Look-Up Table Techniques for Adaptive Digital Predistortion: A Development and Comparison

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***Abstract*—Simple techniques are presented for performing digital predistortion by use of look-up tables. Performance is measured by the traditional spectral regrowth analysis which quantifies the out-of-band distortion. Also included in the performance evaluation is constellation distortion which quantifies the in-band distortion which is important for bit error rate (BER) performance. As an added performance measure, predistortion is also analyzed with respect to its effect on amplifier efficiency. A nonuniform spacing technique is described which is simple to implement and has a performance very close to a cited optimum approach. In addition, scaling the gain of these tables provides further improvement in terms of correction and efficiency performance. Finally, adaptive indexing is introduced. These algorithms allow the various techniques to adapt to changing signal and power amplifier characteristics.**

I. Introduction

ATTEMPTS to linearize power amplifiers have generally focused on reducing spectral regrowth and have been driven by regulatory constraints regarding limits on the out-of-band emissions that are permissible. With the exception of predistortion, the majority of linearization techniques that have been implemented have been analog techniques [1]–[5]. Digital techniques have been described in the open literature [6]–[10], but these have also generally focused on the spectral regrowth issues.

This paper focuses on digital predistortion as the linearization technique. This is one of the simpler linearization techniques that is attractive because a digital solution can be employed in the mobile unit as well as the base station for wireless applications. The implementation used in this work employs a look-up table block in front of the amplifier. The look-up table adjusts the input signal by the inverse characteristic of the amplifier. Thus the cascade of the predistorter and the power amplifier looks linear.

Performance is evaluated with respect to out-of-band emissions but, in addition, it is also evaluated in terms of in-band distortion and amplifier efficiency. This paper introduces three contributions: a simple nonuniform spacing of the look-up table, scaling of the look-up table gain at the operating point, and adaptive indexing. Section II describes both the transmitter model and amplifier model used in this analysis; this section also details the constellation distortion calculation and how the operating point will affect the amplifier efficiency. Next, Section III details the algorithm used for the predistortion and how the look-up tables are derived. The different predistortion approaches are compared and results are summarized in Section IV. Adaptation techniques are outlined in Section V along with conclusions in Section VI.

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II. Models

A. Transmitter

Fig. 1 shows the block diagram of a conventional transmitter. The input data bits d are mapped onto the symbol constellation. The resulting complex stream x, is convolved with the pulse shaping filter and produces the samples v. At this point the (discrete and complex) sample stream is converted to an analog signal via a D/A converter (when no predistorter is present $v = v_{pd}$). The analog waveforms are quadrature modulated, upconverted and amplified. The transmitted waveform is labeled u.

In addition, Fig. 1 shows the analog section of the transmitter modeled as a linear circuit $h(\cdot)$ followed by a nonlinear characteristic function $a(\cdot)$ [11]. The assumption is that the frequency response $H(\omega)$ of the linear circuit is flat in the region of interest and is sufficiently broadband that it introduces negligible distortion in the signal v. The linear circuit $h(\cdot)$ is typically composed of image rejection filters and matching networks. This assumption holds quite well for narrowband signals (such as those used in cellular networks). The function $a(\cdot)$ is the response of the power amplifier.

Fig. 1 also shows the baseband predistortion blocks. Note that it incorporates a receiver (the “Downconversion & Demodulation” block) as well. In practice, since the predistorter will be adapted to variations infrequently, the feedback loop from the output of the amplifier into the existing receiver path is used to perform the predistortion updates. Let v be the discrete sampled stream at the output of the pulse shaping filter. Passing v through the predistorter $f(\cdot)$ results in v_{pd}. For simplicity [and taking the comments about $h(\cdot)$ into account] it shall be assumed that v_{pd} is the input to the amplifier. The output of the amplifier $u = a(v_{pd})$ is the transmitted signal as mentioned earlier.

