Hardware Experiments on Multi-Carrier Waveforms for 5G

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***Abstract*—Emerging new applications, such as Internet of Things (IoT), gigabit wireless connectivity, tactile internet, and many more are expected to impose new and diverse requirements on the design of the fifth generation (5G) of cellular communication systems. In recent years, many alternative multicarrier waveforms are being investigated with the aim to identify to what extent it would be possible to better address these diverse requirements compared to Cyclic Prefix (CP) OFDM, which is currently adopted by LTE/LTE-Advanced. However, most of these investigations considered in many research activities have focused on theoretical considerations or simulations and mainly with emphasis on only one alternative waveform. In this paper, we present ongoing work based on measurement results where real hardware experiments are conducted to investigate the performance of three waveform families: CP-OFDM, filter bank multicarrier with offset quadrature amplitude modulation (FBMC/OQAM) and universal-filtered OFDM (UF-OFDM). FBMC/OQAM has the benefit of very low sidelobes leading to less inter-carrier interference in asynchronous and high mobility scenarios, whereas the typically long filter leads to low efficiency for short blocks and the use of OQAM makes it nontrivial to adopt certain schemes well-developed for CP-OFDM. UF-OFDM combines the benefits of CP-OFDM with the advantage of significantly lower out-of-band radiation while avoiding the drawbacks of FBMC/OQAM. In this paper we compare the performance of these alternative waveforms under several 5G targeted scenarios.**

Keywords- *CP-OFDM; FBMC/OQAM; UF-OFDM, 5G; 5G waveforms*

I. Introduction

Orthogonal frequency division multiplexing (OFDM) has been adopted for multiple wireless standards such as WiFi, WiMax and 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.

In the last few years, a number of research activities on multicarrier transmission are ongoing, e.g., [1] [2] [3] [4], with the aim to identify alternative new waveforms that could better address the requirements for 5G wireless systems.
Future 5G systems are expected to address a wider range of applications and scenarios as illustrated in Fig. 1 such as machine type communications (MTC), high mobility, the support of higher frequency bands, and the coexistence of heterogeneous transmissions, e.g., device to device (D2D) and wireless backhauling [5]. However, CP-OFDM has a reduced spectral efficiency because of the cyclic prefix insertion and suffers from high out-of-band (OOB) leakage which poses the need to use larger guard bands and thus limits the flexibility of spectrum usage. For example, the parameters of CP-OFDM, i.e., CP length or subcarrier spacing, cannot be changed flexibly over adjacent bands or within the same band to handle a variety of traffic types, without insertion of large guard bands. In particular, for asynchronous uplink transmission (relevant to MTC) and high mobility scenarios, the accumulated inter-carrier interference (ICI) becomes very large with CP-OFDM and degrades the overall system performance.

In this paper, based on measurement results obtained from real hardware experiment campaigns, we compare the performance of two alternative multi-carrier waveforms, namely Filter bank Multicarrier with Offset QAM (FBMC/OQAM) and Universal Filtered OFDM (UF-OFDM), along with CP-OFDM, under different scenarios including asynchronous uplink transmission and high speed scenarios. FBMC/OQAM, thanks to its very low OOB leakage, shows higher robustness to high mobility and asynchronous multiple access scenarios compared to the OFDM based waveforms. The long filter without CP/ guard period for FBMC/OQAM results in the high spectral efficiency for long bursts; however, UF-OFDM with short filter is more efficient for very short bursts. UF-OFDM has the advantage of inheriting the benefits of CP-OFDM such as affinity with MIMO and providing higher spectrum efficiency while maintaining the amount of in-band distortion limited with proper choice of additional filtering.

The remainder of this paper is organized as follows. In Section II we first describe the details of FBMC/OQAM and UF-OFDM waveform approaches; then, we describe the experimental setup and the considered scenario details in Section III. In Section IV we compare the performance of the investigated waveforms under several 5G scenarios. Conclusions and future work are given in Section V.

II. Investigated multicarrier waveforms

In this section we describe the investigated waveforms and their implementation. We start with FBMC/OQAM and then followed by UF-OFDM. We skip the description of the well-known CP-OFDM in this section although it remains a potential candidate waveform for 5G systems.

