Tijdschrift Ned. Elektron.- & Radiogenoot. (NERG),
Vol. 70, No. 4, pp. 112-123, Dec. 2005

Multiple Carriers in Wireless Communications – *Curse or Blessing*?

Tim C.W. Schenk, Peter F.M. Smulders and Erik R. Fledderus

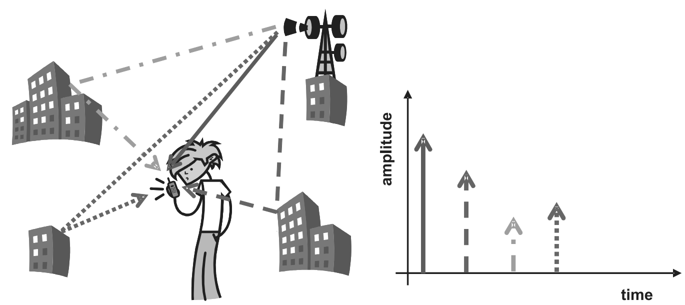
***Abstract*— The use of multi-carrier techniques is a natural choice when regarding wireless systems with high bandwidths and for which the application environment exhibits severe multipath propagation. These techniques provide a way to cope with and benefit from the time-dispersive channel. This, however, comes at the cost of a higher sensitivity to imperfections in the analogue radio frequency front-end. This paper illustrates the sensitivity of the most frequently used multi-carrier technique, i.e. orthogonal frequency division multiplexing (OFDM), to three of the main impairments: phase noise, IQ imbalance and nonlinearities. Furthermore, it is shown that the use of digital signal processing can largely compensate the effects of these non-idealities, overcoming the disadvantages of the use of multi-carrier techniques.**

***Index Terms*— Wideband communication, multipath propagation, physical layer, orthogonal frequency division multiplexing (OFDM), radio front-end impairments, digital compensation.**

I. Introduction

The application of digital modulation is well established to convey data between the transmitter (TX) and receiver (RX) of a wireless communication system. It enables the use of advanced signal processing and coding techniques to improve the transmission quality. Where the application area of these kinds of systems was traditionally in point-to-point links (e.g. in satellite communications and microwave radio links), it has moved over the last decades towards terrestrial wireless, mobile and indoor networks. In parallel, the ever increasing demand for higher speeds in these kinds of networks, has caused a move from narrowband towards wideband systems.

Wireless networks are currently deployed in urban areas and in indoor environments, like offices and homes. An example for the former are GPRS and UMTS and for the latter wireless LAN (Wi-Fi) and Bluetooth. In these environments the transmitted signal experiences multipath propagation before reaching the RX. This means that multiple copies of the transmitted signal arrive with different delays and attenuations at the RX, see Fig. 1. The effect is that the response of the wireless channel is frequency selective and that delayed versions of the transmitted symbols leak into neighbouring symbols, causing inter-symbol interference (ISI). The influence of the multipath on the system performance is generally low, when the largest channel delay is small compared to the symbol time of the system. Or when, similarly, the system bandwidth is small compared to the coherence bandwidth. For those cases the influence of the channel can generally be easily removed using an equalizer with a few taps or a rake receiver with several fingers.



(a) User scenario (b) Multipath Channel

Fig. 1. Wireless communication in a multipath environment.

As the bandwidth, however, increases and systems move towards more time-dispersive environments (e.g. offices), these solutions become highly complex. Hereto, the use of *multiple carriers* was proposed. In these techniques the whole system bandwidth is subdivided into several parallel narrow subbands. When this is implemented in the analogue domain it requires multiple carriers for frequency conversion and steep bandpass filters to separate the non-overlapping subchannels. Therefore, efficient implementations in the digital domain were proposed. The most applied version of these techniques is based on the digital Fourier transform (DFT) and named orthogonal frequency division multiplexing (OFDM), the basics of which will be treated in Section II.

Although OFDM exhibits a high spectral efficiency and the ability to use the multipath channel to its advantage, it has several disadvantages when compared with traditional single carrier systems. These disadvantages lie mainly in the constraints it puts on the quality of the analogue radio frequency (RF) front-end of both TX and RX. The influence of the most important imperfections on the system performance are treated in Section III-A, Section IV-A and Section V-A.

Since stringent specifications for the front-end of the regarded wireless system are required, the analogue part is the most expensive part of the system. Furthermore, Moore's law will influence the digital part in terms of size and price, but has little impact on the analogue part, i.e. the RF front-end; therefore, this part will dominate over time the performance and price of the radio system. Therefore, this paper also addresses

Tim Schenk is with the Radiocommunication Group, Department of Electrical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands (e-mail: T.C.W.Schenk@tue.nl).
Peter Smulders is with the Radiocommunication Group, Department of Electrical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands (e-mail: P.F.M.Smulders@tue.nl).
Erik Fledderus is with TNO Informatie- en Communicatietechnologie, P.O. Box 5050, 2600 GB Delft and with the Radiocommunication Group, Department of Electrical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands (e-mail: E.R.Fledderus@tue.nl).

digital signal processing based algorithms in the baseband part of the system, which are designed to suppress the influence of the analogue impairments. Examples hereof are presented in Section III-B, Section IV-B and Section V-B. A design incorporating these digital compensation techniques allows for higher impairment levels, and thus opens the door for cheaper and more optimized implementation of the RF front-end, e.g., the use of RF CMOS or homodyne transmitters/receivers. This of course at the cost of higher complexity in the digital part.

II. Orthogonal Frequency Division Multiplexing (OFDM)

For a comprehensive description of OFDM and its application in different wireless systems, the reader is referred to [1], [2] and [3]. Here we will treat the basic concept of OFDM and illustrate the application of the technique for three wireless systems.

A. OFDM basics

The concept of using the discrete Fourier transform (DFT) as part of the digital modulation/demodulation in TX and RX part of the wireless system to achieve parallel data transmission was proposed in the early seventies by Weinstein and Ebert in their seminal paper [4]. Due to the properties of the DFT the subchannels are shaped like $\sin(x)/x$. An example of the spectra of three OFDM subcarriers is shown in Fig. 2, which shows that the spectra are partly overlapping, significantly increasing the spectral efficiency as compared to conventional non-overlapping multi-carrier systems. It is clear, however, from Fig. 2 that the separation of the different carriers can not be carried out by bandpass filtering. Therefore, baseband processing is applied which exploits the *orthogonality* property of the subcarriers. This property is apparent from Fig. 2, where at the the maximum of one subcarrier all other carriers have a zero amplitude.

