Highly Efficient Power Amplifier for IMT-2000 BTS Equipment

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IMT-2000 services are growing in Japan, and the demands for power-efficient and physically small base transceiver stations (BTSs) for IMT-2000 have become strong. One way to meet these demands is to reduce the power consumption and size of the large, high-power-consumption power amplifiers (PAs) that are currently being used in BTSs. We have therefore developed a new adaptive digital predistorter (DPD) and a multicarrier signal processing technique for reducing PA nonlinear distortion and have used it to build a new, highly efficient PA for IMT-2000 BTS equipment. The power efficiency of our new PA is double that of conventional PAs. We have already supplied customers in Japan and Europe with enhanced BTSs that contain our new PA. This paper describes these techniques for reducing PA nonlinear distortion and the performance of our new PA.

1. Introduction

In October 2001, NTT DoCoMo,Inc. launched a W-CDMA-based IMT-2000 commercial service in Japan called FOMA. Also, another IMT-2000 service, CDMA2000 1x, was launched by KDDI Corporation in April 2002. FOMA is growing more slowly than expected in terms of the number of subscribers; however, third-generation IMT-2000 cellular phone services will clearly form an infrastructure for mobile speech, video, and high-speed data communications. The number of broadband Internet services is rapidly increasing in fixed networks, and people accustomed to having a broadband environment in their home are now expecting a similar broadband mobile environment. As a result, the IMT-2000 system is evolving to accommodate more subscribers and provide broadband mobile data communications.

The first networks and base transceiver stations (BTSs) for IMT-2000 have been deployed in major cities around Japan; however, these BTSs do not have the capabilities needed to provide full 3G mobile services. The next phase of equipment should support greater capacities and faster data services such as HSDPA (High-Speed Downlink Packet Access) for W-CDMA and CDMA2000 1xEV-DO. The total power consumption of the high-capacity BTSs that are required tends to be higher than that of lower capacity BTSs because they use more radio frequency (RF) carriers and have more baseband signal processing units. As a result, restraints on heat removal make it difficult to fit a high-capacity BTS into the same volume as a current BTS. Because the power amplifier (PA) consumes a large portion of the power, reducing the PA power consumption is a key goal for achieving a high-capacity BTS.

2. Current technologies for nonlinear compensation

In this chapter, we introduce some current techniques for nonlinear compensation of PAs. Most radio communication equipment has a PA, the efficiency of which nearly always needs to be as high as possible. Efficiency is defined as the ratio of RF output power to the total power consumed. There is a general property that amplifier efficiency is inversely proportional to amplifier linearity. If you need high linearity, an amplifier should be operated in class A or AB, which makes the power efficiency quite low. Conversely, if you need high efficiency, an amplifier should be operated near class C, which makes the amplifier very nonlinear. Many nonlinear compensation techniques have been proposed and developed to find an optimal balance between efficiency and linearity.[1)]

2.1 Cartesian loop and polar loop techniques

The Cartesian loop[2)] and polar loop[3)] are well-known feedback linearization techniques. The Cartesian feedback loop suppresses nonlinearity in a complex-baseband that is expressed using rectangular Cartesian coordinates. One of the advantages of the Cartesian loop is that it can reduce the shortcomings of quadrature modulators, for example, carrier leakage caused by DC offsets and gain imbalances of the I/Q signals. The Digital Cartesian loop[4)] can also be used; however, this method requires a large memory to store the table of 2-dimensional coefficients for the I-Q plane. Another problem with this method is how to implement local phase control for the quadrature modulator and demodulator.[5)]

In a polar loop transmitter, the RF signal is directly generated by a VCO (Voltage Controlled Oscillator) whose phase is controlled by feedback signals and whose amplitude is modulated by the difference between a reference signal and a feedback signal. One advantage of the polar loop is that the RF chain is quite simple.

2.2 Feedforward amplifier

The feedforward amplifier[6)] is a popular type of multicarrier PA; its configuration is shown in **Figure 1**. Basically, the nonlinear distortion caused by the main amplifier is canceled out at the final stage of the PA by subtracting the difference between the original signal and the distorted output of the main amplifier.

