BASEBAND PREDISTORTION SYSTEM FOR LINEARISING POWER AMPLIFIERS

TECHNICAL FIELD

The present patent request for industrial invention concerns a predistortion system which linearises amplifiers that exhibit non linear distortion phenomena.

BACKGROUND OF THE INVENTION

Usually an instantaneous non linear amplifier can be modelled by its AM/AM and AM/PM distortion curves [1], [2]. Both types of non linear distortions produce the spectral regrowth of the amplifier output; this spectral regrowth can be classified in the two following categories:

- In band intermodulations
- Out band intermodulations.

The firsts cannot be eliminated by linear filtering and they are responsible for the signal-to-noise ratio degradation and, consequently, for the Bit Error Rate (BER) degradation in digital communication systems. The seconds generates the interference between adjacent channels and they can be filtered out at the amplifier output with a certain output power penalty that is caused by the filter insertion losses.

Baseband predistortion is one of the known techniques to counteract for AM/AM and AM/PM distortions [2][3] and its digital adaptive implementation was widely investigated in the last years [4] [5] [6] [7].

However, even an ideally predistorted amplifier, because of its maximum output power, can be modelled as a device, which in the following will be called soft-limiter, that limits the signal envelope to be lower than a certain maximum value. As a consequence the saturation non linear distortion is not avoidable every time that the signal modulation is characterised by a non constant envelope and the amplifier doesn't work with an adequate difference between the maximum and the mean output power. This situation is typical for multicarrier signals that are characterised by an high peak-to-mean power ratio; consequently, their maximum signal envelope is usually reduced by an operation, that it is called clipping, in order to have a more efficient power amplification even if paying the price of a reduced spectral purity. The difference between the maximum and the working amplifier output power is commonly said the back-off.

The aim of the present invention is to realise a predistortion system to linearise non linear amplifiers in such a way to make cheaper and less complex, or even to eliminate, the amplifier output filters that are used to reduce the out band spectral regrowth.

No one of the already known predistortion systems considers in detail the clipping phenomenon as an integrating part of the predistortion process. The invention consists in the joining of the predistorting action with the signal pre-clipping, in order to avoid or reduce other clipping phenomena and the amplifier saturation and allowing, at the same time, the filtering of the out band intermodulations that are produced by the clipping action itself.

The said objective is achieved trough the predistortion system, by means of what has been discovered, which includes a predistortion circuit, a clipping circuit to reduce the peak-to-mean power ratio of the signal and a device for the filtering of the spectral regrowth that is produced by the clipping circuit itself. The pre-clipping term is used to remark that the clipping operation has to be performed before the predistorting one.

Second aim of the invention is to provide adaptation to the predistortion system.

This second objective is achieved, by means of what has been discovered, by including in the predistortion system both an input-output error circuit that provides the values to modify the action of the said predistortion circuit and a timing circuit to synchronise the input to the output of the system.

Some considerations are reported in the following to better understand the reasons to introduce the clipping before the predistortion circuit:

- Both the predistortion circuit and the RF amplifier introduce non linear distortions (i.e. AM/AM and AM/PM) that only depend on the baseband signal envelope and, consequently, on the instantaneous signal power.
- The ideal combination of the predistortion circuit with the amplifier gives rise to an overall system that is characterised by a completely cancelled AM/PM curve and by a residual AM/AM curve that acts as a soft limiter of the baseband signal envelope.

This means that the RF output of the ideally predistorted amplifier is equivalent to the RF modulation of a complex baseband signal whose envelope is passed through a soft limiter device. The residual distortion introduced by the soft limiter depends on the signal peak-to-mean power ratio and on the input back off to the predistorted system (soft limiter).

A residual distortion is introduced every time the input back off to the predistorted system is lower than the peak-to-mean power ratio of the signal.

The distortions become as more evident as the input signal is characterised by a high peak-to-mean power ratio.

If the predistorted amplifier introduces some clipping on the signal envelope, the consequent spectral regrowth will degrade the signal with respect to the signal-to-noise ratio and the adjacent channel interference.

The signal-to-noise ratio degradation for a fixed input back off is not avoidable because it depends on the in band intermodulations. On the contrary, the linear filtering of the out band intermodulations that are produced by the clipping can reduce the adjacent channel interference.

If the predistorted amplifier generates some clipping, the only way to reduce the adjacent channel interference is to introduce a RF filter at the amplifier output.

The consequence is a significant expense in terms of equipment costs and a reduction of the available output power because of the filter insertion losses.

An idea that characterises this invention is to realise at baseband a clipping on the signal envelope that is analogous to the one that would be introduced by the predistorted amplifier.

Such an approach allows, by the use of devices that in the following we will call post-clipping filters, a baseband counteraction of the adjacent channel interference that are introduced by the clipping circuit itself.

In this way it is possible to obtain the same residual adjacent channel interference, for a given output power, that would be obtained by using RF selective filters, with a significant reduction of the system costs.

However both the clipping and the post-clipping filtering has to be implemented before the predistortion circuit, in order to not vanish the predistorter action.

In this way, the output of the post-clipping filters represents the baseband equivalent of the best residual distorted signal that can be obtained at the predistorted amplifier output.

