Chapter 8

Conclusions and Future Work

Throughout this work we have reviewed some important aspects related to the study of the pre-distortion as a linearization technique for OFDM signals. The review of formal aspects of OFDM signal generation and the development of expressions for the discrete modeling of the transmission process, allowed us to explore how an exact discrete modeling of the OFDM transmission, including the effects of a nonlinearity, can be accomplished by taking advantage of the properties of spectral periodicity associated to the use of cyclic extensions in OFDM symbols. However, as seen in chapter 4, the validity of such modeling will be mainly limited to the knowledge and characteristics of the analog filters included in the chain. This is a subject that has been presented here as an introductory analysis which could be followed by adding a more complete modeling to express with greater generality the influence of the analog filters over the nonlinear chain. Regarding the PD algorithm proposed and evaluated, the main remarks and conclusions may be summarized, in general, in the following items:

The optimum inverse gain identification is a multidimentional optimization problem whose results can, in general, be improved through the adaptive centroid allocation. Among the possible optimization criteria, we tested the use of the probability distribution of the variable in which the nonlinearity depends on, and also took into account the local variation of the estimated curve. The proposed procedure (ELASTIC) is not only a technique for the optimization of the measures of quality in the linearization process, but it is also intended to aid in the optimization of hardware resources since it performs a search for the optimum use of a very limited number of interpolation coefficients through the intelligent distribution of the interpolation resolution determined by the centroid density along the input range.

Increasing the number of coefficients means greater resolution and lower fitting error provided that the PD coefficients have converged to the optimum trained values. However, the time of convergence is significantly dependent on the number of PD coefficients, featuring a non-linear proportional increment with respect to the corresponding number of centroids. Moreover, as the number of centroids increase, the size of the activation matrix and, consequently, the computational burden involved will become larger. In this sense, the use of interpolation sets longer than $N_c = 16$ seems unreasonable for the application of centroid reallocation. Indeed, the performance improvement achieved with the ELASTIC reallocation in comparison to the use of uniform distributions of centroids was not significant for $N_c = 32$ or higher.

According to the formulation of the ELASTIC algorithm, the inclusion of different types of activation functions in the calculation of the gradient is intended to take into account the probability distribution of the signal amplitude that will be present at the input of a *pre-distortion* device. Therefore, if we perform the centroid adaptation in a simple post-distortion scheme, such as the one shown in figure 7.1(a), the activation information available for ELASTIC will be the input signal PDF distorted by the nonlinear HPA (see figure 5.2). This may lead to sub-optimal centroid allocation when the PDF distortion across the HPA is severe in comparison with the influence of the inverse nonlinear gain characteristic and its variations.

If the ELASTIC algorithm for centroid adaptation is initiated before the PD gain coefficients converge to a relatively low error floor, some of the seldom activated coefficients may still be far away from their expected final positions along the inverse PD gain curve. The positions of such coefficients will define an intermediate pattern according to the convergence velocity determined by the probability of activation associated to each coefficient. Under these conditions, we must note that the centroid allocation algorithm has been formulated to account for the probability distribution of the input signal to the PD block as well as for the differences between consecutive gain coefficients, that is, the local variations of the curve, expressed for example in equation (6.67) through the term $(\alpha_k - \alpha_{k-1})$. Consequently, if the intermediate positions of a group of sub-trained coefficients define a shape very different from the expected PD gain, this could be falsely interpreted by the algorithm as a part of the estimated non-linearity and may force the coefficients to concentrate their centroids around this false local variation. This is the main reason for completing the convergence of the coefficients $\boldsymbol{\alpha}$ before initiating the joint centroid adaptation.

The correct operation of the PD in the systems of figures 7.4 and 7.5 was affected by the band-limitation imposed by the filter $\mathbf{h}_1$. Band pass filters are commonly expected to be highly selective, however, in this case it is required that the filter present a soft transition band since the pre-distorter is also a nonlinearity and behaves as such, producing spectral regrowth over the original input signal PSD. The out-of-band components produced by the PD are, however, necessary to completely compensate the effect of the nonlinear distortion. Therefore this excess bandwidth determines a *compensation bandwidth* which should be incorporated when defining the filters response for the transmission up to the HPA.

The LUT implementations can be considered inefficient in terms of memory resource management. However, addressing a table may be faster than calculating the PD gain when the activation functions are defined with a high number of intervals and coefficients. None of the reported PD implementations using LUTs, to the knowledge of the author, include the probability distribution of the PD input data as an effective way of improving the efficiency of the overall system and/or the distortion compensation levels relative to the specific applications and signal characteristics. It is hence interesting to consider exploring the merging of these concepts of activation functions and LUT-based mapping to achieve greater efficiency in the implementation of digital linearization systems.

