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Improving 3GPP-LTE Uplink Control Signaling by Repetition Across Frequency Bands

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Abstract—We propose improvements for the physical uplink control channel (PUCCH) format 2 control signaling in 3GPP-LTE systems. These improvements can be useful for low-cost UE design and optimization planned for the future LTE releases. In the proposed method, instead of repeating a single QPSK symbol across the 12 subcarriers in each OFDM symbol of a resource block as done in the current release of the standard, we pick two QPSK symbols from two independent resource blocks and repeat them across 6 subcarriers each. The proposed method has a performance gain of about 5.5 dB and 1.85 dB over the conventional method with one and two receiving antennas at the base station, respectively. These gains can be achieved without the use of any additional transmission power, time-frequency resources or receiver complexity.

The cell-specific QPSK sequences specified in the standard for PUCCH transmission are chosen according to the conventional repetition across the 12 subcarriers, hence we suggest new cell-specific QPSK sequences which minimize the peak-to-average-power ratio (PAPR) of the PUCCH signal with the proposed method.

I. INTRODUCTION

Machine-type communications (MTC) are supported in the latest releases (10 and 11) of the LTE standard. Devices using the MTC mode are expected to operate with low data rates and relaxed latency requirements. Design of a low-cost user equipment (UE) is currently being studied and optimized to support the MTC mode [1]. These low-cost UEs should be optimized to have link budget improvements in the order of 20 dB compared to the traditional UEs [2]. The important feature of the low-cost UEs is that they should be able to support the small data transmission with a longer battery life, and a case study of such a low-cost UE is available in [3]. In order to save 20 dB in the link budget using a low-cost UE, it is also important to revisit some of the current transmission schemes in the existing LTE systems and optimize their performance. Towards this, we propose an improved scheme for the transmission of control signaling information in the LTE uplink.

The uplink Layer 1/ Layer 2 (L1/L2) control signaling in LTE uses two different methods to send the uplink control data, depending on whether or not the UE has been assigned an uplink resource for uplink shared channel (UL-SCH) transmission. More details about control signaling transmission in LTE uplink can be found in [4]. In this work, we focus on improving the performance of PUCCH format 2 control

Figure 1. Uplink L1/L2 control signaling transmission on PUCCH (reproduced from [4, p. 228])

Table I
RESOURCE BLOCK PARAMETERS FOR PUCCH FORMAT 2 TRANSMISSION

Configuration	N_{sc}^{RB}	N_{symb}^{RB}	Data symbol indices	Reference signal symbol indices
Normal CP	12	7	1,3,4,5,7	2,6
Extended CP	12	6	1,2,3,5,6	4

signaling.¹ The resources used for PUCCH control signaling are located at the edges of the frequency spectrum as shown in Fig. 1. Each resource block consists of 12 OFDM subcarriers (N_{sc}^{RB}) within each of two slots of an uplink subframe. The number of OFDM symbols in each slot of a subframe (N_{symb}^{RB}) depends on the cyclic prefix (CP) length, as shown in Table I.

Related Work and Contributions: Previous works on uplink control signaling in 3GPP-LTE focused on various aspects of the system performance. For PUCCH format 1 control signaling (which involves sending only HARQ acknowledgement bits), multiuser receivers were proposed in [5], [6]. In [7], generalized likelihood ratio test (GLRT) based detectors were developed for multiple receive antennas case. To improve the reliability of uplink control signaling, a power boosting approach was proposed in [8].

For PUCCH format 2, even though the control signaling information is spread across two independent frequency bands (see Fig. 2), the specified Reed–Muller code is not good at extracting the diversity mainly due to the short block length. In our previous work [9], we proposed a complex-field coding (CFC)-based precoding method to extract this diversity for PUCCH format 2 signaling, which improved the error-rate

¹Usually periodic CQI information reports are sent using this format. Sometimes simultaneous transmission of hybrid-automatic repeat request (ARQ) acknowledgments and CQI reports is also done using this format. This format can support a maximum of 13 information bits per subframe.

