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PAPR Reduction in IEEE802.11a Systems Using Artificial Neural Networks

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Abstract – High Peak-to-Average Power Ratio (PAPR) is the main drawback in Orthogonal Frequency Division Multiplexing (OFDM) systems. Most effective PAPR reduction techniques suffer from the problem of the need to perform an exhaustive search to find the best sub-symbol permutation or phase combination for every OFDM symbol before it can be transmitted. In this paper, PAPR reduction based on using suitable pilot tone phases is adopted and it is proposed to train a neural network to produce these phases rather than searching for them. The proposed system is tested for the IEEE802.11a system. Extensive computer simulation tests show that a satisfactorily close performance to the optimum is achieved by the trained neural network. Moreover, as compared with conventional techniques, the proposed system is not iterative, no side information need to be transmitted to the receiver, no data rate loss, no increase in bit error rate and no increase in transmitted signal power and bandwidth.

1. Introduction

Due to its high spectral efficiency, immunity to frequency selective fading, and high data rate transmission, Orthogonal Frequency Division Multiplexing (OFDM) became a popular modulation technique in digital communication systems [1]-[3]. OFDM is the modulation standard for the IEEE802.11a/g wireless LANs, World wide Interoperability for Microwave Access (WIMAX), Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), Asymmetric Digital Subscriber Line (ADSL), etc [2],[3].

However, OFDM systems suffer mainly from the sensitivity to frequency offset and high Peak-to-Average Power Ratio (PAPR) of the transmit signal [1]-[4]. The latter is the major drawback of OFDM systems. High PAPR occurs due to the summation of many subcarrier-modulated signals and the manner in which the phases can align in the frequency domain [2]. A high PAPR requires a wide dynamic range for the high power amplifier (HPA) at the transmitter. That is, the power amplifier needs to be backed-off to accommodate high peaks. This results in significant reduction in transmission power which leads to a very low power efficiency. For example, in the IEEE802.11a system, the typical power efficiency of a class AB power amplifier is only 18% [4].

There are many techniques for PAPR reduction in OFDM systems. The basic techniques include amplitude clipping, clipping and filtering, coding, tone reservation (TR), tone injection (TI), active constellation extension (ACE), partial transmit sequence (PTS), selective mapping (SLM), and interleaving [5]. In the literature, many approaches have been proposed to reduce PAPR depending on modifications and optimizations to these basic techniques.

Amplitude clipping is the simplest technique for PAPR reduction. It causes both in-band and out-of-band distortion. The former results in degradation in error performance [6] and it cannot be reduced by filtering. While out-of-band radiation reduces spectral efficiency, it can be reduced by filtering, but at the expense of a risk of some peak regrowth [3],[5]. Repeated clipping and filtering operation can be used to reduce the overall peak regrowth [3],[5],[7]. The deleterious effects of amplitude clipping may be reduced when it is used together with other techniques like vector hole punching to the constellation diagram of the OFDM signal [8], modulation adaptation and power control [9], and TI [10]. However, any gained advantages are at the expense of increased system complexity.

Coding can also be used to reduce PAPR. The idea is to select the code words that minimize the PAPR for transmission [5],[11]. This approach suffers from data rate loss and from the need to perform an exhaustive search to find the best codes and store large lookup tables for encoding and decoding, especially for large number of subcarriers.

Similarly, TR based approaches that reserve a number of tones, called Peak Reduction Carriers (PRC), need to perform an exhaustive search to find the optimum PRC amplitudes and phases that minimize the PAPR [12]. Usually, PRCs increase the required bandwidth and increase the transmit signal power, which is a common problem with ACE and TI based techniques [5]. Modifications to the latter techniques are presented in [10],[13]-[15] with added system complexity.

PAPR reduction techniques based on interleaving, PTS, and SLM also have the problem of the need to search to find the best permutation or phase factor combination, for every OFDM symbol before it can be transmitted. The search complexity increases exponentially with increased number of subcarriers [5],[16]. Various techniques have been suggested to reduce the search complexity [17]-[23]. These methods achieve significant reduction in search complexity with marginal PAPR performance degradation.