B. Power Amplifier

Power amplifiers can be described by their AM–AM and AM–PM characteristics. Fig. 2 shows a typical set of these

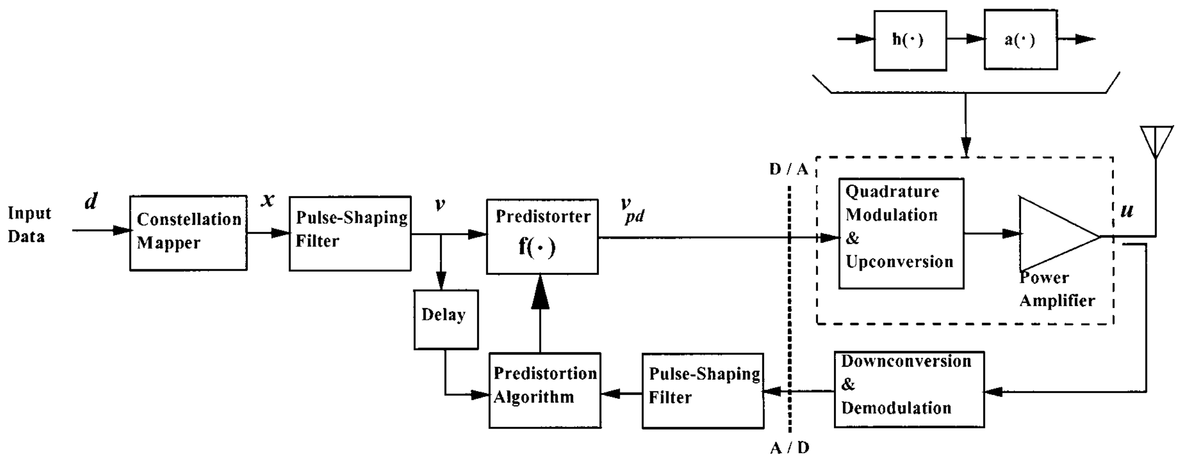

Fig. 1. Block diagram of transmitter with predistortion.

characteristics. In this figure, η is the power added efficiency (PAE) of the amplifier, and $\Delta\Phi$ is the phase rotation (in degrees). The output power $P_{\rm out}$ has been normalized so that the gain is 0 dB when $P_{\rm in} = 0$ dBm. The goal is to operate the amplifier with as high efficiency as possible without creating distortion. The results here use Saleh's model [12] of a TWT amplifier, which can also be used to model solid state amplifiers since the shape of the characteristics are similar. The AM–AM and AM–PM conversion are modeled as

$$A(r) = \frac{\alpha_a r}{1+\beta_a r^2} \quad \text{and} \quad \Delta\Phi(r) = \frac{\alpha_\varphi r^2}{1+\beta_\varphi r^2}. \tag{1}$$

$A(r)$ is the magnitude of the response of the amplifier to the instantaneous input magnitude $r = |v|$ and $\Delta\Phi(r)$ is the phase distortion introduced.

C. Performance Metrics

Traditionally, spectral regrowth has been used as the metric for determining the back-off of the input signal to the amplifier. This is certainly a necessary condition, since regulatory constraints regarding the out-of-band power of a transmitted signal must be met. However, consideration has been given to the constellation distortion [i.e., the in-band signal-to-distortion ratio (SDR)] in this analysis as well. The combination of constellation distortion, the resulting efficiency of the power amplifier, and the out-of-band emissions is used to determine the predistortion technique and input back-off level to be implemented. This integrated approach allows designers of communication systems to tailor the complexity of the predistortion algorithms to fit the desired spectral mask and the bit error rate performance of the system.

Constellation distortion is calculated by the following. Vector A is the desired constellation point and vector B is the demodulated point from the output of the amplifier. The distortion D is the difference of the vectors A and B and is expressed as

