

Extending Design-for-Test Into the Analog and Mixed-Signal Domains

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A growing need exists for the design and testing of mixed-signal communication systems. Among the many factors driving this need are the current high interest in personal communication devices, and a desire for ever faster information transmission rates over the existing telecommunication network. Many of today's communication systems are designed and tested using techniques that cannot be characterized as either digital or analog. The data being processed, and the processing techniques themselves, do not fall neatly into either the digital or analog categories. Two approaches to mixed-signal testing, using currently available test-set hardware and software, have been developed and are presented in this paper. The research being done on a third, experimental, self-test method — and the techniques for accessing internal test nodes — are also discussed.

Introduction

Two types of mixed-signal systems currently available are the *integrated services digital network (ISDN) basic access transceiver* and the so-called *digital radio*. Each of these systems has input and output (I/O) ports with both digital or analog properties. The architectures of these systems include internal analog-to-digital (A/D) and digital-to-analog (D/A) converters, sandwiched between necessary analog and digital signal-processing elements.

In each of these cases, the limited bandwidth medium used to connect the sender to the receiver makes it necessary to recognize that the signal-transmission path is analog, and that analog signal processing will be needed for satisfactory communications over the channel.

For ISDN applications, the intent is to transmit 160 kbits/s of data over ordinary twisted-pair cables, which were originally designed for limited-bandwidth voice communications. Although the information stream to be transmitted begins as a binary representation of either digitized voice or data, in order to conserve bandwidth, the input is converted to analog form. Each consecutive bit pair is encoded as a four-level, analog pulse or "quat" that is low-pass filtered.

In typical digital radio systems, encoded digital data is transmitted over a more-or-less conventional analog radio link. Encoded symbols are used to modulate an analog radio-frequency carrier signal, which is then amplified, fed to an antenna system, and radiated. A remote receiving system captures the desired signal, filters it from a myriad of other signals and noise, amplifies it, and then decodes the transmitted symbols to recover the desired digital data.

Mixed-signal systems, with their combinations of analog and digital elements, create difficult testability problems for their designers and for manufacturing engineers charged with developing test strategies. Although digital testing techniques have been well developed over the past decade, analog testing has lagged. Test strategies and test equipment for mixed-signal systems have the additional complication of the need to combine analog and digital test instrumentation and fixturing on the same platform.

When comparing digital and analog technology, digital has the advantage. Unlike analog systems, digital circuits — regardless of complexity — are based on very few logical building blocks. These building blocks are combined in ever more complex ways to

Panel 1. Abbreviations, Acronyms, and Terms

A/D — analog to digital
D/A — digital to analog
DSP — digital signal processing
IEEE — Institute of Electrical and Electronics Engineers
I/O — input and output
ISDN — integrated services digital network
VLSI — very large-scale integration

perform desired functions. Testing techniques and hardware are similar for all digital systems, with the possible exception of hardware requirements brought about by circuit operating speed.

Analog functions are performed using such fundamental circuit building blocks as amplifiers, oscillators, and filters having custom parameters. These building blocks are combined in unique ways using interface circuitry, which is tailored to the application at hand. Test equipment for analog hardware tends to be application specific. The equipment used to test the voice-frequency channels of a 5ESS® switch, for example, is useless for testing the performance of the power amplifier in a cellular telephone base station. As a consequence, analog test systems, in practice, tend to consist of rack-and-stack assemblages of stand-alone instruments, each performing a specialized test function. Setup, test sequences, data collection, and decision-making on these instruments are usually computer controlled. This approach is essentially a straightforward mechanization of the human test-data collection and analysis activities that have evolved over many years.

The Need for Mixed-Signal Testing

The advent of mixed-signal, very large scale integration (VLSI) devices has enabled engineers to design and build extremely sophisticated transmission systems for use in mass-production consumer and business applications. The ability to transmit data at extremely low error rates, over a radio channel having widely fluctuating transmission properties, is the most challenging design goal for these systems. A modern cellular telephone, for example, is a complex assemblage of integrated circuits executing sophisticated, digital and analog signal-processing algorithms. The integrated circuits

and algorithms are designed to provide noise-free operation in demanding environments.

Proper operation of a cellular system requires that all components, both digital and analog, function harmoniously. For example, digital signal processing (DSP) is based on the assumption that critical analog preprocessing is first performed on the input waveform. If such preprocessing does not remove the noise and interference signals that DSP cannot eliminate, or if the analog preprocessing creates new noise, the system will not function properly.

Sometimes, it is inconvenient or even impossible to access and test separately the analog and digital portions of a system, especially if both analog and digital functions are performed on a single VLSI device. Furthermore, traditional stimulus and response signals, along with classic test specifications, are not suitable for measuring the analog performance of a device in its mixed-signal application.

