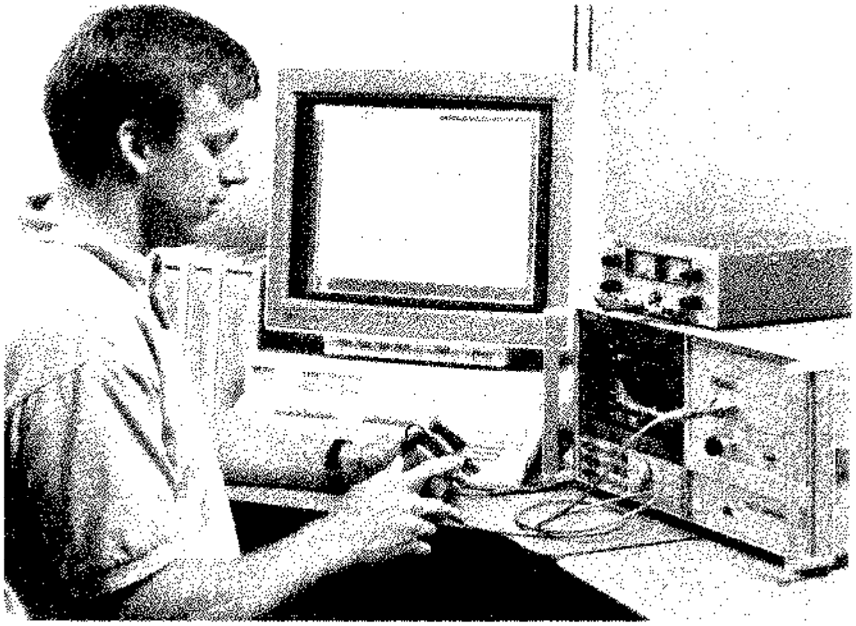
Using High-Frequency Instruments with MDS

Product Note 85150-1



The HP 85150B Microwave Design System (MDS) now makes it possible to use measured data throughout the life cycle of a design. The links to high-frequency network analyzers, spectrum analyzers, and oscilloscopes are without precedent in utility and relevance to the design process.

This product note describes the nature of these instrument links and makes specific observations on their effective use. Afterward, a brief discussion of the instrument drivers in the context of the design cycle is presented.

Capabilities of the Instrument Drivers

The instrument drivers built into MDS read data from several families of high-frequency instruments including oscilloscopes, spectrum analyzers, and network analyzers. MDS controls the instruments and transfers the data using a HP-IB connection. MDS is also able to write data back to these instruments for direct, real-time comparison with a live measurement.

Instrument data is transferred directly into MDS in one easy step from within the DATASET icon, a structure that stores data for future simulations or postprocessing. Data can also be transferred to MDS from remote systems using a local area network or a floppy diskette (see figure 1).

From the INDEX page of the DATASET icon, the `PERFORM/READ` or `PERFORM/WRITE` command (and associated lower level menus) is used to interface with the instrument (see figure 2). During a `READ` operation, the measured data is stored in the DATASET from which the command was invoked. The data can then be used in a subsequent simulation or plotted in the PRESENTATION icon. The PRESENTATION icon is the postprocessor of the HP Microwave Design System.

The list of instruments and computer platforms that are supported by MDS I/O drivers continues to expand. Additional capabilities may exist by the time you read this document. Please consult your local HP representative for updated information about the instrument drivers of the HP Microwave Design System.

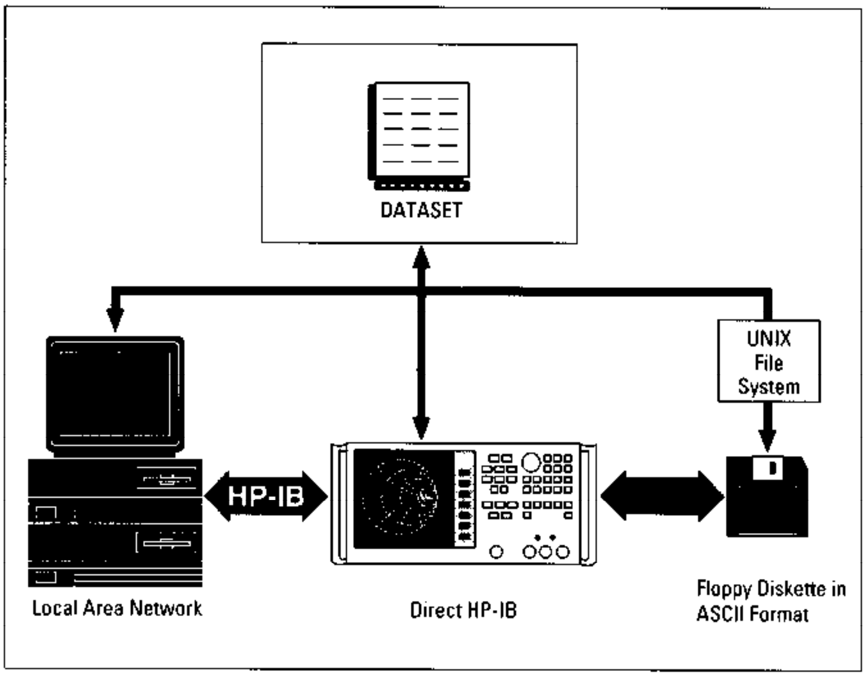


**Figure 1.
There are several ways to transfer data into or out of MDS. This Note concentrates on direct transfers using HP-IB.**