$$\vec{D} = \vec{B} - \vec{A} = \vec{D}_R + j\vec{D}_I. \tag{2}$$

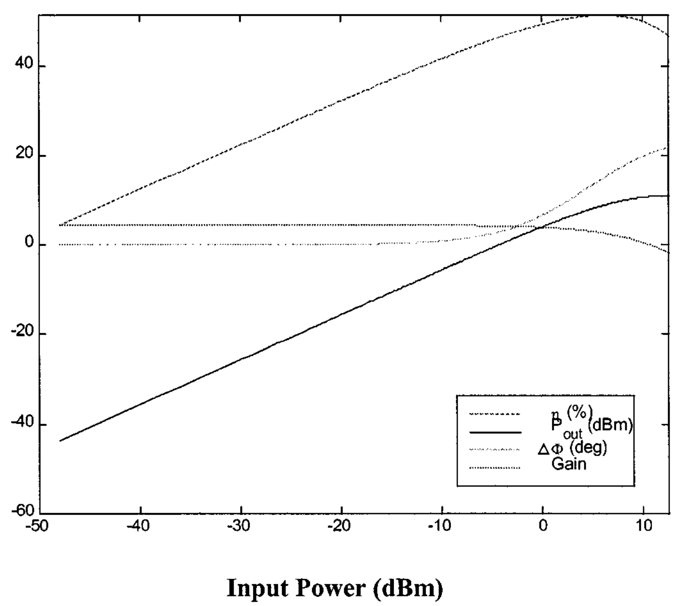

Fig. 2. Power amplifier characteristics, Saleh Model.

The distortion variance is calculated by

$$\begin{aligned}\text{Distortion variance} &= \text{var}\left(\vec{D}_R\right) + \text{var}\left(\vec{D}_I\right)\\ &= \text{mean}\left(\vec{D}_R^2\right) - \left(\text{mean}\left(\vec{D}_R\right)\right)^2\\ &\quad + \text{mean}\left(\vec{D}_I^2\right) - \left(\text{mean}\left(\vec{D}_I\right)\right)^2\end{aligned} \tag{3}$$

and is averaged over all symbols. This calculation resembles the familiar error vector magnitude (EVM) measurement [13]. EVM can be calculated from D by normalizing D with respect to the rms value of vector B and given as a percent. For constellation distortion, this error is evaluated in terms of its variance and is given in decibels.

The out-of-band emissions is the distortion present in those frequencies spanning from the 3 dB roll-off point of the root-raised cosine filters to the band edge. This is done for comparison purposes only since no single application is targeted in these calculations.

D. Amplifier Operating Point and Efficiency with Predistortion

The basic idea of digital predistortion is fairly straightforward. Consider the scenario depicted in Fig. 3. Let r_{in} be the amplitude of the input signal. The desired output is known from the linear response. This value is used to search through the output characteristic of the amplifier. The value $r_{\text{out\_}pd}$ is the desired output amplitude; from which the proper input amplitude to the amplifier is determined $r_{\text{in\_}pd}$. The original input amplitude, r_{in}, is adjusted to produce $r_{\text{in\_}pd}$ [14]. Then $r_{\text{in\_}pd}$ should produce the correct output amplitude to give the overall predistorter-power amplifier chain a linear response. Although not shown, $r_{\text{in\_}pd}$ is also used to determine Φ_{pd} to predistort the phase. Phase is not always corrected, but if it is, it can also compensate for any quadrature modulation errors in addition to the amplifier errors [9]. Note that if the desired output amplitude is beyond the saturation limit of the amplifier, the corresponding $r_{\text{in\_}pd}$ will not be able to fully correct for the nonlinearity.

A pre-distorter can successfully correct distortion up to the full saturation level of the amplifier, (this is the point at which the characteristic levels off and any increase in the input power does not produce an increase in output power). Fig. 4 demonstrates the improvement in the amplifier's operating point, as well as the upper limit to linearization with predistortion. In this figure, the range of input values is represented as a rectangle near the horizontal axis. The first range of input power levels in Fig. 4 is for an amplifier without a linearizer. The peak power cannot exist too far into the nonlinear region or the distortion will be too large for transmission. Here, the amplifier must be backed off from its saturation level an amount equal to the peak-to-average level of the signal.

With a linearizer, the amplifier is allowed to be at a much higher operating point since the distortion in the peaks can be corrected up to the saturation level. The intersection of the linear response and the saturation limit is the maximum input amplitude allowed for correction with predistortion. Any input signal with an amplitude higher than this will not be fully corrected and distortion will increase again.

The benefit of linearization is that a smaller and cheaper amplifier can be built for a given distortion level, and the amplifier efficiency is much higher. Without linearization, the operating point would have to decrease and the average efficiency of the amplifier would decrease, as well.