The development of algorithms, used to process data in mixed-signal testing, is the one area in which breakthroughs are needed. In many applications, the digital generation and collection of test data is relatively straightforward. However, the efficient processing and interpretation of test results are much more complicated. Exploiting the potential of using DSP techniques to analyze test data has only just begun.

Approaches to Mixed-Signal Testing

Three approaches to adapting electronic test equipment and algorithms to the requirements of mixed-signal device and system testing have been identified:

- *The general-purpose approach*, in which a test set can program its hardware to use each pin, in contact with the circuit under test, as either an analog or digital source, or as a sense pin;
- *The multislot-card cage approach*, in which specialized analog or digital instruments can be added to the test set as needed; and
- *The self-test approach*, currently under investigation at the AT&T Bell Laboratories Engineering Research Center in Princeton, New Jersey, in which a mixed-signal system's own D/A and A/D converters are used to generate and capture analog stimulus and response variables. All test access to a system is obtained through existing digital I/O ports. With this approach, a system can be tested on a digital-only test set. All

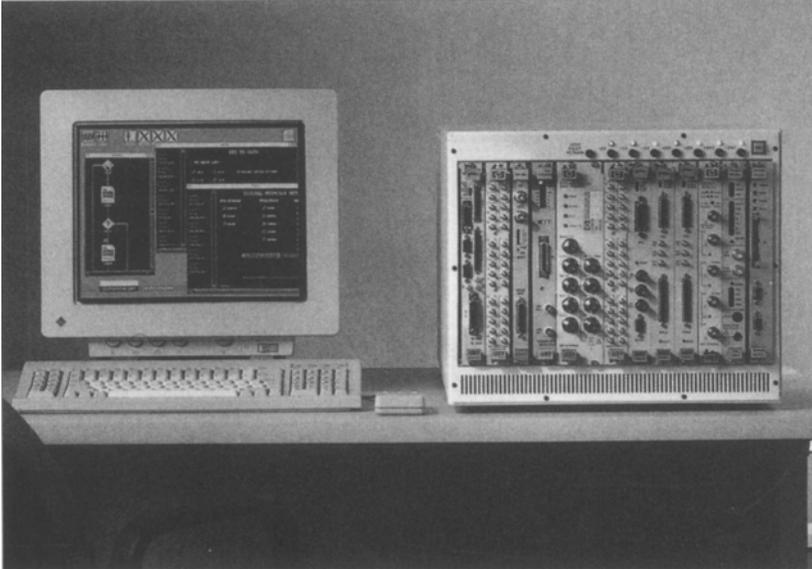


Figure 1. The typical VXIbus test-set system has a wide range of applications. It is potentially lower in cost than other types, because it does not rely on the capabilities of a master stimulus/response mechanism. For noncritical applications, VXIbus test sets can use lower capability, less expensive plug-in cards.

analog signal handling is performed by the device under test.

Development of the means to access analog circuit segments within a system or device is another aspect of mixed-signal testing that is under scrutiny. The Institute of Electrical and Electronics Engineers (IEEE) is currently defining a mixed-signal test-bus standard, which is analogous to the boundary-scan standard used for digital circuits. The analog test-bus proposal, known as IEEE standard P1149.4, advocates the use of digitally controlled switching. Such switching connects internal, analog I/O test points to dedicated, device test pins over internal analog buses.

General-Purpose Test-Pin Approach

Advocates of test sets using this general-purpose, DSP, pin-electronics approach to mixed-signal testing take the position that the digitized version of analog stimulus and response waveforms have the same configuration as digital test stimulus and response vectors. Once the test-set A/D converter digitizes the analog waveforms from a device under test, the resulting signals can be captured in the test set's computer memory and analyzed by DSP techniques. Similarly, digital representations of analog stimuli can be generated — or read out of the test set's memory — in real time, by the test-set computer. Then, these numeric values are fed through a test-set D/A converter, at precisely determined clock rates, in

order to generate analog-stimulus signals with the proper timing and shape.

Examples of this type of test set are the Teradyne A500 series and the Hewlett-Packard 9480 and 9490-series models. (Teradyne is a registered trademark of Teradyne Corp., and Hewlett-Packard is a registered trademark of Hewlett-Packard Inc.)

As soon as analog response variables are captured in digital form, any desired processing and analysis of the response can be performed using the test-set computer. The equivalent of any analog instrument can be realized in software: voltages can be computed, frequency responses performed, harmonic distortion measured, and waveforms displayed.

This method of mixed-signal testing is extremely powerful and flexible, especially when the test set is supplied with an extensive, easy-to-use variety of software tools that implement DSP-based signal generation and analysis. The test equipment can be used in ways that are limited only by the imagination of the test designer. There is no restriction to the built-in processing associated with conventional analog instrumentation.

