Enhanced Alignment Signal for CP-Free OFDM: Concept and Performance

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***Abstract*—Cyclic-prefix orthogonal frequency-division multiplexing (CP-OFDM) is a widely adopted modulation scheme for broadband wireless communication systems. The use of CP makes the scheme robust and facilitates simple and effective channel equalization since it makes the frequency-selective multipath fading to appear as flat-fading at subcarrier level. However, CP causes overhead in the spectrum efficiency and power efficiency. Various schemes have been proposed in the literature to avoid the use of CP or other forms of guard intervals (GIs) between OFDM symbols, but none of those has been fully satisfying. One recent proposal is based on adding a so-called alignment signal to GI-less OFDM signal in such a way that (i) intersymbol interference is avoided and (ii) the multipath channel effect appears as the cyclic convolution between the effective channel impulse response and each OFDM symbol. While assuming channel knowledge on the transmitter side, this approach allows basic OFDM signal processing to be used on the receiver side for channel estimation, equalization, and synchronization. In this work, we provide enhancements to the alignment signal structure and generation, which provide clear improvement in the link performance and reduce the complexity of transmitter processing. Also new insights about the characteristics of alignment signal based CP-free OFDM waveforms are provided.**

***Index Terms*—CP-free OFDM, multicarrier waveforms, cyclic convolution, alignment signal, 5G New Radio, 6G.**

I. Introduction

Cyclic-prefix orthogonal frequency-division multiplexing (CP-OFDM) is the dominant waveform for wireless systems, except for simple low-rate low-power applications [1], [2]. It has numerous benefits but also various downsides, which have been widely investigated in recent literature. This paper focuses on the guard interval (GI) issue, which introduces overheads in spectrum efficiency and energy consumption. The energy overhead of the transmitted signal can be avoided by using zero-prefix or -postfix instead of the cyclic prefix (CP), but due to losses in receiver processing, no significant gain is obtained in the overall link performance [3], [4]. Also other forms of GIs between OFDM symbols have been investigated, e.g., for controlling peak-to-average power ratio (PAPR) [5] or out-of-band emissions [6].

In addition to these overheads, GI based OFDM schemes introduce difficulties in flexible waveform parametrization. Generally, the design of an OFDM system is based on assumption of the maximum channel delay spread on the propagation environment, and conservative choice of this parameter leads to excessive overheads. A new step in OFDM system parametrization was taken in the 5G New Radio, which allows so-called mixed-numerology operation, i.e., the use of different subcarrier spacings and CP-lengths in different subbands (called bandwidth parts) [7]. In 5G New Radio the CP-length scales directly with the assumed subcarrier spacing, and thus the choices for different CP-lengths are quite limited.

In principle, multicarrier modulation schemes without GIs between OFDM symbols would simplify the system parametrization, especially in mixed numerology scenarios, in addition to relaxing the energy and spectrum efficiency overheads. Furthermore, discarding GIs allows to reduce the physical layer latency as more OFDM symbols can be transmitted within the same time unit, making these schemes interesting for possible 6G low-latency use cases. Several techniques have been proposed for shortening or totally eliminating CP, that can be categorized as equalization-based and redundancy-based. Typical examples of the first category include the time-domain equalizers such as shortening impulse response filter (SIRF) [8], symbol cyclic-shift equalization (SCSE) [9], frequency-domain equalizers like zero-forcing (ZF) equalizer in [10], successive interference cancellation (SIC) equalizer [11], or overlapping minimum mean square error (MMSE) equalizer [12]. The latter CP eliminating category usually leverages the spectral or spatial domain redundancy to migigate the inter-symbol interference (ISI) in the receiving OFDM signal. For example, the generalized side-lobe canceler (GSC) in [13] uses the spatial redundancy and Trautmann in [14] uses frequency redundancy to cancel out the ISI without using CP, however, increasing the system complexity or wasting other resources.

Our design is based on the CP-free OFDM method published by Hamamreh et al. [15] which works in ”power domain”. This original scheme makes it possible to transmit OFDM signal without using CP or any other form of GI between OFDM symbols. The main idea is to superimpose an additional signal element, called alignment signal, on top of the time-domain OFDM symbol sequence. The alignment signal aims to provide circularity of each OFDM symbol and eliminate inter-symbol interference (ISI) from the received signal in case of frequency-selective multipath channel. Then the basic subcarrier-wise single-tap channel equalization model [16] is still applicable for the receiver. Obviously, the alignment signal generation procedure relies on channel knowledge on the transmitter (TX) side.Two alternative alignment signal structures are considered in [15] regarding the position of ISI cancelling signal elements. For further improve the performance and keep the merits of CP-free OFDM design, we propose a third alternative termed E-CP-Free OFDM in this paper. The contributions of this paper are:

- A low computational complexity alignment signal generating method is proposed, which drives alignment signal through FFT-domain processing rather than the time domain used in [15].
- Besides the low computational complexity, the FFT-domain alignment signal also avoids the errors coming from pseudo-inverse of time-domain channel convolution matrix calculation which degrades performance of original CP-free OFDM. This advantage is reflected in the lower bit error rate (BER) of the E-CP-Free OFDM in the simulations with TDL-C and TDL-D channels.
- The alignment signal calculated from FFT-domain can be truncated according to the maximum path delay. However, alignment signal length in [15] has to be strictly equal to the OFDM symbol length.