In order to clarify the notation that will be used in the following of the description and in the included figures we remind that a modulated RF signal $x(t)$ can be analytically represented by the following expression

$$x(t) = R_x(t)\cos\{\omega_0 t + \theta_x(t)\}$$

where $R_x(t)$ and $\theta_x(t)$ respectively represent the instantaneous envelope and the instantaneous phase of the modulating signal.

The signal can be equivalently represented at baseband by the complex signal $\hat{x}(t)$ that is defined in polar notation as

$$\hat{x}(t) = R_x(t) \cdot e^{j\theta_x(t)}$$

The complex signal $\hat{x}(t)$ can be also represented by its cartesian notation as

$$\hat{x}(t) = x_I(t) + jx_Q(t)$$

where $x_I(t)$ and $x_Q(t)$ are respectively the so called In-phase and Quadrature signal components and they are related to the polar notation by the following expressions

$$x_I(t) = R_x(t) \cdot \cos\left[\theta_x(t)\right]$$
$$x_Q(t) = R_x(t) \cdot sen\left[\theta_x(t)\right]$$

The relationship between the RF modulated signal and its complex baseband equivalent is expressed by

$$x_{RF}(t) = \text{Re}\left\{\hat{x}(t) \cdot e^{j\omega_0 t}\right\} = x_I(t)\cos\omega_0 t - x_Q(t)\sin\omega_0 t$$

In order to improve the exposition clarity it will be described in the following the system architecture of a possible, but not limiting, realisation of a predistortion system that exploits the invention. This description, which takes advantage of the included figures from 1(a) to 6, will employ the complex baseband signal representation. The Fig.1 (a) represents the scheme of an amplification system that make use of a base band Predistortion System (1) which combines the use of a Clipping and Interpolation Circuit (2) with a Predistortion Circuit (3).

If the Predistortion Circuit (3) works at RF rather than at baseband, the amplification system scheme is quite equivalent to the Quadrature modulation Circuit (9) that is positioned before a Clipping Circuit (5) which as well is positioned before the Predistortion Circuit (3). Specifically the Interpolation Circuit (4) can be realised by a Filling Circuit (4a) that inserts (N-1) zeros, or (N-1) replica of each sample, between the signal input sample, with N being the interpolation factor. The real interpolation function is performed in cascade by the action of the Interpolation Filter Circuit (IFC) (4b).

The signal that has been interpolated in such a way is elaborated by the Clipping Circuit (5) which firstly limits its maximum envelope (by the Clipping Device (5a)) and afterward eliminates the out band spectral regrowth (by the Post Clipping Filters Circuit (PCF) (5b)).

Instead, the Fig.2(b) represents the detail of a Predistortion System (1) that is alternative to that of Fig.2(a). In this case an Interpolation & Clipping Circuit (2) firstly performs the Clipping action by the Clipping Device (5a), which is followed in cascade from a Filling Circuit (4a) that introduces some zeros or some input sample replica. The Filling Circuit (4a) is followed by the Filtering Circuit (4c) that jointly realises the real interpolation filtering (IFC) and the post clipping filtering (PCF) of the signal outband spectral regrowth.

The Fig.3(a) and 3(b) graphically show the clipping operation that is performed on two general complex signals $V_{1,2} = V_{I_{1,2}} + jV_{Q_{1,2}}$ by the Clipping Device (5a).

The Fig.3(b) and 3(a) respectively represent the action of a Cartesian Clipping Device and the action of an Envelope Clipping Device. The first separately cuts each one of the (V_I, V_Q) components that overcomes a certain value, while the second jointly works on the (V_I, V_Q) components by cutting them in such a way that the envelope is lower than a certain threshold).

The Fig.4(a) and 4(b) shows two possible logical schemes to implement the base band Predistortion Circuit (3). The Fig.4(a) scheme includes the use of the Device(3a) to realise the signal conversion from the cartesian representation $\hat{s}(t) = s_I(t) + js_Q(t)$ to the polar representation $\hat{s}(t) = R_s(t)e^{j\theta_s(t)}$.

The signal envelope $R_s(t)$ is used to address the Predistortion Table (6). The Predistortion Table (6) is organised in two Tables (6a) and (6b). When the Fig.4(a) scheme is employed, the signal envelope values $R_p(t)$ of the Predistortion Circuit (3) output are memorised in Table (6b) while the predistortion phase values are memorised in Table (6b). These phase values will provide the predistortion signal phase values $\theta_p(t)$ after they have been added to the input signal phase $\theta_p(t)$. The envelope $R_p(t)$ and the phase $\theta_p(t)$ of the predistortion signal that was obtained in this way are elaborated by the Device (3b) which reconverts the predistortion signal into its Cartesian components $p_I(t)$ and $p_Q(t)$.

The alternative scheme of Fig.4(b), which works directly on the Cartesian components $s_I(t)$ and $s_Q(t)$ of the input signal, performs the predistortion by a complex product of the input signal $\hat{s}(t)$ with the complex signal whose Cartesian components are the Predistortion Table (6) outputs. When the Fig.4(b) scheme is employed, the content of the Table 6(a) and 6(b) is chosen in such a way that the analytical operation that are performed on the input signal would be equivalent to that introduced from the Circuit (3) in Fig.4(a).

