EMI Prevention in Clock-Distribution Circuits

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Introduction

Although the importance of electromagnetic interference (EMI) has been recognized, most system designers have tended to handle the problem by shielding via metal cabinets or through RC networks to limit the rise and fall times of digital pulse waveforms. These design practices were motivated by 1) a lack of EMI-prevention design rules and by 2) designers' tendencies to prioritize apparent system performance only to have that performance subsequently degraded through the later addition to the system of EMI-prevention devices such as metal chassis or RC networks.

With the current trend towards lighter, more compact personal computers and engineering workstations, system designers can no longer rely upon after-the-fact EMI shielding techniques; rather, they must learn to build in EMI protection at the design stage. This application report discusses EMI protection for a clock distributor, an application characterized by multiple simultaneously switching bits and relatively long transmission lines.

Higher-Harmonic Components of Digital Waveforms

In general, the decay rate of a Fourier-spectrum envelope is greater for a waveform with slow rise and fall times than for a waveform with fast rise and fall times. Figures 1 and 2 show a triangular waveform and its spectrum envelope. The 12 dB/octave decay rate shown in Figure 2 means that if two x-axis values of 1X frequency and 2X frequency are considered, the corresponding y-axis values are 1X and 1/4X amplitude, respectively.

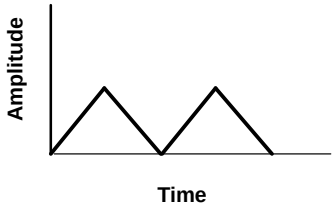


Figure 1. Triangle Wave

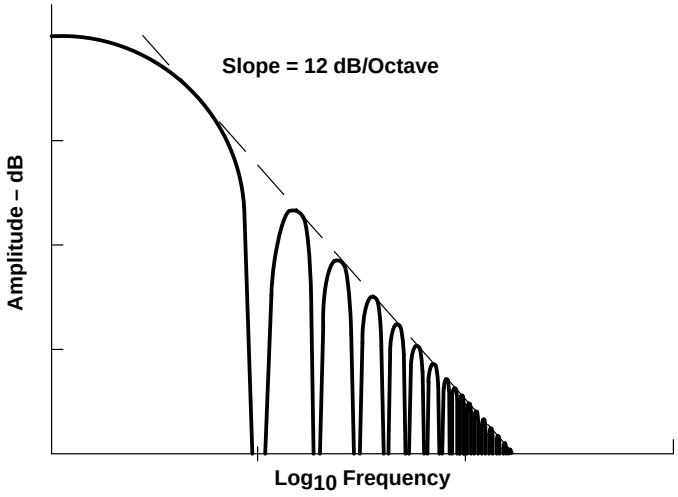


Figure 2. Spectrum Envelope for Triangle Wave of Figure 1

Figures 3 and 4 show an ideal square waveform (0-ns rise and fall times) and its spectrum envelope. Comparing 1X frequency and 2X frequency x-axis values, the corresponding y-axis values are 1X and 1/2X, respectively.

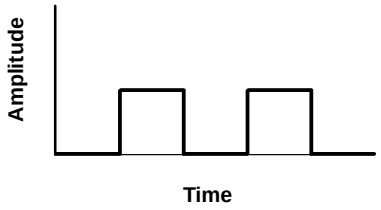


Figure 3. Square Wave

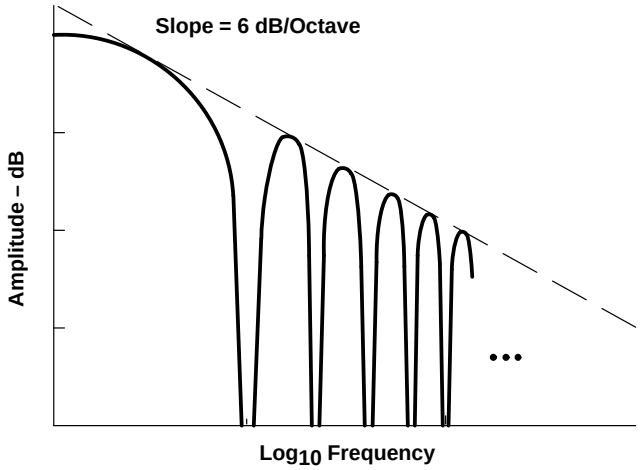


Figure 4. Spectrum Envelope for Square Wave Shown in Figure 3

By comparing Figures 1 and 2 with Figures 3 and 4, it is evident that the ideal square wave, with its sharp discontinuities (0-ns rise and fall times), contains many more higher harmonics than does the triangle wave. Hence, an electronic circuit stimulated by an ideal square wave would require employment of more EMI-protection design techniques than a circuit stimulated by a triangle wave of the form shown in Figure 1.

