FFT-Domain Signal Processing for Spectrally-Enhanced CP-OFDM Waveforms in 5G New Radio

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***Abstract*—Fast Fourier transform (FFT)-domain signal processing has been considered recently as an effective tool for spectrum enhancement of orthogonal frequency-division multiplexing (OFDM)-based waveforms, which is a central element in the fifth generation new radio (5G-NR) developments. Fast-convolution (FC) filtering approximates linear convolution by effective FFT-based block-wise circular convolutions using partly overlapping processing blocks. In earlier work, we have shown that FC processing is a very flexible and efficient tool for filtered OFDM signal generation and receiver-side subband filtering, e.g., for the mixed numerology scenarios of the 5G-NR. However, with the continuous overlap-save and overlap-add processing models with fixed block-size and overlap, the FC-processing blocks are not synchronized to all OFDM symbols of a transmission frame. Furthermore, 5G-NR numerology does not allow to use transform lengths smaller than 128 because this would lead to non-integer cyclic prefix (CP) lengths. Here we present a modified FC processing scheme which avoids these limitations. The scheme is based on extrapolating the CP samples which, as an example, makes it possible to use 16-point transforms in case of a 12-subcarrier-wide subband allocation, greatly reducing the implementation complexity. Also the FC-processing blocks can be aligned with each OFDM symbol, reducing complexity and latency, e.g., in mini-slot transmissions.**

***Index Terms*—filtered-OFDM, multicarrier, waveforms, fast-convolution, physical layer, 5G, 5G New Radio, 5G-NR**

I. Introduction

Orthogonal frequency-division multiplexing (OFDM) is the dominating multicarrier modulation scheme and it is extensively deployed in modern radio access systems. OFDM offers high flexibility and efficiency in allocating spectral resources to different users through the division of subcarriers, simple and robust way of channel equalization due to the inclusion of cyclic prefix (CP), as well as simplicity of combining multiantenna schemes with the core physical layer processing [1]. The main drawback is the limited spectrum localization, especially in challenging new spectrum use scenarios like asynchronous multiple access, as well as mixed numerology cases aiming to use adjustable symbol and CP lengths, subcarrier spacings (SCSs), and frame structures depending on the service requirements [2], [3].

Initial studies on filtered OFDM were based on time-domain filtering [4], [5], and later also polyphase filter bank based solutions have been presented [6], [7]. Fast-convolution-based

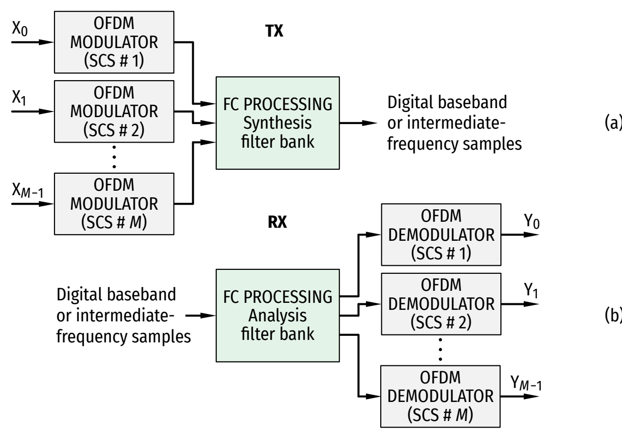

Fig. 1. In fast-convolution (FC)-based filtered OFDM, filtering is applied at subband level, which means one or multiple contiguous physical resource blocks (PRBs) with same subcarrier spacing (SCS), while utilizing normal CP-OFDM waveform for the PRBs. (a) Transmitter processing using the FC synthesis filter bank of M subbands. (b) Receiver processing using FC analysis filter bank.

filtered OFDM has been presented in [8]–[11]. Especially in [11], the flexibility, good performance, and low computational complexity of FC-F-OFDM was clearly demonstrated in the fifth generation new radio (5G-NR) context. Recently the so-called block-filtered OFDM scheme has been proposed [12] and this scheme also applies frequency-domain filtering but for a somewhat different waveform concept. These schemes typically apply filtering in continuous manner over a frame of CP-OFDM (or zero-prefix-OFDM) symbols.

