FIGURE 1.2 The four basic EMC subproblems: (a) radiated emissions; (b) radiated susceptibility; (c) conducted emissions; and (d) conducted susceptibility.
FIGURE 1.3 Other aspects of EMC: (a) electrostatic discharge (ESD), (b) electromagnetic pulse (EMP), (c) lightning, (d) TEMPEST (secure communication and data processing).
Shielding

The term shield usually refers to a metallic enclosure that completely encloses an electronic product or a portion of that product.

Figure 11.1 Illustration of the use of a shielded enclosure: (a) to contain radiated emissions and (b) to exclude radiated emissions.

A shield is, conceptually, a barrier to the transmission of electromagnetic fields.

We may view the effectiveness of a shield as being the ratio of the magnitude of the electric (magnetic) field that is incident on the barrier to the magnitude of the electric (magnetic) field that is transmitted through the barrier.

Ideal values of shielding effectiveness are of the order of hundreds of dB.

Any penetrations (holes, seams, slots or cables) in a shield unless properly treated, may drastically reduce the effectiveness of the shield.
FIGURE 11.2 Important practical considerations that seriously degrade shielding effectiveness: (a) penetration of an enclosure by a cable allowing direct entry of external fields; (b) pigtai1 termination of a cable shield at the entry point to a shielded enclosure; (c) termination of a cable shield to a noisy point causing the shield to radiate.
**FIGURE 11.3** Illustration of the effect of apertures in a shield (illustration of Babinet’s principle).

Babinet’s principle states that the far fields radiated by the original screen with the slot and those radiated by the complementary structure are related by [2]

\[
\begin{align*}
E_{\theta s} &= H_{\theta c} \\
E_{\phi s} &= H_{\phi c} \\
H_{\theta s} &= -\frac{E_{\theta c}}{\eta_0^2} \\
H_{\phi s} &= -\frac{E_{\phi c}}{\eta_0^2}
\end{align*}
\]  

(11.1a)  

(11.1b)  

(11.1c)  

(11.1d)

This illustrates that apertures can be as effective radiators as antennas whose conductor dimensions are those of the aperture.
**Shielding Effectiveness**

**FIGURE 11.4** Illustration of the shielding effectiveness of a conducting barrier to a normal-incidence uniform plane wave.

\[
SE = 20 \log_{10} \left| \frac{E_i}{E_t} \right| = 20 \log_{10} \left| \frac{H_i}{H_t} \right|
\]

assuming that the incident field is a uniform plane wave and the media on each side of the barrier are identical.

**FIGURE 11.5** Illustration of multiple reflections within a shield.
\[ E_i = E_i e^{-j\beta_0 z} \hat{a}_x \]
\[ H_i = \frac{E_i}{\eta_0} e^{-j\beta_0 z} \hat{a}_y \]
\[ \bar{E}_r = E_r e^{j\beta_0 z} \hat{a}_x \]
\[ \bar{H}_r = -\frac{E_r}{\eta_0} e^{j\beta_0 z} \hat{a}_y \]
\[ \bar{E}_1 = E_1 e^{j\beta_0 z} \hat{a}_x \]
\[ \bar{H}_1 = \frac{E_1}{\eta} e^{j\beta_0 z} \hat{a}_y \]
\[ \bar{E}_2 = E_2 e^{j\beta_0 z} \hat{a}_x \]
\[ \bar{H}_2 = -\frac{E_2}{\eta} e^{j\beta_0 z} \hat{a}_y \]
\[ \bar{E}_t = E_t e^{-j\beta_0 z} \hat{a}_x \]
\[ \bar{H}_t = \frac{E_t}{\eta_0} e^{-j\beta_0 z} \hat{a}_y \]

\[ \beta_0 = \omega \sqrt{\mu_0 \varepsilon_0} \]
\[ \eta_0 = \sqrt{\mu_0 / \varepsilon_0} \]
\[ \gamma = \sqrt{j \omega M (\delta + j \omega \varepsilon)} = \alpha + j \beta \]
\[ \eta = \sqrt{\frac{j \omega M}{\delta + j \omega \varepsilon}} = |\eta| / \eta_0 \]

