Adding Errors to Reduce the PAPR and BER of OFDM-based Transmissions

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Abstract—**When transmitting signals, one of the most important issues is to keep the transmission errors as low as possible. Or in other words, to obtain a reliable transmission link, the bit-error-rate (BER) should be kept within certain limits. However, the probability of transmission errors strongly depends on the signal-to-noise ratio (SNR) of the transmitted signals. Hence, the power amplifier plays a key role in the sender part: the more power, the higher the SNR, the lower the probability of transmission errors. Unfortunately, this is a too simple vision.**

One should take care to keep the peak-to-average power ratio (PAPR) of the transmitted signal low in order not to push the power amplifier into its nonlinear operation region. Classical techniques use clipping or backing-off the input signal to reduce the PAPR of the transmitted signal. However, these techniques have a negative influence on the SNR and hence on the BER.

In this paper, we present a technique to reduce the PAPR of the transmitted signals and hence to reduce the BER, by introducing errors into Orthogonal Frequency Division Multiplexing (OFDM) signals in a controlled way. Channel coding will be used to compensate for the introduced errors.

Keywords—peak-to-average power ratio, bit-error-rate, channel coding, OFDM

I. INTRODUCTION

For wideband digital communication applications, the use of Orthogonal Frequency Division Multiplexing (OFDM) has become very popular and widely spread due to many reasons. Signals created based on this modulation scheme are very robust against multi-path fading and make use of the spectrum in a very efficient way. One can think of an OFDM signal as a large set of closely spaced narrow band carriers that are orthogonal to each other and on which the digital data is encoded. The orthogonality prevents crosstalk between the different carriers. [1]

Although these kinds of signals have a lot of advantages, one of the major drawbacks is their probability of having a very high peak-to-average power ratio (PAPR). For an OFDM signal with 128 carriers the PAPR can be as high as 21 dB. This may happen for instance when all 128 carriers are in phase. The crest factor of these signals becomes hence very high, which needs to be avoided in any circumstance when using a transmitter system. When applying a signal with a high crest factor to a power amplifier, one of the main components in a transmitter, will push the amplifier into its nonlinear operation region. However, these nonlinearities will have a negative impact on the bit-error-rate (BER) of the transmission link.

In the past a lot of techniques have been developed to reduce the PAPR, such as backing-off the PA input power, clipping partial transmit sequence, selected mapping, interleaving, and active constellation extension [2]. Other PAPR reduction techniques make use of empty frequency bins within the OFDM signal spectrum to redistribute the signal power [3][4]; that is the tone reservation technique. Moreover, coding can also be used to reduce PAPR. This approach will be further discussed in Section III.

In this paper we present a new approach to reduce the PAPR of transmitted signals in order to reduce the BER. Counterintuitive, the presented technique introduces errors on purpose into the signal. However, introducing these errors is done in a controlled way. At the receiver side, applying channel coding will allow us to compensate for these introduced errors. The idea behind channel coding is to add redundancy in order to obtain a more reliable communication link [3]. Simple channel coding algorithms can only detect errors, but more advanced algorithms also allow correcting for errors. Controlled error introduction together with this error correcting property of channel coding will form the basis of our proposed PAPR reduction technique.

Reducing the PAPR of OFDM signals can not only be a way to reduce the BER of a transmission link, but since it prevents the power amplifier to go into compression, it also provides a technique to enhance the efficiency of the power amplifier. The power amplifier is most efficient near compression. In order to operate the power amplifier near optimum efficiency different techniques are used to compensate for the non-linear behavior near compression. Nowadays, digital pre-distortion (DPD) is the most common method. However, DPD generates higher peak values in the signal and thereby deteriorate the PAPR. This can be prevented by combining DPD and PAPR reduction algorithms in one preprocessing block [4].

This research was funded by a postdoctoral fellowship of the Research Foundation-Flanders (FWO).

In Section II of this paper, the concept of OFDM and PAPR reduction techniques is summarized. Section III describes the idea behind channel coding. Section IV presents the theoretical background of the novel bits scarifying PAPR reduction technique. In Section V, the capabilities of the presented technique are shown on simulations. Conclusions are drawn in Section VI.