Figure 2. PUCCH format 2 for normal CP (reproduced from [4, p. 406])

performance significantly. In the present work, we propose a simpler scheme, in which we pick two QPSK symbols from two independent frequency bands (resource blocks) and repeat them across 6 subcarriers each. By contrast, for the conventional method, a single QPSK symbol is repeated across the 12 subcarriers in each OFDM symbol. By using this new transmission scheme, we are able to transmit each QPSK symbol in both the resource blocks, thereby extracting the available frequency diversity.²

The cell-specific QPSK sequences specified in the standard for the PUCCH transmission are designed to work well with the conventional method. Using the same QPSK sequences for the proposed method resulted in high PAPR values. To address this issue, we did a random search for the new cell-specific QPSK sequences that give better PAPR values for the proposed method. We provide 30 such sequences (for 30 sequence groups) in this work, whose maximum PAPR values with the proposed method are comparable to the PAPR values of the conventional method with the existing sequences.

II. SYSTEM MODEL AND CONVENTIONAL METHOD

For control signaling using the PUCCH format 2 in the LTE uplink, a predefined $(20, N_I)$ -Reed-Muller code is used [11], where N_I is the number of information bits and $N_I \leq 13$.³ The 20 output bits are modulated using 10 QPSK symbols on the 10 OFDM data symbols in two slots of a subframe. Conventionally, the first five QPSK symbols $\{s_1, s_2, s_3, s_4, s_5\}$ are transmitted in the first slot and the remaining five QPSK symbols $\{s_6, s_7, s_8, s_9, s_{10}\}$ are transmitted in the second slot as shown in Fig. 2. As we can observe from the figure,

²Even though we study the PUCCH format 2 signaling in the present work, the proposed method can also be applied to the PUCCH format 2a/2b signaling as well.

³In case of normal CP configuration, N_I can only be ≤ 11 . However in case of extended CP configuration, there is a provision to code both CQI report bits and hybrid-ARQ acknowledgment bits using the same Reed-Muller code. In this case $N_I \leq 13$.

this control signaling information is sent on two independent resource blocks located at the edges of the available bandwidth (BW). Each of the five QPSK data symbols is spread across the 12 subcarriers in each OFDM data symbol of the resource block by using a length-12 phase-rotation cell-specific sequence. The length-12 phase-rotation sequences used for spreading are defined as:

$$r_u^{\alpha(k,l)}(n) = \underbrace{e^{j\alpha(k,l)n}}_{\text{Randomization sequence}} \underbrace{e^{j\phi(u,n)\frac{\pi}{4}}}_{\text{QPSK sequence}} \quad (1)$$

where $\alpha(k,l) = \frac{\pi}{6}n_{cs}(k,l)$, with k denoting the slot index and l , $0 \leq l \leq 6$ denoting the OFDM symbol index. $\phi(u,n) \in \{-3, -1, 1, 3\}$ is independent of l and it only depends on the subcarrier index n , $0 \leq n \leq 11$ and the sequence group index $u \in \{10, 2, \dots, 29\}$. $n_{cs}(k,l)$ definition can be found in [12], and its value always lies between 0 and 11. Note that the same QPSK sequence is used across all the OFDM symbols in each time slot. As shown in (1), the phase-rotation sequence consists of two parts, the first part is the randomization sequence to allow more than one user to transmit on the same PUCCH resource (using the same QPSK sequence). Since different users in the same cell have different $n_{cs}(k,l)$ values, the randomization sequences for the users are orthogonal. Hence, their phase-rotation sequences $(r_u^{\alpha(k,l)}(n))$ result in no intra-cell interference. Because of the orthogonality of the phase-rotation sequences used within a cell, more than one user can transmit their control signaling information on the same PUCCH resources. Depending on the frequency-selectivity of the channel, only a subset of $n_{cs}(k,l) \in \{0, 1, \dots, 11\}$ values can be used in each cell. In other words, limiting the value of $n_{cs}(k,l)$ to only a subset of the set $\{0, 1, \dots, 11\}$ implies orthogonality over a smaller number of subcarriers and hence less sensitivity to the frequency-selectivity of the user channels. Moreover, to randomize the inter-cell interference, the value of $\alpha(k,l)$ is changed across the OFDM symbols in a time slot. The second part of the phase-rotation sequence consists of a cell-specific QPSK sequence. These QPSK sequences are found using computer search and there are 30 different length-12 $\phi(u,n)$ sequences (and hence the QPSK sequences) defined in [12], one for each sequence group. These sequences have the following properties [13]

- Constant modulus in the frequency-domain (can be seen from (1)),
- Low PAPR/cubic metric values for the PUCCH signal.
- Good cross-correlation properties to minimize the inter-cell interference.

