Use S-parameters to describe crosstalk

Eric Bogatin, Alan Blankman - September 13, 2012

If you send a signal into one transmission line, some of it can appear on an adjacent transmission line, even when there is no direct connection. The signal from one transmission line couples through the fringe electric-field and magnetic field lines between them to induce noise on the other line. That’s crosstalk and the noise it causes can result in bit errors in digital systems.

Once this noise gets on an adjacent transmission line, it will propagate just like any other signal and eventually arrive at the ends of the line. A receiver connected to the end will see this crosstalk eating into its signal’s noise budget. In low-level analog applications, as little as 0.01% crosstalk might be tolerable, while in high speed digital applications, as much as 5% crosstalk may be acceptable.

Unfortunately, in many interconnect systems, signal levels from crosstalk can easily exceed 10% of the wanted signal, which will increase the system’s BER (bit error ratio or bit-error rate). Characterizing the amount of crosstalk from an aggressor line to a victim line can often be an important diagnostic in identifying, and eliminating the possible root cause of bit errors.

S-parameter formalism, developed to describe the microwave properties of interconnects, offers a natural way of describing crosstalk for applications from the audio frequency range to the millimeter-wave frequency range. After all, each S-parameter element is really the ratio of a sine wave coming out of one end of an interconnect compared to a sine wave going into another. In a collection of transmission line structures, many of the S-parameter terms are a direct measure of the line-to-line crosstalk. The same formalism can be extended to differential pairs as well.

A coupled-transmission line test vehicle

To illustrate the use of S-parameters to describe crosstalk, a simple test vehicle was constructed with four coupled transmission lines, as shown in Figure 1. Their ends are labeled with index numbers from 1 to 8. Connected to each end is a port, which can be thought of as a short 50-Ω transmission line terminated in 50 Ω. The recommended port assignment to be used to measure this DUT (device under test) has through connections set up as port 1 to port 2, 3 to 4, 5 to 6 and 7 to 8.
Each S-parameter matrix element for this DUT is the ratio of the sine wave coming out of a port to the sine wave going into a port. With eight ports, there are $8 \times 8 = 64$ different combinations of going-ins and coming-outs. The **S-parameter matrix formalism** is used to keep track of each of the combinations. The index number of each matrix element identifies which is the coming-out port and which is the going-in port.

For example, $S_{21}$ is the ratio of the wave coming out port 2 compared to the wave going in port 1. This specific term, for historical reasons, is referred to as the insertion loss. It has information about the attenuation of a signal traveling through the interconnect.

As the ratio of two sine waves, each S-parameter matrix element is a complex number, described by either a real and imaginary value or a magnitude and phase. The magnitude is the ratio of the amplitudes of the wave coming out to the wave going into the port, using 50 $\Omega$ as the impedance of each port.

Most of the S-parameter terms are a direct measure of the crosstalk between ports. The crosstalk of a sine wave entering port 1 on one transmission line and coming out port 3 of an adjacent line is labeled as $S_{31}$. The relative crosstalk for a signal entering port 1 and coming out the other end of the adjacent line at port 4 is labeled as the $S_{41}$ matrix element.

**Crosstalk can be subtle**

Even at “low” frequency, the crosstalk between two adjacent lines often depends on which end of the victim line we look. Backward propagating crosstalk is the sum of capacitive and inductive coupling while forward propagating crosstalk is the difference between capacitive and inductive coupling. We would expect $S_{31}$ not to be the same as $S_{41}$. **Figure 2** shows these two S-parameter terms when measured with a LeCroy SPARQ Signal Integrity Network Analyzer. Even at 20 MHz,
the near and far end crosstalk are different, with the $S_{31}$, near end crosstalk, larger than the $S_{41}$, far end crosstalk.

![Figure 2. Crosstalk to an adjacent line measured with a LeCroy SPARQ Signal Integrity Network Analyzer. Left: horizontal scale is 1 GHz full scale. Right: horizontal scale is 20 GHz full scale. Vertical scale is the same: 40 dB full scale with 0 dB at the top of the plot.](image)

This is yet another counter-intuitive property of the behavior of signals on interconnects. Even though $S_{31}$ and $S_{41}$ are measuring the crosstalk from the same source on the same interconnect, the noise appearing at each end of the victim line is radically different, especially above about 100 MHz.

It is not enough to specify how much crosstalk occurs between two lines. The direction in which the noise is traveling on the victim line must be specified as well. This is why the two ends of the victim line are labeled differently.

Using the S-parameter notation, $S_{31}$ is the noise on the victim line on the end near the source and is referred to as the near end noise. Since the signal on the aggressor is propagating in the direction defined as the forward direction, the near end noise is also the noise propagating on the victim line in the backward direction from the signal.

The $S_{41}$ term is the noise measured on the far end of the victim line, or in the forward direction. With tightly spaced microstrip transmission lines shown in Figure 1, the near-end noise reaches a peak value of only –13 dB, or 22% of the original signal, compared to the far end noise which peaks at about –4 dB which is 63%. These large values are an indication of how tightly coupled are these two transmission lines.