III. Description of Techniques

A. Non-Uniform Spacing of the Look-Up Table

Values of r versus $A(r)$ and r versus $\Delta\Phi(r)$ are stored in look-up tables. For every complex input r, the predistorter looks up the desired output level in $A(r)$ and applies a correction factor based upon $A(r)^{-1}$ to produce $r_{\text{in\_}pd}$. Next, $r_{\text{in\_}pd}$ is compared to the closest value of r in the phase table and the predistorter applies the correction $-\Delta\Phi(r)$. The resulting output, (and thus the input to the amplifier), is a predistorted sample.

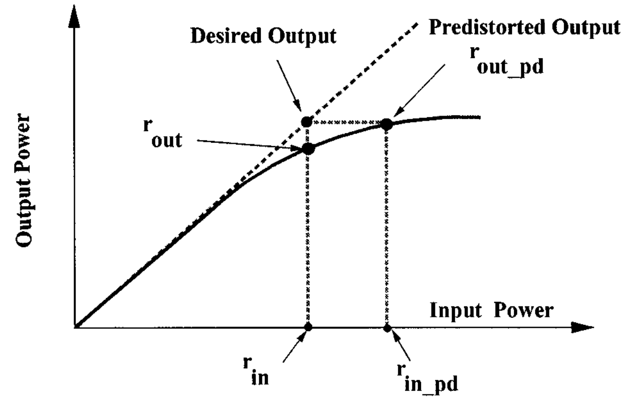

Fig. 3. Conceptual Model of predistortion.

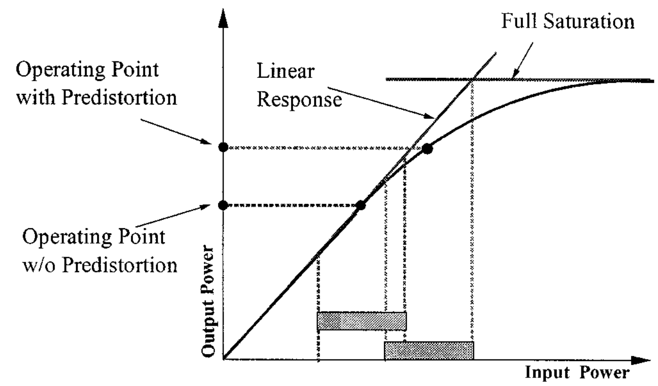

Fig. 4. Operating point improvement.

For the look-up table technique, tradeoffs are evaluated based upon varying the following parameters:

1) the size of the look-up table;
2) the complexity of the algorithm used in calculating the input spacing of the table, (to be explained in the following section);
3) the adaptation capability using 2);
4) the minimum input back-off (IBO) required to meet out-of-band emissions criteria, resulting from 1) and2);
5) the performance in terms of efficiency, SDR, and spurious emissions resulting from 1) through 4).

The spacing of the input levels in the look-up table is derived via a companding function $s(r)$. Equally-spaced amplitude input levels, for example, correspond to $(r) = r$ or whereas equal spacing by power levels corresponds to $s(r) = r^2$. This companding function is used to store the input values in the look-up table. Output values are stored with these corresponding input values. The look-up procedure takes the input value r and does a search among the table entries to determine which entry is appropriate. This could be done by a mapping function. If there is no mapping function, this step involves a search. For other companding functions, the tradeoff will have to be made between the length of time required for a search, the memory required for the mapping function, and the complexity of implementing the mapping function.

A nonuniform spacing of the look-up table that minimizes quantization errors of the look-up table has been explained in detail by Cavers [15]. The results are summarized here. If $a(r)$

is the response of the amplifier to the input, r, the complex gain of the amplifier can be expressed as $g(r) = a(r)/r$. The transfer characteristic of the predistorter is $f(r)$, then

$$f(r)g(r) = C \tag{4}$$

where C is the "linear gain" of the predistorter/amplifier combination and is a constant for the desired linear response. Given the power amplifier characteristic, $a(r)$, the look-up table size, N, and the signal amplitude probability density function, (PDF), $p(r)$, let the compander function be s_q. Then the derivative can be expressed as

$$s_q'(r) = \left(\int w(r)^{1/3}\, dr\right)^{-1} w(r)^{1/3} \tag{5}$$

where

$$w(r) = \frac{r^2}{12N^2} \frac{|g'(r)|^2}{|g(r)|^4} p(r). \tag{6}$$

This companding function takes into account both the derivative of the amplifier gain as well as the weighted PDF of the signal amplitude [15]. This approach is referred to as "QuantE." Another approach which reduces the complexity of estimating the spacing from above, is to define $w(r)$ as

$$w(r) = r^2 p(r). \tag{7}$$

This approach is referred to as "r^2PDF."

