Mastering the New Basestations: Design and Test of Adaptive Digital Pre-distortion Amplifiers and Digital Transceivers for 3G Radios

Application Note

- **What is hindering the success of 3G - and what can be done?**

- **Amplifier linearization technology and its implications for testing**

- **Measurement challenges of adaptive DPD amplifiers and digital radio transceivers**

- **Agilent test and measurement solutions**

Agilent Technologies

Overview

Wireless equipment manufacturers are under pressure to reduce both the capital expense and operating expense costs of 3G infrastructure by as much as 20 percent per year. This trend is expected to continue until infrastructure costs are in line with those of mature 2G (GSM and TDMA) networks. Advances in component technology and digital signal processing, along with standardization of the digital radio interface, are allowing manufacturers to address cost issues with new approaches to wireless network architecture.

One area of focus is the development of more efficient digital radios for basestations. Code division multiple access (CDMA) technologies have higher peak to average ratios than the other 2G technologies, thus present a challenge for amplifier linearization. Advances in CDMA amplifier linearization techniques are enabling the once-separate amplifier, transmitter, and filtering stages to be integrated into a single functional assembly, called a radio transceiver, which includes the power amplifier.

An important linearization technique that enables this improved power amplifier is called adaptive digital pre-distortion (ADPD). The ADPD power amplifier provides the basis for a new type of digital radio transceiver with new capabilities and interfaces that must be tested. This paper examines ADPD technology and the test challenges associated with implementing ADPD amplifiers and digital radio transceivers.

What is Hindering the Success of 3G - and What Can be Done?

Many wireless service providers who have deployed 3G networks have not realized significant increases in average revenue per user (ARPU) given the current demand for data services. Often the services implemented in 3G are also available on 2G or 2.5G platforms, and these services - voice, short message service (SMS), and multi-media message service (MMS) - continue to generate the bulk of the service provider's non-voice revenue. While certain regional deployments (notably in Japan and Korea) have been able to differentiate 2G and 3G services and create a viable market for 3G, globally 3G successes are being hindered. Acquiring and operating a 3G network is very expensive, even more so when ARPU growth is not immediately forthcoming to cover the additional network costs.

In terms of capital expense, 3G basestation transceiver (BTS) hardware is generally more expensive than comparable, mature GSM assets. The higher peak-to-average ratio of the CDMA-type signals for cdma2000 and W-CDMA require extensive circuitry to improve the linear operating range of the power amplifier. Improvements have been achieved by using feed-forward linearization in the power amplifier. Feed-forward amplifiers, which were essential components at the time 3G technologies were first developed, provided the necessary linearization performance for 3G standards. However, feed-forward amplifiers require many parts and extensive tuning, and testing is required during manufacturing at a significantly higher cost. Moreover, these amplifiers are less power-efficient than other technologies with constant envelope modulation.

Operating expenses for the feed-forward amplifiers are also higher. With inefficient feed-forward power amplifiers, the power consumption per basestation site rises dramatically. Additional air conditioning and structures to house the high-power 3G assets may be required.

To support the higher peak data rates of 3G and 3.5G technologies (1xEV-DO and HSDPA), backhaul capacity has to be increased significantly in 3G networks to support anticipated peak-usage demands. Lower utilization rates during off-peak hours can be very expensive unless the service provider has some mechanism for otherwise shifting backhaul capacity.

Given this scenario, equipment manufacturers have been under considerable pressure from wireless service providers to decrease basestation hardware costs by 20 percent or more each year. Once the capital costs of 3G equipment can match the cost of mature 2G assets, a shift in pressure toward the operating expense of the network is expected. Service providers will demand greater basestation efficiency to further reduce operating expenses including the added costs of installing and running extra cooling equipment.

Fortunately, component technologies are advancing and becoming more cost effective, allowing development of new network-equipment architectures that address cost issues, both capital expense and operating costs. At the same time, new efforts to standardize the basestation are underway that could change the business model and the supply chain for network infrastructure supplier. Two industry groups are leading this work:

• Open Base Station Architecture Initiative (OBSAI) – www.obsai.org
• Common Public Radio Interface (CPRI) – www.cpri.info

These groups are calling for implementation of a digital radio architecture that incorporates the merging of a high power amplifier with the essential elements of a transmitter - analog-to-digital (and digital-to-analog) conversion, up- and down-conversion, filtering, and other elements. The resulting digital transceiver will have a major impact on network architecture and tools for testing the basestation.

The evolution of amplifier and transmitter architectures
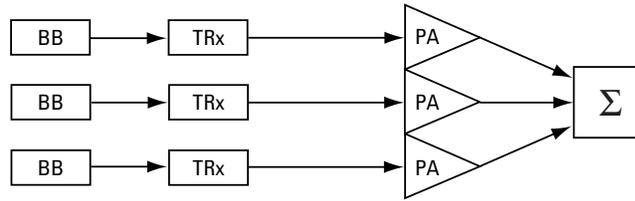
Figure 1. Traditional 1G/2G architectures.
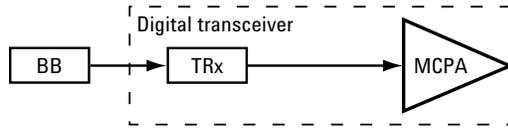
Figure 2. New 3G basestation architectures.

Throughout the history of cellular communications, advances in component technology have driven the evolution of basestation amplifier and transmitter architectures. Each new wave of technology has brought with it a series of new test points and test challenges, as the illustrations in Figures 1 and 2 imply.

Single-carrier equipment used in GSM, for example, typically have analog IQ signals from the baseband output to the transmitter input, and high-powered signal-combining, with a combiner distribution network, for the near antenna elements. Figure 1 illustrates this architecture. Note the following attributes:

- baseband outputs are analog or digital IQ
- TRx does up-conversion and channel filtering
- single carrier power amplifiers (constant envelope modulation) provide high efficiency
- high-powered combining, cavity tuning, and carrier isolation are used

Traditional measurement equipment has long served the design and test requirements of this mature, single-carrier technology.

CDMA, multi-carrier CDMA, and W-CDMA systems have seen several evolutions of transmitter, amplifier, and filter technologies. Analog interfaces have been replaced with digital IQ or digital IF implementations. High power combining in some cases has shifted to lower power combining before the amplifier or even to a digital filtering technology in the digital signal processor (DSP).

Figure 2 illustrates the result of these changes. The baseband unit often utilizes a digital IF output to one or several multi-carrier transmitter blocks. The 1:1 ratio baseband unit and transceiver is not necessary. The transmitter block not only provides the up-conversion and carrier filtering, but is now able to migrate the linearization and error compensation functions of the amplifier to the a digital signal processing on the digital IF output stream from the baseband unit. Moving the linearization task into the digital path provides a cost-effective migration that can utilize advances in silicon technology. However, it now blurs the functional line between radio suppliers and amplifier component suppliers.

While this diagram does not show the receiver block, similar transitions to a digital interface can be assumed as possible migrations.

Future advances in network topology enabled by the remote radio interface (CPRI) will split the transmission function between the baseband modem and the radio head, effectively eliminating the traditional transmitter and power amplifier. Developments in component technology strongly indicate a shift toward baseband linearization and channel filtering. With baseband linearization, the tasks of digital-to-analog (D/A) conversion and RF up-conversion move to the power amplifier. The baseband section will still perform many of the core technology-specific tasks (such as coding, decoding, scrambling, and channelization), but filtering, clipping, and much of the transceiver functionality will be distributed differently in new designs.

Adaptive digital pre-distortion amplifier
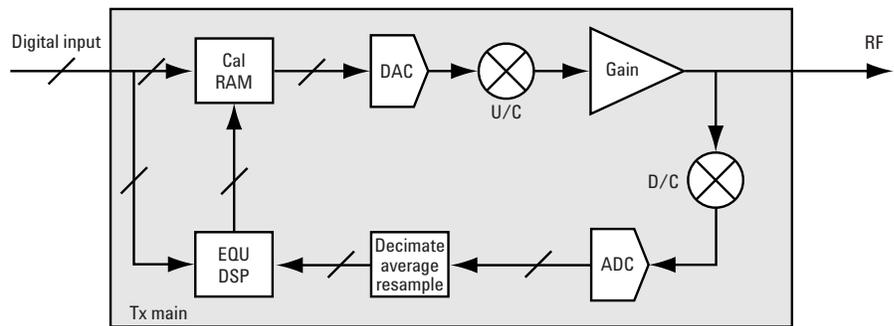
Figure 3. Block diagram of the ADPD amplifier.

Development of the digital power amplifier to replace the current generation of feed-forward amplifiers is helping create a more efficient 3G basestation. Although several classes of digital power amplifiers exist, the most popular designs are implemented in the class commonly called the adaptive digital pre-distortion (ADPD) amplifier, illustrated in Figure 3.

In the ADPD amplifier, the time-domain signal is fed back to equalization DSP. This approach requires fewer amplifier transistors than does the feed-forward design, as the error amplifier is no longer required. Fewer parts result in significant cost savings - typically of 50 percent or more. With fewer transistors, the efficiency typically improves from six to eight percent to greater than 20 percent.

The amplifier design and functionality affects the testing process in some important ways.

• The amplifier now requires a digital input stimulus instead of the usual high-performance RF source.
• New elements (including filters, A/D and D/A converters, up- and down-converters) in the amplifier design increase the importance of calibration and correction.
• Calibration crosses domains (RF-to-bits, bits-to-RF) and because the amplifier's integrated elements are matched at impedances other than 50 ohms for improved performance, traditional network analyzers can no longer be used for characterization.
• Accurate modeling and time-domain characterization of the ADPD amplifier's distortion products are also increasingly important. Narrow-band test tools that do not represent the wideband distortion can give misleading results. This is especially true in characterizing memory effects.[1]

---

1. For an in-depth analysis of characterization and memory effects, see *Analysis, Measurement and Cancellation of the Bandwidth and Amplitude Dependence of Intermodulation Distortion in RF Power Amplifiers*, Joel Vuolevi, Academic Dissertation, Faculty of Technology, University of Oulu, November 2001.