The Fig.5 represents the conceptual scheme for an amplification system that includes the adaptation of a baseband predistortion system. This scheme includes the use of a Synchronisation Circuit (8) for the synchronisation of the Predistortion Circuit (3) input signal $\hat{s}(t)$ with the RF amplifier output signal $\hat{a}(t)$.

A circuit (7) is also employed in order to determine the input-output error signal.

The Fig.6 represents the logical scheme of a potential realisation of the Error Circuit (7) when the Predistortion Circuit (3) is realised by means of the Fig.4(a) scheme.

The signal $\hat{x}(t)$ in Fig.1 represents a complex digital signal at the input to the Predistortion System (1). This signal $\hat{x}(t)$ can be eventually oversampled by the Interpolation Circuit (4) of Fig.2(a) or by the Circuit (4a) of Fig.2(b), if the input sample frequency is not high enough to correctly represent it in a non linear environment.

The Clipping Device (5a) that is shown Fig.2(a) or Fig.2(b) limits the peak-to-mean power ratio of the signal in order to avoid or reduce any other clipping or saturation phenomenon that could be introduced by the Predistortion Circuit (3) and/or the RF Amplifier.

The Clipping Device (5a) reduces the signal peak-to-mean power ratio constraining the envelope of the baseband signal inside a circle of the complex plane, as shown in Fig.3(a), by a technique that is called Envelope Clipping.

It is possible, anyway, to reduce the peak-to-mean power ratio also by using some others clipping strategies. An alternative choice, for example, is to separately clip the In Phase and In Quadrature signal components as shown in Fig.3(b), by a technique that is called Cartesian Clipping. The Cartesian Clipping reduces the signal envelope but it also introduces some extra phase distortion on the signal as shown in Fig.3(b).

Moreover the Cartesian Clipping is not exactly matched to the Envelope Clipping that is introduced by the predistorted amplifier. As a consequence the predistorted amplifier will introduce further clipping if the complex signal clipping is realised outside to the square that is circumscribed to the amplifier clipping circle. On the contrary, unneeded extra distortions is introduced by the Cartesian Clipping if the clipping square is inscribed into the amplifier clipping circle, as shown in Fig.3(b).

However the Cartesian Clipping is easier and cheaper to implement and consequently it may be considered as a good compromise between performance and costs.

Any kind of clipping strategy can be performed before or after the interpolation process (see Fig.2(a) and Fig.2(b)) if the Interpolation Circuit (4) is included in the Predistortion & Clipping Circuit (1).

The Clipping Circuit (5) that is placed after the interpolation circuit represents the best solution in terms of the achievable performance.

The other approach, nevertheless, is characterised by a lower system complexity because the Post Clipping Filters Circuit (4c) acts as the interpolation filter also.

The output $\hat{s}(t)$ of the Clipping & Interpolation Circuit (2) represents the input to the Predistortion Circuit (3). The Predistortion Circuit (3) by the modification of the complex signal components

$s_I(t)$ and $s_Q(t)$, generates the $p_I(t)$ and $p_Q(t)$ in such a way to introduce the AM/AM and AM/PM distortions that compensate for the ones that are introduced by the RF Amplifier.

There are several ways to realise this kind of non linear distortions as reported in [5],[6] and [7]. Both the solutions that are shown in Fig.4(a) and Fig.4(b) make us of some look-up tables in which the desired distortions are memorised, and where the signal envelope $R_s(t)$ is used as unique address in order to reduce the dimension of the Predistortion Tables (6a) and (6b).

Nevertheless, it is possible to consider any other kind of realisation of the Predistortion Circuit (3) without reducing the efficacy and the originality of the main idea that is proposed in this invention where the predistorter action is combined and optimised with the clipping strategy.

The Predistortion Circuit (3), which is shown in Fig.4(a), is probably one of the most intuitive because it directly makes use of the AM/AM and AM/PM distortion curves.

On the contrary, the Predistortion Circuit (3) that is shown in Fig.4(b), uses a Complex Gain representation of the non-linear input-output characteristics. This second approach allows working with Predistortion Tables (6a) and (6b) that are characterised by a lower dimension, even if the overall system complexity is increased.

The Predistortion Circuit (3) may also adapt the distortion to introduce, according to the changes of the working conditions that are caused by ageing, temperature variations, channel or power switching, and so on.

The Error Circuit (7) has the role to estimate the input-output non-linear error of the predistorted system and to provide an error signal $\hat{e}(t)$ to the Predistortion Circuit (3).

The Fig.6 shows a possible implementation of the error circuit, where the envelope (a scaled replica) and the phase of the Predistortion Circuit input $\hat{s}(t)$ are subtracted from the correspondent amplifier output $\hat{a}(t)$.

The two error signals $R_e(t)$ and $\theta_e(t)$ that are obtained in this way are subsequently weighted by two real coefficients α_R and α_θ in order to provide the correcting terms for the action of the Predistortion Circuit (3).

The two error signals are analytically expressed by

$$R_e = \alpha_R \cdot [R_a - G \cdot R_d]$$

$$\theta_e = \alpha_\theta \cdot [\theta_a - \theta_d]$$

where G represents the desired linear gain for the predistorted amplifier.

