Transparent spectral confinement approach for 5G

Jamal Bazzi*, Katsutoshi Kusume*, Petra Weitkemper†, Kazuaki Takeda‡, Anass Benjebbour‡
*DOCOMO Euro-Labs, Munich, Germany.
{j.bazzi, kusume}@docomolab-euro.com
†Universität der Bundeswehr München, Germany
petra.weitkemper@unibw.de
‡5G Laboratory, NTT DOCOMO, INC., Japan
{kazuaki.takeda.bs, benjebbour}@nttdocomo.com

***Abstract*—This paper proposes a transparent spectral confinement approach for OFDM to enable multiplexing of multiple services with diverse requirements in one system band. Besides mobile broadband services, new service types like machine type and ultra-reliable low latency communications foreseen for future 5G systems set new requirements for the chosen waveform to support asynchronous access and multiplexing different numerologies. That is not best handled by OFDM as it is. Thus, various spectral confinement techniques have been proposed in the literature, which, however, require specific processing at both the transmitter and receiver. This tight link would increase signaling overheads to agree on both sides to apply certain respective processing. The transparent approach proposed in this paper decouples the tight link and thus keeps the system simple and robust. We show by means of numerical evaluations that OFDM with spectral confinement techniques like windowing or filtering at the transmitter, but without respective receiver processing, outperforms the conventional OFDM.**

I. Introduction

Future 5G systems or New Radio (NR) as it is being studied within the 3rd Generation Partnership Project (3GPP) [1] [2] are expected to address a wider range of scenarios such as enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC) and Ultra-Reliable Low Latency Communications (URLLC) [3]. It is also expected to support higher frequency bands and coexistence with other systems like, e.g., Device to Device (D2D) and wireless backhaul, relaxed synchronization transmissions, e.g., without timing advance in LTE, and the flexibility of adapting and changing the numerology e.g., different subcarrier spacing and/ or CP length within the same band to handle a variety of traffic types.

Orthogonal frequency division multiplexing (OFDM) has been already adopted for different wireless standards which were designed mainly to support eMBB services with guaranteed synchronization such as WiFi, WiMax and 4G Long Term Evolution (LTE). With the use of cyclic-prefix (CP), OFDM provides numerous advantages such as an efficient implementation through fast Fourier transforms (FFT) to combat severe multipath fading for broadband transmission and its good affinity with multiple-input multiple-output (MIMO) systems. On the other hand, it is also widely recognized that CP-OFDM suffers from various disadvantages. The high out-of-band (OOB) leakage poses the need to use large guard bands in the presence of co-channel interference generated for example from asynchronous transmissions or mixed numerologies within the same band. It also makes the usage of narrow band white spaces difficult. Furthermore, the use of the CP degrades the overall spectral efficiency, and in the cases of asynchronous or high mobility users the accumulated inter-carrier interference (ICI) degrades the overall system performance.

Many research activities were ongoing recently on multi-carrier transmission [4] [5] [6] [7] to identify alternative new waveforms to better address the requirements for 5G wireless systems. The main benefits of most of these new waveforms is the reduced OOB leakage compared to CP-OFDM. However, another important aspect is that NR has to ensure forward compatibility to be a design requirement. This means that devices using the selected new waveform needs to be able to still work even when future enhancements are made on that waveform. To achieve this, transparency in the processing techniques (e.g., spectral confinement techniques) between the transmitter and the receiver is essential.

In this paper, we focus on two waveforms (window OFDM (W-OFDM) and filtered OFDM (f-OFDM)) characterized by lower OBB compared to CP-OFDM and at the same time supporting transparency between the transmitter and the receiver without major performance deterioration. We present a detailed explanation of these two waveforms and highlight their advantages and disadvantages and compare their performance with and without the transmitter/ receiver transparency, along with CP-OFDM, under different scenarios targeted by 5G systems.

