Peak to Average Power Ratio reduction in ECMA-368 ultra wideband communication systems using Adaptive Neural Fuzzy Inference Systems

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Abstract

The Federal Communications Commission (FCC) authorized the use of 7500 MHz of spectrum reserved for unlicensed Ultra Wide Band communications systems, which leads the emergence of some standards. Among these standards: ECMA-368 adopts Multiband Orthogonal Frequency Division Multiplexing (MB-OFDM) technique. However, MB-OFDM signal suffers from high Peak to Average Power Ratio (PAPR), which limits the power efficiency of the High Power Amplifier (HPA) due to nonlinear distortion. In order to avoid this drawback, an efficient scheme based on Adaptive Neural Fuzzy Inference Systems (ANFIS) is proposed. The ANFIS is adjusted by using Active Constellation Expansion (ACE) technique which provides satisfactory results. This proposed solution gives good performance compared to previously available methods with much lower complexity, without iterations, good bit error rate and no increase in transmitted signal power and bandwidth.

Keywords: ECMA-368, MB-OFDM, PAPR, HPA, ACE, ANFIS.

1. Introduction

Originally intended for radar Applications and military communications, the Ultra Wideband (UWB) technology has attracted many uses these recent years. A turning point of this evolution occurred in February 2002 when the Federal Communications Commission (FCC) has implemented a regulation authorizing the use of UWB technology for telecommunications consumer in the United States by assigning a frequency band of 7.5GHz not subject to licensing [9]. The terminology UWB refers at the beginning to waveforms without carriers (carrier-free) made of very short pulses. In this context, a commonly accepted definition is that these signals have a fractional bandwidth (FB), greater than 0.25 with a frequency bandwidth greater than 500MHz [18].

$$FB = \frac{fH - fC}{fC} \text{ with } fC = \frac{fH + fC}{2} \qquad (1)$$

FB is the Fractional Bandwidth, *fH* is the upper frequency, *fL* is the Lower Frequency and *fC* is the Center Frequency. To avoid the disadvantages of the pulse transmission method including the complexity of the Rake receiver due to the density of multipath in the UWB channel, Orthogonal Frequency Division Multiplexing (OFDM) was adopted. OFDM is a technology of modulation which ensures orthogonality in the frequency domain because of employing the sinusoidal basis function [4][6]. According to Muquet et al.,[17] the addition of the cyclic prefix (CP) or the zero padding (ZP) to each symbol, we can easily handle inter-symbol interference (ISI) inflicted by a multipath channel, When the channel is, however, frequency-dispersive, inter-channel interference (ICI) may degrade an OFDM system performance to intolerable levels. To combat this problem, a new MB-OFDM system has been proposed by Batra et al. [3], MBOA-SIG [16], WiMedia Alliance [22] and ECMA-368 [8]. But like all the communication systems based on OFDM, the ECMA-368 suffer from the same embarrassing drawbacks, including the large power envelope fluctuations, which significantly reduces the average power at the output of the high power amplifier (HPA) used in the transmitter. This phenomenon leads to the band distortion which increases the bit error rate (BER) and the spectral widening which also increases adjacent channel interference [2][11]. Several methods have been developed in order to reduce the peak power of the OFDM signals [5][7][21], within these techniques, the Active Constellation Extension Approximate Gradient-Project (ACE-AGP) has been proposed by Krongold and Jones [14], it has aroused great interest since it provides large envelope reductions without the need of side information (data rate is not compromised). In this paper, an efficient proposal based on Adaptive Neural Fuzzy Inference Systems (ANFIS) and ACE-AGP is proposed. The objective is to train the ANFIS to have the same behavior as ACE-AGP algorithm and obtaining its good results but with much lower complexity and fast convergence when using ECMA-368 system.

