DEVELOPMENT AND INVESTIGATION OF APPROXIMATE PHENOMENOLOGICAL MODELS FOR THE COUPLING OF ELECTROMAGNETIC ENERGY THROUGH APERTURES INTO ENCLOSURES

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1.0 Introduction

1.1 EM Interference and Susceptibility of Electronic Systems

1.1.1 *Intentional and Unintentional EM Interference*

- careless people - operate their equipment during the landing of an aircraft
- terrorists - try to defeat electronics used by law-enforcement agencies

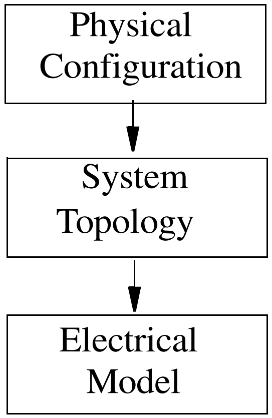
1.1.2 *Countermeasures to EM Terrorism:*

- Teaching design engineers
- Estimating and testing susceptibility levels
- Hardening electronic equipment
- Special detectors that warn about EM attacks

1.2 Problem Definition

- The analysis of available analytical and numerical techniques
- Development and investigation of approximate phenomenological models describing and estimating the coupling of EM energy through apertures into enclosures

2.0 Development of Models in EMC



Physical Configuration

System Topology

Electrical Model

Figure 1. Model development in EMC

Modeling is a primary aspect in developing a correct and proper EMC design for a new product

- describe the physical configuration of a problem
- define the electrical configuration
- develop the electrical model

2.1 Topological Decomposition of Systems (Physical Configuration)

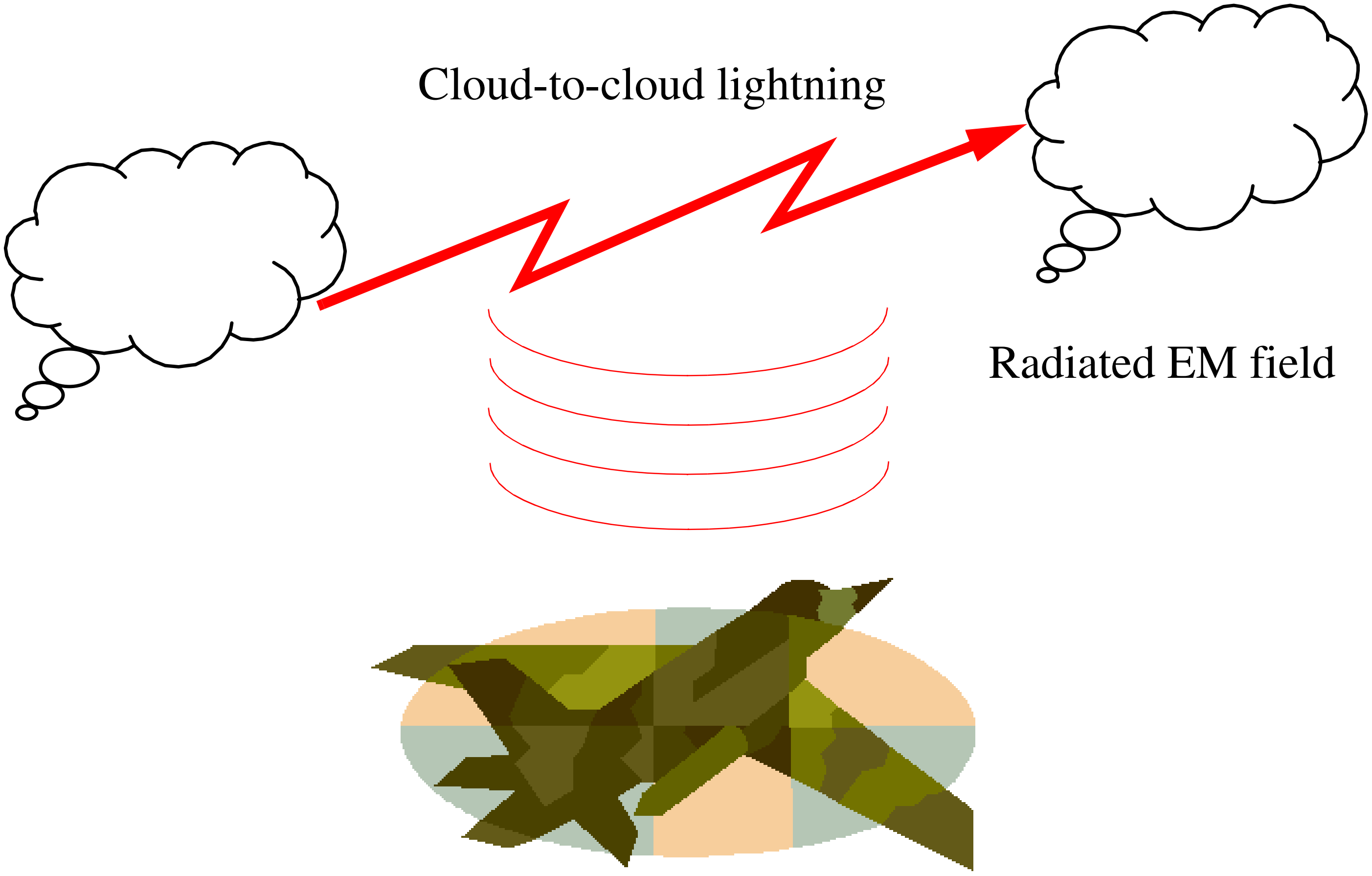


Figure 2. An example of an aircraft and its EM topological diagram: physical configuration

2.2 Topological Decomposition of Systems (Shielding Topology)

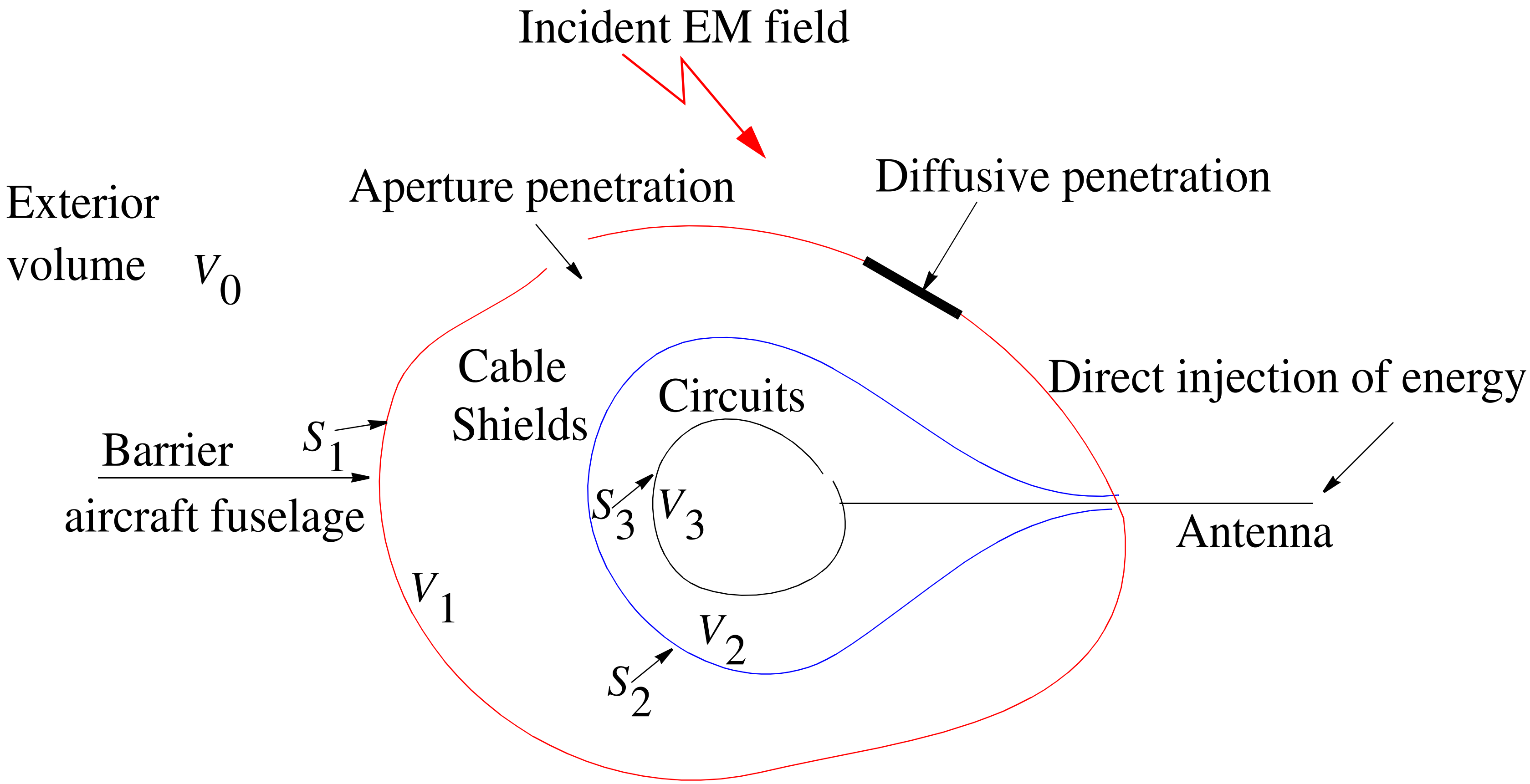


Figure 3. An example of an aircraft and its EM topological diagram: EM shielding topology.

2.3 Modeling Techniques Used in EMC for the Estimation of the EM Field Coupling

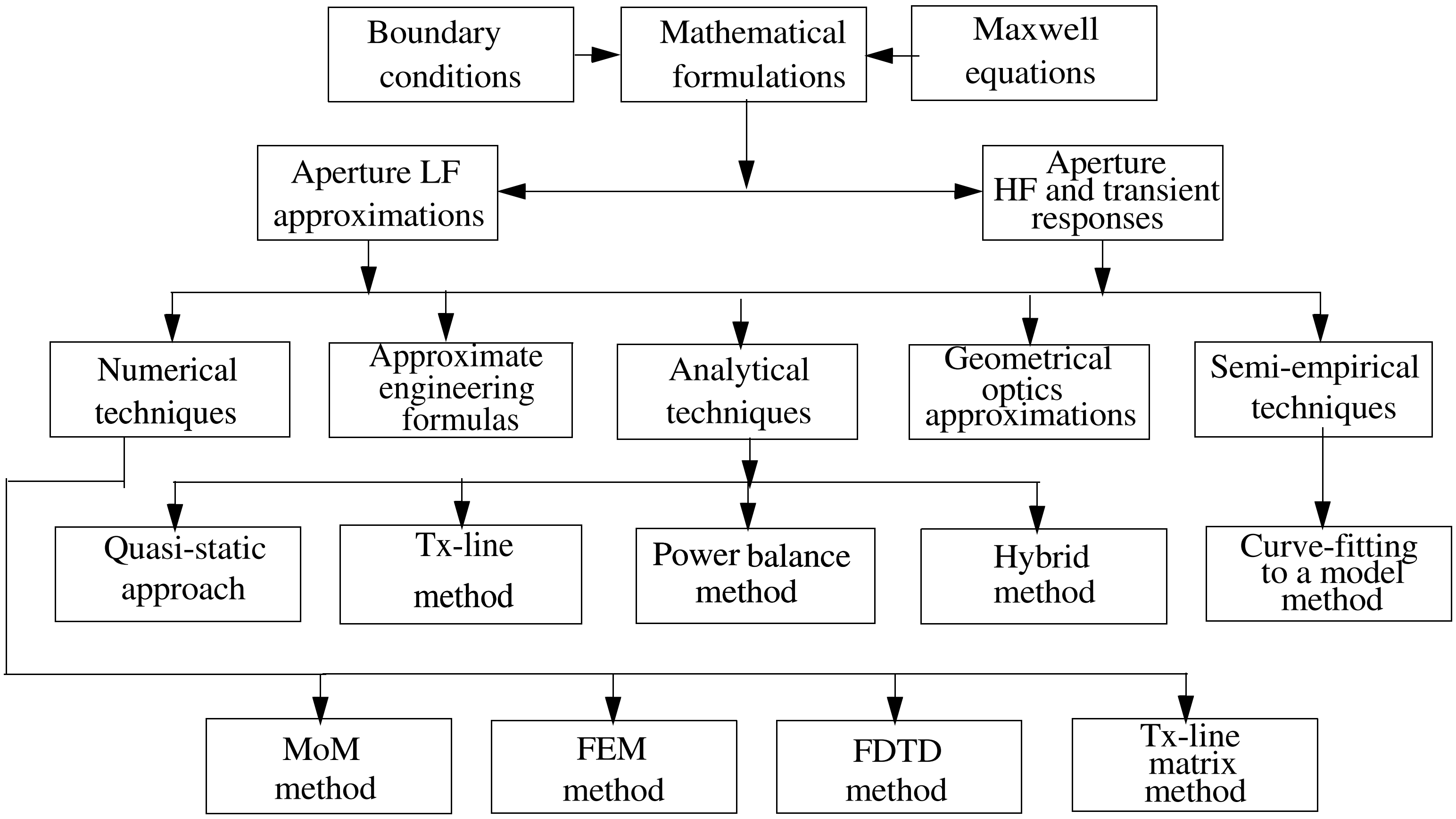


Figure 4. Basic modeling techniques used in EMC for the simulation of EM field penetration through finite apertures

2.4 Modeling and Simulation Validation

Model Validation Using Experimental Methods

- making a measurement of the same effect, then extend the model to cover other configurations which will not be measured

Model Validation Using Non Experimental Methods

- using other validated models to validate a new model

Concepts Frequently Used to Examine the Validity of a Model:

- conservation of energy
- causality
- time of arrival of waveform response components
- low-frequency or high-frequency asymptotic behavior of spectral responses
- other known physical constraints of the solution, such as finite Q at system resonances, etc.