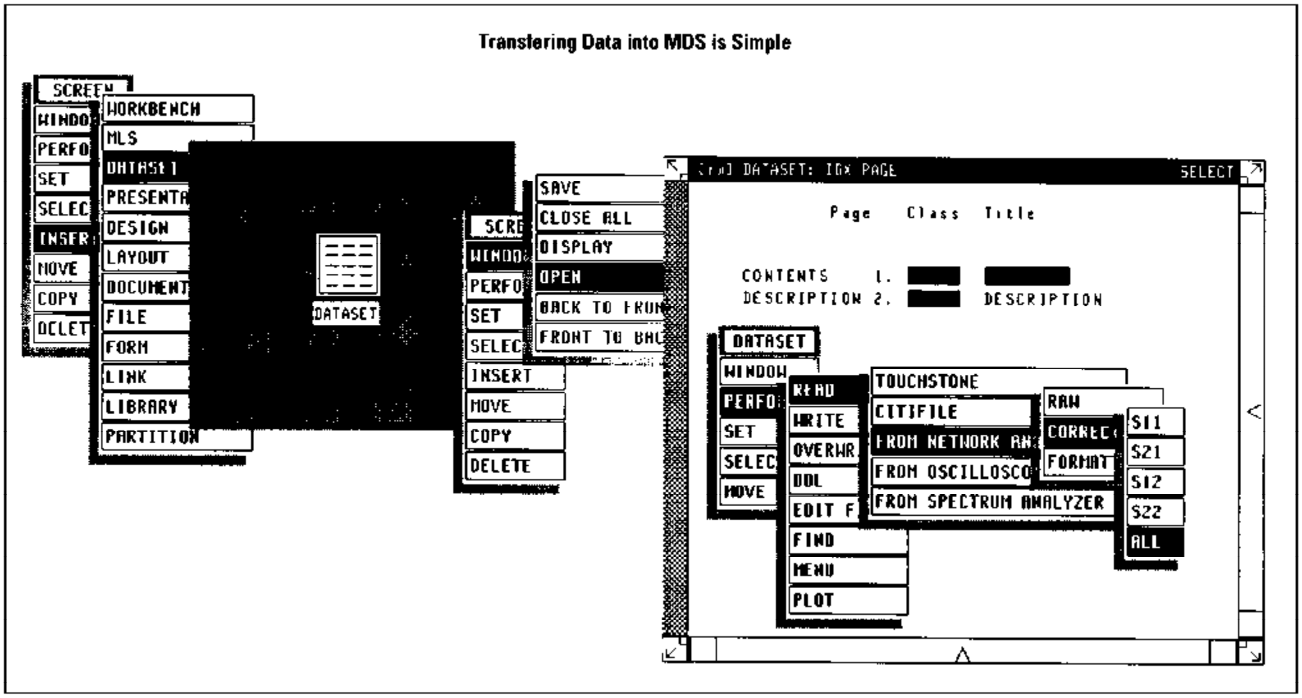


Figure 2.
The data transfer process itself is simple — just insert a Dataset, open it, and use the READ or WRITE commands.

Network Analyzers

When it comes to high-frequency component characterization, the network analyzer has no equal. Unlike oscilloscopes and spectrum analyzers, network analyzers completely characterize components with stimulus-response tests. Use of accuracy-enhancement techniques allows the architecture of a network analyzer system to measure linear components with greater accuracy than other techniques.

Over the years, S-parameters have become widely used, even for components that are not strictly linear. There are several reasons for this.

1) S-parameters uniquely specify the performance of linear circuits and are numerically well-behaved.

2) Conversely, there is no one "parameter" that characterizes nonlinear circuits. Therefore, engineers who are comfortable with S-parameters tend to extend the underlying ideas of reflection and transmission as far as possible (e.g. — using S-parameters at a single power level).

3) The equipment to produce high-quality, accurate data is technologically mature and readily available.

4) S-parameters can be used directly in simulations, giving simulations a high degree of accuracy with little or no modeling effort or interpretation. S-parameters can also accelerate a simulation because fewer calculations are needed.

Perhaps the most important concept is that S-parameters can be used directly as a circuit element in a simulation. There are many ways to measure devices; there are also many kinds of simulators that are commercially available. However, the direct substitution of measurement data for a device, circuit, or subsystem in a simulation without manual entry (or interpretation by an experienced engineer) is perhaps unique to S-parameters.

Another important consideration is the fact that circuit and electromagnetic simulation programs are also sources of S-parameters. It is therefore possible for the HP Microwave Nonlinear Simulator to use its own S-parameter results as the input to subsequent simulations, ad infinitum. There are several ways to import and export S-parameters from HP MDS, including:

- CITIfile — the ASCII data format that HP network analyzers can read or write to diskette
- TOUCHSTONE — the ASCII data format used by many transistor manufacturers who supply S-parameters on diskette
- HP-IB — direct, real-time instrument control using the industry standard interface bus (IEEE-488)

While it is true that S-parameters can be used directly in a simulation, designers often take the time to model devices with equivalent circuits (see figure 3). The goal of the modeler is to create a circuit that has the same frequency or time response as a measured response. The model often provides additional engineering insight, or itself used in a larger circuit.

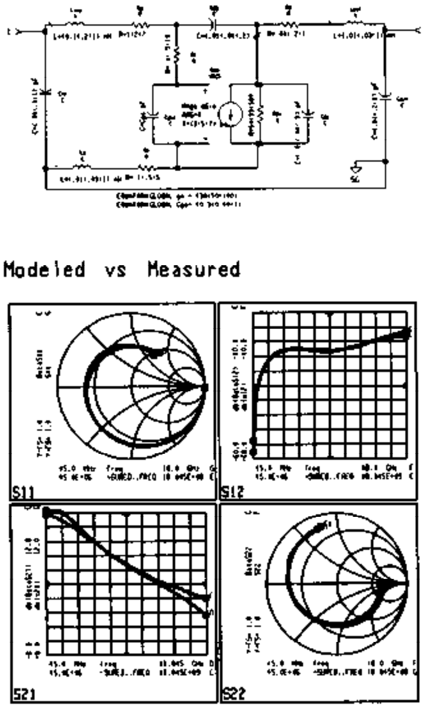


Figure 3. Modeling of transistors usually involves measured S-parameters.

S-parameters are often used to refine existing circuit models. Even if a designer has a reasonable understanding of the model for a transistor, S-parameters can help quantify the parameter values in that model. Typically, optimization is used iteratively to change the parameters until the measured and modeled responses are similar. The HP Microwave Nonlinear Simulator provides several different optimization methods.