Integrating the receiver chain
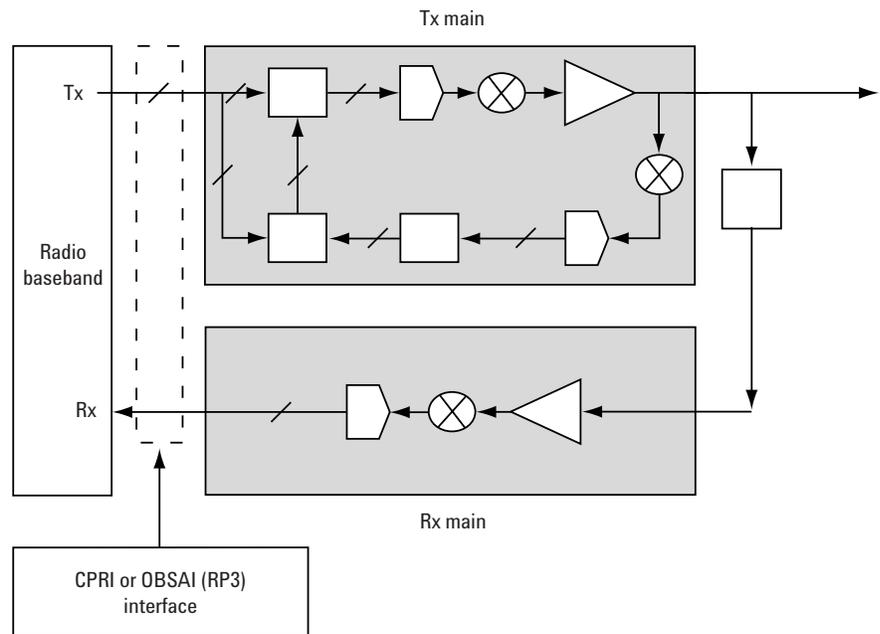
Figure 4. Block diagram of the integrated digital radio.

Architectural changes have been made to integrate the transmitter and power amplifier chain (Tx Main). Similarly changes have been made to the receiver chain (Rx Main) in the digital transceiver. As shown in Figure 4, the integrated digital radio consists of the digital transceiver (Tx Main and Rx Main blocks) and the radio baseband. The digital transceiver contains the up-converter, down-converter, band filtering, and linearization components of the radio. The radio baseband contains the technology-specific baseband coding and channelization.

The integrated digital radio also requires a digital baseband interface with the transmit and receive functions. Each of the industry groups leading the efforts to standardize the radio interface has a specific orientation.

- The OBSAI defines several standard interfaces within the basestation, including the radio interface, the backhaul interface, and the command and control interface. This work encompasses all major radio formats (CDMA, GSM, and W-CDMA). The reference point 3 (RP3) is the most important interface for the content in this paper.
- The CPRI defines the options for the interface between the radio baseband (radio equipment control) and digital radio (radio equipment). This work is focused solely on the interface for W-CDMA radios.

Note: Test and measurement methodology has yet to be standardized in these groups. Also, it will be important for the development of a multi-vendor standard to have some type of verification or conformance assessment program to assure interoperability.

Distributed networks
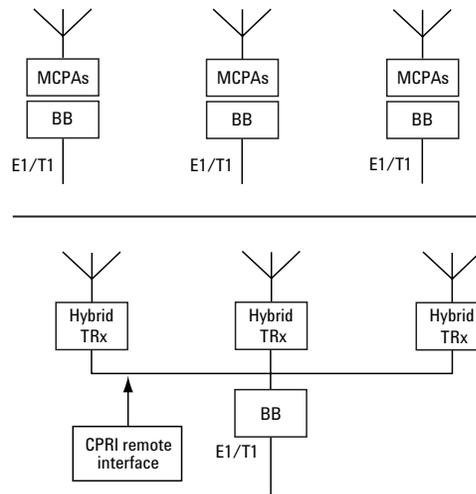
Figure 5. Topology of a traditional (top) and distributed (bottom) network.

Historically, each cell site in a wireless network encompasses a complete basestation with amplifier, antenna, baseband, and backhaul elements. The peak capacity at each site is fixed; the network design does not permit dynamic allocation of backhaul capacity to match network demand as traffic patterns shift over the course of a day.

Backhaul capacity is one of a service provider's biggest operational expenses. Utilization rates have a significant impact on the overall profitability of a network. To achieve more efficient deployment of network resources, service providers want to implement architectures that enable backhaul capacity to be allocated and distributed among cell sites as needed.

In response the industry has come up with a distributed network topology that makes use of the digital transceiver and a low latency remote radio interface. Figure 5 shows an example of this topology using the industry-defined CPRI remote radio interface. Like a traditional network, the distributed topology (also called a "hotel network") provides an RF coverage unit at each physical location - in this case, in the form of the digital transceiver. The baseband core and backhaul capacity, however, become centrally located resources that are shared among the various locations. The distributed elements are all connected by means of the low latency radio interface that can be located several kilometers from the baseband core processing.

Dynamic allocation of the backhaul offers several advantages:

- cost reduction - industry-led studies have shown that service providers can reduce network capital and operating expenses by up to 60 percent. Savings include a lower cost for each radio unit, less power consumption, and higher use of backhaul capacity
- capacity increases - capacity can be added at a central location and allocated dynamically among sites to meet increased and varying traffic demands
- easier upgrades - with baseband core centralization, the number of locations affected by baseband processing updates should be significantly reduced as the standards evolve

While the distributed network is neither a new concept nor one unique to CDMA, improved components, technology standardization, and lower cost of deployment have made it a viable alternative to network operators for their next major deployments.

Technology versus expense

Table 1. Comparison of network costs and benefits.

GSM/GPRS	W-CDMA (1st gen~'00)	W-CDMA (2st gen~'04)
CapEx:	CapEx:	CapEx:
• 40 W/channel	• 40 W/carrier	• 40 W/carrier
• 8 channel Macro-cell BTS	• 6 carrier Macro-cell BTS	• Omni-BTS
• supports 56 users	• supports ~350+ users	• supports ~60+ users
• $30 to $50 k	• $100 to $250 k	• < $10 k per RF unit
OpEx:	OpEx:	OpEx:
• 800 W (1 phase mains)	• 5000 W (3 phase mains)	• 200 W (1 phase mains), per RF unit
• Single or partial E1/T1	• Up to dozens of E1/T1 lines for peak capacity	• Partial E1/T1 with capacity added at centrally located control unit

Table 1 compares the cost associated with the typical 2/2.5G and 3G network configurations.

GSM/GPRS network
A typical mature GSM macro-cell basestation has eight radio cards supporting a three-sectored basestation configuration (2+3+3). Each radio supports up to seven users for a peak capacity of 56 users. A 40 W radio transmission per channel sets the link budget for the system. This type of has been in use over ten years, and the average system costs between $30,000 and $50,000 (US). The base assumption includes the costs of the basestation, signal conditioning, and near antenna elements not shared with other co-located networks.

Because the GMSK modulation used in the GSM basestation is efficient, the overall BTS power consumption is approximately 800 W, assuming approximately 45 to 50 percent efficiency on the single-carrier power amplifiers. The lower data rates that are supported (and lower expected utilization rates) suggest a backhaul capacity requirement of a single E1/T1 line. The actual capacity will be determined by the network planning group to provide a desired level of quality of service (QoS).

W-CDMA network
Early W-CDMA macro-cells could support a tremendous increase in capacity over a GSM macro-cell BTS. A three-sectored basestation, with two carriers per sector, theoretically supported up to 60 users per carrier or about 350 users by macro-cell. Thus, a six-carrier macro-cell could handle about six times the capacity of the 2G (GSM) BTS. But the immaturity of 3G technology has meant a proportional (six time) cost increase. Moreover, although it's possible to add more users to the system, building the new customer base takes time. Today, the service provider is paying for excess capacity in anticipation of tomorrow's capacity needs. While it is difficult to get information on the average selling price of W-CDMA basestations, the information available suggests a significantly higher cost for not only the basestation hardware, but also the housing and air conditioning required to cool the hardware at the installation.

In a W-CDMA basestation, the use of traditional feed-forward amplifiers (assume only six to eight percent efficiency) results in significant power consumption. To accommodate the heat generated and electrical needs, special housing, air conditioning, and mains power must be added.

The peak capacity and data rates supported by the 3G standard are several times those of traditional 2G and 2.5G networks. To achieve the same peak data rates and quality of service levels relative to the BTS capacity, the service provider must allot a much higher backhaul capacity at each antenna site. Utilization rates as the network begins its maturity are still very low.

Technology versus expense
(continued)

Distributed W-CDMA network

A distributed network topology with the remote CPRI interface offers a substantial savings in network deployment and operating expenses. Furthermore, capacity (RF and backhaul) can be increased incrementally as demand for 3G grows. The result will be a higher utilization rate at the network level with lower capital and operating expenses.

The RF unit has capacity similar to that of the 2G or 2.5G macro-cell. With baseband linearization, transceiver efficiency is improved to 20 to 25 percent. Thus, if network loads are equivalent, the RF unit has a lower capital expense and an equal-to-lower operating expense. The net result is that a distributed network topology can make 3G networks cheaper to deploy and less expensive to operate that existing 2G and 2.5G networks. Theoretically, the network-distributed elements could be extended to multi-sector or multi-carrier radios, thus providing an easier network migration to add capacity. Coupled with 3G's migration path to higher rate and higher valued services, the new technology presents an attractive alternative to traditional network deployment.

Amplifier Linearization Technology and Implications for Testing

This section of the application note will review some of the common architectures used to achieve amplifier linearization in basestations. It will also look at the relationship between these architectures and the tools used to test and verify their performance.