In this paper, we present a PAPR reduction technique depending on finding the best PRCs' phases using a trained neural network (NN). This technique is verified with the IEEE802.11a system.

2. Neural Network based PAPR reduction

A useful way to avoid the requirement to search for PAPR minimization parameters is to train a neural network. Such a neural network can significantly simplify the operation of getting these parameters with a great time and computational complexity saving. This concept is successfully used in many works in the literature with TI [24], SLM [25],[26], and to compensate the HPA nonlinear effects on OFDM signals [27].

In [24], a PAPR reduction method for OFDM signals is proposed. The method uses the Hopfield neural network (HNN) with tone injection scheme to reduce PAPR. The proposed neural network is suitable for global search and PAPR is sufficiently reduced without the need to transmit side information of the parameters used for PAPR reduction. The proposed neural network has less computational complexity than conventional neural networks [24]. Numerical experiments showed that a weak gain of about 1 dB PAPR reduction is achieved at the probability of 10^{-5} as compared to conventional TI method. Moreover, the architecture of the proposed method has many IFFTs and enormous computational complexity.

In [25] a neural phase rotator together with Polynomial Cancellation Coding OFDM (PCC-OFDM) is proposed. The proposed system does not use side information to transmit phase rotation factors. The PAPR reduction problem is formulated as a combinatorial optimization problem, and Hopfield neural network and chaotic neural network are applied to solve the problem. Numerical tests showed that a 1.5 dB reduction in PAPR is achieved by the neural network based phase rotator at the probability of 10^{-3} as compared with a random phase rotator.

However, Hopfield neural network suffers from slow convergence and unpredictable solutions during the training stage. Furthermore, the complexity of HNN and difficulty in setting the parameters are major disadvantages in applying HNN to PAPR reduction.

The use of Radial Basis Function Neural network (RBFNN) for PAPR reduction is investigated in [26]. The RBFN can be regarded as a method of adaptive curve-fitting interpolator, and is used to generate optimum mapping pattern to reduce the PAPR. The performance of the proposed RBFNN is evaluated and compared with HNN-based and SLM PAPR reduction methods. As for the proposed RBFNN technique, the PAPR performance is superior to the SLM method and showed similar performance to the HNN-based methods, but with lower complexity.

A completely different treatment to the problem of PAPR reduction by employing neural networks is presented in [27]. It is proposed to test many neural networks with different structures and learning algorithms to compensate the HPA non-linear effects in OFDM, by simulating an inverse model of the HPA in the time domain. Simulation results showed that the proposed system has a limited performance.

The performance of a neural network based PAPR reduction system depends on many parameters related to the used neural network such as the complexity of its structure, learning algorithm, and training parameter settings that avoid divergence and minimize training time. Moreover, it depends on the number and the way the output of the neural network is used to minimize PAPR. That is, when the output of the neural network is loosely related to the PAPR, then more signal processing effort is required as compared to systems where this output direc1tly determines the PAPR. The simplicity of the relation between the output of the neural network and PAPR is essential in such systems because in complicated systems error accumulation is expected when the neural network produces inaccurate outputs, leading to PAPR reduction performance degradation.

Therefore, it is proposed in this paper to train a perceptron neural network using the backpropagation algorithm to learn the relation between the phases of the subsymbols of the OFDM symbol to be transmitted and the phases of the pilot carriers which will cause overall PAPR minimization. The relative simplicity of the neural network and learning algorithm together with suitable settings for the related parameters make the system relatively simple with a better chance to converge to an acceptable performance within a limited time. Moreover, the limited number and dynamic range of pilot carries with respect to the length of an OFDM symbol makes the learning process easier than other systems where more parameters with much greater dynamic ranges are to be estimated by the neural network, such as phase factors for every OFDM symbol candidate [25].

