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

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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, while OFDM provides a nice solution for the digital modem, its front-end requirements should be investigated as well. To that goal, we have set up a simulation environment which comprises both the digital modem and the most important front-end non-idealities. We show that for the same data rate, bandwidth and transmit power constraints Single-Carrier with Cyclic Prefix (SC-CP) allows the design of a more power efficient modem than OFDM and is therefore a better candidate for portable wireless terminals.

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

I. 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 transmitter front-end [4], because of the high Peak-to-Average Power Ratio (PAPR) of the OFDM signal. This inefficiency is especially a problem in the up-link where the transmitter is a battery driven terminal.

Single Carrier transmission with Cyclic Prefix [5], [6] is a closely related transmission scheme which possesses similar 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 non-idealities. This allows a system-level assessment of the performance of the complete transmitter-receiver link, it enables to make trade-offs between specifications 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, linearity of the power amplifier and a voltage-controlled oscillator (VCO) phase noise spec.

In the next section, we will describe in detail our system setup, explaining what is included in the digital modem and the front-end. The following sections, each treat one front-end non-ideality: we explain the model we used and the results we obtained through simulation. We only investigated the influence of the front-end non-idealities, in our setup we didn't compensate these effects.

II. 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 OFDM system uses 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-CP system equivalently contains 64 time samples per symbol, and also a cyclic prefix of 16 samples. To make a fair comparison, we normalized the transmit power in our simulations. The difference in transmit spectrum has only a small impact ($< 0.3\ dB$).

We take a look at OFDM in the mode that provides the highest data rate as described in the standards [2], [3]: OFDM with 64-QAM modulation (hereafter labeled OFDM-64QAM). We compare OFDM-64QAM to SC-CP with 64-QAM modulation (SC-64QAM).

The results are shown for a coding rate of 3/4 with hard decoding in the receiver. The equalization is done with perfect channel knowledge. We obtained the presented results for a Gaussian channel, since all specifications for the front-end implementation loss are standardized for Gaussian channels [2], [3]. We have also performed simulations for multi-path channels and obtained similar results.

Our front-end model (fig. 1) contains most front-end non-ideal effects which are relevant in an OFDM-SC-CP WLAN setup. All effects 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 close-to-ideal resources available.

- 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 III).
- 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 IV).
- Both OFDM and SC-CP use Frequency Domain Processing. Since phase noise diminishes the frequency accuracy, it could have a negative impact on performance (section V).
- Every complex constellation is influenced by the imbalance between the I and Q branches (section VI).

The importance of these parameters in an OFDM context has been stressed in [7]. Since the model by [4] contains the same parameters, we extended it for our simulations. More details on the simulation model can be found there. Note however that [4] uses soft decoding in the receiver, whereas we apply hard decoding.

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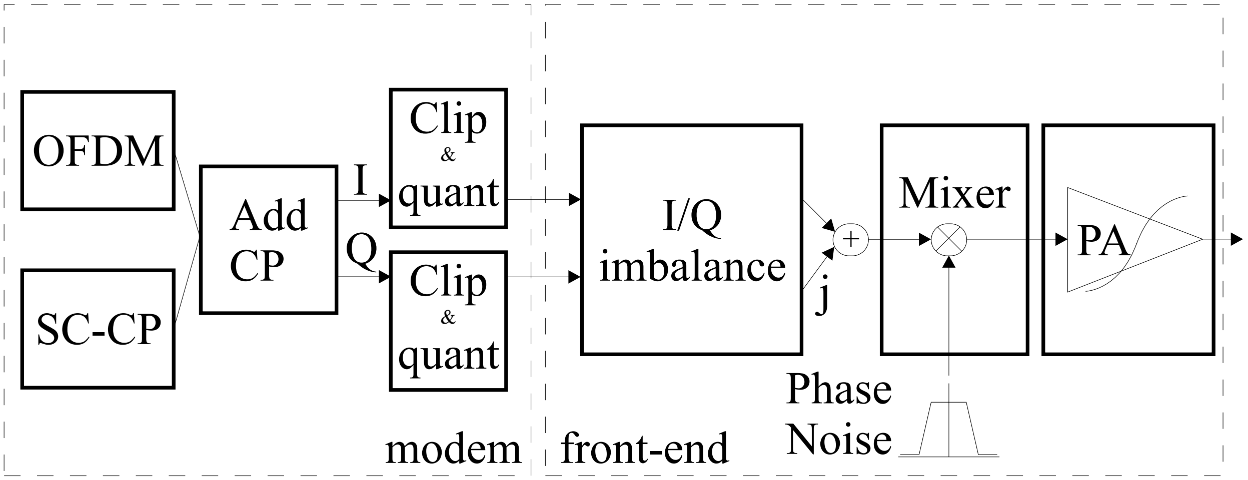