II. OFDM AND PAPR

A. OFDM

Orthogonal frequency-division multiplexing is used to encode digital data on multiple carriers. The digital data to be transmitted is split into multiple data-streams. Each data-stream is then encoded on a carrier, by means of a classical modulation scheme, such as phase-shift keying or quadrature amplitude modulation (QAM) [5]. Figure 1 represents the constellation diagram for a 16 QAM signal. The x-axis represents the in-phase signal (I), the y-axis the quadrature signal (Q). Both axes use the Gray-code (two symbols only differ by one bit) [5].

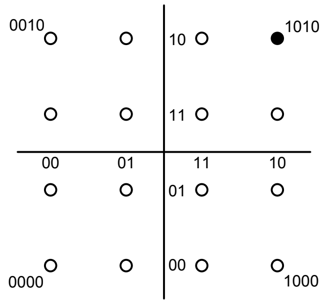

Figure 1. Constellation diagram of a 16 QAM signal

The modulation of each separate carrier is done at a much lower symbol rate as the original symbol rate of the digital data. The different carriers are closely spaced and orthogonal to each other, which prevents crosstalk between the different carriers. Furthermore, this modulation technique makes use of the spectrum in a very efficient way.

After encoding all separate carriers in the frequency domain, the carriers are added together and converted to the time domain by using an inverse Fast Fourier transform (IFFT), which results in the time-domain OFDM signal.

Not all the carriers of an OFDM signal are used for transmitting signal information. For example in a Wireless Fidelity (WiFi) system (802.11 standard) the signal consists out of 64 carriers of which only 52 carriers are used: 48 carriers to transmit data and 4 pilot tones for synchronization purposes.

The major advantage of OFDM signals is that they are extremely robust to bad channel conditions, such as strong attenuation of high frequency components, fading due to multipath and interferences.

B. Peak-to-Average Power Ratio Reduction

The major disadvantage of OFDM signals is that they can have a very high crest factor or peak-to-average power ratio. When looking at Figure 1, one can see that high peaks in the envelope of the complex valued signal $S = I + jQ$ (with $j = \sqrt{-1}$) will occur in the 4 corner symbols {0000, 0010, 1000, 1010} of the constellation diagram. The worst crest factor is obtained when all carriers are encoded with an unfortunate combination of corner symbol.

These high PAPRs will push the power amplifier of the transmitter into its nonlinear operation region. To avoid this, one needs to back-off the input power of the power amplifier, which results in a drop of the SNR of the amplified signal. However, the BER of a signal transmitted through an additive white Gaussian noise channel (AWGN), strongly depends on the SNR of the signal. So by backing-off the input power of the power amplifier, the BER will increase. Hence, it is very important to keep the PAPR of the transmitted signals as low as possible.

For this purpose a lot of techniques have been developed in the past, such as clipping and filtering, convex optimization techniques, redistributing energy over unused carriers [2]. All these techniques have their own advantages and disadvantages. The technique presented in this paper should not be considered as an additional technique, but rather as an extension that can be used together with the existing methods.

III. CHANNEL CODING

When using channel coding one adds redundant information into the transmitted signal in order to improve the reliability of the communication. The most simple channel coding algorithms can only detect error(s). One example is the parity check that can detect if one bit is wrong and request a retransmission. However, if more than one bit is false, the algorithm will not be able to detect it. More advanced algorithms, such as forward error correction (FEC), can not only detect multiple errors, but they can also correct for some of these errors.

The FEC add redundancy by adding parity bits to the information bits. Thus, the sent symbol also called code word contains more bits than just the message. Another consequence is that the valid code words is just a subset of the possible combinations if bits. For example, if the message is four bits and three parity bits are used the number of code words will be equal to 2^4=16, while the possible number of combinations will be 2^7=128. The parity bits are calculated in order to make each code word as unique as possible; that is to maximize the Hamming distance. However one can also select the code word such that the PAPR is reduced [5] but at the expense of Hamming distance.