B. Normalization Point of Look-Up Tables

The last technique to be described is the normalization of the look-up tables. To the best of our knowledge, this has not been addressed in the literature. All look-up tables are scaled such that there is a constant gain, C, as in (4), for amplification. Usually the maximum gain of the amplifier is used (this is the point where the amplifier is fairly linear). Previously, Fig. 4 illustrated the maximum input power allowed with the predistorter. This is based on scaling the look-up table at the maximum gain point. But, as Fig. 5 shows, the look-up table can also be scaled with respect to the gain at the desired operating point. Fig. 5 illustrates that by scaling the look-up table at a higher operating point, the maximum input amplitude allowed for correction has increased. The higher the operating point will increase efficiency, but as the results will show, the normalization will also provide more correction.

IV. Results

A. Look-Up Table Performance

A comparison of the results using the different approaches outlined in Section III-A is shown in Fig. 6. The input back-off (IBO) values are relative to the 1 dB compression point of the amplifier (i.e., IBO of 3 dB means 3 dB below the 1 dB compression point). The constellation distortion (SDR) is plotted in the left graph and out-of-band emissions is plotted in the right graph. The "FltOnly" curve refers to the distortion from only the pulse shaping filters (without an amplifier). The "AmpOnly" curve doesn't use predistortion, and has an amplifier fitted with the parameters $\alpha_a = 1.6623$, $\beta_a = 0.0552$, $\alpha_\varphi = 0.1533$, $\beta_\varphi = 0.3456$ from Saleh's Model [12]. The modulation used was QPSK. The pulse shaping filters were square-root raised cosine filters with a roll-off factor of 25% extending four symbols on either side of the center tap and 16 times oversampled. The nonzero distortion seen in the "FltOnly" curve is from the distortion introduced by the finite-length of the pulse-shaping filter.

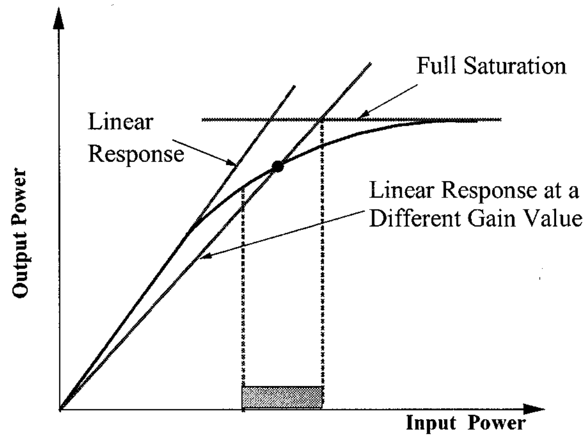

Fig. 5. Normalization of look-up table at different points.