In real digital-circuit applications, square waves are not ideal but instead have finite rise and fall times. Although the decay rate of the spectrum envelope for a real square wave will be greater than the 6 dB/octave rate of the ideal square-wave spectrum envelope, its decay rate will still be small enough to cause EMI problems. The spectrum-envelope decay rate for a square wave is also dependent on its pulse duration, as shorter pulse durations equate to frequency spectra exhibiting higher amplitudes at higher frequencies. In comparing Figures 5 and 6 (time and frequency plots for a 50% duty-cycle square wave) with Figures 7 and 8 (time and frequency plots for a less-than-50% duty-cycle square wave), the following may be observed:

- The amplitude-vs-frequency plot remains flat up to a frequency equal to the inverse of the pulse duration, or $1/t_w$. This first node in the frequency plot occurs at a higher frequency for the less-than-50% duty-cycle waveform than for the 50% duty-cycle waveform.
- Beyond this first node in the frequency plot, both frequency plots have spectrum envelopes that decay at the 6 dB/octave rate.

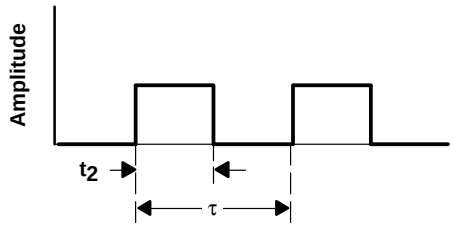


Figure 5. Square Wave, Duty Cycle = 50%

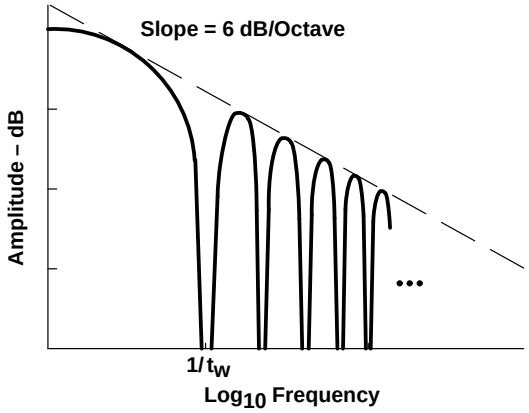


Figure 6. Spectrum Envelope for Square Wave Shown in Figure 5

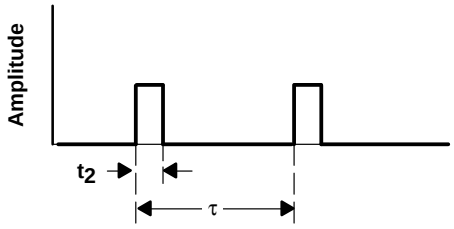


Figure 7. Square Wave, Duty Cycle < 50%

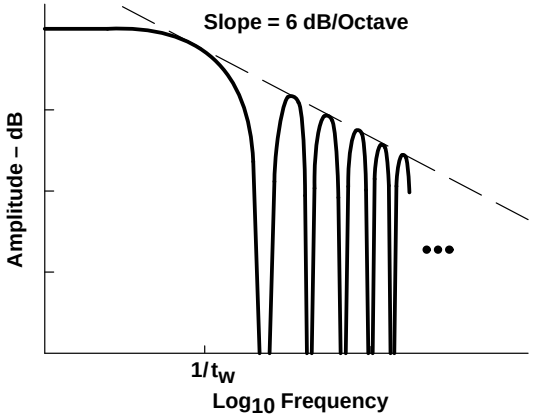
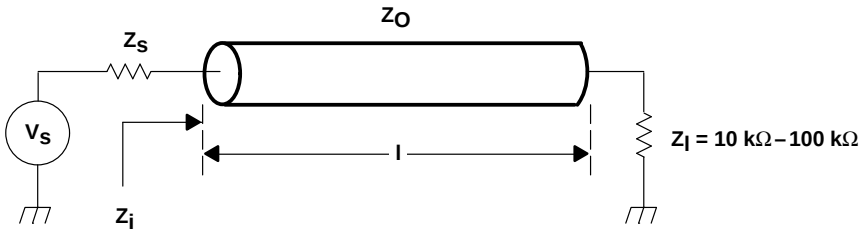