All standardized wireless communication protocols have restrictions on the number of bit errors, the BER. The BER strongly depends on the modulation technique used and the SNR of the signal. Thus, for a given modulation technique the BER can be improved by increasing the signal level, but it can also be improved by using channel coding. Several coding techniques can be found in the literature, such as Reed Solomon code and Turbo codes. They differ in performance and complexity, but it is not uncommon that they can improve the BER with a factor up to 100 [6]. Different coding techniques have been proposed in order to minimize the PAPR and at the same time maximize the Hamming distance (see e.g. [7]-[9]). However, they can be only applied to MSK modulation and become infeasible for larger values of carriers due to the computation needed [2]. Moreover, the coding is a part of the communication protocol and a single user or manufacturer of communications equipment cannot solely change the coding to improve the PAPR. That must be done on a system level.

Typically these transmission errors are caused by noise in the channel and fading, but they can also arise due to imperfections in the communication system. Two examples of possible imperfections are the nonlinear behavior of the transmitting power amplifier and some PAPR reduction techniques, such as clipping; that can for example be seen in [11].

IV. SACRIFYCING BITS

The proposed method in this paper is designed for a wireless communication system that uses a standard channel coding technique. The basic principle consists of altering some transmitted symbols intentionally to achieve better PAPR of the transmitted signal. Thus, bit errors have been deliberately added before channel coding takes place. However, these errors will be corrected at the receiver side by using channel coding.

If one is able to reduce the PAPR of the transmitted signals, the need for strongly backing-off the PA will no longer be present. As a result, one can continue using high signal power (within the given spectrum mask of the communication channel) which results in a high SNR and hence, the BER before channel coding will be reduced. Moreover, errors due to the clipping effect of the PA caused by the high PAPR of the input signal will be reduced. In summary, by adding some bit errors we prevent other errors from arising. At the receiver side, the sacrificed bits will be corrected by using channel coding.

The proposed method can be used for almost any modulation technique, and for an arbitrary number of carriers. For the sake of simplicity, the method will be described and simulated on a 16QAM signal. The constellation diagram is shown in Figure 1. Peaks in the envelope of the signal typically occur when the peak amplitude value at each carrier coincide. From the constellation diagram in Figure 1 it is clear that 4 symbols have the highest amplitude. That is {0000, 0010, 1000, 1010}, the corner symbols. Remark that the constellation diagram is Gray coded. Thus, the diagonal pairs {0000, 1010} and {0010, 1000} only differ in two bits. This means that by changing only two bits, a positive peak value will be turned into a negative peak value. Changing one bit will result in a 90 degrease phase shift.

Consider the following simple example. Assume we are dealing with an OFDM signal with 16QAM modulation and 4 carriers. The maximum amplitude for each carrier is normalized to 1. At a certain time instance all carriers will send the symbol 1010 and all carriers are in phase. This will result in a total peak equal to a normalized value of 4. If we sacrifice two bits, one carrier will send the symbol 0000 instead of 1010 (the other side of the diagonal in Figure 1). This symbol has the same amplitude, but is 180 degrees shifted in phase. Thus instead of having a total peak value equal to a normalized value of 4, the total peak value will be equal to a normalized value of 2. As a result, the global PAPR of the signal will be reduced.

This simple example gives a good illustration, but is not a realistic case. In reality the peaks occur at arbitrary time instants and the optimal compensation will not be as obvious as in the example. The method will detect peak values in the generated signal for each set of symbols. If these peak values are above a certain threshold, the method will replace one symbol with its diagonal equivalent in the constellation diagram.

The threshold must be selected with care. Even though, channel coding will correct for errors, the intentionally added error shall be kept to a minimum. Thus, only the highest peaks shall be reduced. A useful tool for determining the peaks that needs to be reduced is the complementary cumulative distribution function (CCDF) of the signal. The CCDF of the PAPR denotes the probability that the PAPR of a data block exceeds a given threshold.