The remaining part of this paper is organized as follows. In Section II we describe the details of W-OFDM and f-OFDM waveform approaches. Then, in Section III we discuss spectral confinement techniques transparency to the receiver and its corresponding advantages and disadvantages. In Section IV we explain the evaluation scenarios and compare the performance of the investigated waveforms under each of these scenarios. Finally, conclusion and future work are given in Section V.

II. Alternative waveforms

W-OFDM and f-OFDM with their respective spectral confinement techniques (i.e., windowing and filtering), benefit from lower OBB leakage compared to CP-OFDM which make them more suitable for asynchronous multiple access transmissions and to support mixed numerology within the same band. The power spectral density of the investigated waveforms are compared with CP-OFDM as shown in Fig. 1. f-OFDM shows a considerable reduction in the OOB leakage compared to CP-OFDM. The OOB leakage reduction in the cases of W-OFDM

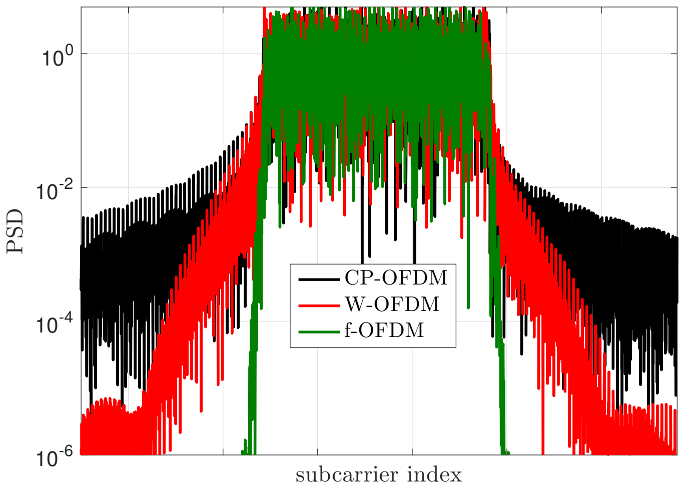

Fig. 1. Spectrum properties of the waveforms.

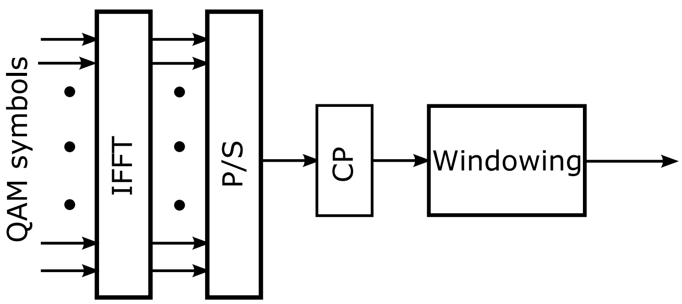

Fig. 2. W-OFDM block diagram.

is not as much as f-OFDM but still considerable compared to CP-OFDM. In addition, they both inherit various benefits of CP-OFDM such as good affinity to MIMO, high spectrum efficiency by maintaining the amount of in-band distortion limited and robustness to multipath fading due the CP. In the remaining of this section we discuss in more details these two alternative waveforms.

A. Window OFDM

Window OFDM applies a time domain windowing to the CP-OFDM signal, as shown in Fig. 2. However, depending on the length of the applied window and channel propagation delays some Inter Symbol Interference (ISI) may be introduced which could affect the performance [8]. At the receiver side and throughout this paper, we consider either windowing which is matched to the transmitter window is applied to the received signal or is omitted. The resulting signal is then passed through the regular CP-OFDM receiver.

