System Implications in Designing a 60 GHz WLAN RF Front-End

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Abstract

In this paper, we seek to evaluate the performance of a 60 GHz WLAN system taking into account RF circuitry imperfections and hardware requirements for various modulation techniques. A model of an RF front-end is developed, including physical imperfections of the circuitry such as power amplifier (PA) nonlinearity and voltage controlled oscillator VCO phase noise. Given the RF front-end model, several modulation techniques such as Orthogonal Frequency Division Multiplexing (OFDM) and Continuous Phase Modulation (CPM) are considered. The evaluation of the system performance in terms of bit error rate allows a better understanding of physical circuitry limitations, and optimal modulation parameters as well as circuit design recommendations can be derived.

Keywords

OFDM, CPM, 60 GHz, Power Amplifier, Phase noise.

1. Introduction

The need for high data rates communication systems has been dramatically increasing in recent years [1]. The 60 GHz band (59–64 GHz), an unlicensed frequency band, has been investigated as a potential band for wireless high data rate transmission. One of its main properties is the existence of strong attenuation due to the oxygen absorption and obstacles, resulting in a good frequency reuse factor, but also limiting the coverage of the cells in the cellular communication network.

Radio frequency (RF) hardware with ideal characteristics is difficult to design for the 60 GHz band. Problems such as power amplifier (PA) non-linearity and oscillator phase noise are more prominent for these circuits than for circuits designed for lower frequencies. Therefore, we should take these effects into account in the overall communication channel.

This report is a first effort in an ongoing work aiming at evaluating the performance of various communication techniques in presence of hardware imperfections. We study how the performance of a system is affected by the non-linearity of the amplifier, and the phase noise of the oscillators and phase-locked loops at the transmitter and receiver. Even for a noiseless channel, the degradation due to non-linearities and phase noise can become severe, leading to poor performance. We have chosen to study an orthogonal frequency division multiplex (OFDM) system, due to its good performance for multipath channels. We also study a CPM system, which is more resistant to the non-linearities of the power amplifier.

In section 2, we give a general background on non-idealities arising from the RF front-end of a wireless tranceiver as well as a brief insight on modulation methods employed in the baseband back-end. Section 3 describes the models of the RF hardware, including phase noise and power amplifier non-linearity. In section 4, some experiments are performed in order to characterize the effects of the hardware imperfections for an OFDM and a CPM system.

2. Background

2.1. System description

Figure 1 shows the block diagram of the communication system. In the baseband modulator block, input symbols are modulated (using CPM or OFDM modulation) and fed into the analog RF front end. The signal is up-converted to the desired frequency band, and then amplified to an adequate power level, to be transmitted through the channel. The receiver amplifies the input signal, and down-converts it to baseband, where it can be demodulated and further processed. Due to nonlinearities in the power amplifier and phase noise of the VCO, the demodulated bits may contain errors even on an noiseless channel.

2.2. Front-end imperfections

Power Amplifier (PA) linearity and Voltage Controlled Oscillator (VCO) stability are critically important in practical systems. If not considered, they may severely degrade the performance of a digital communication system. These imperfections, depicted in Figure 1 as solid line boxes, are studied in this paper.

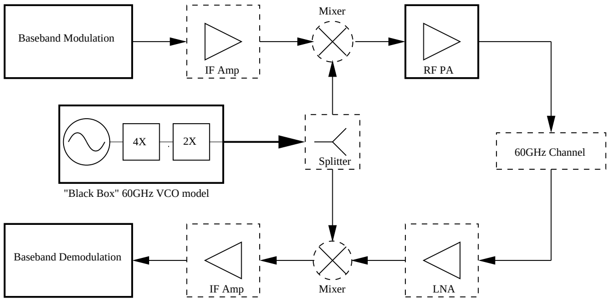

Figure 1: 60 GHz transceiver front-end. Solid lines boxes include non-ideal properties studied in this paper. The baseband modulation investigated are both QPSK/OFDM and CPM schemes.