The problematic/inconvenient aspect of the conventional time-domain filtering based schemes is their high complexity. The complexity can be reduced using classical (e.g., polyphase) filter bank models, however, these solutions have somewhat reduced flexibility in adjusting the subband center frequencies and bandwidths. Since FC is a block-wise processing scheme with fixed block length, the position of the useful parts of the OFDM symbols vary within a frame of transmitted OFDM symbols. With the usual continuous processing model, it is necessary that the CP lengths and useful symbol durations correspond to an integer number of samples at the lower sampling rate used for transmitter OFDM

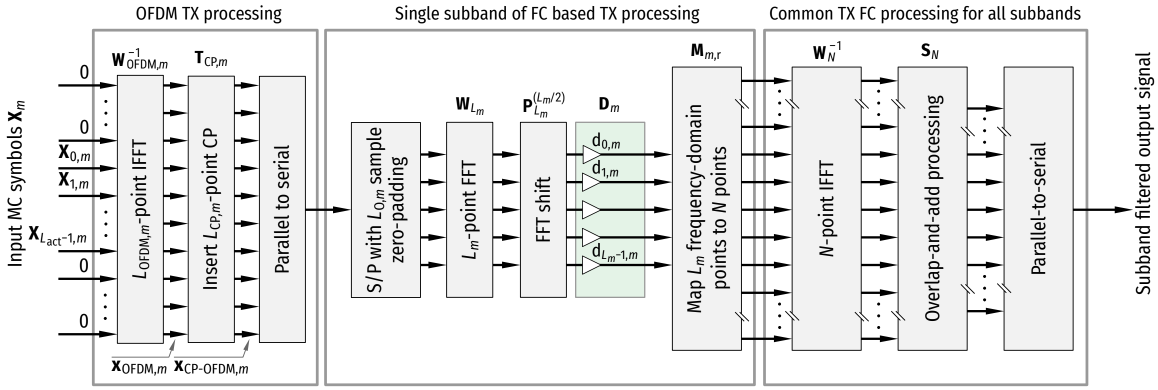

Fig. 2. Block diagram for basic FC-F-OFDM transmitter processing using the overlap-add model.

processing at each subband. In case of narrowband allocations, this limits the choice of the transform sizes, significantly increasing the computational complexity. With the 4G and 5G numerologies, the shortest possible transform length is 128, while length-16 transform would be sufficient when a subband contains one physical-layer resource block (PRB) only. This restriction applies to both time-domain filtering and FC-based solutions with continuous processing model.

This contribution proposes symbol-synchronized discontinuous FC processing targeting at increased flexibility and reduced complexity of FC-F-OFDM. It is shown that the proposed processing supports more flexible parametrization of the FC engine, resulting in reduced complexity with narrow subband allocations and in mini-slot transmission. Important use cases are seen in spectrally well-contained narrowband internet-of-things (NB IoT) transmission with one PRB allocation and in ultra-reliable low-latency communications (URLLC) for generating short transmission bursts, so-called mini-slots, to reduce the radio link latency.

The remainder of this paper is organized as follows. Section II, first shortly reviews the continuous FC-based filtered-OFDM processing. Then, the proposed discontinuous FC processing model is described with implementation alternatives resulting to the reduced complexity and latency. In Section III, the performance of the discontinuous processing is analysed in terms of uncoded bit error rate in different interference and channel conditions and the complexity is compared with the continuous FC processing. Finally, the conclusions are drawn in Section IV.

II. Fast-Convolution Processing Schemes

The block diagram for the basic overlap-add based FC-F-OFDM transmitter (TX) processing for subband m is shown in Fig. 2. First, the CP-OFDM signal is generated by using the smallest inverse fast Fourier transform (IFFT) size equal or larger than $L_{\mathrm{act},m}$ supporting an integer length CP. Then, low-rate CP is added to each OFDM symbol and the signal is converted to serial format. These are all operations equivalent to basic CP-OFDM TX processing. FC processing can, in general, be used to filter any kind of input signals,

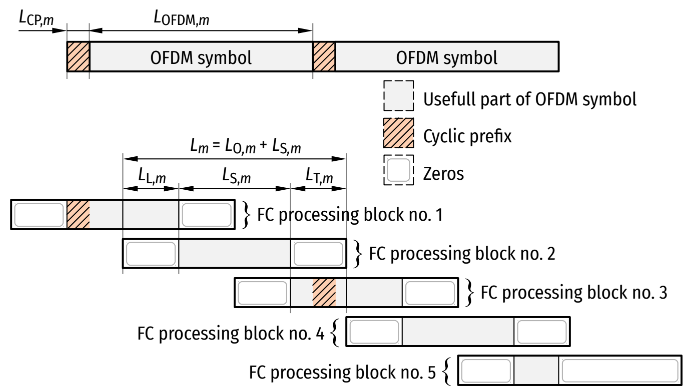

Fig. 3. FC-processing block partitioning in basic continuous overlap-add-based FC-F-OFDM with the overlap factor of $\lambda = 0.5$. FC blocks are not synchronized to CP-OFDM symbols. Five FC-processing blocks are needed for two OFDM symbols.

but in this contribution we concentrate on filtering CP-OFDM subbands.

