation, we consider that the codes are mapped to the PUCCH Format 2 with 24 dimensions, e.g. 1 PRB and 2 symbols, with 8 additional symbols for DMRS. DMRS are known components of $\boldsymbol{x}_m$ and constant for all m. These symbols introduce redundancy which is independent of the transmitted data and can firstly be used to resolve the channel uncertainty and secondly to allow for often simpler receiver structures which split the estimation and detection components.

For $B = 3{,}4$ the performance is far from an orthogonal signal set even though the number of dimensions (24) is larger than 2^B. In general, for $B < 8$, where orthogonal signal sets can be easily constructed, there are clearly potential gains. This reflects the loss in signal energy due to DMRS which is significant. For $B > 4$, the performance degrades significantly, and it should be noted that even by increasing the number of dimensions beyond 24, the performance will not improve since the rate matching procedure simply repeats the bits (symbols) across frequency and time resources. The rate-matching will be beneficial for a frequency-selective channel but not for the simpler AWGN channel model considered in this comparison. Repetition in time will increase the signal energy (since there is a peak power constraint per OFDM symbol) but it will not increase the coding gain.

B	$1 - \rho_{\text{NC,max}}$	$-10\log_{10}(1 - \rho_{\text{NC,max}})$ [dB]
3	0.627322	2.025
4	0.466406	3.312
5	0.466406	3.312
6	0.466406	3.312
7	0.399075	3.990
8	0.349146	4.570
9	0.349146	4.570
10	0.292893	5.333
11	0.283140	5.480

Table 1: Example of asymptotic loss of the 3GPP $(32, B)$ code compared to orthogonal set when mapped to PUCCH Format 2 with 24 dimensions.

For $B > 8$, we will discuss short block-length non-orthogonal constructions that fill the gap shown Table 1 which are based on similar non-orthogonal codes to those in [3] but for lower spectral-efficiency and small block lengths.

Many companies also observed a rank deficiency of RM code for high code rates. Table 2 below, gives a more complete picture of the asymptotic loss for various output lengths N. For high code rates, we also observe rank deficiency, i.e. infinity asymptotic loss. As expected, the asymptotic loss decreases with increasing N. The decrease is not monotonic (visible for smaller B) because a DMRS symbol is added every 3 resource elements in this example.

	N														
B	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32
3	5.94	3.01	1.76	2.43	2.66	2.40	2.77	2.95	2.73	2.53	2.55	2.40	2.27	2.04	2.03
4	Inf	6.79	5.94	6.37	5.40	3.80	3.99	4.20	4.14	4.19	4.30	4.36	3.70	3.17	3.31
5		6.79	5.94	6.37	5.40	3.80	3.99	4.20	4.31	4.48	4.36	4.36	3.70	3.17	3.31
6		Inf	Inf	Inf	6.53	4.35	5.05	4.20	4.31	4.48	4.36	4.47	3.70	3.17	3.31
7			Inf	Inf	7.19	7.56	6.79	5.36	5.55	5.42	5.60	4.68	4.70	4.09	3.99
8			Inf	Inf	7.19	7.56	6.79	5.62	5.55	5.42	5.60	5.46	5.34	5.33	4.57
9				Inf	7.19	7.56	6.79	6.15	5.55	5.67	5.94	5.71	5.64	5.33	4.57
10				Inf	9.82	7.56	6.79	6.15	5.94	5.67	5.94	5.71	5.64	5.33	5.33
11					Inf	Inf	Inf	8.13	6.58	6.11	6.53	6.08	5.94	5.73	5.48

Table 2: Example of asymptotic loss of the 3GPP (N,B) code compared to orthogonal set when mapped to PUCCH Format 2.

Observation 1: The 3GPP RM code is rank deficient for high code rates.

Observation 2: The performance of 3GPP RM codes is far from optimal and there is significant room for improvement.

Proposal 1: Study novel encoding schemes for small payloads designed for non-coherent detection.

3 Transmission with and without DMRS

The majority of codes used in NR for small payloads (e.g. PUCCH) are based on constructions using a combination of a binary channel code (short block-length Reed-Muller or Polar code), a modulation-mapping combined occasionally with an orthogonal spreading function across multiple OFDM symbols and the insertion of DMRS known to the gNB receiver. The intent is to perform channel estimation using the DMRS to allow for quasi-coherent detection at the gNB. Exceptions are PRACH and PUCCH Format 0, since non-coherent detection is implied as no explicit transmission of DMRS is part of the waveform description. Both are examples of non-binary orthogonal transmission. Interestingly, PUCCH Format 1 with 1-bit of payload is an instance of orthogonal transmission in NR, despite the presence of DMRS in the transmitted waveform.