3.0 Some EMC Concepts Relevant to Shielding

3.1 Shielding Effectiveness

for electric fields

$$S_e = 20\log E_i / E_t$$

and for magnetic fields

$$S_m = 20\log H_i / H_t$$

where E_i or H_i is the incident field strength, and E_t or H_t is the field strength of the transmitted wave as it emerges from the shield.

An engineering formula used for enclosures with apertures

$$S_e = 20\log\frac{\lambda}{2l}$$

where l is the longest dimension of the aperture and λ is the wavelength in free space

3.2 Electrically Small Apertures in an Infinitely Thin Conducting Wall

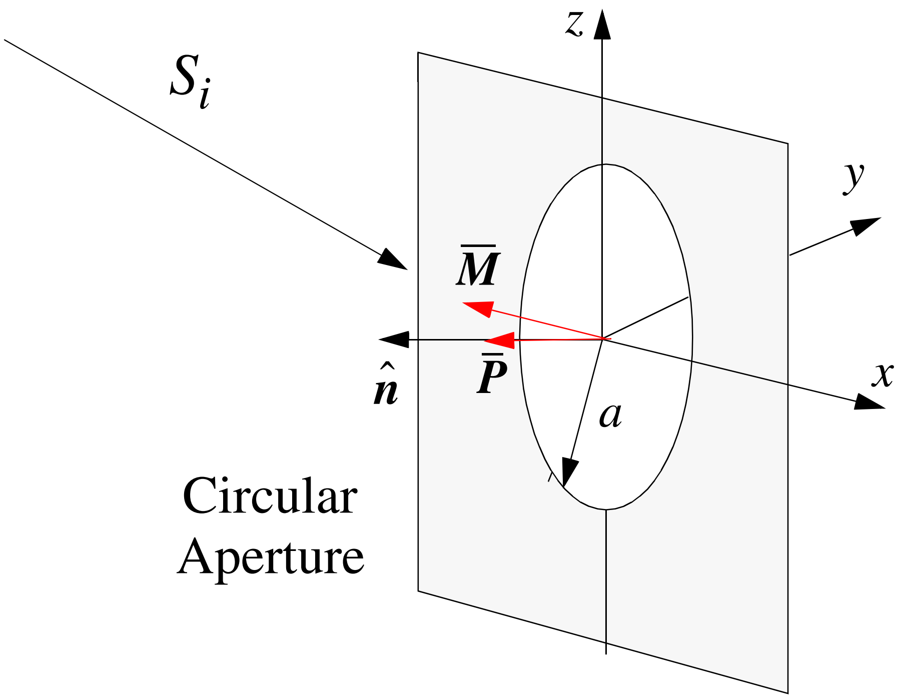


Figure 5. Electric and magnetic dipoles of an aperture

The aperture is equivalent to a magnetic dipole $\bar{M} = -\alpha_m \bar{H}_t$ and an electric dipole $\bar{P} = -\varepsilon_0 \alpha_e \bar{E}_n$, where the electric and magnetic polarizabilities of a small aperture are given correspondingly by $\alpha_e = -2a^3/3$ and $\alpha_m = 4a^3/3$, $\bar{E}_n$ and $\bar{H}_t$ are the normal electric field and the tangential magnetic field, respectively.

The total transmitted power for dipoles radiating in the presence of the ground plane is

$$P_t = \frac{4\pi\eta_0}{3\lambda^2}\left(k^2|\bar{\boldsymbol{M}}|^2 + |\omega\bar{\boldsymbol{P}}|^2\right)$$

where η_0 is the intrinsic impedance of free space, $\bar{\boldsymbol{M}}$ and $\bar{\boldsymbol{P}}$ are induced tangential magnetic and normal electric dipole moments. For parallel and perpendicular polarizations respectively

$$H_{\tan}^{sc} = 2H_i \text{ and } \mathrm{E}_n^{sc} = 2E_i \sin\theta^i \text{ and } H_{\tan}^{sc} = 2H_i \cos\theta^i \text{ and } \mathrm{E}_n^{sc} = 0$$

The normalized shielding effectiveness

$$SE_{nor} = -20\log\left(\frac{E_t/E_i}{E_{t_{ref}}/E_i}\right)$$

where E_i is the incident field strength, E_t is the field strength of the transmitted wave as it emerges from the shield, and $E_{t_{ref}}$ is the field strength of the transmitted wave at normal incidence and parallel polarization.

4.0 Application of the TL Method to the Estimation of the EM Field Penetration into an Enclosure with Aperture

4.1 Approximations Based on a TL Model

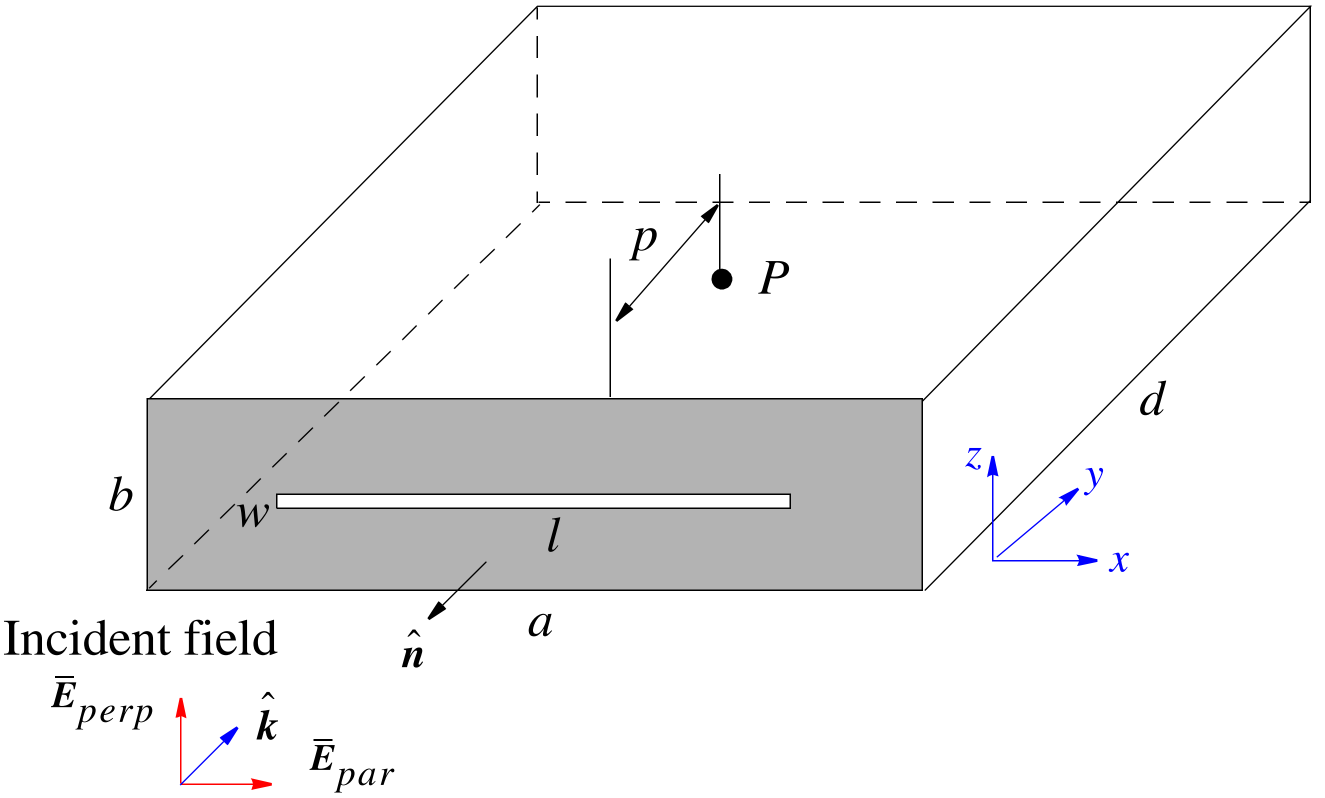


Figure 6. Geometry of a rectangular enclosure with aperture

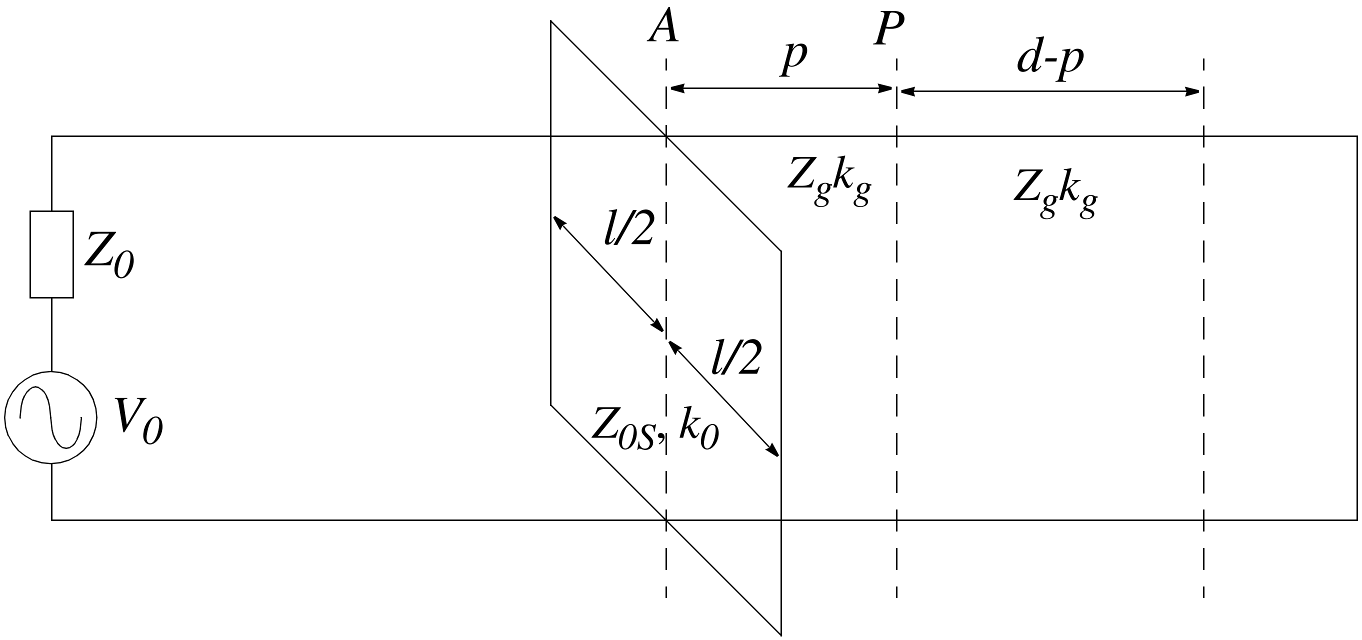


Figure 7. The equivalent circuit of the rectangular enclosure with aperture

The aperture is represented as a length of coplanar TL. The aperture impedance

$$Z_{ap} = jZ_{0_s}\frac{l}{2a}\tan 0.5k_0 l,$$

where Z_{0_s} is the aperture characteristic impedance.

