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Title:	Discussion on Channel Coding for Small Block Lengths
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1. Introduction

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

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 **Erreur ! Source du renvoi introuvable.** but for lower spectral-efficiency and small block lengths.

Observation 1: The performance of 3GPP Short Block-Length codes is far from optimal and there is significant room for improvement.

Proposal 1: Study novel encoding/modulation schemes for transmission of short packages.

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 2: For Short Block Length, DMRS introduce a significant amount of sub-optimality and potential novel coding strategies should aim to reduce this overhead.

4. Potential Novel Techniques

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.

More precisely, separate the input bits $B = B_0 + B_1$ into B_0 and B_1 bits associated with the frequency and time dimension, respectively. This is split is *optional* but can provide two levels of error protection (e.g. higher-protection for ACK/NAK than CSI/SR in a common PUCCH transmission), where by the B_0 bits can be decoded with lower error probability than the B_1 bits.

Without loss of generality, the transmit message $m \in \{0,1,\dots,M-1\}$, $M = 2^B$, is given by $m = m_0 + m_1 B_0$ with $M_0 = 2^{B_0}$ and $M_1 = 2^{B_1}$. The transmit signal $\boldsymbol{R}_m \in \mathbb{C}^{Q\times L}$ of message m for Q sub-carriers and L OFDM symbols is given by

$$\boldsymbol{R}_m = \boldsymbol{F}_{m_0}\mathrm{diag}(\boldsymbol{w}_{m_1}),$$

where $\boldsymbol{F}_{m_0} \in \mathcal{F}^{Q\times L} = \{\boldsymbol{F}_0, \boldsymbol{F}_1, \dots, \boldsymbol{F}_{M_0-1}\}$ is the code sequence m_0 in frequency domain and $\boldsymbol{w}_{m_1}$is codeword m_1 of time-domain code $\boldsymbol{W} = [\boldsymbol{w}_0, \boldsymbol{w}_1, \dots, \boldsymbol{w}_{M_1-1}] \in \mathbb{C}^{L\times M_1}$.

The design of codes $\mathcal{F}$ and $\boldsymbol{W}$ depend on the transmission requirements and the number of available dimensions. For instance, $\mathcal{F}$ should be designed to achieve low PAPR when applied to an uplink transmission. In the extreme case, where $\mathcal{F}$ contains only a single non-zero resource element per OFDM symbol the PAPR will be 0dB. Another criterion is to limit the number of non-zero elements in $\mathcal{F}$ to reduce both decoding complexity and the effects of multi-path propagation.

The time-domain code (or outer code) $\boldsymbol{W}$ can be orthogonal if $QL \geq M$ or non-orthogonal if $QL < M$. In the non-orthogonal case, a non-coherent code can be used and the B_1 bits $\boldsymbol{d} = [d_0, d_1, \dots, d_{B_1-1}]$ are encoded as

$$\boldsymbol{c} = \boldsymbol{dG}$$

where $\boldsymbol{G}$ is the generator matrix and $\boldsymbol{c}$ are the coded bits. Subsequently, the modulated N-PSK symbol $w_{m_1 l}$ of message m_1 and symbol l is obtained by

$$w_{m_1 l} = e^{i2\pi c_n/N}$$

where c_n is the n^{th} entry of $\boldsymbol{c}$. Finally, the transmitted sequence $\boldsymbol{r}_{ml}$ is given by

$$\boldsymbol{r}_{ml} = \boldsymbol{f}_{m_0 l} \cdot w_{m_1 l}$$

where $\boldsymbol{f}_{m_0 l}$ is the sequence on symbol l corresponding to message m_0. As an example, consider $N = 4$ (e.g. QPSK), $B_1 = 8$ and $L = 7$, a good generator matrix in GF4 is given by

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

To show the potential gains, we evaluate the performance for a $B = 11$ bit payload and compare to the NR PUCCH Format 3. Link-level simulation assumptions are given in Table 2 with additional details available in [2]. For PF3 we evaluate both the non-coherent receiver and the coherent receiver, cf. [2]. The simulated solution (called VHC) uses a single resource element ($K_0 = 1$) or sequences with medium PAPR performance (medPAPR). A simple Gold sequence with $\pi/2$-BPSK modulation is also evaluated for comparison.

