and so 8.7 percent of the reflected half-amplitude signal will be re-reflected. This may not be a sufficient amplitude disturbance to cause problems. If it is, the transmission line must be given time for the reflections to diminish.

18.3 CROSSTALK

Initial transmission line analysis is typically performed with assumptions of ideal circumstances, including the assumption that the transmission line is independent of others. In reality, a wire acts as an antenna and is a radiator and receiver of electromagnetic fields. When two nearby wires couple energy between each other, the phenomenon is called *crosstalk* and is another source of signal integrity problems. Crosstalk is not always a problem, but the potential exists, and therefore circuit design and layout should be performed with its consideration in mind.

Energy can be coupled between nearby conductors either capacitively or inductively. High-frequency energy can pass through a capacitor, and a small capacitor is formed when two conductors are in proximity to one another. The capacitance between two wires is a function of their surface area and their spacing. When two wires are run parallel to one another on the same layer of a printed circuit board, their mutually facing surface area is relatively small. A dual stripline configuration, however, can present greater capacitive coupling problems, because wire traces may run parallel one on top of the other with significant surface area. A common PCB routing rule is to route adjacent dual stripline layers orthogonally whenever possible rather than parallel to each other as shown in Fig. 18.13. Minimizing the surface area of a wire that is in close proximity to the other wire reduces capacitive coupling.

Inductive coupling comes about because current flowing through a wire generates a magnetic field. Each wire is a very small inductor. If two wires are run close to each other, the two small inductors can couple their magnetic fields from one to the other. Crosstalk analysis uses the terms *aggressor* and *victim* to aid in analysis. The aggressor is a wire that has current flowing through it and is radiating an electromagnetic field. The victim is a nearby wire onto which the electromagnetic field couples unwanted energy. Because the intensity of the magnetic field is proportional to the current flowing through a wire, heavier loads will result in more coupling between an aggressor and nearby victims. Most crosstalk problems in a digital system are the result of magnetic fields, because of the high currents resulting from low-impedance drivers and fast edge rates.

Separation is an effective defense against crosstalk, because electromagnetic field coupling decreases with the square of distance. Doubling the separation between two wires reduces the coupling at the victim by 75 percent. Dielectric height in a PCB is another contributing factor, because the field intensity increases with the square of height between the aggressor trace and the ground plane. The dielectric ranges in thickness according to the desired characteristic impedance and width of the

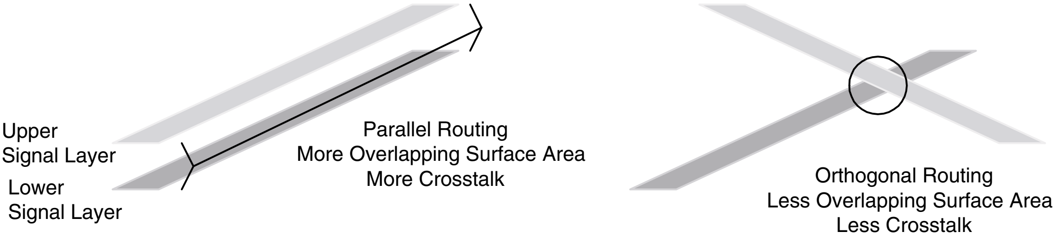

FIGURE 18.13 Dual stripline coupling reduction.

copper traces. As the dielectric gets thinner, the capacitance between the trace and ground plane increases, thereby decreasing Z_O. The trace's inductance must be increased to compensate for this decreased capacitance, indicating that a trace must be narrower to achieve 75 Ω versus 50 Ω with a certain dielectric height. Put another way, a 50-Ω transmission line has a lower dielectric height for a given trace width and, hence, weaker fields to cause crosstalk.

Crosstalk is a three-dimensional problem, and length is the third variable in coupling energy onto a victim trace. Traces that run parallel to each other are parallel antennas. Longer antennas can couple more energy. Therefore, many high-speed PCB designs enforce maximum parallelism rules that define the maximum distance that is allowable for two traces to run parallel to each other. Parallelism rules are related to separation rules. Traces that are spaced farther apart can tolerate longer parallel runs, because the separation reduces the aggressor's radiated field strength.

It is difficult to make generalizations about separation and parallelism rules, because every situation is unique. Furthermore, the formulas that define field strength and coupling coefficients are complex functions that incorporate dimensional and material parameters. A detailed crosstalk analysis requires the use of specialized software that simulates the coupling phenomena using detailed mathematical models of the driver and load circuits, the circuit board materials, and the three-dimensional arrangement of multiple traces. Such programs are known as field solvers and are available from a variety of vendors including Ansoft, Cadence, Innoveda, and Mentor Graphics.

When engineers do not have field-solving software at their disposal, very conservative design rules are often used to minimize the probability of excessive crosstalk. Sensitive signals are spaced apart from others. Parallelism is limited for signals whose spacing approaches the dielectric height where field coupling is greater. These rules are very coarse approximations, and application-specific rules need to be applied for very high-speed designs to avoid potentially thorny signal integrity problems in the prototype. If a great deal of time and money are invested in designing a leading-edge high-speed system, it is prudent to invest some time and money in appropriate signal integrity analysis tools.

One saving grace when dealing with crosstalk is that many signals do not have to be protected from each other if it can be shown that noise caused by crosstalk will not affect the received signal. Consider the case of a microprocessor bus's individual wires that are traveling close together between ICs. Inductive coupling, which is the dominant crosstalk contributor, occurs when current is flowing, because the magnetic field is proportional to current flow. Significant current flows during the switching time of the digital signal. Once the signal has stabilized, the load presents the driver with high impedance. This means that crosstalk between signals that transition together occurs mainly while they are switching and then quiets down after the lines have stabilized. A properly designed system does not sample signals until they have safely stabilized, at which point crosstalk within the group becomes negligible.

The wires that compose a single bus can usually be routed in close proximity to each other without regard for crosstalk within the bus. Clocks require special consideration, because one does not want a great deal of noise from switching bus wires to couple onto the clock wire and cause a false edge to appear. Likewise, the clock's transitions can potentially couple onto data wires and cause an incorrect observation at the receiver. Clocks are usually given preferential routing treatment aside from their low-skew distribution requirement. Clock traces are often routed before all others, and stricter minimum spacing rules may be used to minimize corruption of clock signals. Very conservative systems are designed by dedicating one or more entire PCB signal layers to clock routing so that the clocks can enjoy substantial trace-to-trace spacing minimums.

Although signals within a bus are usually not sensitive to mutual crosstalk, signals that transition asynchronously with respect to each other are prime candidates for trouble. Asynchronous signals, by definition, transition relative to each other without a defined timing relationship. If a system has two buses on different clock domains whose wires are mixed in close proximity with long parallel runs, it is probable that one bus will often transition during the assumed stable time of the other bus