The enclosure is represented by the shorted waveguide whose characteristic impedance Z_g and propagation constant k_g are respectively

$$Z_g = Z_0 / \sqrt{1 - (\lambda / 2a)^2}\ , k_g = k_0 \sqrt{1 - (\lambda / 2a)^2} .$$

The electric and magnetic shielding effectiveness are given by

$$S_e = -20 \log \left| V_p / V'_p \right| = -20 \log \left| (2 V_p) / V_0 \right| .$$

$$S_m = -20 \log \left| I_p / I_{p'} \right| = -20 \log \left| (2 I_p Z_0) / V_0 \right|$$

The TL model

- gives good predictions of the electric and magnetic SE for a simple system topology
- does not consider higher-order TE and TM modes, *i.e.*, limited to lower frequencies
- does not include the polarization of the incident EM field

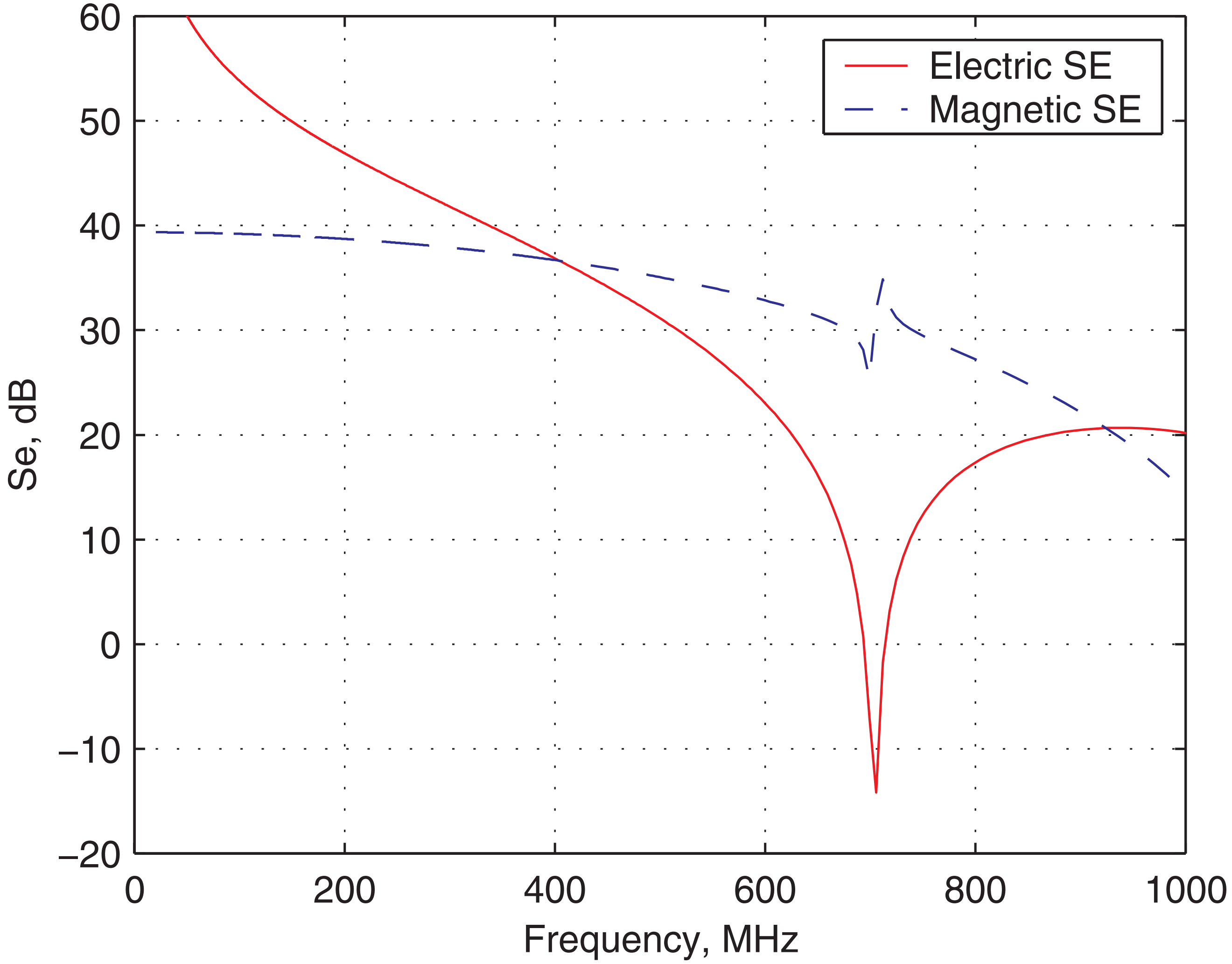
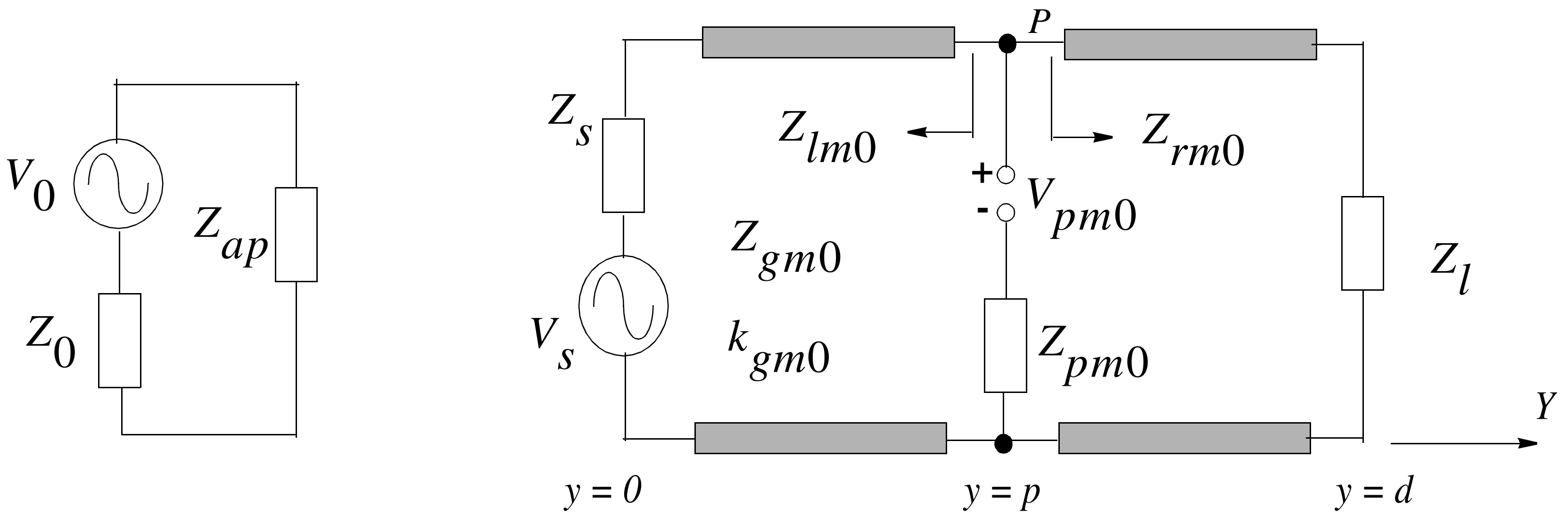


Figure 8. Electric and magnetic shielding effectiveness of an empty rectangular enclosure with aperture

4.2 Approximations Based on a Multimode TL Model



Equivalent Source Circuit

Enclosure Equivalent Circuit

Figure 9. The equivalent circuit of an empty rectangular enclosure with aperture

The equivalent source voltage with source impedance, respectively

$$V_s = V_0 Z_{ap} / (Z_0 + Z_{ap})$$

$$Z_s = Z_0 Z_{ap} / (Z_0 + Z_{ap})$$

The waveguide characteristic impedance of the *m*-th transverse electric $TE^{z}{}_{m0}$ mode of propagation and the propagation constant are given respectively as

$$Z_{gm0} = Z_0 / \sqrt{1-(m\lambda/\ 2a)^2}$$

$$k_{gm0} = k_0\sqrt{1-(m\lambda/\ 2a)^2}\text{, where } n = 1,\ 2,\ 3,\ ..$$

The waveguide characteristic impedance of the *m*-th transverse magnetic $TM^{x}{}_{m1}$ mode of propagation and the propagation constant are respectively

$$Z_{gm1} = Z_0 / \sqrt{1-(m\lambda/\ \lambda_c)^2}$$

$$k_{gm1} = k_0\sqrt{1-(m\lambda/\ \lambda_c)^2}$$

where the cutoff wavelength and mode number are given respectively as

$$\lambda_c = 2a/\ \sqrt{1+(a/\ b)^2} \text{ and } \ n = 1,\ 2,\ 3,\ ..$$

The impedance of the *m*-th mode Z_{rm0} at point *P* on the TL, viewed in the direction of the termination Z_l is

$$Z_{rm0} = \frac{Z_l + jZ_{gm0}\tan[k_{gm0}(d-p)]}{1 + jZ_{nm0}\tan[k_{gm0}(d-p)]}$$

where $Z_{nm0} = Z_l / Z_{gm0}$ is the normalized termination impedance for the *m*-th mode.

The effective impedance at test location *P* considering $Z_l = 0$ is

$$Z_{rm0} = jZ_{gm0}\tan\left[k_{gm0}(d-p)\right]$$

The source impedance of the *m*-th mode Z_{lm0} at test location *P* on the Tx-line, viewed in the direction of the source impedance Z_s, and the equivalent voltage V_{lm0}, are given respectively as

$$Z_{lm0} = \frac{Z_s + jZ_{gm0}\tan(k_{gm0}p)}{1 + jZ_{nm0}\tan(k_{gm0}p)}$$

$$V_{lm0} = V_s / [\cos(k_{gm0}p) + jZ_{nm0}\sin(k_{gm0}p)]$$

The *m*-th mode voltage and the total voltage at test location *P* are respectively

$$V_{pm0} = V_{lm0}Z_{rm0}/(Z_{lm0}+Z_{rm0}),\ V_{tp} = \sum_m V_{lm0}Z_{rm0}/(Z_{lm0}+Z_{rm0})$$

The *m*-th mode current and the total current at test location *P* are respectively

$$I_{pm0} = V_{lm0}/(Z_{lm0}+Z_{rm0}),\ I_{tp} = \sum_m V_{lm0}/(Z_{lm0}+Z_{rm0})$$

The electric and magnetic shielding effectiveness is determined respectively as

$$SE_e = -20\log\left|V_{tp}/V_p^0\right| = -20\log\left|2V_{tp}/V_0\right|$$

$$SE_m = -20\log\left|I_{tp}/I_p^0\right| = -20\log\left|2I_{tp}Z_0/V_0\right|$$

where in the absence of the enclosure

$$V_p^0 = V_0/2 \text{ and } I_p^0 = V_0/2Z_0$$

Higher-Order Modes

The resonant frequencies of the TE^{z}_{m0}, TM^{x}_{m1} modes and unbounded medium wavelengths of the rectangular enclosure with aperture

$$(f_{res})^{TE}_{mnp} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{d}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{a}\right)^2} \quad \begin{array}{l} m = 0,\ 1,\ 2,\ .. \\ n = 0,\ 1,\ 2,\ \ldots m = n \neq 0 \\ p = 1,\ 2,\ 3,\ \ldots \end{array}$$

$$(f_{res})^{TM}_{mnp} = \frac{1}{2\pi\sqrt{\mu\varepsilon}}\sqrt{\left(\frac{m\pi}{d}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{a}\right)^2} \quad \begin{array}{l} m = 1,\ 2,\ 3,\ .. \\ n = 1,\ 2,\ 3,\ \ldots m = n \neq 0 \\ p = 0,\ 1,\ 2,\ \ldots \end{array}$$

Table 1.

Mode order	1	2	3	4	5	6	7	8
TE^{z}_{m0}, MHz	707.11	1118.0	1581.1	2061.6	2549.5	3041.4	3535.5	4031,1
TM^{x}_{m1} ,MHz	1346.3	1600.8	1952.6	2358.5	2795.1	3250.1	3716.5	4190.8
λ_{gm0}, m	0.4242	0.2683	0.1897	0.1456	0.1177	0.0986	0.0848	0.0744

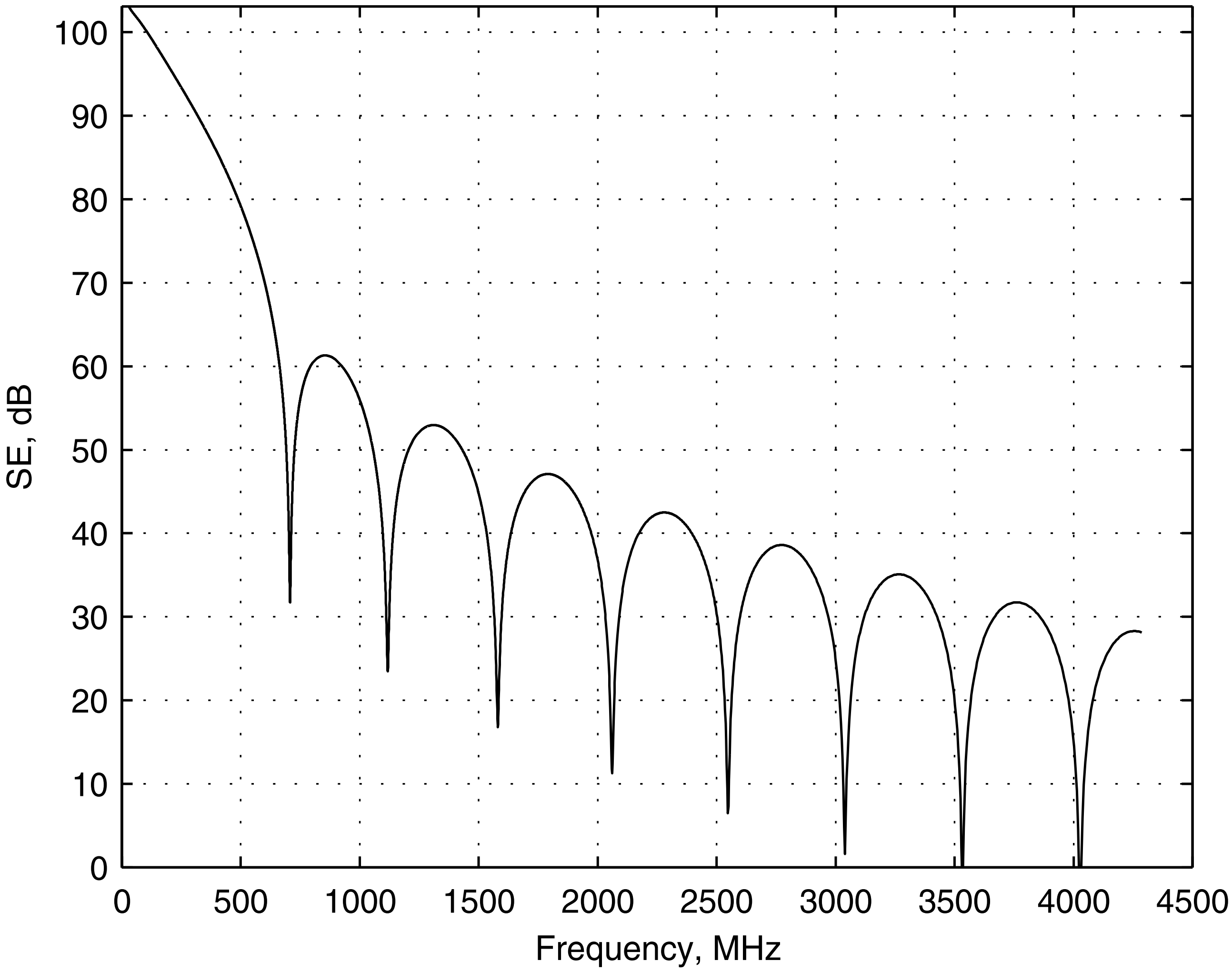


Figure 10. The SE_e of the enclosure ($a = 0.3$ m, $b = 0.12$ m, $d = 0.3$ m, $p = 0.25$ m) with aperture ($l = 0.025$ m, $w = 0.005$ m) obtained by TL simulation.