2. ECMA-368 wireless communication standard

According to ECMA International (2008) The ECMA-368 describes the MB-OFDM ultra wideband (UWB) physical layer (PHY) for wireless personal area (WPAN) by using the unlicensed 3.1 - 10.6 GHz frequency band. Eight data rates were adopted 53.3 Mb/s, 80 Mb/s, 106.7Mb/s, 160 Mb/s, 200 Mb/s, 320 Mb/s, 400 Mb/s, and 480Mb/s. The ECMA-368 band is divided into six groups of band. Band groups 1 to 4 consist of 3 bands each, spanning the bands 1 to 12. Band group 5 contains the two bands 13 and 14. Band group 6 contains the bands 9, 10 and 11. Band group 1 is used for mandatory mode, the remaining band groups are reserved for future use. The relationship between center frequency fc and band number nb is given by: $fc = 2904 + (528 * nb),\ \ nb = 1 \dots 14 (Mhz)$.
The transmitted MB-OFDM symbols are time-interleaved across the 14 bands according to the specified time-frequency code (TFC)[8]. The characteristics of the MB-OFDM symbols are presented in Table 1. Each MB-OFDM symbol is generated by an IFFT on 128 points. In 128 sub-carriers, 100 are dedicated to useful data, 12 pilot subcarriers, 10 guard subcarriers, 5 zero guards and the DC. The subcarrier frequency spacing $\Delta f = 4125$MHz can fulfill the requirement of orthogonality in the OFDM system. The zero-padding suffix duration in time is Tzps = 70.08 ns (37 samples). Four forward error corrections (FEC) coding are used to vary the data rates. The FEC used is a convolutional code with coding rates of 1/3, 1/2, 5/8 and 3/4. At the end each transmitted MB-OFDM symbol has a duration Ts = 312.5ns and contains 165 samples.

Two types of modulation particles have been adopted in ECMA-368. The first one is Quaternary Phase Shift Keying (QPSK) modulation used when data rates is 53.3 up to 200Mb/s and combined with Frequency-Domain Spreading (FDS) and (or) Time-Domain Spreading (TDS) techniques.

Table 1 ECMA-368 system parameters

Parameters	***Value***
Number of data subcarriers	100
Number of pilot subcarriers	12
Number of guard subcarriers	10
Total of subcarriers used	122
Number of null subcarriers	6
Bandwidth	528 MHz
Subcarrier frequency spacing	4.125 MHz
IFFT/FFT period	242.42 ns
Zero padded suffix duration	70.08 ns
Symbol interval	312.5 ns
Symbol rate	3.2 MHz

In this type of modulation 2 bits are encoded using the following equation [19]:

$$y_{QPSK}[K] = K_{MOD} \times [(2 \times b[2K] - 1) + j(2 \times b[2K+1] - 1)] \quad (2)$$

Where $K_{MOD} = 1/\sqrt{2}$ is for normalizing the average symbol power to be a constant unit and *K = 0, 1, 2... n, with n = 49* in the case of use of the Frequency-Domain Spreading (FDS) otherwise n = 99.

The second type of modulation is Dual-Carrier Modulation (DCM): used with data rates of 320 up to 480Mb/s, in this modulation the Bits are divided into groups of 200 bits, then grouped into 50 groups of 4 reordered bits. each group of 4 bits is represented as $b[g(n)]$, $b[g(n)+1]$, $b[g(n)+50]$, $b[g(n)+51]$ where $n \in \{0, 1, ..., 49\}$ and

$$g(n) = \begin{cases} 2n & n \in \{0, 1, \dots, 24\} \\ 2n + 50 & n \in \{25, \dots, 49\} \end{cases} \quad (3)$$

Four binary bits are mapped to two QPSK symbols $x[g(n)]+jx[g(n)+50]$, $x[g(n)+1]+jx[g(n)+51]$, then the DCM modulation uses a matrix H to execute a mapping of the two QPSK symbols into two DCM symbols which form two 16QAM constellations [19]:

$$\begin{bmatrix} x_{g(n)} + jx_{g(n)+50} \\ x_{g(n)+1} + jx_{g(n)+51} \end{bmatrix} = \begin{bmatrix} (2b_{g(kn)} - 1) + j(2b_{g(n)+50} - 1) \\ (2b_{g(n)+1} - 1) + j(2b_{g(n)+51} - 1) \end{bmatrix} \quad (4)$$

$$H = \begin{bmatrix} 2 & 1 \\ 1 & -2 \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} y_{DCM}(n) \\ y_{DCM}(n+50) \end{bmatrix} = K_{MOD}\, H \begin{bmatrix} x_{g(n)} + jx_{g(n)+50} \\ x_{g(n)+1} + jx_{g(n)+51} \end{bmatrix} \quad (6)$$

Where $1/\sqrt{10}$ is for normalizing the average symbol power to be a constant unit.

Twelve of the subcarriers are dedicated to pilot subcarriers. The values of pilot subcarriers depend on data portion of the PPDU and data rate. In PLCP header and data rates of 53.3 and 80Mb/s the pilots sequence is [8]:

$$d_{pilot1}[l] = \begin{cases} 1 - j/\sqrt{2} & l = 0,3 \\ -1 + j/\sqrt{2} & l = 1,2,4,5 \\ 1 + j/\sqrt{2} & l = 8,11 \\ -1 - j/\sqrt{2} & l = 6,7,9,10 \end{cases} \quad (7)$$

Where $l \in \{0, 1, \ldots, 11\}$.