Finally, S-parameters uniquely specify the performance of linear circuits. Large sections of a design can be precomputed or measured and stored for future use. This reduces the number of nodes in a circuit, which directly accelerates the simulation. Since measured S-parameters are among the most accurate measurements that high-frequency designers make, simulations using measured data are arguably as accurate as can be made.

In Practice...

There is one important difference between the S-parameters that are calculated by a circuit simulator and those that are measured with a network analyzer. Simulated S-parameters are not dependent on input signal power, whereas most active circuits are.

When the Microwave Nonlinear Simulator performs an S-parameter analysis, it linearizes each nonlinear circuit element around its DC operating point. Once the nonlinear elements have been linearized, it is impossible to account for frequency conversion or gain compression caused by changes in the input signal amplitude.

To predict the true performance of a circuit, it may be necessary to perform a harmonic balance analysis and manually calculate the "large-signal" S-parameters. For this discussion, a large-signal S-parameter is defined as the reflection or transmission voltage ratios at the fundamental frequency, completely ignoring harmonics. This definition follows from the basic architecture of the network analyzer, which only detects energy at the frequency of the stimulus.

Knowing (and controlling) the input signal levels of the measurement is crucial. Many HP network analyzers allow for a "power flatness" calibration. This is performed by sweeping the source frequency and noting the difference between the source power setting and the power detected by a power meter. The error is subtracted from the source power setting at each frequency, resulting in constant signal power entering the device under test. Strict control of the source power in a measurement system simplifies the task of comparing simulated and measured performance.

The equation used to calculate the large-signal transmission coefficient (gain) from a swept-power harmonic balance simulation is:

```
GAIN =
DB(Vout[*,2]/Vin[*,2])
```

The right index (a "2") in the variables shown above selects only the fundamental frequency component, without any harmonics or DC offset. The left index (an "*") indicates that the independent variable of the expression is the input power level. This equation is inserted on the DISPLAY page of the PRESENTATION icon. It is used to plot gain vs. input power.

Gain compression is plotted with a second equation that normalizes the trace to the (presumably) small-signal gain at the first data point:

```
GAIN_COMP =
GAIN[*] - GAIN[1]
```

A second consideration arises when using an S-parameter element in a nonlinear circuit. The simulator linearly extrapolates the frequency response down to DC. This can disrupt the operating point of the circuit, depending on whether the circuit tends to become an open circuit or a short circuit with decreasing frequency. This can be avoided by adding a data point at a very low frequency or bypassing the DC path around the data element.

Time-Domain Reflectometer Output

Network analyzers and time-domain reflectometers (TDR) are two widely different approaches to measuring the same basic reflection and transmission characteristics. In fact, S-parameters can be converted to the TDR format using a few equations in the PRESENTATION icon.

Time-domain reflectometers measure impedance vs. distance (reflection) and risetime degradation and transit time (transmission). These same quantities can be obtained to superb accuracy at very high frequencies using a network analyzer such as the HP 8510C. Because it is designed for stimulus/ response testing of components, the network analyzer has several advantages over an oscilloscope in terms of dynamic range, accuracy, and frequency coverage.

Therefore, high-speed package designers can perform high-quality measurements or modeling in the frequency domain using S-parameters and then convert the S-parameters to the TDR format within MDS (figure 4). RF and microwave designers also benefit from the insights a TDR brings, since an equivalent circuit of a structure can often be inferred from a TDR trace.

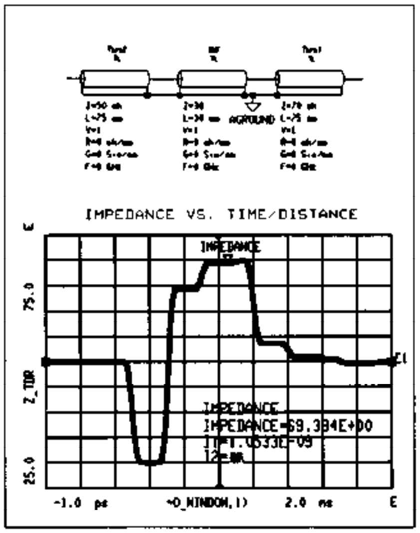


Figure 4. High-quality measured or simulated S-parameters can be applied to many TDR applications.

Oscilloscopes

The HP Microwave Design System supports many high-frequency repetitive sampling oscilloscopes. Included are the HP 54110, HP 54120, HP 54200, and HP 54500 families of oscilloscopes. In addition to a direct transfer of time-domain trace data, MDS also calculates the Fourier series coefficients of the waveform, where possible. Therefore, data versus time and frequency are stored for future use.

Most captured waveforms can be used as ideal voltage stimuli in harmonic balance simulations. The Fourier coefficients stored in the DATASET are used to specify the relative harmonic amplitudes and phases of a spectral source in a circuit simulation. Even though the simulation is done entirely in the frequency domain, the waveform that is captured by the oscilloscope is accurately reproduced in the simulator.

When a captured waveform is substituted for a section of a large circuit, the computational savings can be significant. Figure 5, for example, shows a mixer with a separate local oscillator (LO). The mixer analysis can be greatly accelerated by replacing the sophisticated LO circuitry with a measured voltage waveform (spectrum) source. Moreover, having the measured waveform may make an equivalent model unnecessary, saving time or preserving the proprietary nature of sensitive areas of a design.