Feed-forward linearization technique
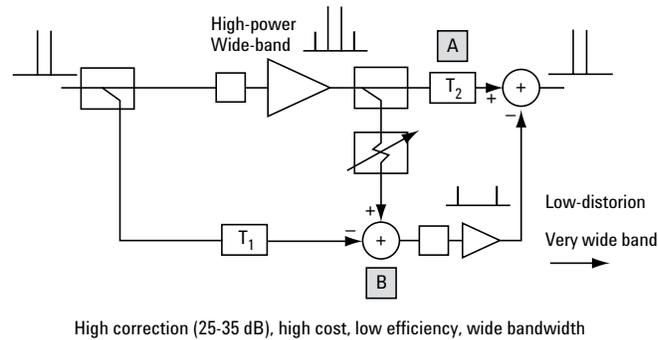
High correction (25-35 dB), high cost, low efficiency, wide bandwidth

Figure 6. Simplified block diagram of a feed-forward amplifier.

The most popular amplifier design today uses the feed-forward linearization technique, illustrated in Figure 6. The amplifier's output voltage is added to an error signal that cancels its distortion. The error signal is obtained by subtracting an attenuated replica of the output signal from a delayed replica of the input signal.

The amplifier's output signal, including distortion, is combined with an inverted version of the amplifier's distortion at the output of the feed-forward amplifier (A). The distortion in the output is theoretically zero, although zero is never achieved. The inverted version of the distortion is obtained by sampling and attenuating the output of the internal high-power wideband amplifier and combining it with a delayed version of an inverted input signal (B). Through careful control of the amplitude and delay of both signals, nearly complete cancellation of the original signal components can be obtained. The resulting distortion signal is then delayed and amplified through an error amplifier to match the inversion of the distortion created by the main high-powered wideband amplifier (A).

Once the amplifier is tuned, feed-forward is essentially a static linearization technique. It corrects for distortion without knowledge of the power amplifier's distortion characteristics, providing 25 to 35 decibels of cancellation over a wide bandwidth. In practice, an active loop may be included to compensate for timing and temperature drift variations. The loop may consist of a training sequence injected into the feed-forward loop that represents a statistically similar signal expected under normal operating mode. While the description and operation of this active loop is not discussed further in this paper, it is important to acknowledge the impact of this active loop in the discussion of test equipment requirements in the next section.

Distortion of the main path and error path may require matched transistor-gain performance blocks to ensure adequate cancellation performance. This can raise the cost of the transistors, as these components may have to be lot-selected or yield-sorted. Furthermore, the bias and efficiency of the error amplifier will reduce the overall operating efficiency - of the power amplifier.

The main drawbacks of the feed-forward technique can be summarized as follows:

- low efficiency, attributable to the error amplifier distortion-correction circuitry
- high cost, a result of the additional components required and possible need for lot-selection and yield-sorting
- extensive tuning requirements, which slow throughput in manufacturing

RF pre-distortion techniques
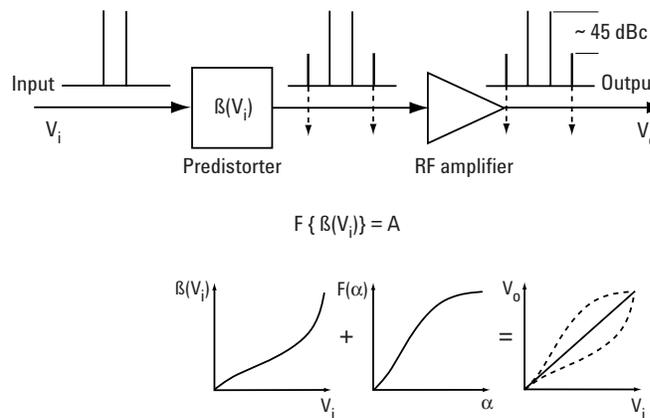
Figure 7. RF pre-distortion combined with feed-forward techniques.

Pre-distortion techniques use the inverse input-output function of the power amplifier to provide correction factors. The basic technique is simple and efficient. However, in order to be effective, pre-distortion requires highly accurate characterization of amplitude- and phase-modulation conversion (AM-to-AM or AM-to-PM). Without a feedback loop mechanism, pre-distortion returns a low amount of correction (5 to 10 dB). With a feedback loop, it can achieve moderate correction factors (10 to 15 dB). A narrow operating bandwidth is required for analog systems.

The RF pre-distortion improvements (approximately 10 dB) can be added to the feed-forward cancellation improvements (approximately 30 dB) when the two techniques are integrated. In this way, cancellation of distortion products over 40 dB is possible. As a result, the amplifier can be driven further into its non-linear performance region with higher output power, better efficiency, and fewer parts.

RF pre-distortion techniques
(continued)

What is needed to test RF pre-distortion amplifier designs?

To test an amplifier that uses RF pre-distortion techniques, a signal generator is needed that can produce a complex, high-performance RF signal that is good enough to stimulate the power amplifier. The signal generator must also have an error margin less than the performance requirements of the amplifier to enable confidence and reduce the statistical impact of the test equipment in the test process.

As previously mentioned, feed-forward architectures typically include a CDMA-type training sequence that statistically represents the actual signal expected when the amplifier is in use. This training sequence is necessary for the stable operation of the amplifier. Because most CDMA amplifiers risk becoming unstable if a CW or multi-tone signal is introduced when the amplifier's active loop is turned on, only a complex (not a CW or multi-tone) test signal can be used.

Spectrum-based measurements such as adjacent channel leakage ratio (ACLR) require an instrument offering high performance with 16 to 20 dB specification limit margin to remove measurement uncertainty and provide statistical confidence in the measurement process. The signal analyzer's phase noise performance and noise figure are also considerations affecting the ability to make spectrum emission mask measurements in the presence of a test signal.

For in-channel modulation quality tests, such as error vector magnitude (EVM), it is important that the analyzer be immune to the effects of multi-carrier environments. Otherwise, the modulation quality figure may be more representative of the analyzer's demodulation algorithm and DSP filtering than of the amplifier's performance.

How much amplifier performance is actually needed?

When the feed-forward technique is combined with RF pre-distortion, the resulting amplifier performance may actually exceed the test equipment's measurement ability without the use of dedicated, RF-tuned filters. This occurs more frequently as amplifier transistor technology continues to increase the output power-per-device and decrease the intermodulation distortion products at the rated output.

Given the advances in today's power transistor technology, use of feed-forward in amplifier design may result in too much performance - more than is needed for the application, more than is required of the network components, and perhaps more than the network operator or service provider can afford. These factors end up adding yet more cost to the network.

RF pre-distortion techniques
(continued)
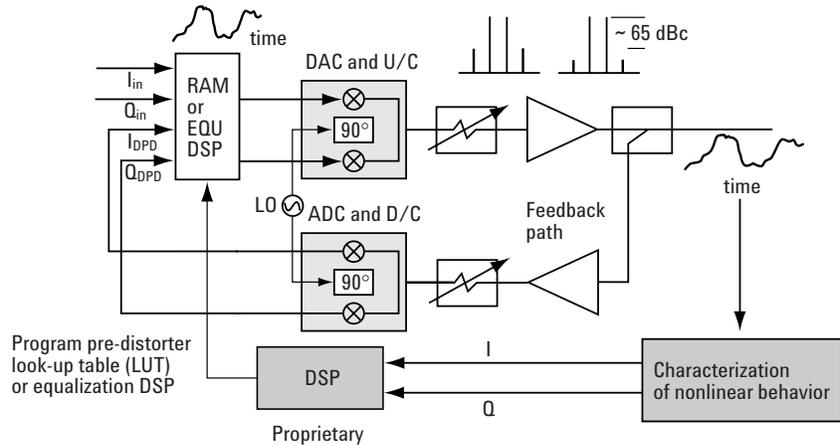
Figure 8. Adaptive digital pre-distortion applied to the power amplifier.

Adaptive digital pre-distortion can deliver similar linearity gains in power amplifiers without the efficiency penalty of the feed-forward technique. With ADPD, distortion characteristics are used to digitally manipulate the magnitude and phase of signals at the baseband. This "pre-distortion" linearizes the entire transmitter chain, providing greater repeatability, component reliability, and efficiency.

The term "adaptive" refers to the active monitoring of the output distortion performance and the dynamic tuning of the pre-distortion parameters such as temperature, envelope power, and bias level. See Figure 8.

Functionally, the amplifier requires a baseband IQ signal pair to drive an equalizer as both phase and amplitude corrections are applied. This is shown in the diagram above with the block labeled "RAM or EQU DSP." Much like the RF pre-distortion, the equalizer combines the input signal with the inverse input-output function of the transmit chain and power amplifier to correct for the linear behavior errors. However, unlike the RF pre-distortion technique, the amplifier will attempt to predict dynamically or adaptively the non-linear behavior of the amplifier's gain block.

This task can be accomplished in one of the following ways: by calibrating the gain block and using a feed-forward look-up table for corrections, or by modeling a family of gain blocks and using a proprietary DSP algorithm to predict the non-linear behavior without using expensive RAM.

Another function of the amplifier is the digital-to-analog conversion and up-conversion to RF. While this function has always been a fundamental part of radio design, it has a special importance now that the linear and non-linear behaviors of this block are corrected in the digital baseband signal flow.

13

RF pre-distortion techniques
(continued)

The feedback path monitors the active performance of the amplifier. In the feedback path, the distorted output is down-converted from RF and then digitized (through the analog-to-digital converter). The resulting error signal is fed back into the equalization DSP. There must be an accurate feedback path that represents the time domain signal at the output of the power amplifier as a time domain correction is applied to the forward signal. To optimize the performance, the necessary corrections need to be applied to the linear and non-linear elements of the feedback chain so that the feedback path measurement errors can be separated from the aggregate signal at the equalization DSP.

The use of a common local oscillator (LO) structure for the up- and down-conversion elements has the added benefits of better phase noise performance on the resultant error signal, and an inherent immunity of the error signal to LO jitter and drift issues. However, it is important to note that from a testing standpoint the amplifiers measurement feedback path will be blind to internally generated LO spurs.

Independent of the implementation method, to obtain high, 20 to 30 dB correction factors, the power amplifier's non-linear behavior needs to be accurately characterized, and the transmit and feedback paths must have accurate correction factors. The error products associated with the gain block must be represented accurately, separate from the independent errors in the transmit and feedback paths. The quantitative importance of correcting these errors is discussed in the next section.