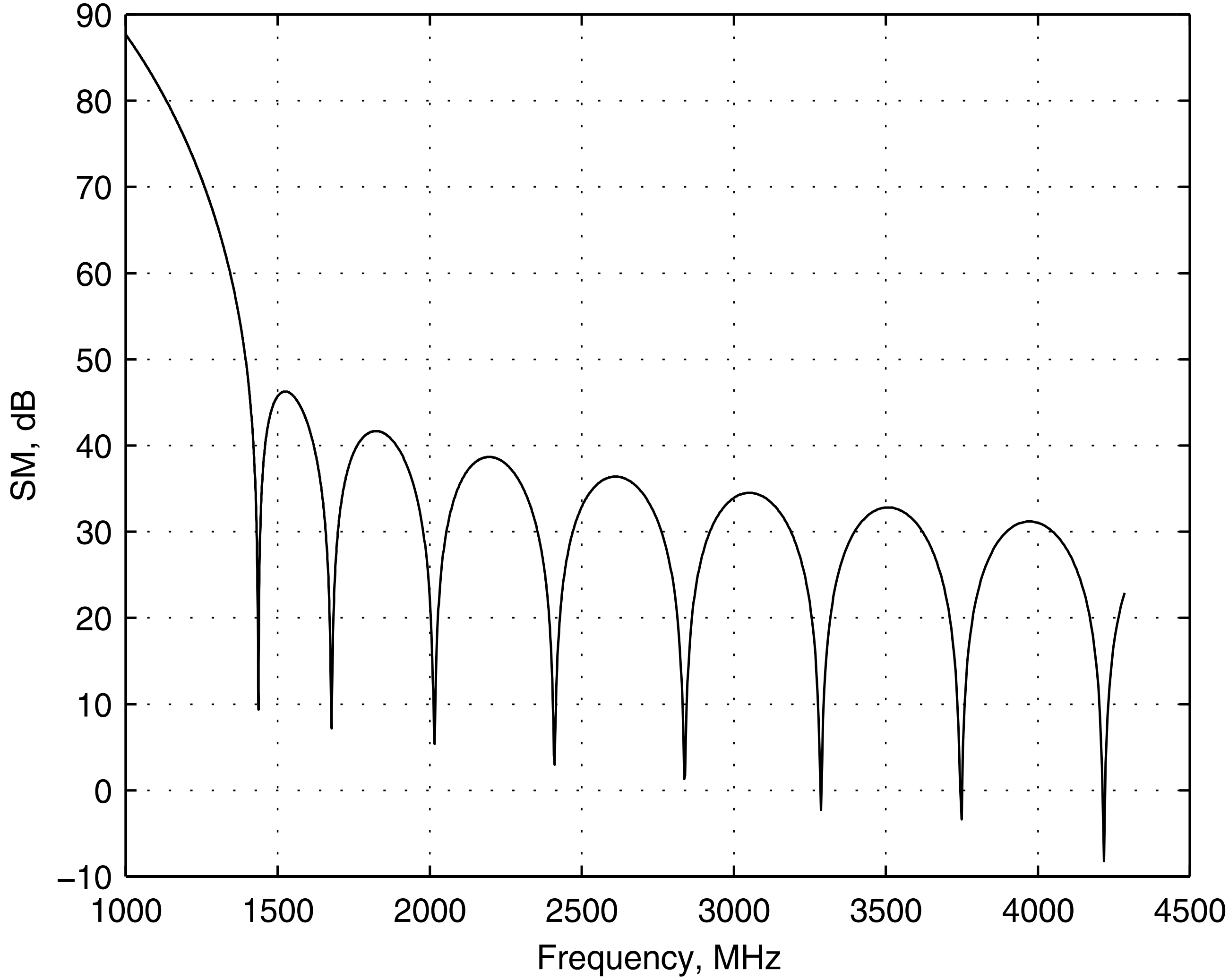


Figure 11. The SE_m of the enclosure (a = 0.3 m, b = 0.12 m, d = 0.3 m, p = 0.25 m) with aperture (l = 0.025 m, w = 0.005 m) obtained by TL simulation.

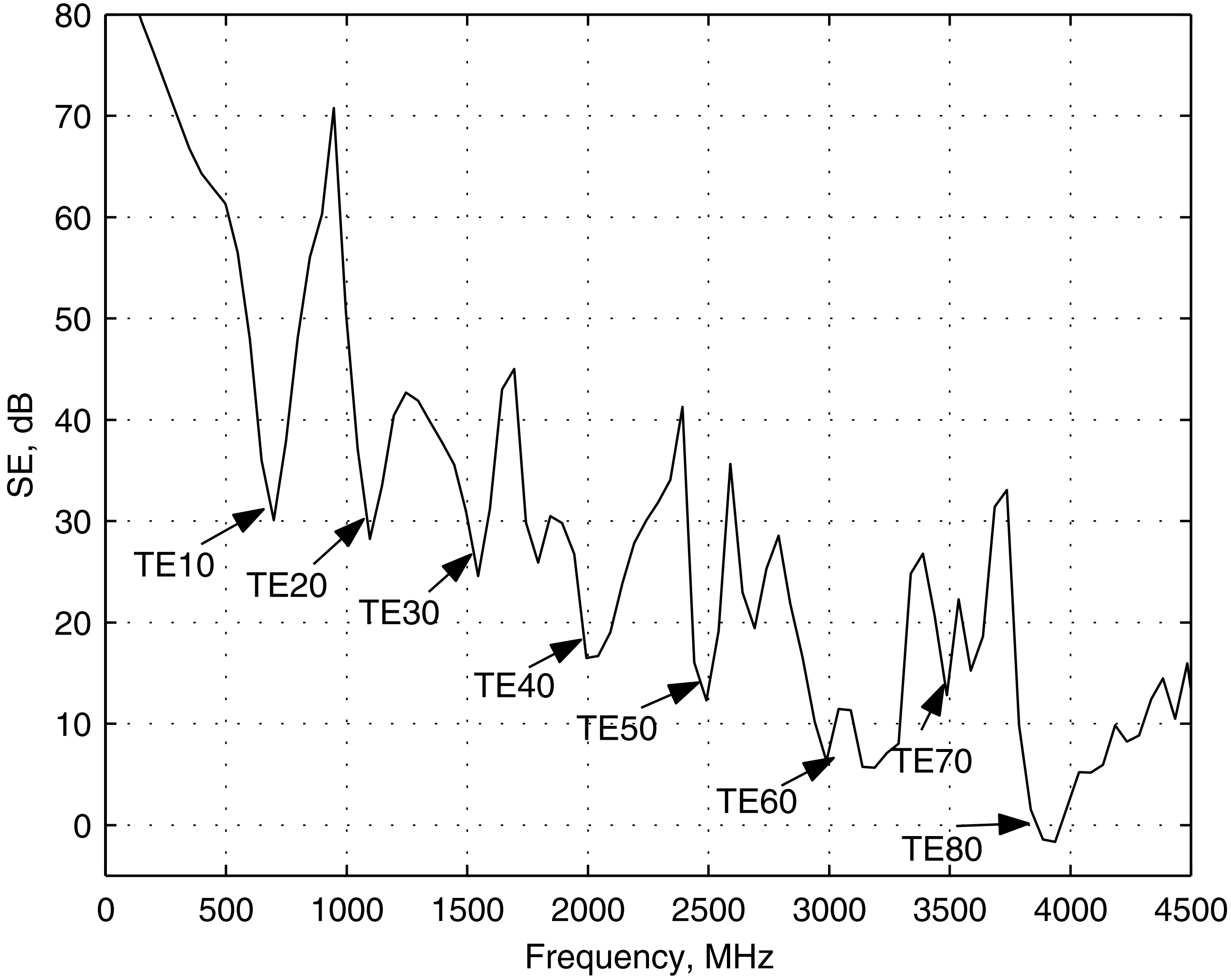


Figure 12. The SE_e of the enclosure (a = 0.3 m, b = 0.12 m, d = 0.3 m, p = 0.25 m) with aperture (l = 0.025 m, w = 0.005 m) obtained by FDTD simulation.

4.3 Introduction of Losses into Enclosures

Distributed losses can be modeled in TLs by including a complex correction factor γ in the expressions for characteristic impedance and propagation constant

Characteristic impedance

$$Z^{l}_{gm0} = \frac{Z_0}{\sqrt{1-(m\lambda/\ 2a)^2}}(1+\gamma_{gm0}-j\gamma_{gm0})$$

Propagation constant

$$k^{l}_{gm0} = k_0\sqrt{1-(m\lambda/\ 2a)^2}(1+\gamma_{gm0}-j\gamma_{gm0})$$

The effect of losses:

- mimic the loading effect of electronics
- appreciably dampen higher-order mode resonances of an empty rectangular enclosure thus improving the SE of the high-Q enclosure at higher frequencies
- the higher-order mode resonant frequencies are lowered by incorporating the losses

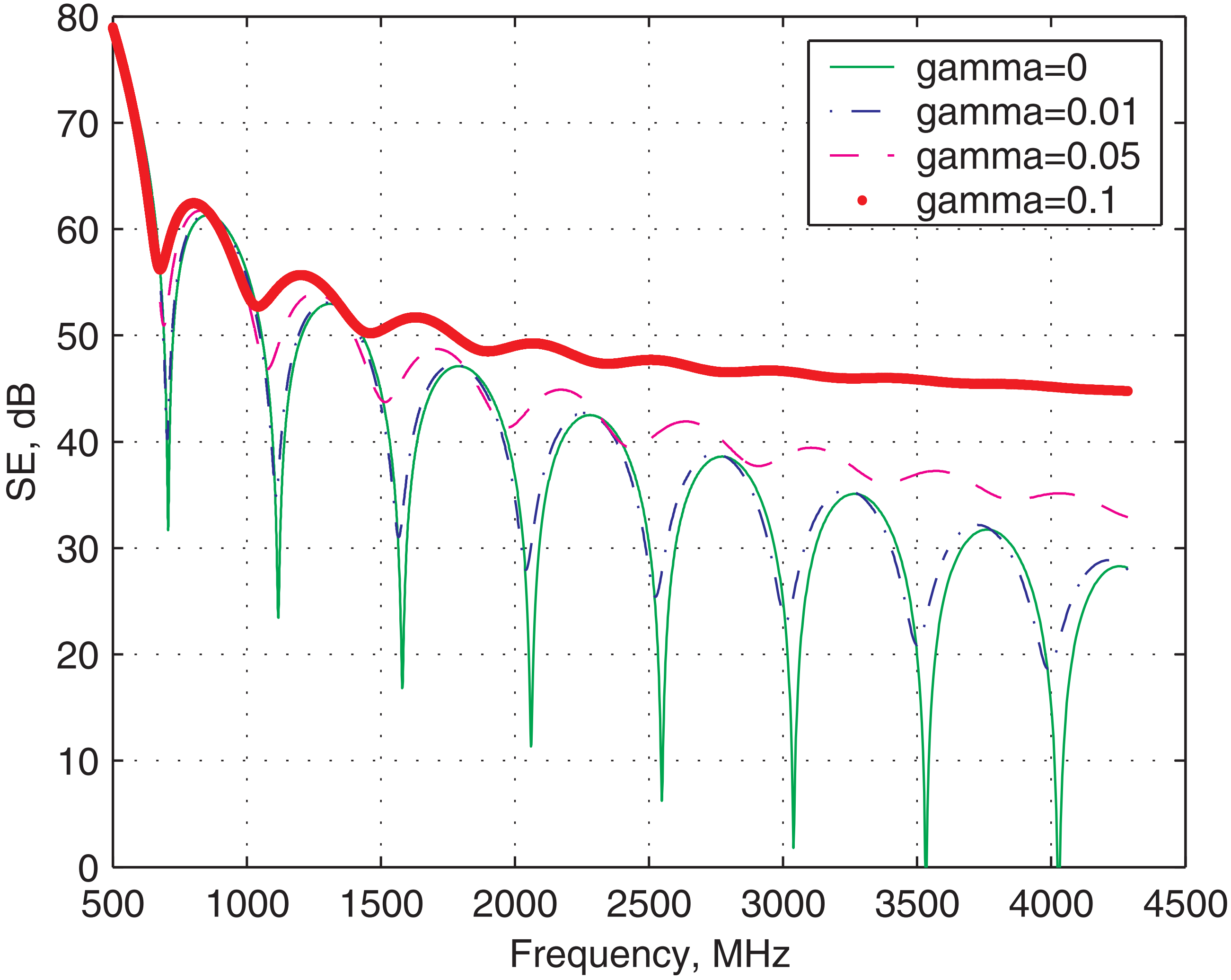


Figure 13. The SE_e of the enclosure (a = 0.3 m, b = 0.12 m, d = 0.3 m, p = 0.25 m) with aperture (l = 0.025 m, w = 0.005 m) with incorporated losses obtained by TL simulation