Fig. 1. System setup containing the baseband and front-end models.

III. QUANTIZATION

A. Approach

If a signal has a large dynamic range (a large PAPR), we need a lot of bits for quantization. We can lower the number of needed bits by decreasing the dynamic range of the signal. The signal will be clipped if it exceeds the clipping level. This clipping introduces additional noise (clipping noise), but this is limited as long as the occurrence of clipping is low enough [8].

Since an OFDM signal with 64-QAM has a PAPR of 17, while SC with 64-QAM has only 1.5, SC will need a smaller word length than OFDM. This word length has a major impact both on implementation cost and performance. As the word length decreases, the power consumption and complexity of digital blocks (such as the DAC and all digital filters) decreases, but at the expense of quantization noise, hence the BER performance. Also the power consumption of analog blocks will decrease significantly as the dynamic range of the signal is lower.

B. Simulation results

An OFDM-64QAM transmitter needs an 8 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 64-QAM. A Single Carrier 64-QAM signal can be represented at digital baseband with 3 bits on the I and Q branch without any implementation loss and without the need for clipping. This reduction in dynamic range for the SC-CP system greatly simplifies the transmitter design.

IV. POWER AMPLIFIER

A. 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. 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 (fig. 2).

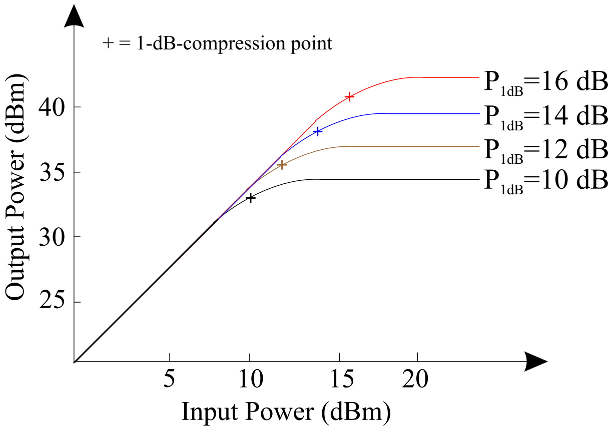

Fig. 2. Transfer function of a class-A power amplifier.

The base band representation of a transfer function of a power amplifier with linear amplification G and a cubic non-linearity is [4]:

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

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

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

B. Simulation results

If we want to limit the implementation loss in an OFDM transmitter due to the power amplifier to 1 dB at a bit error rate of 10^{-5}, then the amplifier should operate at a 7.4 dB back-off between P_{in} (average input power) and P_{1dB} (fig. 4). We have taken 0 dBm as P_{in} ; this implies that the back-off is equal to P_{1dB}. The back-off of 7.4 dB is necessary to accommodate the Peak-to-Average Power Ratio of the OFDM signal. For a class A amplifier this back-off condition results in a maximum power efficiency of 7.5% (fig. 3). The SC-CP transmitter shows the