The rest of this paper is organized as follows. The methodology of basic and enhanced CP-free OFDM schemes are explained in Section 2. Section 3 reports the performance analysis results, which are based on Monte-Carlo simulations. Finally, conclusion and topics for future work are summarized in Section 4.

II. Proposed CP-Free OFDM Signal Model

A. Signal Model

Generally, the baseband model for the kth OFDM symbol can be expressed as

$$\mathbf{x}_k = \mathbf{F}^{\mathrm{H}}\mathbf{X}_k, \tag{1}$$

where $\mathbf{X}_k \in \mathbb{C}^{M\times 1}$ is a vector of subcarrier symbols and $\mathbf{F}^{\mathrm{H}} \in \mathbb{C}^{(M\times M)}$ is the IDFT matrix ($\mathbf{F}$ is the DFT matrix and H stands for the Hermitian). The corresponding received time-domain signal after stationary multipath channel of length $L+1$ is

$$\mathbf{r}_k = \mathbf{C}\mathbf{x}_k = \mathbf{C}\mathbf{F}^{\mathrm{H}}\mathbf{X}_k. \tag{2}$$

Here the channel convolution matrix $\mathbf{C} \in \mathbb{C}^{((M+L)\times M)}$ has the Toepliz structure

$$\mathbf{C} = \begin{bmatrix} \mathbf{C}_0 \\ \mathbf{C}_{\mathrm{ISI}} \end{bmatrix} = \begin{bmatrix} h_0 & 0 & 0 & \dots & 0 \\ h_1 & h_0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ h_L & h_{L-1} & h_{L-2} & \dots & 0 \\ 0 & h_L & h_{L-1} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & h_L \end{bmatrix}, \tag{3}$$

where $\mathbf{C}_0 \in \mathbb{C}^{(M\times M)}$ and $\mathbf{C}_{\mathrm{ISI}} \in \mathbb{C}^{(L\times M)}$. The ISI-free part and ISI part of kth received OFDM symbol are $\mathbf{C}_0\mathbf{x}_k$ and $\mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k$, respectively.

Next we consider a sequence of plain OFDM symbols without any GIs in between. Then the ISI from symbol k to symbol $k+1$ could be cancelled on the RX side by superimposing the signal $-\mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k$ at the beginning of symbol $k+1$. Likewise, circularity of the channel effect could be reached by superimposing the signal $\mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k$ at the beginning of symbol k at the receiver. Thus, the main idea of CP-free OFDM schemes in [15] and this work is to superimpose alignment signal (AS) on the OFDM symbols at the transmitter side, assuming that the TX knows the channel impulse response.

B. CP-Free OFDM Alignment Signal Generation

Let the AS element for symbol k on the TX side to be $\mathbf{b}_k \in \mathbb{C}^{(M\times 1)}$. $\mathbf{ISI}_k \in \mathbb{C}^{(M\times 1)}$ and $\mathbf{CIR}_k \in \mathbb{C}^{(M\times 1)}$ represent ISI cancelling element and circularity providing element. Assuming stationary (or block-fading) channel model, ISI is perfectly cancelled and circularity is provided if the following condition is satisfied:

$$\mathbf{C}\mathbf{b}_k = \mathbf{C}(\mathbf{ISI}_k + \mathbf{CIR}_k) = \begin{bmatrix} \mathbf{0}^{(M\times 1)} \\ -\mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k \end{bmatrix} + \begin{bmatrix} \mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k \\ \mathbf{0}^{(M\times 1)} \end{bmatrix}. \tag{4}$$

The least-squares solution to this equation is provided by the pseudo inverse:

$$\mathbf{b}_k = (\mathbf{C}^{\mathrm{H}}\mathbf{C})^{-1}\mathbf{C}^{\mathrm{H}}(\begin{bmatrix} \mathbf{0}^{(M\times 1)} \\ -\mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k \end{bmatrix} + \begin{bmatrix} \mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k \\ \mathbf{0}^{(M\times 1)} \end{bmatrix}). \tag{5}$$

The pseudo-inverse in (5) incurs high computational complexity, also may involve numerical difficulties which depends on the channel impulse response [15].

