On the Waveforms for 5G Mobile Broadband Communications

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***Abstract*—To realize the vision of ubiquitous mobile broadband where radio access performance should not be a limiting factor for user experience, we need to access very large bandwidths, and thus consider higher frequency bands up to the millimeter wave (mmW) region. Air interface design, including waveforms, is a very important component for the success of 5G mobile broadband (MBB) in terms of flexibility, energy efficiency and cost efficiency. In this paper, we compare two waveforms, orthogonal frequency division multiplexing (OFDM) and filter bank multicarrier (FBMC), in terms of these requirements. We show that OFDM is a suitable waveform for MBB due to reasonably low overhead, low cost and latency; whereas FBMC loses its spectral properties when non-linear power amplifier is used.**

Keywords—5G; clipping; cyclic prefix; high power amplifier; overhead; spetral efficiency; waveform

I. Introduction

5G Radio Access, targeted to be available beyond 2020, is expected to handle a very wide range of use cases and requirements, including among others mobile broadband (MBB) and machine type communications. For mobile broadband, 5G radio access is expected to fulfill the demand of exponentially increasing data traffic and to allow people and machines to enjoy gigabit data rates with virtually zero latency. Compared to existing 4G technologies, such as LTE-Advanced, 5G is targeting much higher throughput with sub-ms latency and utilizing higher carrier frequencies and wider bandwidths, at the same time reducing energy consumption and costs [1].

The selection of the radio waveform plays an important role in the design of 5G radio access, due to its impact on transceiver design, complexity and the radio numerology. So far, orthogonal frequency division multiplexing (OFDM) and DFT-spread (precoded) OFDM (also known as single carrier frequency division multiplexing, SC-FDMA), as well as filter bank multicarrier (FBMC), have been most widely considered. Both OFDM and FBMC are well-known multicarrier techniques where data symbols are transmitted simultaneously over multiple frequency subcarriers. The main difference between OFDM and FBMC relates to the pulse shaping applied at each subcarrier. OFDM uses a simple square window in the time domain allowing a very efficient implementation, whereas in FBMC the pulse shaping at each subcarrier is designed in a specific way, e.g. by utilizing prototype functions with concentrated frequency localization such that the out-of-band (OOB) emissions of the waveform become negligible.

The principle idea of OFDM stems from the mid 1960's. OFDM has frequency-flat subchannels arranged so that the sidebands of the individual carriers overlap without causing intercarrier interference. In 1971, fast Fourier transform (FFT) –based OFDM was introduced, used together with guard time between symbols and time domain filtering over a group of subcarriers in order to mitigate inter-symbol interference (ISI) and inter-carrier interference (ICI). In 1980, in order to guarantee perfect orthogonality between subcarries over a time dispersive channel, the conventional null guards of the OFDM symbol were replaced by a cyclic extension, referred today as cyclic prefix (CP). FBMC has attracted interest in recent years in academic papers and several European Union (EU) research projects in which improvements have been reported [2] e.g. to solve the orthogonality issue thus reducing receiver complexity, to handle short burst transmission and multiple input multiple output (MIMO) channels.

The waveforms to be used in 5G radio access should cope with a set of 5G requirements, such as high spectral efficiency (at least for sub-millimeter-wave frequencies), low latency and limited complexity. In order to gain high spectral efficiency, the waveform should ideally possess limited and preferably adjustable time and frequency overhead, small guard bands and MIMO compatibility. Good time localization is required in order to enable low latency. Especially in an adaptive TDD system with the need of fast and flexible link direction switching, the waveform needs to enable short switching guard times between TDD link directions. Further, in order to enable usage of low cost hardware chips, the computational complexity needs to be limited. For example, the extension to multi-antenna technologies should be simple and not significantly increase the computational complexity of the signal detection. Also, the possible utilization of low cost oscillators and radio frequency front ends may lead to robustness requirements against hardware impairments such as frequency offset and phase noise.