In case of the conventional transmission, for a given cell-specific QPSK sequence, the PAPR of the OFDM signal is the same for all the OFDM symbols in a time slot, i.e., the PAPR value only depends on the cell-specific QPSK sequence.

We assume that both the transmitter and receiver are equipped with a single antenna. We also assume that the channel gains are constant in one time slot, but change from one time slot to the next one. To simplify notation, we assume that the OFDM data symbols which carry the QPSK symbols

are contiguous (there are no reference signal symbols between them). Let $N_{\text{symb}}^{\text{data}}$ denote the number of data symbols in one subframe. For PUCCH format 2, $N_{\text{symb}}^{\text{data}} = 10$ (independently of the CP configuration). At the receiver, after the fast Fourier transform (FFT) operation and after undoing the effect of the phase-rotation sequence, the received signal on the data symbol m can be written as:⁴

$$\mathbf{y}_m = \mathbf{h}_{\lceil \frac{m}{5} \rceil} s_m + \mathbf{w}_m, \quad 1 \leq m \leq 10, \quad (2)$$

where

- $\mathbf{y}_m \triangleq \begin{bmatrix} \mathbf{y}_m' \\ \mathbf{y}_m'' \end{bmatrix} = [y_{m,1}, y_{m,2}, \dots, y_{m,N_{\text{sc}}^{\text{RB}}}]^T$ is the vector of received signals on all $N_{\text{sc}}^{\text{RB}}$ subcarriers of symbol m .
- $\mathbf{h}_{\lceil \frac{m}{5} \rceil} \triangleq \begin{bmatrix} \mathbf{h}_{\lceil \frac{m}{5} \rceil}' \\ \mathbf{h}_{\lceil \frac{m}{5} \rceil}'' \end{bmatrix} = [h_{\lceil \frac{m}{5} \rceil,1}, \dots, h_{\lceil \frac{m}{5} \rceil, N_{\text{sc}}^{\text{RB}}}]^T$ is the frequency-domain channel gain vector in slot $\lceil \frac{m}{5} \rceil$.
- s_m is the m th transmitted QPSK symbol and
- $\mathbf{w}_m \triangleq \begin{bmatrix} \mathbf{w}_m' \\ \mathbf{w}_m'' \end{bmatrix} = [w_{m,1}, w_{m,2}, \dots, w_{m,N_{\text{sc}}^{\text{RB}}}]^T$ is the noise vector on OFDM symbol m , $\mathbf{w}_m \sim \mathcal{CN}(\mathbf{0}, N_0 \mathbf{I})$.

The notation $(\cdot)'_m$ and $(\cdot)''_m$ denote the corresponding values for the first and the last 6 subcarriers of the m th OFDM symbol in a resource block. Assuming that $\mathbf{h}_{\lceil \frac{m}{5} \rceil}$ and N_0 values are perfectly known to the receiver, the optimal detector for s_m , $1 \leq m \leq 10$, is obtained by maximizing the following conditional probability:

$$p(\mathbf{y}_m | \mathbf{h}_{\lceil \frac{m}{5} \rceil}, s_m, N_0) = \frac{1}{(\pi N_0)^{N_{\text{sc}}^{\text{RB}}}} e^{-\frac{\|\mathbf{y}_m - \mathbf{h}_{\lceil \frac{m}{5} \rceil} s_m\|^2}{N_0}}. \quad (3)$$