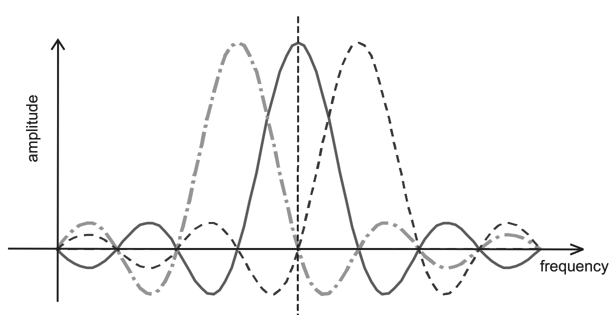


Fig. 2. Spectra of three subcarrier forming an OFDM signal.

The same OFDM signal is depicted in the time-domain in Fig. 3. From this figure it can be concluded that the symbol length contains $\{1, 2, 3\}$ periods of the signal on the different carriers, respectively. Here the number of periods depends on the position of the subcarrier within the OFDM spectrum. To increase the robustness of the OFDM system against ISI, caused by multipath propagation, the addition of a cyclic extension of the symbols was proposed in [4]. Hereto the symbol length is prolonged for N_g samples with a guard interval (GI), which basically prefixes a copy of the last N_g samples to the start of the OFDM symbol. If N_g is chosen sufficiently large compared to the channel length, the ISI is contained in the GI of the symbol. Since it is redundant information it can be disregarded at the RX, removing the influence of ISI.

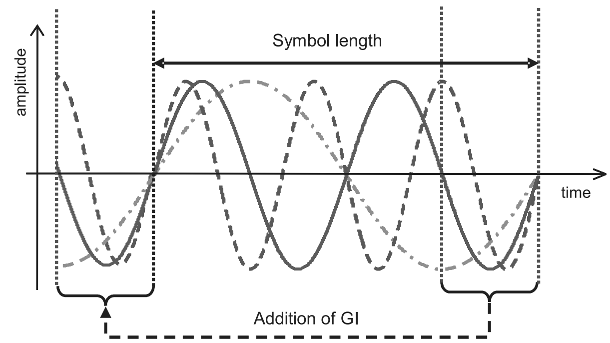


Fig. 3. OFDM signal in the time-domain, showing the addition of the guard interval (GI).

Since the addition of a GI decreases the effective datarate of the system, the ratio between the number of carriers N_c, which is equal to the symbol length in samples, and the GI length N_g is an important design parameter. It must be chosen in a tradeoff between ISI robustness and effective datarate.

The basic OFDM processing in both TX and RX is summarized in the block diagram of Fig. 4. First the baseband processing to the input bitstream is applied, e.g., interleaving, channel coding, puncturing and mapping to complex symbols, here modelled by the block $\mathbf{G}_\mathrm{TX}$. The complex signal is then, after being demultiplexed (DEMUX), fed to the inverse DFT, which converts the signal to the time domain. Many efficient implementations of the (I)DFT exist, which overcome the previously regarded insurmountable complexity of this operation. Subsequently, a GI is added to the signal. Then the signal is converted to the analogue domain and up converted to RF f_RF. Then the signal is transmitted through the wireless (multipath) channel.

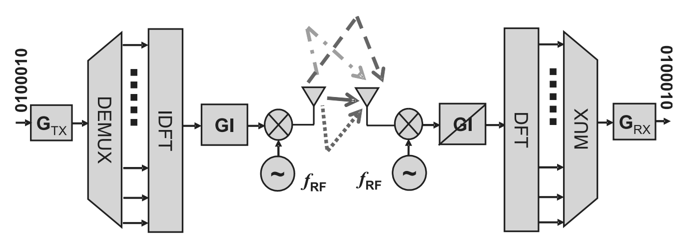


Fig. 4. OFDM system block diagram, showing a generic model for the transmitter and receiver.

The received signal is, subsequently, downconverted to baseband by the RF RX front-end. The output of the analogue-to-digital converter is then passed to the RX baseband processing. This processing removes the GI, which annuls the influence of the ISI. The DFT processing then separates the signals on the different carriers. The multiplexed (MUX) data stream is then processed in the RX processing, here depicted as block $\mathbf{G}_\mathrm{RX}$, where, e.g., channel equalization, decoding and deinterleaving are performed.

B. Turning multipath into an advantage

As mentioned above, the influence of the ISI caused by multipath propagation is removed at the receiver, when the GI is chosen long enough. The other effect of the multipath, the frequency selective fading, remains. Now, however, since the bandwidth is subdivided into parallel carriers, the subcarrier bandwidth is smaller than the channel coherence bandwidth. That is why the channel can be regarded as frequency flat for a certain carrier. This enables to use of a single tap equalizer per subcarrier to compensate for the channel influence.

If we assume the noise experienced in the system is white, the subcarriers having a lower channel transfer experience a lower signal-to-noise ratio (SNR). The detection of the transmitted symbols on such subcarriers yields a higher probability of error. This is schematically depicted in Fig. 5. Here the white carriers have a low probability of correct detection of the transmitted symbols.

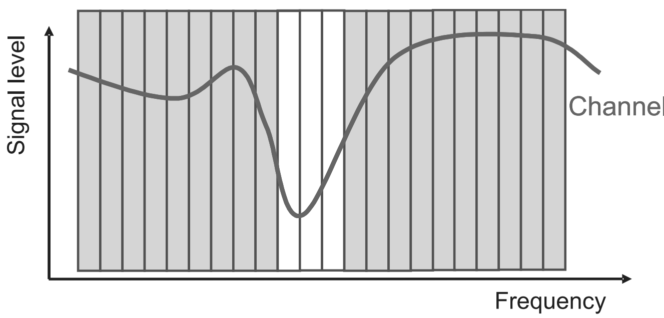


Fig. 5. Subcarriers of an OFDM system experiencing a frequency selective channel.

1) Channel coding: The performance of OFDM in frequency selective fading can be largely improved by the use of channel coding, yielding *coded OFDM* (COFDM). Here the bits are encoded in codewords, which are spread over the different subcarriers using an interleaver. Since the codewords are spread over the different carriers, the probability that a whole codeword is received on a channel with low transfer is lower and thus, the resulting probability of error detection is also lower. It can be shown that the performance of a COFDM system will improve with increasing frequency selectivity, up to channel lengths where ISI occurs. In this way the system benefits from the multipath channel.