Several general comparisons between OFDM and FBMC have been carried out by several contributions in recent literature. In [3] and [4] it was concluded that FBMC overcomes OFDM in terms of reduced overhead and spectral containment, but with the cost of significantly higher complexity. Especially, from overhead point of view, the insertion of CP has been analyzed to be one of the most significant disadvantages of OFDM compared to FBMC. However, in today's 4G systems, such as LTE, the CP overhead is only 7 %; the savings from removing the CP are thus limited. Furthermore, the cyclic property of this extension in OFDM enables usage of efficient one-tap frequency domain equalization. Also, the possibility to convert the fading channel to multiple flat channels enables straightforward extension to MIMO. In OFDM, the shape of the used sinc pulse in frequency domain results in OOB emissions and makes OFDM somewhat sensitive to hardware inaccuracies, which may consequently impact also the link performance. In FBMC, the energy containment in frequency domain increases the robustness towards inter-symbol interference and the insertion of the CP is not needed. Also frequency offset does not significantly affect the performance. The theoretical overhead and spectral containment benefit of FBMC comes with the cost of higher complexity due to the usage of long prototype filters. Extension to the spatial dimension with MIMO transmission further complicates FBMC systems. The absence of CP increases complexity, since one-tap equalization per subcarrier is not feasible. Since the FBCM symbols are dispersed in time, the switching between UL and DL frames will evidently require longer guard periods than in OFDM. Also, it should be noted that the comparisons carried out in the previous literature have been done from a rather theoretical perspective. For example the impact of realistic hardware components, such as high power amplifiers (HPAs) and predistorters have not been taken into consideration [5].

In this paper, we focus on comparing OFDM and FBMC according to a set of 5G requirements, such as high spectral efficiency, low latency and limited complexity. First, we analyze the amount of CP overhead and the frequency numerology of OFDM. Then, we extend the waveform comparison analysis to cover the effect of clipping the waveforms in practical HPAs. Further, we shortly discuss the impact of latency and multi-antenna aspects.

The paper is structured as follows. Detailed analysis of the time and frequency numerology of the investigated waveforms is given in Section II. In Section III, the impact of practical HPAs and clipping is investigated. Latency and multi-antenna aspects are discussed in Section IV. Finally, Section V concludes the paper.

II. Time and Frequency Numerology Considerations

For OFDM, the cost of the baseband is reduced if similar FFT sizes are used for multiple carrier frequencies and bandwidths, enabling reuse of building blocks. The sampling rate should be selected in such a way that the same base clock can be used for different parts of the spectrum. Thus, when increasing carrier frequency from GHz towards millimeter wave (mmW) range, it is proposed simultaneously to increase the used bandwidth and subcarrier (SC) spacing, while keeping the FFT size within a small set of quantized values. Similar scaling can be done in time domain numerology, meaning that e.g. the delay spread and the related frame numerology, such as CP length, may further be variable according to the carrier frequency. This is motivated by reduced delay spreads at increased carrier frequencies due to shorter range, and due to increased beamforming. This principle of scalable radio numerology is illustrated in Fig. 1 with some preliminary numerology values.

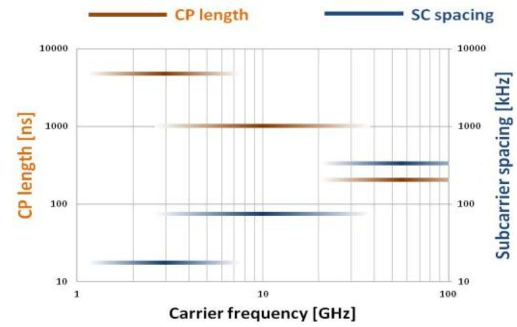

Fig. 1. Scalable OFDM radio numerology.

For more detailed analysis of the values of different time domain steps in Fig. 1, we first consider the impact of CP. In [6], it has been estimated that a CP length of ~1 µs would be feasible for 5G dense deployments with centimeter wave carrier frequency. We now extend this analysis by investigating the OFDM spectral efficiency performance for different channel models. The spectral efficiency (SE) of an OFDM link for one spatial layer can be calculated as

$$SE = \frac{T_{OFDM}}{T_{CP}+T_{OFDM}} \min\left\{SE_{max},\ \log_2\left(1+\frac{\gamma}{\alpha}\right)\right\}, \qquad (1)$$

where T_{CP} and T_{OFDM} are the cyclic prefix length and OFDM symbol length, respectively, SE_{max} is the maximum achievable spectral efficiency limited by the largest modulation and coding rate, α is signal to noise ratio (SNR) degradation due to non-ideal modulation, coding and channel estimation. The SNR γ includes the degradation from too short CP, according to the method described in [7].