Otherwise:

$$d_{pilot2}[l] = \begin{cases} 1 + j/\sqrt{2} & l = 0,3,8,11 \\ -1 - j/\sqrt{2} & l = 1,2,4,5,6,7,9,10 \end{cases} \quad (8)$$

the transmitted radio frequency signal after the IFFT can be described mathematically as follows:

$$S_{RF}(t) = Re\left\{ \sum_{n=0}^{N_{packet-1}} S_n(t - nT_{SYM}) exp\left(j2\pi f_c(q(n))t\right) \right\} \quad (9)$$

Where $Re\{.\}$ represents the real part of the signal, T_{SYM} is the symbol duration (312.5 ns), N_{packet} is the number of symbols in the packet, fc is the center frequency, $q(n)$ is a function that maps the nth symbol to the appropriate frequency, $S_n(t)$ is the complex baseband signal of the nth symbol.

3. Cubic Metric

The classical metric used to measure power fluctuations in MB-OFDM signal ($S_{RF}(t)$) is PAPR (Peak to Average Power Ratio) [23]. However, PAPR does not appropriately take into account the distortion effect due to the nonlinear response of the HPA. For this reason, the Cubic Metric was proposed by the Third Generation Partnership Project [1] . This metric uses higher statistics to evaluate the power de-rating factor in an HPA. It is defined by the 3GPP as:

$$CM = \frac{RCM(dB) - RCM_{ref}(dB)}{K}\,(dB) \quad (10)$$

Where RCM is the Raw Cubic Metric, which is defined for a signal ($S_{RF}(t)$) as:

$$RMC = 20log_{10}\left(\sqrt{E\left\{\left(\frac{|S_{RF}|}{\sqrt{E\{S_{RF}\}}}\right)^3\right\}}\right)(dB) \quad (11)$$

RCM_{ref} is the reference RCM which for OFDM takes the value 1.52 dB, and K is 1.56.

4. ACE-AGP reduction method

The Active Constellation Extension (ACE) method proposed by Krongold and Jones [14] modifies and expands the constellation points within an allowable region which does not affect the demodulation slicer, also, it does not need side information. different algorithms to achieve the PAPR reduction through the ACE are provided. In this paper, the Approximate Gradient-Project (AGP) will be used since it gives a satisfactory result with less iterations. To reduce the PAPR by the ACE-AGP method, the constellations of the signal are moved such that the PAPR of the time domain is reduced and the minimum distance between constellation points does not decrease, so if the symbol $SRF_m(k)$ is extended to the point $SRF_m(k) + C_m(k)$ then the following optimization problem must be solved [10]:

$$\min_{C_m}\left\{\max_{n}\left\{SRF_m(n) + \frac{1}{\sqrt{N}}\sum_{k=0}^{N_c-1} C_m(k)e^{j\frac{2\pi nk}{N}}\right\}\right\} \quad (12)$$

$$Subject\ to\ \|C_m\|^2 \le \Delta P$$

where ΔP limits the power increase. The ACE-AGP adopts an iterative approach to solve this problem. The iterative signal update can be written as follows (Krongold, and Jones)[14]:

1 Apply an IFFT on the modulated signal X^0 to get x^0. Set $i = 0$.

2 Clip any $|x^i[n]| \ge A$ in magnitude and form:

$$\bar{x}[n] = \begin{cases} x^i[n] & |x^i[n]| \le A \\ Ae^{j\theta[n]} & |x^i[n]| > A \end{cases} \quad (13)$$

3 Compute the clipped signal portion:

$$c_{clip}[n] = \bar{x}[n] - x^i[n] \quad (14)$$

4 Apply an FFT to obtain C_{clip}

5 Keep only the components of C_{clip} which are acceptable extension directions for the given sub-channel constellations and set all remaining directions to zero:

$$C_{clip}[n] = \begin{cases} 0 & \left(\left|R\left(C_{clip}[n]\right)\right| + \left|R\left(x^i[n]\right)\right|\right) \le Q \\ 0 & \left(\left|I\left(C_{clip}[n]\right)\right| + \left|I\left(x^i[n]\right)\right|\right) \le Q \end{cases} \quad (15)$$

Q represent modulation constellation.

6 Apply an IFFT to obtain $c_{clipnew}$ and compute:

$$X^i_{new}[n] = X^i[n] + c^i_{clipnew}[n] \quad (16)$$

7 If an acceptable Cubic metric or a maximum iteration count has not been reached, update and go to Step 2. Otherwise, stop the PAPR reduction.