4.4 Aperture-Enclosure Resonance Condition

The condition of the aperture-enclosure resonance is determined as

$$X_s + X_{hm} = X_d$$

where the dominant-mode reactance

$$X_d = Im(Z_{gm0}), \qquad m = 1$$

is compensated by the sum of the equivalent source reactance

$$X_s = Im(Z_s)$$

and the reactance due to non-propagating higher-order modes in the enclosure with aperture

$$X_{hm} = Im\left(\sum_m Z_{gm0}\right), \qquad m \neq 1$$

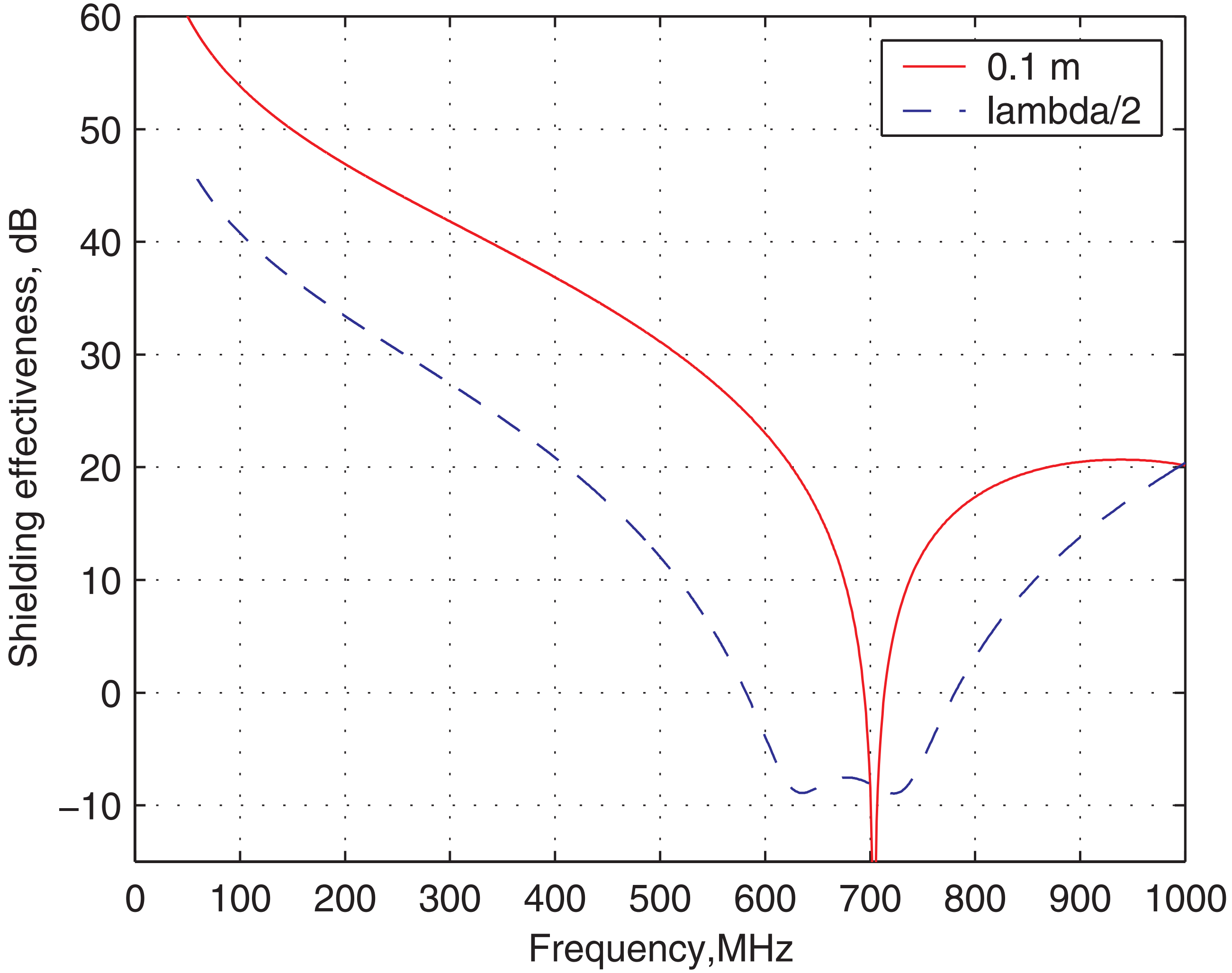


Figure 14. SE degradation at the aperture ($l = 0.2121$ m, $w = 0.005$ m)-enclosure ($a = 0.3$ m, $b = 0.12$ m, $d = 0.3$ m, $p = 0.25$ m) resonance obtained by TL simulation

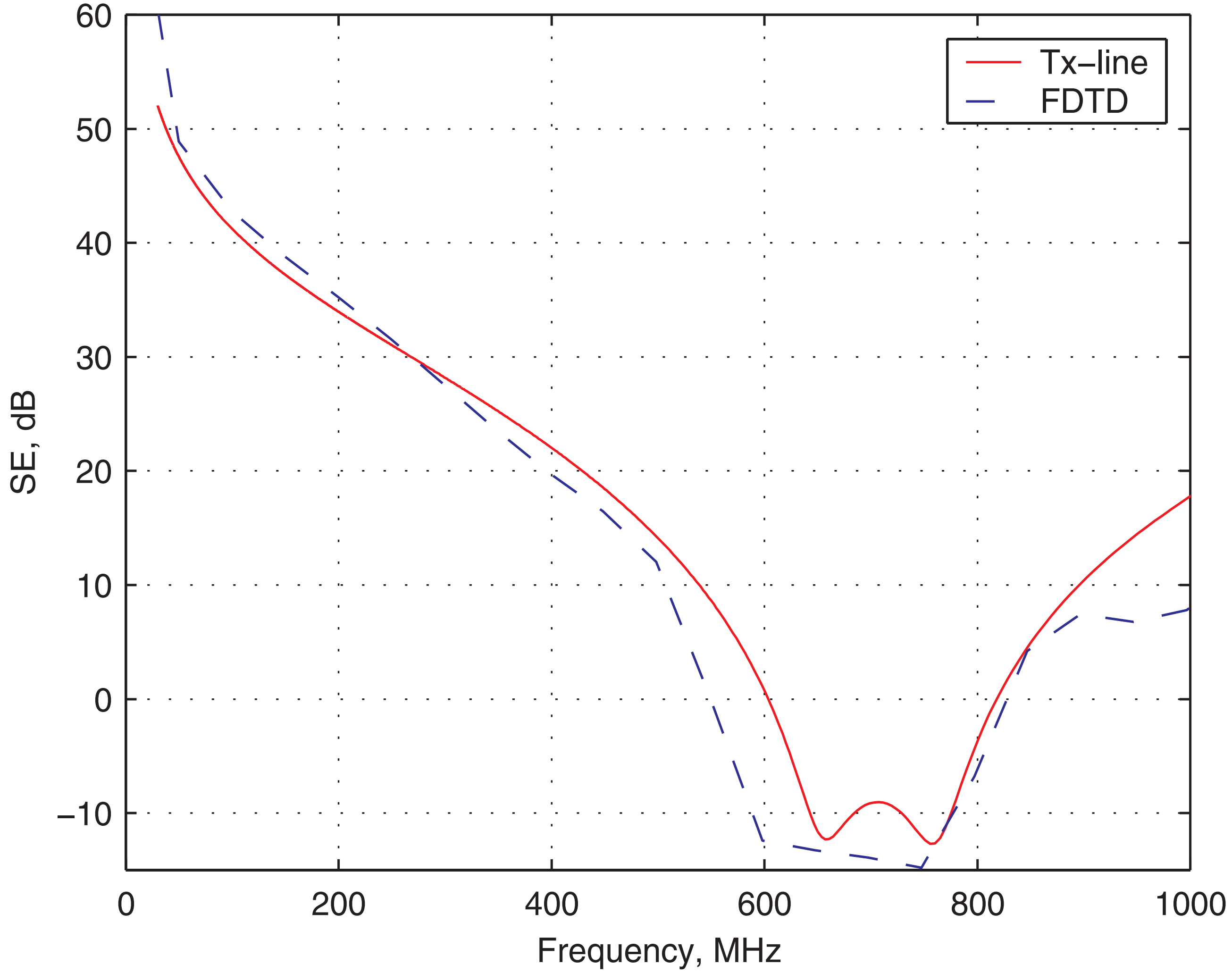


Figure 15. SE degradation at the aperture-enclosure resonance. comparison of TL and FDTD simulations