2) Adaptive modulation: Another way to cope with the multipath is the use of *adaptive modulation*. In this approach an estimate of the channel is available at the TX side of the wireless link. This can be obtained by either using the reciprocity of the channel or by the use of a feedback channel. This channel estimate, as mentioned above, relates to the SNR experienced at the RX. In adaptive modulation, now, subchannels with high channel transfers, or equivalently high SNRs, are assigned symbols of higher order modulation and subchannels with low channel transfer are assigned symbols from a lower order modulation or even no symbols. This is based on the fact that high order multi-level modulations, e.g., M-QAM and M-PSK modulations with high M, achieve a high bit rate per subcarriers, but also require a high SNR for reliable detection. In conventional OFDM, in contrast, all subchannels carry symbols from the same modulation size. Here the subchannels with the lowest SNR determine the probability of error and thus the modulation format. In contrast, a system based on adaptive modulation can maximize the total throughput for a certain probability of error.

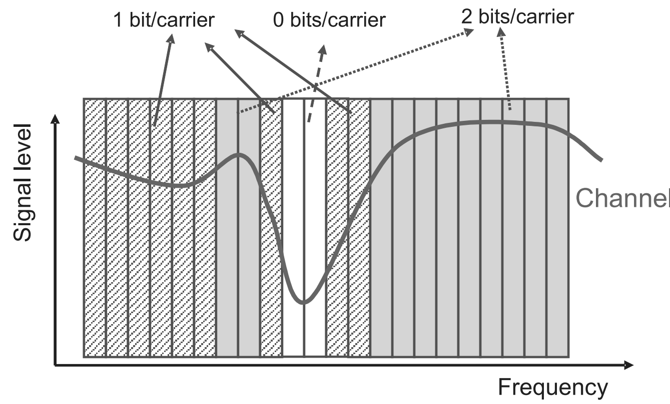


Fig. 6. Adaptive modulation.

The use of adaptive modulation is illustrated in Fig. 6. Here two subcarriers with a very low channel transfer are assigned no bits, nine subcarriers with moderate channel transfer carry 1 bit/subcarrier (e.g., by the use of BPSK modulation) and the eleven subcarriers with the highest channel transfer are assigned 2 bits/subcarrier (e.g., by the use of QPSK modulation). In the case of conventional OFDM all carrier would have been assigned 1 bit/subcarrier, clearly showing the gain of adaptive modulation.

3) Orthogonal frequency division multiple access: The multi-carrier technique OFDM can also be used as a multiple access technique: *Orthogonal frequency division multiple access* (OFDMA). In contrast to conventional OFDM, where all carriers are assigned to one user, in OFDMA the carriers are subdivided between the different users. The scenario of such a scheme is depicted in Fig. 7, where multiple users are receiving simultaneously.

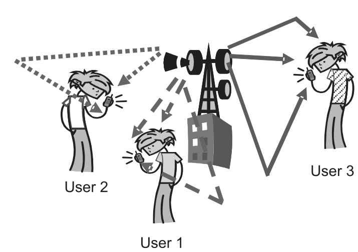


Fig. 7. User scenario for a system applying OFDMA.

Since all the users have their own location, the signals transmitted/received by the users experience different multipath channels. Therefore, also the frequency response of channels corresponding to the different users will differ. In OFDMA we can exploit this to our advantage by assigning those subcarriers to an user, where its channel transfer is high. Clearly this, as for adaptive modulation, requires some knowledge about the channel transfer.

The use of OFDMA is illustrated in Fig. 8, where the left block of carriers is assigned to user 1, the middle to user 2 and

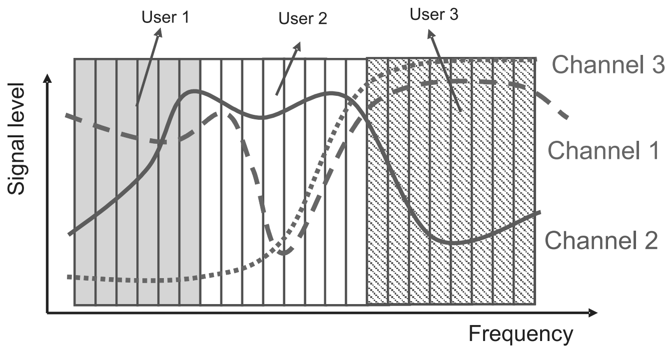


Fig. 8. OFDMA: a multiple access scheme based on OFDM.

the right block to user 3. It is noted that although also channel 1 has its maximum transfer in the right block of subcarriers, it is assigned to user 3, since channel 3 has a low transfer in the left block, where the transfer of channel 1 is still acceptable. Although the assignment is applied in blocks of carriers here, other patterns might be more optimal, especially when this multiple-access technique is combined with channel-coding. For instance individual carriers throughout the spectrum can be assigned to a user, resulting into an interleaved carrier pattern for the different users.

The advantage of OFDMA is that multiple users can be receive/transmit simultaneously, and that the channel transfer is optimized for the combination of users.

C. Wireless Systems using OFDM

The application of OFDM is currently standardized for use in many different kinds of wireless systems, including wireless personal-area-network (PAN), local-area-network (LAN) and metropolitan-area-network (MAN), digital audio broadcasting and digital video broadcasting. To illustrate the application of OFDM in these kinds of systems, the system parameters of Wireless LAN, Ultra Wideband and Wireless MAN are treated here.

1) Wireless LAN: The application of OFDM for wireless local-area-networks (WLANs) was first standardised in 1999 as IEEE 802.11a [5], often referred to as Wi-Fi, where it was applied to the 5 GHz frequency band. A similar system was standardized within ETSI under the name of HiperLAN/2. Both systems specify a system with 20 MHz bandwidth, 64 subcarriers and a GI-length of 16 samples (800 ns). A subset of 48 carriers is used for data transmission, 4 are used for synchronization purposes and the remaining carriers (at the sides of the band) are used as guard bands to minimize the out-of-band radiation. The system applies BPSK, QPSK, 16-QAM and 64-QAM modulation, convolutional coding with rates varying from 1/2 to 3/4, creating data rates ranging from 6 Mbps up to 54 Mbps.

To enable higher speeds in the 2.4 GHz ISM band, where up to then the IEEE 802.11b standard was deployed, the design of the IEEE 802.11a OFDM physical layer (PHY) was ported to the 2.4 GHz band in 2003. This was standardized in the IEEE 802.11g standard [6], which combines the OFDM PHY with the IEEE 802.11b PHY.