The algorithm has to be likewise implemented in Cartesian coordinates if the Predistortion System (1) make use of the Predistortion Circuit (3) that is shown in Fig.4(b).

The magnitude of the adaptation coefficients has to be chosen as a compromise between adaptation speed and noise rejection.

The Synchronisation Circuit (8) has the role to estimate the loop delay of the adaptive system and to compensate it, in order to allow to the Error Circuit (7) to correctly compare the input $\hat{s}(t)$ of the Predistortion Circuit (3) with the output $\hat{a}(t)$ of the amplifier.

We claim:

1. A predistortion system for amplifiers linearisation, that is characterised by the fact of including a predistortion circuit (3) which is in cascade to a clipping circuit (5) that is composed by at least one clipping device (5a) which is followed by at least one post-clipping filter device (5b)
2. According to claim 1, a system that is characterised by the fact of employing at least one predistortion table (6).
3. According to claim 1, a system that is characterised by the fact of employing at least one interpolation circuit (4) of the said signal.

4. According to claim 3, a system that is characterised by the fact that the said interpolation circuit is realised by a circuit (4a) for the insertion of zeros or replica of the first sample between successive samples of the said signal, with the circuit (4a) that is followed by an interpolation filters circuit (4b) or (4c).

5. According to claim 3, a system that is characterised by the fact that the said clipping device (5a) is positioned before the said interpolation circuit (4) and in which the said post-clipping filters device (4c) acts as interpolation filters.

6. According to claim 3, a system that is characterised by the fact that the said clipping circuit (5) is positioned after the said interpolation circuit (4).

7. According to claim 2, a system that is characterised by the employment of an adaptation circuit (10) that is at least composed by a synchronisation circuit (8) and by an error circuit (7) which generates at least one error signal in order to update the said predistortion tables (6).

8. According to claim 2, a system that is characterised by the fact that the said predistortion tables (6) are addressed by the signal at the input of the said predistortion circuit (3).

9. According to claim 1, a system that is characterised by the fact that said clipping device (5a) limits the envelope of the said signal, leaving its phase unchanged.

10. According to claim 1, a system that is characterised by the fact that said clipping device (5a) separately limits the two cartesian components of the said signal, therefore limiting its envelope and also altering its phase.

11. According to claim 7, a system that is characterised by the fact that the said error circuit (7) generates at least one of the said error signal by the subtraction of the envelope and the phase of the amplifier baseband output signal from the corresponding components, at most scaled by a multiplicative coefficient, at the input to the said predistortion

12. According to claim 7, a system that is characterised by the fact that each of the said error signals is multiplied by at least one weighting coefficient.

13. According to claim 7, a system that is characterised by the fact that each value of the said predistortion tables (6) is updated, for each value of their address, by summing to their original content the value of the said error signal or a temporal mean that is performed on a number of values, that is greater or equal to one, that are consecutively assumed by the said error signal for each address value.

References

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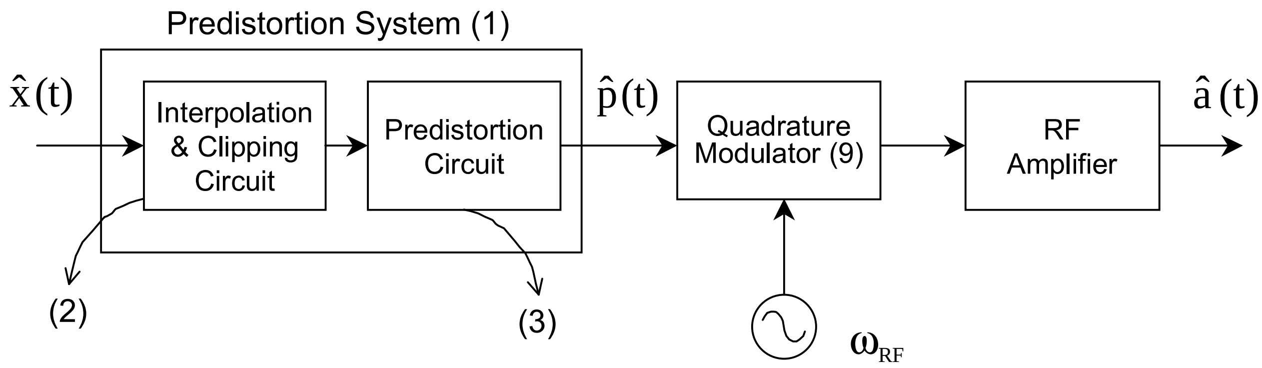


Fig.1(a)