Unfortunately, these powerful test sets are quite expensive. This is due primarily to the need for high accuracy, high speed, and an A/D-to-D/A conversion capability. The converters' limitations also prevent direct application of this method to many systems. These systems either operate at frequencies too high for the

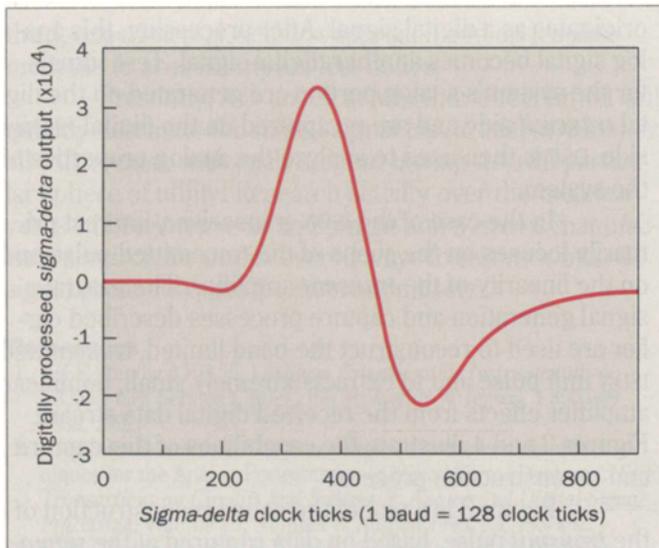


Figure 3. In the case of an ISDN transceiver, interest primarily focuses on the shape of the transmitted pulse and on the linearity of the *transmit* amplifier. The natural signal-generation and capture process described in this paper was used to reconstruct the band-limited, transmitted ISDN unit pulse and to extract extremely small, nonlinear amplifier effects from the received digital data stream. The waveform shown is a DSP reconstruction of the transmitted ISDN pulse, based on data captured at the *sigma-delta* output point.

manufacture VXIbus instruments. (Tektronix is a registered trademark of Tektronix Inc.)

VXIbus systems require a higher level of test-set engineering effort than does a DSP-based test set, because each instrument in the system has to be individually configured. The instruments have to be mounted and interfaced through a relay matrix or scanner. The test-set software has to be reconfigured to include the instrument driver. And, a test fixture must be built to interface the test hardware with the device under test. Essentially, the general-purpose DSP test set has all its instruments built in. To customize the setup, only the fixture needs to be wired.

Software Support Systems

Test-set manufacturers recognize that the time needed to develop and prove test software is a significant bottleneck in achieving delivery goals for many new products. They are also well aware that their market

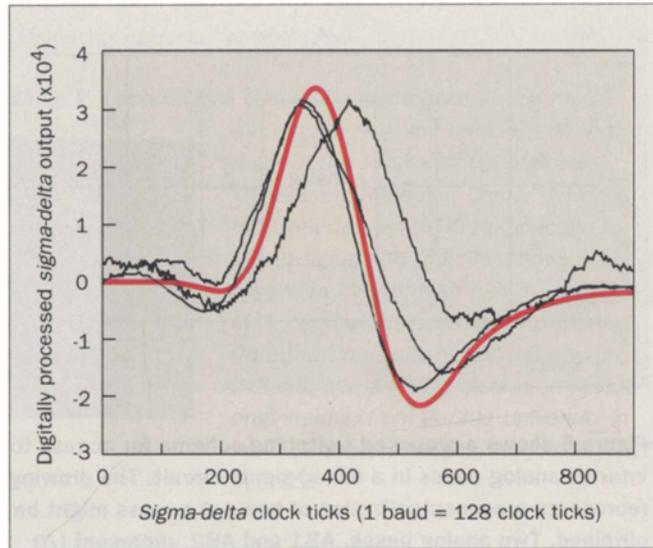


Figure 4 plots nonlinear distortion terms in the ISDN amplifier, extracted using DSP applied to captured loop-back data. To show these effects in the same scale as the linear pulse, it was necessary to magnify them from 3,500 to 9,000 times. No external instrumentation or fixturing, beyond that needed to capture the *sigma-delta* bit stream, was used to generate these results.

share depends mainly on the quality of the test-set software provided to their customers. Most commercial test sets, including both DSP and VXIbus types, are supported by a wide variety of software tools. The latest systems use icons in configuring the test sequence.

Code for individual test modules is written and incrementally compiled, and then each module is manipulated as a high-level graphical image on a test-flow diagram. Many "canned" test routines are provided by the test-set manufacturer. Most manufacturers will provide turn-key test systems, customized for a given application.