2) Ultra Wideband: Recently, the application of OFDM has been proposed for ultra wideband (UWB) communications [7] under the IEEE 802.15.3a PAN framework. This proposal applies a signal bandwidth of 528 MHz, which is divided into 128 subcarriers of which 100 are used for data transmission. The system is based on what is called multiband OFDM, where consecutive symbols are transmitted in different frequency bands. Initial deployment is foreseen in the 3.1-4.9 GHz band, but extensions towards bands up to 10 GHz are envisioned for the future. The proposal is based on QPSK modulation and a variable coding rate resulting into a data rate varying from 53.3 Mbps up to 480 Mbps. Since the allowed transmit powers for these types of systems are low, the application is foreseen in systems combining low cell radii and high data rates.

In parallel to the standardisation by the IEEE, a similar proposal was accepted in May 2005 as the wireless USB [8] specification. Different vendors are now starting to deliver products based on this specification.

3) Wireless MAN: The use of OFDM has also been standardized for application in outdoor networks, for example under the IEEE 802.16 framework. This standardisation effort is focussed on wireless metropolitan-area-networks (WMANs). The initial application was for point-to-point links, with a main focus on providing a cost effective alternative for the wired local-loop. These systems [9] are often collective referred to as WiMax and can operate in the 2-11 GHz band, providing speeds up to 75 Mb/s. The bandwidth is flexible, varying from 1.5 - 20 MHz. The system provides an OFDM and OFDMA-mode with 256 and 2048 subcarriers, respectively.

Recently, an extension to this standard was proposed which extends the application of these systems to mobile networks. This extension of focussed on frequency bands below 6 GHz and applies a scalable OFDMA design. Again the bandwidth is flexible, but at a bandwidth of 5 MHz a maximum datarate of 15 Mbit/s can be achieved. This design is being standardized as IEEE 802.16e and a version is currently being deployed in Korea as Wireless Broadband (WiBro).

III. Phase Noise

As mentioned in the introduction of this paper, OFDM-based systems are very vulnerable to radio front-end induced impairments. The imperfections of the radio frequency (RF) oscillator are treated here, since these have been identified as the major performance limiting factors of OFDM systems. First Section III-A treats the influence of imperfect oscillators on the OFDM signals and then several digital compensation techniques for this influence are reviewed in Section III-B.

A. Influence of Phase Noise

Ideally an RF oscillator would exhibit a power-spectral-density (PSD), which resembles a delta-function at frequency f_{RF}. Any practical oscillator, however, experiences disturbances due to thermal noise, making the PSD differ from the ideal. Since in general the disturbance of the amplitude of the oscillator output is marginal [10], [11], most influence of the oscillator imperfection is noticeable in random deviation of the frequency of the oscillator output. These frequency deviations are often modelled as a random excess phase, and therefore referred to as *phase noise*. Phase noise (PN) will more and more appear to be a factor limiting the performance of OFDM systems, when low-cost implementations or systems with high carrier frequencies are regarded [12], since it is in those cases more challenging to produce an oscillator with sufficient stability.

The RF oscillator process used for down-conversion of the received signal can be modelled as

$$a(t) = e^{-j\{2\pi f_{\mathrm{RF}}t - \theta(t)\}} \quad , \tag{1}$$

where j denotes the imaginary unit, t is the time variable and $\theta(t)$ denotes the PN process. When (1) models a free-running oscillator it can be shown that the corresponding PSD is given by the Lorentzian function [11], as depicted schematically in Fig. 9. The PN process is then fully determined by the 3 dB bandwidth $\Delta f_{3\mathrm{dB}}$ of the PSD.

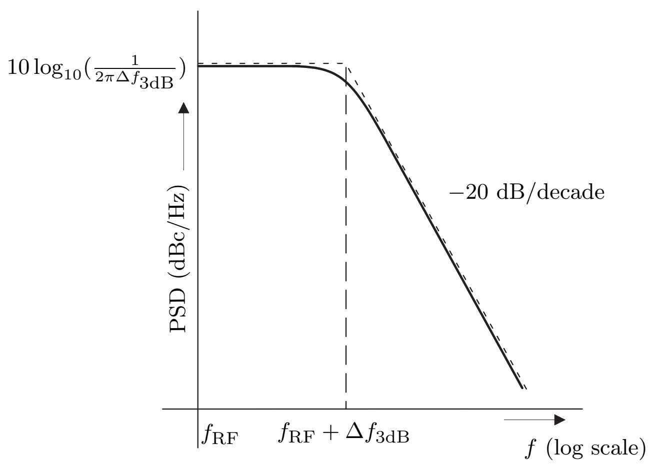


Fig. 9. Single side band representation of the PSD of the oscillator process centred around f_{RF}.

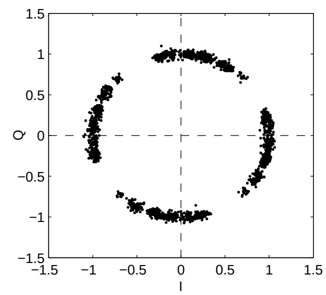
If we, subsequently, regard the influence of PN on the reception of the OFDM symbols, we find that the time domain signal in the baseband receiver is multiplied with the phase noise process $e^{j\theta(t)}$. In the frequency domain this can be seen as a convolution of the OFDM subcarriers, as depicted in Fig. 2, with the PSD of the oscillator process, as depicted in Fig. 9. Clearly this degrades the orthogonality between the subcarriers.

The received signal, behind the DFT-processing in the RX, on the kth carrier of the mth symbol is then given by

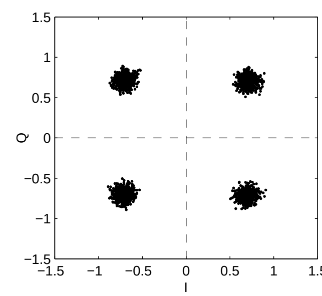
$$x_m(k) = e^{j\alpha_m} H_m(k) s_m(k) + \xi_m(k) \quad , \tag{2}$$

where $s_m(k)$ and $H_m(k)$ denote the transmitted symbol and channel response on the kth carrier of the mth symbol, respectively. The effects of the PN are modelled in a phase rotation common to all carriers, i.e., α_m and the parameter modelling the leakage into carrier kth, i.e. $\xi_m(k)$. The latter is often referred to as inter-carrier-interference (ICI) and consists of a weighted sum of the received symbols on all other subcarriers. The phase rotation $e^{j\alpha_m}$ is given by the average value of $e^{j\theta(t)}$ during the mth symbol.