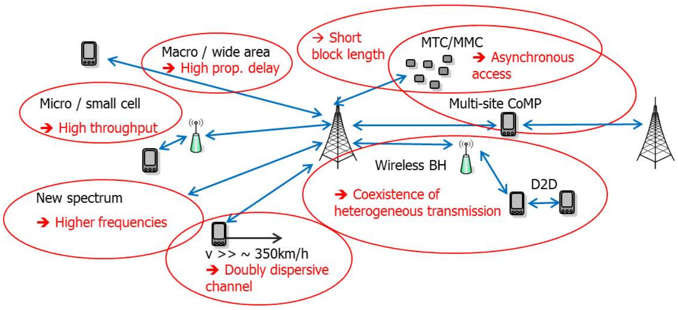

Fig. 1. Examples of 5G services and applications.

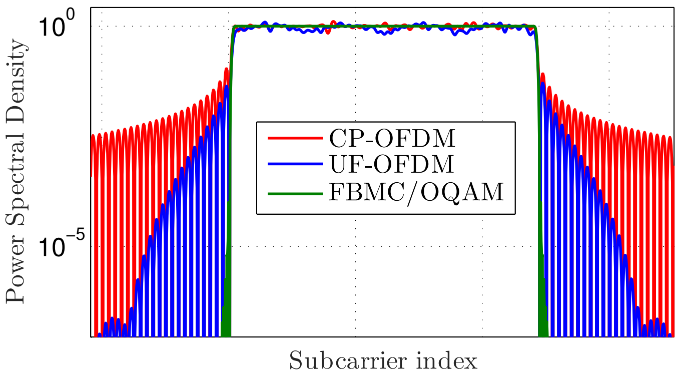

Fig. 2. Spectrum properties of the waveforms.

A. FBMC/OQAM

FBMC/OQAM [6] is a multicarrier modulation scheme where per subcarrier filtering is applied on both transmitter (synthesis filter) and receiver (analysis filter) side. The prototype filters are usually chosen to achieve better localization in frequency domain [7] [8] which target scenarios such as asynchronous transmission without the need of perfect synchronization, use of fragmented spectrum, cognitive radio, high mobility, i.e., high Doppler frequencies and efficient adaptation of basic parameters like subcarrier spacing or symbol duration within the same band. In addition, high spectral efficiency is achieved due to the absence of the CP.

All these desired features of FBMC/OQAM, however, come at the price of the relaxation of the orthogonality condition from the complex field using QAM to the real field using OQAM. Theoretically, OQAM does not show any drawback compared to QAM since they both have the same spectral efficiency. However, several techniques that have been developed for CP-OFDM such as transmit diversity from the orthogonal design (i.e., Alamouti) and scattered pilot-based channel estimation cannot be directly applied to FBMC/OQAM. The main reason behind this is the presence of the so-called intrinsic interference [9]. In this paper, we assume the PHYDYAS [10] prototype filter for FBMC/OQAM without loss of generality.

B. Universal Filtered OFDM

In essence UF-OFDM can be seen as a compromise between no filtering as for pure CP-OFDM and subcarrier filtering as done for FBMC/OQAM. With UF-OFDM, filtering is applied per subband consisting of a group of subcarriers [3].

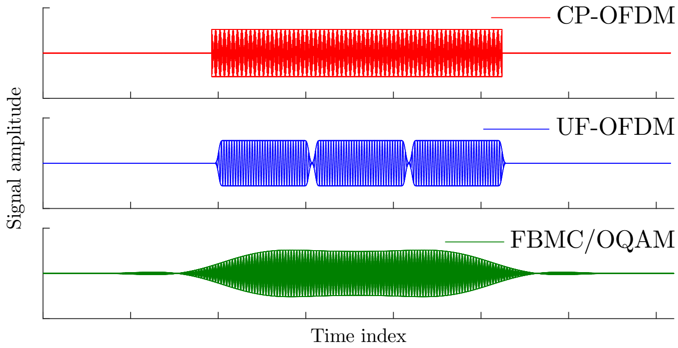

Fig. 3. Example of time domain properties of the waveforms for short burst of three symbols.