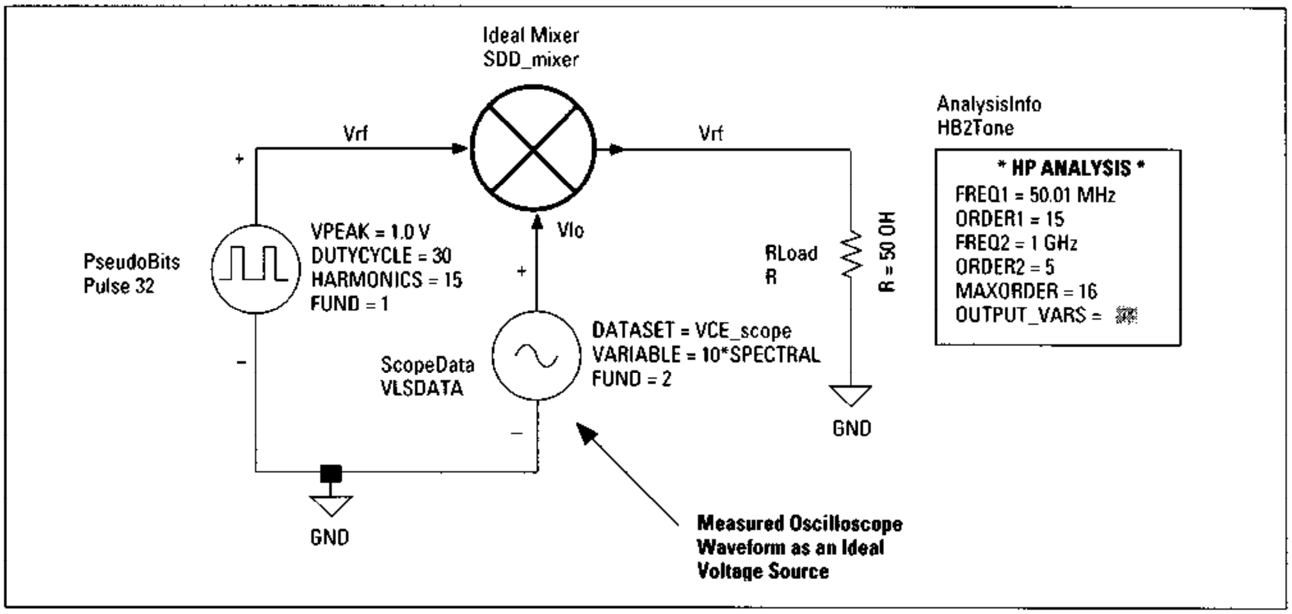


Figure 5. Substituting a measured waveform for a piece of circuitry that is difficult to simulate can save time and actually improve the realism of the simulation.

The waveform capture utility can also be used to:

- Separate a larger circuit into smaller pieces for easier design and simulation.
- Specify a waveform as part of the hardware interface between elements of a system. This helps different designers work in parallel as a team on a larger system.
- Infer nonlinear device characteristics, both visually and through optimization (extraction and troubleshooting).
- Directly compare measured vs. modeled waveforms on the same graticule.

There are several considerations for capturing waveforms for use in the nonlinear simulator, as opposed to simply capturing them for documentation purposes. The first consideration is the limited dynamic range and accuracy of an oscilloscope. Most of the supported oscilloscopes have 6-8 bits of effective resolution, which translates into < 50 dB dynamic range (figure 6). There is little quantitative consequence to FFT data that is < –40 dBc in an unaveraged waveform.

Another consideration is that care must be taken for signals with frequency components above several gigahertz. Without the advanced calibration and error correction routines used by vector network analyzers, very high frequency data can become merely "qualitative." Attention must be paid to the probe attenuation factor, good signal grounding, and impedance loading of the circuit, either through the capacitance of the probe or the 50 Ω input impedance of the instrument.

Consideration must also be given the types of waveforms that can be captured. The Fourier transformation routine of the oscilloscope driver has been optimized for repetitive signals whose spectral lines are harmonically related to a single fundamental frequency. Examples of waveforms that are successfully captured include square waves, half-wave rectified sine waves, and pulses with duty cycles between 5% and 95%.

The best results are obtained when the user has set up the instrument to display 1.5 to 3 periods of the waveform, applied the highest averaging factor, and stored the trace to memory, and the waveform uses >80% of the vertical (voltage) scale.

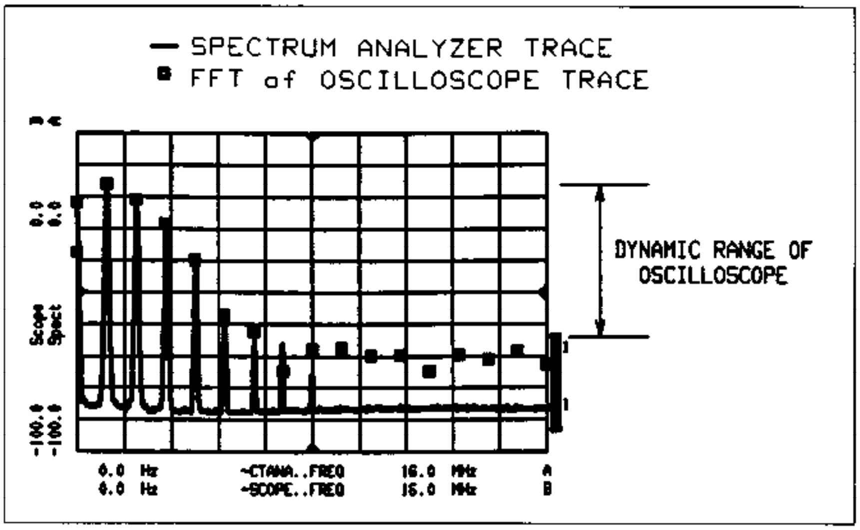


Figure 6.
The quantization noise of an oscilloscope reduces its dynamic range relative to a spectrum analyzer or circuit simulator.

Figure 7 shows a typical waveform and corresponding spectrum, as calculated by MDS. Note the number of harmonics and the relative amplitude of the noise floor (about –50 dBc, also shown in figure 6). MDS calculates spectral components up to the Nyquist rate of the live oscilloscope screen (the period corresponding to two screen pixels along the time axis). When this waveform is used as a stimulus in a harmonic balance analysis, the simulator truncates the spectrum according to the number harmonics (ORDER) specified by the user. Averaging the trace data in the oscilloscope prior to the measurement is therefore optional for lowpass signals, such as the one in figure 6.