Maximizing (3) is equivalent to:

$$\min_{s_m \in \mathcal{S}} \|\mathbf{y}_m - \mathbf{h}_{\lceil \frac{m}{5} \rceil} s_m\|^2 \iff \min_{s_m \in \mathcal{S}} |s_m - \hat{s}_m|^2, \quad (4)$$

$$\hat{s}_m \triangleq \frac{\mathbf{h}_{\lceil \frac{m}{5} \rceil}^H \mathbf{y}_m}{\|\mathbf{h}_{\lceil \frac{m}{5} \rceil}\|^2} = s_m + \frac{\mathbf{h}_{\lceil \frac{m}{5} \rceil}^H \mathbf{w}_m}{\|\mathbf{h}_{\lceil \frac{m}{5} \rceil}\|^2} = s_m + \tilde{w}_m \quad (5)$$

and where $\tilde{w}_m \sim \mathcal{CN}\left(0, N_0 / \|\mathbf{h}_{\lceil \frac{m}{5} \rceil}\|^2\right)$. From (5), we can conclude that the optimal detection rule for the case of perfect channel state information (CSI) at the receiver is to perform maximal-ratio combining (MRC) on all the 12 subcarriers of each OFDM data symbol.

Since the block size of the specified Reed–Muller code is small and that the code rate can be as high as 0.65, it cannot efficiently exploit the frequency diversity available in the resources used for control signaling. To extract more of the frequency diversity inherent in the resources for PUCCH format 2, in [9], [10], we proposed a complex-field coding (CFC)-based precoding technique for pairs of symbols from

Figure 3. Proposed transmission method for PUCCH format 2 for normal CP configuration.

two independent slots of a subframe. In the CFC-based precoding method, we transmit x_m instead of s_m , where x_m are obtained by a linear transformation of pairs of s_m as:

$$\begin{bmatrix} x_m \\ x_{m+5} \end{bmatrix} = \underbrace{\begin{bmatrix} \psi_{1,1} & \psi_{1,2} \\ \psi_{2,1} & \psi_{2,2} \end{bmatrix}}_{\triangleq \Psi} \underbrace{\begin{bmatrix} s_m \\ s_{m+5} \end{bmatrix}}_{\triangleq \mathbf{s}}, \quad 1 \leq m \leq 5 \quad (6)$$

$\triangleq \mathbf{x}$ $\triangleq \mathbf{s}$

where s_m and s_{m+5} denote the QPSK symbols transmitted on the m th and the $(m+5)$ th data symbols. For precoding, we used a 2×2 CFC matrix Ψ generated using the designs specified in [14]. The results from our work in [9] showed that, for a single receive antenna case, the CFC-based precoding technique can provide a gain of 3.5 dB over the conventional method used in LTE. Note that the PAPR of an OFDM symbol with the CFC-based precoding method will be the same as that of an OFDM symbol using the conventional method.

III. PROPOSED METHOD

In this section, we introduce the proposed method for the transmission of control signaling information using PUCCH format 2. As we can see from (6), the main idea of CFC-based precoding is to transmit the information about both s_m and s_{m+5} in both the resource blocks, thereby extracting the diversity. However, the performance of CFC-based precoding method is limited by the minimum product distance. Using the same idea as in the CFC-based precoding, we propose a new method to extract frequency diversity inherent in the resources for PUCCH format 2. In this new method, instead of repeating a single QPSK symbol across all the 12 subcarriers in each OFDM data symbol, we pick two QPSK symbols from two independent frequency bands and repeat each of them across 6 subcarriers as shown in Fig. 3. There are many similar ways in which this repetition across the two frequency bands can be done. The proposed method can also extract the available frequency diversity as each QPSK symbol

⁴Note that $\lceil \frac{m}{5} \rceil$ can only take values 1 and 2 as $1 \leq m \leq 10$.

(a) Perfect CSI at receiver, (20,11) - Reed-Muller code with a single receiving antenna.

(b) Perfect CSI at receiver, (20,13) - Reed-Muller code with a single receiving antenna.

Figure 4. Performance comparison of the proposed method with the conventional method as well as the CFC-based precoding method described in Section II.