B. Filtered OFDM

Filtered OFDM can be seen as a compromise between no filtering as for pure CP-OFDM and subcarrier filtering as done for Filter-Bank Multicarrier [4], as the filtering is applied to a subband consisting of a group of subcarriers as shown in Fig. 3 [7]. The whole system bandwidth is separated into subbands of certain width, each subband is filtered separately and the sum of these filtered subbands is transmitted depending on the allocated frequency resources. The choice of the filter is quite flexible, and it is chosen with the aim to minimize OOB radiation and in-band distortion. Also, the actual performance of the different filters for f-OFDM highly depends on the considered scenario and the particular filter design. f-OFDM keeps the CP as used in CP-OFDM and applies a filter with much longer filter impulse response compared to the CP length. As the filter tails exceed the CP length, there will be certain ISI even for flat channels, but by design of the filter this can be kept rather small. At the receiver side, the received signal is either passed through a filter which is matched to the transmitter filter or simply the receiver filter is omitted. The resulting signal is then passed through the regular CP-OFDM receiver.

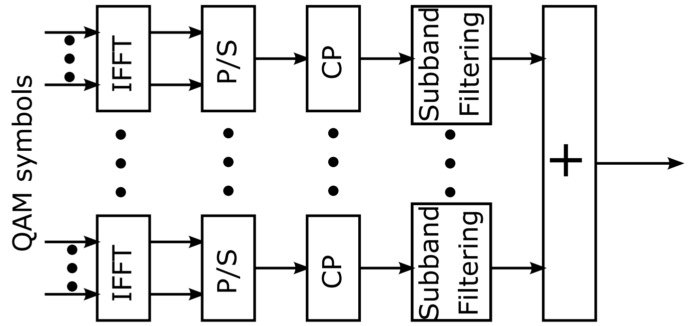

Fig. 3. f-OFDM block diagram.

III. Spectral confinement techniques transparency

In signal processing and digital communications, it is commonly known that the use of a matched filter is optimal for maximizing the signal to noise ratio (SNR) in the presence of additive stochastic noise. A receiver matched filter is equivalent to the conjugated complex time-reversed version of the filter which has been applied at the transmitter side. In order to achieve this, the receiver has to know exactly the filter impulse response used at the transmitter. In addition, the filtering can be chosen differently to satisfy the requirements by taking into account the tradeoff between time and frequency localization. That is, the longer the filter impulse response is, the higher the achievable OOB suppression and the higher the robustness to asynchronous transmission result, but also the longer signal in the time domain becomes, which may introduce inter-symbol interference (ISI) and latency. Therefore, different filter lengths should be supported to accommodate diverse future requirements [9]. To be able to apply a matched filter at the receiver side, the filter impulse responses of all possible filters either have to be specified leading to a huge look-up table and high complexity or have to be signaled to receiver side leading to a huge signaling overhead.

To avoid high complexity and signaling overhead, we propose to define some minimum requirements for the filter to be used (e.g., spectral and temporal masks, adjacent channel leakage ratio (ACLR), error vector magnitude (EVM)). These requirements specify only the features that are really essential for the performance of the system, but leave some room for flexibility for both the transmitter and the receiver to choose the actual filter impulse response as long as these requirements are fulfilled. The extreme case of this proposal is to assume a fully transparent receiver which applies a simple CP-OFDM receiver regardless of any spectral confinement techniques applied at the transmitter side. In this case the receiver does not need to know any additional information and thus nothing additional has to be signaled. However, the drawback of this proposal is that we do not have an optimal match between the transmitter and the receiver which may lead to an SNR loss.

In the next section, we evaluate the two extreme approaches (i.e., the receiver knows exactly the spectral confinement techniques applied at the transmitter and applies the proper receiver processing to maximize SNR or the receiver is fully transparent and applies a simple CP-OFDM without any spectral confinement techniques) under several 5G targeted scenarios.

IV. Performance comparison

In this section, we compare the performances of the investigated waveforms under different scenarios:

- Scenarios with co-channel interference
  - Downlink with mixed numerology
  - Uplink with single numerology and asynchronous transmission
  - Uplink with mixed numerology and synchronous transmission
- Scenarios without co-channel interference
  - Downlink/ uplink with single numerology

The common simulation parameters which are used for the different investigated scenarios are shown in Table I. Other relevant simulation parameters specific for the different investigated properties and scenarios are highlighted in the respective subsections. CP-OFDM performance is also included as a benchmark. All presented results in this section show the performance of the waveforms in terms of the frame error rate (FER) versus SNR for different combinations.