2.2.1. *Amplifier nonlinearities*

Many transmission systems and particularly multicarrier systems show a notable sensitivity to the non-linear effects caused by the use of non-linear amplifiers. The non-linear distortions cause signal compression creating interference between subcarriers [2] called Inter-Carrier Interference (ICI). In order to maintain acceptable performance in presence of nonlinearities, large input back-off may be required resulting in low power efficiency. Therefore, a study of the system is required to find a reasonable trade-off between transmitted power and link performance of the system.

2.2.2. *VCO phase noise*

Another important matter when it comes to design a wireless transceiver is the quality of the VCO. The amount of phase noise present in the VCO is a measure of this quality, usually given as a ratio of power in one phase modulation sideband to the total power per unit bandwidth, or dBc/Hz at a certain offset from the carrier frequency. [1] One can see phase noise as a random change in the phase term of the oscillator.

The existence of this perturbation leads to a mismatched up/down-conversion of the signal. In multicarrier schemes like OFDM, phase noise is a particularly sensitive factor that causes subcarriers to interfere between each other and hence increases the error probability of the communication link. Another effect of phase noise is introducing some uncertainty in the modulated signal. Phase noise and more generally $1/f^{\alpha}$ noise generation for simulation has been extensively studied in [3] and [4]. Some results are reported regarding effects on OFDM systems in [5]. There are several ways of modeling the phase noise process such as an AR filter based model [3], or by shaping the frequency response of phase noise according to some practical measurements using Leeson's noise spectrum model described in [6]. More on this can be found in section 3.2.

2.3. Modulation methods

Among the existing modulation methods, we focused on OFDM and CPM. OFDM issues in broadband wireless systems have been widely discussed [1] and considerations for 60 GHz channel have been reported in [7]. CPM is seen as an attractive modulation technique due to its constant envelope that makes it less sensitive to non-linearities.

2.3.1. *OFDM*

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier transmission technique, which divides the available spectrum into a number of subchannels, each one being modulated by a low rate data stream. OFDM uses the spectrum efficiently by overlapping the subchannels in such a way that they are kept orthogonal [8]. OFDM transmission schemes are particularly interesting in the presence of time dispersion of the channel due to multiple paths arriving at different time. Another advantage is the possibility to adjust the data rate of each subcarrier according to their Signal-to-Noise ratio. On the other hand, OFDM presents several drawbacks of which two of them are analyzed in this paper. First, the OFDM signal is more sensitive to frequency mismatch and phase noise compared to single carrier schemes. Second, the high peak-to-average power ratio of an OFDM signal requires linear amplifiers, which tend to be costly and to reduce the power efficiency. Both effects deteriorate the orthogonality between subcarriers and introduce ICI.

2.3.2. *CPM*

In Continuous Phase Modulation (CPM) the information symbols are transmitted by changing the phase of a carrier signal. The transmitted phase function is continuous over time for all symbol sequences, which makes the envelope of the transmitted signal to be constant. Therefore, non-linear amplifiers are not a problem. In addition, the continuous phase function in CPM creates small spectral side lobes as compared to e.g. the discontinuous phase function in constant amplitude PSK. Each CPM symbol is transmitted by a phase function called the phase response function, having an amplitude depending on the CPM symbol, and the transmitted phase is a superposition of these phase functions. The total phase change for each symbol depends on a parameter called the modulation index, h. A common notation for CPM with a linear phase response function of length one is Continuous Phase Frequency Shift Keying (CPFSK). The continuous phase restriction and phase response functions longer than one CPM symbol introduces finite memory in the modulation. Hence, the Viterbi algorithm is an optimum

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[1] dBc denotes the decibels relative to the carrier power.

receiver for CPM on the AWGN channel. A standard reference of CPM is [9].

3. Modeling the front-end imperfections

In this section, we describe the models we have employed in order to simulate the front-end. We focus our attention on the power amplifier in the transmitter, and on the oscillators in the transmitter and the receiver. We have derived equivalent baseband models of the amplifier nonlinearities and the phase noise.

3.1. Baseband equivalent model of the non-linear amplifier

The non-linear characteristic of the amplifier can be found using single tone measurements. The nonlinearities are usually represented by a power series. The input output relationship of a nonlinear amplifier can thus be written as

$$y(t) = G(x(t)) = \sum_{n=1}^{N} a_n x^n(t) \tag{1}$$

where $x(t)$ is the modulated signal at the input of the amplifier,

$$x(t) = A(t)\cos(2\pi f_0 t + \theta(t)). \tag{2}$$

Both $\theta(t)$ and $A(t)$ are narrow band baseband signal.