This influence of PN on the received signal in an OFDM system applying QPSK modulation is illustrated in Fig. 10. These results are for a system transmitting several packets and not experiencing a channel, i.e., $H_m(k) = 1$ for all k and m. In Fig. 10(a) a typical result is shown for a system having an oscillator characterised by a corner frequency $\Delta f_{3\mathrm{dB}}$ which is low compared to the spacing of the subcarriers. It can be concluded that the dominant effect of PN is the rotation. When $\Delta f_{3\mathrm{dB}}$ is increased, whereas the total noise power remains unchanged, for the situation in Fig. 10(b), the rotational behaviour is less pronounced, but a higher additive behaviour is visible.



(a) Low $\Delta f_{3\mathrm{dB}}$



(b) High $\Delta f_{3\mathrm{dB}}$

Fig. 10. Influence of PN on the reception of QPSK symbols.

It can be concluded from Fig. 10 that the lower and higher frequencies in the PN PSD result in rotational and additive behaviour, respectively. For more indepth information on this behaviour and the influence of PN on the system performance in general, the reader is referred to [13–15].

B. Suppression of Phase Noise

Designing an oscillator with high enough stability to overcome the effects presented in Section III-A is very challenging, especially when low-cost solutions are regarded. In contrast, here we regard the compensation of these effects by the use of signal processing in the digital baseband part of the RX.

Different approaches have been proposed in the literature to remove this rotational part. The techniques can basically be divided into two groups, where the first one uses a data-aided approach and the second one uses detected data-symbols to estimate α_m. For an example of the former the reader is referred to [14]. Basically these techniques exploit that known symbols $s_m(k)$, i.e., pilot symbols, are transmitted on certain subcarriers. Since the rotation is common to all carriers, the location of these pilot carriers is not important, but they are generally equally spaced over the whole system bandwidth, to avoid that all pilots would fall in a channel fade. The second group of techniques first compensates the received signal for the estimated channel response and α_{m-1}, which was estimated in the previous symbol. Now, the average rotation of this corrected symbol gives an estimate of $\Delta\alpha_m$, which provides the estimate of $\alpha_m = \alpha_{m-1} + \Delta\alpha_m$.

Next to the compensation of the rotational part, also suppression of the PN-caused ICI component $\xi_m(k)$ is possible. Recently, some approaches have been proposed for this ICI compensation [16], [17]. These techniques use that the ICI at a certain carrier is dominated by the neighbouring carriers. Some gain in performance is achieved here, but the overall effect is limited at low SNRs and in fading channels.

IV. IQ IMBALANCE

In this section we discuss the influence of a mismatch between the I and Q branch, known as IQ imbalance. This mismatch occurs due to limited accuracy in the implementation of the RF front-end and results into a limited image rejection. Although IQ imbalance can occur in any quadrature receiver, we here focus on a homodyne receiver [18], as illustrated in Fig. 11. The advantage of these direct conversion type of RXs is that no costly surface acoustic wave (SAW) filter is necessary, only two low-pass filters (LPFs), which can more easily be integrated.

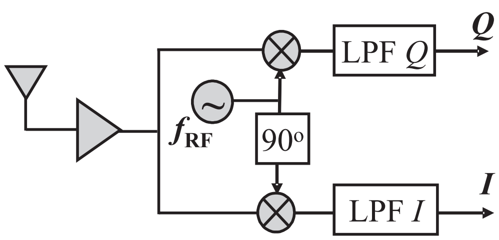
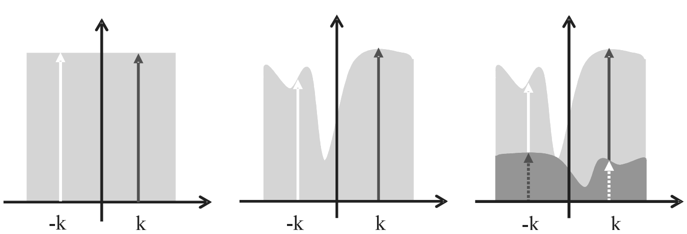


Fig. 11. Schematic representation of a direct conversion based RX.

First we will regard the influence of IQ imbalance in Section IV-A and then review several digital compensation approaches in Section IV-B.

A. Influence of IQ imbalance

The IQ imbalance in the structure of Fig. 11 has several sources, but regarding the influence we can distinguish between two types of IQ imbalance: frequency independent and frequency selective IQ imbalance. An example of the first group is the mismatch which occurs when the phase shift between the signal used for up/down-conversion of the I and Q signal is not exactly 90 degrees. The frequency selective IQ imbalance for instance occurs due to a mismatch between the low-pass filters (LPFs) in the I and Q branches, see Fig. 11. In a practical RX the frequency independent behaviour will be dominant. Hereto, we will focus on this behaviour here.



(a) TX baseband (b) RX RF (c) RX baseband

Fig. 12. The influence of the IQ imbalance on the reception of an OFDM signal.

The influence of IQ imbalance is shown schematically in Fig. 12. The transmitted baseband signal is shown in Fig. 12(a), where two carriers ($-k$ and k) are highlighted. These carriers have the same separation from DC. The signal is up converted to RF and transmitted to the frequency selective channel, where the received RF signal is depicted in Fig. 12(b). It is clear that carrier $-k$ is more attenuated by the channel than carrier k. Subsequently, the RX signal is down converted to baseband using the homodyne structure of Fig. 11. Since this structure exhibits IQ mismatch, the mirror is not fully rejected, and mixes down into the regarded baseband channel. This is illustrated in Fig. 12(c), which shows that carrier k experiences a contribution of the signal received on the mirror carrier $-k$ and vice versa.

The effect on the received baseband signal can be expressed as

$$x_m(k) = K_1 H_m(k) s_m(k) + K_2 H_m^*(-k) s_m^*(-k) \quad , \qquad (3)$$

where * denotes complex conjugation and K_1 and K_2 model the imbalance. The effect of mirror leakage as shown in Fig. 12(c) is also apparent from (3). In general K_1 is larger than K_2 and in a system with ideal matching $K_1 = 1$ and $K_2 = 0$.