5. Adaptive Neural Fuzzy Inference Systems

Recently the Neuro-Fuzzy Systems have attracted much intension since they offer many attractive characteristics that overcome some of the limitations in classical computational systems. The purpose of fuzzy logic is to find a link between an input space and an output space, and the main mechanism for this is a list of "if-then" statements called rules. Rules are usually expressed in the form: IF A THEN B, where A and B are labels of fuzzy sets [12]. In this paper we use the typical fuzzy rule in a Sugeno fuzzy model [15][13], which has the following format:

$$if\ x\ is\ A\ and\ y\ is\ B\ then\ z = f(x,y) \quad (17)$$

where A and B are fuzzy sets in the antecedent and $z = f(x,y)$ is a crisp function in the consequent. We consider the first-order Sugeno fuzzy inference system which contains two rules:

$$\begin{aligned} &if\ x\ is\ A_1 and\ y\ is\ B_1 then\ f_1 = p_1x + q_1y + r_1 \\ &if\ x\ is\ A_2 and\ y\ is\ B_2 then\ f_2 = p_2x + q_2y + r_2 \end{aligned} \quad (18)$$

The firing strengths w_1 and w_2 are usually obtained as the product of the membership grades in the premise part, and the output f is the weighted average of each rule's output.

$$\begin{cases} f_1 = p_1x + q_1y + r_1 \\ f_2 = p_2x + q_2y + r_2 \end{cases} \Rightarrow f = \frac{w_1f_1 + w_2f_2}{w_1 + w_2} = \overline{w_1}f_1 + \overline{w_2}f_2 \quad (19)$$

To make the learning easier for the Sugeno fuzzy model, it is necessary to introduce the fuzzy model into the framework of adaptive networks that can systematically compute gradient vectors. The resultant network architecture is called Adaptive Neural Fuzzy Inference Systems (ANFIS). By using an input and output data set, ANFIS can build a Fuzzy Inference System (FIS), whose membership function parameters are here tuned using a backpropagation algorithm in combination with Least Squares (LS) method. In this paper the implemented ANFIS is detailed in Figure 1.

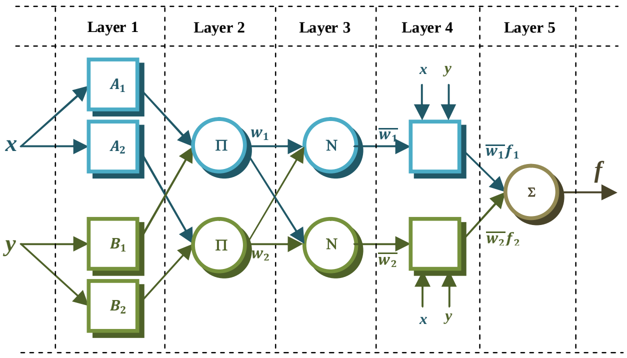

Fig. 1 ANFIS architecture adopted

The proposed ANFIS consists of five layers:

Layer 1: each node in this layer generates membership grades of linguistic labels (Ω_i^j indicates the output of the *ith* node in *jth* layer).

$$\Omega_i^1 = \mu A_i(x) = exp\left(-\frac{(x - c_i)^2}{2\sigma_i^2}\right) \quad (20)$$

where A_i is the linguistic label (small, large, etc.) associated with this node, c_i and σ_i^2 are, respectively, the center and variance corresponding to the Gaussian membership function.

Layer 2: each node in this layer calculates the firing strength of a rule via multiplication

$$\Omega_i^2 = w_i = \mu A_i(x) * \mu B_i(x) \quad (21)$$

Layer 3: node *i* in this layer calculates the ratio of the *ith* rule's firing strength

$$\Omega_i^3 = \frac{w_i}{w_1 + w_2} = \overline{w_i} \quad (22)$$

Layer 4: node i in this layer computes the contribution of *ith* rule to the overall output

$$\Omega_i^4 = \overline{w_i}f_i = \overline{w_i}(p_ix + q_iy + r_i) \quad (23)$$

where $\overline{w}_i$ is the output of layer 3, and $\{p_i, q_i, r_i\}$ is the parameter set.

Layer 5: computes the overall output

$$\Omega_i^5 = f = \sum_i \overline{w}_i f_i \quad (24)$$

In the following subsections, an ANFIS system is developed to learn which time-domain signals exhibit low envelope fluctuations, and another ANFIS operating in frequency-domain is proposed to learn which constellation regions are allowed or forbidden [13](Figure 2).