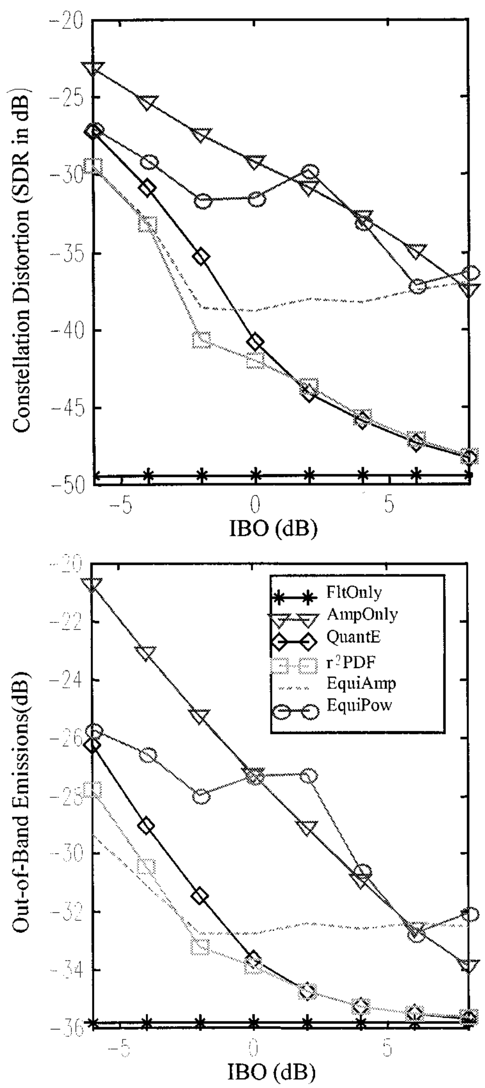

Fig. 6. Performance of look-up table spproaches with ten points.

As seen from the figure, the new companding function, "r^2PDF," described by (5) and (7) is very close to Caver's technique, "QuantE," described by (5) and (6). When the amplifier is pushed well into saturation, (i.e., -3 dB IBO), the new companding function and equally-spaced voltage, "Equi-Amp," techniques slightly outperform "QuantE." At these levels most of the distortion is from the nonlinearity of the amplifier and not the quantization error of the table. As the input is backed down from this heavy saturation point, the "QuantE" and "r^2PDF" techniques outperform the equally-spaced voltage and equally-spaced power, "Equi-Pow," look-up tables.

B. Performance Gains from Increasing Table Size

For larger look-up table sizes, the performance of all approaches naturally improves. However, the marginal difference is the greatest for the equally-spaced techniques, as shown in Fig. 7.

From a complexity point of view, therefore, there is a tradeoff between the speed of initialization and adaptation required. With respect to complexity, the ordering of these techniques in terms of increasing number of computations starts with the simplest being equally-spaced, then the new "r^2PDF" approach, and lastly the spacing as presented in [15]. In terms of the threshold out-of-band emissions, constellation distortion desired, and the efficiency of the amplifier operating point, there is a tradeoff between the size of the look-up table and performance. The ordering of decreasing table size is now opposite (i.e., "QuantE" requires the least number of points and equally-spaced requires the most table points for the same performance). Note here that in terms of efficiency, the predistortion technique that allows the amplifier to be operated at the lowest IBO will be the most efficient.

C. Performance Gains from Normalizing the Table at Different Points

Three different cases were investigated in normalizing the look-up tables. The table was first normalized at the linear gain point (maximum gain) and this table was used to calculate the constellation distortion and amplifier efficiency at all input back-off values. This was compared to the second case of normalizing the look-up table at the 1 dB compression point and reproducing the same results for all back-off values. Lastly, results were generated by normalizing the look-up table at each back-off value (i.e., the table changes for each back-off point). Fig. 8 shows these results for both constellation distortion and amplifier efficiency.

This figure shows that the best performance in both efficiency and distortion is when the table is re-normalized at each back-off point. If the look-up table can only be initialized once per session, it would be wise to normalize the table at the operating point rather than the linear gain point. Similar results were computed for the equally-spaced look-up tables and the optimally spaced look-up table.

V. Adaptive Indexing

A. Varying Signal and Power Amplifier Characteristics

The need for the predistorter to dynamically adapt to changing system characteristics arises when either the signal