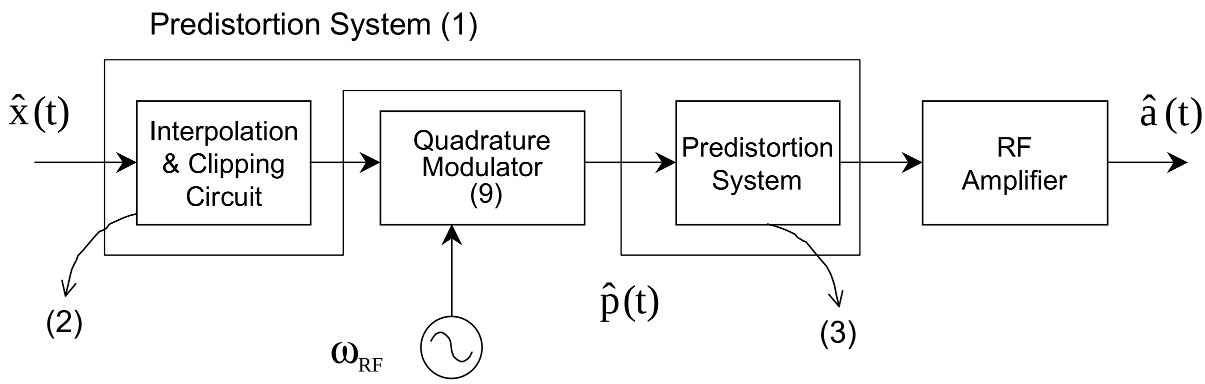
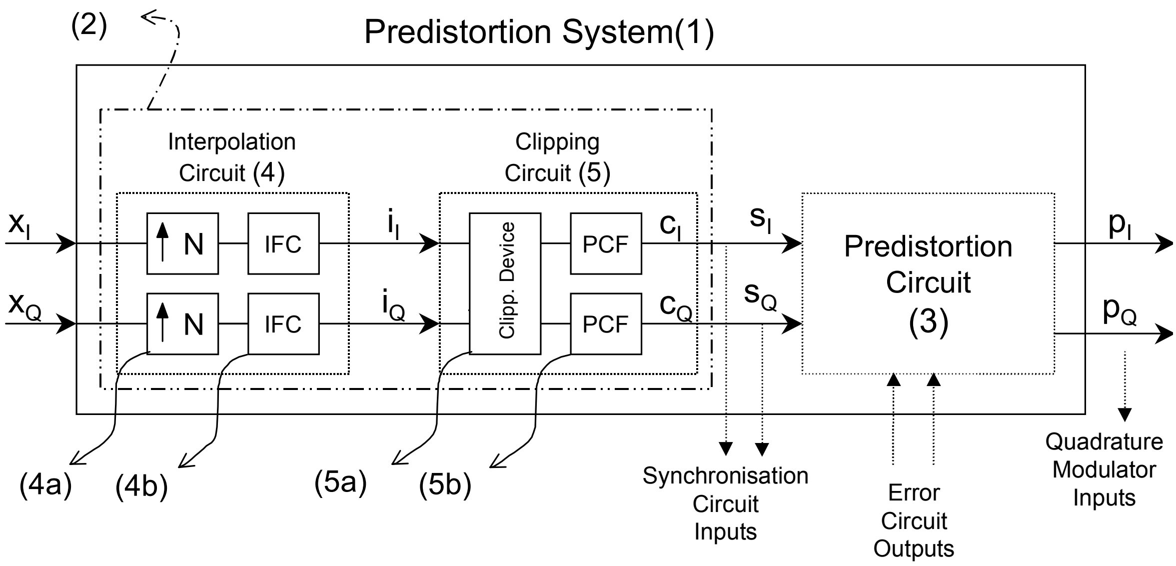
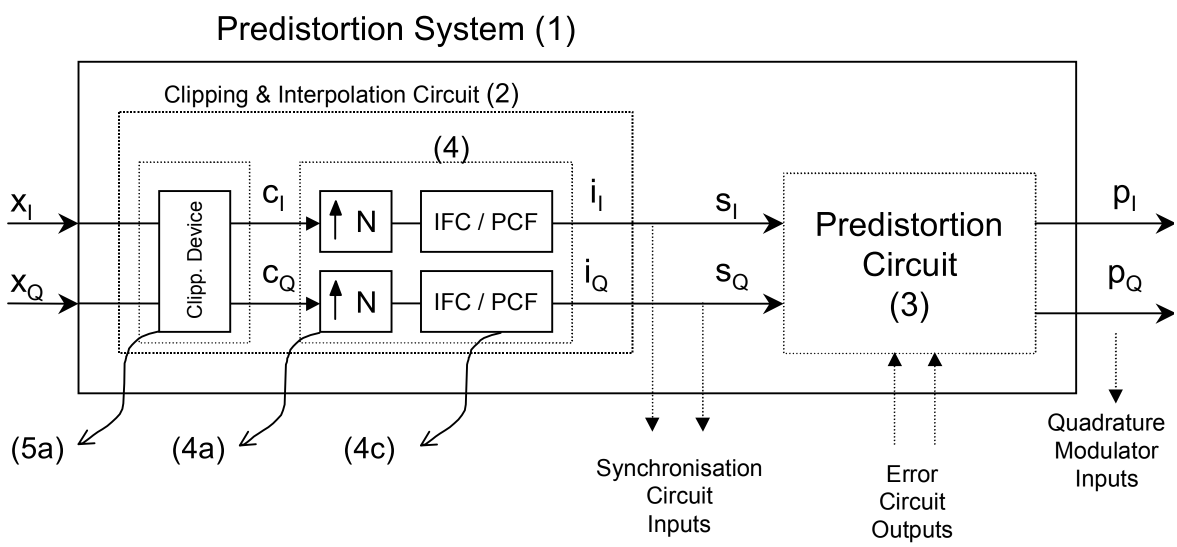


