PWM CODING AND FILTERING OF AN OFDM ENVELOPE SIGNAL IN A C BAND EER TRANSMITTER ARCHITECTURE

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Abstract – This paper concerns the simulation of OFDM envelope path in an EER architecture. The envelope information is clipped to reduce the dynamic variation, PWM coded and low-pass filtered. The PWM coding is simulated with a modified Schmitt trigger with different hysteresis values. The reference voltage shape and frequency choice are discussed. The low-pass filter parameters depend on the frequency of the reference voltage signal and are summarized. The conclusion shows the tradeoff between spectral response and EVM results for choosing Fcomp (frequency of reference signal in the trigger) and h (hysteresis parameter). All simulations are done under HP-ADS software for 16-QAM modulation scheme.

Keywords – EER, architecture, PWM, OFDM, clipping.

I. INTRODUCTION

New 3rd Generation and WLAN (wireless local area networks) standards such as Hiperlan2, WiFi5 and IEEE 802.11a uses OFDM (Orthogonal Frequency Division Multiplex) at 5 GHz. The advantages of OFDM is a high data rate transfer (several Mega-bauds) and robustness in multi-paths environment. Each of the N sub-carriers (N = 64 for Hiperlan2 and IEEE 802.11a standards) of the OFDM uses a QAM modulation scheme (BPSK, QPSK, 16-QAM or 64 QAM). The high disadvantage of OFDM is that the complex envelope of the emitted signal is non-constant. Consequently the power is varying and causes strong non-linearities in the radio-frequency transmitter. Linearization methods are highly needed. EER (Envelope Elimination and Restoration) introduced by Kahn in 1957 [1] is a solution to linearise, keeping high efficiency at the same time. EER is based on the decomposition of the emitted signal in magnitude (envelope varying signal) and phase (constant power signal). Each signals is amplified. Recombination of the information is accomplished by supply modulation of the radio-frequency power amplifier (RF PA).

In EER architecture, the envelope is amplified by a class S amplifier (Pulse Width Modulation coding, class D amplification and low-pass filtering to restore the information). This is all the more difficult to realize that the variation of the signal is important. A clipping operation can be added before PWM in order to reduce the envelope dynamic. The focus of this paper is to give considerations on envelope clipping, coding and filtering operations in such this architecture for OFDM signals.

II. EER ARCHITECTURE FOR OFDM TRANSMITTER

EER architecture principle for OFDM signal is illustrated on Fig. 1. The constant power phase signal, after IQ modulation, drives a high efficiency PA. Due to this power property we can use a RF switched PA (typically class E or F) that will maintain the efficiency of the transmitter. The envelope signal (at symbol frequency, 20 MHz for Hiperlan2 and IEEE 802.11a) has to drive the supply of this PA. The amplification of this signal can be done using the switched supply principle (class D [4]). This is known as class S amplification.