is now transmitted in both the frequency bands. Note that the proposed method does not consume any additional time-frequency resources compared to the conventional method used in current releases of the standard. Using the proposed way of repetition as in Fig. 3, to preserve the orthogonality of the phase-rotation sequences, the value of $n_{cs}(k, l)$ should now belong to a subset of the set $\{0, 2, 4, 6, 8, 10\}$ (or equivalently $\{1, 3, 5, 7, 9, 11\}$). Because of this, at most 6 users can transmit on the same PUCCH resources using the proposed method. However in case of the propagation environments in which the channel gain does not remain constant over 12 subcarriers, the proposed method does not incur any additional loss compared to the conventional method. For the proposed method, at the receiver, after the FFT operation and undoing the effect of the phase-rotation sequence, the received signal on the data symbol m can be written as:

$$\mathbf{y}_m = \begin{bmatrix} \mathbf{y}'_m \\ \mathbf{y}_m \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} \mathbf{h}'_{\lceil \frac{m}{5} \rceil} & 0 \\ 0 & \mathbf{h}''_{\lceil \frac{m}{5} \rceil} \end{bmatrix} \begin{bmatrix} s_m \\ s_{m+5} \end{bmatrix} \\ \begin{bmatrix} \mathbf{h}'_{\lceil \frac{m}{5} \rceil} & 0 \\ 0 & \mathbf{h}''_{\lceil \frac{m}{5} \rceil} \end{bmatrix} \begin{bmatrix} s_m \\ s_{m-5} \end{bmatrix} \end{bmatrix} + \mathbf{w}_m, \text{ for } 1 \leq m \leq 5$$

$$\mathbf{y}_m = \begin{bmatrix} \mathbf{y}'_{m-5} \\ \mathbf{y}_m \end{bmatrix} = \begin{bmatrix} \mathbf{h}''_{\lceil \frac{m-5}{5} \rceil} & 0 \\ 0 & \mathbf{h}'_{\lceil \frac{m-5}{5} \rceil} \end{bmatrix} \begin{bmatrix} s_{m-5} \\ s_m \end{bmatrix} + \mathbf{w}_m, \text{ for } 6 \leq m \leq 10$$

where $\mathbf{h}'_{\lceil \frac{m}{5} \rceil} = [h_{\lceil \frac{m}{5} \rceil, 1}, \dots, h_{\lceil \frac{m}{5} \rceil, (N_{sc}^{RB}/2)}]^T$ and $\mathbf{h}''_{\lceil \frac{m}{5} \rceil} = [h_{\lceil \frac{m}{5} \rceil, (N_{sc}^{RB}/2)+1}, \dots, h_{\lceil \frac{m}{5} \rceil, N_{sc}^{RB}}]^T$ are the channel gain vectors for the first and the last 6 subcarriers in slot $\lceil \frac{m}{5} \rceil$, respectively. To decode a QPSK symbol s_m , we collect the corresponding received signals as:

$$\begin{bmatrix} \mathbf{y}'_m \\ \mathbf{y}_{m+5} \end{bmatrix} = \begin{bmatrix} \mathbf{h}'_{\lceil \frac{m}{5} \rceil} \\ \mathbf{h}''_{\lceil \frac{m}{5} \rceil} \end{bmatrix} s_m + \begin{bmatrix} \mathbf{w}'_m \\ \mathbf{w}_{m+5} \end{bmatrix}, \text{ for } 1 \leq m \leq 5$$

$$\begin{bmatrix} \mathbf{y}'_{m-5} \\ \mathbf{y}_m \end{bmatrix} = \begin{bmatrix} \mathbf{h}''_{\lceil \frac{m-5}{5} \rceil} \\ \mathbf{h}'_{\lceil \frac{m-5}{5} \rceil} \end{bmatrix} s_{m-5} + \begin{bmatrix} \mathbf{w}_{m-5} \\ \mathbf{w}_m \end{bmatrix}, \text{ for } 6 \leq m \leq 10$$

Once the corresponding received signals for each s_m are collected, we can apply MRC on them to decode the symbols. Note that the proposed method does not add any additional receiver complexity.