The feedforward amplifier is a mature, well-proven design that is used in many commercial products, including current W-CDMA BTSs. It has good stability and linearity, but it also has an obvious disadvantage: its power efficiency is relatively low due to power loss in the delay line at the main amplifier's output and the power wasted in the sub-amplifier. Unfortunately, with this type of amplifier there seems to be no room for improving the power efficiency enough for use in a practical, high-capacity W-CDMA BTS.

3. Predistortion

3.1 Principle of predistortion

Predistortion[7)-9)] is another popular technique for compensating for the nonlinear distortion in PAs. **Figure 2** shows the principle of predistortion. The transfer characteristic of the predistorter, $G(v_i)$, complements that of the PA, $F(\alpha)$, where α is the power or envelope of input v_i. Before the signal is fed to the PA, it is predistorted with $G(v_i)$ so that the resulting system distortion is low. Unlike the case with a conventional feedforward amplifier, when predistortion is used there is no need for a delay component or sub-amplifier, so the power overhead of these additional components is avoided. Therefore, predistortion can lead to high efficiency.

When predistortion is used in practical applications, the nonlinear characteristics of the PA

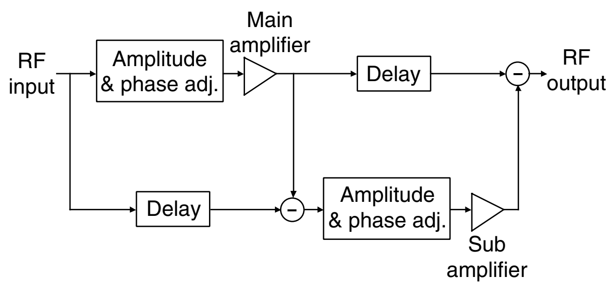

Figure 1
Configuration of feedforward amplifier.

become unstable due to the tolerance spread of devices and the effects of temperature and aging. Therefore, the estimation of PA characteristics must be adapted to compensate for these time-variant nonlinearities. Adaptive predistortion by digital processing seems to be the most promising method for nonlinear compensation, because 1) it is suitable for digital modulation, which is common in modern communications, and 2) it is easy to implement sophisticated algorithms for estimating amplifier nonlinearity.

There are several methods of implementing adaptive predistortion, and they can be classified according to whether they are analog or digital and according to the stage where they are implemented (complex baseband, IF, or RF). Although there are both advantages and disadvantages to these various methods, whichever method is used we can expect to see the same basic benefit. In this paper, we will focus on baseband predistortion.

3.2 Baseband predistorter

The configuration of the baseband predistorter[10] is shown in **Figure 3**. Signals are predistorted by multiplying, in the complex-number domain, the input signal by the predistortion coefficients for the operating range of baseband input signal powers or envelopes. These coefficients are stored in a look-up table (LUT). The resultant complex signals are converted to an intermediate frequency (IF) or to RF by a quadrature modulator and then fed to the main amplifier. The distorted feedback signal from the main amplifier output is used to estimate the nonlinear distortion characteristics using adaptive algorithms, and the LUT coefficients are updated according to the time-variant characteristics.

The algorithms used for calculating the LUT coefficients can be categorized into two types. One type is based on a kind of MMSE (Minimize Mean Square Error) criteria that defines an error as a difference between the original signal and the feedback signal. The other type is based on minimizing undesired power emission by using a hill-climb algorithm. Both types of algorithm have advantages and disadvantages in terms of the convergence speed, type of feedback signal (vector/scalar), and immunity from errors caused by analog circuitry. In general, the MMSE algorithm has a faster convergence, while the hill-climb algorithm has better immunity to incompleteness because it does not require a strict sample timing for the feedback signals.