The actual FC processing per subband starts by partitioning the time-domain input sample stream to FC blocks, as illustrated in Fig. 3. Note that the exact number of FC-processing blocks depends on the input sequence length, overlap factor, and fast Fourier transform (FFT) size L_m. Next, we take L_m-point FFT of each processing block and apply FFT-shift operation which essentially places the DC-carrier in the middle of each vector. Then, a frequency-domain window $\mathbf{D}_m$ is applied to implement the designed filter response. This frequency-domain window consists of zeros in the stopband, ones in the passband, and separately optimized, non-trivial transition band weights, thus having an inbuilt simplicity for minimized storage and computational complexity. After frequency-domain windowing the given subband is placed at the allocated FFT bins with transition-band values possibly exceeding the nominal allocation range. The values of overlapping transition-band bins of adjacent subbands are added together.

The N-point IFFT is a common part for all subbands. It converts the frequency-division multiplexed subband signals

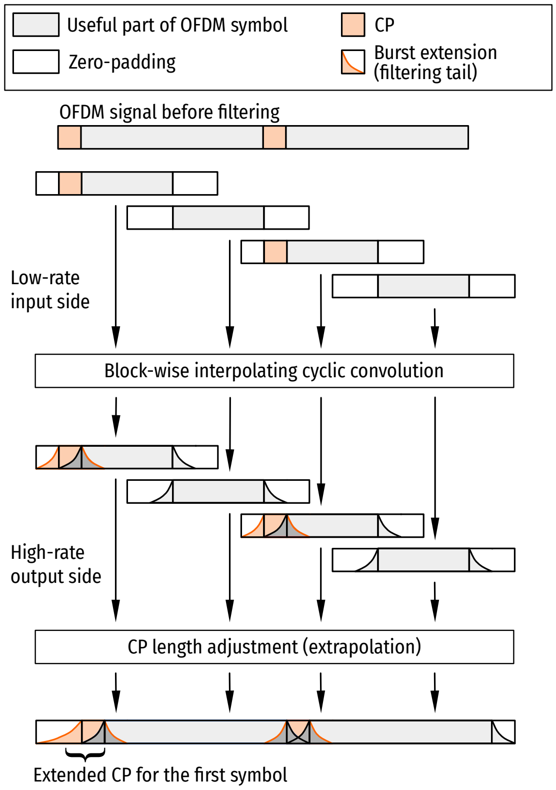

Fig. 4. Discontinuous overlap-add processing for FC-F-OFDM. FC-processing blocks are synchronized to the OFDM symbols. Four FC-processing blocks are needed for two OFDM symbols. The FC overlap factor is dynamic: $0.5 - N_{\text{CP}}/N$ for the first block and 0.5 for the second block of each OFDM symbol.

to time domain per FC-block. Next, overlap-add (OLA) processing is used to combine samples from each FC-block and to construct the filtered time-domain representation of the transmitted signal. More detailed description of the FC filtering process can be found, e.g., from [11].

Depending on the numerology, various overlap factors may be applied in FC-F-OFDM processing. Here we consider 50 % and 25 % overlaps (overlap factor is $\lambda = 0.5$ or $\lambda = 0.25$). The overlap of 50 % is a safe choice by which the FC-processing related in-band and out-of-band distortion effects can be ignored while supporting high modulation and coding schemes (MCSs) (≥ 256-QAM). For 25 % overlap, the computational complexity is significantly reduced compared with 50 % overlap, but both in-band and out-of-band interference effects are higher, and become critical with high MCSs. The smaller overlap is potentially interesting for massive machine-type communications (MTC) scenarios. These overlaps can be considered as extreme cases with reasonable performance-complexity trade-off. In the following examples we assume 50 % overlap, with dynamic adaptation in case of discontinuous processing.

The basic continuous FC-processing flow of FC-F-OFDM transmitter is illustrated in Fig. 3. The assumed overlap factor is $\lambda = 0.5$ (50 % overlap). From Fig. 3 we can observe how the FC processing is continuous by collecting $L_m/2$ samples from the input sample stream to each FC processing block. Here, $L_{\text{OFDM},m} = L_m$ is the OFDM and FC processing block IFFT and FFT sizes, respectively. Also, the overlap factor is constant over all FC processing blocks.

Fig. 4 illustrates the proposed discontinuous TX FC-F-OFDM processing flow for a mini-slot of two OFDM symbols. It can be observed that in discontinuous processing, two FC-processing blocks are synchronized to each OFDM symbol, where the first FC block contains the first half of the OFDM symbol and the second FC block contains the second half of the OFDM symbol. In addition, the first FC-processing block contains the low-rate CP samples. This reduces the overlap in the beginning of the first FC block, such that overlap factor becomes $\lambda = (L_m/2 - L_{\text{CP},m})/L_m$. In practice, this reduction is relatively small, causing only minor increase in the related distortion effects.