C. Enhanced CP-Free OFDM Alignment Signal Generation

In order to relax fore-mentioned issues, we propose a novel approach to generate AS in FFT-domain based on subband-wise channel coefficient estimates. Since ideal $(k+1)_{th}$ ISI cancelling signal and k_{th} circularity providing signal has the same value $-\mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k$ but different sign (can be observed from equation (4)). The calculation of AS element value can be simplified by only calculating ISI cancelling signal or circularity signal. Let AS element $\mathbf{a}_k \in \mathbb{C}^{(M\times 1)}$ for symbol k in this design cancels ISI in the receiver side as shown in (6).

$$\mathbf{C}\mathbf{a}_k = \begin{bmatrix} \mathbf{0}^{(M\times 1)} \\ -\mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k \end{bmatrix}. \tag{6}$$

The channel and AS element $\mathbf{a}_k$ are supposed to be circularly convoluted. The channel impulse response $\mathbf{H} \in \mathbb{C}^{(M\times M)}$ shown in (7) is known by the channel estimation process and shared with transmitter before generating message signal. Then, the equation (6) can be written as (8)

$$\mathbf{H} = \mathrm{diag}[H_0, H_1, \dots, H_{M-1}]. \tag{7}$$

$$\mathbf{F}(\mathbf{C}\mathbf{a}_k) = \mathbf{H}\mathbf{F}\mathbf{a}_k = \mathbf{F}\begin{bmatrix} \mathbf{0}^{((M-L)\times 1)} \\ -\mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k \end{bmatrix}. \tag{8}$$

Then, an IFFT matrix $\mathbf{F}^{\mathrm{H}}$ and inverse of channel impulse response $\mathbf{H}^{-1}$ are multiplied on (8) for getting alignment signal as shown in (9).

$$\mathbf{a}_k = \mathbf{F}^{\mathrm{H}}\mathbf{H}^{-1}\mathbf{F}\begin{bmatrix} \mathbf{0}^{((M-L)\times 1)} \\ -\mathbf{C}_{\mathrm{ISI}}\mathbf{x}_k \end{bmatrix}. \tag{9}$$

All in all, the process includes taking FFT of the ISI part of each OFDM symbol and multiplying each resulting FFT bin by the inverse of the corresponding subcarrier channel coefficient H_k obtained through pilot based channel estimation. Finally, the ISI-cancelling signal is obtained by taking IFFT of the result. Then the AS of symbol k is constructed using (10).

$$\hat{\mathbf{a}}_k = \mathbf{a}_k - \mathbf{a}_{k+1}. \quad (10)$$

With the above mentioned process, the AS of the E-CP-Free OFDM signal can be demonstrated by Fig. 1. This is a length-M vector, but the significant samples are at the end of it, and it can be truncated to a length that corresponds to the maximum channel delay spread, or CP length in CP-OFDM systems. The effect of the truncation length will be examined in the numerical results section. In this study, we propose to insert

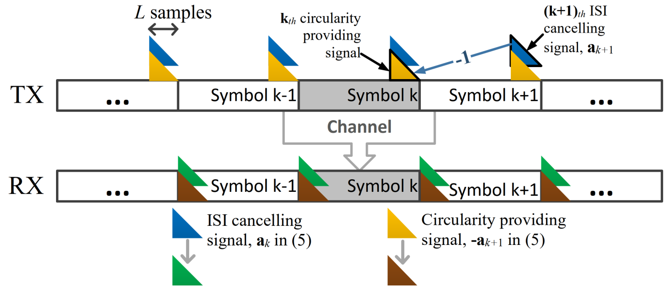

Fig. 1. Enhanced CP-free OFDM structure of one slot and location of the alignment signal elements for each OFDM symbol.

the circularity providing AS element of symbol k at the end of symbol $k-1$ and ISI cancelling AS element at the end of symbol k. To achieve this, the transmission frame is extended by L samples in the beginning to accommodate the circularity providing AS element for the first OFDM symbol.