The system bandwidth is divided into multiple subbands of certain widths each filtered individually. The sum signal is RF processed and transmitted via the air. The choice of the filter is quite flexible. One potential design parameter for example is to minimize out-of-band (OOB) radiation and in-band distortion. For the concrete filter design, basically any well-known tool can be used. The careful design of the filter, however, is important in order to allow for low OOB distortion while limiting in-band distortion. For the measurements shown in this paper we used the Dolph-Chebyshev design with predefined sidelobe attenuation. The variant of UF-OFDM used here has no CP in contrast to CP-OFDM as e.g. used in LTE, but instead, adds a zero-prefix to account for the symbol ramps between symbols in the time domain. The filter is chosen such that it has a short time response so that the filter tails are fully covered within the zero padding. Consequently, the symbols do not overlap in time domain and no inter-symbol interference (ISI) occurs for frequency flat fading channels.

The power spectral density of FBMC/OQAM and UF-OFDM compared with CP-OFDM is shown in Fig. 2. FBMC/OQAM shows a considerable reduction in the OOB leakage compared to CP-OFDM. The OOB leakage reduction in the cases of UF-OFDM is not as much as FBMC/OQAM but still considerably higher than CP-OFDM. The lower OOB leakage enables several new scenarios such as asynchronous multiple access and high mobility as we will also observe in the measurement results in the later sections.

Fig. 3 show an example of the time domain signal amplitude of the investigated waveforms for a short burst of three symbols. For scenarios where short burst transmission and/ or extremely low delays are of interest, UF-OFDM approach is more suitable than FBMC/OQAM. This is because long filters are typically used for FBMC/OQAM as seen from Fig. 3, which decrease the overall efficiency and increase the delay in case of uplink and very short bursts.

III. Measurement Setup

A. Trial Set-up and Simulation Chains

The demonstrator shown in Fig. 4 consists of a National Instruments (NI) customized 2-channel wireless transmitter (TX) emulating the end user device, the 2-channel wireless receiver (RX) PXI digital radio system emulating the base station and an SPIRENT SR5500 2 channel fading emulator. In

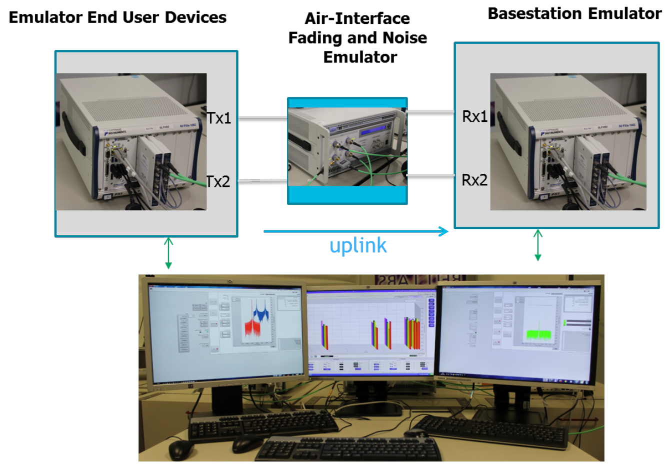

Fig. 4. Open-loop demonstrator for waveforms.

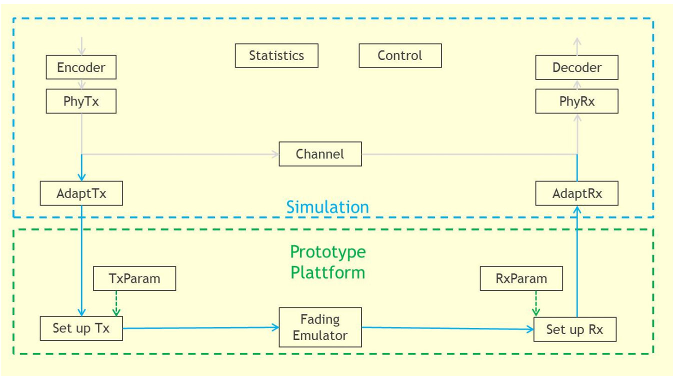

Fig. 5. Functional block diagram for simulation and trials.