Fig. 5 shows a detailed example of the sample-level interpolation and extrapolation process. In the discontinuous case, the FC-processing blocks are synchronized to the OFDM symbols. Then only four FC-processing blocks are used, instead of five in the continuous processing model (see Fig. 3), resulting in reduced complexity. The CP part is included in the leading overlapping section of the first FC block of each OFDM symbol and the CP length is fine-tuned in the overlap-add process for consecutive OFDM symbols at high rate. The time resolution in adjusting the CP length is equal to the sampling interval at high rate (as in traditional CP-OFDM).

As an example, in the 10 MHz 5G-NR case with 15 kHz subcarrier spacing (SCS) and normal CP length, the high sampling rate is 15.36 MHz, the useful OFDM symbol duration is 1024 high-rate samples, and the CP length is 80 high-rate samples for the first symbol of each slot of 7 symbols, and 72 samples for the others. Then in the continuous processing model, the smallest possible short transform length is 128, corresponding to 1.92 MHz sampling rate, and the CP lengths are 10 and 9 low-rate samples, respectively. However, using the discontinuous FC-processing model with narrow subband allocations, like 12, 24, 48 subcarriers (SCs), the short transform (FFT) length can be reduced to 16, 32, or 64, respectively. The same IFFT lengths are used for the subband OFDM signal generation.

In generic setting, the discontinuous FC-F-OFDM process can be formulated as follows. First the CP-OFDM symbols are generated at the minimum feasible sampling rate for each subband and, if needed, the CP length is truncated to the highest integer number of low-rate samples which does not exceed the CP length of the transmitted signal. FC-based filtering is applied to each CP-OFDM symbol individually to generate filtered symbols at the high (output) sampling rate. The CP-OFDM signal for a transmission slot is constructed from the generated individual symbols using the overlap-add principle. When combining the individual symbols, their spacing is adjusted (with the precision of the output sampling interval) to correspond to the precise CP duration. This process extrapolates additional high-rate samples to reach the targeted

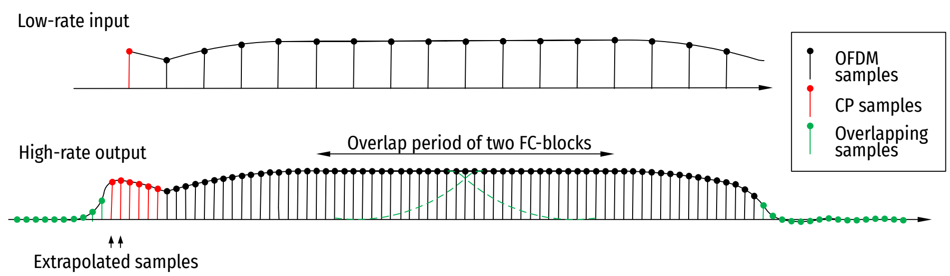

Fig. 5. Discontinuous overlap-add processing for a single CP-OFDM symbol with 50 % FC overlap, interpolation factor of four, and high-rate OFDM symbol duration of 64. CP length is one sample at low rate and six samples at high rate (corresponding to one and half low-rate samples)

CP length, in addition to interpolating new samples between the samples generated at low rate.

In basic form, the proposed scheme is suitable for scenarios where the overall symbol durations of all subband signals to be transmitted have equal lengths and the symbols are synchronized. It is notable that different durations (e.g., different CP lengths) are allowed for different CP-OFDM symbol intervals within a transmission slot.

The scheme is particularly beneficial in cases like Fig. 4, where the FC-block length is equal to the OFDM-symbol duration (a common assumption in earlier studies of FC-F-OFDM) and two halves of the basic-OFDM symbol are processed in two consecutive FC blocks. Then the FC blocks are synchronized to the OFDM symbols, and the CP is also processed within the first FC block. Such discontinuous FC-based TX filter processing reduces computational complexity through dynamically adjustable overlap of consecutive CP-OFDM symbols.

The proposed scheme allows to reduce the complexity in the case of (i) short transmissions (e.g. mini-slot) (ii) in multiplexing multiple relatively narrow subbands (e.g., gateway for MTC communications), and (iii) user equipment (UE) side TX processing, assuming that only one numerology is transmitted. Moreover, in case of parallelized hardware implementations, it is a benefit that each OFDM symbol can be generated and filtered independently of the others. This also minimizes the TX signal processing latency.