III. Numerical Results

A. Simulation Setting and Assumptions

All results presented below are with the OFDM FFT size of 256 with 64 active subcarriers and 15 kHz subcarrier spacing. We assume 64QAM modulation with NLOS channel TDL-C and 256QAM modulation with LOS channel TDL-D. High-order modulations are more sensitive to different imperfections, clearly illustrating the performance of different schemes. We use 24 taps for the TDL-C channel. TDL-C taps follow the Rayleigh fading and the average power of each tap is defined in 3GPP [17]. For TDL-D channel, 13 taps are used. The first tap follows the Ricean distribution with a K-factor of $K_1 = 13.3dB$ and $0dB$ mean power. The rest of the TDL-D taps follow the Rayleigh fading and average power of each tap is defined in 3GPP [17]. For both channels, we test the performance with three different RMS channel delay spread values, $\{0.1, 0.3, 1\}$ μs. The corresponding maximum delay spread values are about $\{0.87, 2.6, 8.7\}$ μs for the TDL-C channel and $\{1.25, 3.8. 12.5\}$ μs for the TDL-D channel. It should be noted that highest maximum delay spread values of both channels exceed the CP-length used in the plain CP-OFDM refernce system, 4.7 μs (18 samples) following the LTE numerology [1]. The path loss is not considered in both channel models. As a constant attenuation of radio energy, the path loss impact can be reflected in the SNR in the simulation.

We assume that channel knowledge on the receiver side is always obtained through basic FFT-domain channel estimation using a single training symbol with known binary phase-shift keying (BPSK) symbols in each subcarrier, at the same energy level as data symbols on the average. In case of E-CP-Free OFDM, AS is applied also on the training symbol. The channel knowledge is needed also on the TX side for AS generation. Generally, it could be based feedback from the receiver or, in case of time-division duplexing (TDD), on channel estimation of the reverse link while relying on channel reciprocity. Without considering the detailed scheme, we assume that the TX channel knowledge is also based on a single training symbol at the same signal-to-noise ratio (SNR) as channel estimation at the receiver. The results include also reference simulations assuming perfect channel information (PCI) on the transmitter side for AS generation. However, the receiver processing of all included schemes is always based on channel estimation. We begin by assuming full-band PCI or channel estimation, later the effect of channel estimation bandwidth in AS generation is evaluated.

B. Bit Error Rate Performance

In this paper, the uncoded BER is use as the main metric to compare the E-CP-Free OFDM performance against conventional CP-Free OFDM in block-fading multipath channel models.

1) BER in NLOS TDL-C Channel: First, The link performance results assuming PCI in AS generation are shown in Fig. 2 for original [15] and E-CP-Free OFDM schemes using CP-OFDM (CP length 18) and GI-free OFDM (plain OFDM without any GI) as reference schemes. It can be seen that the CP-OFDM still outperforms all GI-free versions when measured by BER. The original CP-free and GI-free OFDMs can be classified as the worst category. Our E-CP-Free OFDM lays in between the CP-OFDM and the two worst cases, however, closer to the CP-OFDM case, especially when the channel delay spread is small. Specifically, the performance loss of E-CP-Free OFDM with $\tau = 0.1\mu s$ is insignificant at the above 1 % BER range. With $\tau = 0.3\mu s$, the performance loss grows from about 0.3 dB at 10 % BER to about 4 dB at 1 % BER. From this first glance, the E-CP-Free OFDM shows a potential of spectrum and energy efficiency without significantly compromising the BER performance. In later comparisons, we will use the CP-OFDM as bench mark for BER performance.

Second, Fig. 3 shows the link performances of E-CP-Free OFDM and CP-OFDM (CP length 18) with full-band channel estimation in AS generation, 64QAM modulation, and TDL-C channels. With $\tau = 0.1\mu s$, the performance loss with respect to the PCI case (and CP-OFDM case as well) is about 1 dB in the 1-10 % BER range. With $\tau = 0.3\mu s$, the additional performance loss due to channel estimation based AS generation is about 2 dB in the same BER range.

2) BER in LOS TDL-D Channel: Figs. 4, 5 show the corresponding results in the LOS channel case, i.e., TDL-D channel with 256QAM modulation. With $\tau = 0.1\mu s$, E-CP-Free OFDM reaches the CP-OFDM performance with PCI and has below 1 dB performance loss in the interesting BER

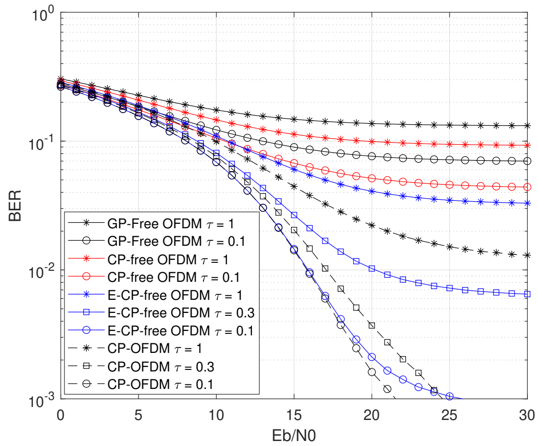

Fig. 2. BER performance of GI-free OFDM, original CP-free OFDM, E-CP-Free OFDM, and CP-OFDM with CP-length of 18 in block-fading TDL-C cha