IV. NUMERICAL RESULTS FOR AN LTE-LIKE SYSTEM

In this section, we present link-level numerical results for an LTE-like system with 300 subcarriers (25 resource blocks) and a subcarrier spacing of 15 kHz. These parameters correspond to an LTE system with 5 MHz channel BW. For the fading process, we used the ITU - Vehicular A channel model with 20 Hz Doppler frequency and with a Rayleigh fading distribution. We used the normal CP configuration for $N_I = 11$ bits and the extended CP configuration for $N_I = 13$ bits. In the simulations, we considered a single user transmitting on a single PUCCH resource block pair.⁵ We assume that perfect CSI is available at the receiver along with perfect information about noise variance value. Monte-Carlo simulation was used to obtain the block-error rate (BLER) performance, and at each point in the curves, we observed at least 1000 block errors. Fig. 4 shows a performance comparison of the proposed method with the conventional method and the CFC-based precoding method. For the case of a single receiving antenna at the eNodeB, at a BLER of 10^{-2} and with $N_I = 11$ bits, the proposed method with repetition across frequency bands has a performance gain of about 2 dB and 3.3 dB over the CFC-based precoding method and the conventional method, respectively. For the $N_I = 13$ bits case, the gains are 2 dB and 5.5 dB, respectively. The gain for the proposed method over the CFC-based precoding method can be explained using the following argument. Even though both the methods can extract the diversity available in the frequency resources, in case of the CFC-based precoding, the pairwise error probability (PEP) of a symbol depends on the minimum product distance, whose maximum value is 1 [14]. However, for the proposed method, the PEP depends on the minimum Euclidean distance, which is $\sqrt{2}$. As shown in Fig. 5, for the case of two receiving antennas at the eNodeB with $N_I = 13$ bits, the gain for the proposed

⁵In an ideal case, with more than one user transmitting on the same PUCCH resources, there is no intra-cell interference. In case of the residual interference as in a practical system, approximating the interference term using a Gaussian model fits well with the simulation model considered in our work.

Figure 5. Performance comparison of the proposed method with the conventional method as well as the linear CFC-based precoding method when the receiver has two antennas. In this simulation, $N_f = 13$ bits.

Table II
MAXIMUM PAPR VALUE (IN DB) COMPARISON FOR ALL THE SEQUENCE GROUPS.

Sequence group u	Conv. Method	Prop. Method	Sequence group u	Conv. Method	Prop. Method
0	2.92	6.40	15	3.12	4.92
1	2.64	5.27	16	4.01	6.38
2	2.93	4.86	17	3.89	5.44
3	3.77	5.55	18	3.28	3.98
4	2.83	5.63	19	3.95	5.30
5	2.51	5.06	20	2.87	5.51
6	4.09	4.26	21	3.82	6.10
7	2.66	5.35	22	2.98	4.51
8	2.40	3.64	23	2.64	5.27
9	2.33	5.88	24	3.45	5.69
10	3.91	5.23	25	2.87	4.60
11	3.27	5.83	26	2.55	4.32
12	2.40	4.84	27	3.90	5.27
13	3.36	4.64	28	3.89	5.36
14	3.46	3.91	29	3.40	4.99

method over the CFC-based precoding and the conventional method is 1 dB and 1.85 dB, respectively.

V. PAPR COMPARISON

For the proposed method, using the cell-specific QPSK sequences specified in [12] will result in different PAPR values compared to the PAPR values of the conventional method. For the proposed method, even though the same QPSK sequence is used across all the OFDM symbols in a time slot, the PAPR value for an OFDM symbol changes depending on which two QPSK symbols are transmitted. Because of this, we compare the maximum PAPR values (in dB) of the conventional method and the proposed method in Table II.⁶ As we can see from the table, for the conventional case, the maximum PAPR value ranges from 2.3 to 4.1 dB. For the proposed method with repetition of two QPSK symbols in each OFDM symbol, the maximum PAPR value ranges from 3.64 to 6.4 dB. The maximum PAPR value of the proposed method is higher than that of the conventional method. To address this high PAPR issue for the proposed method, we did a random search in order to find new QPSK sequences which work well for

⁶The CFC-based precoding method has the same PAPR as the conventional method.

Table III
NEW QPSK SEQUENCES AND THEIR MAXIMUM PAPR VALUES (IN DB) FOR THE PROPOSED METHOD.

