A SINGLE-CARRIER - OFDM COMPARISON FOR BROADBAND WIRELESS COMMUNICATION

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Abstract—**OFDM is a popular modulation scheme for broadband wireless communication. It elegantly handles multi-path and has low complexity. Recently, Single-Carrier with Frequency-Domain processing (SC-FD) is gaining attention as a possible competitor for OFDM: it is based on the same principles and therefore, it has similar multi-path handling capabilities and low complexity. Moreover, SC-FD promises a several other attractive advantages, such as power amplifier efficiency and inherent frequency diversity exploitation. Current performance comparisons do not consider these effects combined. In this paper, we make the comparison in a realistic scenario considering both the power amplifier efficiency and frequency diversity. Our results show that in a multi-path environment SC-FD can outperform OFDM by 4 dB, largely due to the better frequency diversity exploitation. Therefore, SC-FD is a good alternative to OFDM for battery-powered terminals, and is therefore especially suited for up-link communication.**

I. Introduction

OFDM [1] is a widely recognized and standardized modulation technique for broadband wireless systems: because of its ability to elegantly cope with a multi-path environment, it is used for Wireless LAN [2][3], DAB [4], DVB [5], Fixed Wireless Access [6], ...

The basic principles behind OFDM can also be used for Single-Carrier transmission, resulting in the so-called Single-Carrier with Frequency-Domain processing (SC-FD). It inherits OFDM's ability to cope with multi-path and its low complexity.

Since the introduction of both modulation schemes, the advantages and disadvantages between them have been compared frequently ([7], [8], [9], [10], [11], [12]). Recently, this comparison has gained more attention, since both schemes are considered for the Fixed Broadband Wireless Access ([6]).

One of the main points of comparison is the impact of the Power Amplifier (PA) on both schemes. SC-FD is believed to allow for a more power efficient power amplifier than OFDM. Previous comparisons have not investigated this impact of the Power Amplifier on the Bit Error Rate performance in a realistic multi-path scenario. [12] only considers the spectral regrowth due to the power amplifier, but not the impact on the performance. [7], [10] only compare the ideal multi-path performance (so no channel estimation, clipping, filtering, ...). [8] considers the effect on the BER performance for AWGN channels. [11], [9] do not consider the impact of the Power Amplifier.

In this paper, we analyze the effect of the power amplifier on OFDM and SC-FD in a realistic multi-path scenario. In section II, we briefly summarize the principles of OFDM and SC-FD. Section III describes the characteristics of a power amplifier and analyzes the effect on the performance of OFDM and SC-FD. Section IV takes into account imperfections to obtain a realistic performance comparison. Finally, we summarize the conclusions of this paper.

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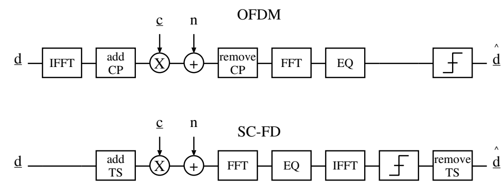

Fig. 1. The OFDM and SC-FD setup.

II. OFDM vs SC-FD

The two basic principles of OFDM and SC-FD are the cyclic extension and the use of the (I)FFT. We now briefly summarize their application.

A. OFDM

The basic idea of OFDM transmission is to divide the available bandwidth into N_{sc} sub-carriers. If the number of sub-carriers is high enough, the bandwidth per sub-carrier is narrow compared to the coherence bandwidth of the channel. Therefore, each sub-carrier approximately experiences flat fading and can thus only requires a single-tap equalizer.

A spectrally and computationally efficient method to put the data on the sub-carriers is by means of an IFFT. The addition of a cyclic prefix ensures that the channel always appears cyclic and thus the linear convolution with the channel can be considered a circular convolution. This guarantees that the received signal can be equalized by means of a single-tap equalizer per sub-carrier. This operation is performed in the frequency domain, thus after the received data passed through an FFT. Figure 1 shows an OFDM link.

Uncoded OFDM loses all frequency diversity inherent in the channel: a dip in the channel erases the information data on the sub-carriers affected by the dip and the information cannot be recovered by the other carriers. This mechanism results in a poor BER performance. Adding sufficiently strong coding spreads the information over multiple sub-carriers. This recovers the frequency diversity and improves the BER performance.