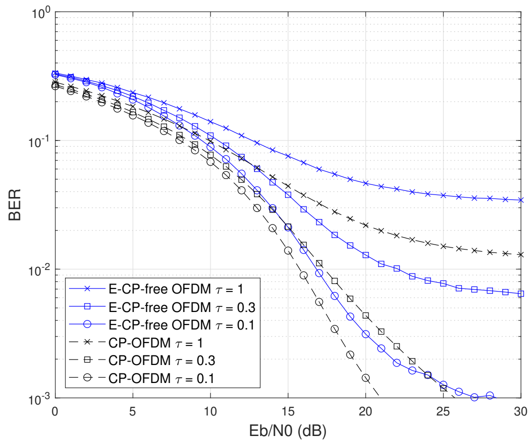

Fig. 3. BER performance of E-CP-Free OFDM, and CP-OFDM with CP-length of 18 in block-fading TDL-C channel with 64QAM modulation and training symbol based full-band channel estimation for AS generation.

range with full-band channel estimation. With τ = 0.3μs, the performance loss at 10 % BER is insignificant with PCI and about 1 dB with channel estimation. At 1 % BER level, the loss is about 2 dB with PCI and the effect of channel estimation is small. Even with τ = 1μs, the performance loss at 10 % BER level is about 1 dB with PCI and 1.5 dB with channel estimation, however, the error floor is clearly above 1%.

C. Impact of Channel Estimation Bandwidth and AS Length

As mentioned earlier, the alignment signal is not confined in spectrum to the range of active subcarriers. Consequently, channel knowledge in wider frequency band is needed for precise alignment signal generation. With FFT-domain channel estimation based AS generation, this effect can be easily tested by varying the number of active subcarriers used in training symbols and AS calculations. We show the impact of the channel estimation bandwidth on the BER performance in Fig. 6. It is easy to see that limiting the bandwidth to the active subcarriers severely degrades the performance of E-CP-Free OFDM, and we have tested that the same applies to the original scheme [15]. However, full-band channel knowledge is not necessary. With the used parameters (FFT-size of 256 and 64

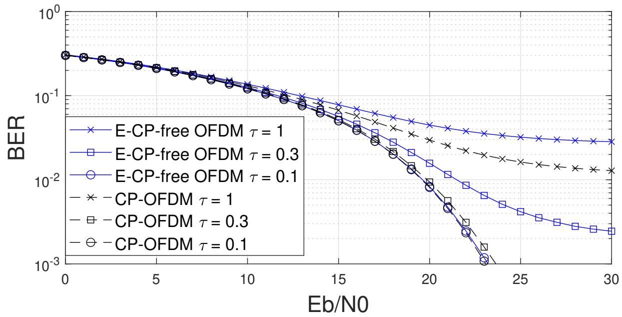

Fig. 4. BER performance of E-CP-Free OFDM and CP-OFDM with CP-length of 18 in block-fading TDL-D channel with 256QAM modulation and PCI assumption.

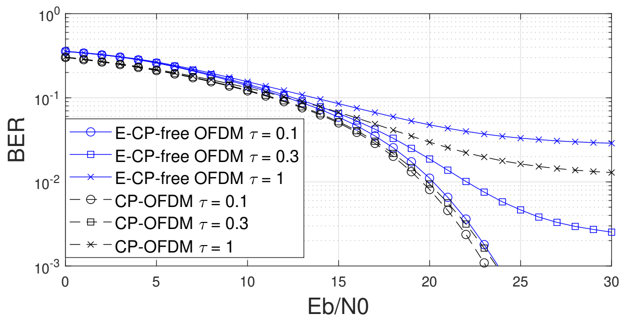

Fig. 5. BER performance of enhanced CP-free OFDM, and CP-OFDM with CP-length of 18 in block-fading TDL-D channel with 256QAM modulation and training symbol based full-band channel estimation for AS generation.

active subcarriers), 20 additional subcarriers (10 on both sides) in channel estimation brings the performance significantly closer to that of the full-band channel estimation.

In Fig 7, we investigate the effect of CP and AS lengths on the BER performance. For CP-OFDM, the results are consistent with the knowledge that there is no need to extend the CP-length beyond the maximum channel delay spread. With E-CP-Free OFDM, the performance saturates with AS lengths smaller than the maximum delay spread at a higher level than with CP-OFDM. The phenomenon is more obvious when there is no dominant path, for example, TDL-C channel in Fig. 7 (a) where the inflection points appears when the lengths of AS equal to {5, 6, 7} for τ={0.1, 0.3, 1}, respectively. In contrast, the result of TDL-D channel in Fig. 7 (b) show that the performance improvement stops when AS length reaches 4 for all time delay spread scenarios. The very likely cause is that the line-of-sight path in TDL-D channels, dominates the final performance.