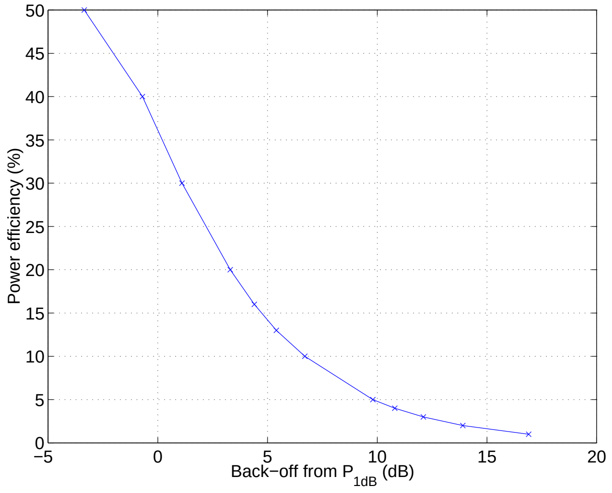

Fig. 3. Power efficiency of a class-A power amplifier.

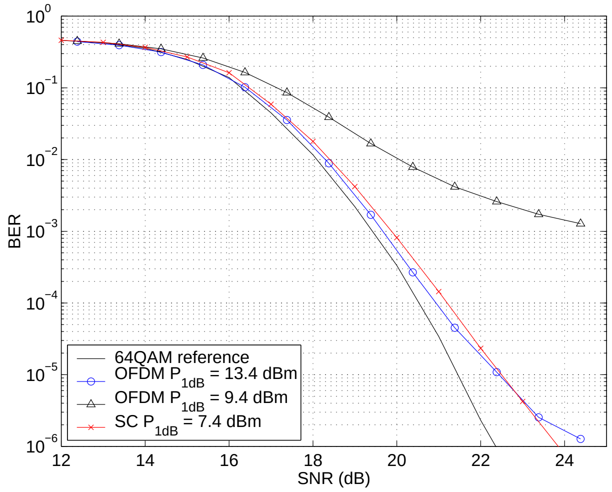

Fig. 4. OFDM is very sensitive to the power amplifier back-off, while SC-CP is not.

same implementation loss of 1 dB for a back-off of only 1.4 dB (fig. 4), because of the lower PAPR for SC-CP. This results in a maximum power efficiency of about 30% (the theoretical maximum for an ideal class A amplifier is 50%). Clearly, SC-CP systems can provide a considerable saving in power consumption (up to 400% !), while preserving the data rate and bit error rate.

V. PHASE NOISE

A. 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 non-ideality is called phase noise. We have used the same baseband phase noise model as in [9]: the power spectral density of the phase noise is modeled by a piecewise linear function, as shown in figure 5. The positive frequencies are given random phases. The spectrum values at the negative frequencies are the complex conjugate of the positive. This ensures that a real phase is generated and thus that no amplitude noise is generated. The same approach was followed by [10].

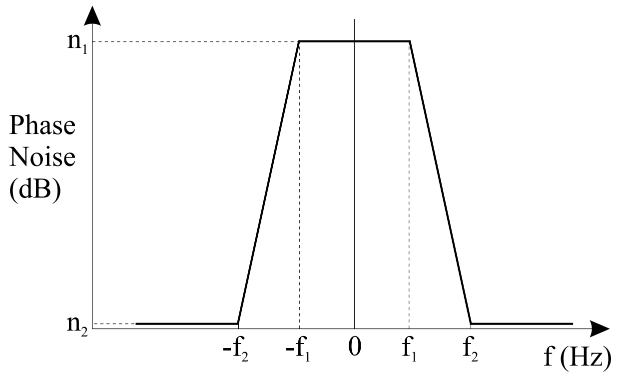

Fig. 5. Equivalent baseband model of the Power Spectral Density function of phase noise of a PLL-based frequency synthesizer.