The spectral efficiency performance per layer for two channel power delay profiles (PDPs), namely ITU indoor hotspot (InH) NLoS and ITU urban macro (UMa) NLoS are presented correspondingly in Figures 2 and 3 for several SC spacing values varying from 60 kHz to 600 kHz. Results for ITU urban micro (UMi) NLoS would lie in between InH and UMa. We use 40 dB channel SNR (including error vector magnitude (EVM)). Maximum modulation is 256-QAM with rate 0.9, which gives SE_{max} = 7.2 bps/Hz.

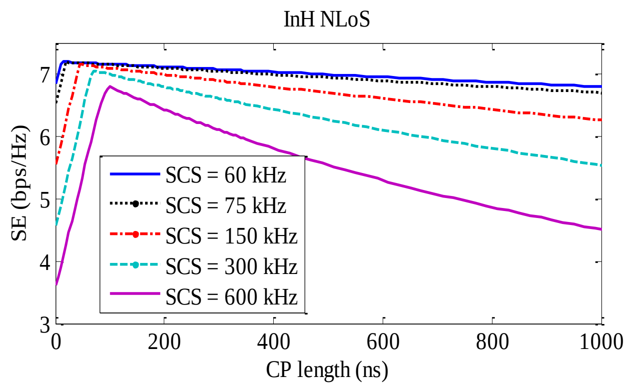

Fig. 2. Spectral efficiency as a function of CP length for InH.

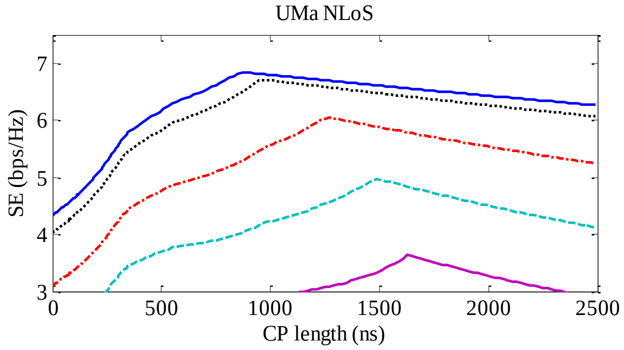

Fig. 3. Spectral efficiency as a function of CP length for UMa.

By comparing the difference of the optimal spectral efficiency values to the spectral efficiency achieved with 1 µs CP length in Figures 2-3 with 60 kHz SC spacing, we notice that the degradation in SE performance is at maximum about 5-6%. Thus, to overcome the channel delay spread, 1 µs CP length seems to be sufficient for all investigated channel models. Timing alignment (TA) needs further to be used in macro and large cells to compensate the propagation delay. Thus, with TA, we can conclude that 1 µs CP length should be feasible for channels varying from indoor hotspot to outdoor micro and macro, causing less than 6% overhead with 60 kHz SC spacing.

As a corresponding example for mmW region, we use the 802.11ad conference room channel model [8]. This channel has very short delay spread, and as seen in Fig. 4, the optimal CP length is very small.

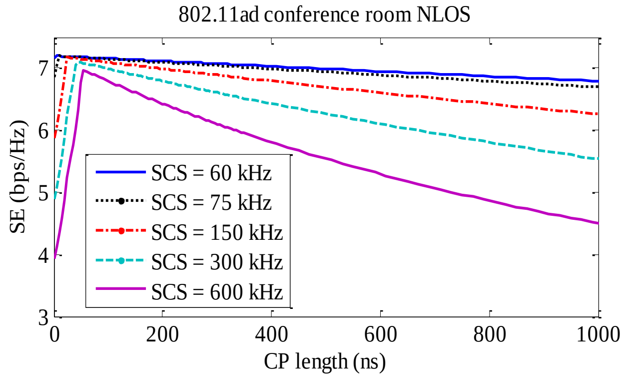

Fig. 4. Spectral efficiency as a function of CP length for 802.11ad conference room.