4. Wideband aspects of PA

The downlink bandwidth of a W-CDMA system is 5 MHz per carrier, and up to four carriers can be simultaneously transmitted. Therefore, to eliminate 3rd-order intermodulation distortion (IMD), a minimum bandwidth of 60 MHz (5 MHz $\times$ 4 carriers $\times$ 3) will be needed, and to eliminate 5th-order IMD a minimum bandwidth of 100 MHz will be needed. Power amplifiers having such wide

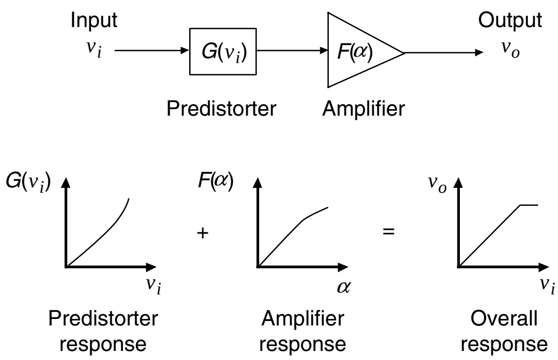

Figure 2
Principle of predistortion amplifier.

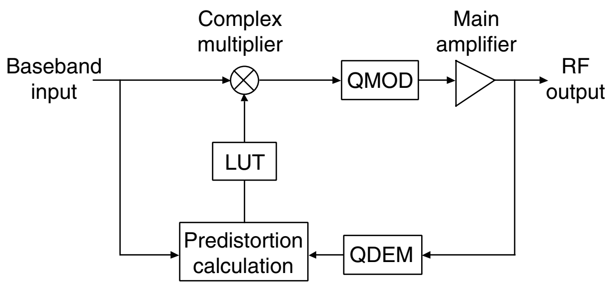

Figure 3
Configuration of baseband predistorter.

bandwidths exhibit considerable wideband distortion.

The PA narrowband nonlinearity is simply expressed as a function of the instantaneous input amplitude. This kind of distortion is called memory-less distortion. The coefficients of amplitude and phase distortion for the operating range of input-signal powers or envelopes are stored in an LUT as functions of the input signal. Predistortion for the memory-less distortion is done by multiplication of the input signal and the appropriate LUT coefficients in the complex-number domain.

The expression for wideband PA nonlinearity is more complicated than the one for narrowband PA nonlinearity. This is mainly due to the fact that the PA wideband nonlinearity has memory; that is, the PA nonlinear distortion is determined not only by the current signal but also by the previous signals. This property of PA distortion is known as the "memory effect."[11] Nonlinearity with memory is observed as an asymmetrical intermodulation distortion in the frequency domain. The mechanisms of nonlinear distortion with memory effect are not clear, but several possibilities are being investigated. The memory effect seems to be caused by three main factors: high impedances in the bias and drain circuitry at the signal envelope frequencies, a cumulative carrier effect on transistor surfaces, and thermal effects. Each of these factors has a different timeconstant.

PA distortion with memory is difficult to mitigate by using the conventional predistortion method, which estimates the coefficients as a function of the instantaneous input. We therefore developed a new predistorter to overcome these difficulties.[12] The proposed technique can compensate for the nonlinear distortion caused by the memory effect and is based on a model in which nonlinear characteristics are time-variant and depend on signal dynamics.[13] The LUT coefficients are generated by considering the signals that are affected by the memory effect and are adaptively estimated to track the time-variant nonlinearity.

5. Multicarrier signal processing

In this chapter, we describe the multicarrier operation of a BTS. Cellular phone operators for W-CDMA systems use three or four carriers in their services simultaneously. Current BTSs have dedicated modulators for each carrier and duplex the carriers in the RF chain. This configuration has the disadvantages that 1) the floor noise is increased due to the power summation and 2) the resultant RF multicarrier signals have a relatively high peak-to-average ratio (PAR), which lowers the PA's efficiency. Multicarrier synthesis with baseband digital processing is a useful way of avoiding the noise increase and controlling the PAR of the multicarrier signal.