B. Single-Carrier with Frequency-Domain processing

Single-Carrier transmits the data in the time domain. A training sequence is added which ensures the channel appears cyclic at the receiver [11], [9]. This again allows to have the same simple one-tap equalizer in the frequency domain. The decisions have to be taken in the time domain, so after the equalization an IFFT is needed.

Compared to OFDM, SC-FD uses the same building blocks, but with the IFFT moved from the transmitter to the receiver (figure 1). This also means Single-Carrier transmits the data in the time domain, whereas OFDM puts the data in the frequency domain. This has a very important consequence: the information of each SC-FD symbol is spread out over the complete frequency band. This means that dips in the channel do not wipe out complete symbols, because the information of each symbol can be recovered from the other carriers. Therefore, SC-FD exploits the frequency diversity in the channel and thus has a better uncoded performance than OFDM. Coding improves the SC-FD performance, whereas for OFDM coding is needed to exploit the frequency diversity and improve the performance.

III. Power Amplifier

A. Power Amplifier Characteristics

For non-constant envelope signals a linear power amplifier is needed. We assume a class A power amplifier with back-off for its linearity. The back-off determines the power consumption of the power amplifier and also its linear dynamic range. Since the linear dynamic range directly relates to the distortion, the back-off also determines the Bit Error Rate.

The linearity of the power amplifier is quantified by the 1-dB-compression point P_{1dB}, defined as the input power at which the non-linearity lowers the output power by 1 dB compared to the ideal amplifier.

The baseband representation of the transfer function of a class A power amplifier with linear amplification G and a cubic non-linearity is [13]

$$\mathbf{y} = \mathbf{x} \cdot G \cdot (1 - \alpha \frac{3}{4} |\mathbf{x}|^2) \quad (1)$$

with $\mathbf{x}$ the input baseband representation of the signal and $\mathbf{y}$ the output.

The coefficient α can be expressed as a function of P_{1dB} as

$$\alpha = \frac{4}{3(1 - 10^{-1/20}) P_{1dB}^2} \quad (2)$$

In our setup, we set the average input power $P_{in} = 6dBm$; the linear gain of the power amp is $23dB$, such that we operate at $29dBm$ average output power, which is a specified average output power for the 5GHz band. The higher the P_{1dB} compression point, the further the signal is separated from the distortion area of the power amplifier transfer characteristic. The smaller the distortion added by the power amplifier, the smaller the BER performance degradation. However, the higher the backoff between P_{in} and P_{1dB} the smaller the PA efficiency, as can be seen in figure 2. A class A power amplifier has a theoretical maximum efficiency of 50%. This efficiency drops rapidly with increasing back-off.

B. AWGN

OFDM has a large dynamic range compared to SC-FD, especially for low constellation sizes [12]. Therefore, the P_{1dB}-P_{in} back-off needs to be larger for OFDM to accommodate the signal in the linear range of the power amplifier transfer function.

This is shown in figure 3 for uncoded BPSK transmission over an AWGN channel. OFDM and SC-FD have the same performance in case of an ideal power amplifier. The performance

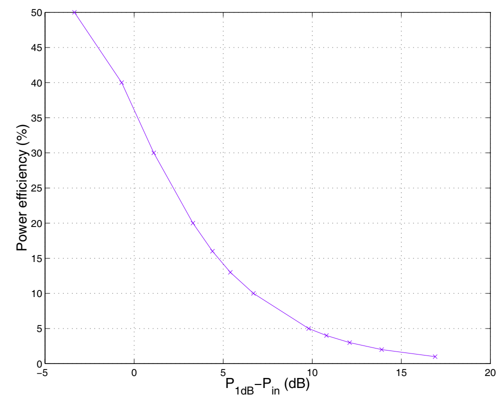

Fig. 2. Power efficiency of a class-A power amplifier as a function of the back-off $P_{1dB} - P_{in}$.