V. SIMULATION RESULTS

The simulations are based on an OFDM signal with 16QAM modulation and 48 carriers. The number of carriers corresponds to the number of carriers used in a Wi-Fi system. The data sequence is a random sequence with a length of 10^4 symbols. The peak value sequence of the OFDM signal is detected and two different methods are used to reduce the peak. The first method is to introducing one error only and the second is to introduce one or two errors. Both methods look for the corner symbols {0000, 0010, 1000, 1010} and replace the symbol with an adjacent corner symbol (one error) or any of the corner symbols (one or two errors). All possible combinations are evaluated and the lowest peak is selected. The results are presented in CCDF diagrams based on 10000 simulations. The result from introducing one bit error is shown in Figure 2 and introducing one or two bits are shown in Figure 3.

It is evident that both methods reduce the PAPR. For a given probability the PAPR is reduced by approximately 0.7 dB when introducing one bit error and 0.9 dB when introducing one or two bits error. The total number of bits in the simulation was $4 \cdot 10^4$. The conditions for the simulations have been to limit the number of added errors and only one peak per sequence has been reduced. An alternative approach can be set a threshold for the peaks and to allow more added errors. However, that has not been covered in this study.

One should keep in mind that the suggested method is complementary to existing methods. By reducing the PAPR with 1 dB the average signal power can be increased by 1 dB. Increasing the signal power by 1dB will improve the BER before using channel coding with approximately a factor 3. The achieved PAPR reduction will lead to more energy efficient

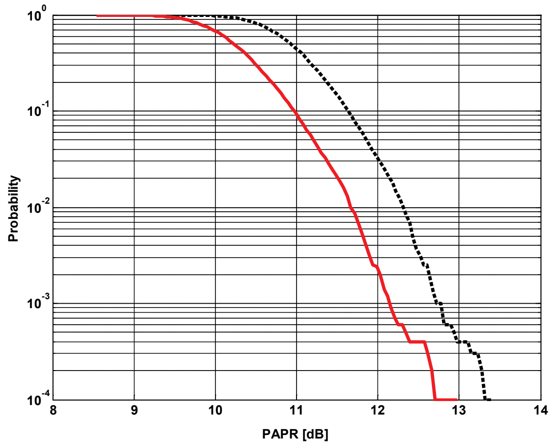

Figure 2. CCDF for an 48 carrier, 16QAM OFDM signal without any PAPR reduction (dashed black) and with introducing one bit error (red solid)

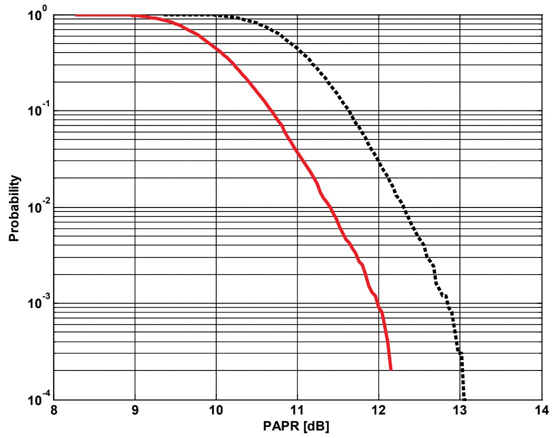

Figure 3. CCDF for an 48 carrier, 16QAM OFDM signal without any PAPR reduction (dashed black) and with introducing one or tw bits error (red solid).

transmitters. Moreover, methods combining DPD with PAPR sometimes still use clipping and filtering for the highest peaks [4]. For these applications sacrificing bits might be an attractive alternative.

VI. Conclusion

In this paper we present a very simple PAPR reduction technique based on introducing in a controlled way, errors on purpose in the transmitted digital communication stream. The errors are corrected at the receiver side by channel coding.

The method requires a communication protocol using channel coding, but it is independent of the coding method. Thus, it can be implemented in a single device and do not require any changes on a system level.

Based on simulation results we have proven that the presented method can reduce the PAPR. The method is simple and can with advantage be used together with other PAPR reduction and DPD methods on order to improve the efficiency and BER.

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