**Boundary conditions:**
\[ \bar{E}_i (z=0) + \bar{E}_r (z=0) = \bar{E}_1 (z=0) + \bar{E}_2 (z=0) \]
\[ \bar{E}_1 (z=t) + \bar{E}_2 (z=t) = \bar{E}_t (z=t) \]
\[ \bar{H}_i (z=0) + \bar{H}_r (z=0) = \bar{H}_1 (z=0) + \bar{H}_2 (z=0) \]
\[ \bar{H}_1 (z=t) + \bar{H}_2 (z=t) = \bar{H}_t (z=t) \]

\[ E_i + E_r = E_1 + E_2 \]
\[ E_i e^{-\delta t} + E_2 e^{\delta t} = E_t e^{-j\beta_0 t} \]
\[ \frac{E_i}{\eta_0} - \frac{E_r}{\eta_0} = \frac{E_1}{\eta} - \frac{E_2}{\eta} \]
\[ \frac{E_i e^{-\delta t} - E_2 e^{\delta t}}{\eta} = \frac{E_t e^{-j\beta_0 t}}{\eta_0} \]

**Assumed to be known**
\[ \frac{E_i}{E_t} = \frac{(\eta_0 + \eta)^2}{4 \eta_0 \eta} \left[ 1 - \frac{(\eta_0 - \eta)^2}{(\eta_0 + \eta)^2} e^{-2\alpha t} e^{-j2\beta t} \right] e^{\alpha t} e^{j\beta t} e^{-j\beta_0 t} \]

For shields constructed of a good conductor,
\[ \beta = \alpha = \frac{1}{\delta} \]
\[ \eta \ll \eta_0 \Rightarrow \frac{\eta_0 - \eta}{\eta_0 + \eta} \approx 1 \text{ and } \frac{(\eta_0 + \eta)^2}{4 \eta_0 \eta} \approx \frac{\eta_0}{4 \eta} \]
\[ \frac{E_i}{E_t} \approx \frac{\eta_0}{4 \eta} \left[ 1 - e^{-2t/\delta} e^{-j2t/\delta} \right] e^{t/\delta} e^{j(\beta - \beta_0) t} \]

- (reflection loss)
- \( M/\Delta M \) (multiple-reflection loss)
- \( A \) (absorption loss)
\[ \frac{\left| E_i \right|}{E_t} \approx \frac{\eta_0}{4\eta} e^{t/\delta} \left| 1 - e^{-2t/\delta} e^{-j2t/\delta} \right| = R \times A \times M \]

The shielding effectiveness in dB is

\[ SE_{dB} \approx 20 \log_{10} \left( \frac{\eta_0}{4\eta} \right) + 20 \log_{10} e^{t/\delta} + 20 \log_{10} \left| 1 - e^{-2t/\delta} e^{-j2t/\delta} \right| \]

\[ R_{dB} \quad A_{dB} \quad M_{dB} \]

\( M_{dB} \) can be neglected for shields whose thicknesses are much greater than a skin depth, \( t \gg \delta \).

\[ \eta = \sqrt{\frac{i \omega M}{\delta + j \omega \varepsilon}} \approx \sqrt{\frac{i \omega M}{\delta}} = \sqrt{\frac{\omega M}{\delta}} / 4\pi \quad \eta_0 = \sqrt{\frac{M_0}{\varepsilon_0}} \quad |\eta| = \sqrt{\frac{\omega M_0}{\delta}} \]

\[ R_{dB} = 20 \log_{10} \left( \frac{1}{4} \sqrt{\frac{\delta}{\omega M_0 \varepsilon_0}} \right) \quad M = M_r M_0 \quad \varepsilon = \varepsilon_0 \]

\( \delta = \delta_r \delta_{cu} \), where \( \delta_{cu} = 5.8 \times 10^7 \) S/m and \( \delta_r \) is the conductivity relative to copper.

\[ R_{dB} = 168 + 10 \log_{10} \left( \frac{\delta_r}{M_r \delta_{cu}} \right) \] - is greatest at low frequencies and for high-conductivity metals

\[ \delta = \frac{1}{\alpha} = \frac{1}{\sqrt{\pi f M_0 \varepsilon}} = \frac{0.06609}{\sqrt{f M_0 \delta}} \quad m = \frac{2.6}{\sqrt{f M_0 \delta_r}} \] inches = \( \frac{2602}{\sqrt{f M_0 \delta_r}} \) mils

\[ A_{dB} = 20 \log_{10} e^{t/\delta} = 20 \left( \frac{t}{\delta} \right) \log_{10} e = 8.6859 \frac{t}{\delta} = 131.4 \sqrt{f} M_r \delta_r \] (t in m)

\[ = 3.338 \sqrt{f} M_r \delta_r \] (t in inches)

\( 1 \text{ mil} = 10^{-2} \text{ in} \)
**Figure 11.8** Shielding effectiveness of 20 mil copper.