Figure 8. Spectrum Envelope for Square Wave Shown in Figure 7

Transmission Line and Radiated Emissions

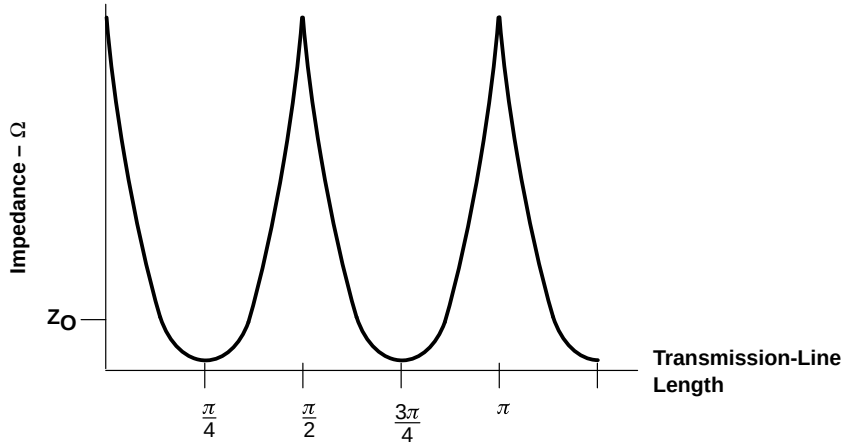
The transmission lines connected to clock drivers or bus drivers are often relatively long. When transient currents flow on such transmission lines, the transmission lines act as efficient antennae, radiating high-frequency electromagnetic waves. If such a transmission line is unterminated, its radiated spectrum shows maximum peak voltage.

In the transmission line shown in Figure 9, the input impedance of the receiver is high (10 kΩ to 100 kΩ) relative to the transmission-line characteristic impedance (Z_O). The transmission-line input impedance versus length can be represented by a cotangent function. For a particular signal frequency, the transmission-line input impedance is at a minimum when the transmission-line length is an odd multiple of 1/4 of the wavelength of the signal. When the frequency spectrum of the output waveform of the driver shown in Figure 9 contains such frequency components, current through the transmission line and radiated emissions from the transmission line are maximized.