B. Simulation results

Our simulations show that the considered SC-CP and OFDM systems have the same phase noise sensitivity (fig. 6): we found a 3 dB decrease at a BER of 10^{-4} with the following phase noise parameters: $n_1 = -74\,dB$, $n_2 = -135\,dB$, $f_1 = 10\,kHz$, $f_2 = 1\,MHz$. Therefore both systems have the same VCO spec: an in-band integrated phase noise of -31 dBc.

OFDM and SC-CP do not have the same phase noise sensitivity in all system setups: assuming a fixed signal and phase noise bandwidth, 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 [10]. For large N ($N = 512, 1024$) 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.

VI. I/Q IMBALANCE

A. Model

The I/Q imbalance can be modeled as a combination of 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 the following model

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

B. 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-64QAM and OFDM-64QAM experience the same sensitivity: for a lengthening/shortening of 5%

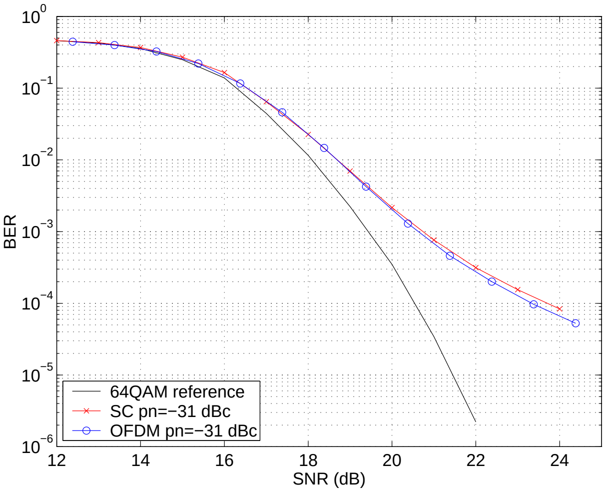

Fig. 6. The considered OFDM and SC-CP systems have the same phase noise sensitivity.

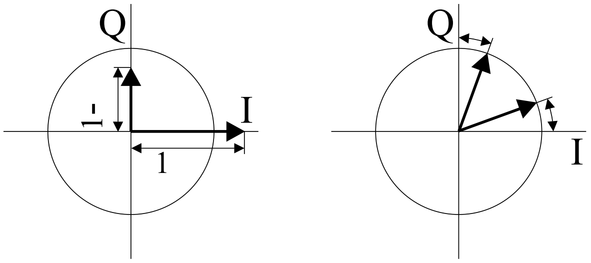

Fig. 7. I/Q imbalance has 2 effects: gain mismatch and imperfect quadrature.

($\epsilon = 0.05$) our simulations show a degradation of 2.4 dB for a bit error rate of 10^{-5} (fig. 8). Imperfect quadrature generation, expressed by $\Delta\phi$, has the same influence on both modulation techniques: a little over 2 dB at a bit error rate of 10^{-5} when taking $\Delta\phi = 3^o$ (fig. 9).

VII. CONCLUSIONS

We compared OFDM and SC-CP for WLAN modems. To that end we have set up a simulation environment to study the effect of front-end non-idealities on digital modem performance. 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-CP systems significantly 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.

In this paper, we only analyzed the influence of front-end non-idealities on the digital modem performance. It would be interesting to investigate to what extent these non-idealities can be compensated.

REFERENCES

[1] J. Bingham, “Multicarrier modulation for data transmission: An idea whose time has come,” *IEEE Communications Magazine*, pp. 5–14, May 1990.

[2] “HIPERLAN type 2 functional specification data link control (DLC) layer,” Tech. Rep., ETSI EP BRAN - DTS/BRAN030003-1 V0.j, October 1999.