A. Scenarios with co-channel interference

1) Downlink with mixed numerologies: As discussed earlier, 5G systems are required to support mixed numerologies within the same band to handle a variety of traffic types. We assume a DL transmission with two users being allocated a 720 kHz transmission bandwidth each. The user of interest or target user equipment (UE) uses the 15 kHz SC spacing numerology while the interfering user uses the 30 kHz SC spacing numerology. The center of the first SC of the 30 kHz SC spacings numerology is aligned to the center of the first SC of the 15 kHz SC spacings numerology. A frequency domain guard band of 180 kHz (i.e., one resource block in the case of 15 kHz SC spacing) is assumed between the users. We could observe from Fig. 4 that for the case of TDL-C channel model with a delay spread of 300 ns both f-OFDM and W-OFDM could achieve the same performance as interference free CP-OFDM when the optimal matched filter/ window is applied at the receiver respectively. However, with the fully transparent receiver we observe a slight performance degradation. For the case of TDL-C channel model with a delay spread of 1000 ns, f-OFDM with optimal matched filter also achieves the same performance as interference free CP-OFDM, however,

[1]Only most relevant MCS cases are shown for each evaluated scenario.

TABLE I. Common simulation parameters.

Carrier Frequency	4 GHz
System bandwidth	10 MHz
TTI length	1 ms
Subcarrier (SC) spacing	Single numerology case: 15 kHz Mixed numerology case: target user 15 kHz, interfering user 30 kHz
Number of OFDM symbols per TTI	15 kHz SC spacing case: 14 30 kHz SC spacing case: 28
CP duration	15 kHz SC spacing case: 4.7 μs 30 kHz SC spacing case: 2.35 μs
FFT size	15 kHz SC spacing case: 1024 30 kHz SC spacing case: 512
Antenna configuration	1 Tx and 1 Rx
Channel coding	LTE Turbo code Max-Log-MAP decoding 6 iterations
Modulation and coding schemes (MCS) [1]	MCS 1: 16QAM - coding rate = 1/2 MCS 2: 64QAM - coding rate = 3/4 MCS 3: 256QAM - coding rate = 3/4
Channel estimation	Ideal
Channel model	TDL-C with 300 ns delay spread, 3km/h TDL-C with 1000 ns delay spread, 3km/h
W-OFDM - window type	Raised-cosine window
W-OFDM - window length	15 kHz SC spacing case: 52 at Tx, 52 or no window at Rx 30 kHz SC spacing case: 26 at Tx, 26 or no window at Rx
f-OFDM - filter type	Low pass (von Hann window)
f-OFDM - filter length	512 at Tx, 512 or no filter at Rx
f-OFDM - tone offset [10]	5 SC (2.5 on each side)

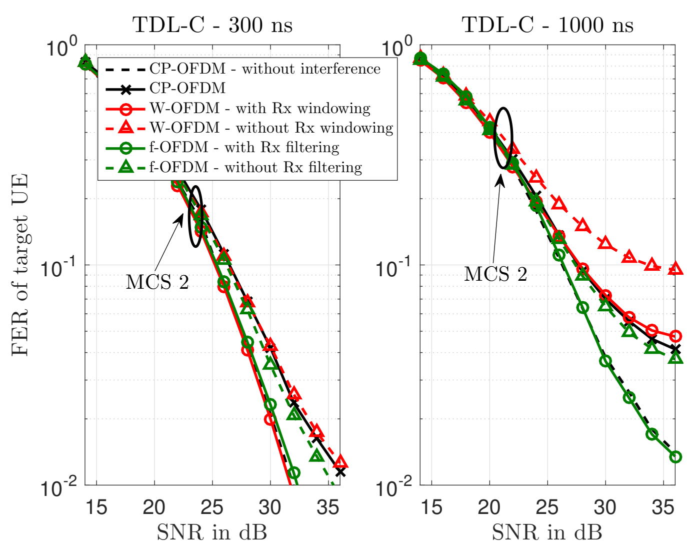

Fig. 4. FER vs. SNR for a mixed numerologies DL transmission.