Figure 1 shows the BLER performance for 1 PRB. As expected, the non-coherent receiver outperforms the coherent detection at the expense of increased complexity. Constructing 2^{11} Gold sequences with non-coherent detection (correlation) outperforms both PF3 detectors highlighting the inherent loss due to the addition of DMRS. The proposed VHC solution is able to balance complexity and performance. We observe gains of 1.5dB and 2.9dB for the protected bits B_0 compared to the PF3 NCD and PF3 CD, respectively. The overall VHC is still outperforming PF3 CD, without considering the significantly lower PAPR (0dB compared to ~4dB, [2]). Using medium PAPR sequences achieves the same performance as the Gold sequences but with much lower decoding complexity, [2].

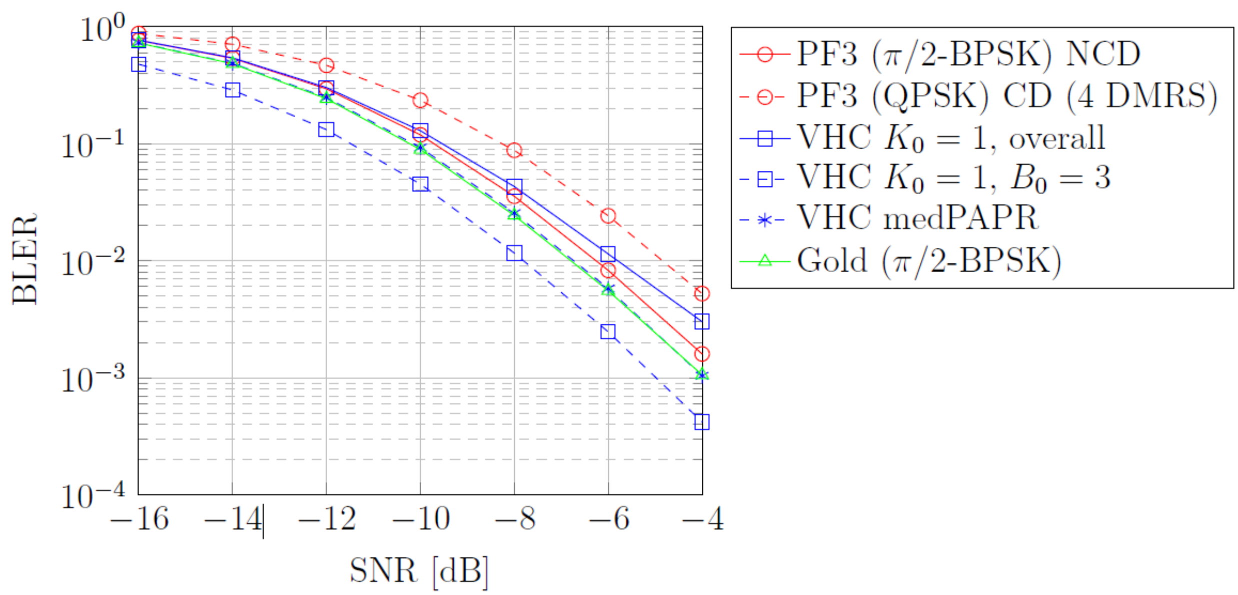

Figure 1: 11 bits, 1 PRB

When increasing the frequency resources to 15 PRBs the performance gap between the PF3 receivers and the proposed VHC solution widens significantly as shown in Figure 2. We observe a gain of 3dB and 3.9 dB @1%BLER compared to PF3 NCD and PF3 CD, respectively. This is due to the fact that up to $B_0 = 7$ bits can be encoded with orthogonal sequences in the frequency domain and only $B_1 = 4$ bits with the non-coherent code in the time dimension, significantly increasing coding gain, resulting in almost the same BLER as the B_0 bits.