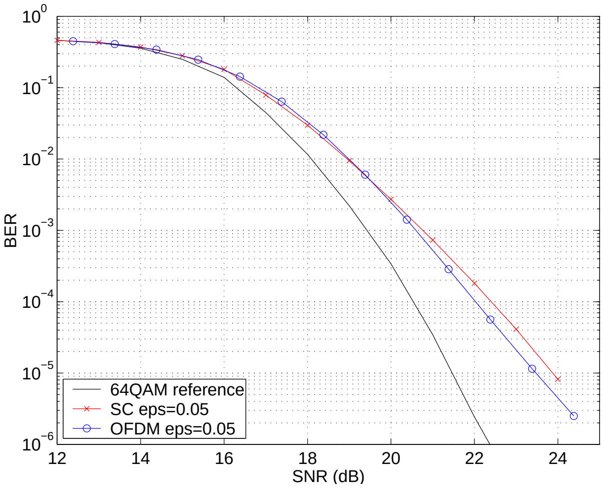

Fig. 8. OFDM and SC-CP have the same sensitivity to I/Q gain mismatch.

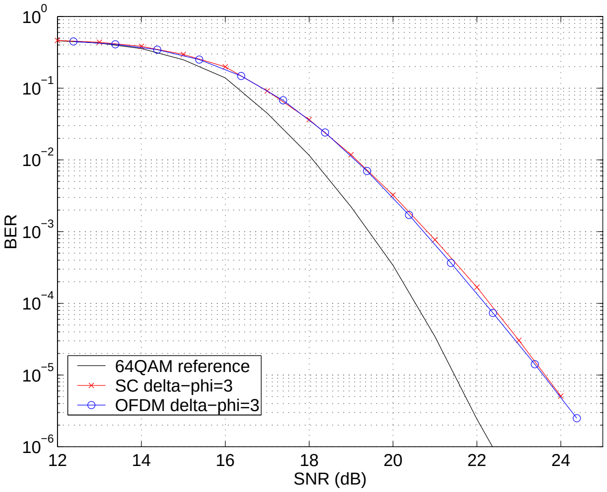

Fig. 9. OFDM and SC-CP have the same sensitivity to imperfect quadrature generation.

[3] “Draft supplement to standard for LAN/MAN part 11: MAC and PHY specifications: High speed physical layer in the 5GHz band,” Tech. Rep., IEEE P802.11a/D7.0, July 1999.

[4] B. Côme, R. Ness, S. Donnay, L. Van der Perre, W. Eberle, P. Wambacq, M. Engels, and I. Bolsens, “Impact of front-end non-idealities on bit error rate performance of WLAN-OFDM transceivers,” *Microwave Journal*, vol. 44, no. 2, pp. 126–140, February 2001.

[5] H. Sari, G. Karam, and I. Jeanclaude, “Frequency-domain equalization of mobile radio and terrestrial broadcast channels,” in *Globecom*, San Francisco, 1995, pp. 1–5.

[6] A. Czylwik, “Comparison between adaptive OFDM and single carrier modulation with frequency domain equalization,” in *VTC*, Phoenix, 1997, pp. 865–869.

[7] Keith Baldwin, Karen Halford, and Steve Halford (Intersil), “Secrets of OFDM engineering,” *Presentation on Workshop on OFDM in WLANS, London*, April 2001.

[8] D.J.G. Mestdagh, P. Spruyt, and B. Biran, “Analysis of clipping effect in DMT-based ADSL systems,” *IEEE International Conference on Communications (ICC’94)*, vol. 1, pp. 293–300, 1994.

[9] P. Robertson and S. Kaiser, “Analysis of the effects of phase-noise in orthogonal frequency division multiplex (OFDM) systems,” *IEEE International Conference on Communications,ICC’95*, vol. 3, pp. 1652–1657, 1995.

[10] T. Pollet, M. Van Bladel, and M. Moeneclaey, “BER sensitivity of OFDM systems to carrier frequency offset and wiener phase noise,” *IEEE Transactions on Communications*, vol. 43, no. 2/3/4, pp. 191–193, February/March/April 1995.