D. Signal Properties

The CP in the traditional OFDM signal is a segment of OFDM symbol with pre-defined length according to the expected channel delay spread and targeted overheads. Thus, the signal properties, such as power spectral density (PSD), out-of-band (OOB) spectrum, and peak to average power ratio (PAPR) of CP-OFDM are usually constant. With E-CP-Free OFDM, the signal properties present certain level of temporal dynamics because of the channel dependent AS superimposed

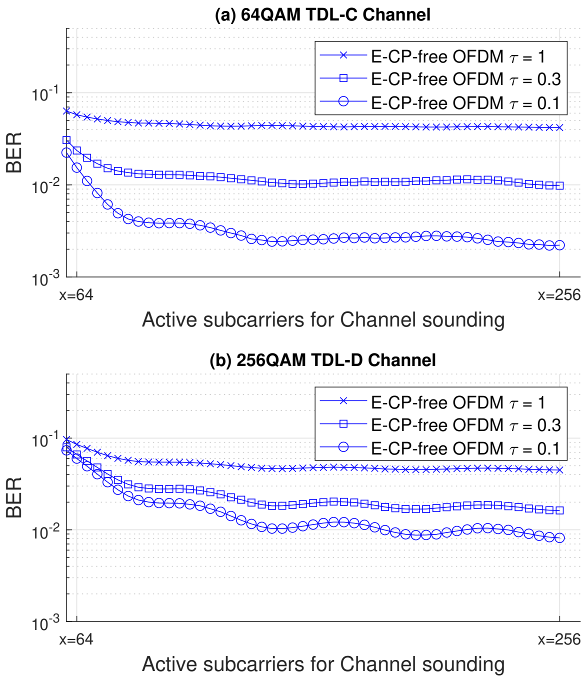

Fig. 6. Channel estimation bandwidth effect on E-CP-Free OFDM with training symbol based estimation and SNR of 20 dB. (a) 64QAM modulation and TDL-C channel. (b) 256QAM modulation and TDL-D channel.

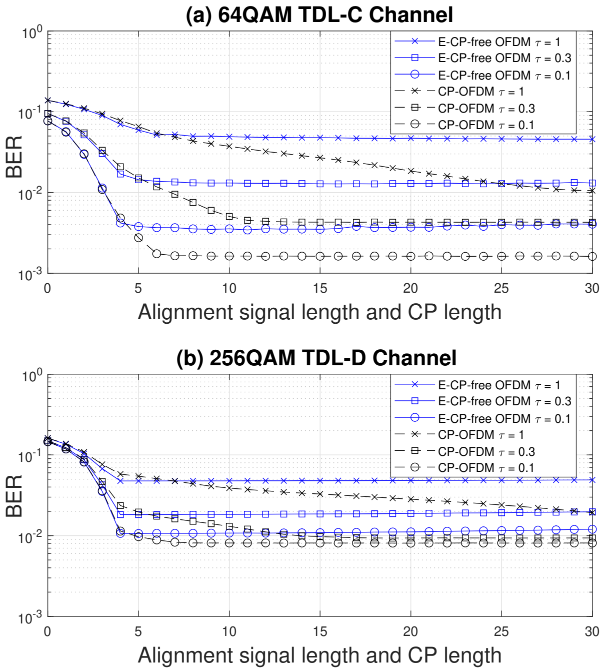

Fig. 7. CP-length effect on CP-OFDM and AS length effect on E-CP-Free OFDM with training symbol based full-band channel estimation and 20 dB SNR. (a) 64QAM modulation and TDL-C channel. (b) 256QAM modulation and TDL-D channel.

on top of the transmitted data bearing signal. The PSD and PAPR characteristics of E-CP-Free OFDM signals are illustrated in Figs. 8 and 9 for the two channel models.

The cumulative distribution functions (CCDFs) of PAPR are presented in Fig. 8 for E-CP-Free OFDM signals in TDL-C and TDL-D channels. In the TDL-C scenario, clear PAPR deteriorating trend can be seen with increasing channel delay spread. Strong frequency selectivity results in strong AS signals, leading to increased PAPR of E-CP-Free OFDM signals with larger delay spreads. In the TDL-D scenario, the PAPRs with different channel delay spread values show high consistency because of the presence of the dominating direct path and milder frequency selectivity. Anyway, even with TDL-C channel, the PAPR increase with respect to plain CP-OFDM is modest, about 0.3 dB with $\tau = 1\mu$s, and with TDL-D, the PAPR increase is insignificant.