In Figures 2, 3, and 4, phase noise (PN) has not been taken into account. PN is caused by implementation technology and hardware design, and in multicarrier systems, the effect of PN depends on the subcarrier spacing [9]. The noise-to-signal ratio caused by PN ICI is given by [10]:

$$\left(\frac{N}{S}\right)_{ICI} = \int_{-\infty}^{\infty} P(f)W(f)df, \qquad (2)$$

where $P(f)$ is the PN power spectral density (PSD) dependent on the oscillator design, $W(f)$ is given by

$$W(f) = \sum_{n\neq 0} \mathrm{sinc}^2\left(\frac{f}{f_u}+n\right) \qquad (3)$$

and f_u is the subcarrier spacing. In addition to PN, the Doppler effect also causes ICI in OFDM. According to the classical Jakes model of Doppler spread, the ICI power can be computed as a function of the generic Doppler spectral density, given by [11]:

$$P_{ICI,Jakes} = 1 - 2\int_0^1 (1-f)J_0\left(2\pi f_{d_{max}} T_s f\right)df\ , \qquad (4)$$

where J_0 is the zeroth order Bessel function, $f_{d_{max}}$ is the maximum Doppler frequency and T_s is the symbol length.

Fig. 5 shows the optimal subcarrier spacing and CP length for two frequencies and with cell radius of 10 m: 6 GHz (for which we use InH and UMa channels), and 60 GHz (802.11ad conference room). Jointly optimal values for the CP length and SC spacing (SCS) are found for a SNR of 16 dB, taking into account phase noise (2), Doppler spread (4) at 50 km/h velocity and a nominal EVM of 40 dB due to other imperfections. The measured PN PSD of a phase-locked loop 90 nm CMOS oscillator for ~37.6 GHz [12] is used as a basis to roughly estimate the PN effect at 6 GHz and 60 GHz, by shifting the PN PSD by -20 dBc/Hz per decade of decrease in the carrier frequency. The PN ICI is calculated over bandwidths of 2 GHz and 200 MHz for 60 GHz and 6 GHz carrier frequencies respectively. Only PN ICI term is analyzed, meaning that the PN common phase error (CPE) term is not taken into account, since it can be assumed to be sufficiently corrected with pilots provided that the subcarrier spacing is larger than the significant part of the CPE. ICI compensation algorithms are not considered.

From Fig. 5 it can be seen that the estimated subcarrier spacing values even for mmW frequency area are still reasonably low and together with much shorter required CP length the overhead can be kept relatively low. In order to take CPE and different RF technologies into account, increasing the SC spacing slightly and adding some pilots for ICI estimation and compensation can further be considered, leading to a small additional increase in overhead.

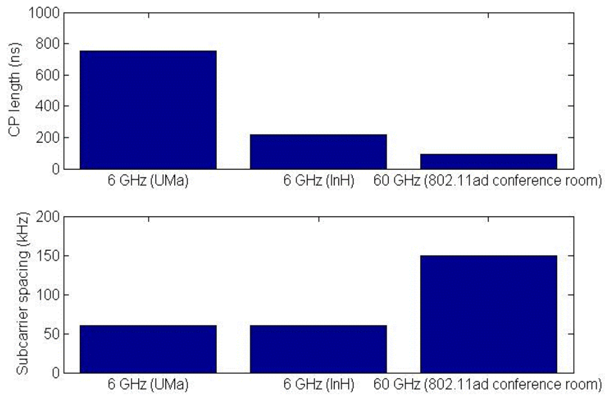

Fig. 5. Optimal CP length and subcarrier spacing.

III. COMPARISON OF SPECTRAL REGROWTH OF CLIPPED OFDM, FBMC, AND SC FDMA

Most transmitters are equipped with high power amplifiers that are inherently nonlinear with respect to signals with envelope fluctuations. A large variety of radio signals used in modern communications have non-constant amplitude. In spectrum-sharing systems, the spectral regrowth caused by nonlinear distortions is of prime interest. Filter bank based multicarrier transmission attracted recently a lot of research activity due to a lower out-of-band emission compared to the OFDM [13]-[15]. However, as OFDM, FBMC is a multicarrier signal, and thus it may exhibit large envelope fluctuations. It is important, therefore, to compare the spectral regrowth of FBMC with other waveform types after nonlinear amplification.