Sequence group u	Sequence $\phi(u, n)$	Maximum PAPR
0	-1 3 3 1 3 1 1 -1 1 3 3 -1	3.01
1	3 -3 1 -1 -3 1 -1 -1 -3 -3 -3 -1	3.68
2	1 -1 -3 -3 1 -1 1 3 1 1 3 -1	3.84
3	-3 -3 3 -3 -3 -1 -3 1 -1 -1 3 -3	3.86
4	3 -3 -1 3 1 -3 3 3 3 -1 -3 -3	3.88
5	-1 -3 -3 -1 -1 1 1 -3 1 3 1 -1	3.94
6	-1 3 3 -3 3 3 3 3 -1 -3 -1 3	3.01
7	-1 3 1 -3 3 -3 1 3 -3 -3 3 3	3.93
8	-1 -1 -1 -3 1 -1 3 -1 1 3 -1 -3	3.93
9	3 1 -3 3 1 3 1 -3 -1 3 3 3	3.50
10	-1 3 3 -3 1 -1 -1 -1 -1 1 -1 -1	3.77
11	-3 -3 3 3 -1 -3 -1 1 -3 3 -3 -3	3.84
12	-1 3 1 3 -1 1 3 -3 -3 1 -1 -1	3.88
13	-3 -3 1 -3 3 1 -1 -1 1 1 3 -1	3.94
14	-1 -1 -1 -3 1 -1 -3 3 -3 1 3 -1	3.96
15	-3 1 -3 3 1 1 -3 -1 -1 -1 -1 -3	3.97
16	3 -1 -3 -1 3 3 1 -3 -3 3 -3 -3	3.00
17	-1 -1 1 -1 -3 1 -3 -3 3 1 1 -3	3.77
18	3 -3 -3 -1 -1 3 3 -1 3 1 1 -1	3.93
19	-3 3 -3 1 3 -1 -1 -3 1 -1 -1 -1	3.93
20	-1 -1 -1 1 -3 -1 3 -3 3 -1 -3 1	3.96
21	1 -3 3 1 -1 -1 -1 1 1 3 -1 1	3.64
22	-1 -1 3 -3 3 -3 3 -3 3 1 3 -3	3.01
23	-3 -1 3 -1 -3 3 -1 -3 -3 -3 -1 1	3.01
24	1 -1 1 -3 3 1 3 3 3 -3 1 1	3.78
25	1 1 1 -3 -3 -3 1 -3 -1 1 3 -1	3.90
26	-3 1 -1 3 -3 -1 -3 3 3 1 1 -3	3.96
27	-3 -1 1 1 1 1 -3 3 1 -1 3 -1	3.96
28	-3 1 3 -3 -1 -1 3 -3 3 -3 3 1	3.97
29	-3 -3 3 1 -1 3 -3 -3 -3 -1 3 -1	3.97

the proposed method. The new sequences together with their maximum PAPR value in dB are listed in Table. III. As we can note from the Table III, the maximum PAPR values of the new sequences are comparable to the PAPR values of the conventional method with the existing sequences. In other words, if we use the new QPSK sequences suggested in Table III for the proposed method, and the existing QPSK sequences for the conventional method and the CFC-based precoding method, gains similar to the ones shown in Figs. 4, 5 can also be seen if one takes into account for the power amplifier efficiency (which depends on the PAPR of the transmitted signal). We observed that these new sequences suggested in Table III also have low cross-correlation properties.

VI. DISCUSSION AND FUTURE WORK

The low-cost UE design for the MTC mode in LTE systems requires a fresh look at the optimization of the transmission schemes in the current LTE standards. Towards this, we proposed a simple transmission method for the PUCCH format 2 control signaling, which can bring significant gains in terms of error-rate performance (and hence power savings). These gains can be achieved without requiring any additional transmission power, time-frequency resources or receiver complexity. Even though we studied only the PUCCH format 2 control signaling performance in this work, the proposed method can also be applied for the PUCCH format 2a, 2b signaling as well. The proposed method in its current form may not be backward

compatible with the existing standards. However in the future, when backward compatibility is not a strict requirement for the future LTE releases, it might be worth to consider the proposed method as a possible improvement over the existing PUCCH transmission.

The new QPSK sequences suggested for the proposed method are based on minimizing the maximum PAPR value and they are found by a random search. One may find better (optimized) sequences by doing an exhaustive search. Another possible extension to the current work is to compare the proposed method with the conventional method using the cubic metric as a performance measure, and find new QPSK sequences with respect to minimizing the cubic metric. In our present work, we considered only the link-level simulations to present the results, it might also be interesting to study the gains for the proposed method in a system-level network simulator.

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