Fig. 9 shows the PSDs of CP-OFDM and E-CP-Free OFDM with different RMS delay spread values. We use the normalized OOB emission power which is defined as the ratio of the out-of-band and in-band powers (denoted by P_{OOB}) to indicate the PSDs stability. For both TDL-C and TDL-D channels, the average P_{OOB} of CP-OFDM signals are around -21 dB. The average of P_{OOB} for E-CP-Free OFDM in TDL-D channel are around -20 dB and standard deviations (STD) are $\{0.0022, 0.0026, 0.0023\}$ when τ=$\{0.1, 0.3, 1\}$, respectively, for all choices of τ. The average and STD of P_{OOB} for E-CP-Free OFDM in TDL-C channel are $\{$-19.2, -18, -17.1$\}$ dB and $\{0.006, 0.0139, 0.0204\}$ when τ=$\{0.1, 0.3, 1\}$. These results indicate quite significantly increased and highly variable channel-dependant P_{OOB}, especially with TDL-C channels. The phenomenon is represented by varying PSD shapes in TLD-C channels and rather constant PSD shapes in TDL-D channels in Fig. 9. The root for this phenomenon is the dependency of AS on the channel conditions. TDL-D channels have a dominant path leading to more stable AS with low power level.

IV. Conclusion

In this paper, an enhanced alignment signal based CP-free OFDM scheme was introduced and termed as E-CP-Free OFDM. The novel elements beyond the original scheme [15] include new AS structure, AS signal generation FFT-domain, and testing the scheme with practical channel models widely used in 5G-NR developments. It was demonstrated that the performance of the proposed scheme clearly outperforms the original one. The BER performance was found to be good with 256QAM modulation in TDL-D type LOS channels with channel delay spread values up to about (4μs), while using 15 kHz subcarrier spacing (recall that the normal CP length of LTE is 4.7μs). In TDL-C channel with 64QAM, the performance is good with maximum delay spread up to 1-2 μs. Due to the dependence of AS on the channel, the properties like OOB emission and PAPR of the E-CP-Free OFDM are dynamic in time. It was found that E-CP-Free OFDM increases the PAPR with TDL-C channel somewhat, about 0.3 dB with the highest delay spread value considered. With TDL-D channels, the PAPR degradation is marginal. Perhaps the most critical issue is increased out-of-band emissions due to the poor spectrum confinement of the AS signal. This is

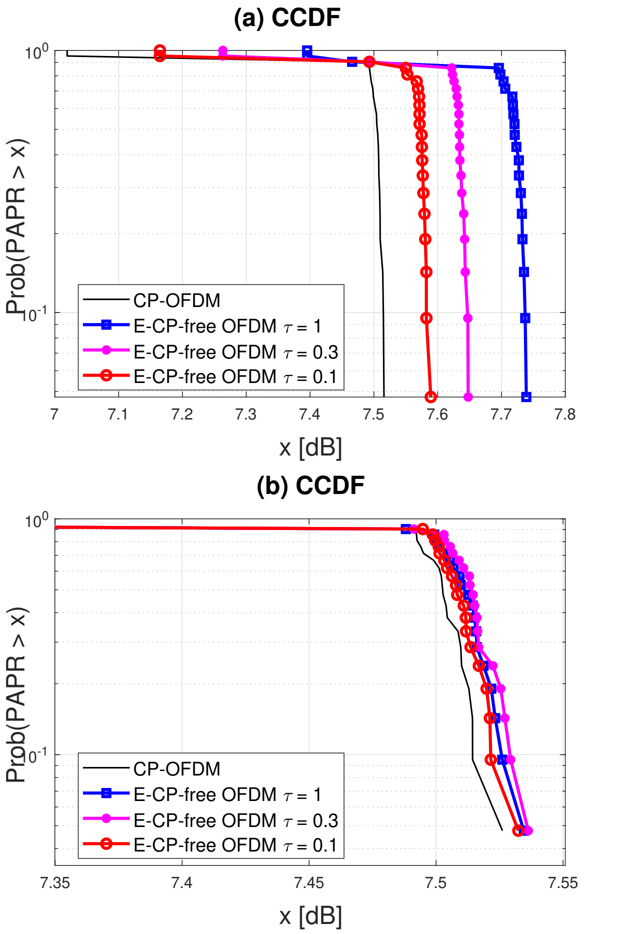

Fig. 8. CCDFs of PAPR for E-CP-Free OFDM and CP-OFDM. (a) 64QAM modulation and TDL-C channel. (b) 256QAM modulation and TDL-D channel.

