The practical radiation formulas presented in Chapter 2 and applied from that point onward have been established via the process described in this appendix.

When the source is at a distance $D < \lambda/2\pi$ (near-field conditions), the E/H ratio of an electromagnetic field departs from the free-space impedance $Z_0$, which is:

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = \sqrt{\frac{4\pi \times 10^{-7} \text{ Henry/m}}{1 \text{ (10}^{-9} \text{ F/m)}}} = 120\pi, \text{ or } 377 \Omega$$

The near-field E/H ratio depends on the source impedance but can never exceed $377 \times \lambda/2\pi D$ nor be less than $377 \times 2\pi D/\lambda$. The question of how source-circuit and wave impedance are related in the near field is important because the estimation of E and H, and the shielding effectiveness of barriers, are dependent on this relation.

The development of a discrete relation between circuit impedance, $Z_c$, and wave impedance, $Z_w$, in the near field is beyond the scope of this handbook. However, the following mathematical relations are suggested for all conditions in which the circuit dimensions, $D \ll \lambda$: 

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For $Z_c \geq Z_0$ (high-Z source):

$$Z_w = \frac{Z_0 \lambda}{2\pi D}, \text{ for } Z_c > \frac{Z_0 \lambda}{2\pi D} \geq Z_0$$

$$\equiv Z_c, \text{ for } \frac{Z_0 \lambda}{2\pi D} > Z_c \geq Z_0$$

$$\equiv Z_0, \text{ for } Z_c = Z_0$$

For $Z_c \leq Z_0$ (low-Z source):

$$Z_w = Z_c, \text{ for } Z_c > Z_c \geq \frac{Z_0 2\pi D}{\lambda}$$

$$\equiv \frac{Z_0 2\pi D}{\lambda}, \text{ for } Z_c > \frac{Z_0 2\pi D}{\lambda} > Z_c$$

These equations are plotted in Fig. A.1 for several values of common circuit impedances of 50, 100, 300 and 600 Ω. To the extent that these conditions exist, the finite source circuit impedance, then, does not "permit" an infinitely high or null wave impedance $E/H$.

Rewriting the above equations in more practical terms, the near-field wave impedance for any circuit is:

$$Z_w (\Omega) = \frac{18000}{D \times F_{\text{MHz}}}, \text{ for } Z_c = \frac{18000}{D \times F}$$

$$Z_w (\Omega) = Z_c, \text{ for } \frac{18000}{D \times F} \geq Z_c > 7.9 \text{ DF}$$

$$Z_w (\Omega) = 7.9 \text{ DF}, \text{ for } 7.9 \text{ DF} \geq Z_c$$

**Far-Field Values**

The E field radiated by an isolated wire at a distance $D > \lambda/2\pi$ is:

$$E_{V/m} = \frac{1}{D} \times 60\pi \times \frac{I'}{\lambda}$$
If, instead, we have two wires carrying equal but opposite currents, the radiated field in the plane of the two wires is calculated from the phase lag of the equal and opposite fields:

$$E = \frac{1}{D} \times 60\pi \times \frac{I}{\lambda} \times \sin \frac{2\pi s}{\lambda}$$

Recognizing that, for small values of "x," \(\sin x = x\), replacing \(\lambda\) by \(300/F_{\text{MHz}}\) and expressing \(\ell \times s\) in cm²:

$$E_{\mu V/m} = \frac{1.3}{D_m} \times \frac{V}{Z_L} (\ell \times s) F_{\text{MHz}}^2$$

This is the same expression as the loop model, in the far field.

**Values at Transition Distance**

Replacing \(F\) by its corresponding value at the near-far transition distance, i.e., \(F_{\text{NF}} = 300/2\pi D\), or \(48/D_m\):
E_{\mu V/m} = \frac{1.3}{D} \times \frac{V}{Z_L} \times l \times s \times \left(\frac{48}{D}\right)^2

= \frac{V \times (l \times s) \text{ cm}^2}{Z} \times \frac{3000}{D^3}

This new formula is used as the reference value to calculate the near-field terms, since the near-field wave impedance will become asymptotic to the impedance of the source circuit, increasing from 377 Ω to Z_c (if Z_c > 377 Ω) for high-impedance circuits, or decreasing to Z_c if Z_c < 377 Ω.

Near-Field Values (i.e., $F < F_{NF}$)

$$E_{\mu V/m} = \frac{V \times (l \times s) \text{ cm}^2}{Z} \times \frac{3000}{D^3}, \text{multiplied by:}$$

$$\frac{F}{F_{NF}}, \text{if } Z < 377(F/F_{NF}), \text{or } \frac{Z}{377}, \text{if } Z > 377(F/F_{NF})$$

Therefore,

1) If $Z < 377(F/F_{NF})$ (low-Z circuit), or $Z < 7.9 F \times D$:

$$E_{\mu V/m} = \frac{62 V \times (l \times s)}{Z \times D^2} \cdot F_{MHz}$$

2) If $Z > 377(F/F_{NF})$ (high-Z circuit), or $Z > 7.9 F \times D$:

$$E_{\mu V/m} = \frac{7.9 V \times A}{D^3}$$

**Quasi-static Values for E or H**

In the near field, field prediction curves of Chapter 2 (Fig. 2.6) show that E becomes constant for a given drive voltage and distance. This raises the question: What happens to the associated H field? The previous equations, plus Figs. A2 and A3, provide the answer.
For a constant voltage excitation, the wave impedance increases when $F$ decreases below $F_{NF}$, until it reaches $Z_c$ (unless $Z_c = \infty$). This would meet the case of a monopole, or open loop excited in dc, creating a static E field but no H field.

Conversely, for a magnetic, low-Z circuit, the wave impedance decreases when $F$ decreases below $F_{NF}$, until it reaches $Z_c$ (unless $Z_c = 0$). Therefore, the associated E field decreases, but not down to zero, unless $Z_c = 0$. This would meet the case of a perfectly shorted loop at dc, having no E field and a static H field.

FIGURE A.2  Wave Impedance vs. Circuit Impedance
FIGURE A.3 Electric and Magnetic Field Trends at Very Low Frequencies (Quasi-static)
Appendix B

Some Validation Results
Supporting the Simplified Radiation Model

Several validation measurements performed by the author on simple circuits, as well as other measurements reported in the literature, give an indication of the error margin incurred.

Figures B.1 and B.2 show the results for a personal computer single-layer board radiation and a backplane with 10 MHz clock runs, both measured on calibrated FCC test sites. Interestingly, in Fig. B.1, the influence of changing from a clock oscillator supplied by source A to one provided by source B, with slightly different rise times, is clearly visible.

The compilation of about 60 radiated test results, compared to the predicted results per this book’s method, showed a mean of differences of 8.5 dB.
FIGURE B.1 Measured vs. Predicted Radiated Emissions from a PCB, 3 m Test Site per FCC Part 15-J (Ref. 22) (continued next page)
OSC. = 7.5 MHz Clock
A = Loop Area, 6.5 cm²
B = Driver Module

FIGURE B.1 (continued)
FIGURE B.2  Measured vs. Predicted Radiated Emissions from PCB Traces
References

8. Charoy, A. PCB Design Seminars. (Various times and locations.)
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   Government Printing Office.
   (RTCA).
    IEEE EMC Symposium*. Piscataway, NJ: Institute of Electrical and Electronics Engi-
   neers, 1981.
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