Pre-distortion cancellation theory

What's next: Adaptive digital pre-distortion
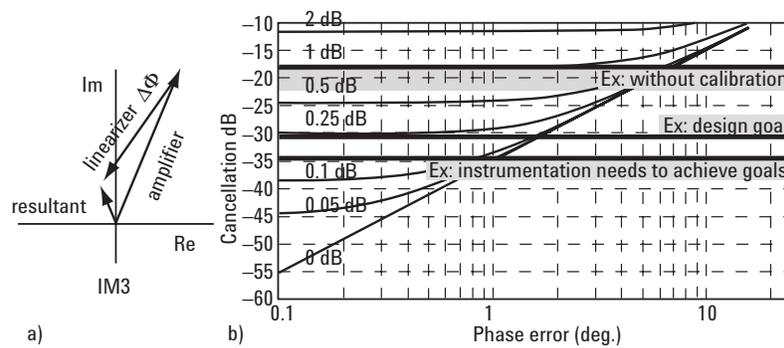
Figure 9. Impact of phase and amplitude error performance on adaptive cancellation. (Source: Refer to page note 1 on page 5.)

The diagram in Figure 9 represents the theoretical limits of the amount of correction (cancellation) that can be achieved in the power amplifier. The gradient curves (0 dB, 0.05 dB, 0.1 dB, etc.) show cumulative RF error in decibels. Essentially, the diagram illustrates the AM/AM correction performance that can be achieved in the implementation. The vertical axis shows the theoretical cancellation in decibels based on the RF correction performance relative to the absolute phase error correction performance, which is shown on the horizontal axis.

The correction limits are determined by the accuracy with which the amplitude and phase of the distortion products can be measured and corrected. For example, when the amplitude correction error is 0.1 dB and the phase correction error is 0.7 degrees, the maximum theoretical correction is –35 dB.

The linearity, relative flatness, and dynamic range of the feedback loop are important factors in determining the amount of cancellation that can be achieved in the device. Since the equalization DSP is expecting an accurate time domain representation of the output signal, errors in the measurement of that time domain signal in the feedback path limit the DSP effectiveness by the amount of those errors. In narrowband applications, it is difficult to achieve cancellation much greater than about 20 dB without consideration and correction of the transmit and feedback path errors. These errors can be much more significant for wider bandwidth feedback paths as errors from bandpass filters, anti-alias filters, image and LO rejection filters, and other components begin to impact the desired signal.

Higher performance can be achieved through careful consideration of the linearity, flatness, and dynamic range of the signal generation and analysis tools. If, for example, the design goal is to achieve 30 dB cancellation performance of the feedback loop, the measuring equipment must be able to provide amplitude and phase measurement accuracies that fall within the grayed area of the graph (between 16 and 22 dB of cancellation). In order to achieve these accuracies, it is essential to correct for instantaneous amplitude and phase flatness, accurately measure the lower-level distortion products, and then consider the dynamic range and measurement accuracy limits of the signal analyzer, which ultimately determine the limits of correction.

What's next: Adaptive digital pre-distortion (continued)

Note that historically a network analyzer could be used to give accurate performance characterization of the transmit and receive paths of feed forward and RF pre-distorted amplifier blocks. With the new adaptive digital predistorted amplifiers, there are two important considerations that affect the test methodology. First, the ability to match parts and components at low frequency offers a distinct advantage. To get more than the performance expected at a 50 ohm match impedance for each functional block, the integrated functional blocks can be matched at lower impedances to enhance their efficiency and performance. Thus, measuring the performance of the individual devices with a network analyzer (matched to 50 ohms) does not give an accurate performance representation of the newly integrated block. Second, it is important to characterize the fully-integrated amplifier once the integrated blocks have been assembled. The fully-integrated digital amplifier includes a digital input and RF analog output on the transmit path, and RF analog input and digital output on the feedback path. The traditional network analyzer can no longer be used for the phase and flatness performance characterization.

Phase and amplitude corrections

The following example illustrates the performance improvements achieved in measurement equipment with phase and amplitude corrections. Since the circuitry of a high performance vector signal analyzer is similar to the feedback path of an ADPD amplifier, the performance improvements described from calibration shown in Figure 10 are similar to those expected improvements in an ADPD amplifier.

EVM = 11.1% before Cal   EVM = 0.8% after Cal
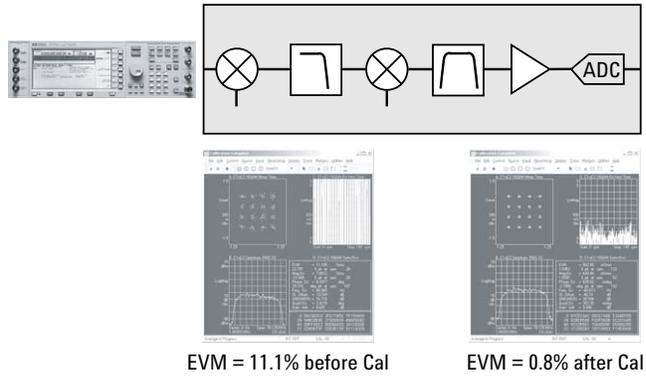
Figure 10. Block diagram of a high performance signal analyzer.

A 50 M-symbol/s 16 QAM signal representing approximately 65 MHz of band-width is generated and put into a high-performance vector signal analyzer, in this case the Agilent PSA 80BW system, as diagrammed in Figure 10.

Before additional correction is applied, amplitude flatness is approximately (1 dB and phase error is approximately 2 degrees.) These values are typical of the best commercially available equipment on the market. The residual error signal (EVM) of 11.1 percent before calibration is due largely to the performance of the signal analyzer.

Without changing the input signal, corrections to the phase and amplitude are made that improve performance to 0.1dB with less than 1 degree of phase error. The error signal of 0.8 percent (a better than 10 dB improvement) now is due largely to the residual error of the signal source. If the internal residual errors of the signal source were further corrected with an enhanced calibration, it would be possible to discern any additional errors on an analog input chain, increasing the confidence level of the enhanced calibration.

17

Dynamic range and linearity
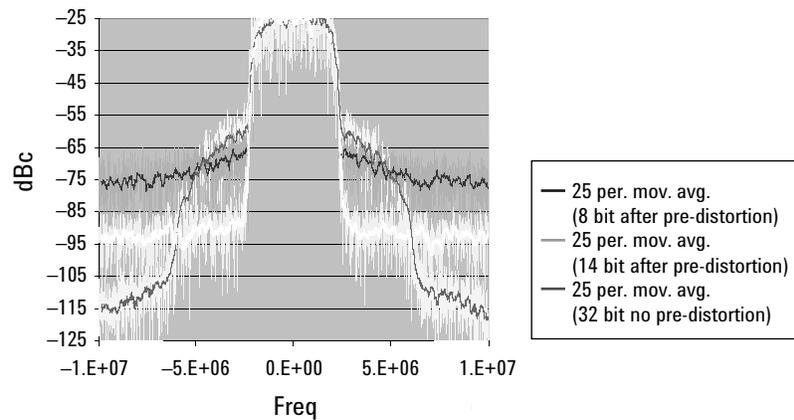
Figure 11. Impact of dynamic range and linearity on performance.

The graph in Figure 11 shows cancellation performance as a function of dynamic range. Performance is modeled using the Agilent ADS Linearization DesignGuide and a sample algorithm. Although performance will vary according to the algorithm used, these results are representative of what can be achieved in a system.

Note that

• the D/A converter is always 16 bits
• the look-up table (LUT) resolution is 32 bits and size is 256 entries
• the D/A converter bandwidth is 122.9 MHz
• the 8-bit A/D converter bandwidth is modeled as infinite in bandwidth
• the 14-bit A/D converter bandwidth limitation is 81.92 MHz

In this example, a modestly distorted signal with sidebands down about 35 to 40 dB is pre-distorted with a theoretically perfect 8-bit acquisition system. The cancellation of about 8 to 10 dB is limited primarily as a limit of 8-bit dynamic range. The phase and flatness are assumed to be perfect.

Re-running the simulation with a theoretical 14-bit acquisition system, even with a bandwidth-limited A/D (shown in white), yields over 30 dB of error correction.

If the number of entries in the LUT are kept constant at 256, the dynamic range of the 14-bit acquisition system provides a significant improvement over the 8-bit system. Similarly, scaled performance could be expected from 10- and 12-bit systems.

Information bandwidth and signal analysis
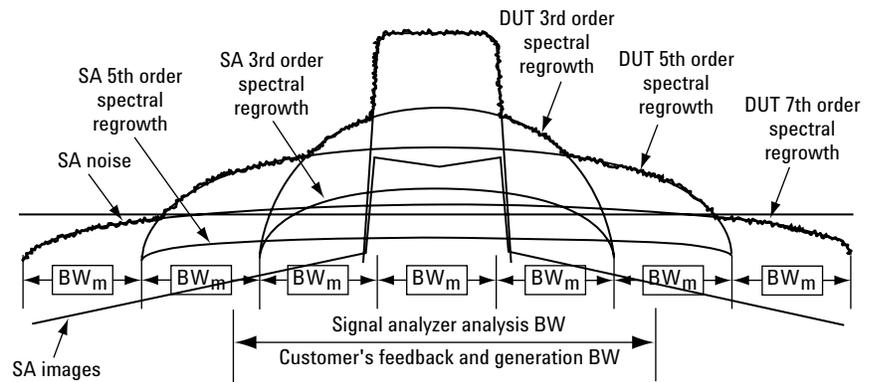
Figure 12. Distortion products of a device under test.

The non-linearities of the power amplifier result in third-order distortion products, fifth-order, seventh-order, and so on. The summation of these products creates the signal's unwanted shoulders.