A. Time-domain ANFIS (FIST)

The first proposal is based on the time-domain ECMA-368 signal. We train our ANFIS by using the signals with low Cubic Metric obtained by the ACE-AGP algorithm. Since ANFIS only works with integer signals, we need to first decompose the time-domain original signal into real and imaginary parts. The sequence of training is described as follows:

1 Use the ACE-AGP algorithm to obtain x^{AGP} a signal with reduced envelope fluctuations from the original signal x^{Org}.

2 Decompose the x^{AGP} and x^{Org} signals into real and imaginary parts $(x_{Re}^{AGP}, x_{Im}^{AGP})$ $(x_{Re}^{Org}, x_{Im}^{Org})$.

3 Create tow ANFIS models $FIST_{Re}$, $FIST_{Im}$ for real and imaginary parts.

4 Obtain x_{Re}^{FIST} and x_{Im}^{FIST} by training the two models $FIST_{Re}$ and $FIST_{Im}$ with the pairs $[x_{Re}^{Org}\ x_{Re}^{AGP}]$ and $[x_{Im}^{Org}\ x_{Im}^{AGP}]$ respectively .

5 Obtain x^{FIST} with $x^{FIST} = x_{Re}^{FIST} + j\, x_{Im}^{FIST}$.

B. Time-Frequency domain ANFIS (FISF)

The main problem with the time-domain training scheme is that the ANFIS is not able to learn which regions in the constellation are allowed or not from the time-domain signal. For this reason, a second ANFIS working on the frequency-domain is proposed. In this scheme, the already obtained signals with the first Time-domain ANFIS are introduced to the second ANFIS by using a DFT. The training sequence is described as follows:

1 Apply DFT on x^{FIST} *and* x^{AGP} to obtain the frequency-domain signals X^{FIST} and X^{AGP}.

2 Separate the four constellation regions of training signals X^{FIST} and X^{AGP} and decompose each one into real and imaginary parts in order to train eight ANFIS.

3 Obtain $X_{Re\,1}^{FISF}, X_{Re\,2}^{FISF}, X_{Re\,3}^{FISF}$ and $X_{Re\,4}^{FISF}$ by training four models $FISF_{Re\,1}$, $FISF_{Re\,2}$, $FISF_{Re\,3}$ and $FISF_{Re\,4}$.

4 Obtain $X_{Im\,1}^{FISF}, X_{Im\,2}^{FISF}, X_{Re\,3}^{FISF}$ and $X_{Im\,4}^{FISF}$ by training four models $FISF_{Im\,1}$, $FISF_{Im\,2}$, $FISF_{Im\,3}$ and $FISF_{Im\,4}$.

5 Concatenate all the results to get :

$$X^{FISF} = X_{Re\,k}^{FISF} + j\, X_{Im\,k}^{FISF}\ , k = 1,2,3,4$$

C. Complexity Analysis

The implemented ANFIS are composed by fives layers as shown in Figure 2. the complexity of Time-domain ANFIS and Time-frequency ANFIS is, in terms of number of integer multiplications, is $18{\times}N$ and $36{\times}N$, respectively, while the number of integer additions is $16{\times}N$ *and* $32{\times}N$, respectively, with N represents number of subcarriers (N=128). The complexity of the ACE-AGP algorithm, in terms of complex multiplications and additions is $N_{iter}{\times}(2N+\ N/2\ \log_2(N))$ and $N_{iter}{\times}(4N+\ N\ \log_2(N))$, respectively [13], where N_{iter} is the number of iterations, while for the Partial Transmit Sequences (PTS) algorithm The complexity, in terms of complex multiplications and additions is $2NJ+(V{\times}(N/2\log_2(N)))$ and $JN(2(V-1)+1)+(V{\times}(N\log_2(N)))$, respectively [20], where V is the partial sequences number and J is the superpositions of all partial sequences. In Table 2, a complexity comparison for ANFIS, ACE-AGP and PTS algorithms is summarized.