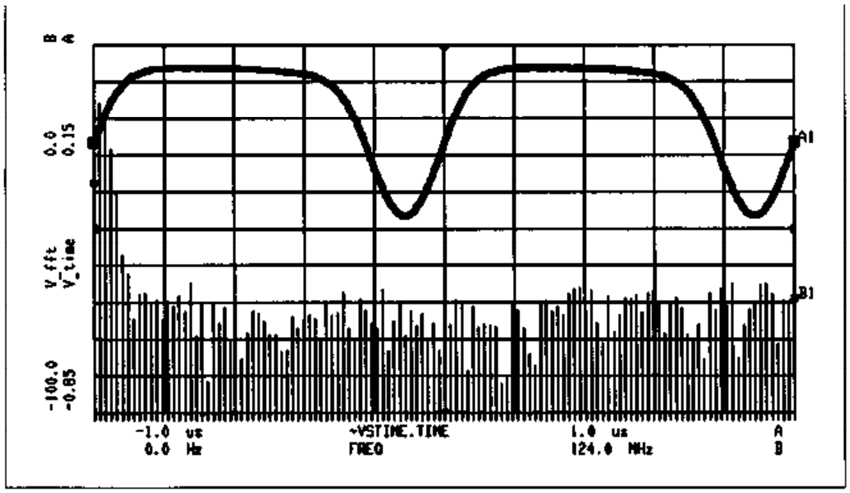


Figure 7. Example of a waveform easily used by MDS for use as a circuit stimulus.

Modulated signals and pulsed RF signals are examples of waveforms that cannot be captured for use as a circuit stimulus (see figure 8). These have multiple fundamental frequencies and are difficult to represent (quantitatively) in the number of time samples allocated to oscilloscope traces.

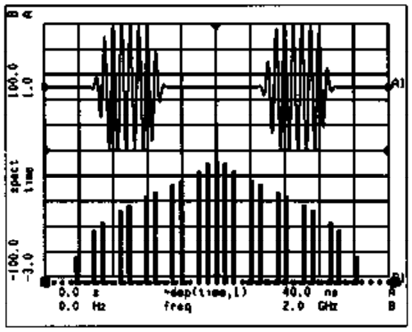


Figure 8. Example of a waveform (and spectrum) that MDS cannot use as a circuit stimulus.

Waveforms that are dominated by a harmonic frequency instead of the fundamental, such as the output of a frequency multiplier, can also be difficult to characterize. Currently, MDS relies on the algorithms of the oscilloscope to estimate the period of the waveform. Occasionally, however, such signals cause the oscilloscope to underestimate the true period of the waveform. In practical terms, this means that the energy in the true fundamental frequency (and possibly other low harmonics) is lost altogether. The signal in figure 9, for example, is dominated by its second harmonic. The careful observer will note the alternating amplitude of the peaks of the thicker trace, even though the signal produced a stable trigger on the instrument. Even if the calculated frequency spectrum is not quantitatively accurate, the actual time-domain voltage values of the oscilloscope trace are transferred and stored without error.

In Practice...

It can be useful to set up a temporary PRESENTATION icon to plot measured data as it is being gathered to be certain that the data is valid. In doing so, another verification can be made. Since the raw time-domain trace is stored with the FFT results, it helps to plot the raw time-domain trace on the same plot as the "time series" of the spectral data. (The "time series" post-processor function `TS(node)` converts a frequency spectrum into a time waveform.) The two traces should have exactly the same shape and amplitude. If they do not agree, then the waveform that would be used in a circuit simulation will be different from the one that was measured (figure 9). Note the slight difference between the thick trace (raw oscilloscope data) and the thinner trace (inverse Fourier transform of trace FFT).

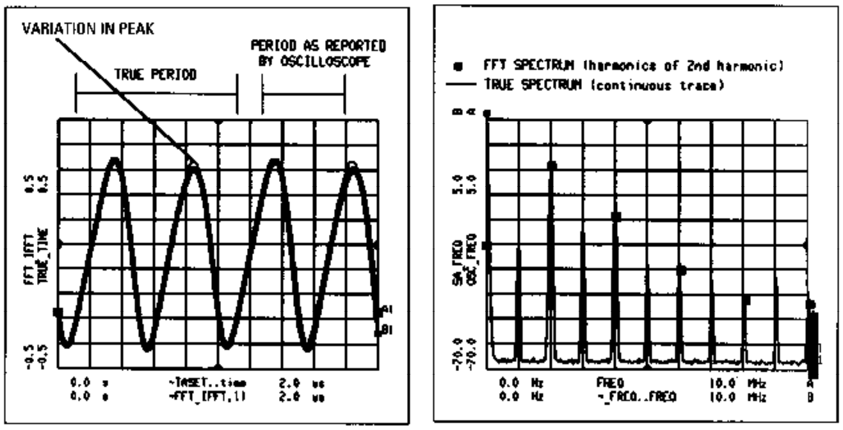


Figure 9. This is a waveform dominated by its second harmonic. Note the difference between the raw time-domain trace and the trace that would be used in a simulation.

Note also that a constant x-axis time shift can occur between the oscilloscope trace and the simulator result (the offset is more visible in figure 10). This happens because the oscilloscope and the simulator define the time origin differently.

There is one more consideration when gathering oscilloscope data for direct comparison with a nonlinear circuit simulation. The input signal itself must be characterized for amplitude, frequency, and harmonic content.

Attention should be paid to the impedance mismatch between the output impedance of the source and the input impedance of the device under test, since they form a voltage divider. Recall that the open-circuited voltage of a 50 Ω source is twice the voltage that appears across a matched input.

One should also consider the conversion factors between RMS and peak voltages. All of this is necessary because nonlinear circuit performance is quite dependent on the amplitude of the input signal. If the goal is to verify the accuracy of a simulation, it is critical that:

- the simulation stimulus be changed to match the amplitude of the waveform that was actually measured,

or,

- the signal power in the measurement system be changed until it matches the amplitude of the stimulus in the simulation.