$$Z_i = -jZ_o cot\left(\frac{2\pi l}{\pi}\right)$$

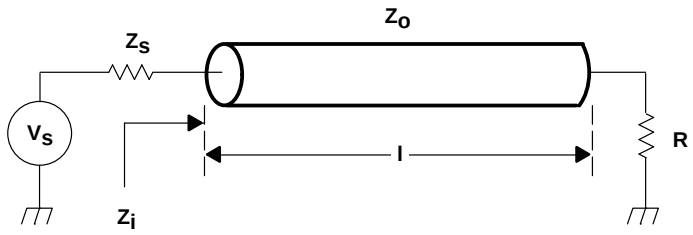
(a) MODEL OF TRANSMISSION LINE SHOWING HIGH INPUT IMPEDANCE OF RECEIVER



(b) PLOT OF TRANSMISSION-LINE INPUT IMPEDANCE VERSUS LENGTH

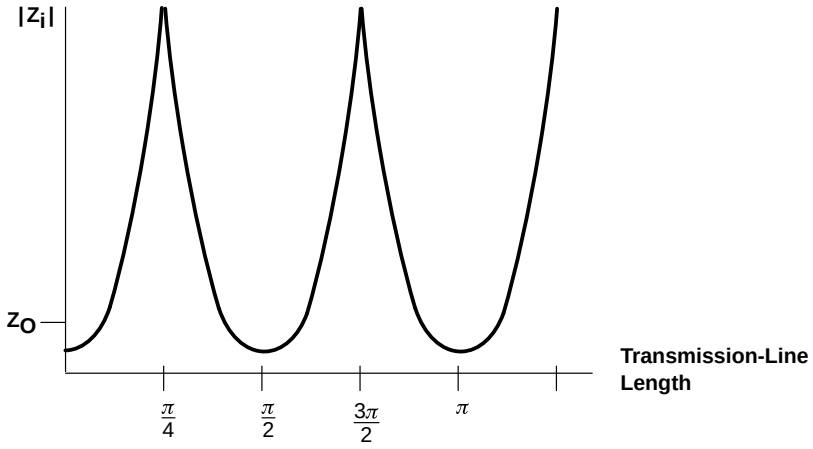
Figure 9. Transmission Line With a Driver and a Receiver

On the other hand, if the transmission line is terminated with less impedance than the transmission-line characteristic impedance (Z_O) (see Figure 10), the transmission-line input impedance versus length can be represented by a tangent function. For a particular signal frequency, the transmission-line input impedance is minimized when the transmission-line length is an integer multiple of 1/2 of the wavelength of the signal. Radiated emissions are maximized at these frequencies.



$$Z_i = -jZ_o tan\left(\frac{2\pi l}{\pi}\right)$$

(a) MODEL OF TRANSMISSION LINE SHOWING TERMINATION RESISTOR R < Z_O

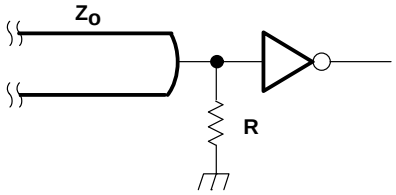


(b) PLOT OF TRANSMISSION-LINE INPUT IMPEDANCE VERSUS LENGTH

Figure 10. Transmission Line With a Termination Resistor Value Less Than Z_O

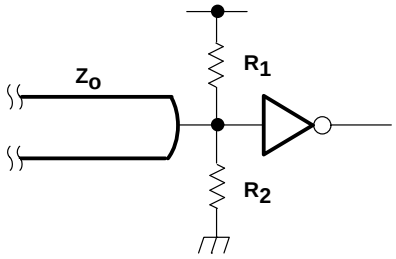
In summary, impedance mismatching causes a maximum current flow on the transmission line, thus maximizing radiated emissions. It is obviously desirable to assure impedance matching to minimize radiated emissions. There are two basic methods of assuring impedance matching: 1) termination at a line end point, and 2) termination at a line start point.

Terminating the end of a transmission line can be done either by use of a pulldown resistor (see Figure 11) or through parallel resistors (the so-called Thevenin's termination; see Figure 12). Termination at a transmission-line start point is done via a damping resistor (see Figure 13).



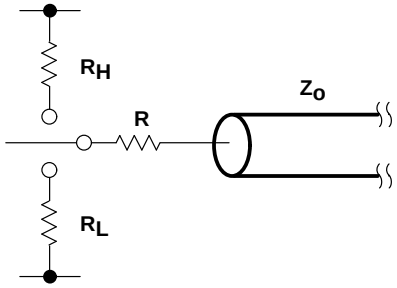
$$Z_o = R$$

Figure 11. Impedance Matching Through a Pulldown Resistor



$$Z_o = \frac{R_1 \times R_2}{R_1 + R_2}$$

Figure 12. Impedance Matching Through Parallel Resistors (Thevenin's Termination)



$$Z_o = \frac{R_H + R_L}{2} + R$$

Figure 13. Impedance Matching Through a Damping Resistor

For a clock-distribution circuit, in which transmission is restricted to a single direction, termination at the transmission-line start point (i.e., through a damping resistor) is recommended as this approach minimizes power consumption (albeit at the cost of a slight increase in the clock signal rise and fall times). In contrast, a Thevenin (end-of-transmission-line) termination is recommended for bus interface circuits wherein bidirectional signal flow is assumed.

The Antenna Effect

When relatively long transmission lines have a high characteristic impedance, they tend to mimic antennae, both receiving and radiating noise easily, so it is desirable to design transmission lines with as low a characteristic impedance as possible. When a multilayered printed-circuit board (PCB) is used, transmission lines can be laid out on an intermediate layer; the shielding effects of the V_{CC} and GND planes of the PCB will then suppress vertically polarized waves.