The amplification of signals with a high PAR requires a large backoff margin to ensure sufficient linearity, even when an ideal predistorter is employed. Although predistortion can compensate for PA nonlinearity, it cannot enhance a PA's saturation power. An insufficient backoff margin results in hard clipping of the output signal, which causes intermodulation distortion and a consequent reduction in power efficiency. However, the backoff margin and therefore the power efficiency can be significantly increased through the combination of a predistorter and multicarrier peak suppression. Our new PA therefore incorporates our new predistorter combined with multicarrier peak suppression.

6. Performance

We have developed a highly efficient PA that adopts a new digital predistorter (DPD) and multicarrier peak suppressor (MCPS). **Figure 4** shows the configuration of the new PA, and **Table 1** shows its specifications. The combination of DPD and MCPS in this PA gives it double the power efficiency of a conventional feedforward amplifier. Our DPD improves the linearity of the PA and dramatically reduces the backoff margin

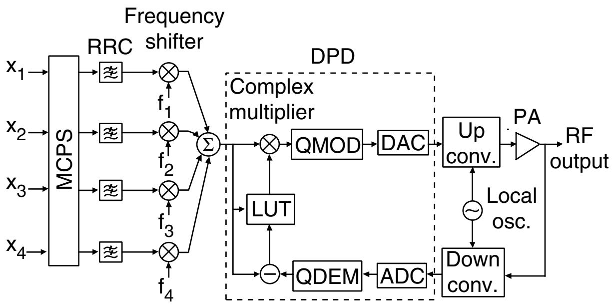

Figure 4
Configuration of new PA.

Table 1
Specifications of new PA.

Item	Value
RF output power	47 dBm
Number of carriers	4
Carrier frequency	2 GHz band
Bandwidth	20 MHz

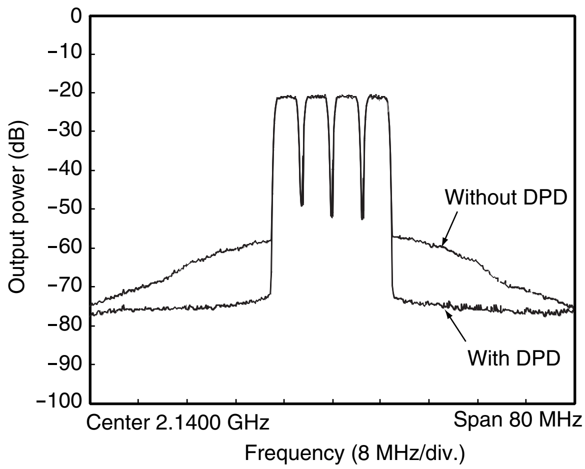

Figure 5
Power spectra of new PA with four carriers.

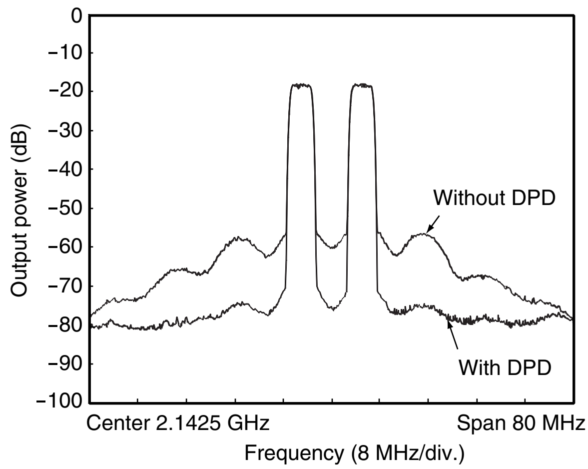

Figure 6
Power spectra of new PA with two carriers.

of the PA's operating point. At the same time, it also provides the required spectral emission properties, even when there is strong nonlinear distortion due to the memory effect. The MCPS reduces the peak power of the DPD input, which also helps reduce the backoff margin of the PA and ensures stable predistortion.