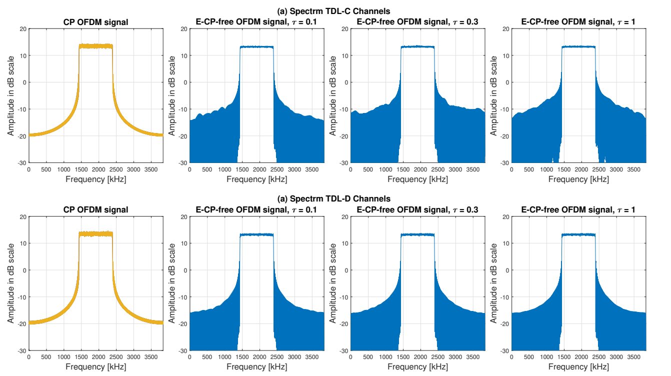

Fig. 9. PSDs of E-CP-Free OFDM, and CP-OFDM with CP-length of 18. (a) 64QAM modulation and TDL-C channel. (b) 256QAM modulation and TDL-D channel.

especially critical with the TDL-C channel, even with modest delay spread, while the effect is still modest with TDL-D.

The second critical issue is that the channel estimation bandwidth should be wider than the bandwidth of active subcarriers which, no doubt, limits the general applicability of the scheme. Therefore, an important topic for future work is to investigate possibilities of reducing the channel estimation bandwidth and AS bandwidth through more advanced channel estimation and AS generation techniques. Also filtering the composite E-CP-Free OFDM signal in the filtered-OFDM spirit [18] is an intersting direction. In addition, applying AS signal in the non-orthogonal FDM systems (e.g., time-precoding enabled SE-FDM in [19]) for joint ISI and intercarrier interference (ICI) cancellation is also in the scope of our vision in future studies towards 6G communications.

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The Improvements and Responses to Reviewing Comments

1. Thanks for the positive feedback from Reviewer 1, 2 and 3. The contributions of the paper have been highlighted at the end of Section I (highlighted).

2. The improvements and Responses to comments from Review 4
   a. ***Comment 1***: *The novel contribution of this work with respect to the related research must be highlighted. The current presentation related to the contribution of this work seems inadequate and does not fully justify the underlying concepts and techniques.*
   Improvement: The contributions of the paper have been highlighted at the end of Section I (highlighted).

   b. ***Comment 2***: *The channel model has not been defined adequately. It must be defined with the corresponding fading model, frequency selectivity aspects, and large-scale/path-loss.*
   Improvement: The detailed channel models have been given in Section III-A. Simulation Setting and Assumptions (highlighted).

   c. ***Comment 3***: *Section II devoted to CP-free OFDM is redundant as the corresponding discussion can be seen in many related work. Thus it is strongly recommended to shorted this section by using cross-referencing.*
   Comment 4: *A separate section must be introduced to describe the proposed extension to CP-free OFDM.*
   Improvement: We have shortened the length of the CP-Free-OFDM text and made it in a separate subsection as Section II-A in blue. A separate subsection Section II-B (highlighted) is introduced to describe the E-CP-Free-OFDM proposed by us.

   d. ***Comment 5***: *Lack of adequate analysis is a major concern about this manuscript. The contribution can be improved if an average BER can be derived and compared against the existing schemes analytically.*
   Response: In this paper, the bit error rate (BER) is used as the primary metric to compare the E-CP-Free-OFDM performance against conventional CP-Free-OFDM. For the OFDM system, the BER performance over the whole used frequency spectral can be considered as the average BER of parallel sub-carriers. In the ideal channel condition, The BER of each parallel sub-carrier have closed-form expressions and well documented in the literature. However, the channel impairments such as ICI (usually caused by carrier frequency offset, Doppler spread) and ISI (usually caused by multipath propagation), often result in irreducible BER floors which the closed-form has been documented in Chapter 6.4 and 6.5 respectively in Wireless Communications (by Andrea Goldsmith, 2005). The level of the irreducible BER floor relies on the severity of the ICI, ISI and measures for reducing the ICI and ISI impacts. ICI and its mitigation strategies are out of the scope of this paper. While the AS signal design method in E-CP-Free-OFDM is the approach to reduce the ISI with less computing burden (in FFT domain) and fewer errors (avoiding the pseudo-inverse operation). Thus, one performance metric of the E-CP-Free-OFDM is the reduction for the BER floor comparing with the normal CP-Free-FODM, which is shown in Figure 2.

   e. ***Comment 6***: *Some of the figures need to be re-generated to show the subtle changes of the curves. Thus, it is recommended to run the Monte-Carlo simulations more iterations to make those curves more smoother.*
   Improvement: We have updated the smoother curves in Figure 7 and 8 with more iterations in the simulations (highlighted).