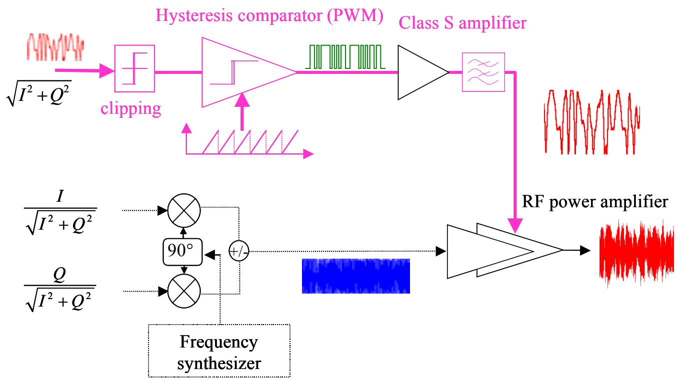

Fig. 1. EER architecture principle for OFDM signal

Class S amplification is composed by three steps : PWM coding, class D amplification and low-pass filtering. The PWM modulation can be realized in different ways. One suitable for RF architecture is to use a Schmitt trigger with a varying reference signal. The choice of the reference signal shape and frequency has to be carefully considered because of spectral consequences [2]. The problem of too fast signal variation is solved by creating an hysteresis on the comparator. The hysteresis limit the minimum width of pulses that can be generated but has an impact on the quality of the signal. The low-pass filter used to restore the low frequency envelope information has parameters determined by the shape and frequency of the reference signal used. The dynamic of an OFDM signal can be lowered to facilitate the PWM coding and reduce the difficulty of supply variation operation. This is called top and bottom clipping on the signal.

Simulations under HP-ADS will help us to see the influence of these operations on the emitted signal quality. The quality estimation is given in terms of EVM (Error Vector Measurement) calculus according to the IEEE 802.11a specifications and spectrum compared to Hiperlan2 typical limits (-40 dBc at 30 MHz offset from the center frequency). We choose a 16-QAM modulation scheme.

III. DYNAMIC OF AN OFDM ENVELOPE SIGNAL

The OFDM signal is characterized by the high variation of its envelope. When the signal has a high number of sub-carriers (N > 30) the Central limit theorem is valid. The complex emitted signal can be considered following a Gaussian law and its envelope a Rayleigh one. Simulations results of Fig. 2 shows the distribution of envelope OFDM signal for N = 16, 32, 64, 128 and 256 sub-carriers.

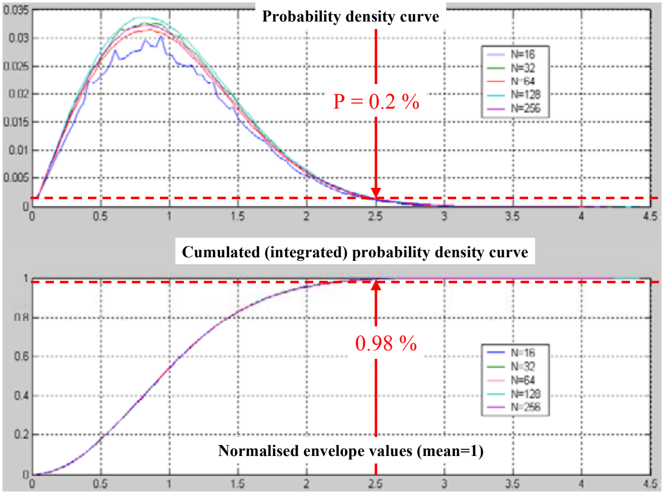

Fig. 2. OFDM envelope simulation for different number of sub-carriers

Distributions shows that the Rayleigh law is well approximated for N > 16. The difference is on the peak value for each N. Looking at cumulated probability showed that only 0.2 % of realization are considered upper than 2.5 times the average value. The higher the number of sub-carriers, the higher the peak to average power ratio (PAPR). It cannot be talk about peak to minimum power ratio (PMPR or Dynamic) without a bottom threshold because OFDM envelope signal minimum value is 0. This would result in a PMPR (Dynamic) value of infinity dB.

$$\begin{aligned} PMPR &= P_{\max} - P_{\min} \\ PAPR &= P_{\max} - P_{mean} \end{aligned} \quad (1)$$

PAPR is majored by N in the case of OFDM signal. That is 15, 18 and 21 dB for N = 32, 64 and 128 sub-carriers. These values are by far too high even if the peak power has a very small probability to occurs. Reducing amplitude of the envelope signal by threshold is known as clipping operation.