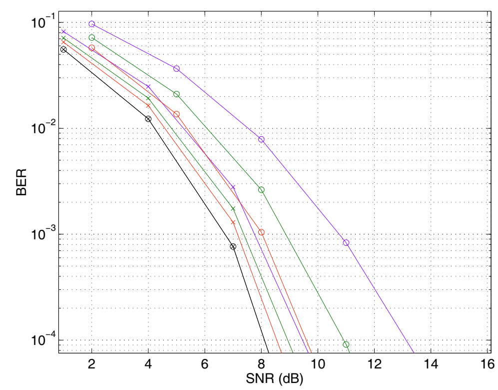

Fig. 3. The impact of power amplifier back-off $P_{1dB} = [\infty\ 6.4\ 4.4\ 2.4] dBm$ on SC-FD(x) and OFDM(o) in AWGN.

of SC-FD does not change much if the P_{1dB}-P_{in} back-off is decreased, whereas the OFDM performance deteriorates quite rapidly: for $P_{1dB} = [6.4\ \ 4.4\ \ 2.4] dBm$ the degradation at a BER of 10^{-3} is $[0.5\ 0.7\ 1.0]$dB for SC-FD and $[1.3\ 2.1\ 4.0]$dB for OFDM. These results show that in an AWGN channel the performance advantage of SC-FD over OFDM increases as the PA back-off decreases.

C. Multi-path

Figure 4 shows the impact of a power amplifier on the performance of OFDM and SC-FD in a multi-path environment (4 independent Rayleigh fading taps) with Perfect Channel Knowledge. They have different reference curves as was explained in section II due to frequency diversity: as already shown in [7], SC-FD significantly outperforms OFDM for uncoded communication over a multipath channel. The impact of the power amplifier on SC-FD is similarly small as for the AWGN case. The fast deterioration of the OFDM performance as a function of the P_{1dB}-P_{in} back-off has disappeared: the impact is comparable to the SC-FD degradation. This is because the impact of the power amplifier distortion is no longer the dominant source of errors. For OFDM almost all bit errors are introduced by the lack of frequency diversity ; therefore, the curves indicating the

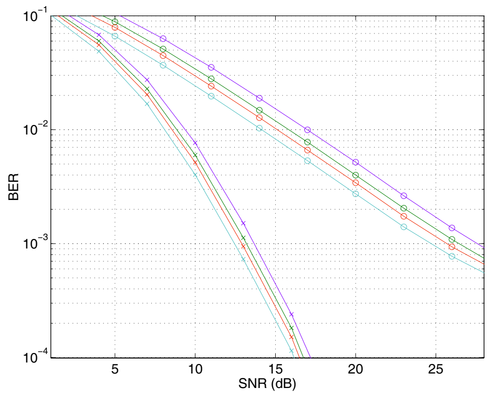

Fig. 4. The impact of PA back-off $P_{1dB} = [\infty \ \ 6.4 \ \ 4.4 \ \ 2.4] dBm$ on SC-FD(x) and OFDM(o) in Multi-Path with Perfect Channel Knowledge.

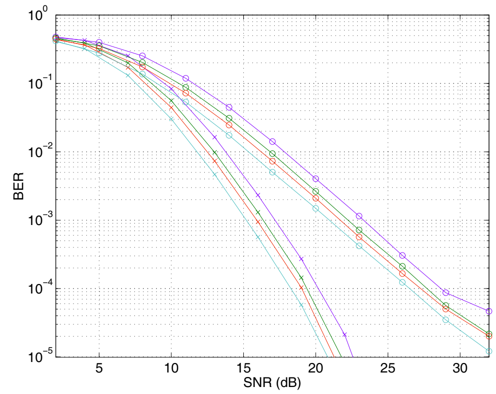

Fig. 5. The impact of PA back-off $P_{1dB} = [\infty \ \ 6.4 \ \ 4.4 \ \ 2.4] dBm$ on SC-FD(x) and OFDM(o) in Multi-Path with coding (R=3/4), Channel/Noise Estimation, Clipping (4σ) and quantizing (8 bits) and SRRC filtering ($\alpha = 0.25$).

PA impact on OFDM are situated close together.