Fig.1(b)



(2)
Predistortion System(1)
Interpolation Circuit (4)
Clipping Circuit (5)
x_I
x_Q
N
N
IFC
IFC
i_I
i_Q
Clipp. Device
PCF
PCF
c_I
c_Q
s_I
s_Q
Predistortion Circuit (3)
p_I
p_Q
(4a)
(4b)
(5a)
(5b)
Synchronisation Circuit Inputs
Error Circuit Outputs
Quadrature Modulator Inputs

Fig.2(a)



Predistortion System (1)
Clipping & Interpolation Circuit (2)
(4)
x_I
x_Q
Clipp. Device
c_I
c_Q
N
N
IFC / PCF
IFC / PCF
i_I
i_Q
s_I
s_Q
Predistortion Circuit (3)
p_I
p_Q
(5a)
(4a)
(4c)
Synchronisation Circuit Inputs
Error Circuit Outputs
Quadrature Modulator Inputs

Fig. 2(b)

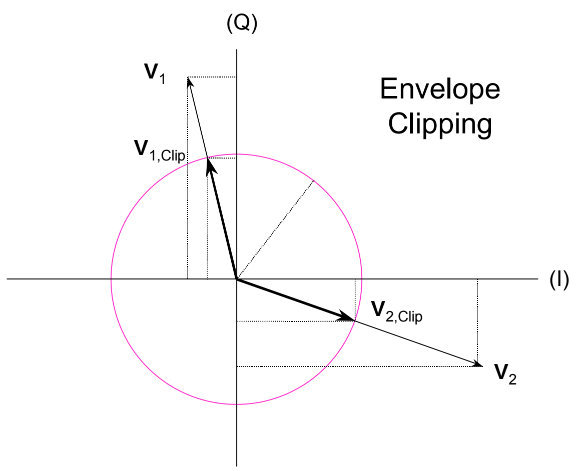


Fig.3(a)

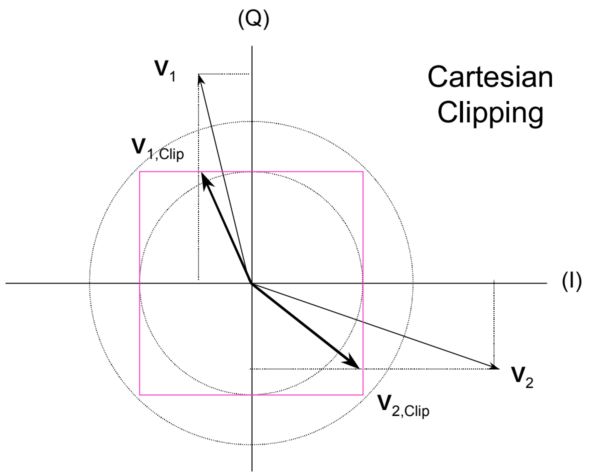


Fig.3(b)