6.1 Experimental results

In this section, we present the results of some experiments we conducted with our new PA. **Figures 5** and **6** show the output power spectra of the new PA with and without DPD. Figure 5 shows the spectra with four carriers, a carrier separation of 5 MHz, and a total output power of 47 dBm. Figure 6 shows the spectra with two carriers, a carrier separation of 10 MHz, and a total power of 47 dBm. The baseband input signal is specified by the Test Model 1 for 64 dedicated physical channels (DPCHs) that is specified in the 3GPP document in Reference 14). As can be seen, higher order intermodulation distortions are significantly suppressed by DPD. Figure 6 shows that the in-band intermodulation caused by 10 MHz-separated carriers is also significantly reduced.

Figure 7 shows the adjacent channel leakage power ratio (ACLR) versus output power of the new PA when there are four carriers. The solid lines and dashed lines indicate, respectively, the ACLR characteristics with and without predistortion. The triangles and squares indicate, respectively, the ACLR at +5 MHz and +10 MHz from the center of the 4th carrier in the upper sideband. This figure shows that, at an output power of 47 dBm, DPD improves the ACLRs by 17 dB or more. Also, at a carrier separation of 5 MHz and an ACLR of 52 dB, DPD reduces the backoff margin by 10.5 dB. This improvement means that for any given ACLR, the backoff margin of the PA can be reduced and therefore its efficiency can be increased.

6.2 MCPS signal processing

In this section, we describe the results of some performance simulations of the multicarrier peak suppression technique. MCPS can suppress the peak power with a sacrifice in signal quality, for example, an increase in the EVM (Error Vector Magnitude), PCDE (Peak Code Domain Error), and BER (Bit Error Rate) in the downlink. The signal quality required in the downlink is specified by the third generation partnership project (3GPP).

Figure 8 shows the EVM and PCDE versus peak-to-average ratio (PAR) of the new PA. The signal source is the Test Model 1 for 64 DPCHs.[14] As can be seen, the EVM and PCDE become worse as the PAR decreases. The EVM is defined as the average vector magnitude of the error between the ideal signal and the signal under evaluation; therefore, this value corresponds to the average BER, because the error vector is equivalent to Gaussian noise. The code domain error is expressed as the power that falls into each channelization code channel. The PCDE indicates the worst-case desired-to-undesired ratio in a code channel. Figure 8 shows that our MCPS reduces the peak power by more than 3 dB with a considerable degradation of the EVM and PCDE.

6.3 Commercial products

Figures 9 and **10** show photographs of commercial PA units we have developed for NTT DoCoMo,Inc. and Evolium SAS, respectively. These units contain a 4-carrier modulator with an MCPS and DPD. The units also perform all of the monitoring and controlling functions for the 3GPP application layer. We have confirmed that the combination of DPD and MCPS is a powerful way of achieving a highly power-efficient amplifier and that it significantly reduces the power consumption of the amplifier unit. As a result, it also makes it possible to reduce the physical size of a BTS because it relaxes the thermal conditions. The DPD also helps reduce the cost of PA mass-production because it reduces the number of RF components and the time needed for tuning.

7. Conclusion

In this paper, we introduced a new adaptive digital predistorter that makes it possible to eliminate the frequency-selective intermodulation distortion caused by the memory effect in high-power, wideband amplifiers. We also proposed a multicarrier peak suppression method that is ef-

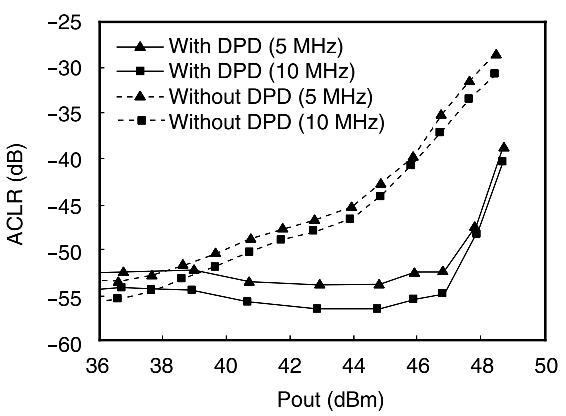

Figure 7
ACLR vs. output power of the new PA.

