

Agenda Item: 8.1.1.1

Source: National Taiwan University

Title: **Precoder Flexibility and Forward Compatibility of CPS-OFDM Waveform**

Document for: Discussion and Decision

1 Introduction

In the study item proposal of 5G new radio access technology (RAT) [1], it was agreed that Phase I specification of the new RAT must be forward compatible (in terms of efficient co-cell/site/carrier operation) with Phase II specification and beyond. For the fundamental physical layer signal structure, new radio (NR) waveform is based on OFDM with potential support of non-orthogonal property and multiple access. Fundamental radio frequency (RF) aspects that may impact decisions on the new RAT are required to be considered. Besides, the new RAT is necessary to enable efficient multiplexing of traffic for different services and use cases on the same contiguous block of spectrum.

In RAN1#86 meeting [2], there are several agreements with respect to new waveform development. Here we briefly enumerate the key agreements related to our work:

- At least up to 40 GHz for eMBB and URLLC services, NR supports CP-OFDM based waveform with Y^1 greater than that of LTE (assuming $Y=90\%$ for LTE) for DL and UL, possibly with additional low PAPR/CM technique(s) (e.g., DFT-S-OFDM, etc.)
- In-band frequency multiplexing of different numerologies is supported in NR for both DL and UL.
- From RAN1 perspective, spectral confinement techniques for a waveform at the transmitter are transparent to the receiver.
- NR uplink should target at least the same link budget (i.e. MCL) as LTE uplink, under the same usage scenarios and similar deployment configurations (e.g., same carrier frequency).
- When considering DL and UL waveforms for spectrum band above 40GHz, RAN1 should at least consider the impact of low PA efficiency, phase noise, and Doppler impairments.
- RAN1 should continue study whether/how to support guard-band for inter-subband interfering scenarios (e.g., cases 2/3/4) with considerations of the specification/performance impact.

1.1 Review of Previous Work

In RAN1#85 and RAN1#86 meetings, we have proposed a circularly pulse-shaped (CPS) precoding technique for OFDM-based waveforms to facilitate 5G fragmented spectrum usage [3]-[6]. This proposed scheme is called CPS-OFDM, which is characterized by precoder flexibility with multiple access support. In [4], we analyzed the transmitter complexity and derived the closed-form expression of the power spectral density (PSD) for CPS-OFDM so as to justify that the implementation is very efficient and the out-of-subband (OOSB) emission can be lowered without block extension, respectively. With CPS precoder serving as a pre-processing of OFDM modulation, the peak-to-average power ratio (PAPR) can be reduced. Moreover, the corresponding decoder at the receiver can improve the bit-error rate (BER) performance, which is subject to channel frequency selectivity. The evaluation results of CPS-OFDM and its performance comparisons with other waveform candidates are presented in [5] in terms of transmitter complexity, PSD with power amplifier (PA) nonlinearity, and uncoded BER. In [6], we provided preliminary simulation results to demonstrate that CPS-OFDM is much more robust to asynchronous transmissions and mixed numerologies than legacy OFDM and DFT-s-OFDM.