A large variety of HPA models have been derived and applied to solving research and practical tasks. The soft-envelope limiter (SEL) model [16] is a frequently used HPA representation. The SEL pattern is used for characterization of relatively linear (till the saturation) HPAs, as well as for modelling the predistorter-HPA cascade providing the minimal in-band distortion of the input signal.

In this paper, we compare the spectral regrowth of three waveforms, FBMC, OFDM and SC-FDMA, passed through the SEL with the input-output relation represented as

$$s_{\text{out}}(t) = \begin{cases} s_{\text{in}}(t), & \text{if } |s_{\text{in}}(t)| < A_{\text{cl}} \\ A_{\text{cl}} \exp\left(jarg\left(s_{\text{in}}(t)\right)\right), & \text{otherwise} \end{cases} \quad (5)$$

where $s_{\text{in}}(t)$ and $s_{\text{out}}(t)$ are the respective input and output signals of the cascade, A_{cl} is the cascade clipping level defined by the HPA maximal output power, and arg $(\cdot)$ denotes the argument of a complex-valued number. The severity of clipping is characterized by the clipping ratio (CR), $\text{CR} = A_{\text{cl}}/\sqrt{p_{\text{in}}}$, where p_{in} is the input signal power. Eq. (5) represents an amplitude-dependent nonlinear transform resulting in nonlinear distortions of a signal with envelope variations. Characteristics of FBMC are essentially defined by the prototype filter, and in our simulations, we used a prototype filter designed on the basis of [14]-[15].

Fig. 6 represents the power spectral density (PSD) of FBMC passing through the SEL (5). For comparison, in Fig. 7, we present graphs of PSD of an OFDM signal. Due to the absence of the cyclic prefix and guard bands in the frequency domain, the FBMC is more power efficient than the OFDM [13], and following [13], we have compensated for this by using a 1.2 dB higher CR for FBMC than for OFDM. The curves are given for 4-QAM modulation, and an LTE-type numerology with total number of subcarriers 2048, from which 1200 subcarriers are non-zero. The presented results show that the FBMC outperforms the OFDM in the sense of a lower out-of-band emission only in the case of linear amplification. In the case of nonlinear amplification, this advantage vanishes. This observation can be explained by different PSD shapes of original OFDM and FBMC. Since both signals can be considered Gaussian for a large number of components, the same theory can be applied for an analysis of their passing through nonlinear HPAs. For example, the spectral regrowth after clipping can be analyzed on the basis of [17]. According to this theory, the PSD after clipping is a function of the input PSD. But the spectral regrowth of the original (undistorted) OFDM decays faster than that of the undistorted FBMC, and this fact results in a similar spectral regrowth in the case of the SEL.

The analysis can easily be extended also to SC-FDMA passing throught the SEL (5). Although SC-FDMA is a single-carrier signal, it exhibits envelope fluctuations [18], and thus the signal is distorted when passing through the amplitude-dependent nonlinear device. The PSD of SC-FDMA after SEL is shown in Fig. 8, and it is similar to that of OFDM.

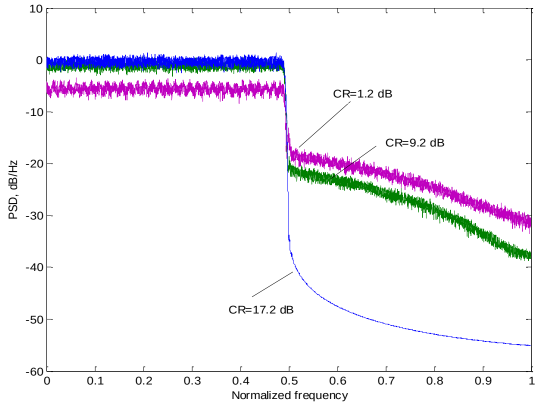

Fig. 6. PSD of ideally predistorted FBMC.

