OFDM versus Single Carrier with Cyclic Prefix: a system-based comparison for binary modulation

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Abstract

In recent years, wireless indoor networks have received a lot of scientific and industrial attention. Most systems rely on the use of Orthogonal Frequency Division Multiplexing (OFDM) because of its capability to elegantly cope with multi-path interference. However, to evaluate the complete system, we should not only consider the digital modem, but also take into account the influence of the front-end. To that goal, we have set up a simulation environment which comprises both the digital modem and the most important front-end distortions. We show that for the same data rate, bandwidth and transmit power constraints Single-Carrier with Cyclic Prefix (SC-CP) allows the design of more power efficient modems than OFDM and is therefore a very suitable candidate for portable wireless modems.

Keywords

OFDM, Single-Carrier with Cyclic Prefix, multi-path, front-end, power efficiency.

1. Introduction

OFDM is recognized as an interesting modulation technique in a reflective environment, because of its capability to enable low-cost multi-path mitigation [1]. Therefore, all recent standards for WLANs [2, 3] support OFDM modulation. However, OFDM requires an expensive and power inefficient front-end [4], because of the high Peak-to-Average Power Ratio (PAPR) of the OFDM signal.

Single Carrier transmission with Cyclic Prefix [5, 6] is a closely related transmission scheme which possesses the same attractive multi-path interference mitigation properties as OFDM. SC-CP therefore can achieve a performance and digital complexity comparable to OFDM, but it is expected to be more front-end friendly.

To verify and quantify these expectations, we compare the sensitivity of OFDM and SC-CP to front-end non-idealities. To this end, we have set up a simulation environment, comprising both a baseband model and a front-end model with the most important distortion effects. This allows a system-level assessment of the performance of the complete transmitter-receiver link, it enables to make trade-offs between efficiency or accuracy of front-end blocks and overall performance and thus to define principal specs, such as digital-to-analog and analog-to-digital converter (DAC/ADC) resolution, power amplifier linearity and a voltage-controlled oscillator (VCO) phase noise spec.

2. System setup

Our digital baseband simulation block (fig. 1) supports OFDM and SC-CP. As a case study, we have used an OFDM-based WLAN (such as Hiperlan-II [2] and IEEE 802.11a [3]). The SC-CP was inspired on that system.

The digital modem is sampled at 20 MHz. The system has 64 sub-carriers per symbol, out of which 48 carry data, 4 are pilot signals and 12 are zero carriers. The cyclic prefix contains 16 samples. The SC systems equivalently contain 64 time samples per symbol, and also a cyclic prefix of 16 samples. To make a fair comparison, we apply a transmit power normalization.

We take a look at OFDM in the mode that provides the largest range as described in the standards [2, 3]: OFDM with BPSK modulation (hereafter labeled OFDM-BPSK). Since this mode also yields the smallest dynamic range, it will result in the most efficient front-end. We compare OFDM-BPSK to two binary SC-CP systems: SC-CP with BPSK modulation (SC-BPSK) and SC-CP with MSK modulation (SC-MSK).

The results are shown for a coding rate of 3/4 (which is the most demanding case in [2, 3]). The equalization is done with perfect channel knowledge. We obtained the presented results for a Gaussian channel, since all specifications for front-end implementation losses are standardized for Gaussian channels [2, 3]. We have also performed simulations for multi-path channels and obtained similar results. All distortions are considered at the transmit side only. This is justified since we are studying an up-link scenario: the transmitter is a terminal with a non-ideal front-end, while the receiver is a base station with more and more ideal resources available.

Our front-end model (fig. 1) contains most front-end distortion effects which are relevant in an OFDM-SC-CP WLAN setup.

- As in every digital modem, the word length and the clipping level at the output of the digital transmitter modem and the input of the receiver modem have a large impact on complexity of the DAC and the ADC (section 3).
- The large PAPR of an OFDM signal requires a highly linear power amplifier ; therefore the non-linearity of the power amplifier must be taken into account (section 4).
- Both OFDM and SC-CP use Frequency Domain Processing. Since phase noise diminishes the frequency accuracy, it has a negative impact on performance (section 5).
- Every complex constellation is influenced by the imbalance between I and Q branch (section 6).

The importance of these parameters in an OFDM context has been stressed in [7]. Since the model by [4] contains the same parameters, we used and extended it for our simulations.