To clearly show the effect of the IQ imbalance on the reception of an OFDM signal, a noiseless system applying 16-QAM modulation is regarded. The system does not experience a wireless channel, but has a 10% amplitude and 5° phase imbalance between the I and Q branches of the RX. The received signal is depicted in Fig. 13, which shows that the transmitted 16-QAM points are distorted by an additive rotated 16-QAM constellation of lower amplitude. This is due to the leakage of the mirror carrier $-k$, where the rotation and reduced amplitude are due to the imbalance parameter K_2. Furthermore, one may observe a minor rotation and decrease in amplitude due to the multiplication of the desired signal (on carrier k) with imbalance parameter K_1.

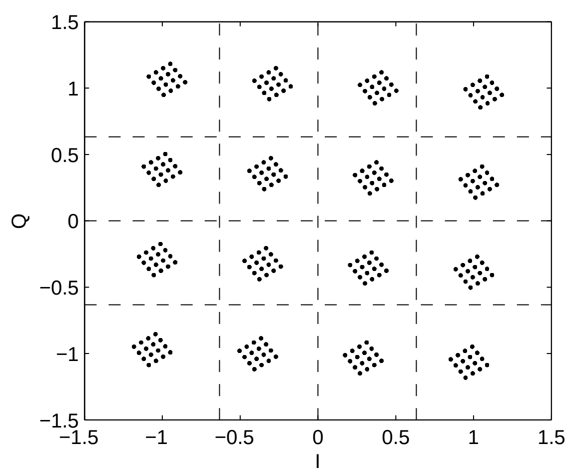


Fig. 13. Influence of IQ imbalance on the reception of 16-QAM symbols in a noiseless channel-less scenario.

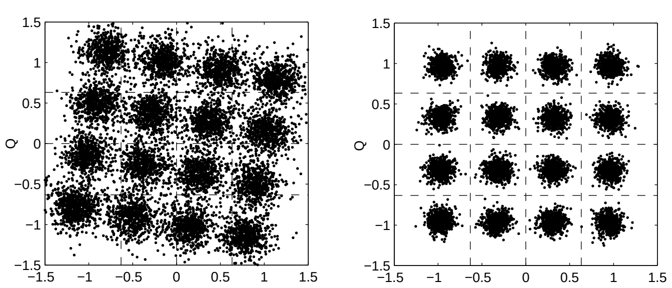
B. Suppression of IQ imbalance

The occurrence of IQ imbalance can be circumvented by increasing the accuracy of the implemented mixing structure, which would result into a more expensive solution. The use of compensation techniques for this RF impairment is, however, promising, since the IQ imbalance variation with time is negligible and the influence of IQ imbalance has a very specific structure, as was shown in Section IV-A.

Several compensation approaches have been proposed for the compensation of IQ imbalance, mainly focussing on imbalances in the RX. Again data-aided and blind techniques can be distinguished. An effective data-aided technique was proposed by the authors of [19], which is applicable for systems applying a block of pilot carrier preceding the data carriers. It applies the fact that the estimate of the wireless channel will not be smooth, when IQ imbalance occurs in the down conversion. A blind method was proposed by the authors of [20], where the imbalance parameters are estimated by using the statistical independence of the datasymbols transmitted on carrier k and $-k$. Both methods can be applied to significantly suppress the RX based IQ imbalance.

When the system, however, experiences both TX and RX IQ imbalance, these techniques will not suffice. Therefore, the authors recently proposed a data-aided approach for joint estimation of TX and RX induced IQ imbalance [21]. This method effectively compensates for the joint TX and RX IQ imbalance in the digital baseband part of the RX.

An example of results achieved with the blind compensation method for RX IQ imbalance [20] is shown in Fig. 14. Here a scenario with severe RX imbalance and experiencing additive RX noise is regarded. It is clear from Fig. 14(a) that detection of the receiver 16-QAM points before digital compensation would result in many errors. The results after the compensation are shown in Fig. 14(b). It can be concluded that the rotation and attenuation of the signal (by K_1) has been successfully removed. Furthermore, the scatter plot of the constellation points are much smaller after compensation, showing that also the mirror leakage is removed. The remaining impairment is due to the additive RX noise.



(a) received baseband signal (b) received signal after compensation

Fig. 14. Effects of IQ imbalance compensation.

V. Nonlinearities

One of the major drawbacks of an OFDM system over a single-carrier system, is that the time-domain OFDM signal exhibits a large peak-to-average-power ratio (PAPR), which, as will be shown in Section V-A, requires a highly linear system. The PAPR is dependent on the order of the applied modulation scheme and the number of subcarriers. If the number of subcarriers N_c or the M-QAM modulation order increases the PAPR becomes higher. Figure 15 illustrates the PAPR dependence on N_c for a system applying 64-QAM modulation. It, hereto, shows the inverse cumulative distribution function for the PAPR of the OFDM-symbols for different number of subcarriers, which indicates the chance that the PAPR is larger than the value on the x-axis.

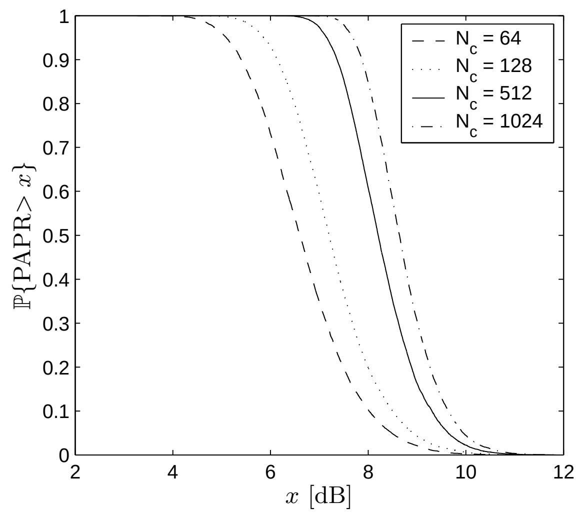


Fig. 15. PAPR of 64-QAM OFDM symbols for different number of subcarriers N_c.

It can be concluded from the figure that for 1024 subcarriers 50% of the symbols possesses a PAPR which is higher than 9 dB. This would not be a disadvantage in a fully linear wireless system. Any practical system, however, has nonlinear parts like for instance the power amplifier (PA) in the TX and low-noise amplifier (LNA) in the RX. The influence of these nonlinearities on the signal is discussed in Section V-A and suppression approaches are reviewed in Section V-B.