They remain close together if coding ($R = 3/4$, IEEE802.11a compliant) is added to this system. For $P_{1dB} = [6.4 \ \ 4.4 \ \ 2.4] dBm$ the degradation at a BER of 10^{-5} is $[0.4 \ \ 0.7 \ \ 1.1]$dB for SC-FD and $[1.0 \ \ 1.75 \ \ 2.75]$dB for OFDM. These results tell us two things. First, the impact of the PA on SC-FD is the same for AWGN as for multi-path ; for OFDM, on the other hand, the impact of the PA is decreased in multi-path, because the impact of the lack of frequency diversity dominates the performance. Second, the use of frequency diversity dominates the performance comparison between the two schemes: the advantage of SC-FD caused by the frequency diversity is about 8 dB at 10^{-5} and this far exceeds the additional benefit (0.6 to 1.6 dB) by the power amplifier.

IV. Realistic scenario

A. Model

To quantify the difference between OFDM and SC-FD, other effects need to be taken into account.

In the previous section we assumed Perfect Channel Knowledge. In practice, the channel needs to be estimated. The MMSE equalization for SC-FD also requires a noise estimate. Both the channel and noise need to be estimated based on a know preamble or Training Symbol. Both methods are described in [14] and are based on the fact that the number of taps in the time domain channel response is limited.

The OFDM and SC-FD symbols are not transmitted as such, but they need to be filtered to limit the out-of-band radiation. To this end, we applied a Square-Root-Raised-Cosine (SRRC) filter at transmitter and receiver. For OFDM, the zero-carriers limit the out-of-band radiation. For SC-FD, we apply a SRRC filter with a roll-off $\alpha = 0.25$, a delay of 5 taps and an oversampling by 4 ; this gives both OFDM and SC-FD a 20% guardband against out-of-band radiation and allows for fair comparison.

OFDM is clipped and quantized to limit the Peak-to-Average-Power-Ratio (PAPR). This is beneficial since the limited dynamic range enables a smaller back-off. SC-FD needs to be clipped and quantized as well but the impact is a lot smaller. [13] shows that clipping at 4σ and a quantization of 8 bits to be a good solution for a realistic OFDM.

B. Performance

The results of this analysis are shown in figure 5 for coded ($R = 3/4$) BPSK. The impact of the PA is for $P_{1dB} = [6.4 \ \ 4.4 \ \ 2.4] dBm$ is $[0.75 \ \ 1.1 \ \ 1.9]$ for SC-FD and $[0.75 \ \ 1.2 \ \ 2.2]$ for OFDM at a BER of 10^{-4}, where the difference in frequency diversity is still 8 dB.

This shows that in a realistic system the advantage of SC-FD over OFDM comes almost completely due to its effective use of the frequency diversity present in the channel. The impact of the PA power efficiency is negligible.

A more natural way of quantifying the difference in performance not based on (SNR,ber)-curves, but on (P_{T_x},*Goodput*)-curves. Goodput is defined as

$$\begin{aligned} Goodput &= R_{raw} \cdot R_{ce} \cdot R \cdot R_{Tx} \cdot (1 - PER) \qquad (3) \\ &= R_{max} \cdot (1 - PER) \qquad (4) \end{aligned}$$

Goodput indicates the actual throughput at MAC level. It starts from the raw physical throughput R_{raw} (based on the constellation size and the sampling time) ; R_{ce} accounts for the cyclic extension overhead ; R represents the coding overhead and R_{Tx} deals with the amount of useful transmission time in a frame. Finally, erroneously received packets need to be retransmitted: (1-PER) accounts for the loss of actual throughput because of retransmissions. Since we designed the comparison of OFDM and SC-FD to be fair, they both have the same maximum achievable throughput R_{max} ; therefore, we can set it to 1 and compare the relative performance of OFDM and SC-FD.