**Figure 11.9** Shielding effectiveness of 20 mil steel (SAE 1045).
Figure 11.6  Approximate calculation of shielding effectiveness for uniform plane waves.

The transmission coefficient at the left boundary is

\[
\frac{E_t}{E_i} \approx \frac{2\eta}{\eta_0 + \eta} \quad \text{very small since } \eta \ll \eta_0 \text{ (very little of the electric field is transmitted through the left (first) boundary)}
\]

The transmission coefficient at the right boundary is

\[
\frac{E_t}{E_i} \approx \frac{2\eta_0}{\eta_0 + \eta} \approx 2 \quad \text{since } \eta \ll \eta_0 \text{ (the primary transmission occurs at the right (second) boundary)}
\]

\[
\frac{H_t}{H_i} = \frac{E_t}{E_i/\eta_0} = \frac{E_t}{E_i} \frac{\eta_0}{\eta} = \frac{2\eta_0}{\eta_0 + \eta} \approx 2 \quad \text{(primary transmission of the magnetic field occurs at the left interface)}
\]

\[
\frac{H_t}{H_i} = \frac{E_t}{E_i/\eta} = \frac{E_t}{E_i} \frac{\eta}{\eta_0} = \frac{2\eta}{\eta_0 + \eta} \quad \text{very small} \quad \text{Absorption is more important for the reduction of magnetic fields}
\]
Equation (11.33) shows that the absorption loss increases with increasing frequency as $\sqrt{f}$ on a decibel scale. This is quite different from the absorption loss being proportional to the square root of frequency so that it increases at a rate of 10 dB/decade on a decibel scale. Therefore the absorption loss increases quite rapidly with increasing frequency. Ferromagnetic materials where $\mu_r \gg 1$ increase this loss over copper (assuming that $\mu_r, \sigma_r \gg 1$). The absorption loss can also be understood in terms of the thickness of the shield relative to a skin depth, as is evident in (11.33):

$$A_{dB} = 8.6859t/\delta$$  
(11.34)

$$= 8.7 \text{ dB} \quad \text{for } t/\delta = 1$$

$$= 17.4 \text{ dB} \quad \text{for } t/\delta = 2$$

This illustrates the importance of skin depth in absorption loss.

Observe that the reflection loss is a function of the ratio $\sigma_r/\mu_r$, whereas the absorption loss is a function of the product $\sigma_r\mu_r$. Table 11.1 shows these factors for various materials.

Figure 11.8 shows the components of the shielding effectiveness for a 20 mil thickness of copper as a function of frequency from 10 Hz to 10 MHz. Observe that the absorption loss is dominant above 2 MHz. Figure 11.9 shows the same data for Steel (SAE 1045) for a 20 mil thickness. These data are plotted from 10 Hz to only 1 MHz. Note that for this material reflection loss dominates only below 20 kHz. These data indicate that reflection loss is the primary contributor to the shielding effectiveness at low frequencies for either ferrous or nonferrous shielding materials. At the higher frequencies ferrous materials increase the absorption loss and the total shielding effectiveness. It is worthwhile reiterating that for electric fields the primary transmission occurs at the second boundary,

| TABLE 11.1 |
|--------------|------|------|----------|----------|
| Material     | $\sigma_r$ | $\mu_r$ | $\mu_r\sigma_r$ | $\sigma_r/\mu_r$ |
| Silver       | 1.05  | 1     | 1.05       | 1.05       |
| Copper       | 1     | 1     | 1          | 1          |
| Gold         | 0.7   | 1     | 0.7        | 0.7        |
| Aluminum     | 0.61  | 1     | 0.61       | 0.61       |
| Brass        | 0.26  | 1     | 0.26       | 0.26       |
| Bronze       | 0.18  | 1     | 0.18       | 0.18       |
| Tin          | 0.15  | 1     | 0.15       | 0.15       |
| Lead         | 0.08  | 1     | 0.08       | 0.08       |
| Nickel       | 0.2   | 100   | 20         | $2 \times 10^{-3}$ |
| Stainless steel (430) | 0.02 | 500   | 10         | $4 \times 10^{-5}$ |
| Steel (SAE 1045) | 0.1 | 1000  | 100        | $1 \times 10^{-4}$ |
| Mumetal (at 1 kHz) | 0.03 | 20,000 | 600        | $1.5 \times 10^{-6}$ |
| Superpermalloy (at 1 kHz) | 0.03 | 100,000 | 3000       | $3 \times 10^{-7}$ |