Future work

A number of open possibilities regarding the improvement and further evaluation of the proposed algorithms and PD techniques can be listed at this point:

- An interesting task that must be undertaken in the near future is the implementation of the proposed PD scheme in a real prototype to evaluate its performance in comparison with some of the available commercial adjustable PD devices like the MAX2009 (http://www.maxim-ic.com/solutions.cfm/cpk/36/scpk/1311/pl_pk/14/ln/en) which is an integrated PD unit that features compatibility with the 802.11 standards. Through this study it should be possible to define the specific technical limits and conditions that could justify the application of this technique in real systems.

- Future designs for the estimation of the PD gain curve for an unknown nonlinearity may consider some criteria for the incremental determination of the sufficient number of interpolation coefficients given the sharpness or smoothness of an estimated morphology and the required level of nonlinear distortion compensation for each specific application. Thus, starting from a minimum of $N_c = 4$ centroids to span the dynamic range, the bi-dimensional optimization (centroids and gain coefficients) can be carried out for incremental resolution steps until a sufficient correction floor is detected. A long term monitoring of the residual error may be necessary for such adjustment.

- The algorithms were presented assuming a fixed and normalized dynamic range $[0, 1]$. Hence, a suitable scaling of the sampled signals is assumed in order to fix the unitary gain as the ideal response. Such scaling can be easily implemented through the control of linear attenuators at the return path. Nevertheless, one could expect the appearance of gain stability problems that are implicit to most types of closed-loop control. Therefore, a careful analysis of these non-trivial topics on the stability of the adaptive architecture of a real PD system must be considered.

- The fine compensation of the memory effect along the chain with adaptive filtering stages is a major challenge in the quest for optimal PD performance. Real adaptive schemes must include adaptive filters to compensate for the memory effect introduced along the analog part of the transmission chain, which is a major obstacle

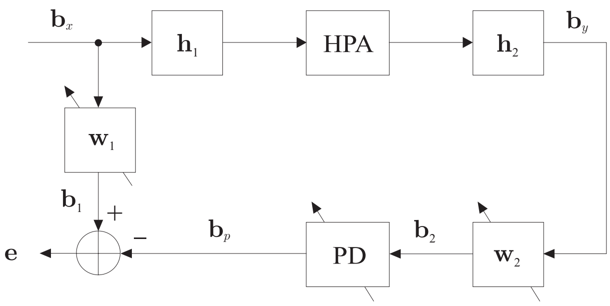

Figure 8.1: Joint optimization of a PD block and adaptive filtering coefficients for the compensation of the nonlinear distortion introduced by the HPA and the fractional delays introduced by the analog filters $\mathbf{h}_1$ and $\mathbf{h}_2$.

to achieve optimal performance of the PD. Therefore, a complete evaluation of the proposed linearization scheme in a real chain must be carried out by considering the exhaustive modeling of the fractional delays introduced by analog filters along the signal path. The compensation of fractional delays requires the inclusion of adaptive stages with memory, such as interpolators or filters, in the pre-distortion branch. Among the previous approaches to the present study, some schemes considering the joint adaptation of a pre-distortion gain and a set of adaptive filters were investigated. The results obtained for the adaptive scheme in figure 8.1, for instance, presented some major difficulties that should be reviewed for a future implementation. The main drawback was a percentage of gain migration to the coefficients of the adaptive filters $\mathbf{w}_1$ and $\mathbf{w}_2$ which tend to compensate for the responses of $\mathbf{h}_1$ and $\mathbf{h}_2$ and their related time shifts, but also tend to compensate for the linear part of the HPA gain. This constitutes another important challenge for a future design, since the nonlinearity compensation in a real system will consider analog memory effects whose compensation must be implemented as part of the discrete signal processing and without introducing additional hardware. Linear gain blocking using orthogonal projectors is one of the possible low-cost alternatives considered for the continuity of this research line.

The number of vehicular applications where linear and efficient amplification units are required increases every year. As a matter of fact, nowadays, HPA linearization is a field of great interest for the new High Altitude Platform Systems (HAPS) currently being developed to provide communications coverage in specific areas at a lower cost than satellite-based networks. Although linearization is a subject normally associated to electronics and communications technologies, many of the linearization techniques that are proposed for the specific treatment of power amplifiers are also extensible to other applications of nonlinear compensation or nonlinear system identification in a variety of fields. This encourages us to keep working from the scope of communications signal processing and contributing to the development of new advances in this wide-ranging research field.