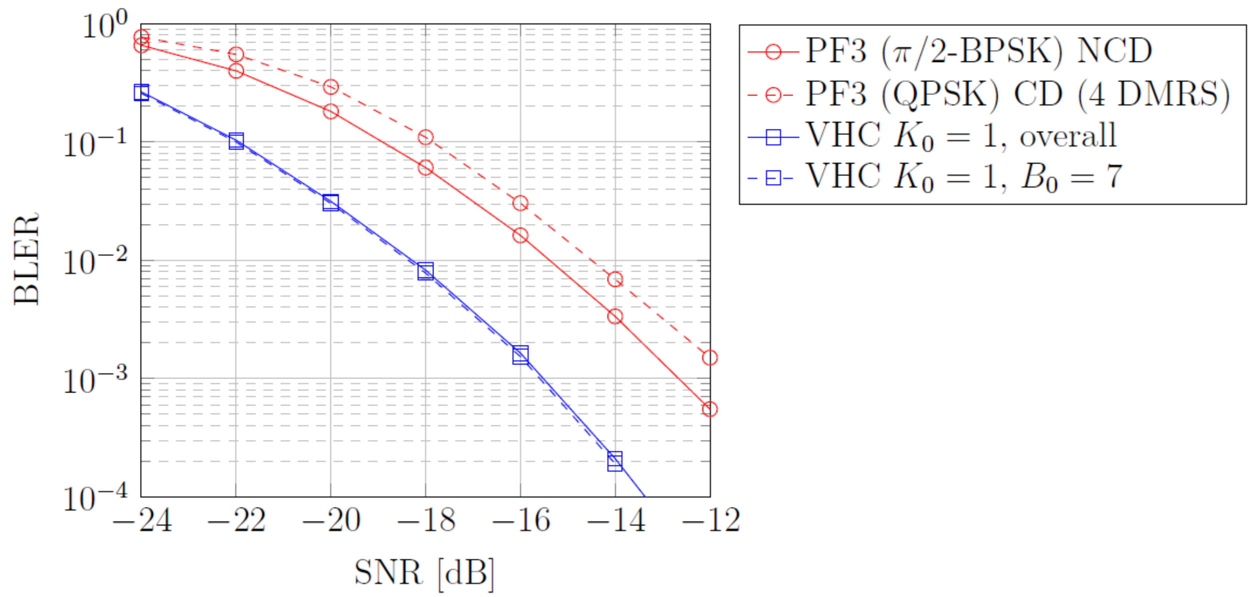

Figure 2: 11 bits, 15 PRB

Observation 3: Simulations of novel coding strategies show significant performance improvements over NR Short Block-Length Codes.

5. Conclusion

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

Observation 1: The performance of 3GPP Short Block-Length codes is far from optimal and there is significant room for improvement.

Proposal 1: Study novel encoding/modulation schemes for transmission of short packages.

Observation 2: For Short Block Length, DMRS introduce a significant amount of sub-optimality and potential novel coding strategies should aim to reduce this overhead.

Observation 3: Simulations of novel coding strategies show significant performance improvements over NR Short Block-Length Codes.

6. References

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

[2] RP-212941, “Discussion on DMRS-less PUCCH for UL Coverage Enhancements”, EURECOM, RAN#94e, Dec, 2021.

[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.

7. Appendix

Link-Level simulation assumptions are shown in Table 2 below.

Parameter	Value
Carrier Frequency	2.6 GHz
Bandwidth	100 MHz (273 PRB)
SCS	30 kHz
Channel Model	TDL-C [8, Table 7.7.2-3]
Delay Spread	300 ns
MIMO Correlation	low
UE Velocity	3 km/h
Number of TXRUs at BS	2
Number of slots	100,000
PUCCH Format	PUCCH Format 3
Payload Size	4 and 11 bits
Frequency Hopping	Intra-slot frequency hopping enabled
Number of Transmit chains	1
PUCCH Duration	14 symbols
Number of PRBs	1
Modulation	QPSK
Receiver	Non-coherent and coherent
DMRS	2 or 4

Table 2 Link-level simulation assumptions.