III. Numerical results

In this section, we will analyze the performance of the discontinuous FC processing in terms of uncoded bit error rate (BER) in different interference and channel conditions, and also show complexity comparison between continuous and discontinuous FC processing. Here with assume the overlap factor of 0.5. Continuous FC processing with the overlap of 0.25 provides slightly degraded spectral containment and error vector magnitude (EVM) performance compared to the overlap of 0.5 with the benefit of somewhat lower implementation complexity.

Figs. 6 and 7 compare the simulated BER performance of different CP-OFDM configurations, with or without subband filtering in 10 MHz long-term evolution (LTE)-like uplink scenario, with the high-rate IFFT size of $N = 1024$ and subcarrier spacing of 15 kHz. Table I shows details of the considered scenarios and filtering configurations. The used channel model is tapped-delay line (TDL)-C, which is one of the channel models considered in the 5G-NR development [13]. Two different values of the root mean squared (RMS) channel delay spread, 300 ns and 1000 ns, are used here. Two subband configurations are considered: single PRB or four PRBs of 12 subcarriers. In both cases, four deactivated subcarriers are used as for transition bands. Focusing on the asynchronous up-link scenario, different instances of the channel model are always used for the three adjacent subbands included in the simulations. Perfect power control is assumed in such a way that the three adjacent subbands are always received at the same power level and constant SNR for all channel instances.

Fig. 6 shows the BER simulation results for TDL-C 300 ns channel. In this case the channel maximum delay spread (about 2.6 µs) is well below the CP length (about 4.7 µs). When comparing with basic synchronous OFDM, we can see minor performance degradation of the schemes with filtering at both ends, while the degradation of the RX-filtering-only scheme is more visible. In the asynchronous case, the benefits of subband-filtered OFDM are clearly visible. Discontinuous TX filtering with the minimum short transform length exhibits minor performance loss, especially with the short transform length of 16. However, this can considered to be insignificant in practical systems with channel coding for which the uncoded BER of 1 – 10 % is sufficient.

Fig. 7 shows the BER simulation results for TDL-C 1000 ns channel. In this case the channel maximum delay spread (about 8.7 µs) exceeds the CP length (about 4.7 µs), resulting in higher error floor in all configurations. The same conclusions can be made as above, except that discontinuous TX filtering with the minimum short transform length reaches the performance of other FC-filtered schemes in all cases.

Fig. 8 compares the computational complexity of different filtered OFDM schemes for different subband configurations, again in the 10 MHz LTE case. The overlap factors of 0.25 and 0.5 are used for continuous processing, and 0.5 for discontinuous processing. The complexity is plotted as a function of the slot (TX burst) length, in the range from 1 to 14

TABLE I
TRANSMISSION SCENARIOS AND FILTERING CONFIGURATIONS.

Synchronicity	Quasi-synchronous: No timing offset and no frequency offset between different uplink signals		Asynchronous: Timing offset of 256 samples ($L_{\mathrm{OFDM},m}/4$) between the target subband for BER evaluation and adjacent subbands on both sides.	
Allocated subband width	1 PRB, 12 SCs: 8 active SCs and 4-SC guardbands between adjacent active subbands		4 PRBs, 48 SCs: 44 active SCs and 4-SC guardband between adjacent active subbands	
Filtering configuration	No filtering on TX and receiver (RX) sides	No TX filtering, RX filtering with continuous FC model with $L_{\mathrm{RX}} = 128$	Continuous TX and RX filtering, $L_{\mathrm{RX}} = L_{\mathrm{RX}} = 128$	Discontinuous TX filtering, continuous RX filtering, $L_{\mathrm{TX}} = \{16, 64, 128\}$, $L_{\mathrm{RX}} = 128$

OFDM symbols, using the number of real multiplications per transmitted quadrature amplitude modulation (QAM) symbol as the complexity metric. Using the split-radix algorithm, an FFT or IFFT of length L takes $L\log_2(L) - 3L + 4$ real multiplications. The short FC-transform length L is equal to the IFFT length in OFDM generation and it is selected as the smallest feasible power-of-two value. Notably, the smallest value of L in continuous processing is 128, while in discontinuous processing we can use $L = 16$ for single PRB (12 subcarriers) allocation and $L = 64$ for four-PRB (48 subcarriers) allocation. In addition to the 1-PRB and 4-PRB subband cases, also the fullband allocation with 50 PRBs and 600 active subcarriers is included in the comparison.