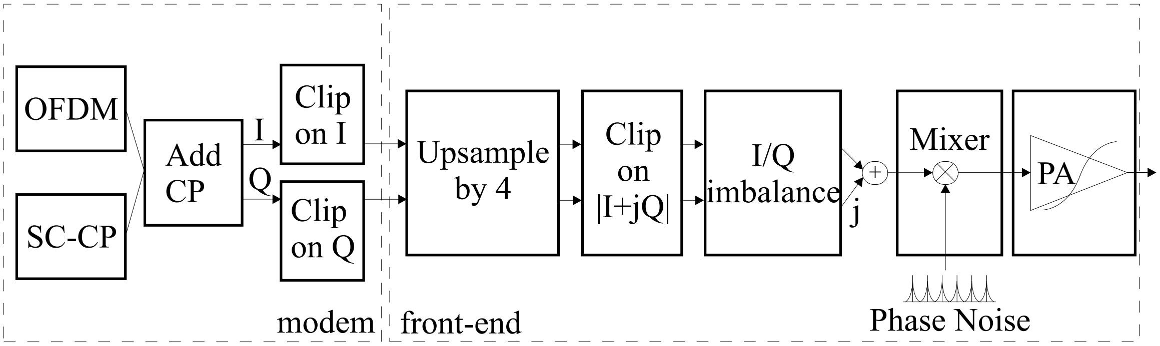

Figure 1: System setup containing the baseband and front-end models.

3. Quantization

3.1. Approach

The word length of the transmitted signal at the output of the digital modem has a major impact both on implementation cost and performance. As the word length decreases, the power consumption and complexity of digital-to-analog converter (DAC) decreases, but at the expense of quantization noise, hence the BER performance.

However, the word length can be limited with acceptable performance degradation. For a given word length, clipping enhances the average signal-to-quantization noise power ratio. On the other hand, it also introduces an additional noise source: clipping noise. Therefore, we have to solve a joint optimization problem on the word length and the normalized clipping level (ratio of the clipping level to the rms amplitude of the time-domain signal).

3.2. Simulation results

An OFDM transmitter needs at least a 6 bits DAC (with additional clipping at 4 times the variance of the transmitted signal) to keep the subsequent implementation loss at a BER of 10^{-5} below 0.2 dB for BPSK. A Single Carrier binary signal can be represented at digital baseband with 1 bit on each used branch (I for BSPK and I and Q for MSK) without any implementation loss and without the need for clipping. This reduction in dynamic range for SC-CP systems greatly simplifies the transmitter design.

4. Power Amplifier

4.1. Model

For non-constant envelope signals (as OFDM signals always are) we need a linear power amplifier. We assume a class A power amplifier with back-off. To keep the amplifier out of saturation, we also introduce additional clipping on the modulus of the signal (fig. 1). The back-off directly determines the power consumption of the power amplifier and also its linear dynamic range and the additional clipping level, therefore the distortion and thus the bit error rate.

The linearity of the power amplifier is quantified by the 1-dB-compression point, defined as the input power at which the non-linearity lowers the output power by 1 dB compared to the ideal amplifier (fig. 2).

The base band representation of a transfer function of a power amplifier with linear amplification G and a cubic non-

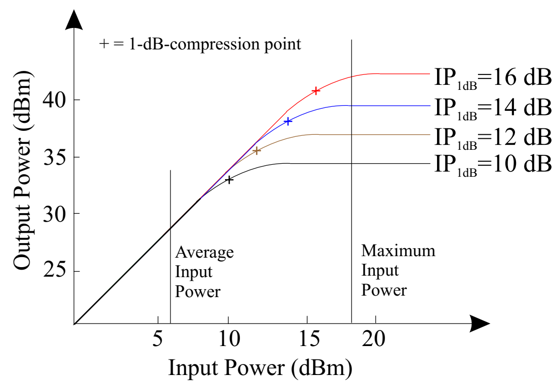

Figure 2: Transfer function of a class-A power amplifier.

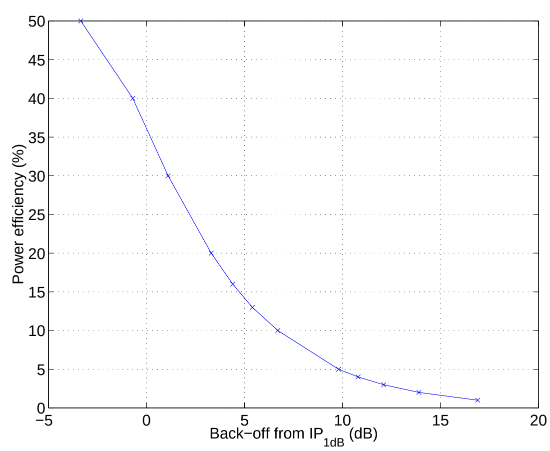

Figure 3: Power efficiency of a class-A power amplifier.