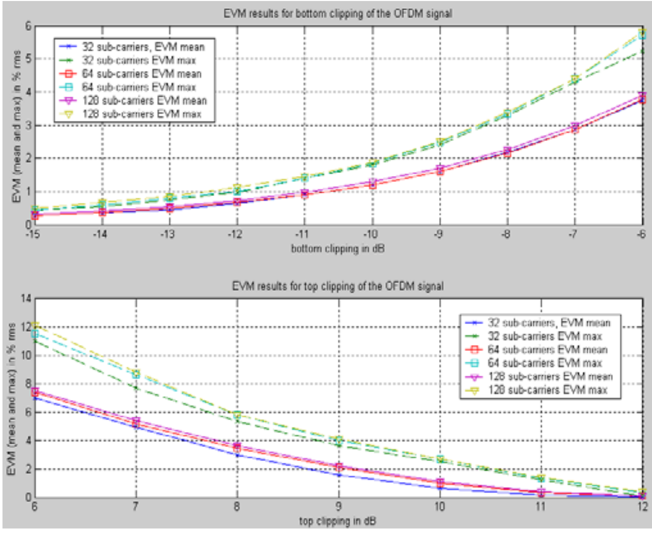

Fig. 3. EVM results for bottom and top clipping

We define bottom and top clipping for the minimum and maximum values of the envelope signal. The results of Fig. 3 are indicated in dB relative to the average power of the envelope signal. Results of EVM (mean and maximum) demonstrated the impact of the number of sub-carriers and the possibility to reduce PMPR and PAPR without strong spectral degradation. A maximum of 1 % for the EVM can be achieved with –13 and +11 dB values (which correspond to 24 dB of dynamic).

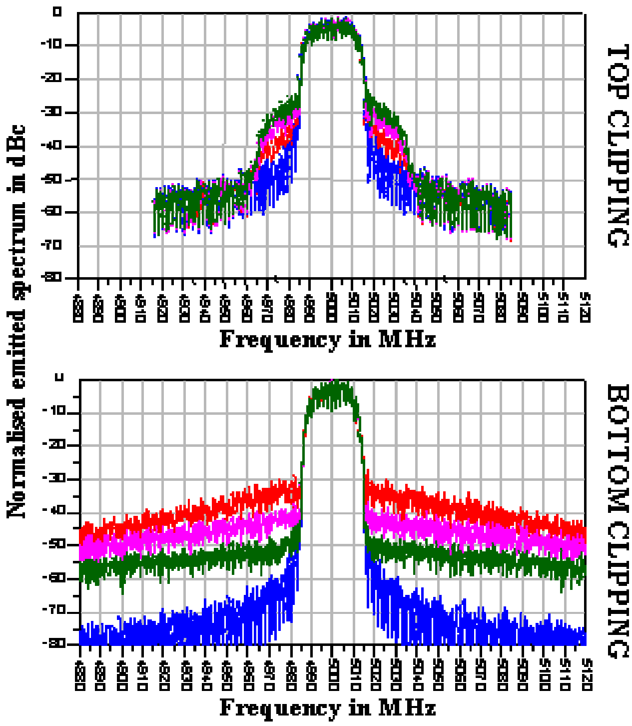

Fig. 4. Emitted spectrum for 4, 6 and 10 dB top clipping (up) and for –6, -10 and –14 dB bottom clipping (down)

Spectrum responses from bottom and top clipping is showed on Fig. 4. It can be seen that spectral requirement of –40 dBc (typical for Hiperlan2) is fulfilled for –14 dB (bottom) and +10 dB (top) clipping. Looking at EVM results, we choose an upper limit of +12 dB and a lower limit of –14 dB. Consequently PAPR = 12 dB and PMPR = 26 dB are fixed for the simulations. This results of a mean EVM of 0.5 % and a maximum EVM of 0.8 % before PWM coding and filtering operations.

IV. PWM CODING AND FILTERING

The generation of the PWM signal is accomplished with a trigger/comparator. First step, we will discuss about the shape of the periodic signal used : triangular or saw-tooth. Each one can be generated with simple circuits using an integrator. The difference lays on the non-symmetry of charging and discharging time. Influence of these shapes on the PWM spectrum is analyzed in [2] where it is demonstrated that spectral expression is dependent of Bessel coefficients. The choice between triangular and saw-tooth is made with using a single sinus at the input of the PWM coder.