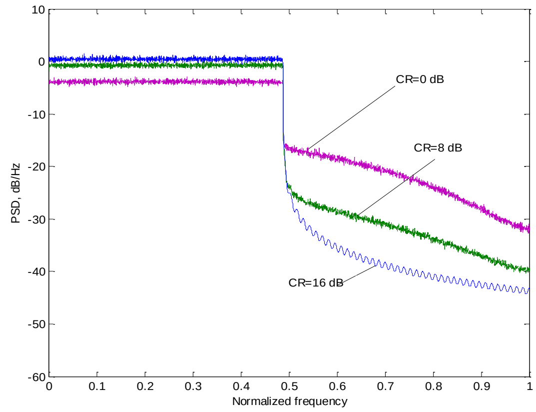

Fig. 7. PSD of ideally predistorted OFDM.

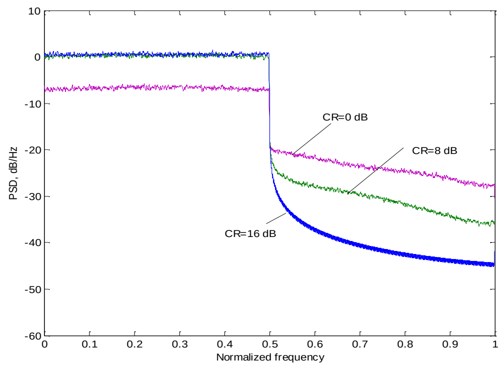

Fig. 8. PSD of ideally predistorted SC-FDMA.

IV. LATENCY AND MIMO

The good time-localization properties of OFDM waveform makes it optimal from latency perspective. On contrary, the good frequency-localization of FBMC symbols makes them correspondingly dispersed in time. Consequently, the transmission of a frame consisting of FBMC symbols is subject to pre- and post-cursors. These tails can be shortened with the cost of spectral regrowth, but the frame length should still be half a symbol longer compared to OFDM in order to obtain the same link performance [5]. Consequently, FBMC requires utilization of longer guard times between transmissions to different link directions, increasing system latency in comparison to OFDM. This is an important aspect in adaptive TDD systems which demand frequent link direction switching. Some recent work attempt to solve this orthogonality issue of OQAM-FBMC, e.g. [19] circular filtering is used in OQAM, and a CP is added in block basis. These methods show promising improvements for a SISO multipath channel.

It may be feasible to assume that a 5G transceiver operating over large bandwidths will be able to possess the required baseband processing capabilities to deal with basic FBMC. However, the FBMC complexity increases further with the extension to the spatial dimension with MIMO transmission. This is a noticeable aspect to be considered, since limited computational complexity can be seen as a fundamental requirement for 5G. In [2] a result in a 2x2 MIMO channel was shown, based on so called punctured Tomlinson Harashima precoding (THP) to improve performance by precoding, by not using one or more antennas on some subcarriers. Since OFDM has the capability of converting the fading channel into multiple flat channels and since the equalization of the spatial channel can be done subcarrier-wise, OFDM allows straightforward and simple extension to very large MIMO and high gain beamforming solutions which provide energy efficient transmission and reception, especially in higher frequency bands.

V. CONCLUSIONS

In this paper, we discussed and compared OFDM and FBMC waveforms according to a set of 5G requirements. In order to discuss the spectral efficiency of OFDM, we presented the idea of OFDM numerology scalable according to carrier frequency varying from 6 GHz up to mmW. We then analyzed both time and frequency numerology of OFDM with the conclusion that even though some overhead exists, it is still in feasible limits.

Both OFDM and FBMC are affected by nonlinear amplification. This effect should be noted especially in case of FBMC, where FBMC loses the spectral properties of the waveform under the studied HPA model.

Good time-localization properties of OFDM waveform makes it optimal from latency perspective. Very large MIMO and high gain beamforming provide energy efficient and cost efficient MBB solution, especially in higher frequency bands. Though recent research on FBMC has shown promising improvements, feasibility with practical implementations remains for further research, especially for higher frequency bands in mmW region requiring high gain beamforming to fulfill link budget requirement for the 5G multiple gigabit MBB.

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