Writing $x(t)$ in terms of its equivalent low-pass, and substituting in (1), it emerges that only odd terms in the series contribute in the output around the desired frequency band, and the equivalent input-output relation in the baseband can be written as

$$\tilde{y}(t) = \sum_{m=0}^{\frac{N-1}{2}} \frac{a_{2m+1}}{2^{2m}} \binom{2m+1}{m+1} |\tilde{x}(t)|^{2m+1} e^{j\theta(t)} \tag{3}$$

where $\tilde{x}(t)$ and $\tilde{y}(t)$ are equivalent baseband input and output of the nonlinear amplifier.

A similar procedure can be followed to find the effect of the intermodulation terms in the baseband [10] but this is not considered in this study. The input-output characteristic of the nonlinear amplifier is shown in figure 2. The model was derived by fitting a power series to the amplitude and phase curves of a 60 GHz power amplifier.

3.2. Baseband Representation of Phase Noise

Phase noise originates from several sources; one part stems from instabilities in the transmitter oscillator, another part from the receiver oscillator, but also Doppler effects and channel noise passing through the phase-locked loop contributes to the total phase noise. In this document, we generate the phase noise process $\phi(t)$ as a Gaussian distributed random process with a variance σ_n^2. Its spectrum is defined by an AR filter whose transfer function is given as

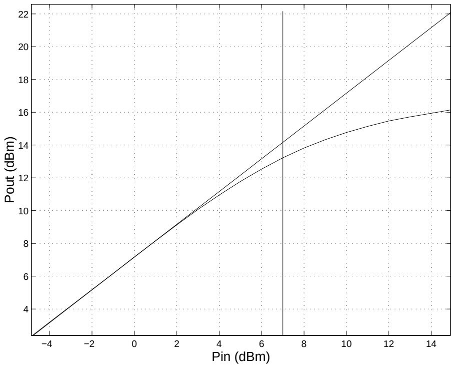

Figure 2: AM-AM effect in nonlinear amplifier

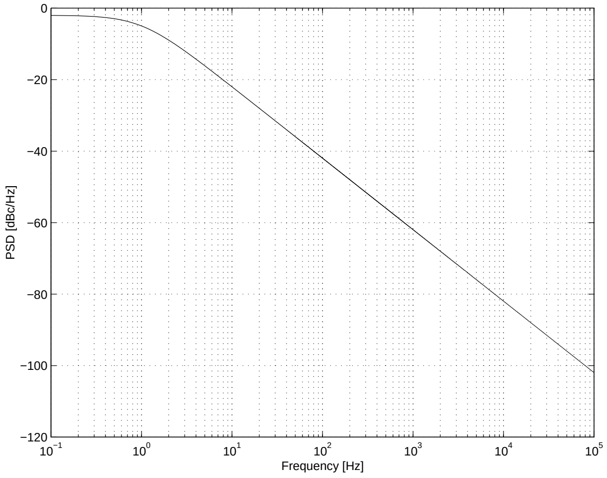

Figure 3: Phase noise power spectral density.

$$H(z) = \frac{A}{1 - \alpha z^{-1}} \tag{4}$$

where A and α are parameters used to control the cutoff frequency and the power of the phase noise. The spectrum of phase noise generated by this model is shown in figure (3).

We also define a phase SNR as

$$SNR = 10\log_{10}(\frac{\pi^2}{\sigma_n^2}), \tag{5}$$

where σ_n^2 is the phase noise power. Here it is important to notice that a VCO with phase noise will have a resulting bandwidth which is not only varying with the phase noise power but also with the phase noise process bandwidth that is dictated by the AR filter.