Fig. 5 the functional block diagram for the simulation and trials to investigate new 5G air interfaces is shown. The simulation part contains the overall communication system functionality (upper part of Fig. 5). The radio channel forms an integral part of this simulation chain (lower part of Fig. 5). An alternative way of its implementation is providing the radio channel in the framework of an experimental setup forming the second part of the overall configuration. Specific interfaces of the simulation part are used for integrating the experimental setup into the overall system. In order to have a fair comparison the signal processing is the same for simulation and measurement, but for the measurements a fading emulator is replacing the simulated channel as illustrated in Fig. 5.

B. Measurement Scenarios

1) Robustness against fading: CP-OFDM is very robust to frequency-selective fading as long as the CP is chosen longer than the maximum channel delay. But this leads to a significant loss of spectral efficiency especially if the symbol duration becomes smaller, e.g., due to increased subcarrier (SC) spacing at higher carrier frequencies. Furthermore, CP-OFDM is not robust to time-varying channels and shows a poor performance in case of high Doppler spread due to high mobility of the users as illustrated in Fig. 6. Therefore, the robustness to such fading scenarios is a quite relevant measure for candidate waveforms for 5G.

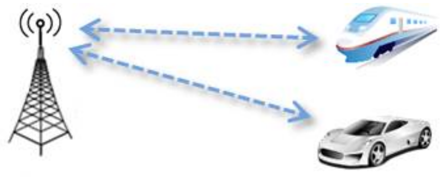

Fig. 6. Robustness against doubly dispersive channels.

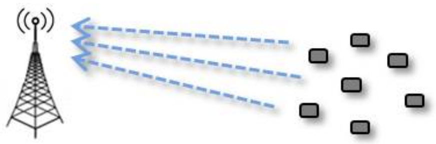

Fig. 7. Robustness against time- and frequency misalignment.

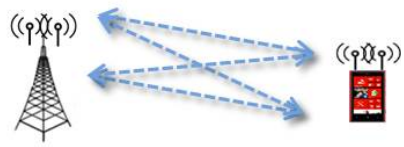

Fig. 8. Support of MIMO for high data rate.

2) Asynchronous Access: Perfect synchronization in time and frequency between transmitter and receiver is another essential condition for CP-OFDM to work properly. To this end, several procedures leading to a certain amount of overhead are implemented in LTE to ensure this synchronity. For mobile broadband traffic this might be negligible, but for sensor devices or other IoT applications as shown in Fig. 7 the overhead needed to maintain this synchronity in uplink communication may not be acceptable and some asynchronity should be supported. To investigate the suitability of the alternative waveforms in this respect, multiple link tests with time- or frequency misalignment were conducted.

3) MIMO: Fig. 8 illustrates MIMO transmissions which are an essential feature to achieve high data rate communication in wireless systems. By spatial multiplexing the data rate can be increased significantly. Therefore the applicability of MIMO spatial multiplexing is an important requirement for alternative waveforms, especially as some alternative waveforms like FBMC/OQAM are sometimes said to be incompatible with well-known MIMO schemes.

IV. Measurement Results

In this section, we compare the performances of the investigated waveforms according to the measurement setup and scenarios introduced in Section III. The evaluation parameters are summarized in Table I. Other relevant parameters specific for the different investigated properties and scenarios are highlighted in the respective subsections.

Channel estimation in the case of FBMC/OQAM has to be treated carefully due to the presence of the intrinsic interference. Different scattered pilot solutions for FBMC/OQAM channel estimation have been already proposed in the literature, e.g., [9] [11] [12]. In our measurements, we use the solution proposed in [11] where one precoding symbol from

TABLE I. MEASUREMENT PARAMETERS.