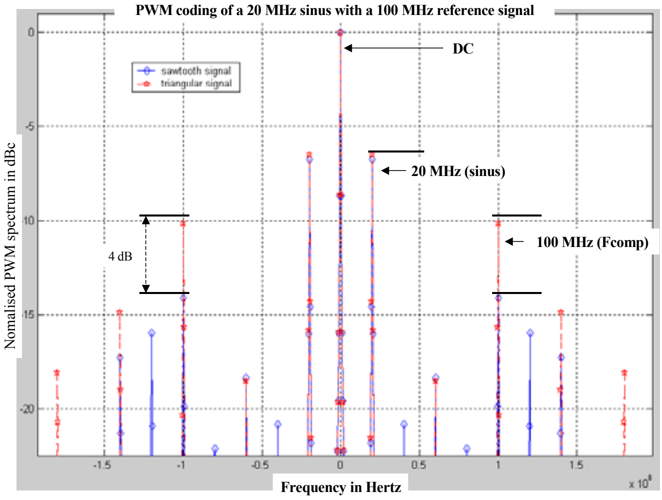

Fig. 5. Spectrum from PWM coding of a 20 MHz sinus with triangular and saw-tooth 100 MHz reference signal.

Whatever the frequency (Fcomp) of the reference signal is, we observed that the corresponding Fcomp frequency is by far higher for the triangle (see Fig. 5). Others spectral frequencies components are at least 10 dB below the useful signal. According to this simulation, the optimum comparison signal shape is a saw-tooth.

The comparator used to generate PWM has a hysteresis. This avoids the presence of too thin pulses driving the class D PA. The Schmitt trigger was simulated using a fast operational amplifier (OP.A) with positive feedback (Fig. 6). When varying the reference signal, the hysteresis phenomenon shifts. A low hysteresis (< 1 %) corresponds to an ideal comparator but suppose the OP.A. to have an infinite slew-rate at its output

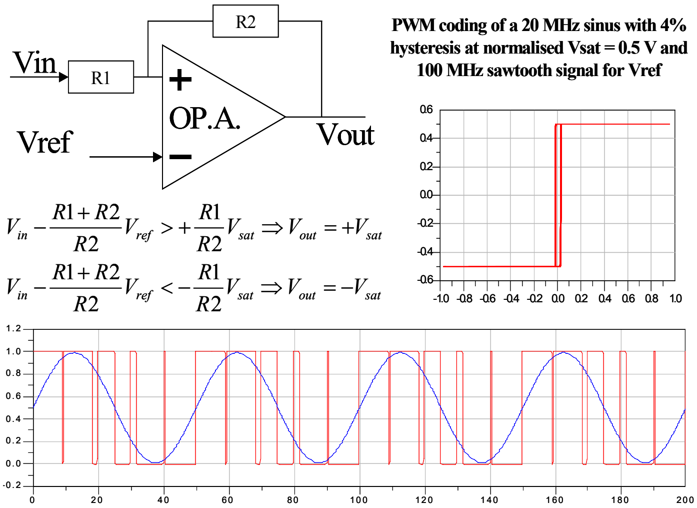

Fig. 6. Realization of PWM coding with a Schmitt trigger and illustration for a 20 MHz sinus (4% hysteresis)

The hysteresis is the possibility to generate thin pulses. It avoids the possibility of voltage peaks. Considering the circuit of Fig. 6, we define the hysteresis parameter **h** as the voltage ratio between the width of the hysteresis and the total input value possible.

$$h = \frac{2\dfrac{R1}{R2}V_{sat}}{\max\left(V_{in} - \dfrac{R1+R2}{R2}V_{ref}\right)} \tag{2}$$

In the simulation of OFDM PWM coding we will introduce the parameter **h** for 4, 6 and 10 %. Fig. 7 illustrates the influence of hysteresis on the width of PWM pulses generated for a 20 MHz sinus (using a 100 MHz saw-tooth signal for comparison). Due to saw-tooth shape (periodic return to zero), the rising edge of PWM pulse appears at the same period while varying **h.** The falling edge happens at (constant) delayed time widening the total width of the pulse.