A. Influence of Non-linearities

For illustration purposes Fig. 16 schematically depicts the transfer of a nonlinear PA. It shows that the PA delivers linear amplification for input powers up to a certain level. Beyond this level the amplification decreases compared to the linear curve. When the input power is even higher clipping occurs, i.e., the output power is limited to the maximal output power of the PA.

To minimize the influence of nonlinearities and clipping, we would like to locate the signal in the linear region. This linear region is bounded by the point where the transfer deviates 1 dB from the linear response, i.e., the 1 dB compression point. Although Fig. 16 shows the nonlinear transfer of the amplitude, often referred to as AM-AM transfer, also AM-PM behaviour occurs, i.e., phase deviations occur at high input levels. In the remainder of this section we will focus on the former.

When transmitted in the nonlinear region of the system, the time-domain signal will be distorted. This will result in a two-fold behaviour. First, in-band distortion of the detected signal occurs, since the nonlinearities basically destroy the orthogonality between the carriers, which decreases the system

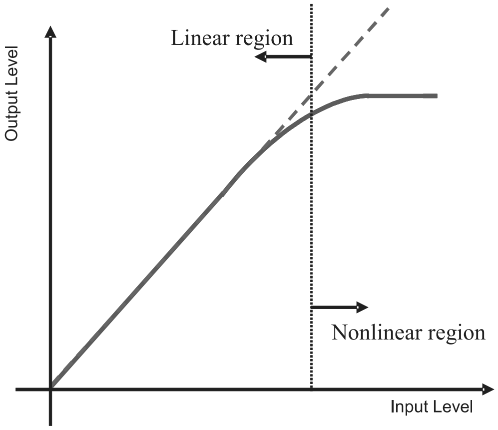
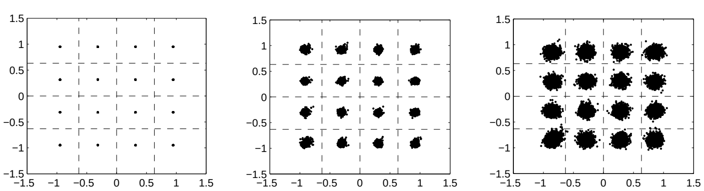


Fig. 16. Transfer of a nonlinear power amplifier.

performance. Furthermore, these nonlinearities introduce out-of-band leakage due to spectral regrowth, i.e., the transmission levels in neighbouring bands are increased. Since the allowed transmit powers in neighbouring bands are limited by regulations, this posses a problem for the overall system design.

An example of the first effect is shown in Fig. 17, where a received 16-QAM modulation is shown for a 64 subcarrier OFDM system having a nonlinear PA, where the AM-AM distortion is modelled like in [22]. Again a channel-less and noiseless scenario is assumed. The signal is fed at different levels to the PA. Hereto an back-off (BO) is applied, which is the difference between the average input power level and the input power corresponding to the border between the linear and nonlinear region. The higher the BO is the more linear the transfer is that the signal experiences, but also the lower the output power becomes.



(a) BO = 11 dB (b) BO = 5 dB (c) BO = 3 dB

Fig. 17. The effects of a nonlinear PA on the received constellation for different BO values.

It can be concluded from Fig. 17 that for a BO of 11 dB almost no influence of the nonlinearities is visible. This can be explained by the fact that the chance that the PAPR is lager than 11 dB is smaller than 10^{-4}. It is thus very unlikely that one of the peaks falls in the nonlinear region. This is different for smaller values of BO, as is clear from Fig. 17(b) and Fig. 17(c), where a growth of the scatter points is observable, which corresponds to an increased probability of erroneous detection of the transmitted symbols.

B. Suppression of Non-linearities

The conventional method to overcome the influence of nonlinearities, by applying a BO, reduces the output power and is, thus, very energy in-efficient. Therefore, different signal processing techniques were proposed to overcome this problem. The approaches can be split into techniques which try to reduce the PAPR of the signal and techniques that try to compensate for the nonlinear behaviour.

Several techniques have been proposed of the last few years to reduce the PAPR of an OFDM signal. The use of complementary block codes for this purpose was proposed in [23]. The authors of [24] propose a technique named selected mapping, where different codes words are generated representing the same data. The codeword resulting into the lowest PAPR is then selected and transmitted. The use of linear combination of partial transmit sequences was proposed in [25]. In this approach blocks of carrier are multiplied with different phase shifts. The combination of phase shifts that results in the lowest PAPR is selected and the resulting symbol is transmitted. It is noted that the last two techniques require some extra information to be transmitted, i.e., which codeword or combination of phase shifts is used, and reduce the effective datarate in that way. By decreasing the PAPR the system can apply a lower BO and thus operate more efficient.

Linearisation techniques can be applied in both TX or RX of the OFDM system. When it is placed in the TX it is often referred to as digital predistortion. In this technique the TX signal is multiplied with a transfer, which compensates for the nonlinear characteristic of the PA. The combination of their transfers results into a linear transfer up to the point where the PA output power is maximum, where the clipping will again occur. This is illustrated in Fig. 18. The linearisation can be implemented in different ways: one option is to estimate the nonlinear characteristic in an offline calibration mode and another option is the use of an adaptive algorithm. For more information on digital predistortion the reader is referred to [26].

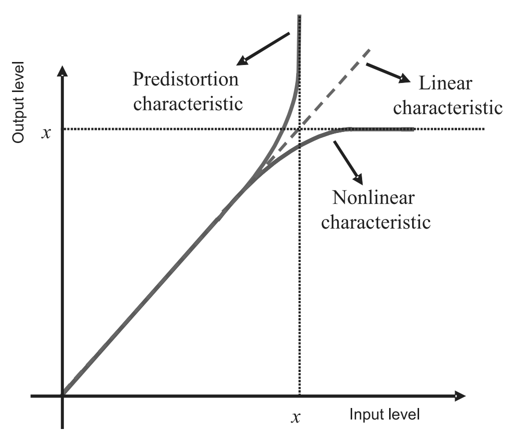


Fig. 18. Nonlinear and predistortion characteristics.

Although compensation for the nonlinearities generally is done at the TX, it can also be carried out at the RX, enabling joint compensation of the nonlinearites throughout the transmission chain. The disadvantage is that it does not help to decrease the out-of-band radiation, but it does enable the correction for clipped signals, decreasing the probability of erroneous detection.

The individual techniques highlighted in this section might require a considerable complexity in the baseband part of the wireless system to significantly reduce the performance degradation due to non-linearities. However, when combinations of the different techniques are applied, the complexity can be minimized.