Figure 12 illustrates how the distortion products of the device under test (DUT) fold into the band of interest underneath the dominant signal and the higher order intermodulation products. These distortion products must be accurately measured before being eliminated through pre-distortion. Consequently, the amount of instantaneous bandwidth available in a signal analyzer will limit the amount of correction possible. Another limiting factor is the internally generated distortion or noise of the measuring device. The lower the ratio of the DUT's distortion signal to the analyzer's interfering signal, the less one is able to characterize and correct the power amplifier distortion using pre-distortion. The interfering signals inherent in a signal analyzer include

- third-order distortion
- fifth-order distortion
- noise
- images

For linearization analysis, the analyzer's accuracy depends on its distortion, sensitivity, image rejection, and bandwidth specifications.

Measurement equipment performance

In the discussion of linearization techniques, some of the measurement requirements important in the design and manufacture of ADPD amplifiers and digital radios were mentioned. To develop, test, implement, and optimize an ADPD amplifier requires measurement equipment with uncompromising performance. Wide bandwidth, high dynamic range, linearity, and flatness are all important instrumentation features used in amplifier design for

- behavior modeling
- analysis and cancellation of higher-order intermodulation distortion products
- construction of look-up tables unique to each gain block

To correct the linear behavior of the other signal components in the transmit, feedback, and receive chains, it is necessary to isolate the error terms in each path. The performance of the measurement equipment therefore must be greater than the performance of the device being measured so that calibration or corrections can be transferred to the device under test.

Calibration enhances the measurement equipment's ability to

- isolate error products in transmit and feedback loops
- improve transmit and cancellation performance of the digital amplifier

When considering the effects of ADPD, it is important to remember that the integrated DPD amplifier and digital radio have digital interfaces. Digital stimulus and measurement must be provided at these interfaces if the system design does not include other access points. There is also a need to measure and characterize the integrated receiver that is part of the radio system, in this case without the presence of a baseband radio. The digital transceiver may be a field replaceable unit and in some network topologies, there may not be a 1:1 ratio of baseband unit to digital transceiver unit.

These measurement challenges are examined in more detail in the next section.

Measurement Challenges of Adaptive Digital Pre-distortion Amplifiers and Digital Radio Transceivers
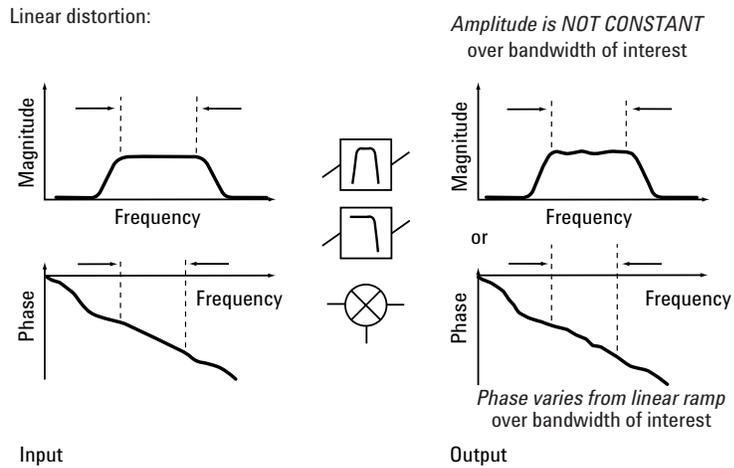
Figure 13. Errors in a digital transmitter or receiver caused linear distortion.

To model the behavior of an ADPD amplifier or to calibrate the feedback loop, distortion in the transmit, receive, and feedback paths must be characterized accurately. Distortion in an integrated transmitter (or receiver) is caused by the combination of non-linear and linear errors in the different components, illustrated in Figures 13 and 14.

Devices that behave in a linear fashion impose only magnitude and phase changes on input signals. Any sinusoid introduced at the input will appear at the output at the same frequency. No new signals are created.

A linear network adds distortion to a signal when

- the signal's amplitude, which is constant at the input, does not remain constant at the output over the bandwidth of interest, or
- the phase, which is linear at the input, does not remain linear at the output over the bandwidth of interest

If a complex, time-varying signal is passed through a linear network, the amplitude and phase shifts can dramatically distort the time-domain waveform. The effects of linear distortion on transmitter or receiver performance are more significant in the case of wideband signals.

The main linear components in the integrated transmitter and receiver are bandpass or baseband filters. However, other devices that are not inherently linear, such as up-converters, down-converters, and amplifiers, can also contribute to linear distortion in the transmit/receive chain or feedback loop.

Distortion mechanisms in integrated transmitters and receivers
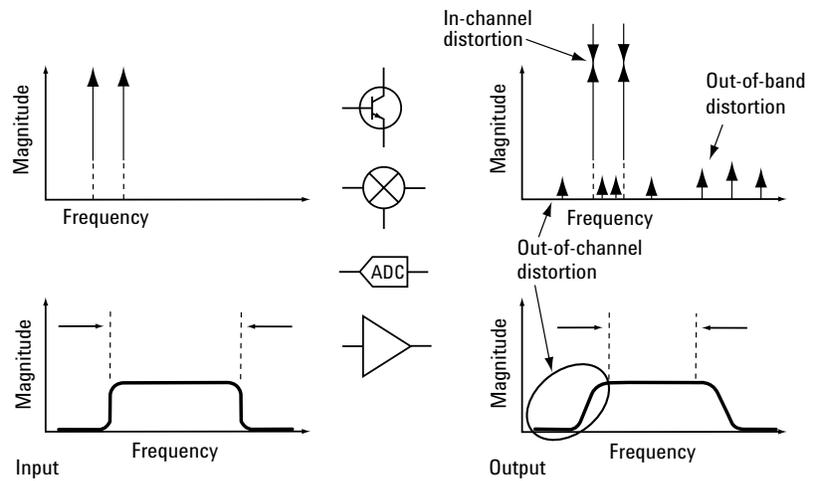
Figure 14. Non-linear distortion caused by the power amplifiers.

Non-linear devices can shift input signals in frequency (as a mixer does, for example) or can create new signals in the form of harmonics or intermodulation products.

In digital communication systems, the most significant source of non-linear distortion is the power amplifier. The distortion resulting from non-linear behavior is often classified as the following

- in-channel
- out-of-channel (adjacent channel, alternate channel), or
- out-of-band

For complex, digitally modulated signals, third-order intermodulation distortion results in spectral re-growth in the adjacent channel, while higher-order intermodulation distortion results in spectral re-growth farther away from the main channel.

Characterizing distortion in components

Continuous-wave (CW) stimulus measurements have traditionally been used to characterize distortion in components. A network analyzer can measure linear distortion such as amplitude flatness, phase linearity, or group delay. Note that if the component being measured is a mixer, frequency translation must be taken into account.

Measurements of harmonic distortion and two-tone intermodulation distortion are typically used to characterize non-linear behavior in components such as transistors, mixers, and amplifiers. Total harmonic distortion and intermodulation distortion are specification parameters for D/A and A/D converters. Gain compression and AM to PM conversion measurements are used to gauge the effects of distortion in the main channel.

Tonal (CW) distortion testing is scalar in nature. Even if complex CW testing is performed, linear independence of the Fourier components and their distortion mechanisms is assumed. In fact, these distortion mechanisms are not independent. Therefore, one must use complex waveforms and utilize the time-domain as well for proper modeling, measurements, and analysis.

Since individual components cannot be isolated in integrated transmitters and receivers and the end products have non-linear components, CW-stimulus measurements are not suitable for characterizing distortion in these devices. The characteristic performance of the amplifier is dependent on the statistically representative signal expected during the operation. Therefore, more realistic complex stimulus and mixed-signal (bits-to-RF or RF-to-bits) measurements are required.

Characterization with complex stimulus
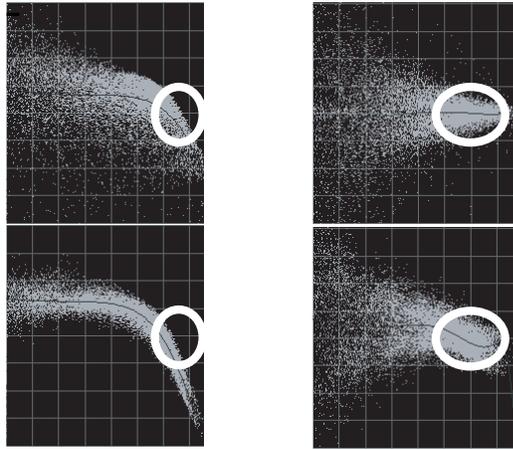
Figure 15. AM-to-AM and AM-to-PM results for 25 MHz versus 80 MHz.

An accurate method of non-linear modeling uses a "real-world" complex stimulus signal. Complex stimulus-response (CSR) measurements are made with a signal source and a vector signal analyzer, which measures distortion in the power amplifier's output using the input signal as a reference.

In CSR measurements, AM-to-AM and AM-to-PM characterization of magnitude and phase is usually performed on the time-sampled baseband waveform. Alignment of the time samples of the input and output time waveforms is required, so that a magnitude-versus-phase comparison is obtained at every instance.

Figure 15 shows the measured results of the AM-to-AM (left) and AM-to-PM (right) for a 20 MHz stimulus (represented by a four-carrier W-CDMA test model signal). The bandwidth of the measuring instrument affects the measurement accuracy, as shown in the Figure 15 examples, where gain compression and AM-to-PM performance of the 20 MHz signal is measured using a 25 MHz instantaneous bandwidth (top) and an 80 MHz instantaneous bandwidth (bottom).

As discussed previously (see section on information bandwidth and signal analysis), a wider bandwidth may be required to accurately characterize the power amplifier when significant distortion is present.

In this case, the 80 MHz bandwidth is large enough to capture the entire third-order intermodulation products (as well as most of the fifth-order products), providing information needed to understand the power amplifier's behavior and to correct for distortion.