W-OFDM suffers from the accumulated ISI which dominate the performance. Similarly, f-OFDM and W-OFDM with a transparent receiver show a performance degradation compared to the matched filter/ window receivers.

2) Uplink with mixed numerologies/ asynchronous transmission: In addition to mixed numerologies within the same band, UL is expected to support asynchronous multiple access. In this subsection, we show the performance of the evaluated waveforms under these two scenarios. The general setup of the two evaluated scenarios is shown in Fig. 5. We assume an UL transmission with three users: one user of interest or target UE located in the middle and two interfering users, one on each side of the user of interest. Each user has a 720 kHz allocated

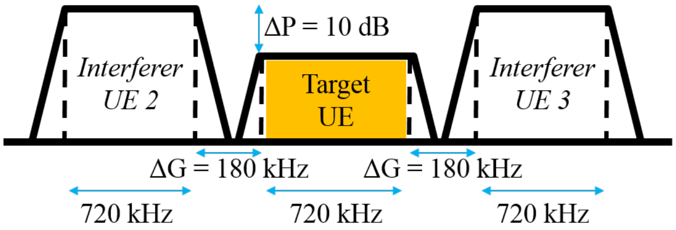

Fig. 5. UL asynchronous access and mixed numerologies setup.

transmission bandwidth and the interfering users have a 10 dB higher power (ΔP) compared to the user of interest. A frequency domain guard band of 180 kHz (i.e., one resource block in the case of 15 kHz SC spacing) is assumed between the users.

For the asynchronous multiple access setup, we assume that all three users use the same numerology of 15 kHz SC spacing and the two interfering users have a timing offset of 128 samples compared to the user of interest.

For the mixed numerologies setup, we assume that three users are synchronized in the time domain and the user of interest uses the 15 kHz SC spacing numerology while the interfering users use the 30 kHz SC spacing numerology. Similarly to the downlink case, we assume the center of the first SC of the 30 kHz SC spacings numerology is aligned to the center of the first SC of the 15 kHz SC spacings numerology.

Fig. 6 and Fig. 7 show the performance of the waveforms in terms of FER versus SNR under these two scenarios. We could clearly observe that both f-OFDM and W-OFDM, even without dedicated receiver processing, outperform CP-OFDM due to their lower OOB leakage as shown in Section II. In addition, in the presence of co-channel interference a dedicated receiver processing is beneficial for W-OFDM as well as for f-OFDM to obtain better performance. The benefits of the frequency localization are not fully obtained when CP-OFDM receiver is simply applied. An appropriate receiver processing becomes more relevant for scenarios with higher interference.

B. Scenarios without co-channel interference

1) Downlink/ uplink with single numerology: In this subsection, we evaluate the performance of the investigated waveforms under scenarios with a single user with numerology of 15 kHz SC spacing within the system band. For the first scenario, we assume a DL transmission with one user being allocated the full transmission bandwidth (i.e., 9 MHz), while for the second scenario we assume an UL transmission with one user being allocated a small fraction of the transmission bandwidth equal to 720 kHz. In these two scenarios the low OBB leakage is not important since there is no co-channel interference. However, it remains interesting to evaluate the impact of windowing and filtering on the performance.

Fig. 8 and Fig. 9 show the performance of the waveforms under these two DL and UL scenarios, respectively. For the case of TDL-C channel model with a delay spread of 300 ns where the maximum channel delay spread is still within the CP duration, we could observe that all waveforms have very similar performance compared to conventional CP-OFDM.