Self-Test Approach

A new approach to mixed-signal testing, potentially applicable to many mixed-signal transmission systems, is currently being studied at the AT&T Bell Laboratories Engineering Research Center.² This approach exploits the fact that signals flowing through these systems change from analog to digital format, or vice versa, and signal processing occurs both before and after A/D or D/A conversion. Figure 2 is a diagram of an ISDN

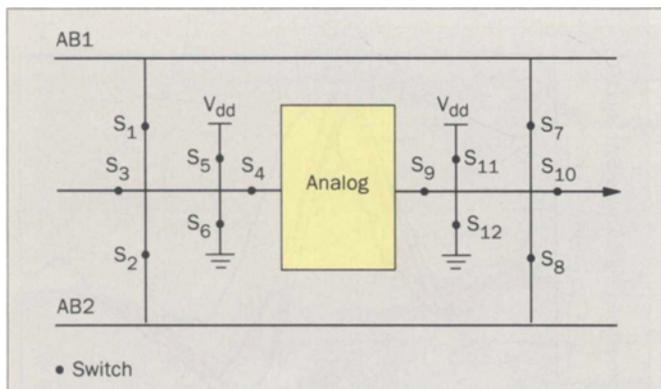


Figure 5 shows a proposed switching scheme for access to internal analog nodes in a mixed-signal circuit. The drawing represents a conceptualization of how I/O access might be obtained. Two analog buses, AB1 and AB2, represent I/O access points to internal circuitry. If it is assumed, for example, that all switches are open — with the exception of switches 1, 4, 8, and 9 — input access to the analog block is obtained over bus AB1, and its analog output is available on bus AB2. Other possible combinations of switch closings can be programmed, in order to give the test designer maximum access to the various analog modules in the device under test.

basic-access transceiver, a typical example of one of these systems. The system's signals originate from a digital processor. These digital signals are converted to analog signals for processing and transmission. Then, they are reconverted at the receiver for further processing. Finally, the digital version of the transmitted pulse is "sliced," and the original digital information is recovered.

This device, designed with testability in mind, provides the option of collecting digital data at any of the points indicated by the dotted lines in Figure 2.

The ISDN system operates in full-duplex mode, which means that *transmit* and *receive* signals exist simultaneously on ordinary twisted-pair transmission cable. The function of the echo canceler in Figure 2 is to remove the local signal from the composite waveform, leaving only the remote *receive* signal for further processing and digital detection. Capturing the composite waveform at the A/D conversion point provides sufficient information to characterize the performance of the ISDN transceiver's *transmit* path, because both local and remote signals exist. The analog stimulus for the system

originates as a digital signal. After processing, this analog signal becomes another digital signal. Test signals for the system's analog portion are generated on the digital *transmit* side and are recaptured on the digital *receive* side. DSP is then used to analyze the analog properties of the system.

In the case of the ISDN transceiver, interest primarily focuses on the shape of the transmitted pulse and on the linearity of the *transmit* amplifier. The natural signal-generation and capture processes described earlier are used to reconstruct the band-limited, transmitted, ISDN unit pulse and to extract extremely small, nonlinear amplifier effects from the received digital data stream. Figures 3 and 4 illustrate the capabilities of this capture and reconstruction process.

Figure 3 is a plot of the actual reconstruction of the *transmit* pulse, based on data captured at the *sigma-delta* output point. Figure 4 plots extremely small, nonlinear distortion terms introduced into the pulse by the line driver. To show these effects in the same scale as the linear pulse, it was necessary to magnify them from 3,500 to 9,000 times. No external instrumentation or fixturing, beyond that needed to capture the *sigma-delta* bit stream, was used to generate these results.

IEEE P1149.4 Mixed-Signal Bus. An IEEE standards group is working to establish an analog test-bus standard that will permit testing internal analog elements in a mixed-signal system over dedicated device test pins.³ Figure 5 illustrates one conceptualization of how I/O access might be obtained. Two analog buses, AB1 and AB2, represent I/O access points to internal circuitry. If it is assumed, for example, that all switches are open — with the exception of switches 1, 4, 8, and 9 — input access to the analog block is obtained over bus AB1, and its analog output is available on bus AB2. Other possible combinations of switch closings can be programmed, in order to provide maximum access to the various analog modules in the device under test.

Once access to a mixed-signal system is established over this bus, analog testing — implementing any of the methods described earlier — can be used to verify the correct operation of the analog element.

Conclusions

Two current approaches to mixed-signal testing, using currently available test-set hardware and software, have been discussed. Research is continuing on the

third, experimental, self-test approach and on feasible methods to access internal test nodes.

Presently, it is not clear whether one method will quickly dominate the mixed-signal test arena, or whether all will coexist, with each method having its own particular sphere of utility. Research activity over the next few years will be intense as equipment and systems manufacturers search for undiscovered ways to test new mixed-signal products quickly and economically.

References

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