3. System Overview

For an OFDM system with N sub-carriers, the baseband time domain signal is produced by IFFT. In discrete form can be written as

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j(2\pi k \Delta f t)} \qquad 0 \le t \le T \tag{1}$$

where X_k is the symbol carried by the k^{th} subcarrier, Δf is the frequency difference between subcarriers, and T is the OFDM symbol duration. Since the signal which passes through the power amplifier, is in the continuous time domain, which can be significantly higher than the discrete-time estimate, it is necessary to oversample the signal by a factor of at least 4 to enable accurate peak detection [3]. For an oversampling factor of L, the input signal to the IFFT is extended by including $N(L$-1) zeros in the centre of the signal. The PAPR of the transmitted signal can be expressed as

$$PAPR(x) = 10\log_{10}\left(\frac{\max|x(n)|^2}{E[|x(n)|^2]}\right) \tag{2}$$

where $|x(n)|$ returns the magnitude of $x(n)$, and E[.] denotes the expectation operation.

In practical OFDM-based applications, not all subcarriers are used to transmit the information data. Some subcarriers are set to zero to prevent out-of-band radiation. For example, in an IEEE802.11a system, 64 tones are employed, in which 48 tones are data carriers, 4 carriers are pilot tones and the remaining 12 tones are unused and are set to zero. Since these unused tones do not affect the original data carriers, they can be used to reduce the PAPR without increasing the BER or a reduction in data throughput, but this will result in a broadening of the original spectrum. However, pilot tones are normally employed to enable carrier frequency offset and channel estimation. In order to minimize the channel mean square error, the pilot tones must be equidistant and equi-powered [3]. For optimal channel estimation, all pilot tones must have the same amplitude, but there are no particular requirements for the phase. PAPR reduction can be achieved by optimizing the phase values of pilot tones with keeping their magnitude constant to meet channel estimation requirements and to avoid increasing the transmit signal power.

4. Proposed neural network Based System

For a PAPR reduction technique based on optimizing pilot tone phases, we propose in this paper the use of pre-trained neural network to produce the required pilot phases rather than getting them by exhaustive searches. The use of a neural network is more useful than conventional searching for pilot phases which requires the generation of huge lookup tables containing all possible data arrangements together with the optimum values of the pilot tone phases. For each one of these data arrangements, all possible pilot phases must be examined to determine the optimum value that should be stored in the lookup table. This table must be constructed and made available to be searched once for every OFDM symbol before it can be transmitted. Or else, when fast enough processing capability is available; the examination of all possible pilot phases is performed in real time for each OFDM symbol. However, the computational complexity increases and becomes impractical to perform as the number of subcarriers increases. Therefore, training a neural network to produce the pilot phases is more practical. The block diagram of the proposed system is shown in Fig.1.

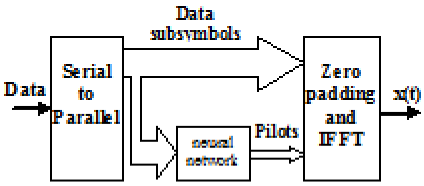

Figure 1. Proposed system.

The neural network takes an OFDM symbol and suggests a suitable pilot phase arrangement that can reduce the PAPR of the transmit signal. These pilot tones are positioned within the data tones in equidistant places. The resulting OFDM block is then oversampled and transformed to the time domain using IFFT.

The structure of the proposed neural network is shown in Fig.2(a). The overall neural network consists of ν subnets, where ν is the number of pilot tones. Each subnet has input nodes equal to the number of data tones, a single hidden layer of suitable number of nodes, and a single output node to produce the phase of the specific pilot tone, as shown in Fig.2(b). All subnets have the same structure.

The neural network must be trained before operation by using a large enough set of OFDM symbols as inputs and the related PAPR minimizing pilot phases as targets. The accuracy of operation of the neural network will depend on how much the training data is representative to the various actual values. Once the neural network learns the relation between OFDM symbols and pilot phases, with some acceptable error, then it can be used as a very fast and more efficient alternative to conventional searching techniques. The challenge is to use training parameters that can result in an accurate enough neural network, and when used in the system of Fig.1, can achieve a PAPR reduction performance as close as possible to the case when optimum pilot phases are employed.