Ideally, a complex baseband signal $\tilde{x}(t) = A(t)e^{j\theta(t)}$ is upconverted by a phase noise-free VCO with center frequency f_0 and the output of the mixer is given by

$$x(t) = Re\{A(t)e^{2\pi f_0 t + \theta(t)}\} \quad (6)$$

However, due to physical imperfections present in the VCO, the phase of the carrier is not fixed but rather affected by a random phase noise process $\phi(t)$ so that $x(t)$ becomes

$$x(t) = Re\{A(t)e^{2\pi f_0 t + \theta(t) + \phi(t)}\} \quad (7)$$

The equivalent complex baseband modulation affected by phase noise is

$$\tilde{x}(t) = A(t)e^{j\theta(t) + \phi(t)} \quad (8)$$

This process can be used to simulate the total phase noise experienced by the modulation. We may look at $e^{j\phi(t)}$ as the combination of phase disturbances occuring in the transmitter and receiver oscillators as well as disturbances arising from the channel (e.g Doppler shift).

4. Experiments

4.1. Simulation setup

4.1.1. OFDM

The system in figure 1 is used as the setup for this simulation. An OFDM signal with 256 subcarriers, each modulated by 16QAM or DQPSK, is generated in the baseband modulator. During upconversion phase noise is introduced by the oscillator, and the power amplifier will further distort the signal.

4.1.2. CPM

A CPM system consisting of a transmitter and a Viterbi detector performing coherent detection, combined with a simple phase estimator, has been simulated with the phase noise process. The CPM system is: binary CPFSK with $h = 1/2$ (MSK) or 4-ary CPFSK with $h = 1/4$ and Gray mapping, which gives 2 bits per CPM symbol.

4.2. Results

4.2.1. OFDM

The effect of amplifier non-linearity on the OFDM signal can be seen by looking at the received signal constellation after the FFT block. As shown in figure 4, due to the randomness of the nonconstant amplitude signal in each subcarrier interval, a distribution of signal points is received, instead of a single point. Also because of the amplifier gain compression, the center of these clouds gets closer to the origin. Another effect is the rotation of the signal space due to AM-PM effect. The variance of the distribution is a function of the number of subcarriers and the center depends on the power of the transmitted signal. When the number of subcarriers is increased, a Gaussian distribution will be a valid approximation for the distribution of the received points in the signal space (figure 5). Therefore, the effect of the nonlinearity on the performance of the system can be completely described by the mean and the variance of the signal points.

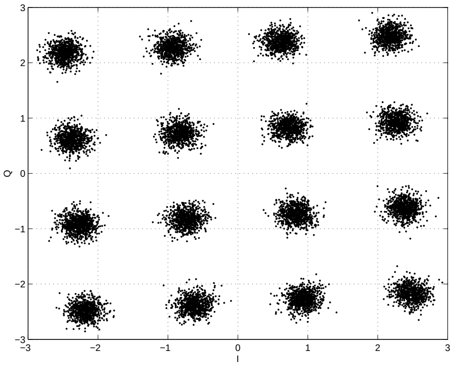

Figure 4: Received signal constellation for N=256 and IBO=3.27dB

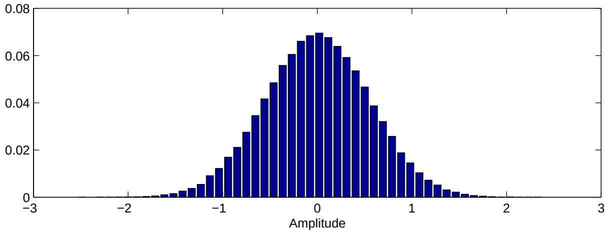

Figure 5: PDF of the amplitude of OFDM signal with 256 subcarriers

Using a Gaussian approximation, the bit error rate of an OFDM system with 256 subcarriers in the presence of a non-linearity has been computed. Note that because of the rotation of the signal space and the power compression, the received signal constellation is not symmetrical and the distance between adjacent points in the signal constellation are not the same. Therefore we can not use the standard methods of calculating bit error rate for 16 QAM. The conditional symbol error probability must be found first and then the total symbol error rate can be derived by averaging the conditional probabilities. Figure 6 shows simulation results for the bit error rate versus amplifier input back-off in a noise-free system. The BER versus SNR for a system including AWGN channel is shown in figure 8.