From Fig. 8 and an extensive set of additional plots, we can observe the following:

1) Discontinuous processing for all parameterizations and slot lengths provides lower complexity than continuous processing with 50 % overlap. Discontinuous processing also provides constant complexity over different slot lengths. With short slot lengths, the complexity of discontinuous schemes is significantly lower than that of continuous transmission with 50 % overlap.
2) With multiple relatively narrow subbands, this benefit is pronounced and significant also for higher slot lengths. In these cases, the complexity of discontinuous processing is lower or similar to that of the continuous processing with 25 % overlap.
3) We remind that with 50 % overlap, the imperfections of FC processing can be ignored, while the use of 25 % overlap degrades the performance with high MCSs.
4) Discontinuous processing allows to generate a single-PRB subband signal (e.g. for NB IoT) by using the FFT size of 16 for the OFDM symbol generation and FC processing at the sampling rate of 240 kHz, while prior art implementation require sampling rate of 1.92 MHz with the FFT size of 128.

IV. CONCLUSIONS

Discontinuous symbol-synchronized fast-convolution (FC) processing was found to offer various benefits over the basic continuous FC scheme in terms of reduced complexity and latency and increased parametrization flexibility. The additional distortion effects due the proposed scheme were found to have minor impact on the link-level performance. The benefits are particularly important in specific application scenarios, like transmission of single or multiple narrow subbands, and mini-slot transmission, which is a core element in the ultra-reliable low-latency transmission service of fifth generation new radio (5G-NR).

In this paper we have considered discontinuous FC processing on the transmitter side only. An important topic for future studies is to adapt this scheme also for FC-based F-OFDM (FC-F-OFDM) processing on the receiver side.

ACKNOWLEDGMENT

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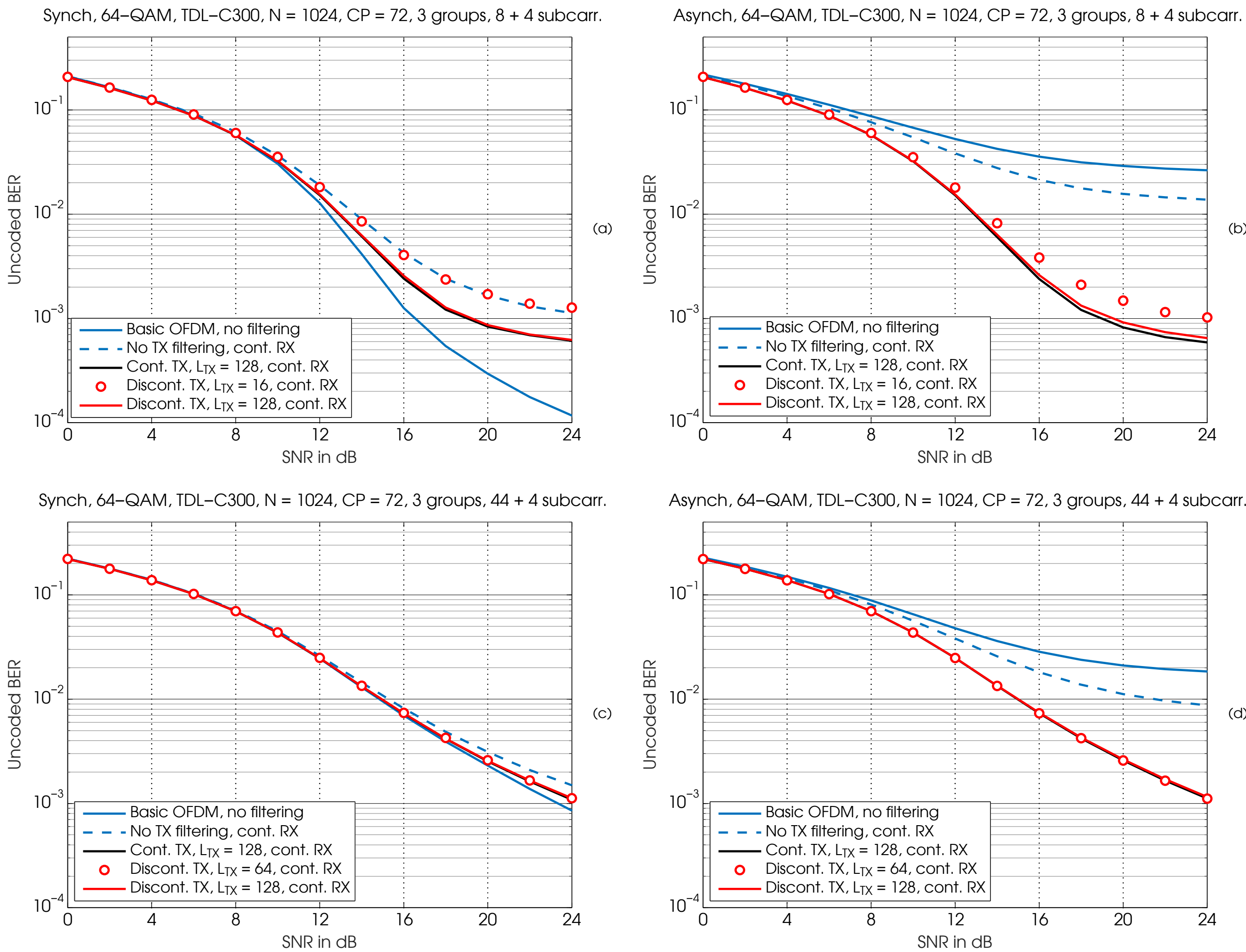