Knowing that the stimulus conditions are comparable allows quantitative comparison of nodal waveforms between measurements and simulations.

Spectrum Analyzers

High-frequency spectrum analyzers are another important class of nonlinear test instruments. Like oscilloscopes, spectrum analyzers are passive: they are only able to characterize the arbitrary signals to which they "listen." However, nonlinear component characteristics can often be inferred from spectrum analyzer data, given a simple, known stimulus.

Spectrum analyzers are also capable of significantly higher dynamic range than a repetitive sampling oscilloscope, due to the narrower bandwidth at the detector (in the IF). A spectrum analyzer is therefore able to identify low-level nonlinearities (e.g. — for TOI testing) long before the human eye would see them in an oscilloscope waveform. Spectrum analyzers are also available to higher frequencies than oscilloscopes. They can easily measure multiple-tone signals, especially tones that are closely spaced from higher-order IMD products.

There is no a single descriptive "parameter" for nonlinear components that is the equivalent of the linear S-parameter. In the absence of such a parameter, data from a spectrum analyzer is probably the next best thing.

Fortunately, MDS is able to read data from the active or stored traces of most HP high-frequency spectrum analyzers. MDS can also write data back to the spectrum analyzer's display for real-time comparison with a live measurement. Supported instruments include the HP 8560 and HP 8590 families of portable analyzers, the modular HP 70000 family of analyzers, and the older HP 8566B and 8568B standalone spectrum analyzers.

Spectrum analyzer data is used most often to compare measured vs. modeled nonlinear response at specified signal amplitudes and frequencies. Third-order intercept, harmonic distortion, and other parameters are directly derived from spectral data. An example that compares a harmonic balance simulation with a measured spectrum is shown in figure 10.

Because spectrum analyzer data is scalar (contains no phase information), it is not usable as a voltage stimulus in a circuit simulation. Figure 11 shows a sawtooth waveform with and without its frequency-domain phase information. A semiconductor, for example, may or may not be operating in its breakdown region based on the instantaneous amplitude in the time domain. If desired, however, individual spectrum analyzer trace values can still be used in simulation equations and optimization goals where signal amplitude is needed.

The HP 71500A microwave transition analyzer is a promising exception to the larger family of spectrum analyzers. Among its many unique capabilities, it is able to measure both magnitude and phase of high-frequency signals. At this writing, an MDS driver is under development that will exploit the capabilities of this unique instrument.

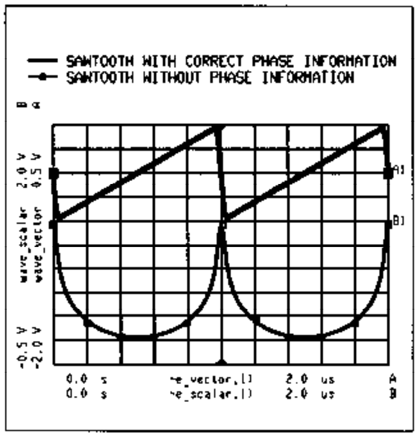


Figure 11. These two waveforms would seem to have identical frequency spectrums on a spectrum analyzer. The lower trace has no phase information.

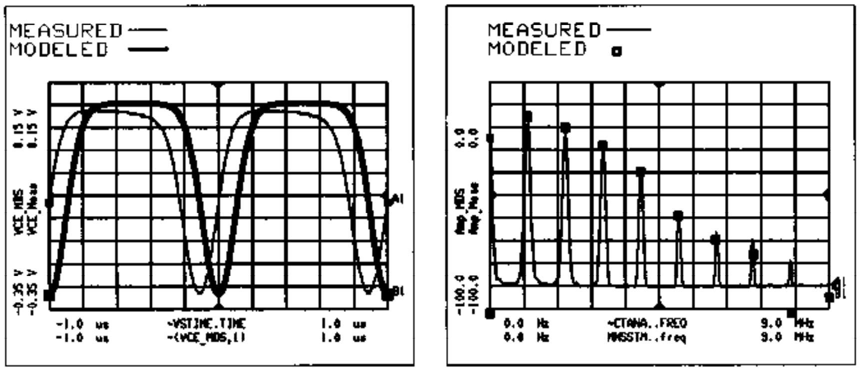


Figure 10. Design verification: A comparison of measured and modeled harmonic distortion of a clipping amplifier.

In Practice...

As cautioned in the *Oscilloscopes* section above, it is good practice to plot the data in a temporary PRESENTATION icon as it is gathered to be certain that the data is valid. It is also good practice to characterize the input signal, both for absolute amplitude and for harmonic content. Because nonlinear circuits are quite dependent on the signal power of the stimulus, quantitative comparisons between measured and simulated spectra are only valid for comparable stimuli.

Furthermore, the harmonic content of the actual source should be used in the simulation if the harmonics can become significant. Many synthesized signal sources have harmonics and spurious products that are at least 40 dB below the fundamental. If this is verified experimentally, harmonic content can be safely ignored in many simulations.

However, a contrary example exposes the limitations of that assumption: a limiting amplifier with more than 50 dB of small-signal gain. If a source harmonic was less than 40 dB below the fundamental, the harmonic by itself could saturate the amplifier, and probably should be included in the simulated stimulus. MDS allows the user to specify the amplitudes of many harmonics on any source.

If the goal is to verify the accuracy of a simulation, it is critical that

- the simulation stimulus be changed to match the amplitude of the signal that was actually measured,

or,

- the signal power in the measurement system be changed until it matches the amplitude of the stimulus in the simulation.

As with any spectrum analyzer measurement, it is important to establish the resolution bandwidth, video bandwidth, input attenuation, and other parameters that give the best measurement. The data is converted to linear peak voltage as it is being transferred so that it is stored in the same format as harmonic balance simulation results. Note that the "threshold" function of the spectrum analyzer produces non-zero trace data.