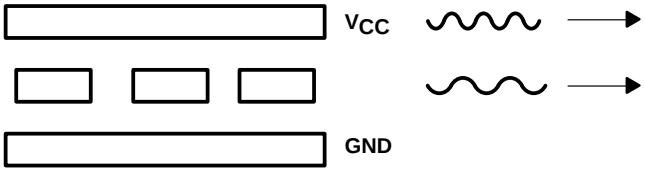
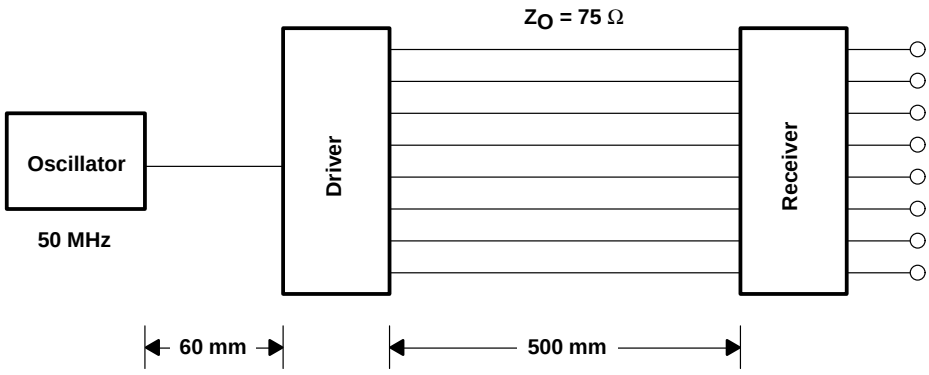


Figure 14. Antenna Effect of Transmission Lines

Spectrum Analyzer Results

Data from the test setup shown in Figure 15 was examined via a spectrum analyzer to determine which element of the test setup was most critical relative to radiated emissions (the oscillator, the shielded line, the driver, the transmission lines, or the receiver) and to observe the effects of line terminations. The data as plotted in Figure 16 showed that the oscillator exhibits a maximum value of 47dBμV/m at 150 MHz and that the oscillator has high shielding capability. Table 1 gives the mean and maximum values for the four plots in Figure 16. It is clear from Figure 16 that the transmission line is the most significant contributor to radiated emissions.



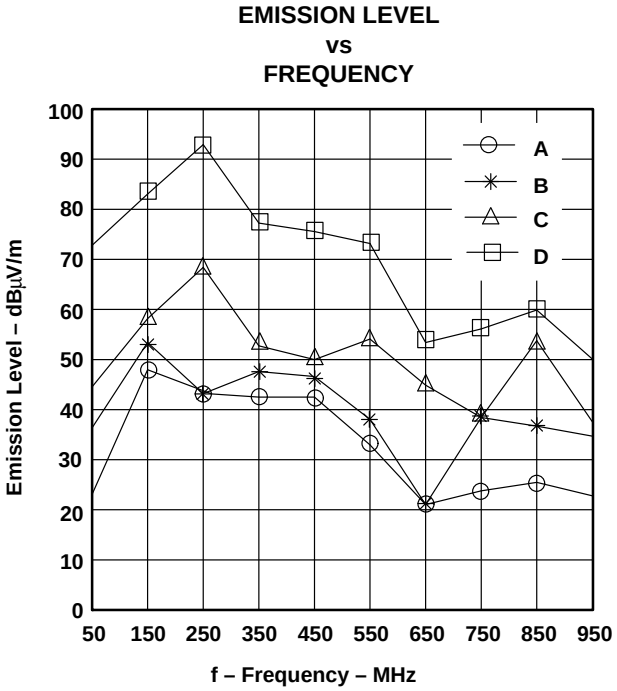
DRIVER	RECEIVER
CDC209	CDC204
CDC204	CDC204
CDC303	AS245
ABT240	ABT240

Figure 15. Block Diagram of Test Setup for Measuring Radiated Emissions

Table 1. Comparison of Radiated Emissions

	MEAN	MAX
A	33	47
B	38	54
C	49	68
D	67	93

Units: dBμV/m
Driver: CDC208
Receiver: CDC204



A = Oscillator
B = Oscillator + Shielded Line
C = Oscillator + Shielded Line + Driver
D = Oscillator + Shielded Line + Driver + Transmission Line + Receiver