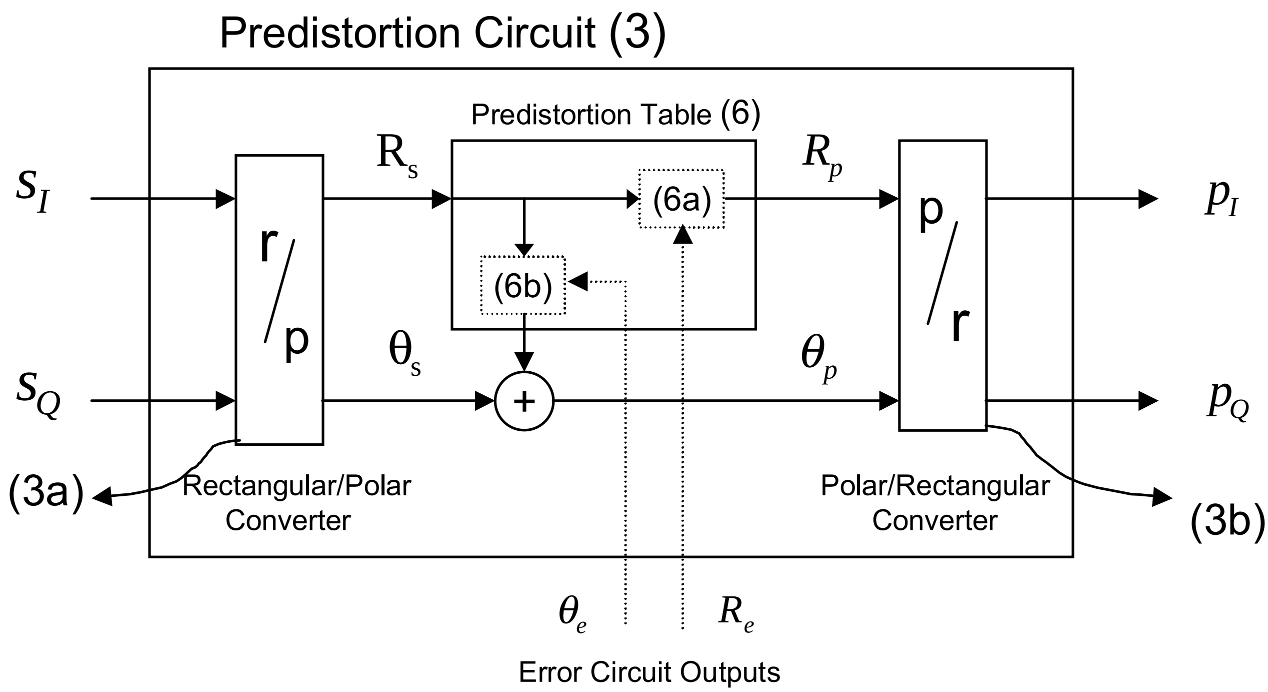
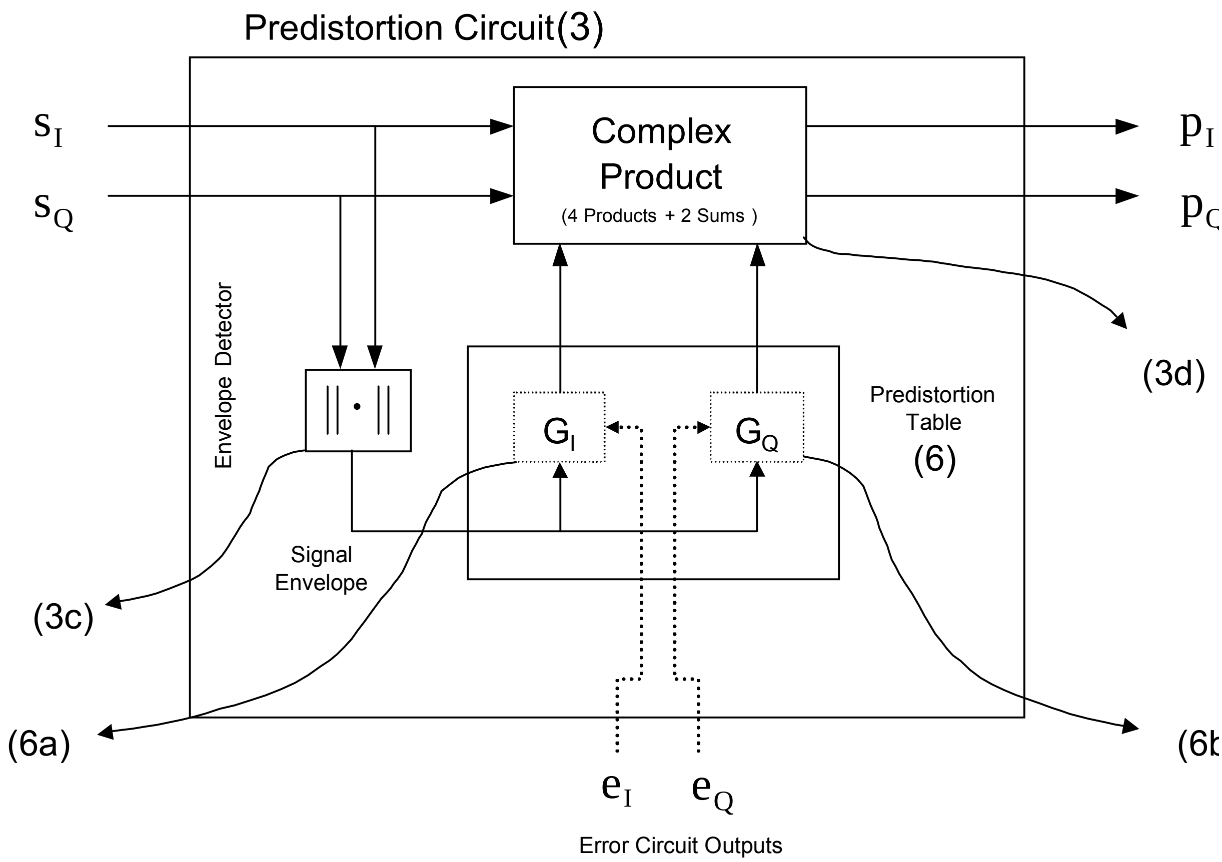
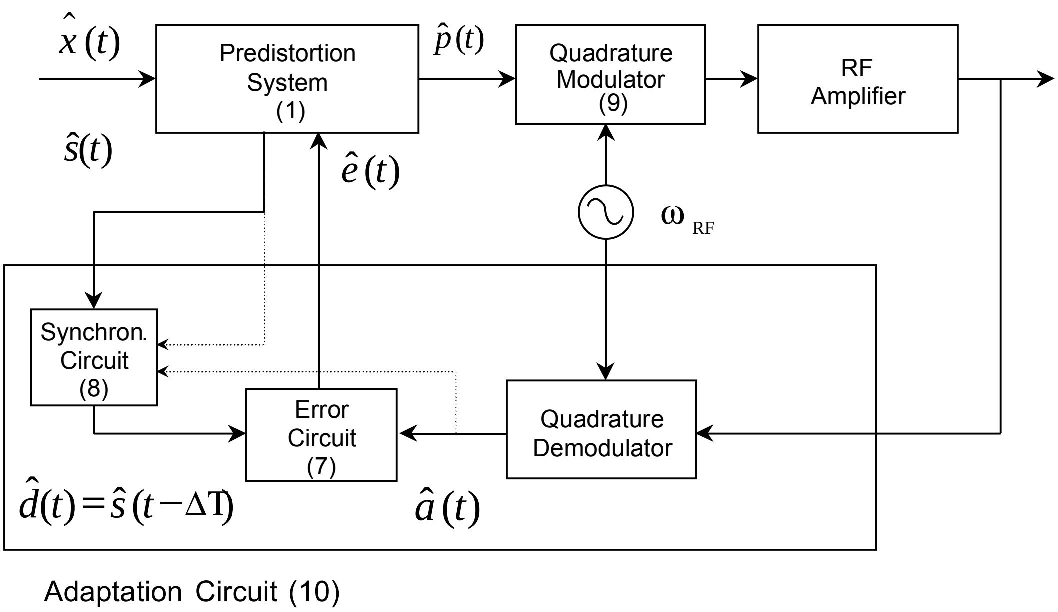