Isolating linear and non-linear components
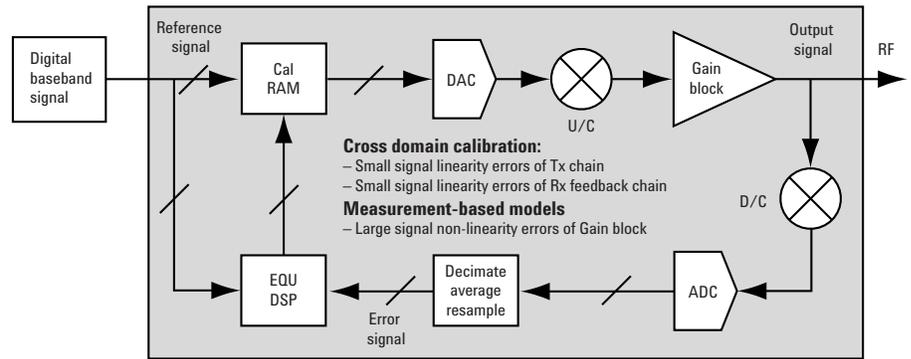
Figure 16. Isolating linear from non-linear components in the digital transceiver.

The desired inputs to the equalization DSP are the time-domain error signal expected from the gain block (large signal non-linear performance) and the input reference signal. Since the known reference signal from the baseband is given, the challenge remains to understand the components of the error signal so that the resultant adjustments can be made to the transmit signal to optimize the output signal. In practice, unless corrections have been applied, the error signal compared at the equalization DSP will be a combination of the small signal errors in the transmit path, the small signal errors in the feedback path, and the large signal errors of the gain block. To isolate the large signal errors that need to be compared in the equalization DSP, the small signal errors of the transmit and feedback paths need to be isolated and corrected.

In the integrated end-device, the linear and non-linear error components can be isolated. The transmit path is measured from the reference signal to the output signal, so that signal impairments can be quantified and acceptable levels of correction are applied to deliver the expected results. See Figure 16.

Separately, the feedback path is measured from the output signal to the error signal are corrected, so that the feedback path will represent the true signal at the output of the amplifier and not the combined errors of internal feedback path and the distortion of the gain block. As noted earlier, isolating the errors in the feedback path requires high quality circuitry. Instrument-grade circuitry in the internal feedback path can improve the quality of the feedback path and the level of error cancellation in the amplifier. Providing an analog stimulus with reduced internal residual errors can improve the visibility to errors in the internal feedback path of the amplifier.

Once hardware corrections have been applied to these respective paths, the equalization DSP can accurately apply the necessary corrections to the large signal errors generated by the gain block.

Digital radio test challenges
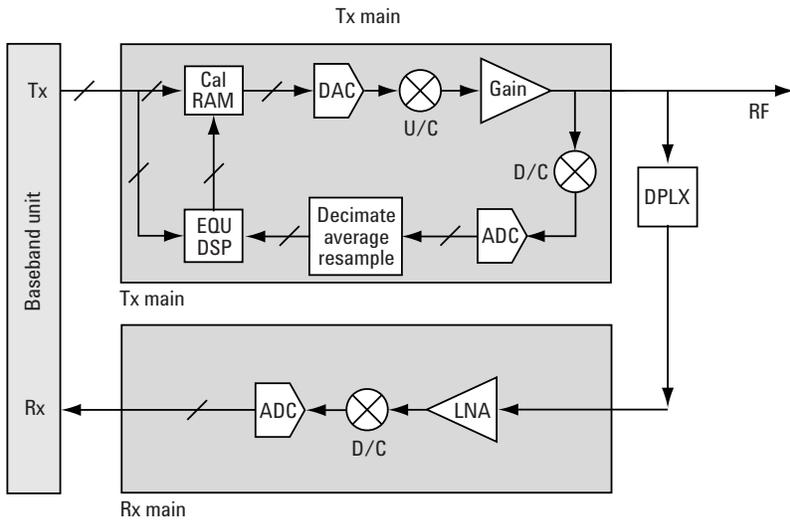
Figure 17. ADPD amplifier's integrated transmitter and receiver chains.

The measurement issues discussed thus far apply to modern digital radios that incorporate ADPD amplifier technology as part of a digital transceiver. Other challenges are introduced in the design and manufacture of the digital radio's integrated receiver chain as well.

Traditionally, the radio's diplexer and low noise amplifier (LNA) were separate components whose performance could be characterized by measuring S-parameters (insertion loss and impedance) and perhaps noise figure. The down-conversion chain, filtering, and A/D conversion were supplied separately in the baseband radio. Together the down-conversion chain and baseband radio were tested for receiver sensitivity, which became one of the most important specifications for determining basestation receiver performance.

With the removal of baseband processing from the digital radio in the integrated design, it becomes more difficult to measure sensitivity on the digital radio receiver chain, illustrated in Figure 17. The receive elements that must be controlled in the manufacturing process are now integrated within the digital radio, and a new way to access and measure their performance is needed. This will be discussed in the next section on test and measurement solutions.

Test and Measurement Solutions

Adaptive digital predistorted amp

Hybrid transceiver
Tx main

Baseband unit

Tx

Rx

Rx main

CPRI or OBSAI (RP3) interface
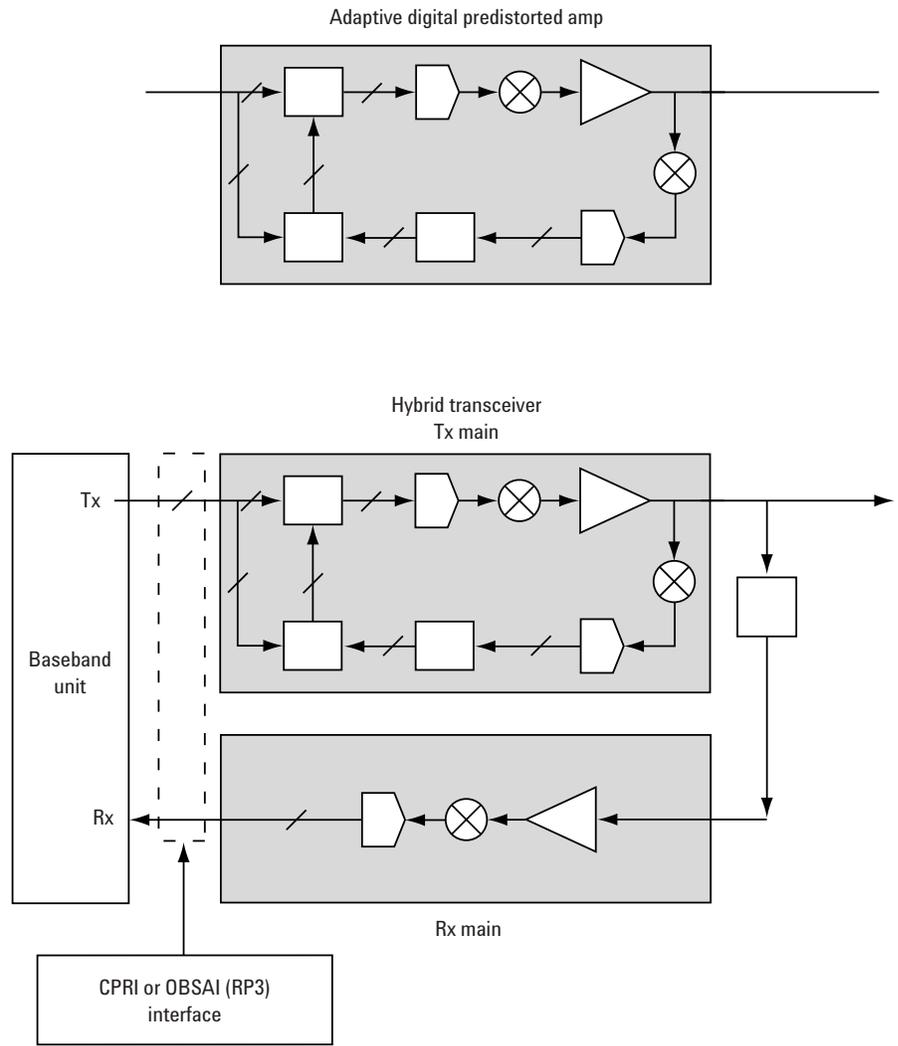
Figure 18. Block diagrams of the ADPD amplifier and digital transceiver.

Solutions exist for overcoming the measurement challenges, as illustrated in the following applications:

- device modeling and characterization
- calibration and error correction in the amplifier transmit chain
- feedback loop calibration
- receiver calibration and sensitivity metrics

Advanced network architectures such as those illustrated in Figure 18 require equally advanced measurement tools. Agilent products meet these measurement challenges to keep designers and manufacturers at the cutting edge of communication technology.

Device modeling and characterization
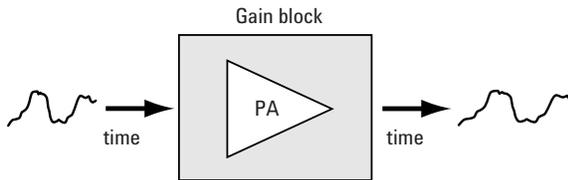
Gain block

Figure 19. Characterizing the power amplifier gain block.

To develop, characterize, and verify the equalization DSP necessary for adaptive pre-distortion in an amplifier (for example, the gain block shown in Figure 19), several important conditions must be met.

Often pre-distortion models are validated and rebuilt using measurement-based models. Therefore, the development environment must link to the signal generation and analysis tools with enough performance for accurate characterization. It is important that the measurement equipment itself does not impair the results of the modeling. First, the RF equipment used for testing must have enough dynamic range to characterize the higher-order distortion elements. Additionally, the instantaneous bandwidth of the signal generator and signal analyzer must be wide enough so as not to impair the accurate characterization of the device. Finally, the corrected phase and flatness performance must be established. This performance directly affects the amount of cancellation that can be achieved with the equalization DSP algorithm.

Figure 9 has previously represented the expect cancellation results versus flatness and phase error performance.

**Tools for device modeling
and characterization**
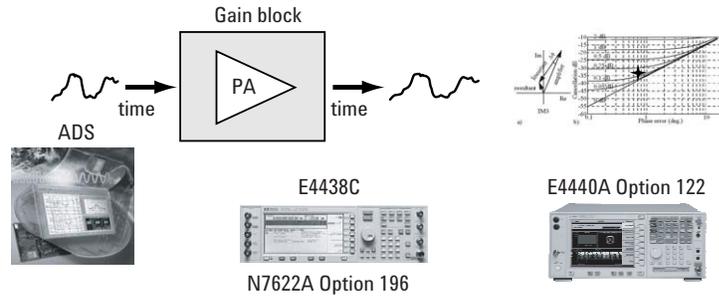
Figure 20. Agilent solutions for testing ADPD amplifiers and digital transceivers.