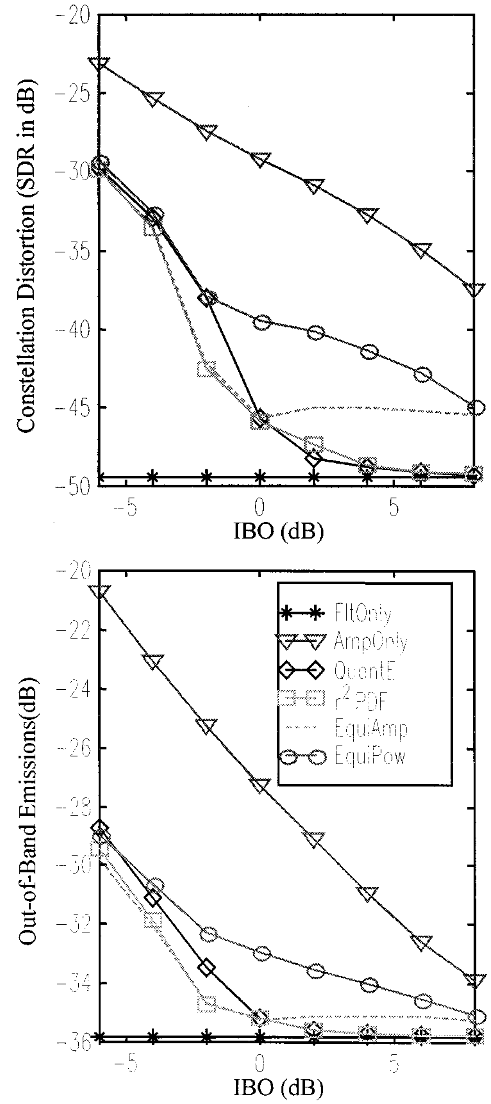

Fig. 7. Performance of look-up table approaches with 25 points.

characteristics (i.e., the PDF) or the power amplifier characteristics (e.g., as a function of temperature) change. As an illustration for the need for an adaptation technique, Fig. 9 shows the comparison of constellation distortion and out-of-band emissions between using the QPSK signal amplitude PDF to calculate the table spacing and the 16-QAM signal amplitude PDF when the 16-QAM signal constellation is used in transmission. The spacing of the polynomial fit was based on the sub-optimum (r^2PDF) approach.

As seen in the figure, when the wrong modulation scheme is used to calculate the spacing of the look-up table, a noticeable degradation occurs. There are a number of situations in which the need for adaptation arises. Some of these include:

1) *Dynamic Modulation Schemes:* Based on the feedback regarding the signal-to-noise plus interference ratio, a variety of constellations can be used to maximize data throughput. For example, in a TDMA system, each time slot could carry a different modulation scheme.
2) *Multi-Carrier Systems:* In systems which use multi-carrier modulation (e.g., OFDM), the number of transmitted

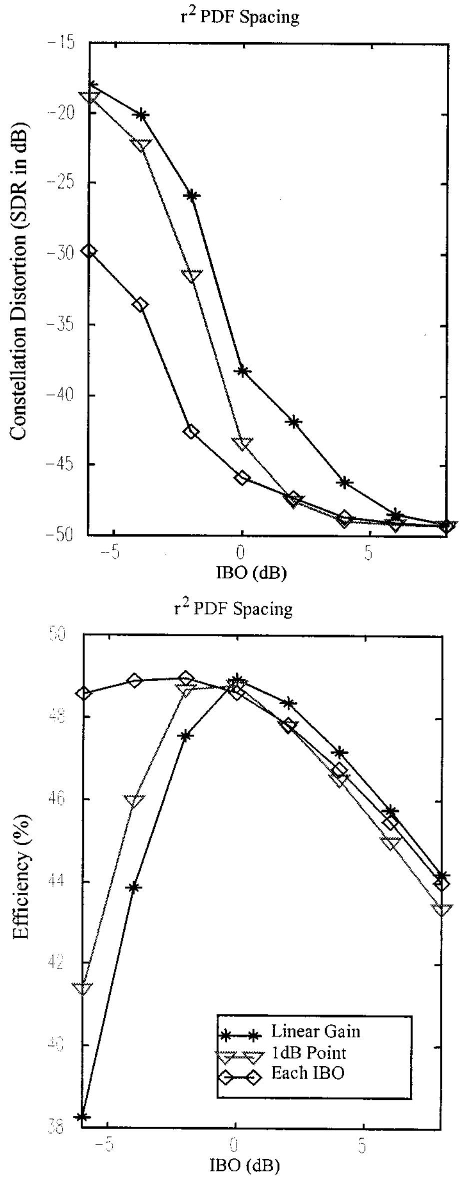

Fig. 8. Normalization point of table.

