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Original Research

Identification and Characterization of Internal and External Sources of Electromagnetic Compatibility (EMC) Issues in Complex Circuits

Ahmed Ben Youssef[1] and Karim Trabelsi[2]

[1]University of Sousse, Department of Electrical Engineering, Avenue de la République, Sousse, Tunisia.
[2]University of Gabès, Department of Electrical Engineering, Route El Ferdaous, Gabès, Tunisia.

Abstract
Electromagnetic compatibility challenges are persistent in increasingly dense electronic platforms where mixed-signal, power conversion, and wireless subsystems coexist. As integration rises, coupling paths multiply across conductors, dielectric volumes, and free space, while device-level switching edges sharpen and spectral content broadens. In this context, distinguishing internal and external sources of disruption and attributing observed emissions or susceptibility to specific mechanisms is necessary for practical design iteration. This paper investigates internal sources such as digital edge transitions, clock-distribution skew, switched-mode power converters, and substrate or ground-network resonances, as well as external sources including intentional radiators, conducted disturbances on harnesses, and ambient impulsive fields. A modeling framework is developed that links field-theoretic representations, circuit reductions, and measurement artifacts to a common set of parameters that can be extracted with moderate effort. The analysis emphasizes bandwidth-aware decomposition of interference, the role of impedances seen by aggressors and victims, and the influence of geometry on modal content. A measurement and diagnostics section discusses probing strategies, calibration drift, and fixture parasitics, with attention to reconstruction of equivalent sources from partial observations. A final section translates the characterization into layout and filtering strategies, power distribution design, and shielding tradeoffs. The objective is to provide a neutral, technically grounded account of identification and characterization practices that scale from board to small system level without presupposing a single numerical method or instrument, thereby supporting reproducible reasoning from root-cause hypotheses to mitigation decisions.

1. Introduction

Complex circuits that combine high-speed logic, precision analog functions, and power conversion form layered electromagnetic systems in which energy transfer is governed simultaneously by conduction through networks of interconnects and by radiation through near- and intermediate-field coupling [1]. In these systems, electromagnetic compatibility issues arise not as isolated anomalies but as the aggregate of interacting mechanisms whose signatures overlap in time, frequency, and space. Internal sources originate from switching transitions, bias distribution, and control loops, while external sources include incident fields from radios, neighboring equipment, conducted disturbances along cables, and electrostatic or lightning-induced discharges. A systematic account of these contributors must begin with definitions of sources, paths, and victims, and proceed toward parameterizations that admit measurement or inference under practical constraints. Understanding such systems requires a multi-domain perspective in which time-domain transients, frequency-domain resonances, and spatial distributions of fields are interpreted as aspects of the same underlying electromagnetic behavior.

When conceptualizing internal sources, it is helpful to regard composite waveforms as superpositions of elementary events whose spectral envelopes are shaped by rise time, topology, and load

Interference Category	Origin	Coupling Path	Measurement Domain
Internal Sources	Switching edges, bias loops	Traces, planes, vias	Time / Frequency
External Sources	Radiated fields, ESD, lightning	Apertures, cables	Frequency / Spatial
Mixed Coupling	Conducted + radiated overlap	Shared grounds, returns	Hybrid

Table 1. *Classification of interference sources and coupling mechanisms..*

Mitigation Approach	Action	Trade-off	Effective Range
Geometry Optimization	Minimize loop area, tight returns	Layout constraints	Broadband
Decoupling Network	Reduce voltage ripple	Space, cost	Low–Mid Freq.
Ferrite / CM Chokes	Block HF noise	Saturation, heat	Mid–High Freq.
Shielding / Enclosure	Contain or reflect fields	Weight, cost	High Freq.
Ground Segregation	Isolate noisy domains	Complexity	Broadband

Table 2. *Common EMI mitigation strategies and trade-offs..*

Measurement Technique	Observable	Use Case	Notes
Oscilloscope / TDR	Voltage/current vs. time	Switching transients	Source localization
Spectrum Analyzer	Emission spectrum	Radiated/conducted noise	Pre-compliance check
VNA	S/Z/Y parameters	Coupling path ID	Reciprocity-based model
Near-Field Probe	Local E/H fields	PCB hotspot mapping	Needs calibration
Current Probe	CM/DM currents	Cable, ground currents	Non-intrusive

Table 3. *Diagnostic and measurement techniques for EMI characterization..*

dynamics. A digital line that toggles at a nominal rate contributes harmonics across wide bands when its edges are fast relative to the loop inductances and return-path distribution; a switching converter injects differential-mode currents at the fundamental and its sidebands, while common-mode currents emerge from asymmetries and capacitive structures. Each source thus possesses both deterministic and stochastic attributes. The deterministic component is tied to the underlying circuit operation, whereas the stochastic component reflects the complex coupling between nonlinear devices, parasitic impedances, and power-supply modulation [2]. The total field observed within or outside the system becomes a statistical superposition of many such contributions, some coherent and some random, giving rise to interference patterns that vary with frequency and geometry. External sources, by contrast, must be projected onto the system's effective apertures, harness impedances, and enclosure modes to quantify susceptibility. The system can be viewed as a network of coupled oscillators in which external excitation may inject energy into internal resonances, leading to amplification at particular frequencies or transient bursts that corrupt signal integrity. Measuring and modeling either category in isolation can be misleading when energy flows through shared pathways such as ground networks, connector transitions, or multilayer substrate resonances that blur distinctions between radiation and conduction.