VI. Conclusions

The applications multiple carriers can effectively be used to overcome the impact of multipath propagation on the performance of wireless systems applying high bandwidths. The most applied multi-carrier technique is orthogonal frequency division multiplexing (OFDM). It is shown that OFDM effectively divides the frequency selective channel into frequency flat parallel subchannels. The addition of a guard interval to the OFDM symbols removes the influence of inter-symbol-interference. Furthermore, the application of channel coding, OFDMA and adaptive modulation turn the time dispersive channel into an advantage, by exploiting the provided frequency diversity. This is the reason why the application of OFDM is proposed for use in many wireless systems over the last few years.

It is also explained that OFDM is sensitive to imperfections in the analogue front-end of the transmitter and receiver. It is shown that phase noise, IQ imbalance and nonlinearities impose severe performance degradations to an OFDM system. This paper, however, also highlights that the application of digital signal processing can largely overcome these disadvantages. A design incorporating these digital compensation techniques allows for higher impairment levels, and thus opens the door for cheaper and more optimized implementation of the RF front-end.

Overall it can be concluded that multi-carrier techniques are a natural choice for wideband systems to be applied in multipath environments, especially since its major drawbacks can largely be solved by emerging digital compensation techniques.

Acknowledgements

This work was carried out within the B4 Broadband Radio@hand project, which is supported in part by the Dutch Ministry of Economic Affairs under grant BTS01063 and by Agere Systems.

References

[1] A.R.S. Bahai and B.R. Saltzberg, *Multi-Carrier Digital Communications - Theory and Applications of OFDM*, Kluwer Academic/Plenum, 1999.

[2] R.D.J. van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*, Artech House Publishers, 2000.

[3] J. Heiskala and J. Terry, *OFDM Wireless LANs: a theoretical and practical guide*, Sams Publishing, Indianapolis, USA, 2002.

[4] S. Weinstein and P. Ebert, "Data transmission by frequency-division multiplexing using the discrete Fourier transform," *IEEE Trans. on Commun.*, vol. 19, pp. 628–634, Oct. 1971.

[5] *IEEE 802.11a standard*, ISO/IEC 802-11:1999/Amd 1:2000(E).

[6] *IEEE 802.11g standard*, Further Higher-Speed Physical Layer Extension in the 2.4 GHz Band, 2003.

[7] Multiband OFDM Alliance, "MB-OFDM proposal specifications for IEEE," available from `http://www.multibandofdm.org/`, 2004.

[8] "Wireless USB Specification," available from `http://www.usb.org/`, 2005.

[9] *IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems*, IEEE Std 802.16-2004, 2004.

[10] M. Lax, "Classical noise. V. Noise in self-sustained oscillators," *Phys. Rev.*, vol. CAS-160, pp. 290-307, 1967.

[11] A. Demir, A. Mehrotra, and J. Roychowdhury, "Phase noise in oscillators: a unifying theory and numerical methods for characterization," *IEEE Trans. on Circuits and Systems*, pp. 655–674, May 2000.

[12] P.F.M. Smulders, "Exploiting the 60 GHz band for local wireless multimedia access: prospects and future directions," *IEEE Commun. Magazine*, vol. 40, 2002.

[13] T. Pollet, M. van Bladel, and M. Moeneclaey, "BER sensitivity of OFDM systems to carrier frequency offset and wiener phase noise," *IEEE Trans. on Commun.*, vol. 43, no. 2/3/4, pp. 191–193, Feb./Mar./Apr. 1995.

[14] A.G. Armada and M. Calvo, "Phase noise and subcarrier spacing effects on the performance of an OFDM communication system," *IEEE Commun. Letters*, vol. 2, no. 1, pp. 11–13, Jan. 1998.

[15] R. Hasholzner, C. Drewes, and J.S. Hammerschmidt, "The effects of phase noise on 26 Mb/s OFDMA broadband radio in the local loop systems," in *Proc. International Zurich Seminar on Broadband Communications 1998*, Feb. 1998, pp. 105–112.

[16] R.A. Casas, S.L. Biracree, and A.E. Youtz, "Time domain phase noise correction for OFDM signals," *IEEE Trans. on Broadcasting*, vol. 48, no. 3, pp. 230–236, Sept. 2002.

[17] D. Petrovic, W. Rave, and G. Fettweis, "Intercarrier interference due to Phase Noise in OFDM - estimation and suppression," in *Proc. IEEE VTC Fall 2004, LA*, Sept. 2004, pp. 1901–1905.

[18] A.A. Abidi, "Direct-conversion radio transceivers for digital communications," *IEEE J. Solid-State Circuits*, vol. 30, pp. 1399–1410, Dec. 1995.

[19] J. Tubbax, B. Come, L. van der Perre, S. Donnay, M. Engels, and C. Desset, "Joint compensation of IQ imbalance and phase noise," in *Proc. 57th IEEE Vehicular Technology Conference 2003-Spring*, April 2003, vol. 3, pp. 1605–1609.

[20] M. Windisch and G. Fettweis., "Standard-independent I/Q imbalance compensation in OFDM direct-conversion receivers," in *Proc. 9th International OFDM Workshop*, Sept. 2004.

[21] T.C.W. Schenk, P.F.M. Smulders, and E.R. Fledderus, "Estimation and compensation of TX and RX IQ imbalance in OFDM based MIMO systems," *Accepted for IEEE Radio and Wireless Symposium (RWS 2006)*, Jan. 2006.

[22] C. Rapp, "Effects of HPA-nonlinearities on a 4-DPSK/OFDM-signal for a digital sound broadcasting system," in *Proc. of the second Europeaan conference on Satelitte Communication, Liege, Belgium*, Oct. 1991, pp. 179–184.

[23] R.D.J. van Nee, "OFDM codes for peak-to-average power reduction and error correction," in *Proc. of the IEEE Global Telecommunications Conference, 1996*, Nov. 1996, vol. 1, pp. 740–744.

[24] R.W. Bauml, R.F.H. Fischer, and J.B. Huber, "Reducing the peak-to-average power ratio of multicarrier modulation by selected mapping," *Electronics Letters*, vol. 32, pp. 2056–2057, Oct. 1996.

[25] S.H. Muller and J.B. Huber, "OFDM with reduced peak-to-average power ratio by optimum combination of partial transmit sequences," *Electron. Lett.*, vol. 33, pp. 368–369, Feb. 1997.

[26] S.C. Cripps, *Advanced Techniques in RF Power Amplifier Design*, Artech House, 2002.