Figure 16

Effects of Impedance Matching

Practically speaking, impedance matching is the easiest way to minimize radiated emissions. Figures 17 and 18 show test setups (transmitter = CDC208; receiver = CDC204) with unterminated transmission lines and with transmission lines terminated with 56-Ω damping resistors, respectively. The oscilloscope display for the transmitted waveform from the test setup of Figure 17 showed significant overshoot and undershoot due to signal reflections, and a spectrum analyzer showed a maximum value of 90 dBμV/m. In contrast, the transmitted waveform from the test setup of Figure 18 showed no overshoot and undershoot, and the amplitudes of higher-harmonic components were reduced.

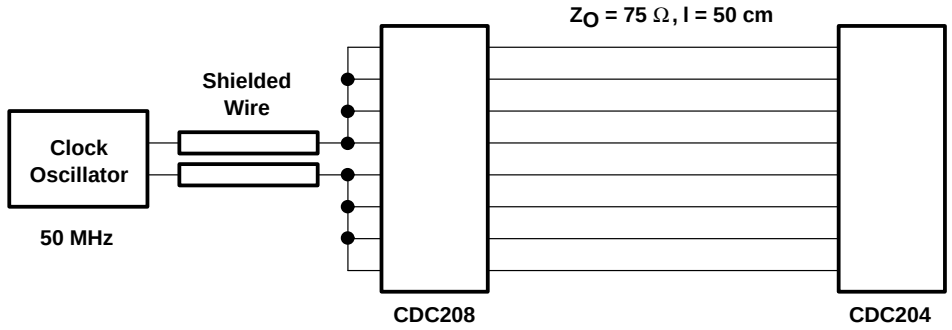


Figure 17. Test Setup With Unterminated Transmission Lines

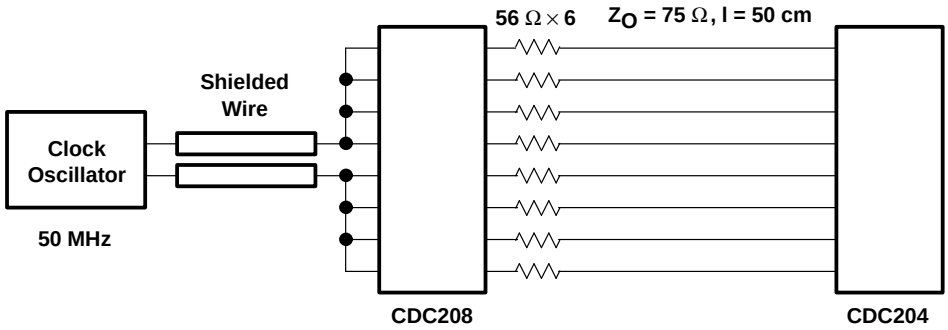


Figure 18. Test Setup With 56-Ω Damping-Resistor Terminations

Similar analyses were made using CDC204/CDC204 and ABT240/ABT240 transmitter/receiver pairs. The results for all three transmitter/receiver pairs for unterminated transmission lines are summarized in Table 2.

Table 2

INTERFACE	MIN	MAX
CDC208–CDC204	8.8	17
CDC204–CDC204	4.9	9.2
ABT240–ABT240	7.3	13

Units: dBμV/m
NOTE: MIN and MAX values at higher harmonics

In the case of transmission lines terminated with 56-Ω damping resistors, the data values in Table 2 could be expected to improve by 5 to 9 dBμV/m (means) and 9 to 17 dBμV/m (maximums).

Figures 19 through 22 show EMI evaluation results for CDC208, CDC204, ABT240, and CDC303 devices in both unterminated and damping-resistor-terminated configurations. The x-axis (frequency) values in these figures are odd higher harmonics for the given transmission lines. The radiated emission values in these figures are relatively high for the following reasons:

- The transmission lines were up to 500 mm in length.
- The transmission lines were laid out on a surface layer of the PCB.
- The PCBs were not shielded by metal cabinets.

Figures 19 through 22 clearly show that when signal reflections are controlled by impedance matching, the radiated emissions are reduced.