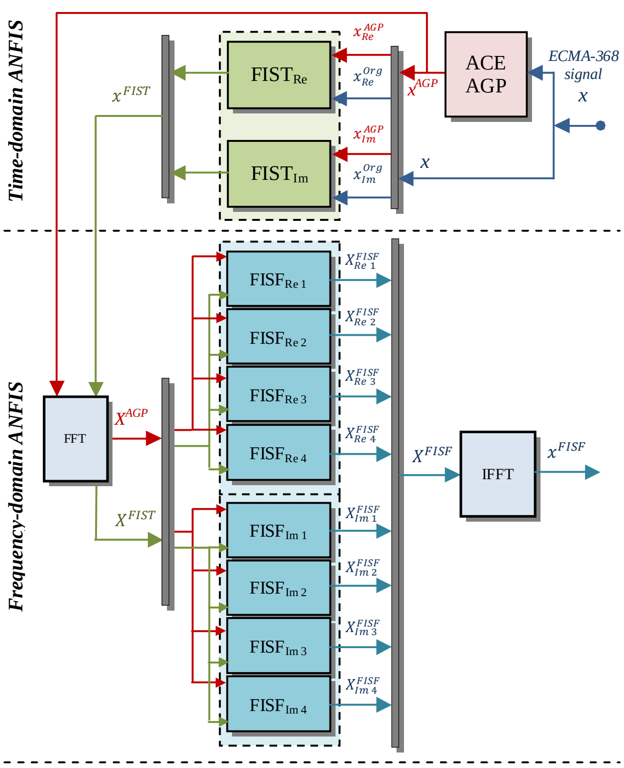

Fig. 2 The proposed models architecture

Table 2 Complexity Comparison.

	ACE-AGP (N_{iter} =50)	*PTS* (J=64 , V=8)	*Time-domain ANFIS*	*Time-Frequency-domain ANFIS*
FFT	100	64	0	2
Complex Mult	35200	23552	-	1280
Complex Adds	70400	268288	-	2560
Integer Mult	-	-	2304	4608
Integer Adds	-	-	2048	4096
Check operations	50	64	-	-

6. Results

First, we study the ANFIS performances when reducing Cubic Metric in ECMA-368 communication system by using Monte Carlo simulations with 10000 MB-OFDM symbols generated as shown in Figure 5. Two data rates are used 200 and 480 Mb/s to test the ANFIS system in two cases: The first one is QPSK modulation and the second is DCM modulation (16QAM). The results of this solution are compared to ACE-AGP and PTS algorithms. For the ACE-AGP, the maximum of iterations was 2000 iterations and the threshold set at A = 4.86 dB, whereas for PTS the partial sequences number was V = 8 and the superpositions of all partial sequences was J = 64. In Figure 3 The curves shown represent the Cubic Metric by using the complementary cumulative distribution function (CCDF).

$$CCDF(CM(x)) = Prob(CM(x) > b) \quad (24)$$

We can easily see that the loss in performance of the proposed Time-Frequency ANFIS system relatively to the Time-domain ANFIS system is less than 0.14 dB in terms of CM. The performances of the two proposed ANFIS solutions exceed those of the PTS algorithm with less complexity and convergence time. Regarding the performance loss in terms of CM, it is less than 1dB with respect to ACE-AGP with 2000 iterations. This performance loss is automatically reduced when the number of iterations N_{iter} is reduced (Figure 4) and with a significant complexity of the ACE-AGP algorithm.

Figure 5 represents the power spectral density of the output signal simulated with Time-domain ANFIS, Time-Frequency ANFIS and ACE-AGP algorithm. It is observed that the ANFIS solution doesn't affect the power spectral density of the transmitted signal and respects the mask of the power spectral density defined by ECMA-368 and FCC.