5.0 Application of the FDTD Technique to the Estimation of the EM Field Penetration into an Enclosure with Aperture

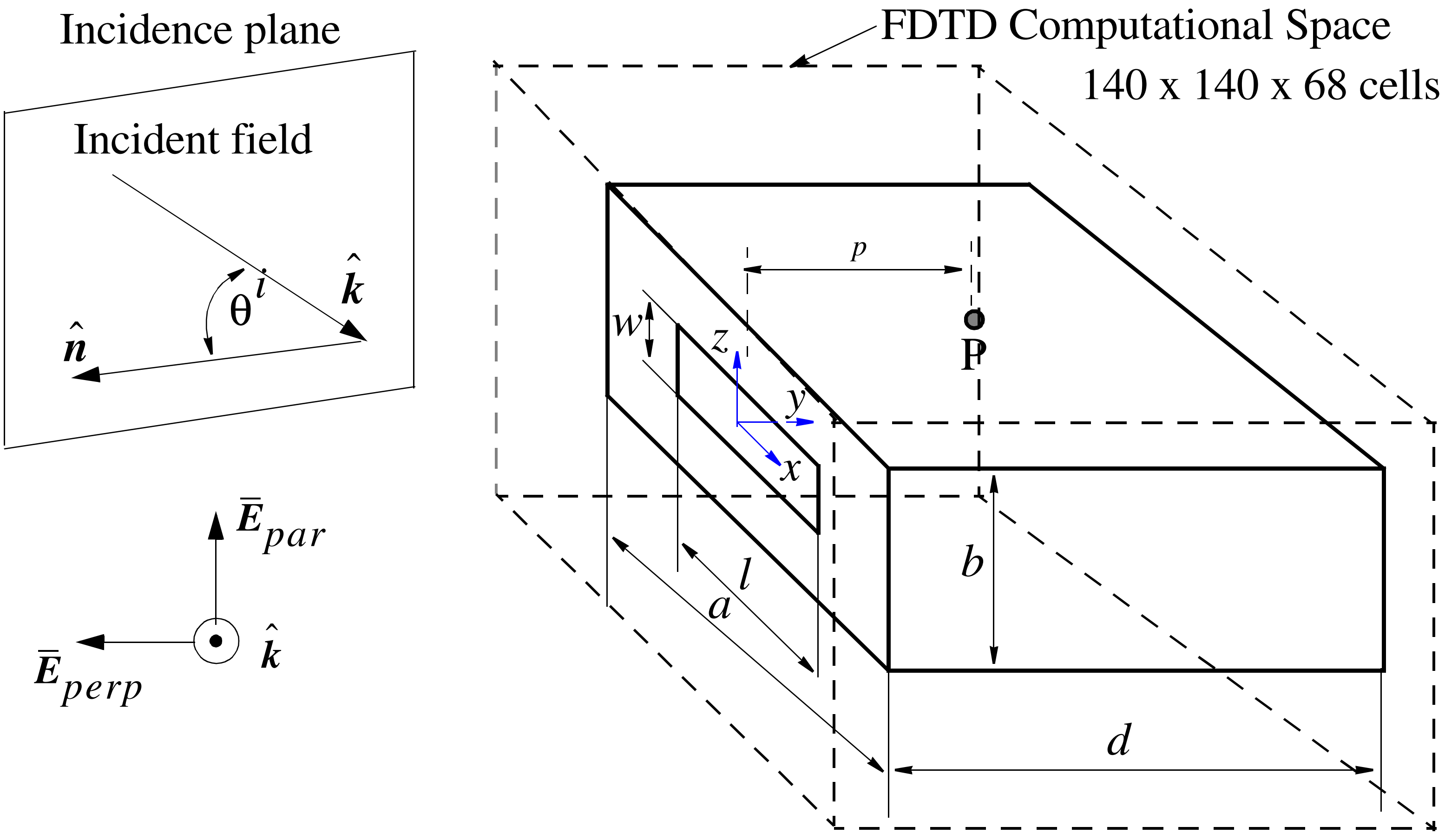


Figure 16. FDTD model geometry

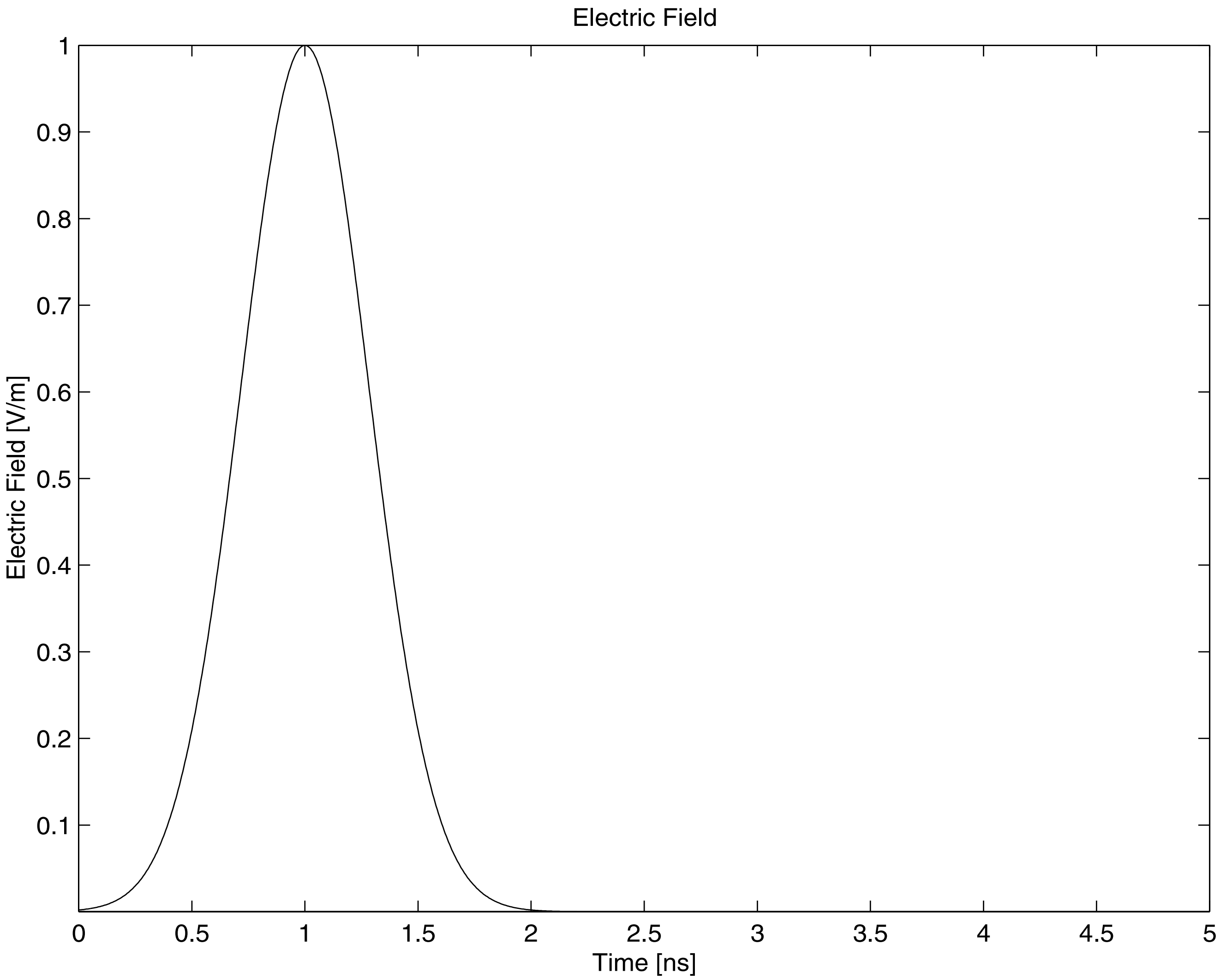


Figure 17. Incident field

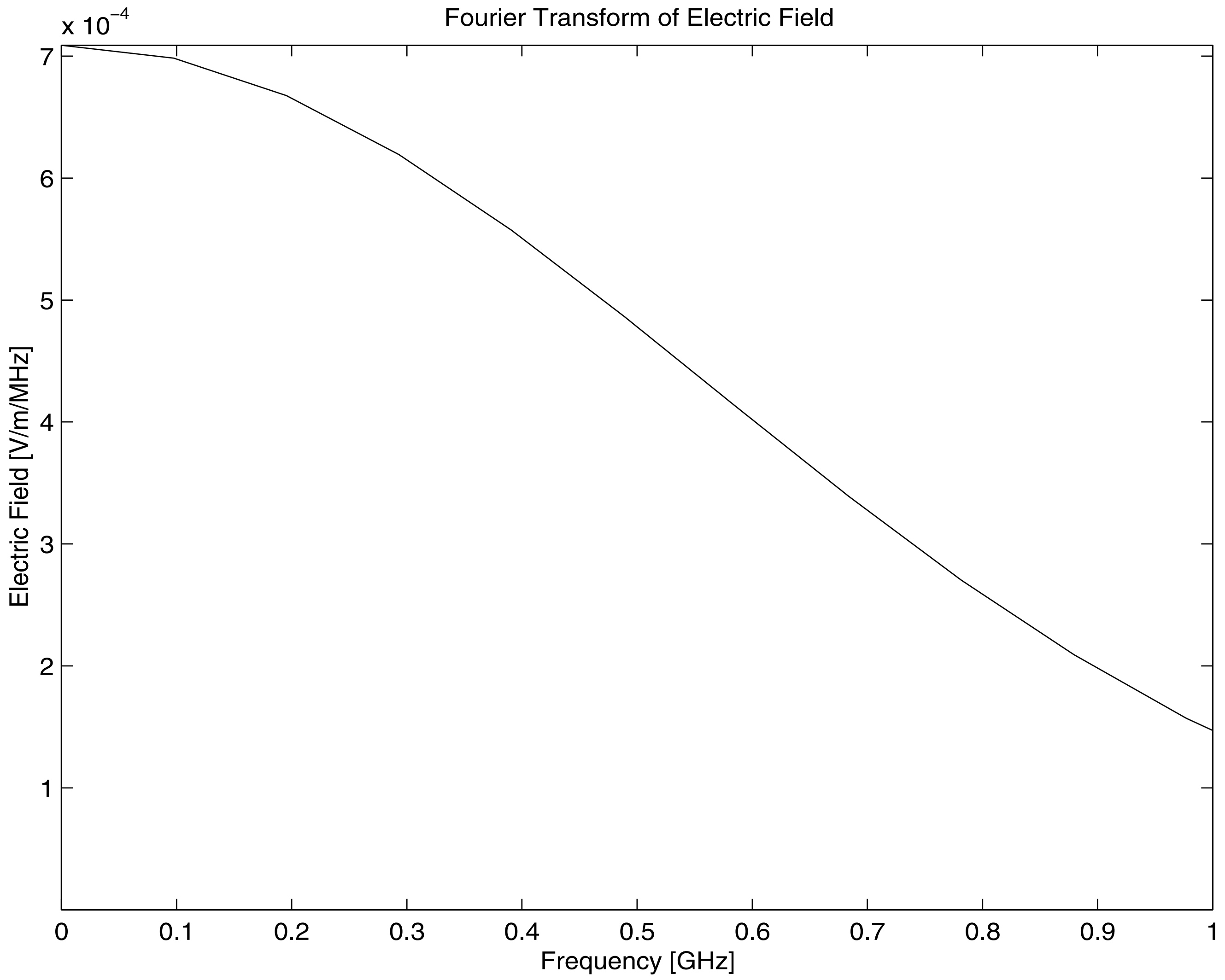


Figure 18. Fourier transform of the incident field

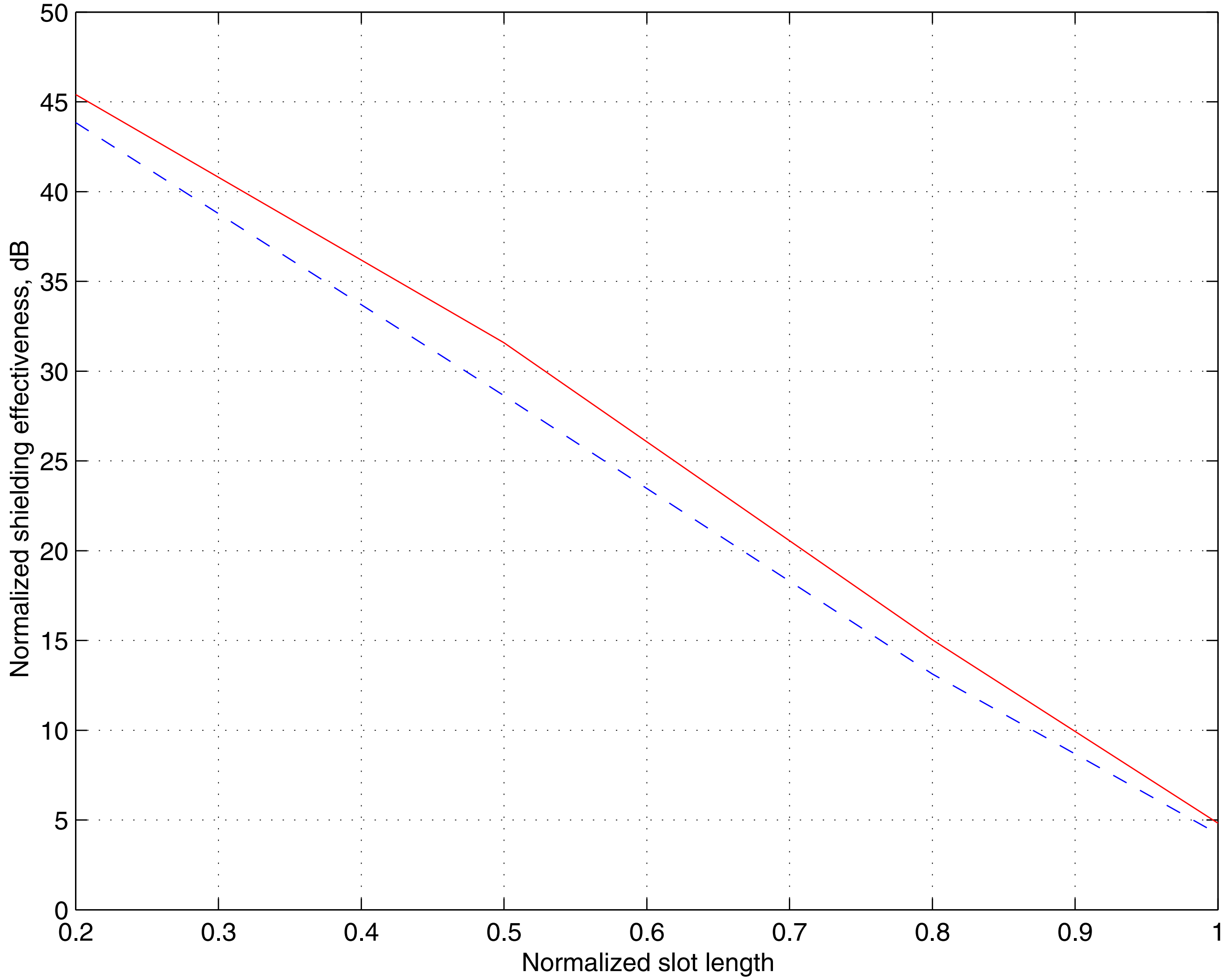


Figure 19. Normalized shielding effectiveness vs. normalized slot length for TL and FDTD models

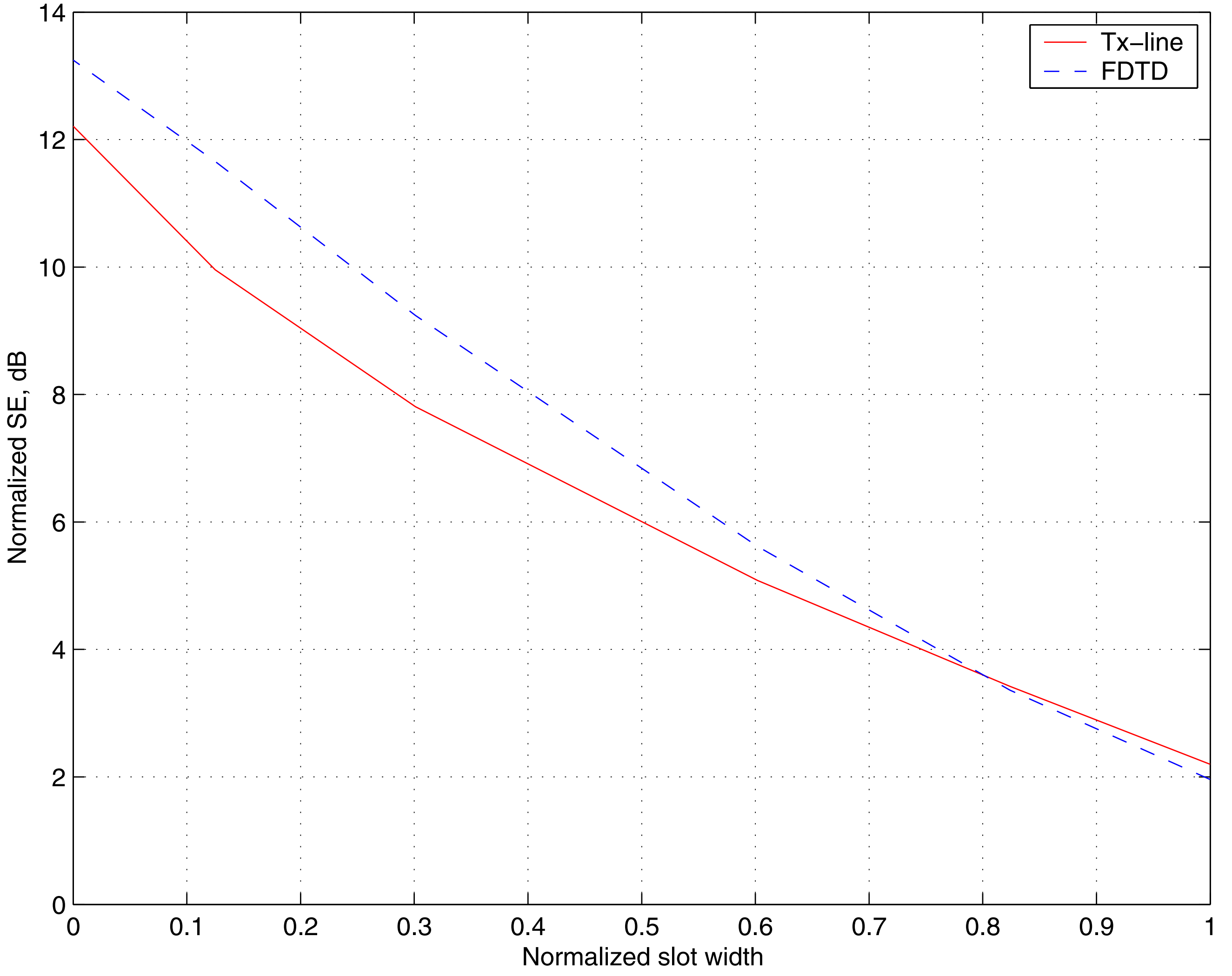


Figure 20. Normalized shielding effectiveness vs. normalized slot width for TL and FDTD models