Carrier Frequency	2.6 GHz
Subcarrier Spacing	15 kHz
FFT size	1024
Sub-frame length	14 OFDM symbols (28 FBMC/OQAM symbols)
Channel model	AWGN 3GPP Extended Vehicular A (EVA)
Maximum Doppler frequency	range between 0 and 1500 Hz
Channel coding	Uncoded / LTE Turbo code
Pilot Grid	LTE downlink scattered pilot grid
Cyclic prefix	LTE normal cyclic prefix
FBMC/OQAM prototype filter	PHYDYAS - Filter length 4094
UF-OFDM prototype filter	Dolph-Chebyshev - Filter length 80
Length of test vector	1 ms (1 subframe)

the neighborhood of the pilot symbol is used to force the intrinsic interference at the pilot position on the receiver side to be zero. The channel estimation procedure at the receiver side is exactly the same as for CP-OFDM and UF-OFDM approaches and is performed in the following order:

1) Estimate the channel at the pilot positions
2) Interpolate in the frequency domain
3) Interpolate in the time domain

A. *Robustness against fading*

High mobility, which is an essential requirement for 5G systems [5], is a specific challenge for multicarrier waveforms as the channel variation introduces ICI that can significantly degrade the performance. One aspect influencing the ICI is the spectral property of the waveform: the lower the side lobes per subcarrier in frequency domain are, the more robust the waveform is against high Doppler spread.

We assume single input single output with linear zero-forcing receiver setup, 9 MHz system bandwidth and EVA fading channel model with two different maximum Doppler frequency of 722 Hz and 1500 Hz which corresponds to a user speed of 300 km/h and 620 km/h respectively at 2.6 GHz carrier frequency.

Fig. 9 shows the performance of the waveforms in terms of the frame error rate (FER) versus the signal to noise ratio (SNR) for the case of maximum Doppler frequency of 722 Hz. Two different MCS values are assumed: MCS = 5 (QPSK, code rate of 0.3183), MCS = 12 (16QAM, code rate of 0.3591). The results indicate a good robustness for the different waveforms against this Doppler spread already for a carrier spacing of 15 kHz as defined for LTE and assumed in the measurements here.

In Fig. 10, the FER vs SNR performance is shown for the case of maximum Doppler frequency of 1500 Hz and MCS value of 5. The significantly improved performance of FBMC/OQAM compared to other waveforms is shown under this extreme condition. FBMC/OQAM shows a gain of around 2 dB at a 10% FER for this scenario. Similar maximum Doppler frequency could also occur at even lower speeds when the carrier frequency is increased.

FBMC/OQAM is more suited for high speed scenarios compared to the other alternative waveforms, however, the performance can be improved even more by using higher carrier spacings in certain subbands within a single TTI as discussed in [13] for UF-OFDM.

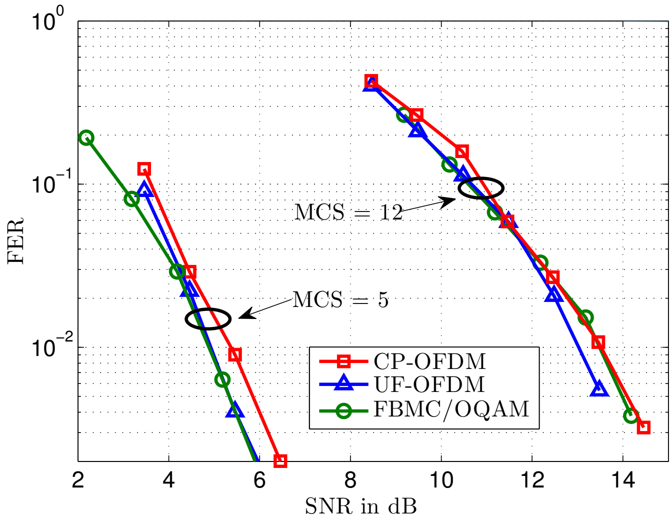

Fig. 9. Robustness to high Doppler spread for 300 km/h at 2.6 GHz.