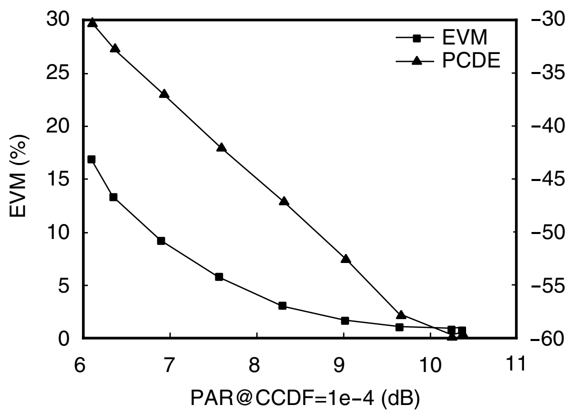

Figure 8
EVM and PCDE vs. PAR of the MCPS.

Figure 9
Photograph of new PA developed for NTT DoCoMo.

Figure 10
Photograph of new PA developed for Evolium.

fective for reducing the backoff margin. We have developed a highly efficient power amplifier for W-CDMA BTSs that employs a digital predistorter and multicarrier peak suppression. The power efficiency of the amplifier is almost double that of current feedforward amplifiers. This improvement in power efficiency leads to a significant reduction of the total power consumption of BTSs equipment and makes it possible to realize the high-capacity BTSs that will be essential for upcoming IMT-2000 systems.

References

1) P. B. Kenington: High-linearity RF amplifier design. Artech House, USA, 2000.
2) M. Johansson and T. Mattsson: Transmitter linearization using Cartesian feedback for linear TDMA modulation. Proc. of IEEE Vehicular Technology Conf., St. Louis, 1991, p.386-392.
3) V. Petrovic and W. Gosling: Polar-loop transmitter. *IEE Electronics Letters*, **15**, 10, p.286-288 (1979).
4) M. Minowa, M. Onoda, E. Fukuda, and Y. Daido: Backoff improvement for an 800-MHz GaAs FET amplifier for a QPSK transmitter using an adaptive nonlinear distortion canceller. Proc. of IEEE Vehicular Technology Conf., Orlando, 1990, p.542-546.
5) Y. Oishi and T. Takano: Cartesian feedback amplifier with soft landing. Proc. of IEEE PIMRC Conf., Boston, 1992, p.12.7.1-12.7.5.
6) R. Meyer, R. Eschenbach, and W. Edgerley, Jr.: A wide-band feedforward amplifier. *IEEE Journal of Solid-State Circuits*, **Sc-9**, 6, p.442-428 (1974).
7) Y. Nagata: Linear amplification technique for digital mobile communications. Proc. of IEEE Vehicular Technology Conf., San Francisco, CA, 1989, p.159-164.
8) A. S. Wright and W. G. Durtled: Experimental performance of an adaptive digital linearized power amplifier. *IEEE Trans. on Vehicular Technology*, **41**, 4, p.395-400 (1992).
9) J. Cavers: Amplifier linearization using a digital predistorter with fast adaptation and low memory requirement. *IEEE Trans. on Vehicular Technology*, **39**, 4, p.374-382 (1990).
10) Y. Moriyama et al.: A trial manufacture of power amplifier with adaptive algorithm predistorter (in Japanese). Proc. of IEICE Society Conf., B-5-157, 1997, p.410.

11) A. Wright: Multi-carrier WCDMA basestation design considerations - Amplifier linearization and crest factor control. *Technology white paper of PMC-Sierra, Inc.*, Issue 1, Aug. 2002.
12) H. Ishikawa et al.: Development of adaptive predistortion amplifier for W-CDMA base station (in Japanese). Proc. of IEICE Society Conf., C-2-31, 2002, p.53.
13) T. Maniwa et al.: A study of baseband predistortion linearizer for W-CDMA mobile station (in Japanese). Proc. of IEICE Society Conf., B-5-150, 1998, p.400.
14) The third generation partnership project: Base station conformance testing (FDD). 3GPP TS 25.141, v3.10.0, release 1999, June 2000.

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