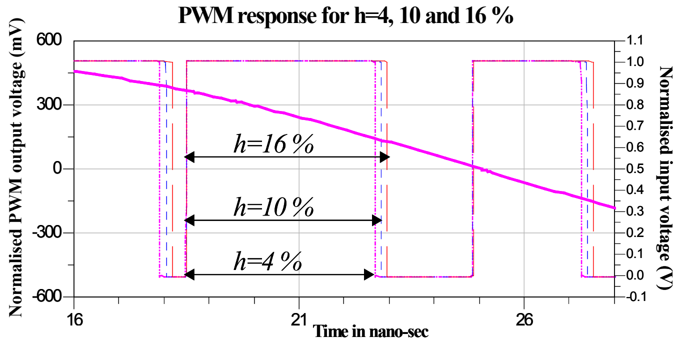

Fig. 7. PWM coding of a 20 MHz sinus with a 100 MHz saw-tooth for h=4, 10 and 16 %

Following step is the choice of Fcomp value. PWM signal is spectrally complex to express [2] and inter-leaving products are produced. That implies constructive or destructive non-symmetrical repartition. The low-pass filtering operation has to be adapted for each value of Fcomp because the filter must attenuate the corresponding spectral frequency. We choose a Cauer type filter and set band-pass and band-stop limits separately. It was showed in [6] that the useful bandwidth of the envelope signal has to be at least 60 MHz. Besides, the filter bandwidth and selectivity must be chosen carefully not to alter spectral information.

In the case of OFDM envelope coding, results from EVM and spectral influence of the two parameters Fcomp and **h** will be summarized.

V. SIMULATION OF PWM CODING AN OFDM ENVELOPE SIGNAL

Simulation of OFDM modulation is realized under HP-ADS. The envelope signal is restored with a low-pass filter after being PWM coded. Pass-band and stop-band parameters are determined thanks to spectrum before and after PWM coding. The pass-band corresponds to the frequency limit until which the two spectrums are different. The stop-band attenuation (–40 dB) is set to cancel the high Fcomp component. As a result, the selectivity is not the same for different Fcomp values.

Table 1. Cauer low-pass filter parameters

F-comp.	**60 MHz**	**80 MHz**	**100 MHz**	**120 MHz**	**140 MHz**
F-pass	20 MHz	30 MHz	35 MHz	35 MHz	35 MHz
F-stop	F-comp.	F-comp	F-comp	F-comp	F-comp
Stop level	-40 dB	-40 dB	-40 dB	-40 dB	-40 dB

The number of sub-carriers between 32 and 256 do not modify filter parameters due to Rayleigh property discussed in part III. Results for these values of N are in a 0.1 to 0.3 % EVM difference. EVM results are plotted on Fig. 8 where filtering operation reveals to be more suitable for 120 MHz than for 100 MHz.