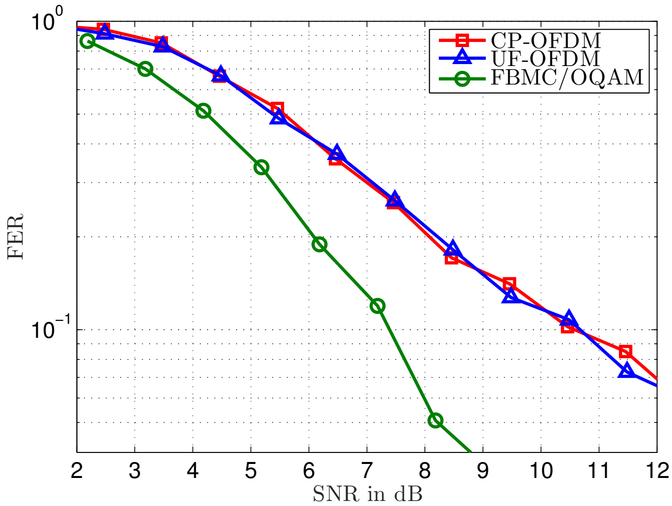

Fig. 10. Robustness to high Doppler spread for 620 km/h at 2.6 GHz.

B. *Asynchronous Access: Multiple link tests with time- or frequency misalignment*

Asynchronous transmission can be two-fold, either in time or in frequency, where both aspects have significant impact on the performance of a certain waveform. The orthogonality of the subcarriers is destroyed and consequently, interference between users occurs. Nevertheless, for both cases, the OOB radiation plays a crucial role: the lower the OOB is, the less sensitive the system is to both imperfections. As both considered alternative waveforms have significantly lower OOB compared to CP-OFDM, both are more robust to asynchronous transmission.

In Fig. 11 an asynchronous setup with different delays and powers of users on neighboring resources is shown. In order to reduce the interference between neighboring users, a certain number of guard SCs is introduced between the users, which in turn reduces the spectral efficiency. The better the OOB suppression of the applied filter is, the less guard SCs are needed to achieve a reasonable performance.

We assume two neighboring users with EVA fading channel

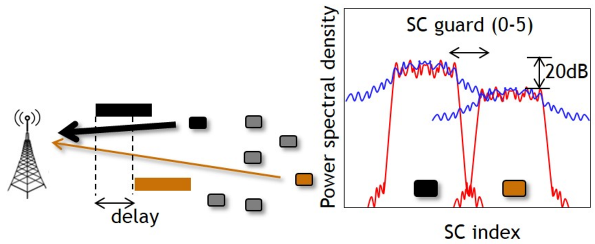

Fig. 11. Asynchronous multiple access with time misalignment.

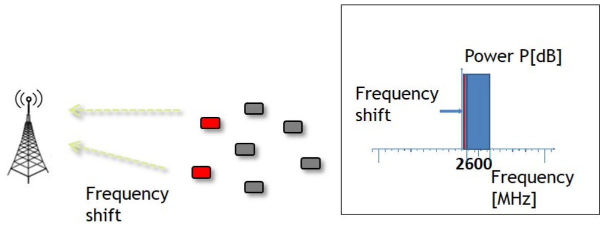

Fig. 13. Asynchronous multiple access with frequency misalignment.

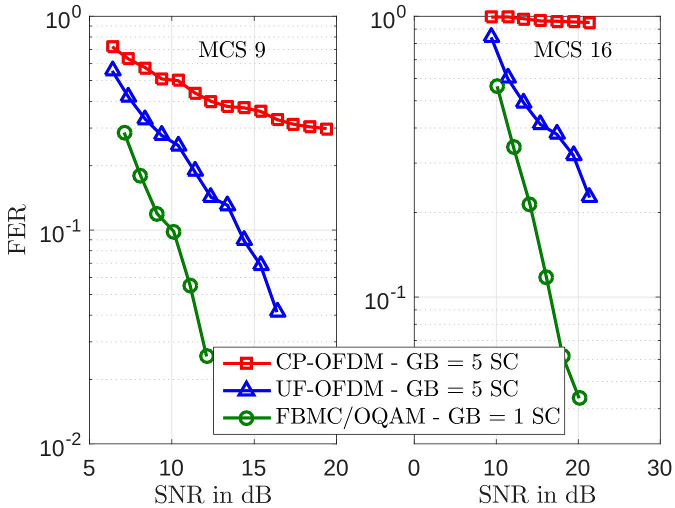

Fig. 12. FER of weaker user for asynchronous access with time misalignment (cf. Fig. 11) under a Doppler spread corresponding to 120 km/h at 2.6 GHz.