Figure 7 present BER results of an OFDM system using DQPSK, and of a standard DQPSK system, for different phase SNR as defined in equation 5. In this simulation, we inject a phase noise in the transmitted baseband signal. We assume that phase noise is introduced by the transmitter and receiver VCOs without contribution from the channel.

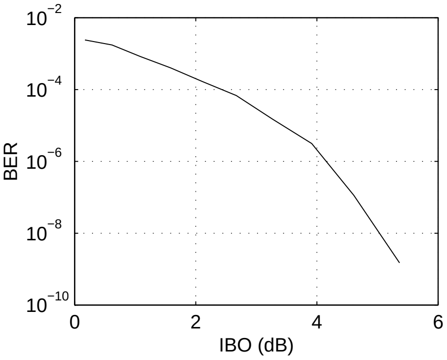

Figure 6: Bit error rate versus amplifier input backoff for a noise-free system

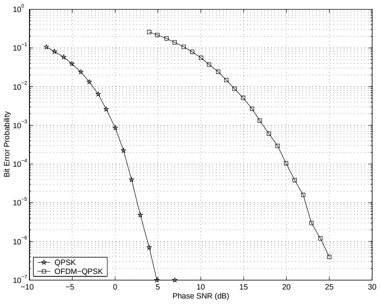

Figure 7: BER vs phase SNR for QPSK and QPSK/OFDM

4.2.2. *CPM*

In the CPM system simulations, the phase noise process has the same bandwidth as in the OFDM system simulations. Furthermore, the bandwidths of the CPM system and the OFDM system are the same. This means that when QPSK or DQPSK is used in the OFDM system and 4-ary CPM is used in the CPM system, the bit rates are the same.

In figure 9 the bit error rate for CPM caused by the phase noise is shown. It is clearly seen that the 4-ary CPFSK is more sensitive to the phase noise, which is no surprise since the phase trajectories are much more dense than in MSK. However, the bit rate is twice as high with the 4-ary CPFSK as compared to MSK.

5. Conclusions

We have performed system simulations of OFDM, CPM, and single-carrier QPSK, including RF circuitry imperfections. The results show that with the assumed models, the OFDM system is highly sensitive to amplifier nonlinearities and oscillator phase noise. The CPM system is immune towards amplifier nonlinearities, and less sensitive than OFDM towards phase noise.

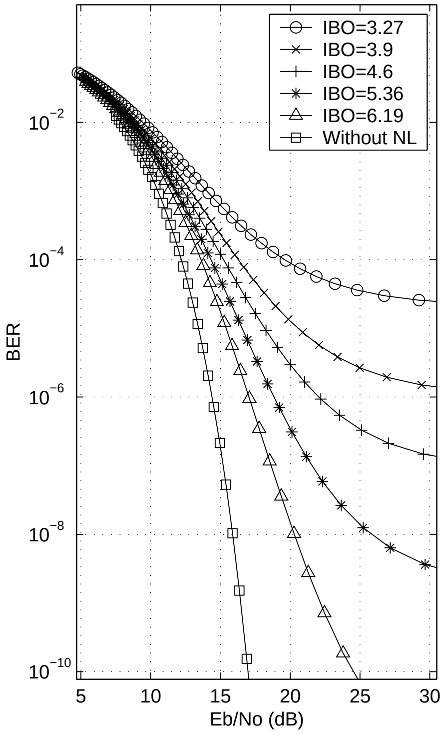

Figure 8: Bit error rate versus SNR for different IBOs

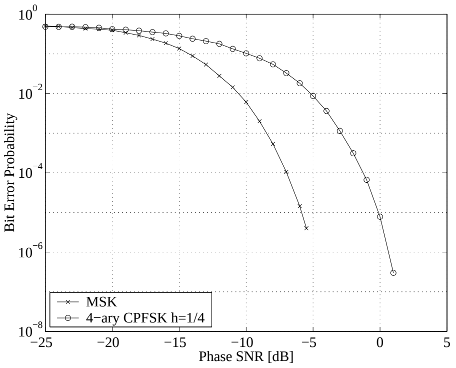

Figure 9: BER vs. phase SNR for MSK and 4-ary CPFSK $h = 1/4$.

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