A more complete treatment requires recognizing that conduction and radiation are not separate phenomena but complementary manifestations of Maxwell's equations. Currents flowing through traces or vias inevitably produce magnetic fields, and voltage gradients across planes or components give rise to electric fields that may extend into free space. Conversely, incident electromagnetic waves induce currents and voltages in conductors according to boundary conditions. The boundary between circuit and field analysis therefore becomes conceptual rather than physical. Engineers traditionally separate "signal integrity," "power integrity," and "electromagnetic compatibility" as distinct disciplines, but in practice they form a continuum [3]. A power converter's switching ripple that distorts an analog reference may also excite enclosure modes that radiate outward; conversely, an external field entering through an aperture can perturb sensitive bias networks. Thus, mitigation must be approached holistically through hierarchical modeling and experiment.

At the circuit level, mitigation begins with geometry. Minimizing loop area, maintaining tight coupling between signal and return paths, and using controlled impedance routing all serve to confine magnetic flux and reduce radiation. Decoupling networks, composed of capacitors distributed across frequency decades, establish low-impedance reservoirs that suppress differential and common-mode voltage excursions. Ferrite beads and common-mode chokes insert frequency-selective impedance that damp resonant currents along cables or harnesses. Shielding, whether by continuous conductive enclosures or laminated structures, provides boundary conditions that reflect or absorb incident fields. Yet these classical measures must be tailored through analysis, because excessive filtering or shielding can introduce ground shifts, resonant cavities, or thermal penalties that degrade performance elsewhere. Therefore, design optimization is a trade-off across electrical, mechanical, and thermal domains, guided by both simulation and measurement. [4]

From a measurement standpoint, the challenge lies in distinguishing the contributions of overlapping sources. Time-domain measurements using oscilloscopes or time-domain reflectometers can capture switching transients, while frequency-domain analysis through spectrum analyzers or near-field probes reveals the distribution of energy across bands. Correlation techniques and vector network analysis enable identification of dominant coupling paths by measuring transfer functions between potential aggressors and victims. Advanced methods, such as time-domain scanning of magnetic or electric fields above printed circuit boards, permit visualization of current distributions and resonant hot spots. These observations, when interpreted through models, allow the derivation of equivalent circuit representations whose parameters can be used in system-level simulations. The goal is not merely to measure emissions or susceptibility but to infer causal mechanisms, thereby enabling design modifications grounded in physical understanding.

At higher levels of integration, particularly in mixed-signal systems, parasitic coupling within multilayer substrates and packages becomes significant. The dielectric stack-up, via placement, and plane segmentation create resonant cavities that can propagate energy laterally over several centimeters. Such resonances can link unrelated functional blocks—digital logic transitions may excite standing waves that couple into sensitive analog front ends [5]. Similarly, in system-in-package designs, bond wires, redistribution layers, and micro-bumps act as unintended antennas. Accurate modeling requires combining electromagnetic solvers with behavioral circuit descriptions. Time-domain co-simulation allows the nonlinear switching behavior of transistors to drive field solvers that compute the resulting emissions, thus bridging the gap between device physics and system-level electromagnetic performance.

External coupling mechanisms also demand attention. Radiated susceptibility often depends on polarization, incidence angle, and the electrical dimensions of apertures or cables. Conducted susceptibility, on the other hand, arises when disturbances propagate along shared conductors such as power lines, communication buses, or reference planes. In real installations, both occur simultaneously: a radiated wave can induce conducted currents that re-radiate elsewhere, forming feedback loops that complicate mitigation. The environment itself—metallic enclosures, nearby structures, and cable layouts—alters the field distribution and may either shield or amplify certain frequencies. Hence, laboratory compliance testing using standardized setups provides only partial insight; field conditions must also be considered to ensure robustness under deployment. [6]

The theoretical foundation for analyzing these interactions lies in network theory extended to include electromagnetic coupling. Each subsystem can be represented by multiport parameters—impedance, admittance, or scattering matrices—that encapsulate both conductive and radiative behavior. When interconnected, these matrices predict energy transfer and reflection across boundaries. Incorporating stochastic models for source variability and uncertainty in parameters enables statistical assessment of electromagnetic compatibility. This probabilistic approach is essential because modern systems exhibit variability in component tolerances, environmental conditions, and operational states that preclude deterministic prediction. Monte Carlo simulation, surrogate modeling, and machine-learning-based inference have begun to supplement classical analysis by identifying patterns that correlate design parameters with emission or susceptibility outcomes.