¹ Y (%) = transmission bandwidth configuration / channel bandwidth * 100%

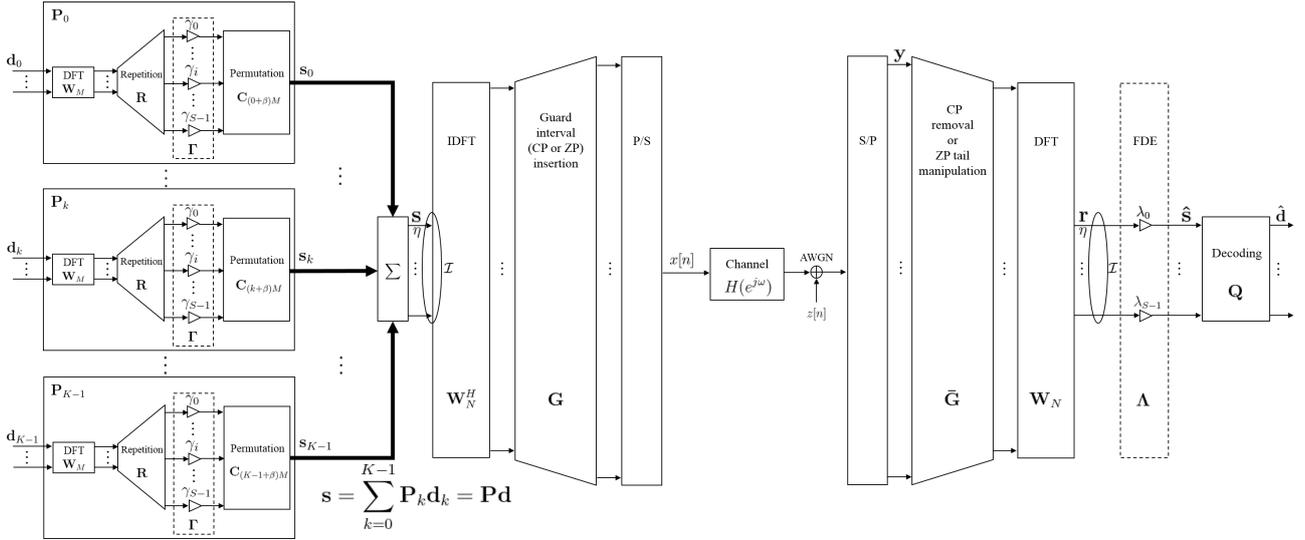


Figure 1: CPS-OFDM transceiver model.

1.2 Contributions

This document demonstrates that CPS-OFDM waveform enjoys precoder flexibility in determining desired transmission properties (e.g., low PAPR, low OOSB emission, etc.) and guarantees forward compatibility with most of spectral confinement techniques (e.g., filtering, windowing, etc.).

2 CPS-OFDM Transceiver Structure

The system model of CPS-OFDM realized in an efficient way [4] is illustrated in Figure 1. Multicarrier modulation is actualized by the inverse DFT matrix \mathbf{W}_N^H . The insertion of guard interval (GI) is represented by the matrix \mathbf{G} , which is usually chosen to be either

$$\mathbf{G}_{\text{cp}} = \begin{bmatrix} \mathbf{0}_{G \times (N-G)} & \mathbf{I}_G \\ & \mathbf{I}_N \end{bmatrix} \text{ or } \mathbf{G}_{\text{zp}} = \begin{bmatrix} \mathbf{I}_N \\ \mathbf{0}_{G \times N} \end{bmatrix} \quad (1)$$

for cyclic prefix (CP) or zero padding (ZP) to prevent the inter-block interference (IBI) stemmed from multipath propagation whose delay spread order is L , $\mathbf{G} \in \mathbb{R}^{(N+G) \times N}$, $G \geq L$. Let K and M denote the number of shaped subcarriers and sub-blocks, respectively. The data vector $\mathbf{d} = [\mathbf{d}_0^T | \dots | \mathbf{d}_k^T | \dots | \mathbf{d}_{K-1}^T]^T \in \mathbb{C}^{S \times 1}$ consists of D quadrature amplitude modulation (QAM) symbols and Z null symbols, $S = D + Z$. The coefficients on the S subcarriers indexed by \mathcal{I} are given by

$$\mathbf{s} = \sum_{k=0}^{K-1} \mathbf{P}_k \mathbf{d}_k \quad (2)$$

$$= \sum_{k=0}^{K-1} \mathbf{C}_{(k+\beta)M} \mathbf{\Gamma} \mathbf{R} \mathbf{W}_M \mathbf{d}_k, \quad (3)$$

where $\mathbf{R} = [\mathbf{I}_M \dots \mathbf{I}_M]^T$ is a repetition matrix formed by identity matrices, $\mathbf{\Gamma} = \text{diag}(\mathbf{g}) = \text{diag}([\gamma_0, \gamma_1, \dots, \gamma_{S-1}]^T)$ is a diagonal matrix, and $\mathbf{C}_{(k+\beta)M}$ is a permutation matrix defined as

$$\mathbf{C}_0 = \mathbf{I}_S, \quad \mathbf{C}_{(k+\beta)M} = \begin{bmatrix} \mathbf{0} & \mathbf{I}_{(k+\beta)M} \\ \mathbf{I}_{S-(k+\beta)M} & \mathbf{0} \end{bmatrix}. \quad (4)$$