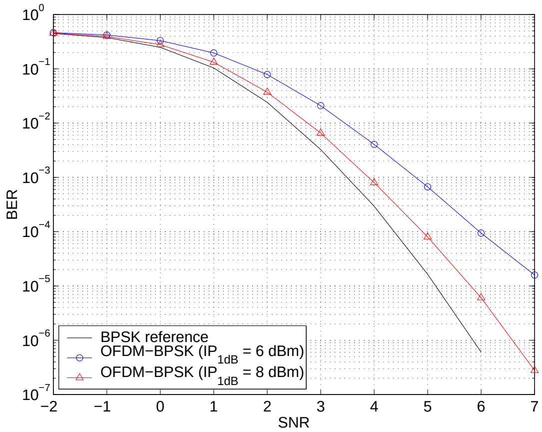

Figure 4: OFDM is very sensitive to the power amplifier back-off.

linearity is [4]:

$$y = xG(1 - \alpha\frac{3}{4}|x|^2) \tag{1}$$

The coefficient α can be expressed as a function of IP_{1dB} or x_{sat} as

$$\alpha = \frac{4}{3(1-10^{-1/20})IP_{1dB}^2} = \frac{1}{3x_{sat}^2} \tag{2}$$

where x_{sat} is the saturation limit.

4.2. Simulation results

If we want to limit the implementation loss in an OFDM transmitter due to power amplifier to 0.5 dB at a bit error rate of 10^{-5}, then the amplifier should operate at a 2 dB back-off between P_{in} (average input power, in our case 6 dBm) and IP_{1dB} (the 1-dB-compression point) (fig. 4). This back-off is necessary to accommodate the Peak-to-Average Power Ratio of the OFDM signal. For a class A amplifier (whose linearity is needed for OFDM) this back-off condition results in a power efficiency of 25% (fig. 3). For BPSK and certainly for MSK (for which the PAPR is always 1), we can use a more efficient amplifier, such as the one proposed in [8], which displays a practical efficiency of 74%. Clearly, SC-CP systems can provide a considerable saving in power consumption (up to 300% !), while preserving the data rate and bit error rate.

5. Phase Noise

5.1. Model

The ideal local oscillator (LO) produces only the required frequency, in other words, the spectrum has a Dirac impulse at the desired frequency. The output of a real oscillator is not only concentrated at the oscillator frequency, but also in a band around that frequency. This unwanted distortion is called phase noise. Often the power spectral density of such noise is modeled by a piecewise linear function, as shown in figure 5.

5.2. Simulation results

Our simulations show that the SC-CP systems have the same phase noise sensitivity as OFDM (fig. 6): we found a 2 dB de-

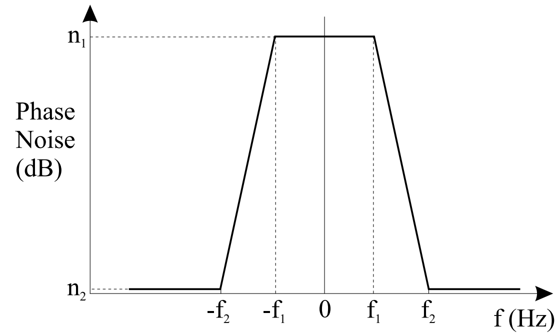

Figure 5: Power Spectral Density function of Phase Noise.

crease at a BER of 10^{-4} with the following phase noise parameters: $n_1 = -55\,dB$, $n_2 = -135\,dB$, $f_1 = 10\,kHz$, $f_2 = 1\,MHz$. Therefore all systems have the same VCO spec: an in-band integrated phase noise of -12 dBc.

OFDM and SC-CP do not always have the same phase noise sensitivity: the fundamental parameter is the number of sub-carriers N. For large N, the degradation of an OFDM system due to phase noise is proportional to the number of sub-carriers, while the phase noise degradation of SC-CP is independent of N. These statements were obtained analytically by [9]. For large N ($N = 512, 1024, 2048$) our simulations indeed show that the phase noise sensitivity of OFDM grows with N: so in that case, OFDM is a lot more sensitive to phase noise than SC-CP. On the other hand, in our system (for $N = 64$) the assumption of large N is not valid: OFDM and SC-CP have about the same phase noise sensitivity.

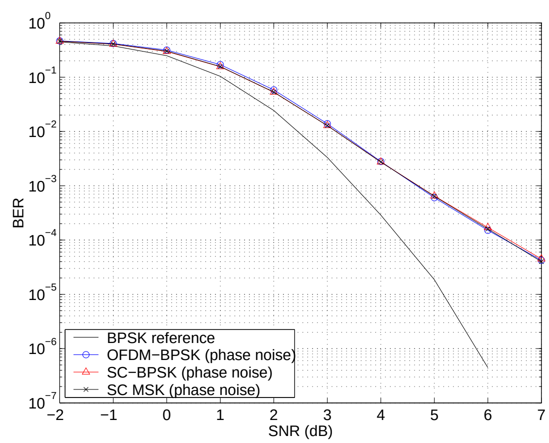

Figure 6: OFDM and SC have the same phase noise sensitivity.