Channel uncertainty in NR is commonly addressed by channel estimation which firstly suffers from signal energy overhead due to use of DMRS and secondly from noise enhancement due to quasi-coherent detection using the *estimates* in the place of the true channel, which in turn induces a performance penalty.

In coverage-limited scenarios, spectral-efficiency and receiver signal-to-noise ratios are both very low. As a result, the use of DMRS inherently introduces a non-negligible amount of sub-optimality that we should strive to reduce for short block-length cases. Transmission schemes without DMRS are thus to be considered when it comes to coverage enhancement system configurations.

For short block-lengths and/or low-spectral efficiency, codes can be designed for non-coherent detection (NCD). Two classes can be considered, *orthogonal* codes and *non-orthogonal* codes. When spectral-efficiency is sufficiently low it is possible to use an orthogonal transmission and this should be the chosen method. Although there is no formal proof in the scientific literature, it is widely believed that an orthogonal transmission is optimal for cases of vanishing spectral-efficiency when there is channel uncertainty at the receiver.

When the number of dimensions is not sufficiently high to use an orthogonal signal set, some form of non-orthogonal transmission is required. The conventional approach is to use DMRS signals to estimate the channel and then generate sufficient statistics for detection of the coded bit-sequence stemming from a channel code (including any rate-matching or interleaving) under the assumption that the channel is estimated perfectly. The channel code is thus constructed assuming a coherent metric in the decision rule, typically the maximum-likelihood decision rule with perfect channel state information.

Observation 3: For short block lengths, DMRS introduce a significant amount of sub-optimality and potential novel coding strategies should aim to reduce this overhead.

4 Linear Block Codes for Non-Coherent Detection

The sequences encoding up to 11 bits should be designed to maximize the performance for non-coherent detection, i.e. sequence correlation. At the same time, they should offer enough structure to enable a low complexity receiver implementation.

A promising technique proposed during the SI on UL coverage enhancements consists of using a product-code, where the B input bits are encoded *independently* in frequency-domain (vertical) and time-domain (horizontal). This vertical and horizontal coding (VHC) strategy allows the two components to be decoded independently which reduces the complexity in the receiver.

In either dimension, if enough resources K are available, e.g. $B \leq \lfloor \log_2 K \rfloor$, then B bits can be transmitted in K resources with orthogonal sequences. However, if the available resources are not enough, a linear block code can be used to generate the codewords that are mapped to the resources.

Consider a non-coherent code where B bits $\boldsymbol{d} = [d_0, d_1, \dots, d_B]$ are encoded as

$$\boldsymbol{c} = \boldsymbol{d}\boldsymbol{G}$$

where $\boldsymbol{G}$ is the generator matrix and $\boldsymbol{c}$ are the coded bits which, for instance, can subsequently be modulated to N-PSK symbols and mapped to the available resources. As an example, consider $N = 4$ (e.g. QPSK), $B = 8$ and $K = 7$, a good (i.e. for non-coherent detection) generator matrix in base-4 is given by

$$\boldsymbol{G} = \begin{bmatrix} 1 & 0 & 0 & 0 & 2 & 3 & 3 \\ 0 & 1 & 0 & 0 & 2 & 3 & 3 \\ 0 & 0 & 1 & 0 & 2 & 3 & 3 \\ 0 & 0 & 0 & 1 & 0 & 1 & 2 \end{bmatrix}$$

For $K = 14$, the generator matrix is

$$\boldsymbol{G} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 3 & 3 & 0 & 1 & 2 & 0 & 0 & 1 & 2 \\ 0 & 1 & 0 & 0 & 1 & 3 & 3 & 0 & 2 & 0 & 1 & 2 & 0 & 1 \\ 0 & 0 & 1 & 0 & 3 & 0 & 2 & 0 & 1 & 1 & 1 & 0 & 2 & 3 \\ 0 & 0 & 0 & 1 & 1 & 0 & 2 & 0 & 1 & 0 & 2 & 2 & 1 & 3 \end{bmatrix}$$