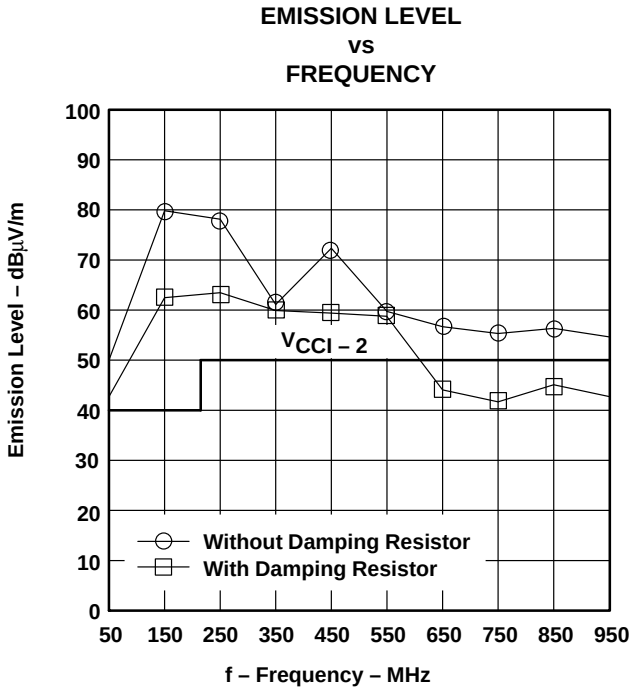


Figure 19. EMI Evaluation Results (Device Under Test = CDC208)

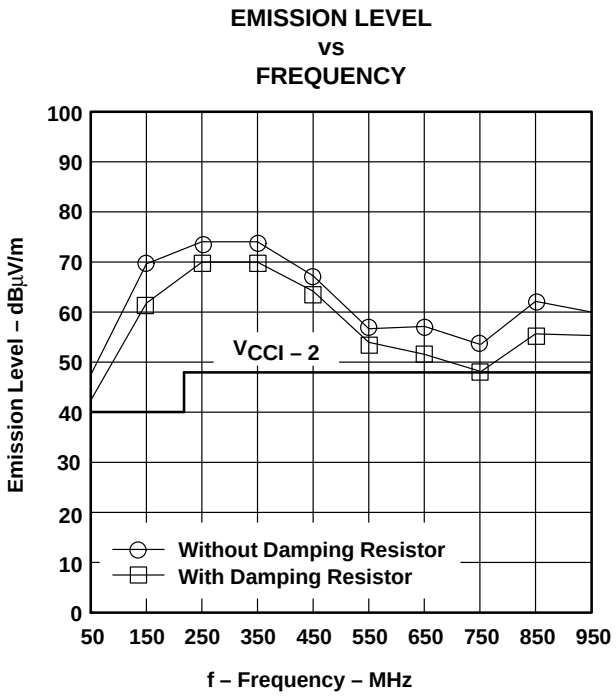


Figure 20. EMI Evaluation Results (Device Under Test = CDC204)

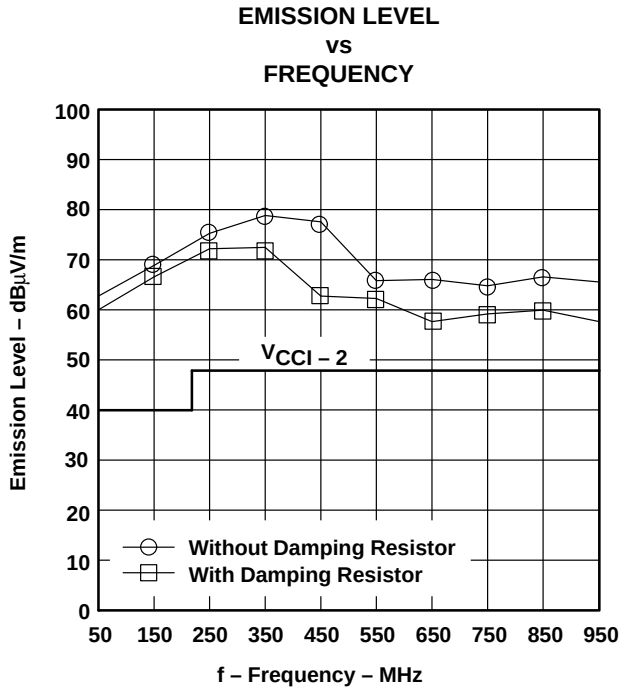


Figure 21. EMI Evaluation Results (Device Under Test = ABT240)