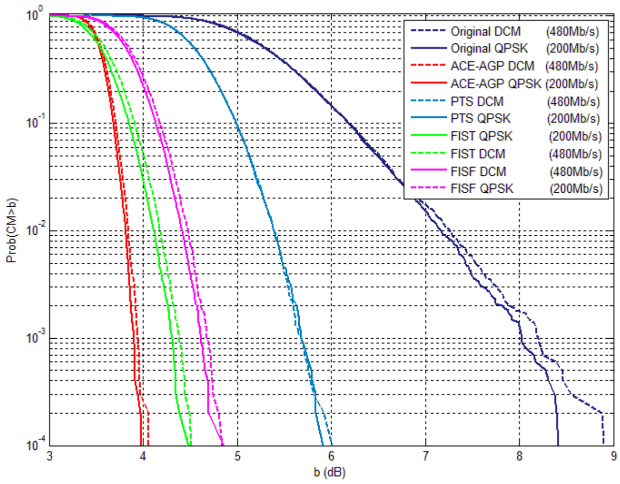

Fig. 3 Cubic Metric comparison

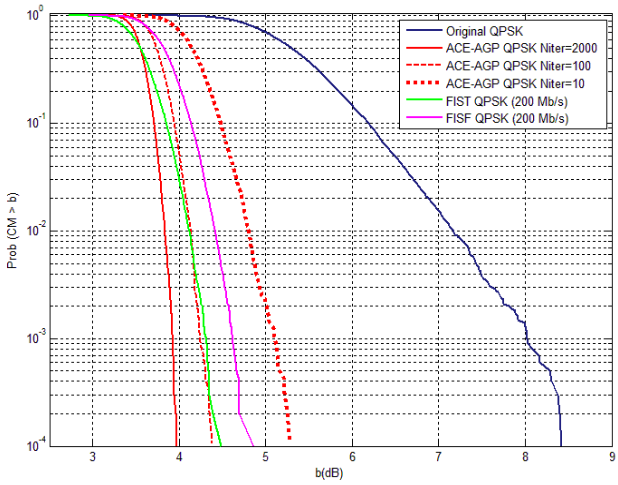

Fig. 4 Cubic Metric comparison with different number of iterations of ACE-AGP algorithm

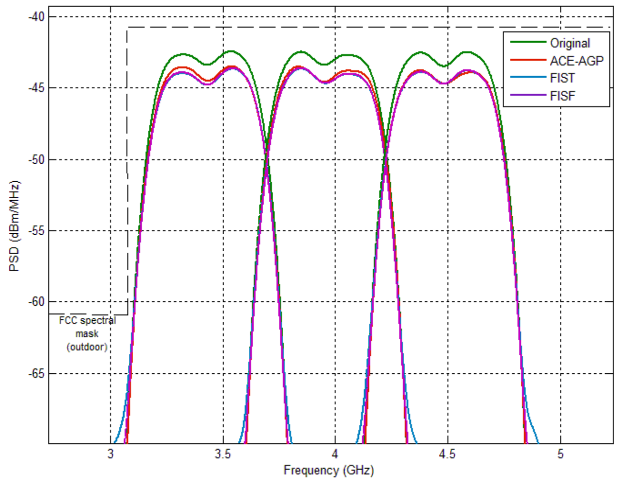

Fig. 5 The power spectral density

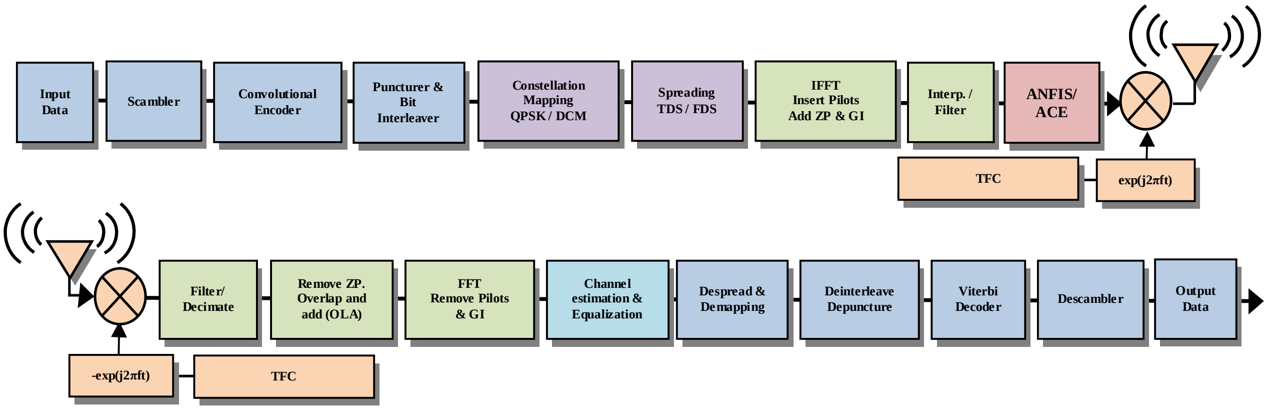

Fig. 6 TX/RX architecture for an ECMA-368 system including the proposed ANFIS

To strengthen the results obtained previously a BER simulations was performed by using the transmission and reception (TX / RX) chains shown in Figure 6. To plot the BER curves of the channel model CM1, CM2, CM3 and CM4 defined by IEEE802.15.3a, an Additive White Gaussian Noise (AWGN) channel was used. These simulations adopt three different data rates 53.3, 200 and 480 Mb/s, and the time frequency codes TFC1 of the band group number 1[8]. In Figures 7, 8, 9 and 10 it can be seen that the ANFIS solution does not significantly affect the BER in all channel models and data rates used for this simulation.