5 Simulation Results

In this section, we compare the performance of the 5G RM code and a linear block code optimized for non-coherent detection from Section 4 in AWGN channels. We assume a $B = 8$ bit payload, 1 PRB and either $L = 7$ or $L = 14$ OFDM symbols. The output bits of the channel code are mapped to L QPSK symbols which are transmitted on a single active resource element in each OFDM symbol. Due to the phase ambiguity in RM code, we assume a fixed QPSK symbol on the last OFDM symbol. Hence, the output of the RM code is 12 bits and 26 bits for $L = 7$ and $L = 14$, respectively.

Table 3 shows the asymptotic loss $10\log(1-\rho_{\text{NC,max}})$ for the 5G RM code and the non-coherent code. It can be observed that for $L=7$, both codes have similar asymptotic loss, but for $L=14$, the non-coherent code is about 6 dB better.

L	RM code	Non-Coherent Code
7	6.36 dB	5.44 dB
14	8.45 dB	2.34 dB

Table 3: Asymptotic loss for the simulated configuration.

The impact on BLER and BER is shown in Figure 1 and Figure 2, respectively. As expected from the asymptotic loss, for $L=7$, the performance gap is small, about 0.4 dB at 1%BLER. On the other hand, the BLER performance gap is significant for $L=14$, about 2 dB at 1%BLER. However, the BER performance gap is much smaller, ~0.5 dB, because the dominant RM errors are mostly one-bit message errors.

Nevertheless, these example simulations show that the RM code has inferior performance compared to a code that is designed for non-coherent detection.

Observation 4: Linear block codes designed for non-coherent detection significantly outperform RM codes.

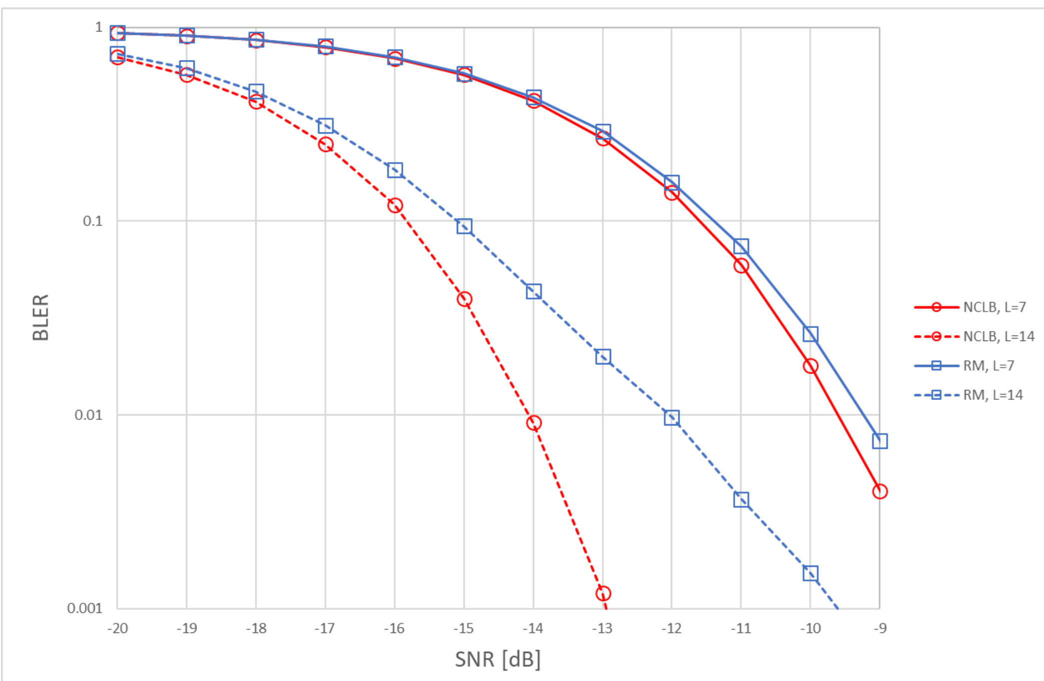

Figure 1: AWGN, BLER performance of Non-coherent linear block (NCLB) code and RM code.