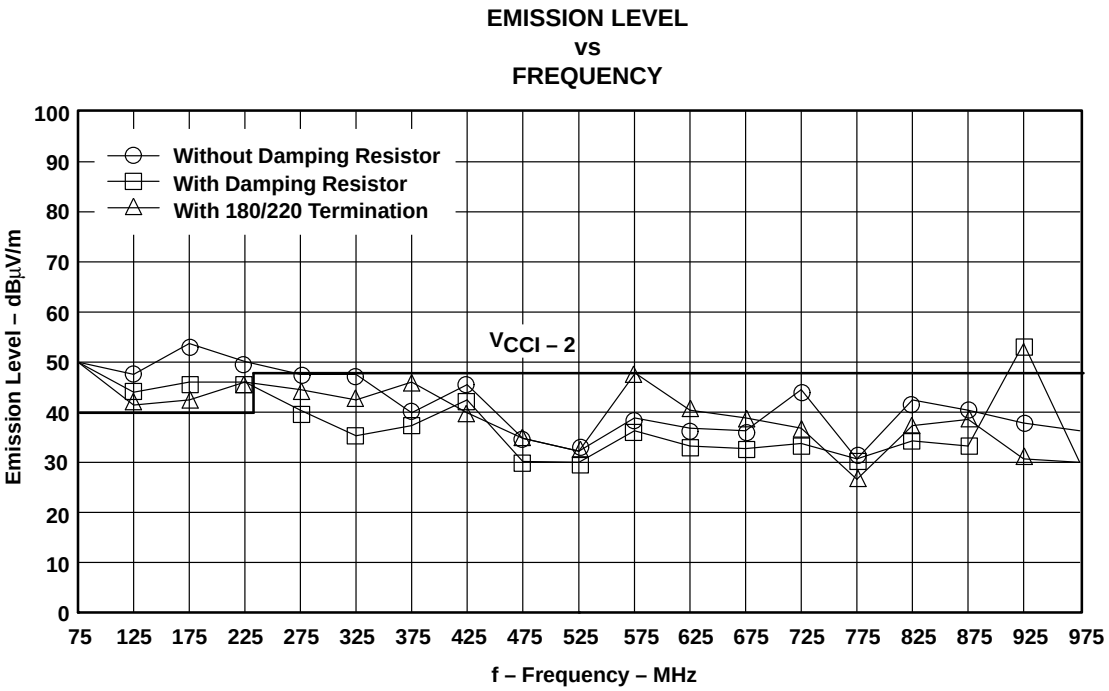


Figure 22. EMI Evaluation Results (Device Under Test = CDC303)

Summary of Methods for EMI Prevention

Characteristic Impedance of the Transmission Line

A transmission line should be designed with as low a characteristic impedance as possible to reduce the antenna effect. Long transmission lines such as those in clock-driver or bus-interface circuits should be laid out in intermediate PCB layers rather than surface layers (the characteristic impedance of intermediate-layer lines is on the order of 50 Ω, while surface-layer lines have 75-Ω characteristic impedances).

PCB Shielding Effects

Laying out transmission lines between PCB V_{CC} and GND planes both reduces their characteristic impedance and reduces horizontal polarization through shielding by PCB copper planes. The metal stiffeners at the PCB edges also shield against horizontal polarization.

Impedance Matching

Radiated emissions are high when transmitted signals exhibit overshoot, undershoot, and ringing. Careful impedance matching must be maintained between drivers and transmission lines and between transmission lines and receivers to minimize these effects. For clock-distribution circuits, use of 10-Ω damping resistors between the drivers and transmission lines or pulldown resistors, Thevenin's terminations, or clamp diodes between the transmission lines and receiver inputs is recommended.

Conclusion

As the data in this application report shows, unsuitable transmission-line terminations both contribute to radiated emissions and cause signal distortion. The evaluations described in this report seek not to measure exact values of radiated emissions but rather to demonstrate the effectiveness of impedance matching for reducing both radiated emissions and signal distortion.