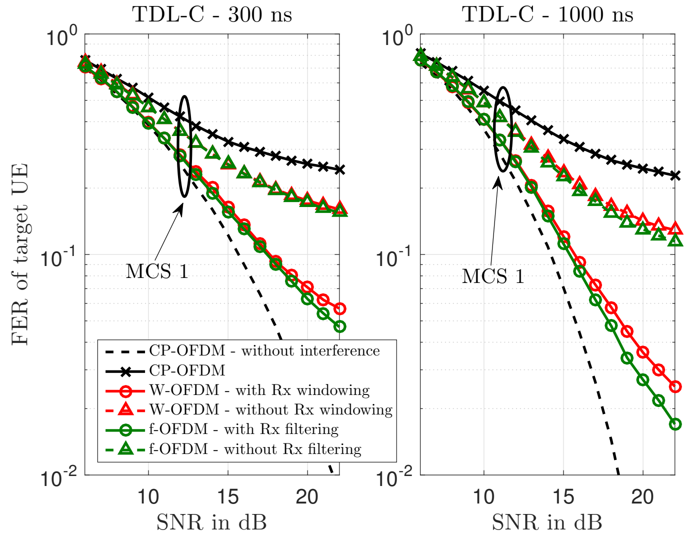

Fig. 6. FER vs. SNR for a single numerology UL asynchronous transmission.

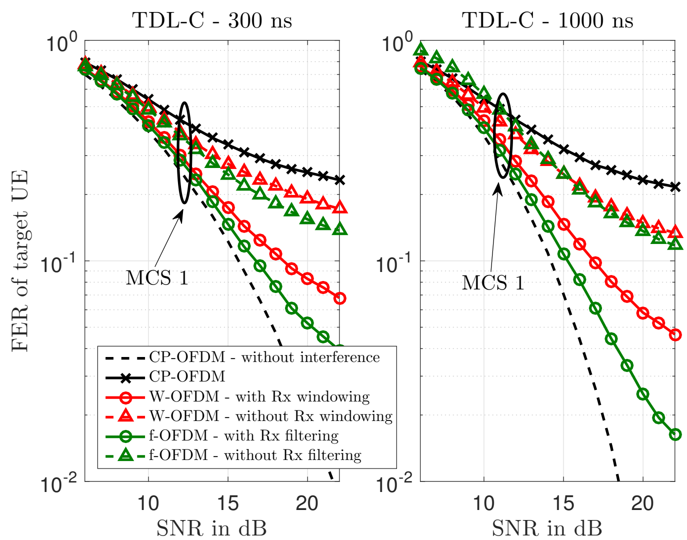

Fig. 7. FER vs. SNR for a mixed numerologies UL synchronous transmission.

However, for the case of TDL-C channel model with a delay spread of 1000 ns where the maximum channel delay spread exceeds the duration of the CP, f-OFDM performance remains comparable with conventional CP-OFDM whereas W-OFDM performance is largely degraded due to the accumulated ISI. The larger impact of ISI in the case of W-OFDM compared to f-OFDM is due to the larger power of the window tail compared to the filter tail. In addition a small degradation is observed for f-OFDM in Fig. 9 for high MCS. Due to the filtering, the edge subcarriers of the filtered subband have lower power which lead to the performance degradation. Such degradation is observed only in the cases of narrow filter bandwidth.

We could also observe that no dedicated receiver processing (i.e., windowing/ filtering) is needed neither for W-OFDM nor for f-OFDM. The good performance can be obtained independent of the receiver processing. That means, f-OFDM and W-OFDM can be transparent to the receiver. The receiver does not need to know the transmitter processing, but can simply