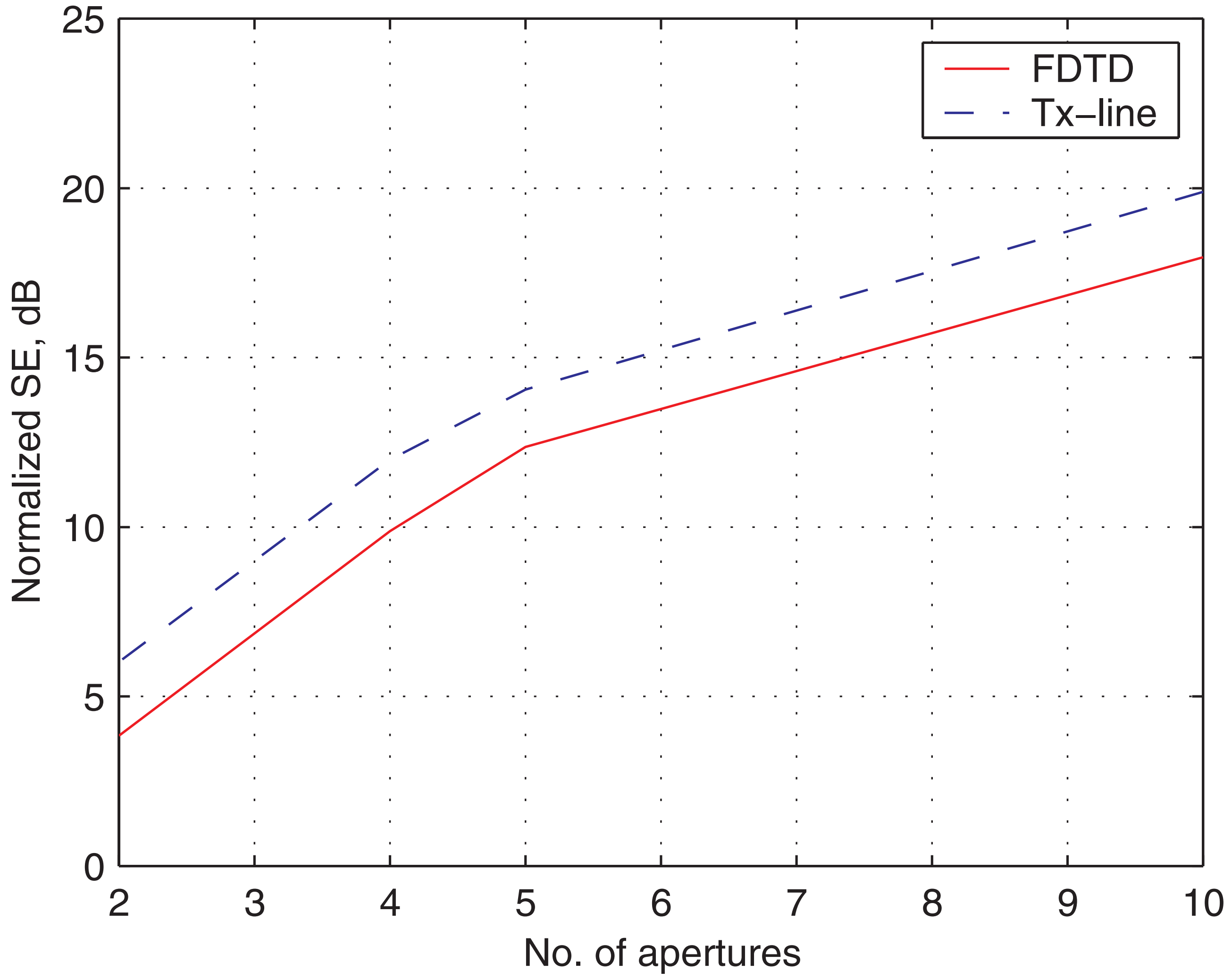


Figure 21. Normalized shielding effectiveness SE_{nor} vs. the number of slots

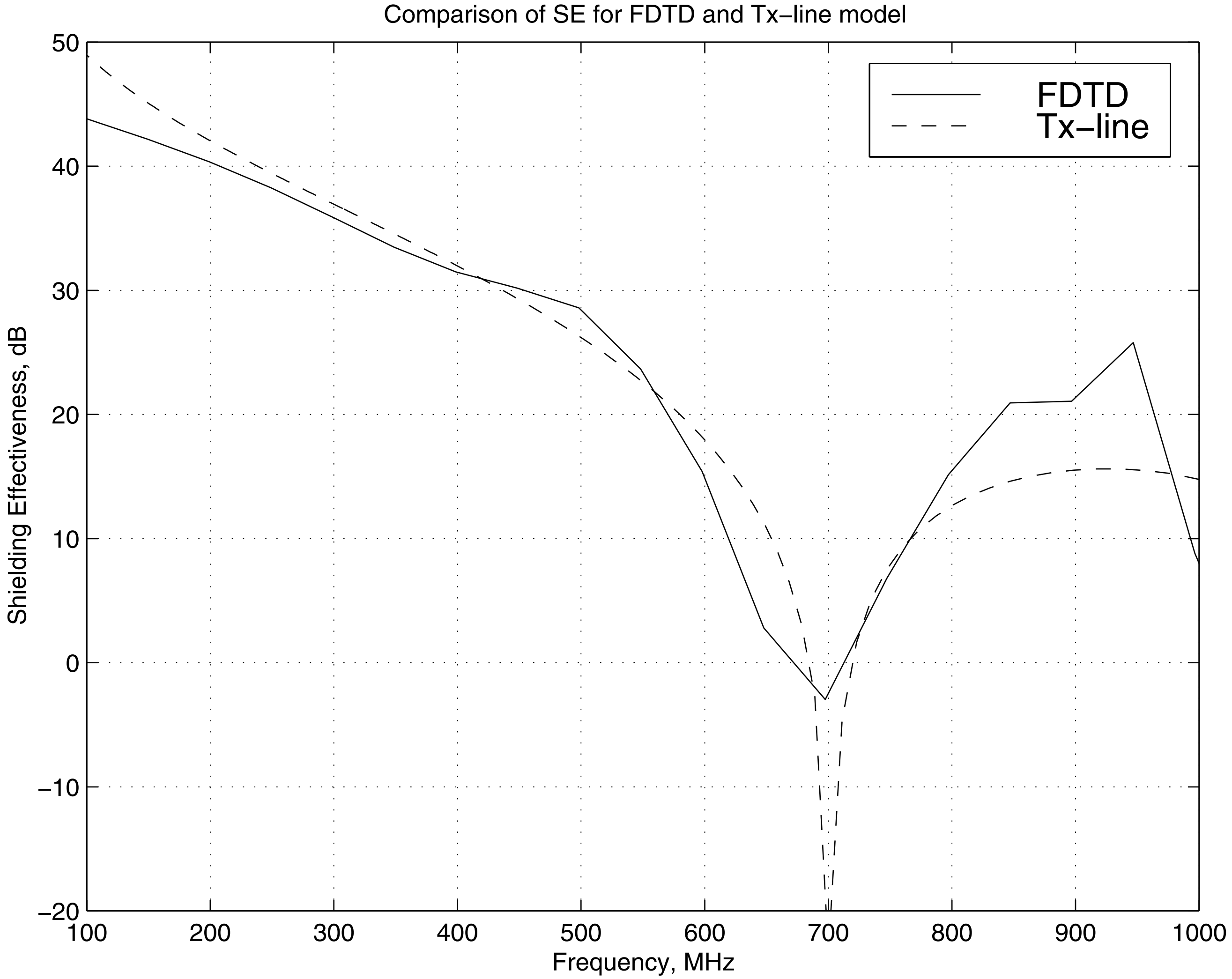


Figure 22. Shielding effectiveness for FDTD and TL model at normal incidence and parallel polarization.