Agilent offers comprehensive solutions for modeling and characterizing ADPD amplifier and digital transceiver devices. (Some of these are shown in Figure 20.)

Advanced Design System (ADS)
- the ADS Linearization DesignGuide (E5614AN) has a Digital Pre-distortion Library that enables rapid development of equalization DSPs for DPD amplifiers
- the DesignGuide connects with Agilent's hardware stimulus and response measurement equipment to function in closed-loop emulation with the digital pre-distortion algorithm
- connected solutions also allow measurement equipment to directly replace simulation for the development of measurement-based models

89604A Distortion Suite
- this software suite measures the differential distortion across a two-port component
- tt uses real-world, complex stimuli (from a signal generator or the user's signal)
- measurements displayed include AM-to-AM, AM-to-PM, CCDFs of DUTs input and output signals, and delta-EVM (net EVM of the DUT)
- time- and phase-aligned I/Q waveforms of the input and output are provided
- software supports single-channel and dual-channel hardware configurations

ESG - E4438C Signal Generator
- the ESG has 80 MHz of signal generation at RF, with a 16-bit baseband generator
- N7622A Signal Studio Tool Kit provides Option 196 (Narrowband Corrections) that will significantly enhance the phase and flatness performance of the baseband signals created in the ESG
- the performance can improve the characterization of the device by reducing the residual errors of an RF signal generator

PSA - E4440A (Option 122) Signal Analyzer
- the Option 122 IF section provides the PSA with an industry-leading internal 80 MHz of instantaneous bandwidth in a 14-bit acquisition system
- the high-performance internal calibration of the wideband IF makes the PSA ideal for DPD applications
- the PSA combines wideband, high dynamic range with excellent phase, and amplitude flatness performance and linearity
- accurate wideband, high-dynamic-range analysis enables better response measurements of devices

Calibration and error correction in the amplifier transmit chain
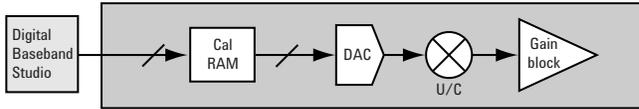
Figure 21. Calibrating and correcting errors in the transmit chain.

The solution requirements for verifying the look-up table and calibrating the transmit chain (Figure 21) are similar to those for characterizing a stand-alone gain block. However, in this integrated system, an additional challenge exists of simulating the wideband signal at the digital input with high enough sample rate and bit resolution to create a statistically representative signal. Signal generation therefore must occur at the digital input to the amplifier.

The RF measurement equipment must have enough dynamic range to characterize the higher order distortion elements that affect the resultant time-domain signal. The sample rate and bit resolution of the pattern generator and the instantaneous bandwidth and dynamic range of the signal analyzer must be fast, deep, and wide enough that accurate characterization of the device is not impaired. Finally, the characterization of the device is no longer RF-to-RF, but a digital-pattern-to-RF (or bits-to-RF).

Tools for calibration and error correction

89604A distortion suite software

N5110B – Baseband Studio
Option 134/194

DPD AMP
Pre-distorter look-up table
MCPA

E4440A – Option 122
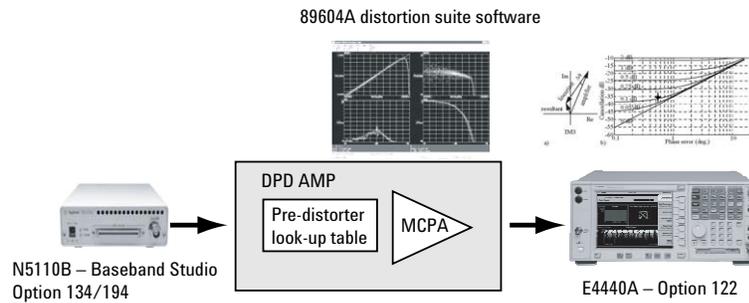
Figure 22. Agilent solutions for calibrating and verifying ADPD amplifiers and digital transceivers.

Agilent solutions can be used to calibrate and verify ADPD amplifier and digital transceiver devices. (Some of these are illustrated in Figure 22.)

N5510B - Baseband Studio - Option 194 Play Waveform
- N5510B consists of the N5101A PC card and the N5102A Digital Signal Interface Module. Option 194 enables digital I/Q or digital IF signals to be generated directly from a PC into an industry-standard interface
- logic is configurable (CMOS, TTL, LVDS) and data format is flexible (serial/parallel, 4 to 16 bit words)
- optional sample rates are offered from 40 Msa to 200 Msa/s digital IQ 16 bits (6.4 Gb/s)
- optional memory is offered to 512 Msa (2 GB - Option 022)
- several commonly available breakout boards (including Mictor and Samtec) can be used with the interface module, and pin-out details are included for developing one's own breakout boards
- programming and clocking flexibility enables this interface module to adapt to a wide range of digital circuits

89604A Distortion Suite
- this software suite measures the differential distortion across a two-port component
- it uses real-world, complex stimuli (from a signal generator or the user's signal)
- measurements displayed include AM-to-AM, AM-to-PM, and delta-EVM (net EVM of the DUT)
- time- and phase-aligned I/Q waveforms of the input and output are provided
- software supports single-channel and dual-channel hardware configurations

PSA - E4440A (Option 122) Signal Analyzer
- the Option 122 IF section provides the PSA with an industry-leading internal 80 MHz of instantaneous bandwidth in a 14-bit acquisition system
- the high-performance internal calibration of the wideband IF makes the PSA ideal for DPD applications
- the PSA combines wideband, high dynamic range with excellent phase and amplitude flatness performance, and linearity
- accurate wideband, high-dynamic-range analysis enables better response measurements of devices

Feedback loop calibration
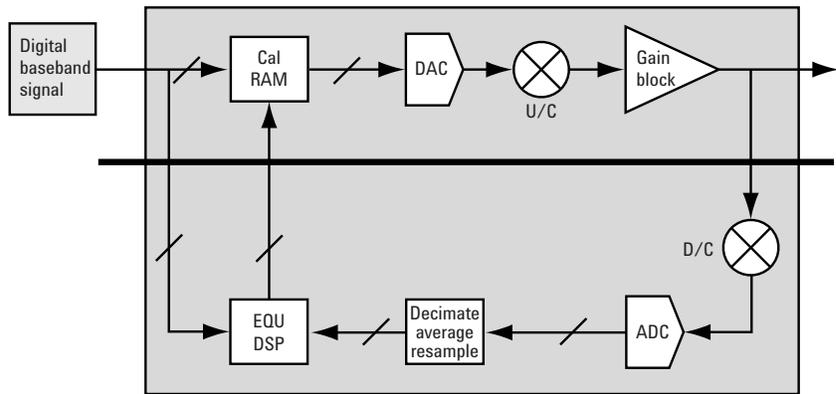
Figure 23. Feedback loop calibration.

In a power amplifier, the performance of the feedback path (shown in Figure 23) has a large impact on equalization performance. Using the block diagram of a signal analyzer as an analogy, an accurate method can be developed for verifying the DPD amplifier feedback loop in an integrated device. An accurate way of calibrating the receiver feedback path is also needed.

In the ADPD amplifier feedback loop input, the stimulus occurs at RF and the analysis at the digital plane. Thus the signal analyzer must accept digital inputs, and the RF stimulus must have high performance corrections across the stimulus bandwidth. Characterization of the amplifier will be RF-to-digital pattern (or RF-to-bits).

Through high performance corrections in the feedback path and a transfer of the calibration data into a correction table, the internal feedback loop may provide enough traceability to allow built-in-self-test on the RF output of the amplifier. Such capability is highly desirable in a basestation as it lowers maintenance costs by self-correcting, calibrating, and possibly diagnosing performance.

Tools for feedback loop calibration
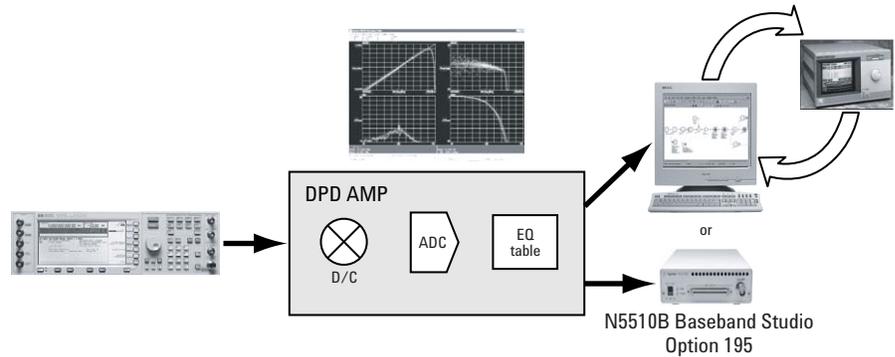
Figure 24. Agilent solutions for feedback loop calibration in ADPD amplifiers and digital transceivers.

Agilent solutions for feedback loop calibration, illustrated in Figure 24, are described below.