Fig. 6. Performance simulation results with TDL-C 300 ns channel and 64-QAM modulation. Left: Quasi-syncronous cases. Right: Asynchronous cases (quarter-symbol timing offset). Top: 1 PRB allocated for each subband (12 SCSs, 8 active SCs and 4 SCs for guardband). Bottom: 4 PRBs allocated for each subband (48 SCs, 44 active SCs and 4 SCs for guardband).

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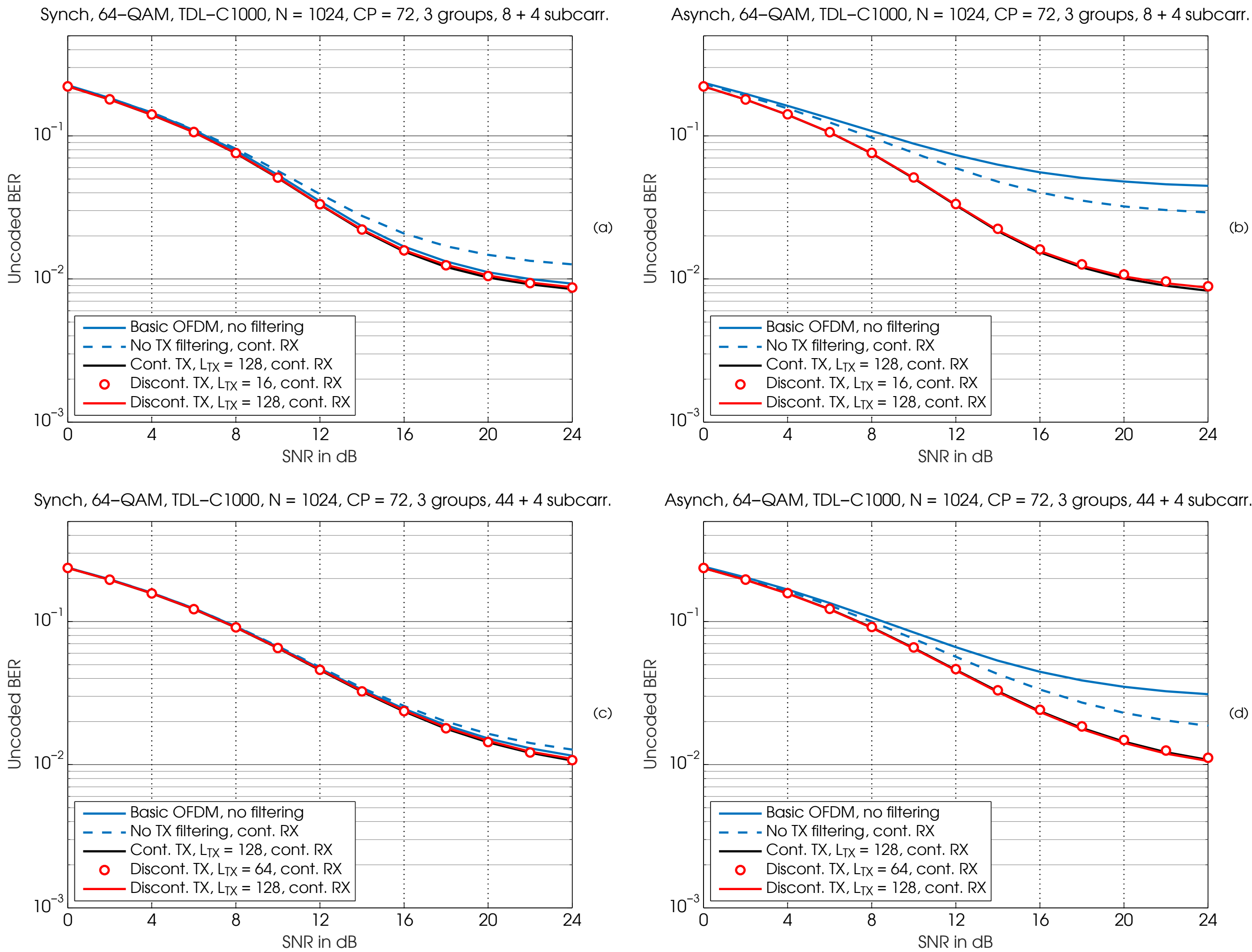