6.0 Experimental Investigation of the SE of an Enclosure with Aperture

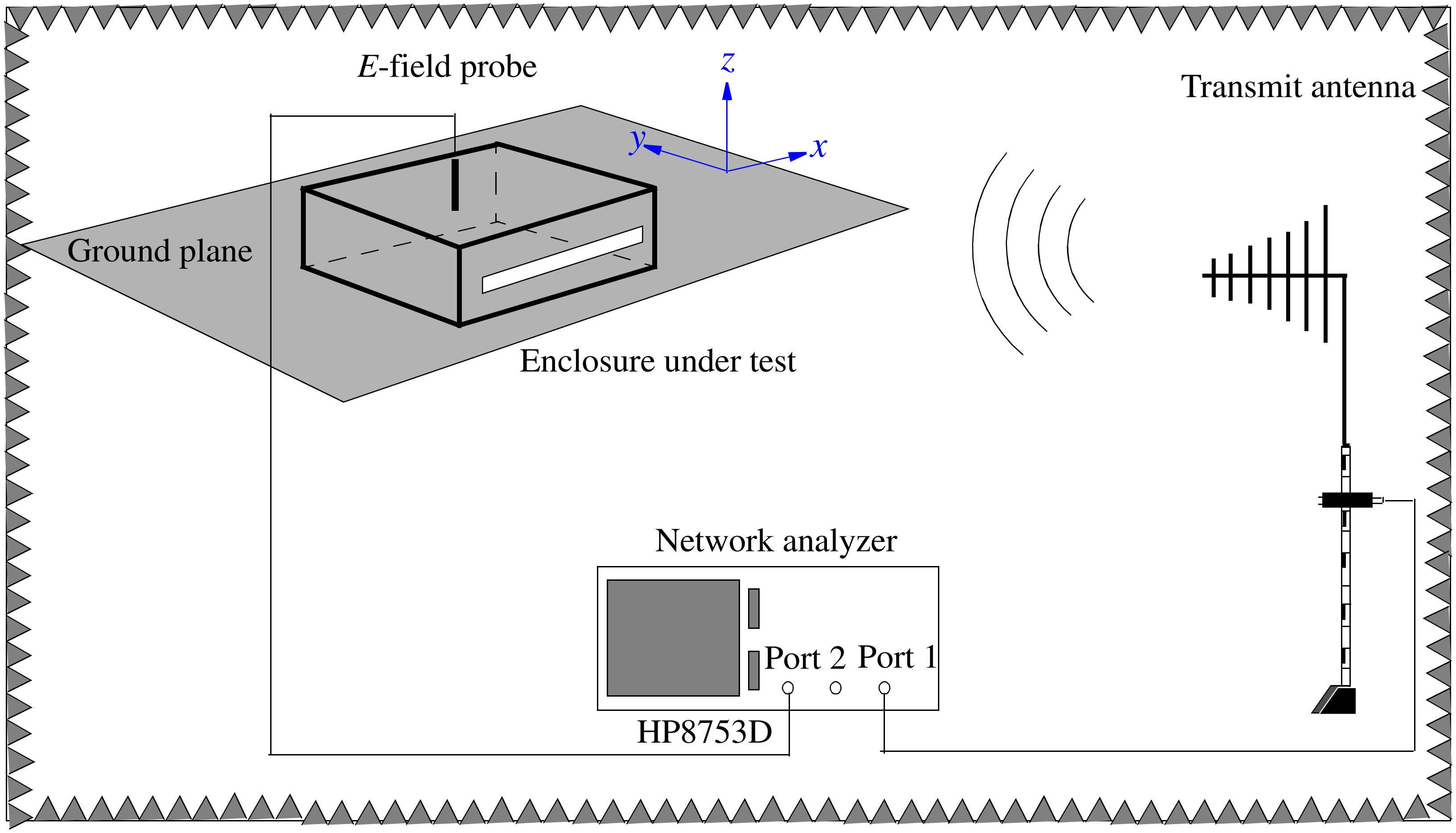


Figure 23. Shielding effectiveness measurement setup

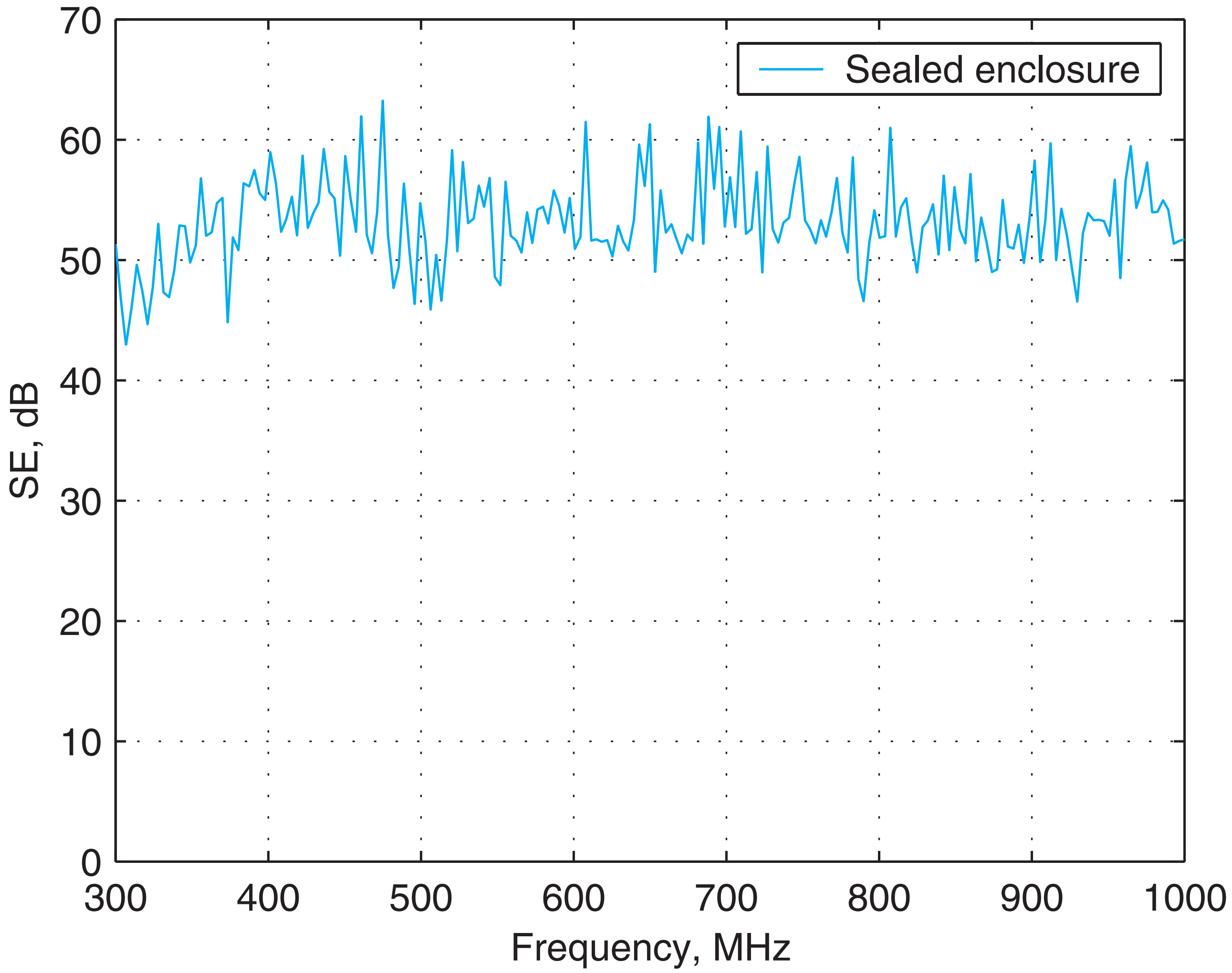


Figure 24. Shielding effectiveness of the electromagnetically sealed empty rectangular enclosure

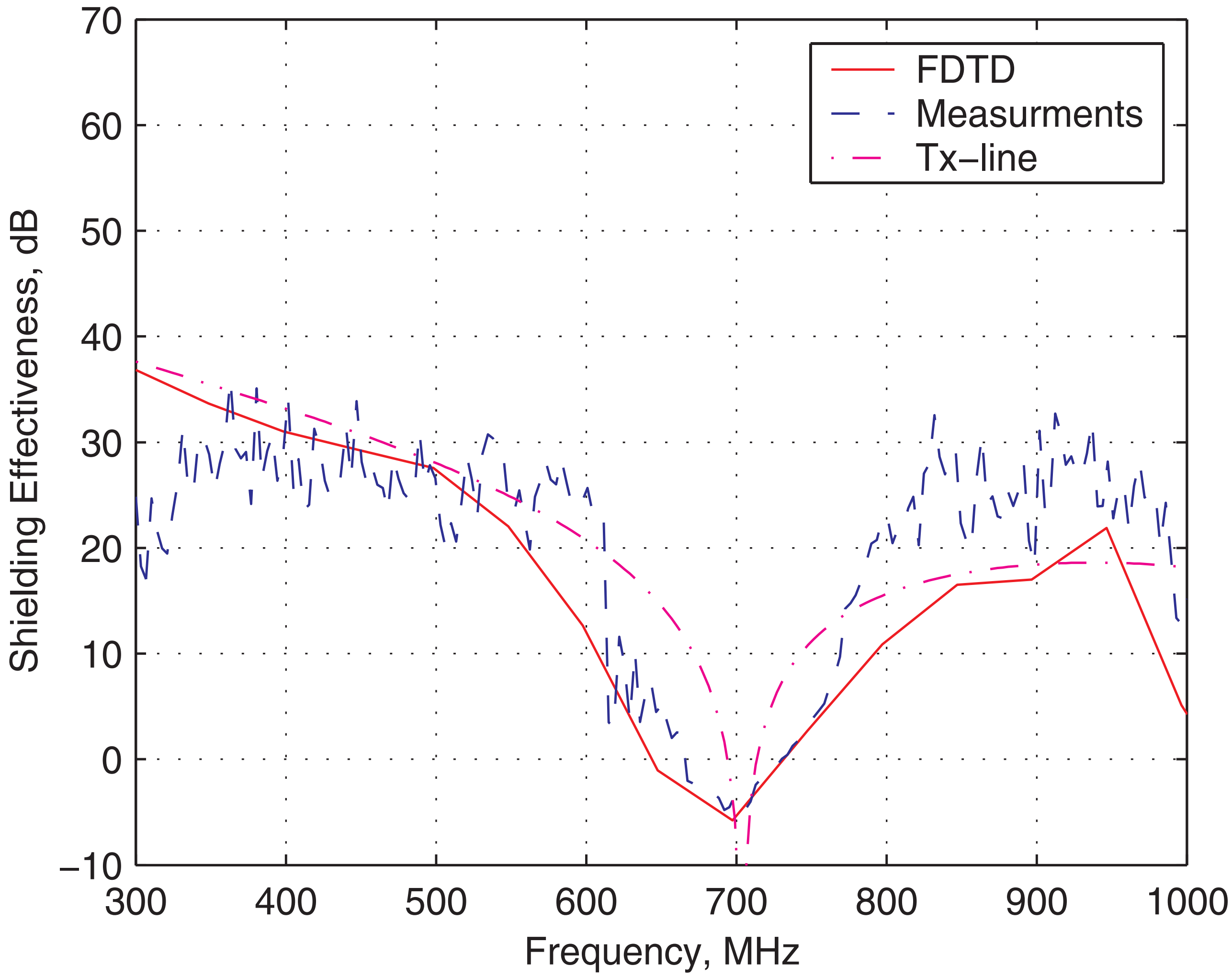


Figure 25. Computed and measured shielding effectiveness of the rectangular enclosure with aperture of 0.1 by 0.005 m.

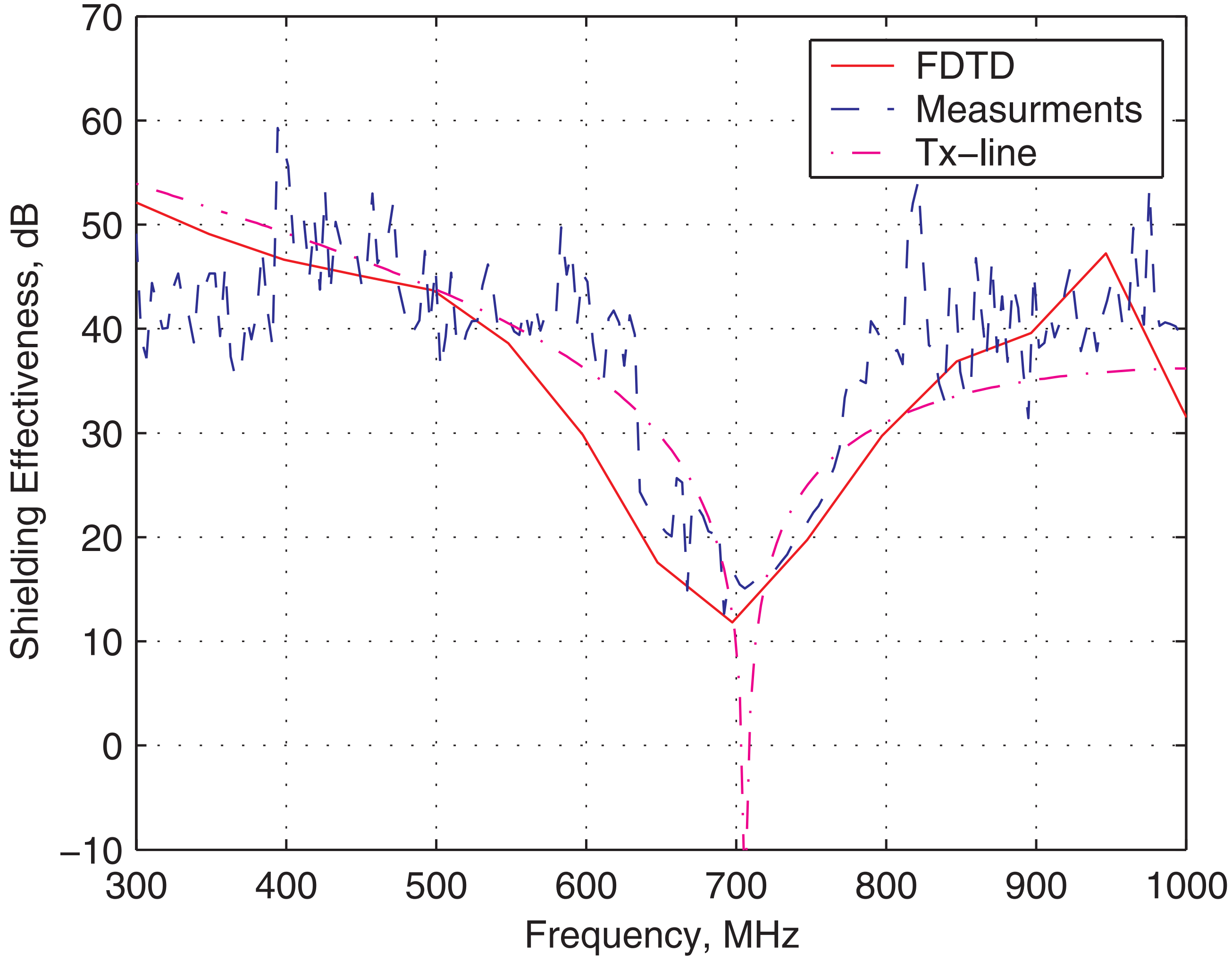


Figure 26. Computed and measured shielding effectiveness of the rectangular enclosure with aperture of 0.05 by 0.005 m.

7.0 Conclusions

- SE of a rectangular enclosure has been investigated using the TL method
- an estimate of the SE depending on the slot length and width variation and the number of slots has been developed. The developed method is good for comparing the relative shielding of different slot sizes or comparing relative shielding against some standard slot
- energy transfer into an enclosure may be reduced at the design stage by geometrically trimming the size and the number of slots. From SE point of view, it is better to have more smaller slots
- the problem of EM coupling into a rectangular enclosure through an aperture has been studied based on a multimode approach. The contributions of individual as well as multiple higher-order modes to the SE of the enclosure have been considered
- losses can be easily incorporated in the TL model and may be used to mimic the loading effect of electronics

- EM coupling into a rectangular enclosure with aperture under aperture-enclosure resonant conditions has been investigated using the TL model. A pair of aperture-enclosure resonances have been found which significantly reduce the SE
- energy transfer into an enclosure may be reduced at the design stage by detuning the aperture-enclosure resonances by geometrically trimming the shape of the aperture or enclosure
- good agreement between the results obtained for the TL and the FDTD models has been obtained
- solution time is the key advantage of the developed model.

References:

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[4] I. Belokour, J. LoVetri, and S. Kashyap, "A Higher-Order Mode Transmission Line Model of the Shielding Effectiveness of Enclosures with Apertures", 2001 *IEEE EMC International Symposium Proceedings,* Montreal, Quebec., pp. 702-707,