Fig.4(a)



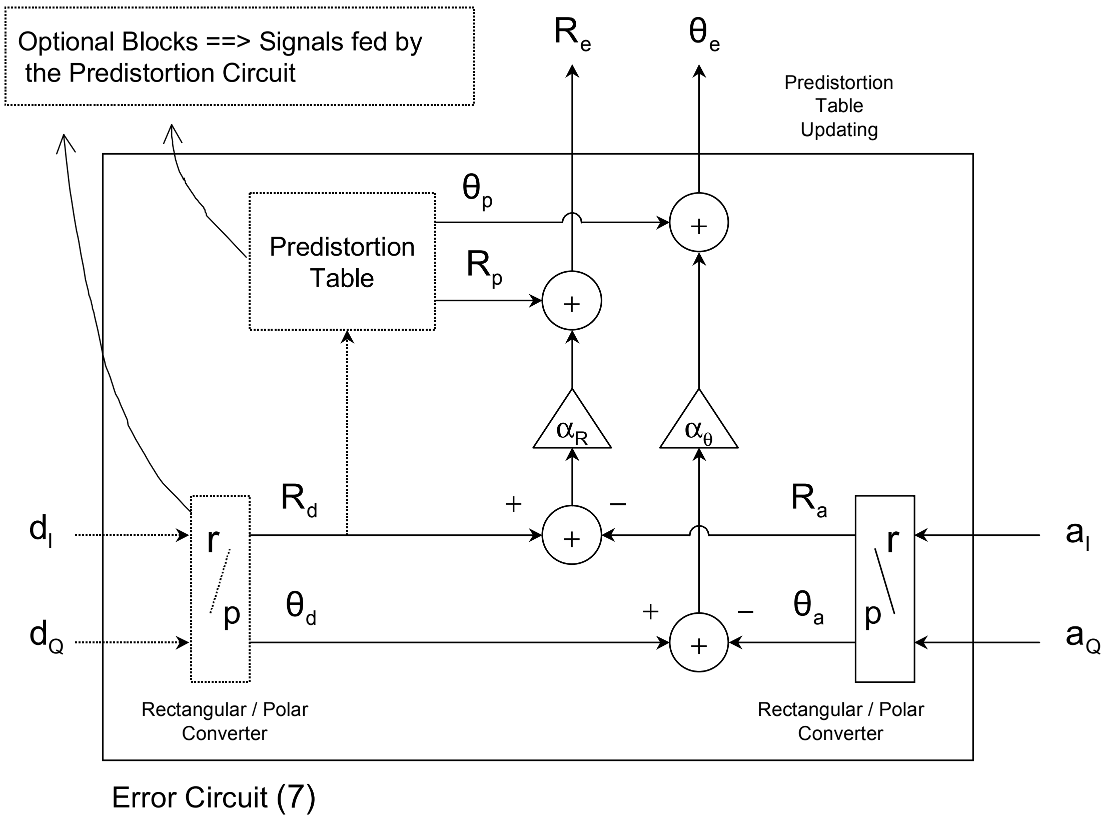
Predistortion Circuit(3)
s_I
s_Q
Complex
Product
(4 Products + 2 Sums)
p_I
p_Q
(3d)
Envelope Detector
Predistortion
Table
(6)
G_I
G_Q
Signal
Envelope
(3c)
(6a)
(6b)
e_I
e_Q
Error Circuit Outputs

Fig.4(b)



$\hat{x}(t)$
Predistortion
System
(1)
$\hat{p}(t)$
Quadrature
Modulator
(9)
RF
Amplifier
$\hat{s}(t)$
$\hat{e}(t)$
ω_{RF}
Synchron.
Circuit
(8)
Error
Circuit
(7)
Quadrature
Demodulator
$\hat{d}(t)=\hat{s}(t-\Delta T)$
$\hat{a}(t)$
Adaptation Circuit (10)

Fig. 5



Optional Blocks ==> Signals fed by the Predistortion Circuit
R_e
θ_e
Predistortion Table Updating
θ_p
Predistortion Table
R_p
+
α_R
α_θ
R_d
+
−
R_a
d_I
r
p
θ_d
+
−
θ_a
d_Q
a_I
a_Q
Rectangular / Polar Converter
Rectangular / Polar Converter
Error Circuit (7)

Fig. 6