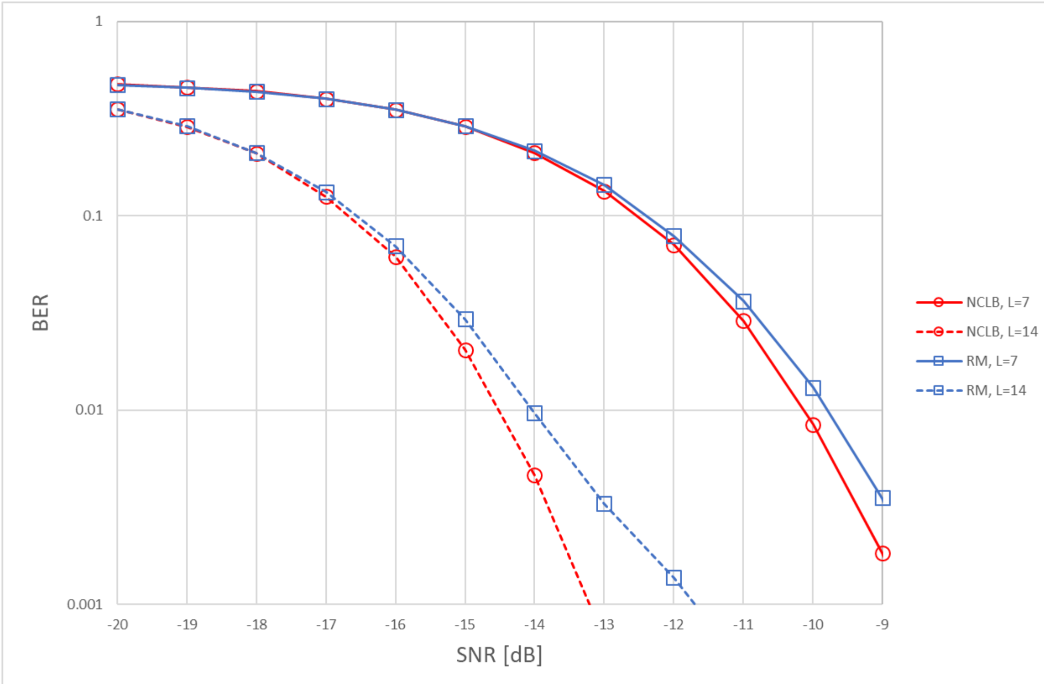

Figure 2: AWGN, BER performance of Non-coherent linear block (NCLB) code and RM code.

6 Conclusion

In this contribution, the following proposals and observations have been made:

Observation 1: Coverage enhancement is one of the key KPIs in 6G. Previous studies of coverage enhancements showed that significant performance improvements in the transmission of small UCI payloads are possible.

Observation 2: The 3GPP RM code is rank deficient for high code rates.

Observation 3: The performance of 3GPP RM codes is far from optimal and there is significant room for improvement.

Proposal 1: Study novel encoding schemes for small payloads designed for non-coherent detection.

Observation 4: For short block lengths, DMRS introduce a significant amount of sub-optimality and potential novel coding strategies should aim to reduce this overhead.

Observation 5: Linear block codes designed for non-coherent detection significantly outperform RM codes.

7 References

[1] TS 38.212, “Multiplexing and channel coding”, V19.0.0, 3GPP, June 2023.

[2] R1-2606309, “Discussion on Uplink Transmission Schemes for Uplink Control Channels”, RAN1#126

[3] Knopp, R. and Leib, H. ,”M-ary Phase Coding for the Non-coherent AWGN Channel,” IEEE Transactions on Information Theory, vol. 40, no. 6, Nov. 1994.

[4] 3GPP TR 38.830, “Study on NR coverage enhancements (Release 17)," V17.0.0, Dec. 2020.

[5] RP-202928, “New WID on NR coverage enhancements”, Rel-17, RAN90e, Dec. 2020.

8 Appendix

Link-Level simulation assumptions are shown in Table 4 below.

Parameter	Value
Carrier Frequency	2.6 GHz (FDD)
Channel BW	100MHz (273 PRBs @ 30kHz SCS)
SCS	30 kHz
Channel Model	AWGN
Number of receive antennas at gNB	1
Number of transmit antennas at UE	1
UCI payload size	8 bits
Number of slots simulated	50,000
Receiver	Non-coherent detection
Modulation	QPSK

Table 4: Link-level simulation assumptions.