Two parameters μ and β are to shift the output pulses and the intra-subband subcarriers, respectively. We say that \mathbf{g} is the shaping vector formed by the frequency-domain shaping coefficients $\gamma_0, \gamma_1, \dots, \gamma_{S-1}$. The transmitted signal is formulated as

$$\mathbf{x} = \mathbf{G} [\mathbf{W}_N^H]_T \mathbf{s}. \quad (5)$$

At the receiver, the multicarrier signal with CP or ZP redundancy via a multipath channel can be efficiently processed by the DFT matrix \mathbf{W}_N and the one-tap frequency-domain equalization (FDE). The received data vector can then be obtained by

$$\begin{aligned} \hat{\mathbf{d}} &= \mathbf{Q}\mathbf{\Lambda}\mathbf{r} \\ &= \mathbf{d} + \mathbf{Q}\mathbf{\Lambda}\mathbf{z}, \end{aligned} \quad (6)$$

where the diagonal matrix $\mathbf{\Lambda}$ and the decoding matrix \mathbf{Q} are used for the FDE and compensating \mathbf{P} , respectively, in zero forcing (ZF) or minimum mean square error (MMSE) manner.

3 Precoder Flexibility and Forward Compatibility

5G NR highlights three main use cases: enhanced mobile broadband (eMBB), ultra-reliable and low latency communications (URLLC), and massive machine type communications (mMTC) with the frequency ranges up to 100 GHz. The fundamental physical layer signal structure shall be flexible enough in order to fulfil their diverse requirements and support different transmission properties. In addition, multiplexing them in the same contiguous band efficiently is a challenging task that may be handled by adopting transmitting waveforms featuring low OOSB emission. PAPR is also a crucial issue that directly impacts on power amplifier (PA) efficiency and even the expected OOSB emission especially for high frequency band operation. CPS-OFDM is therefore known as a promising waveform that can meet the above demands by just setting the appropriate parameters K , M , and \mathbf{g} of the precoder. Furthermore, obviously, it is feasible to apply any time-domain processing technique (e.g., filtering, windowing, etc.) to the CPS-OFDM transmitter, hence the forward compatibility is guaranteed for Phase I specification. Related performance evaluation results can be found in [5]-[7]. Benefited from the subband precoder technique preserving orthogonal multiple access among users, CPS-OFDM may assist NR to coexist with LTE in the current licensed band [8]-[9].

Table 1 indicates that CPS-OFDM provides a generalized precoder structure in terms of K , M , and \mathbf{g} . The time-domain redundancy type modeled as the matrix \mathbf{G} for each waveform generation has also been mentioned. OFDM and DFT-s-OFDM are two legacy waveforms applied to downlink and uplink, respectively. GI DFT-s-OFDM, CP-SC, SC-CPS, and GPO proposed by [10], [11], [12], and [13] can be viewed as variants of DFT-s-OFDM waveforms that intend to reduce PAPR especially when high frequency band (above 40 GHz) is considered. GI DFT-s-OFDM features adding Zadoff-Chu sequence to the time-domain tail of each block transmission for time-frequency tracking. CP-SC, SC-CPS, and GPO waveforms characterize low PAPR performance at the cost of spectral efficiency loss due to their excess bandwidth requirements. Note that there was a discussion for such tradeoff between PAPR reduction and excess bandwidth in RAN1#42 meeting [14].

Unlike GI DFT-s-OFDM, CP-SC, SC-CPS, and GPO restricted to $K = 1$, CPS-OFDM supports $K (> 1)$ shaped subcarriers that enable phase noise and time-varying channel tracking for every block transmission at the certain frequency positions. That is to say, scattered pilot assignment for each user is possible. Moreover, with proper design on the shaping coefficients, OOSB emission and PAPR can be jointly optimized to meet the given criteria.

The foundation of 5G NR OFDM-based waveform generation using digital implementation shall jointly take CPS precoder and time-domain processor into consideration as illustrated in Figure 2. Further study in the future is still needed.

Table 1: A generalized precoder structure provided by CPS-OFDM.