Another consideration for spectrum analyzer data is that the number of trace points is usually fixed. The HP 8566B, for example, uses 1001 points per trace. Traces of this length can show great detail in the post-processor (effectively 100 points per horizontal division), which allows the user to "zoom in" on the frequency axis by a factor of ten or more. This is useful for measuring mixers over a wide bandwidth in a single measurement, yet with enough resolution to see close-in sidebands (see figure 12).

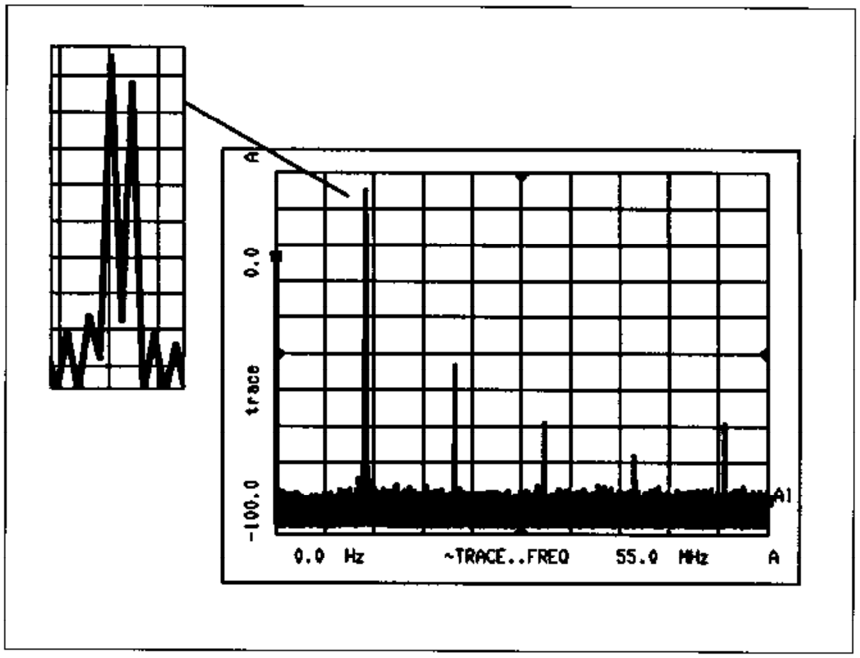


Figure 12. Spectrum analyzers are invaluable for characterizing mixers.

Instrument Links to CAE in the Design Process

This section will discuss the instrument drivers in the life cycle of a design. The design process has been divided into three major phases relative to measurement needs.

The first phase comes early in the design cycle when individual parts are characterized. Measured data, or circuit equivalents derived from the data, are actively incorporated into simulations. The second phase occurs when the performance of a prototype is compared to simulations. This step is called "design verification."

Performance tuning and troubleshooting form the third measurement phase of a design. To date, simulation tools have not been used extensively for recreating poor performance in high-frequency circuits, either on a production line, in rework, or in service applications. However, new links to instruments and documentation systems will make CAE more attractive for troubleshooting and servicing applications.

Early in the Process: Characterization

As a design is conceived and refined, the engineer begins evaluating specific components that could be used to implement his block diagram. Measurements (and equivalent circuit models derived from measurements) are used to represent low-level components in a larger circuit. Information about devices and signals from other designs becomes the basis of the new design, or even its external specification.

This information, in the form of experience or measured data, gives the designer an advantage on a new design. In the optimization algorithms in the circuit simulator, an improvement in the initial condition can provide faster convergence. Likewise, an improvement in a designer's understanding of the performance of his circuit helps reduce the design cycle.

One way to obtain this information is to fully characterize the most critical components and signal paths early in the design, while changes are easy to make. Semiconductors are particularly troublesome, because they vary so much from device to device (typically 10-20%) and are so critical to the performance of the larger design.

Even passive components present difficulties. Parasitic effects can turn a surface mount inductor into a capacitor at frequencies above its self-resonance (figure 13). It may never be possible to anticipate all of the surprises that a hardware designer encounters, such as amplifier instability, but characterization of the building blocks of a design can help eliminate the more obvious problems.

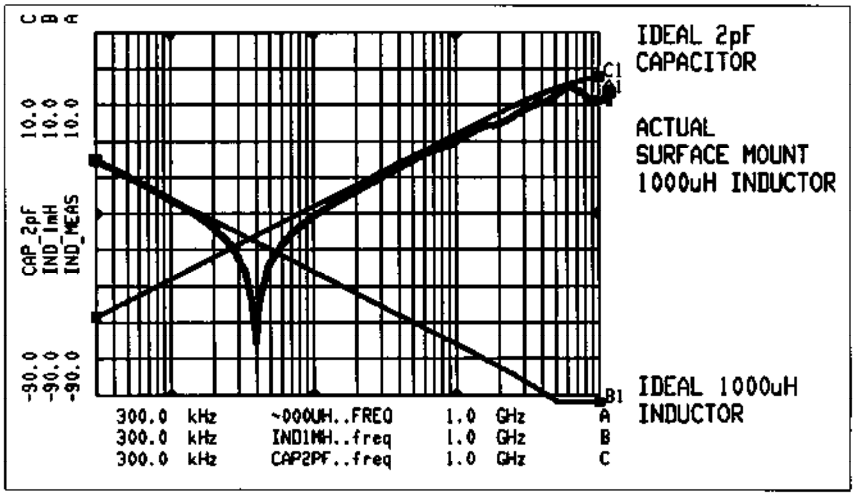


Figure 13.
This 1000 µH surface-mounted inductor actually behaves like a 2 pF capacitor above 10 MHz.

Transistors and semiconductors

Because transistors can dramatically affect the performance of a design, it is critical that a good model (or measurement) of the targeted device exists early in the design process.

For nonlinear devices, DC and high-frequency S-parameters measurements must be performed. For small-signal devices, the high-frequency S-parameters are usually sufficient. In either case, the measurements are converted to an equivalent circuit through the iterative use of a simulation, optimization, or extraction tool.