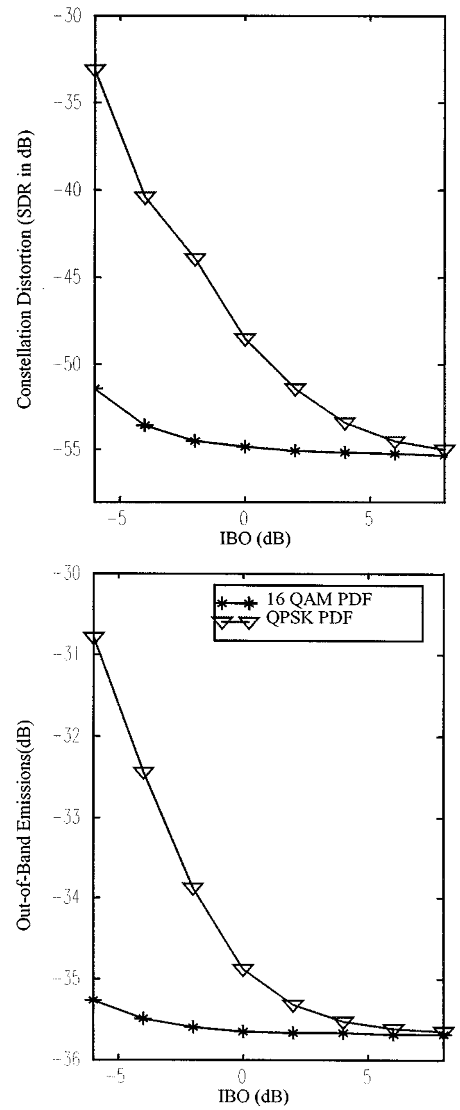

Fig. 9. Performance comparison using the wrong constellation amplitude PDF.

carriers can vary depending on the traffic load. This will change the distribution of the transmitted signal.

3) *CDMA:* Base stations in a CDMA system can transmit one to several signals, wherein each one is convolved with a distinct PN spreading sequence. The number of such signals will, again, depend on the traffic load.
4) *Time and Temperature Variation of the Power Amplifier Characteristics:* Temperature, aging, and bias fluctuations can cause the PA characteristics to change. Temperature variation occurs during a single usage session because the components heat up with usage; whereas, aging occurs over a period of months or years.

B. Linked Lists for Look-Up Tables

In the standard table look-up technique, the table is simply arranged in ascending value. Based on the input sample (with no mapping function implemented) the table is searched until the closest stored input value is found. If an input/output pair needs to be inserted or deleted, this will affect the memory location of all entries which follow this pair. But, with a linked list, each entry has a pointer to the next entry's memory location (the first and last entries have specific, reserved values which indicate the head and tail of the list). In this manner, two objectives are achieved:

1) the ordering of the list is not connected to memory locations; and
2) the changes in the table can be achieved by simply changing the appropriate pointers, thereby removing the need for reordering the table.

Note that once an entry is changed or deleted, its location is declared free and future updates can be overwritten on this location. Consequently, in addition to providing an efficient way of updating the look-up table, this procedure reduces the memory required for performing updates by not having a completely separate table generated before removing the outdated data.

This technique is useful for temporal and temperature changes of the amplifier, as well as a signal whose amplitude

PDF changes slowly over the ensemble values. It can be used for a multi-carrier or CDMA case where the system is willing to accept a degradation in performance for short periods of time while the predistortion values are updated to reflect the changes in the signal characteristics.

VI. Summary and Conclusion

Techniques for performing baseband predistortion have been described. The cost function that was defined (over which the optimization is performed) includes constellation distortion as well as spectral regrowth. A new look-up table technique was described which proved not only to be simple to implement, but it introduces negligible degradation relative to the optimum approach. Currently, normalization of the tables at different operating points and its effect on amplifier efficiency have not been addressed in the literature. It was revealed that normalization of the table at the operating point had a better performance than normalizing the table at a linear gain point. It was also demonstrated that this normalization increases the overall efficiency of the amplifier since its maximum operating point also increases. Finally, adaptive indexing was described for nonuniformly spaced look-up tables which allows these tables to adapt to changing signal and power amplifier characteristics.

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