6. I/Q imbalance

6.1. Model

The I/Q imbalance results from two effects: a gain mismatch between the I and Q paths (denoted by ϵ) and an imperfect quadrature generation ($\Delta\phi$). Their effect on the I and Q branch is illustrated in figure 7.

To simulate the I/Q imbalance on $x(t) = I + \jmath Q$ at baseband, we use at the output

$$y(t) = (1-\epsilon)e^{-\jmath\Delta\phi}I(t) + \jmath(1+\epsilon)e^{\jmath\Delta\phi}Q(t) \tag{3}$$

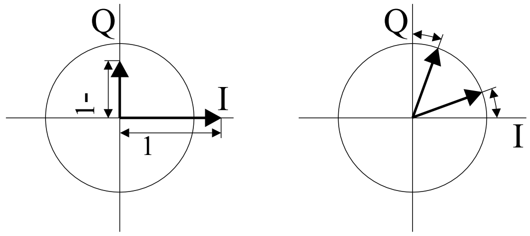

Figure 7: I/Q imbalance has 2 effects: gain mismatch and imperfect quadrature.

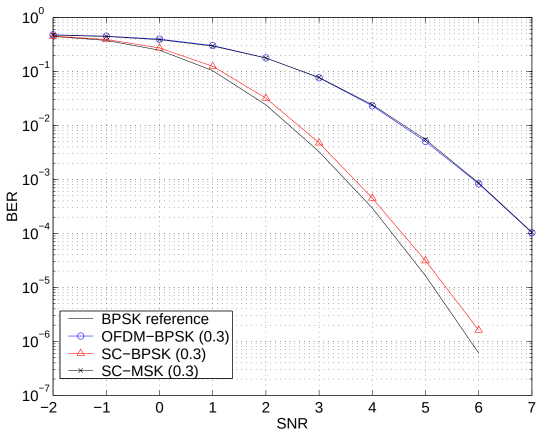

Figure 8: SC-BPSK is insensitive to I/Q gain mismatch ; OFDM-BPSK and SC-MSK are not.

6.2. Simulation results

We investigated the influence of both effects separately. As far as the difference in gain between the I and Q branch is concerned, we found that SC-MSK and OFDM-BPSK experience the same sensitivity: for a lengthening/shortening of 30% ($\epsilon = 0.3$) our simulations show a degradation of 2.6 dB even for a bit error rate of 10^{-4} (fig. 8). Both modulation techniques make use of both the I and Q branch. SC-BPSK on the other hand, uses only one branch in the transmitter and therefore is nearly insensitive to a mismatch, as is shown by the degradation of only 0.2 dB at 10^{-4} (and lower). Imperfect quadrature generation, expressed by $\Delta\phi$, has the same influence on all 3 modulation techniques: a little over 1 dB at a bit error rate of 10^{-5} when taking $\Delta\phi = 30^o$ (fig. 9).

7. Conclusions

We compared OFDM and SC-CP for WLAN modems. To that end we have set up a simulation environment to combine the effect of digital processing and front-end distortions. We have shown that OFDM and SC-CP display the same sensitivity to some parameters, such as phase noise and I/Q imbalance. However, SC-BPSK and even more so SC-MSK drastically increase the power efficiency of the modem and lower the dynamic range of the transmitted signals, while preserving the data rate and bit error rate. Therefore, SC-CP is a very good candidate for portable high data rate terminals.

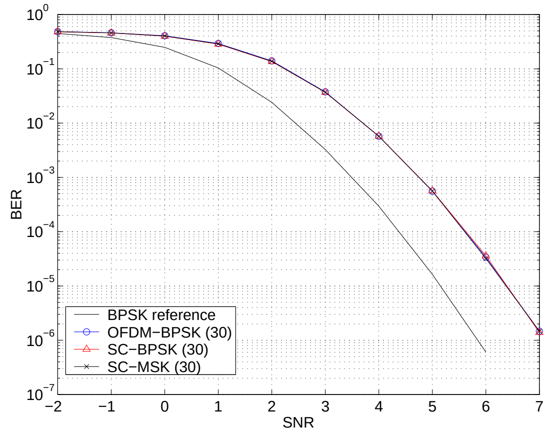

Figure 9: All 3 binary systems have the same sensitivity to imperfect quadrature generation.

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