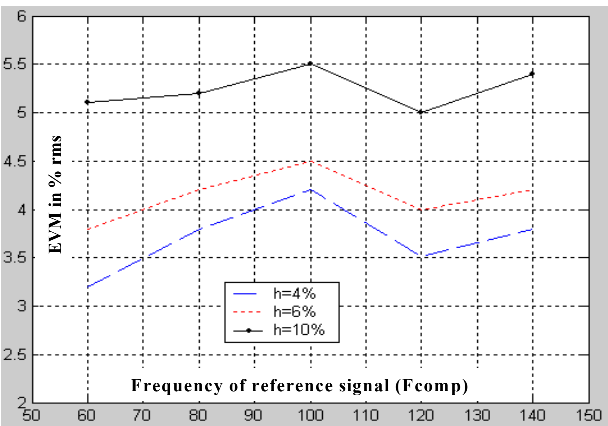

Fig. 8. EVM results for different values of the hysteresis

The presence of added spectral components is seen on Fig. 9 where spectrums of envelope signal after filtering are represented. We can see the inter-modulation product at 40 MHz for Fcomp = 140 MHz. It is not present at lower values of Fcomp. The spectrum of the envelope needs 60 MHz to be preserved [6]. As a result, Fcomp lower than twice this frequency (120 MHz) causes a small overlapping effect (the time between two rising edge is a bit shorter than 1/Fcomp). The convolution effect of the spectrum at Fcomp harmonics requests the frequency Fcomp to be high. However inter-modulation products appear for important values of the reference frequency and the generation of the saw-tooth is limited by circuit possibilities (Fcomp low is preferred).

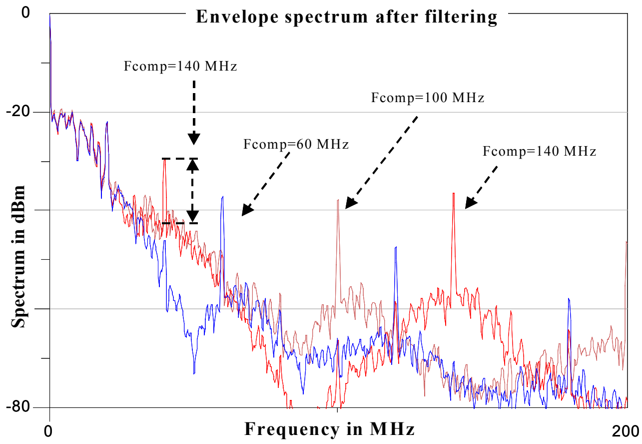

Fig. 9. Envelope spectrum after filtering the PWM signal for different values of Fcomp (h=4%).

The EVM performance is clearly dependent on the low-pass filtering operation. Designing a filter adapted for this type of signal at a given Fcomp would ameliorate performances but it implies that the reference frequency is choosed before. This explains the EVM shape of Fig. 8. The optimum Fcomp according to EVM performances is 120 MHz or 60 MHz depending on the hysteresis.

As previously demonstrated, hysteresis widens pulses of PWM signal. This extends results in a non-uniform increase of the average coded value (constant extra-width is added whenever the pulse started). This produces a distortion of information and modification of the power repartition as shown on Fig. 10.

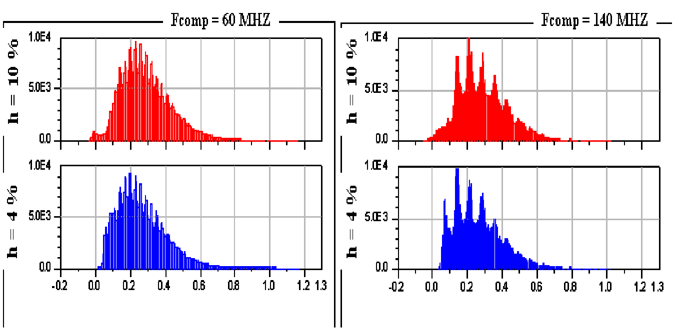

Fig. 10. Normalized histogram of envelope after clipping, PWM coding and filtering for Fcomp = 60 and 120 MHz, h=4 and 10 %

The consequence of 10 % hysteresis is important at low values of the envelope because bottom clipping value is not respected. The solution at strong hysteresis effect is to clip again the envelope after the filter. The hysteresis, as expected, should be low enough not to distort the envelope and high enough to respect trigger maximum voltage variation. The higher the hysteresis, the higher the EVM. The histogram of the envelope signal is rippled due to inter-modulation products which were not cancelled enough by the filter (40 MHz for Fcomp=140 MHz).