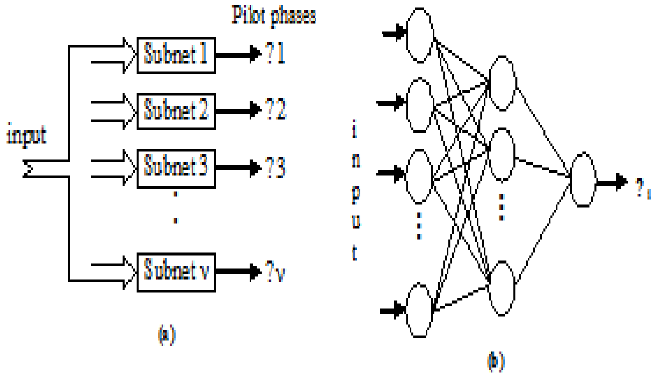

Figure 2. (a) Structure of the overall neural network; (b) Structure of the ith subnet.

5. Computer Simulation and Results

The performance of the proposed neural network based PAPR reduction technique is tested for the case of IEEE802.11a system. Firstly, the input data patterns (OFDM data subsymbols) and the corresponding targets (optimum pilot phases), necessary to train the neural network, are generated. The data subsymbols and pilots are QPSK modulated, therefore, there are 448 possible data blocks and for each one of these blocks there are 44 possible pilot phase arrangements.

However, to train the neural network, it is not necessary to generate all of the possible data patterns. Practically, a subset of the 448 data patterns will be enough to reach satisfactory operation. In the simulations, 100000 independent Gussialy distributed random OFDM data blocks are generated and for each block, the four optimum pilot tone phases that result in the minimum PAPR are determined. The magnitude of the pilots are taken to be equal and constant such that the power of the transmit signal is not affected and to suit channel estimation requirements at the receiver. Also, the 12 unused tones are left unused in order not to affect transmission bandwidth.

Moreover, using the actual values of the QPSK modulated data and pilot subsymbols will require very intensive complex number arithmetic computations to be used in training the neural network. Therefore, to simplify the case, the QPSK data and pilots are mapped to uinipolr 4PAM symbols, resulting in real-valued integer input and target patterns to train the neural network.

The subnets of the neural network shown in Fig.2 are identical in structure. Each subnet has 48 input nodes and a single hidden layer having 48 nodes, all connected to a single output node at which a pilot tone phase is produced. Another similar structure neural network but with 60 hidden nodes is also tested.

The subnets of these two neural networks are trained. The backpropagation learning rule with suitable training parameters are employed together with only 1000 training patterns. Such a small sized training data is used in order to shorten the training time. After the neural networks have finished learning, they are used in the system of Fig.1 with a new set of OFDM blocks.

The capability of the proposed system to minimize PAPR is presented in Fig.3, by plotting the complementary cumulative density function (CCDF) of the PAPR values. The CCDF of the PAPR denotes the probability that the PAPR of a data block exceeds a given threshold, PAPRo. For the purpose of comparison, the CCDF of the original OFDM blocks and the same OFDM blocks with the optimum pilot phases being used, are plotted in Fig.3. The plots of this figure show that there is no significant advantage gained from using the trained neural networks. That is, for a probability of 10^{-4} the CCDF of the neural network with 60 hidden nodes is only 0.8 dB better than the original OFDM, and it is far away from the optimum value by 2 dB and the performance of the neural network with 48 hidden nodes is even worse. Therefore, it is concluded that the 1000 training patterns are not enough for the system to learn the relation between the subsymbols of the OFDM symbol to be transmitted and the required pilot tone phases that minimize the PAPR.

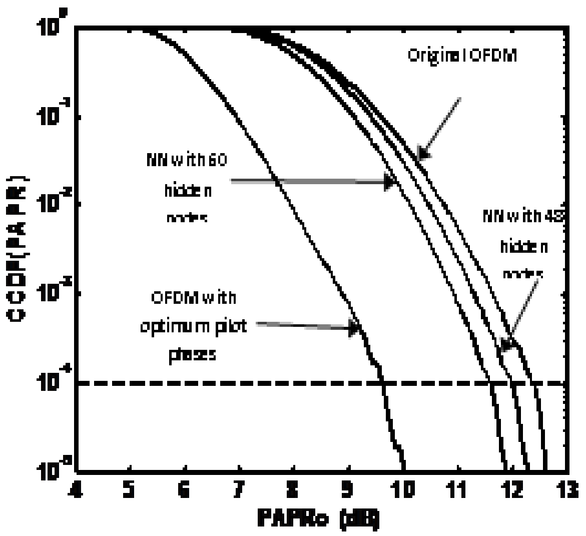

Figure 3. Performance of proposed system with 1000 training patterns.