Designers have standardized on several nonlinear transistor models. They include the Gummel-Poon for bipolar junction transistors, and Curtice Quadratic, Curtice Cubic, and Statz models for GaAs MESFETs. These models have sophisticated equations that relate voltages at the terminals of the transistors to currents flowing between them. A set of coefficients can be determined that describe how an individual device will be behave under a range of voltage and current conditions. The process of obtaining these coefficients is called parameter extraction. Specialized measurement equipment and software is available for the designer to perform extractions, such as the HP 94000 IC-CAP extraction software.

Extraction tools typically use dc voltage-current or voltage-capacitance measurements to determine the majority of the model coefficients (or parameters). The values of certain small parasitics are difficult to extrapolate from dc measurements, so they are refined using accurate high-frequency S-parameters.

The amount of effort required to characterize small-signal linear devices is much less than for nonlinear devices. The measured S-parameters can be used directly in a simulation, with no modeling at all, if desired. Often, however, a simple "extraction" will be performed by optimizing the values of a linear equivalent circuit such that the performance of the equivalent model is the same as the measured performance.

Finally, designers often want to base a design on a "typical" device, rather than a random sample of one wafer. Many devices are measured from a variety of wafers and the results combined to form a statistical understanding of the device. The S-parameters can be averaged directly. Alternatively, an extraction can be performed on each device, and individual coefficients (such as nominal gate-source capacitance) are averaged together. The latter method, given some degree of repeatability in the measurement/extraction process, is the preferred method, although less convenient.

General-purpose components

As noted above, S-parameters of individual components can be used directly in both linear and nonlinear simulations without any modeling effort whatsoever. An S-parameter library of gain blocks, surface mount parts, foundry elements, fixtures, transitions, etc. can be used to enhance the accuracy of a circuit simulation. S-parameter blocks can also reduce the computational burden of a simulation.

Signals and waveforms

A large design is often partitioned into smaller pieces in the beginning of a design and developed in parallel. Waveforms that pass between sections of a large design (or originate in another part of a system) can be captured and used as the stimulus to individual circuits. Spectral information can also be captured to be the basis of an optimization.

For simple signals, both waveform and spectrum capture are possible using a supported oscilloscope or spectrum analyzer, respectively. More complex signals can be captured by a spectrum analyzer for comparison, but not as a circuit stimulus. Considerations for signal complexity are described in the Oscilloscopes and Spectrum Analyzers sections.

After Prototyping: Design Verification

After one or more pieces of a design have been prototyped, the designer has two tasks. First, he must understand the shortcomings of the design and decide how to improve them. Measurements provide this information. Second, he must adjust the values and topology of the simulated circuit to reproduce the failure of the prototype. The simulated and measured results are directly compared in both cases.

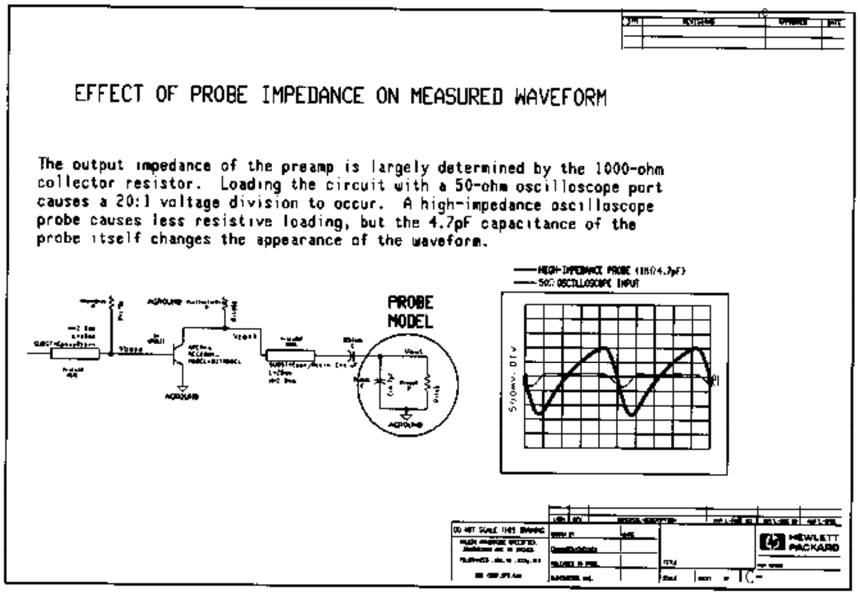
Once the failures are understood and accurately predicted by the simulator, improvements can also be simulated with confidence. While it is often possible to "fix" a design without resimulation, the effort required to model a problem is repaid each time a similar circuit is designed.

"Design verification" has been used for the process of comparing measured and modeled performance. The instrument drivers and documentation facilities of MDS make design verification simple. The simulation results, measurement results, and postprocessing capabilities all can be accessed within the unified MDS environment.

Away from the Designer's Desk: Performance Tuning and Troubleshooting

MDS can help improve the performance of a circuit even after the design leaves the designer's desk. The simulator can be used to recreate and diagnose poor circuit performance in manufacturing or in service applications. Also, tuning and repair procedures can be developed by production and service engineers for field use (see figure 14).

By documenting circuit performance, faults can be located more easily and corrected. Good documentation also preserves design intent, which can make replacements or field modifications easier. While simulation tools have limited application in the field itself, the insights required to diagnose or predict problems can be communicated more effectively with MDS.



EFFECT OF PROBE IMPEDANCE ON MEASURED WAVEFORM

The output impedance of the preamp is largely determined by the 1000-ohm collector resistor. Loading the circuit with a 50-ohm oscilloscope port causes a 20:1 voltage division to occur. A high-impedance oscilloscope probe causes less resistive loading, but the 4.7pF capacitance of the probe itself changes the appearance of the waveform.

Figure 14. Example of documentation that can be developed with a design tool to anticipate difficulties in the field.

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