Spectral re-growth due to hysteresis are less important than PWM ones. Fcomp is chosen considering the lowest spectral re-growth. This implies to have a reference frequency inferior to 100 MHz.

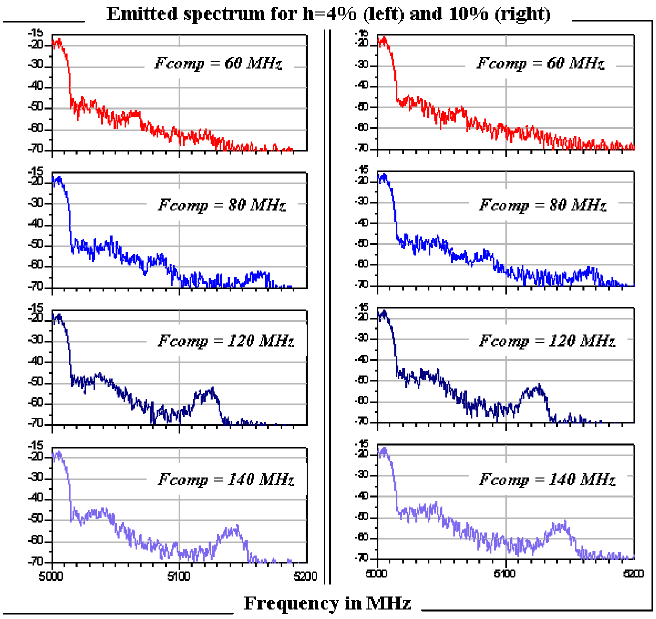

Fig. 11. Emitted spectrum for different values of Fcomp (60 to 140 MHz) and h (4 and 10 %)

The optimum Fcomp value is to be adapted to the circuit possibilities (hysteresis, maximum frequency generated) and to the signal information (not to distort it). Due to PWM expression, higher Fcomp values were considered to have better performances but inter-modulation products and spectral re-growth imply to lower this frequency.

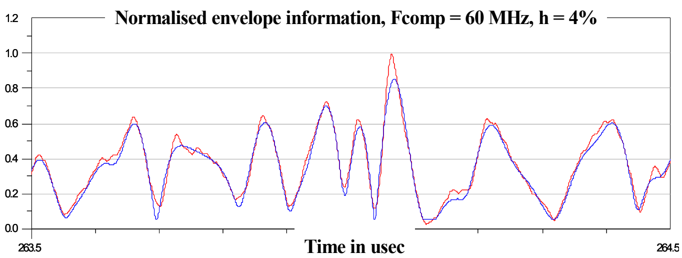

Fig. 12. Envelope information before and after PWM coding and filtering operations for Fcomp = 60 MHz and h = 4 %.

For an OFDM 20 MHz signal with 32 to 256 sub-carriers, a value of 60 to 80 MHz is a good choice (3.5 % of EVM considering a hysteresis of 4 %). Fig. 12 shows the envelope information restored after a PWM coding with Fcomp = 60 MHz (4 % hysteresis).

VI. CONCLUSION

In an EER architecture, the envelope can be clipped and PWM coded to be amplified by a high efficiency amplifier before supply modulation operation. Top and bottom clipping of the envelope signal enable to reduce the PAPR down to 12 dB and the total dynamic to 26 dB resulting in an EVM inferior to 1%.

PWM operation can be realized with a Schmitt trigger using a saw-tooth reference signal. The hysteresis avoids the generation of too thin pulses but causes distortions. This one should be minimum but is dependant on the comparator possibilities (slew-rate). This implies a tradeoff between signal quality and the speed of the trigger.

Fcomp is chosen considering filtering possibilities. The low-pass filter used is to be adapted to each Fcomp value. It is difficult to cancel inter-modulation products without distortions. Spectrally, A high reference frequency is not suited because of filter requirements. EVM performances in these simulations reveals 60 MHz a good choice for the OFDM signal considered.

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