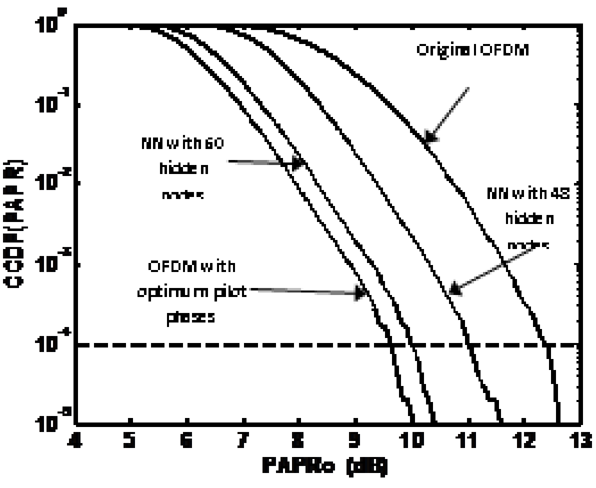

Figure 4. Performance of proposed system with 10000 training patterns.

Next, the same neural networks are retrained with 10000 training patterns. The CCDFs for the 100000 test OFDM symbols with the default pilot phases, the optimum pilot phases, pilot phases produced by the 48 hidden node neural network, and pilot phases produced by the 60 hidden node neural network are plotted in Fig.4. The plots show that the performance of both of the tested neural networks has become closer to the optimum phased pilot OFDM. The neural network with 60 nodes in the hidden layer is better than that with 48 hidden nodes, and achieves an advantage of 2.4 dB with respect to the original OFDM for a probability of 10^{-4}. However, a closer performance to the optimum is expected if more training patterns and/or other neural network structures are used, but at the expense of higher system complexity, slower training and risk of divergence. The neural network with 60 hidden nodes trained by 10000 data patterns seem to be capable of achieving an acceptable performance when it operates under conditions similar to those used in the simulations. Moreover, it has significant advantages when compared with conventional PAPR reduction techniques. That is, it is not iterative, no search operation is required, no side information need to be transmitted to the receiver, no data rate loss, no increase in bit error rate and no increase in transmitted signal power and bandwidth.

The proposed system is not complicated in structure since the number of output nodes is limited to the number of pilot carriers which is small with respect to the total length of the OFDM block in all OFDM systems. It is also less complex (in neural network structure and learning algorithm) and capable of achieving higher PAPR reduction when compared to most of the neural network based PAPR reduction systems presented in the literature. Even more PAPR reduction may be achieved by the proposed system when its output is modified and extended to produce suitable amplitudes and phases for the pilot carriers and/or unused unused tones. This may be investigated in a future work.

6. Conclusion

We proposed the use of a neural network to find the phases of peak reduction carriers instead of applying exhaustive searches to find them before an OFDM symbol can be transmitted. Backpropagation neural networks of different structures and training patterns are tested for the case of IEEE802.11a system. The tests show that a satisfactorily close performance to the optimum can be achieved by a neural network with a single hidden layer consisting of 60 nodes, trained by 10000 data patterns.

The proposed system is an efficient alternative to conventional PAPR reduction techniques that suffer from the need to transmit side information to the receiver, data rate loss, increase in bit error rate and increase in transmitted signal power and bandwidth. On the other hand, it is less complex structure and learning algorithm and capable of achieving higher PAPR reduction with respect to most of the neural network based PAPR reduction systems in the literature.

Several modifications can be examined in future works to further optimize the structure, learning rule, training data patterns and related parameters such that closer performance to the optimum is achieved.

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