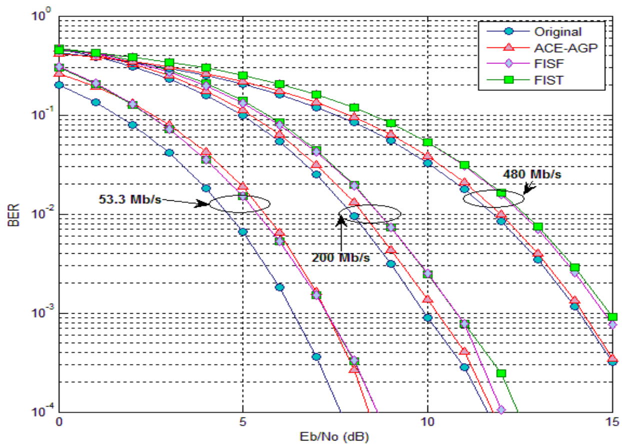

Fig. 7 BER comparison for different schemes (CM1)

7. Conclusion

In this paper a new solution based on ANFIS for reducing the envelope fluctuations in real ECMA-368 communication system signals has been described, evaluated and compared with ACE-AGP and PTS algorithms. The results show that the proposed ANFIS reduces significantly the power fluctuations more than ACE-AGP (when the number of iterations is reduced) and PTS algorithms with less complexity and without significant deformation of power spectral density (respecting the ECMA-368 and FCC power spectral density mask). To support these results, a BER simulation was performed with three different data rates 53.3, 200 and 480Mb/s by using a CM1, CM2, CM3 and CM4 IEEE802.15.3a UWB channel models. The results show that the ANFIS based solution does not affect significantly the original BER.

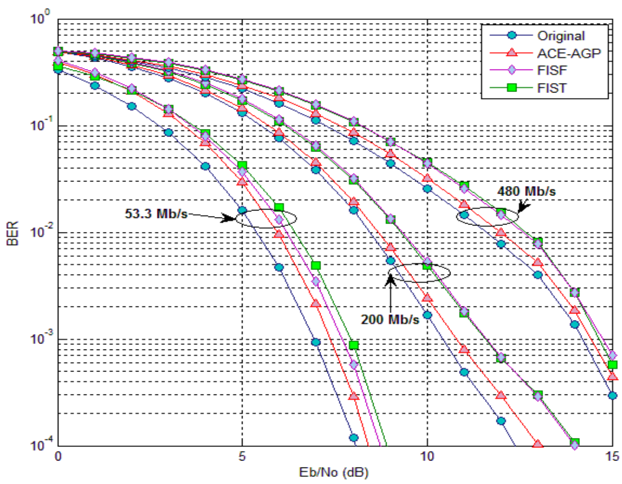

Fig. 8 BER comparison for different schemes (CM2)

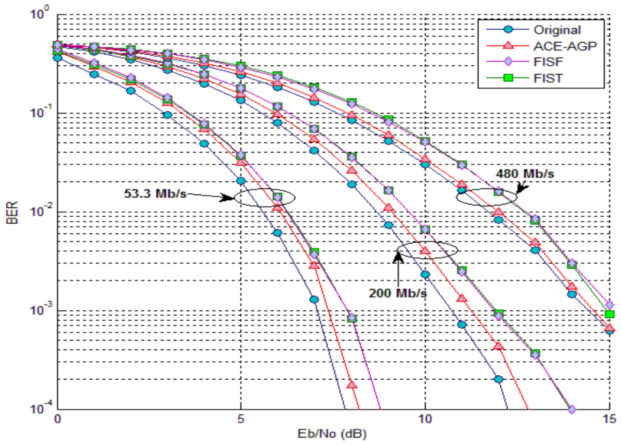

Fig. 9 BER comparison for different schemes (CM3)

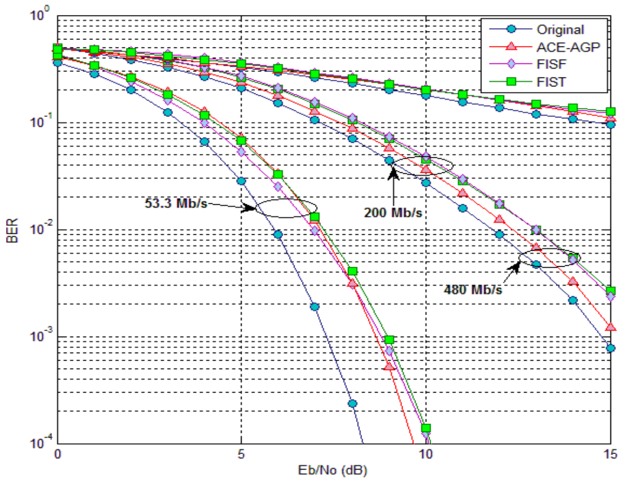

Fig. 10 BER comparison for different schemes (CM4)

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