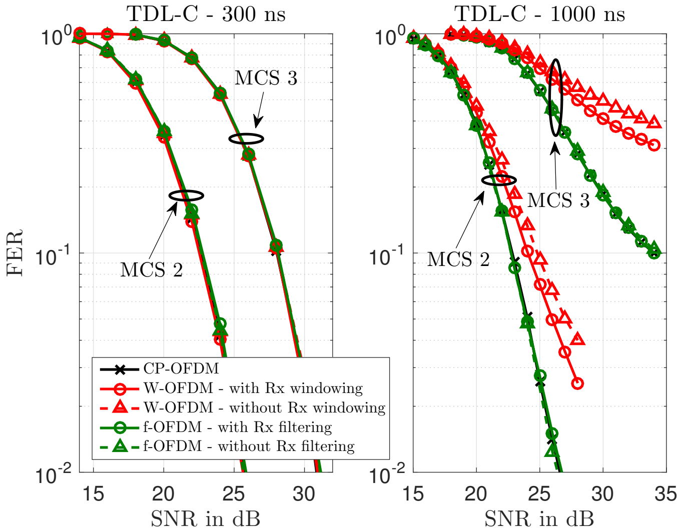

Fig. 8. FER vs. SNR for a single numerology DL transmission.

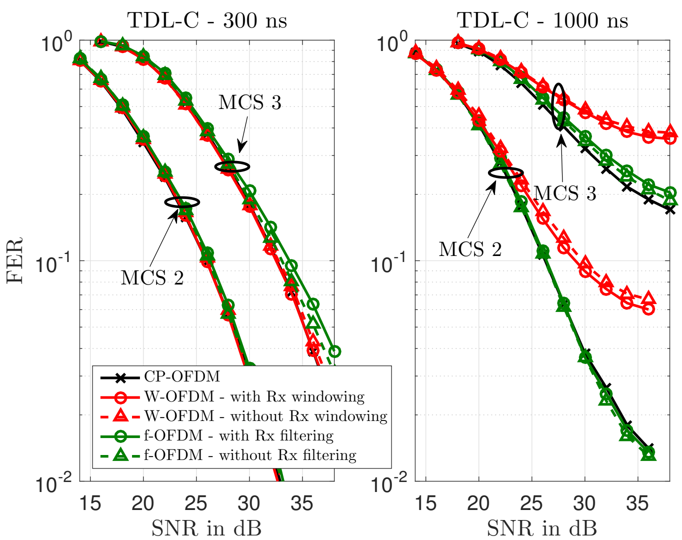

Fig. 9. FER vs. SNR for a single numerology UL transmission.

use CP-OFDM receiver without performance degradation.

V. Conclusions

In this paper we have presented a general overview about the waveform design for future 5G systems. This includes numerical evaluations and comparisons of the conventional CP-OFDM with two multi-carrier OFDM-based waveforms with different spectral confinement techniques (W-OFDM and f-OFDM) under several 5G targeted scenarios. We have also proposed a technique to reduce the complexity and signaling overhead resulting from the need of the receiver to know all the details of the applied spectral confinement technique at the transmitter side. We also discussed the advantages and disadvantages of having such spectral confinement techniques (i.e., windowing, filtering) which are applied at the transmitter transparent to the receiver.

The numerical evaluations showed that W-OFDM and f-OFDM, thanks to their very lower OOB leakage compared to CP-OFDM, have higher robustness to co-channel interference which may occur due to asynchronous multiple access and mixed numerologies within the same band. We have also observed that a dedicated receiver processing is beneficial for W-OFDM as well as for f OFDM to obtain good performance, whereas the benefits of the frequency localization are not fully obtained when CP-OFDM receiver is simply applied. In DL and UL transmissions without co-channel interference, all evaluated have similar performance in the case of short channel delay spread, whereas W-OFDM showed a degradation in the case of long channel delay spread due to the accumulated ISI. We have also observed that in this case no dedicated receiver processing is needed neither for W-OFDM nor for f- OFDM and the good performance can be obtained independent of the receiver processing.

Overall it can be concluded that although a dedicated receiver processing is beneficial in interference scenarios, the effort needed to achieve this in terms of signaling maybe too high. Even with a transparent receiver like pure CP-OFDM receiver the robustness towards asynchronous access or mixed numerology can be significantly improved by the spectral confinement techniques at the transmitter.

In the future, other transmitter and receiver mismatch possibilities (e.g., transmitter applying filtering and receiver applying windowing or vice-versa) will be studied and evaluated.

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