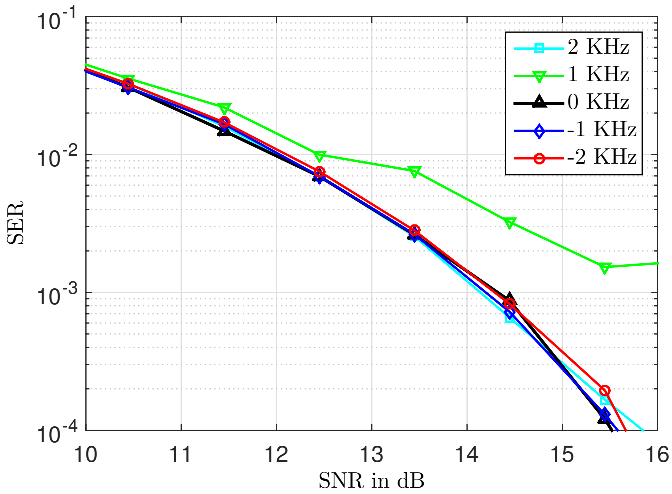

Fig. 14. SER for CP-OFDM for asynchronous access with frequency misalignment (cf. Fig. 13) over an AWGN channel.

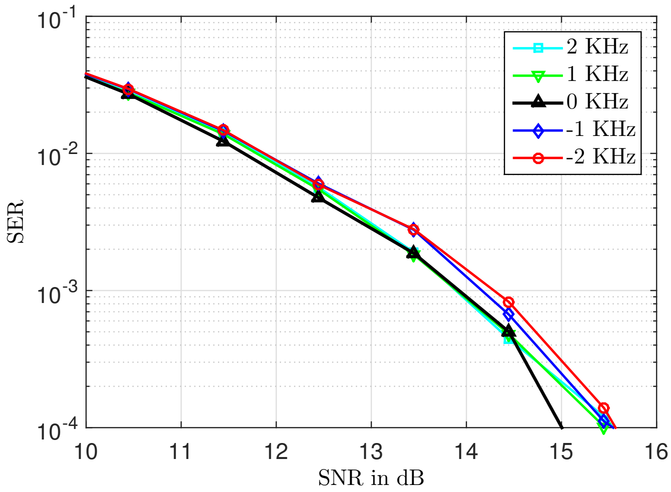

Fig. 15. SER for UF-OFDM for asynchronous access with frequency misalignment (cf. Fig. 13) over an AWGN channel.

model with maximum Doppler frequency of 289 Hz which corresponds to a user speed of 120 km/h at the 2.6 GHz carrier frequency. Two different MCS values are assumed: MCS = 9 (QPSK, code rate of 0.5580), MCS = 16 (16QAM, code rate of 0.5543). Each user has four resource blocks allocated (i.e.,a bandwidth of 720 kHz) and as power control techniques may not be applied in the case of MTC, the near far effect is also considered here by setting the power of the interfering user to be 20 dB higher compared to the user of interest. The timing offset between the two users is assumed to be half a symbol duration or 33 μs representing the worst case timing offset. In Fig. 12 the FER vs SNR performance of FBMC/OQAM and UF-OFDM with 1 and 5 guard subcarriers respectively are compared with CP-OFDM with 5 guard subcarriers as an example to show the robustness of the alternative waveforms. We could clearly observe that both alternative waveforms outperform CP-OFDM due to their better OOB suppression. FBMC/OQAM needs the least amount of guard subcarriers, in this scenario only 1 guard subcarrier, to achieve similar performance as without any timing offset due to its very good OOB suppression. This means with waveforms providing good OOB suppression the overhead to achieve synchronous reception of users in uplink can be reduced by introducing only a small amount of guard SCs between the users which may be more efficient for MTC devices.

Fig. 13 illustrates a case of frequency misalignment between uplink users, where two users are located next to each other in frequency domain, but one of the users has a certain frequency shift, e.g., due to imperfect oscillators. The frequency shift is selected in range of some kHz and destroys the orthogonality of the subcarriers belonging to the two users. Also in this case, the frequency shape of the filter and the respective OOB radiation are the main factor for the amount of interference.