Advanced Design System (ADS)
- ADS has a link to the 16700A Logic Analyzer
- IQ vectors captured on the digital bus can be imported into the ADS for measurements

89604A Distortion Suite
- this software suite measures the differential distortion across a two-port component
- it uses real-world, complex stimuli (from a signal generator or the user's signal)
- measurements displayed include AM-to-AM, AM-to-PM, and delta-EVM (net EVM of the DUT)
- time- and phase-aligned I/Q waveforms of the input and output are provided
- software supports single-channel and dual-channel hardware configurations; file-based information can be used to represent a signal port; analysis is RF-to-bits

ESG - E4438C Signal Generator
- the ESG offers 80 MHz of signal generation at RF
- it includes a 16-bit baseband generator
- N7622A Signal Studio Tool Kit provides Option 196 (Narrowband Corrections) that will significantly enhance the phase and flatness performance of the baseband signals created in the ESG
- the performance can improve the characterization of the device by reducing the residual errors of an RF signal generator

N5110B - Baseband Studio - Option 195 Capture Waveform
- N5510B consists of the N5101A PC card and the N5102A Digital Signal Interface Module. Option 195 enables digital I/Q or digital IF signals to be analyzed directly in a PC from an industry-standard interface
- logic is configurable (CMOS, TTL, LVDS) and data format is flexible (serial/parallel, 4 to 16 bit words)
- optional sample rates are offered from 40 Msa to 200 Msa/s digital IQ 16 bits (6.4 Gb/s)
- optional memory is offered to 512 Msa (2 GB - Option 022)
- several commonly available breakout boards (including Mictor and amtec) can be used with the interface module, and pin-out details are included for developing one's own breakout boards

Receiver sensitivity metrics

Hybrid transceiver

Radio baseband

Rx

Rx main

CPRI or OBSAI (RP3) interface
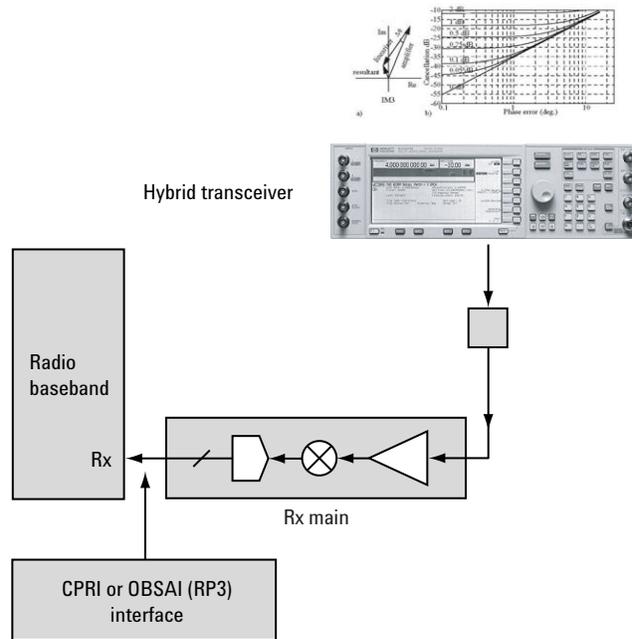
Figure 25. Verifying the receiver chain.

When the receiver chain is integrated into the digital radio, the measurement challenge becomes how to independently assess receiver sensitivity while controlling those variables present in a manufacturing environment that can degrade receiver performance. The hardware components that affect receiver sensitivity - diplexer, low noise amplifier, filters, A/D converter, and so on - have all been incorporated into a new digital radio design.

Receiver sensitivity is sometimes measured using the conceptual "golden radio." However, this approach is not ideally suited for manufacturing nor does it truly give an independent assessment of performance.

The tools needed to measure receiver sensitivity are

• a signal generator with fully coded signal generation capability, because the statistically representative signal used in other applications is not sufficient
• a signal analyzer that can decode, descramble, and add the signal-processing steps (such as Forward Error Correction) necessary to produce bit-error-ratio/block-error-ratio (BER/BLER) results

Calibration is also important, and implementing corrections can enhance the performance of the digital receiver. Techniques similar to the feedback loop should be adequate.

Other measurement considerations include the following:

• signal analyzer must have a digital input; the analysis must include correlation of key results for the product development or manufacturing environment
• high performance corrections are needed across the RF stimulus bandwidth for device calibration
• sevice characterization will be RF-to-digital pattern (or RF-to-bits)

Tools for measuring receiver sensitivity
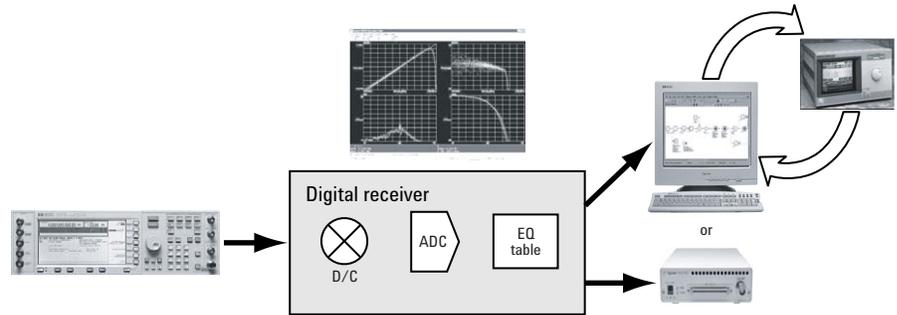
Figure 26. Agilent solutions for measuring receiver sensitivity.

Agilent solutions for measuring receiver sensitivity, illustrated in Figure 26, are described below.

Advanced Design System (ADS)
- the ADS has design libraries for all major cellular standards; these libraries make it possible to simulate a complete communication link for BER and BLER stimulus and analysis
- with connected solutions, simulation can be replaced directly with measurement equipment to make BER/BLER measurements from RF-to-RF, RF-to-IF, and RF-to-the digital plane
- correlation of BER/BLER performance with metrics such as Net EVM is possible to demonstrate a viable measurement strategy for manufacturing and verification of design

89604A Distortion Suite
- this software suite measures the differential distortion across a two-port component
- it uses real-world, complex stimuli (from a signal generator or the user's signal)
- measurements displayed include AM-to-AM, AM-to-PM, and delta-EVM (net EVM of the DUT)
- time- and phase-aligned signals at the input and output are provided
- software supports single-channel and dual-channel hardware configurations; file-based information can be used to represent a signal port; analysis is bits-to-RF

ESG - E4438C Signal Generator
- the ESG offers 80 MHz of signal generation at RF
- it includes a 16-bit baseband generator
- N7622A Signal Studio Tool Kit provides Option 196 (Narrowband Corrections) that will significantly enhance the phase and flatness performance of the baseband signals created in the ESG
- the performance can improve the characterization of the device by reducing the residual errors of an RF signal generator

N5110B - Baseband Studio - Option 195 Capture Waveform
- N5510B consists of the N5101A PC card and the N5102A Digital Signal Interface Module. Option 195 enables digital I/Q or digital IF signals to be analyzed directly in a PC from an industry-standard interface
- Logic is configurable (CMOS, TTL, LVDS) and data format is flexible (serial/parallel, 4 to 16 bit words)
- optional sample rates are offered from 40 Msa to 200 Msa/s digital Q 16 bits (6.4 Gb/s)
- optional memory is offered to 512 Msa (2 GB - Option 022)
- several commonly available breakout boards (including Mictor and Samtec) can be used with the interface module, and pin-out details are included or developing one's own breakout boards

Table 2: Equipment configuration for application testing.

Applications	ADS	Distortion Suite 89604A	ESG E4438C with N7622A Opt. 196	PSA E4440A Opt. 122	N5510B Opt. 194 Play Waveform	N5510B Opt 195 Capture Waveform
Device modeling and characterization of amplifier gain block	✔	✔	✔	✔		
Calibration and error correction of digital transmitter path		✔		✔	✔	
Calibration and error correction of ADPD feedback path	✔	✔	✔			✔
Receiver path calibration, error correction, and Rx sensitivity	✔	✔	✔			✔

For more information on Agilent test and measurement products, please visit **www.agilent.com**

Agilent Technologies' Test and Measurement Support, Services, and Assistance
Agilent Technologies aims to maximize the value you receive, while minimizing your risk and problems. We strive to ensure that you get the test and measurement capabilities you paid for and obtain the support you need. Our extensive support resources and services can help you choose the right Agilent products for your applications and apply them successfully. Every instrument and system we sell has a global warranty. Two concepts underlie Agilent's overall support policy: "Our Promise" and "Your Advantage."

Our Promise
Our Promise means your Agilent test and measurement equipment will meet its advertised performance and functionality. When you are choosing new equipment, we will help you with product information, including realistic performance specifications and practical recommendations from experienced test engineers. When you receive your new Agilent equipment, we can help verify that it works properly and help with initial product operation.

Your Advantage
Your Advantage means that Agilent offers a wide range of additional expert test and measurement services, which you can purchase according to your unique technical and business needs. Solve problems efficiently and gain a competitive edge by contracting with us for calibration, extra-cost upgrades, out-of-warranty repairs, and onsite education and training, as well as design, system integration, project management, and other professional engineering services. Experienced Agilent engineers and technicians worldwide can help you maximize your productivity, optimize the return on investment of your Agilent instruments and systems, and obtain dependable measurement accuracy for the life of those products.

✉ Agilent Email Updates

www.agilent.com/find/emailupdates
Get the latest information on the products and applications you select.

Agilent T&M Software and Connectivity
Agilent's Test and Measurement software and connectivity products, solutions and developer network allows you to take time out of connecting your instruments to your computer with tools based on PC standards, so you can focus on your tasks, not on your connections. Visit **www.agilent.com/find/connectivity** for more information.

For more information on Agilent Technologies' products, applications or services, please contact your local Agilent office. The complete list is available at:

www.agilent.com/find/contactus

Phone or Fax

United States:
(tel) 800 829 4444
(fax) 800 829 4433
Canada:
(tel) 877 894 4414
(fax) 800 746 4866
China:
(tel) 800 810 0189
(fax) 800 820 2816
Europe:
(tel) 31 20 547 2111
Japan:
(tel) (81) 426 56 7832
(fax) (81) 426 56 7840

Korea:
(tel) (080) 769 0800
(fax) (080)769 0900
Latin America:
(tel) (305) 269 7500
Taiwan:
(tel) 0800 047 866
(fax) 0800 286 331
Other Asia Pacific Countries:
(tel) (65) 6375 8100
(fax) (65) 6755 0042
Email: tm_ap@agilent.com
Contacts revised: 1/12/05

Product specifications and descriptions in this document subject to change without notice.

© Agilent Technologies, Inc. 2005
Printed in USA, February 16, 2005
5989-1872EN

Agilent Technologies