The formalism of S-parameters automatically takes into account which port the signal enters and each port in which it comes out. This makes S-parameters a natural tool to describe crosstalk. Use S-parameters to describe crosstalk

**Frequency and time domain responses**

While the formalism of S-parameters was created based on the behavior of sine waves, for all linear, passive, time invariant interconnects, knowing the behavior of sine wave signals is to know the behavior of any waveform.

A common time-domain waveform to display is a 0 V-to-1 V step edge, with a Gaussian rise time. The response of the system to each frequency component in this signal is described by the S-parameters. Using algebra, the step edge is converted to the frequency domain. Each frequency component is multiplied by the S-parameter value at that frequency, and the result is converted back to the time
domain. The result is how a step edge waveform would be treated by the DUT.

For example, the exact same frequency domain data used in Figure 2 is shown in Figure 3 but now displayed in the time domain as the response to a step edge. The near-end and far-end crosstalk have very different signatures. Again, using algebra, the rise time of the stimulus signal can be changed to illustrate how signals will couple over to the adjacent victim line.

![Figure 3. The same crosstalk to the adjacent victim line as previously shown, but in the time domain using a step edge as the signal entering the active line. Vertical scale is 10% crosstalk per division and horizontal scale is 0.5 ns per division.](image)

In this example, the peak value of the near-end crosstalk, 13%, described by the $S_{31}$ term, is insensitive to a signal rise time of either 50 ps or 200 ps. The peak far end noise, however, is very sensitive to the rise time, varying from -40% to -25% as the rise time increases.

This time domain display of near and far end crosstalk is the same data as displayed in the frequency domain, it’s just displayed differently. Flexibility in transforming between the time and frequency domain responses enables, at a glance, a measure of the noise expected for a specific system rise time.

**Crosstalk drops off with spacing**

The S-parameter matrix elements describe not just the coupling between any two conductors, but they also take into account the impact on the crosstalk from the direction of propagation of the signals. Figure 4 shows the measured near end crosstalk to the other ports. As would be expected, the near-end noise between port 1 and the three adjacent ports decreases as the port is physically moved away.
Figure 4. Near end crosstalk between one aggressor line and the adjacent victim lines, in the frequency domain (left) and the time domain (right). Scale for the frequency domain is 20 GHz full scale horizontal and 40 dB full scale vertical with 0 dB at the top. Scale for the time domain is 0.5 nsec/div and 10% per division vertical. The scale for $S_{51}$ and $S_{71}$ in the time domain was zoomed to 1% per division.

While the near-end crosstalk drops off for the farther away ports, the signature of the frequency domain response of the near-end noise is more similar to the far-end noise, just dramatically reduced. A glance at the time-domain responses of the $S_{51}$ and $S_{71}$ S-parameter matrix elements confirms that even though the noise is measured at the near end ports, the $S_{51}$ and $S_{71}$ responses are dominated by reflected far end noise spikes.

**The differential response**

These same four single-ended transmission lines can be viewed as two differential pairs. In many high speed digital applications, a differential pair is also called a channel. On differential pairs, signals are described as being differential or common signals. The S-parameter formalism can be extended to include the channel-to-channel crosstalk for all combinations of differential or common signals as aggressors or victims.

The test board in Figure 1 uses eight ports connected to four individual, single-ended transmission lines, as differential channels. There are only four ports and two differential pairs. Applying the labeling scheme used for the single-ended ports, the differential ports would be assigned as diff port 1 to diff port 2 and diff port 3 connected to diff port 4.

As part of the accepted formalism of differential or mixed mode S-parameters, the letters D and C designate differential signals or common signals respectively. Any combination of a type of signal entering a diff port and a type of signal coming out a diff port are identified by the coming out letter, the going in letter, the coming out port and the going in port.

For example:

- $S_{DD31}$ is the near end crosstalk for differential to differential signals
- $S_{DD41}$ is the far end crosstalk for differential to differential signals
- $S_{CC31}$ is the near end crosstalk for common to common signals
- $S_{CC41}$ is the far end crosstalk for common to common signals
- $S_{CD31}$ is the crosstalk of a differential signal as the aggressor, converting to near end common signal
The channel-to-channel differential and common crosstalk are shown in Figure 5. This clearly shows the advantage of tightly coupled differential pairs to reduce channel-to-channel crosstalk.

![Figure 5. Channel-to-channel diff and comm crosstalk in the frequency domain: 20 GHz full scale and 80 dB full scale with 0 dB at the top of the screen.](image)

The differential signal near and far end crosstalk is more than 20 dB lower than the common near and far end crosstalk. This graphically illustrates why differential signaling can sometimes decrease crosstalk between channels over common signals or single-ended signals.

Crosstalk between high speed signals is complicated. It depends on which end of the aggressor line the signal enters and on which end of the victim line you look. It varies with frequency in a complex way and may vary with rise time. The S-parameter formalism is a natural way of characterizing this complex behavior. Each matrix element describes the crosstalk between any pair of ports displayed in the time or frequency domains. They can be measured with a network analyzer or simulated with many popular circuit or electromagnetic simulators. If crosstalk is an important problem in your designs, it may be time to embrace S-parameters.

References