Figs. 14 and 15 show the uncoded symbol error rate (SER) results for the case that both users apply CP-OFDM or both users apply UF-OFDM, respectively, to visualize the effect of frequency misalignment for the SNR region 10-16 dB. CP-OFDM shows significant impact and degradation for very

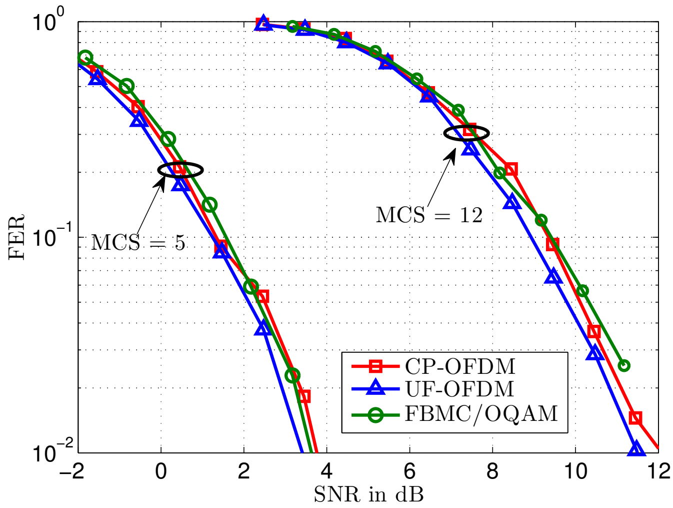

Fig. 16. MIMO capability of FBMC/OQAM and UF-OFDM using spatial multiplexing under a Doppler spread corresponding to 120 km/h at 2.6 GHz.

small frequency shifts of 1kHz already. In the UF-OFDM case the performance is reasonable up to a frequency offset of 2 kHz and the SER values are significantly improved in respect to the CP-OFDM case for a well aligned system. The FBMC/OQAM measurements are ongoing and the results will be included in the final version of this paper.

The results show the potential for a highly optimized radio access with heterogeneous traffic: synchronized high-speed traffic and slightly asynchronous sensor type type traffic in adjacent frequency band. Furthermore network upgrade scenarios for 4G and 5G coexistence are well supported.

C. 2x2 MIMO Trials applying spatial multiplexing

One essential feature for alternative waveforms to be competitive with CP-OFDM is the straight-forward application of MIMO schemes as they are the main driver for increased data rates via spatial multiplexing or beamforming. Therefore any alternative waveform should support the main MIMO modes as defined for LTE. Especially, FBMC/OQAM is often assumed to be incompatible with MIMO, although any MIMO scheme based on linear processing can be applied in a straightforward manner.

To confirm that, we assume 2x2 open-loop spatial multiplexing with linear MMSE receiver setup, 9 MHz system bandwidth and EVA fading channel model with maximum Doppler frequency of 289 Hz. Two different MCS values are assumed: MCS = 5 (QPSK, code rate of 0.3327), MCS = 12 (16QAM, code rate of 0.3755).

Fig. 16 shows the performance of the waveforms in terms of FER versus SNR for the different MCS values. We could observe that all the waveforms have comparable performance and none is outperforming the others for the evaluated MCS values. The situation changes for certain other MIMO schemes like, e.g., Alamouti space-time coding, as in contrast to UF-OFDM, FBMC/OQAM can not apply this transmit diversity scheme in a straight forward manner (cf. Section II-A).

V. Conclusions

Real hardware experiments were conducted to compare the performance of two alternative multi-carrier waveforms, FBMC/OQAM and UF-OFDM, with conventional CP-OFDM. The measurement results of the performance of the three waveforms were presented and discussed in this paper. In particular, the two alternative multi-carrier waveforms support more flexible usage of spectrum (e.g., asynchronous transmission) and new applications and scenarios (e.g., high speed scenario.) Waveforms ([14], [15]) as UF-OFDM which modifies the CP-OFDM concept by subband-wise filtering would be able to reuse the same MIMO schemes designed for LTE/LTE-Advanced, flexibly adapt the subcarrier spacing to the scenario and allow network upgrades with 4G and 5G coexistence.

In the future, further experiments are planned to further evaluate the performance with multiple antenna systems and higher order modulation. Other alternative waveforms will also be considered.

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