18.1 TRANSMISSION LINES

Transmission lines, reflections, and impedance matching have been alluded to previously. The term *transmission line* can refer to any conductive path carrying a signal between two points, although its usual meaning is in the context of a conductive path whose length is significant relative to the signal's highest-frequency component. Circuits are normally drawn assuming ideal conductors whose lengths are negligible and assuming that the voltage at any instant in time is constant across the entire conductor. When a wire "becomes a transmission line," it means that it can no longer be considered ideal. An electrical signal propagates down a wire with finite velocity, which guarantees that a changing signal at one end will take a finite time to reach the other end. When a signal's rate of change is slow relative to the wire's delay, many nonideal characteristics can be ignored. Older digital circuits that ran at several megahertz with slow transition times were often not subject to transmission line effects, because the wire delay was short compared to the signal's rate of change.

A signal that changes rapidly forces one end of a transmission line to a significantly different voltage from other points along that conductor. At the instant this rapid change is produced by a driver, the signal has not yet reached the load at the end of the wire. Rather than observing current and voltage that are in proportion to the load impedance, they are in proportion to the characteristic impedance of the transmission line, commonly written as Z_O. Z_O is not a DC load; it represents the reactance developed by the conductors' inductive and capacitive characteristics. It is the impedance that would be observed between the two conductors of an infinitely long transmission line at nonzero frequency. When a high-frequency signal transitions before the driver sees the end load, it is as if the transmission line is infinitely long at that moment in time.

Transmission lines are composed of a signal path and a return path, each of which can be modeled using discrete lumped elements as shown in Fig. 18.1. The model shown is that of an unbalanced transmission line wherein all of the inductive and lossy properties are represented in one conductor. This is acceptable for many transmission lines in a digital system, because printed circuit boards commonly consist of etched wire conductors adjacent to ground planes that have negligible inductance and resistance. A balanced transmission line model, such as that representing a twisted pair cable, would show series inductance and resistance in both conductors. Analysis is simplified by assuming lossless conductors, which is often a suitable starting point in a digital system with moderate wire lengths. Using this simplification, the characteristic impedance is defined as $Z_O = \sqrt{L \div C}$.

Characteristic impedance is an important attribute, because it defines how a high-speed signal propagates down a transmission line. A signal's energy can fully transfer only between different transmission line segments that have equal Z_O. An impedance discontinuity results when two transmission lines are joined with differing Z_O. Impedance discontinuities result in some of a signal's energy being reflected back in the direction from which it arrived. This phenomenon is the crux of many signal integrity problems. An improperly terminated transmission line has the potential to cause reflections from each end of the wire so that the original signal is corrupted to the point of being rendered useless. A reflection coefficient, represented by the Greek letter gamma (Γ), that determines the fraction of the incident voltage that is reflected back from an impedance discontinuity is defined in the following equation:

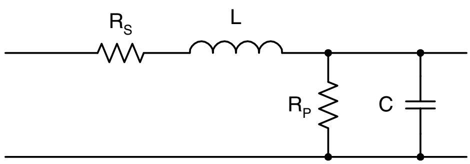

FIGURE 18.1 Lumped transmission line model.

$$\Gamma = \frac{Z_L - Z_O}{Z_L + Z_O}$$

Gamma is a dimensionless quantity that ranges from +1 to –1 and is a function of Z_O and the next segment's impedance, Z_L. It can be seen from this relationship that, when a transmission line is left open, $Z_L = \infty$ and $\Gamma = 1$: the entire voltage is reflected back to the source. This is the default situation for most digital signals, because a high-impedance logic input is effectively an open circuit from a transmission line perspective. Incidentally, a short-circuited transmission line, though not very desirable for digital signals, results in $\Gamma = -1$, because $Z_L = 0$, and causes the reflected signal to cancel the incident signal at the load. When a resistor equal to Z_O is placed at the end of a transmission line such that it connects the line's signal and return paths, $\Gamma = 0$, the line is said to be terminated, and no reflections are induced.

Transmission line reflections are perhaps best understood in a qualitative manner by looking at a time-domain view of a propagating signal. Figure 18.2 shows three scenarios that illustrate the benefits of termination and the effects of the reflection coefficient. The first scenario shows an edge injected into a 1 ns transmission line (about 6 in [0.15 m] long) that is improperly designed. Substantial bounce is present at the load. A high-speed clock is shown in the second scenario injected into the same transmission line. Note the bounce at both logic levels that can potentially create detection problems at the load. Poorly designed transmission lines can exhibit a wide variety of troublesome transient phenomena. Some may be better or worse than what is shown here. The third scenario shows the same clock injected into the same transmission line but with proper termination. The signal integrity is about as good as can be expected in a real circuit. There will always be small transients, even when a transmission line is properly matched, because of nonideal characteristics including stray inductance and capacitance in wires and termination components.

The need to minimize impedance discontinuities in modern printed circuit boards has given rise to the concept of controlled-impedance PCB design and manufacture. When a signal path and return path are arranged in various topologies, Z_O of the resultant transmission line is deterministic to an accuracy defined by the tolerance of the dimensions and electrical properties of the PCB materials. If all traces on a PCB are manufactured with similar Z_O, signals are subject to low reflection coefficients as they travel throughout the board. Three of the common PCB transmission line topologies are microstrip, symmetric stripline, and asymmetric stripline as illustrated in Fig. 18.3. These topologies assume one or two continuous ground planes adjacent to each signal layer. A continuous ground plane offers low sheet inductance with excellent high-frequency characteristics. Microstrip transmission lines are fabricated on the surface layers of PCBs where there is a single ground plane underneath the surface signal layer. A symmetrical stripline is evenly suspended between the two ground planes, while an asymmetric stripline has unequal spacings. Dual asymmetric striplines are implemented to achieve higher wiring density in a PCB versus symmetric striplines because of the higher ratio of signal to ground plane layers. Dual striplines have the potential for interference between adjacent signal layers, requiring more careful layout than with single striplines.

Z_O is a function of the trace geometry (width and thickness) and the relative permittivity and height of the dielectric, or insulator, that separates the ground planes from the traces. Relative permittivity, ε_r, also called the *dielectric constant,* quantifies the effect of an insulating material on the capacitance between two conductors relative to free space. The relative permittivity of free space is 1 by definition. Common insulators have ε_r ranging from 2 to 10. For microstrip and stripline topologies, Z_O is defined in the following equations:*

* *IPC-2141—Controlled Impedance Circuit Boards and High-Speed Logic Design,* Institute for Interconnecting and Packaging Electronic Circuits, 1996, pp. 11–14.