CPS-OFDM	K	M	\mathbf{g} (shaping vector)	\mathbf{G} (time-domain redundancy type)
OFDM	K	1	$[1, 0, 0, \dots, 0]^T$	\mathbf{G}_{cp}
DFT-s-OFDM	1	M	$[\mathbf{1}_M^T, 0, 0, \dots, 0]^T$	\mathbf{G}_{cp}
GI DFT-s-OFDM [10]	1	M	$[\mathbf{1}_M^T, 0, 0, \dots, 0]^T$	\mathbf{I}_N
CP-SC [11]	1	M	$[\mathbf{g}_{\text{RRRC}}^T, 0, 0, \dots, 0]^T$	\mathbf{G}_{zp}
SC-CPS [12]	1	M	$[\mathbf{g}_{\text{RC}}^T, 0, 0, \dots, 0]^T$	\mathbf{G}_{cp}
GPO [13]	1	M	$\mathbf{g}_{\text{LGMSK}}$	\mathbf{G}_{cp}

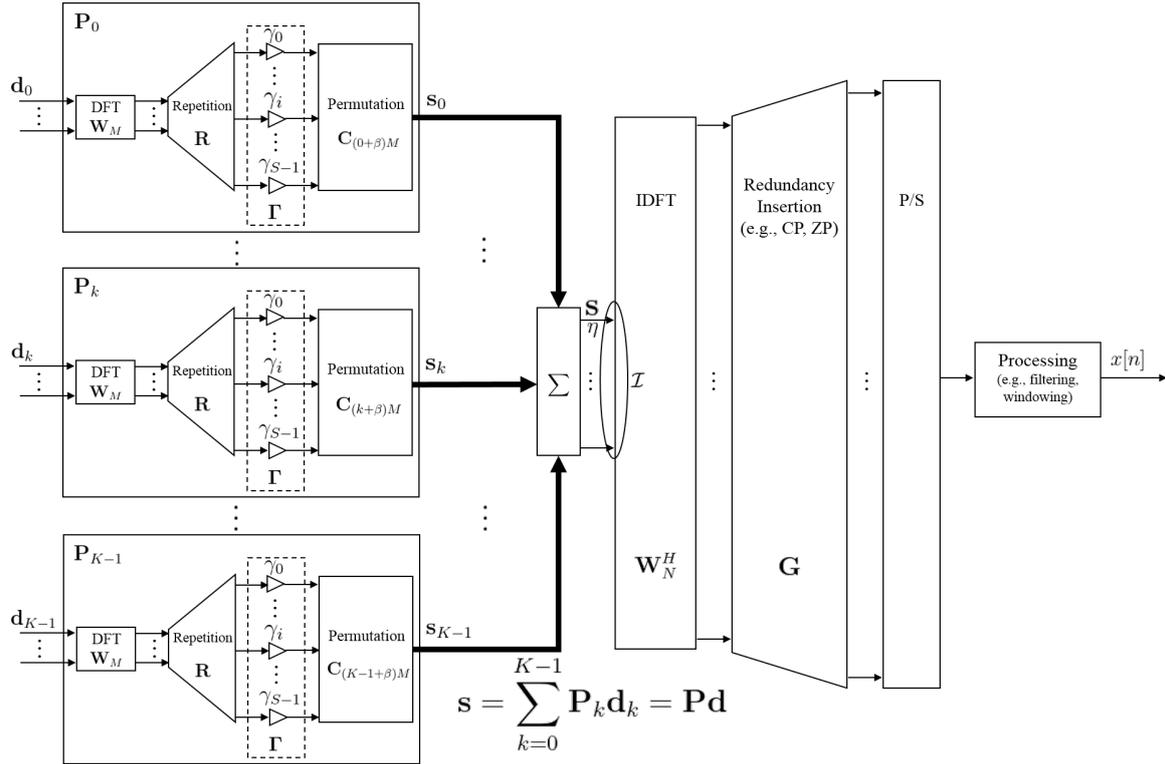


Figure 2: 5G NR OFDM-based waveform generation.

4 Summary

CPS-OFDM waveform characterized by precoder flexibility with multiple access support and forward compatibility is designed to facilitate 5G fragmented spectrum usage. Based on the analysis and the evaluations in this document, we summarize the observations and then make one proposal as follows:

Observation 1: *CPS-OFDM waveform enjoys the flexibility in determining desired transmission properties (e.g., low PAPR, low OOSB emission, etc.) by choosing parameters K , M , and shaping coefficients of the precoder.*

Observation 2: *CPS precoding technique is obviously compatible with other spectral confinement techniques (e.g., filtering, windowing, etc.) at the transmitter.*

Proposal 1: *CPS-OFDM can be considered as one of highly-potential waveforms in NR, since it provides precoder flexibility in determining desired transmission properties and guarantees forward compatibility.*

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