Fig. 7. Performance simulation results with TDL-C 1000 ns channel and 64-QAM modulation. Left: Quasi-syncronous cases. Right: Asynchronous cases (quarter-symbol timing offset). Top: 1 PRB allocated for each subband (12 SCs, 8 active SCs and 4 SCs guardband). Bottom: 4 PRBs allocated for each subband (48 SCs, 44 active SCs and 4 SCs for guardband)

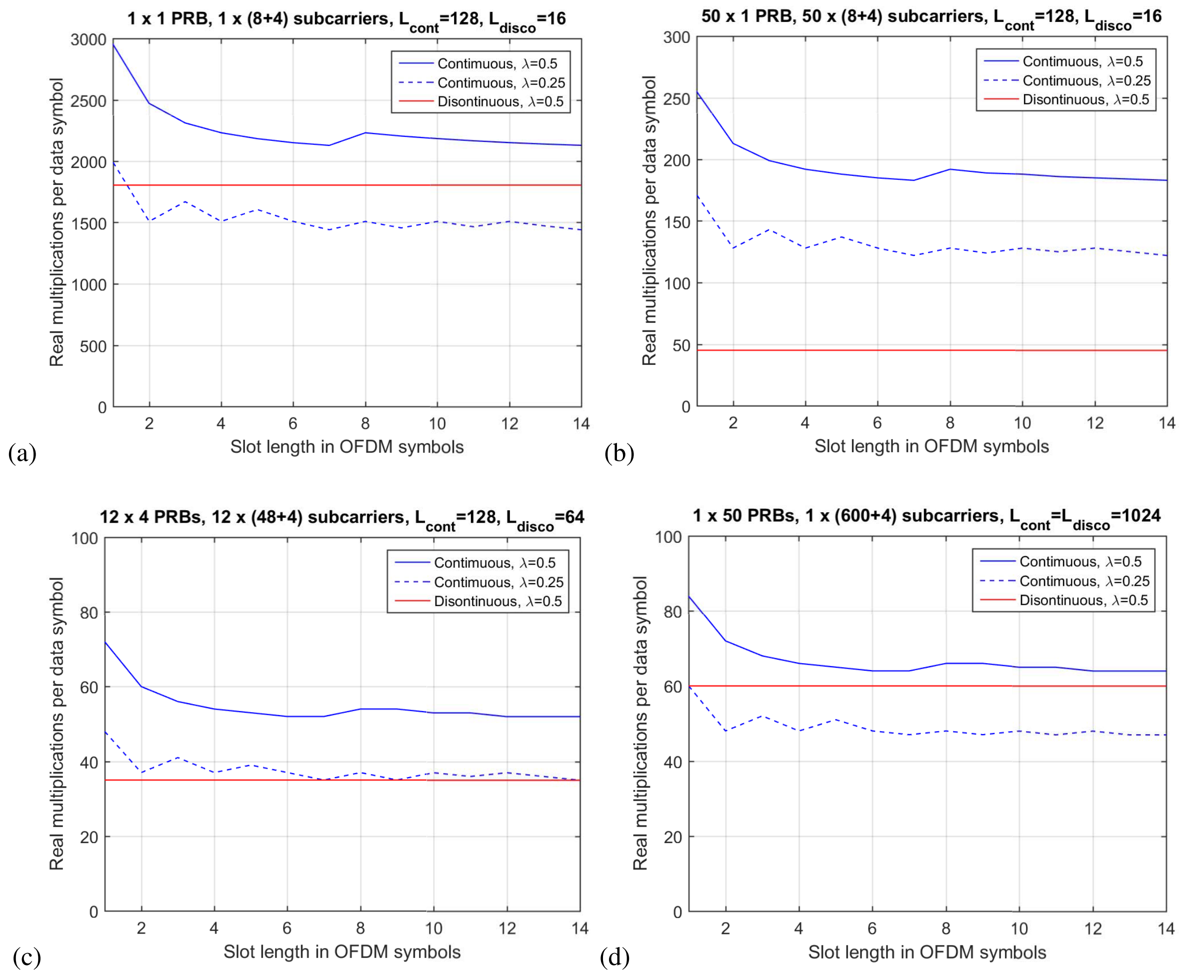

Fig. 8. Computational complexity of continuous FC-F-OFDM with 25 % and 50 % overlaps and discontinuous FC-F-OFDM with 50 % overlap. (a) Single 1-PRB wide subband. (b) 50 1-PRB wide subbands. (c) 12 4-PRB wide subbands. (d) Single 50-PRB wide subband.