The same relative measure can be derived for the total power consumed at the transmitter. If we assume the path loss, noise power, Noise Figure and Implementation Loss are identical for OFDM and SC-FD (which is necessary for a fair comparison), we define the relative consumed power at the transmitter as

$$P_{T_x} = \frac{SNR}{\mu(P_{1dB})} \qquad (5)$$

This means the total consumed power at the transmitter is proportional to the SNR (since higher SNR means more transmitted

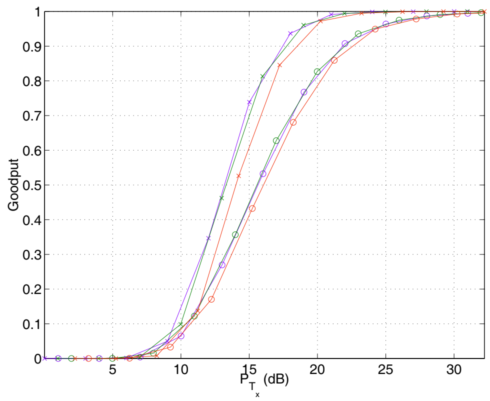

Fig. 6. The goodput as a function of the total consumed transmitter power P_{T_x} and the impact of PA back-off $P_{1dB} = [6.4\ \ 4.4\ \ 2.4] dBm$ on SC-FD(x) and OFDM(o) in Multi-Path with coding (R=3/4), Channel/Noise Estimation, Clipping (4σ) and quantizing (8 bits) and SRRC filtering ($\alpha = 0.25$).

power) and inversely proportional to the PA efficiency $\mu(P_{1dB})$, which is determined by the back-off from the 1dB-compression point P_{1dB} (figure 2). We assume the power consumption at the transmitter is largely determined by the PA power consumption, thus by the transmitted power and the PA efficiency.

(4) and (5) allow to transform the $(BER/PER, SNR)$-curves as in figure 5 into $(Goodput, P_{T_x})$ as in figure 6.

If we target 90% of the maximum achievable goodput, then SC-FD can deliver this at 4.2 dB less consumed transmitter power. The back-off $P_{1dB} - P_{in}$ has a double influence on the $(Goodput, P_{T_x})$-curves. For decreasing back-off, first, the BER/PER increases. This decreases the $Goodput$ through (4). On the other hand, a lower back-off results in a higher PA efficiency μ (as shown in figure 2) and a higher efficiency in a lower consumed transmitter power P_{T_x} through (5). Figure 6 shows this trade-off results in an optimum back-off of $P_{1dB} = 4.4\, dBm$ for which both OFDM and SC-FD reach their most power efficient curve.

These results demonstrate that SC-FD can be more power efficient than OFDM. Therefore, SC-FD is a valuable candidate for broadband wireless communication, especially for up-link transmission when the transmitter is a battery-powered mobile terminal. This is in fact the core idea in the mixed-mode proposal by Falconer et al. [15] in which the authors support the use of SC-FD for up-link transmission, while OFDM is still used in the down-link. Apart from impact on the BER/PER performance or goodput, we should note that other considerations have to be made. The power amplifier also determines the amount of out-of-band radiation for which specifications exist. This has been studied in [12]. The authors indicate OFDM is indeed more sensitive to PA impact concerning out-of-band radiation. This statement remains valid in a multi-path environment since this effect does not depend on the channel.

The difference in performance between OFDM and SC-FD depends also on the code rate R and the constellation size. In this paper, we have taken $R = 3/4$, as specified in the IEEE802.11a standard, for BPSK transmission. The code $R = 3/4$ is a frequently used code rate, making a trade-off between code performance and code overhead. The BPSK transmission is the modulation scheme with the largest range and highest robustness. Therefore, we believe the ($R = 3/4$,BPSK) setting is a relevant case study. Naturally, we will investigate other code rates and modulation types to analyze their impact.

V. Conclusions

In this paper, we compared the performance of OFDM and Single-Carrier with Frequency-Domain processing (SC-FD) in a realistic scenario, including multi-path and the most important imperfections. Our results show that in a multi-path environment SC-FD performs better due to the inherent frequency diversity exploitation. The impact of the Power Amplifier Back-off has a negligible effect in a multi-path environment. A detailed case study in a realistic scenario including most important imperfections reveals that coded ($R = 3/4$) BPSK SC-FD has a 4.2 dB advantage over its OFDM counterpart. Therefore, SC-FD is an attractive candidate for broadband wireless transmission, especially for battery-powered uplink transmission.

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