Ultimately, electromagnetic compatibility is not a property that can be added post hoc but a quality that must emerge from the integration of design philosophy, layout discipline, and system architecture. Early partitioning of noisy and sensitive functions, proper referencing of grounds, and consistent impedance control form the first line of defense [7]. Beyond design, manufacturing variation and aging can alter coupling paths, necessitating margin in specifications. The aim is to achieve not zero interference—a physical impossibility—but controlled coexistence in which emissions remain below regulatory and functional thresholds while immunity margins accommodate foreseeable disturbances. Such balance reflects a mature understanding of the electromagnetic ecosystem within which all electronic systems operate.

The present work focuses on identification and characterization, rather than exhaustive modeling, to maintain fidelity to what can be extracted without speculative assumptions. The approach integrates field formulations that describe how currents and charges generate fields, circuit reductions that retain lumped impedances and controlled sources, and experimentally accessible observables such as near-field probe voltages, current probe readings, and radiated emission profiles. Each technique offers incomplete but complementary visibility. Field solutions deliver geometric sensitivity but can be computationally expensive or ill-conditioned; circuit models are tractable but may omit distributed effects; measurements reflect the real article but often include fixture and probe loading. By aligning these views with consistent parameters—currents, voltages, impedances, admittances, and modal field quantities—the analysis supports attribution of observed signatures to plausible source-path-victim chains.

Throughout, the emphasis is on neutral interpretation [8]. The paper does not presume a singular mitigation hierarchy, since effectiveness depends on geometry, spectral occupancy, regulatory constraints, and product-level requirements. Instead, it develops diagnostic constructs that map observed artifacts to internal or external source classes and quantifies their coupling via measurable impedances and transfer functions. The methods are illustrated by equations that encode power balance, reciprocity-inspired transfer measures, and stochastic representations of impulsive and narrowband interference. The concluding section summarizes implications for layout, filtering, and shielding, noting the conditions under which each lever is most informative for decision making.

2. Background and Definitions

A working vocabulary clarifies how internal and external sources are separated in analysis. Internal sources are excitations generated within the circuit boundaries by intended functions such as logic transitions, PWM gating, or bias control activity. External sources are excitations that impinge on the system boundary via fields or conductive networks not governed by internal control. A practical boundary is set by the combination of printed circuit board, attached harnesses, and enclosures, recognizing that cables can be modeled as extensions of the system rather than purely external.

In deterministic descriptions, sources are represented by impressed electric fields, magnetic fields, or equivalent Thevenin or Norton generators inserted into circuit graphs that symbolize interconnects and components [9]. The continuum statement of electromagnetic behavior is Maxwell's system written in terms of fields, constitutive relations, and sources. The interconversion between field and circuit parameters is mediated by definitions of voltages and currents along contours, surfaces, and volumes that map the distributed object to a network description without discarding geometric dependence. This mapping is accurate only when the chosen granularity preserves relevant resonances, delay, and modal structure.

A frequency-domain viewpoint often aids classification. Internal switching actions populate bands tied to carriers, harmonics, and intermodulation products of clocks and control loops. External radiofrequency fields carry spectral features set by communication standards or interfering emitters. The mutual visibility of sources and victims depends on impedances encountered along coupling paths, including return plane discontinuities, vias, stitching capacitances, transformer stray parameters, and enclosure seams. Modal language—differential mode, common mode, cavity modes—offers a compact representation for how geometry selects and shapes spectral content.

A useful abstraction is the decomposition of total fields into contributions from equivalent electric and magnetic surface currents defined over boundaries that enclose the circuit volume [10]. With that device, a distributed radiator or receptor can be conceptualized as a set of surface integrals whose kernels are dyadic Green's functions. Observability then becomes a question of whether particular measurement configurations sufficiently excite or sense those surface currents. The calibration issue appears naturally: probes and fixtures create their own equivalent sources and alter boundary conditions locally, responding not only to the device under test but also to placeable modes in the setup.

To support quantitative reasoning, let the circuit network be represented by a directed graph whose edge set corresponds to conductive traces and whose node set represents junctions and reference planes, possibly including idealized ports for cables and enclosures. The accompanying continuum volume carries fields that satisfy boundary conditions at interfaces between conductors and dielectrics. From this pair of descriptions, one can define transfer functions that relate impressed sources to victim responses, establishing an identification pathway where measured transfer magnitudes and phases guide attribution of the dominant mechanisms among candidates.

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \qquad \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}, \qquad \nabla \cdot \mathbf{D} = \rho, \qquad \nabla \cdot \mathbf{B} = 0$$

Constitutive relations in linear regions read $\mathbf{D} = \varepsilon \mathbf{E}$, $\mathbf{B} = \mu \mathbf{H}$, and $\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_{\mathrm{imp}}$ where $\mathbf{J}_{\mathrm{imp}}$ encodes impressed sources arising internally or externally. Network-level variables are defined as line integrals of $\mathbf{E}$ along chosen paths to form voltages and surface integrals of $\mathbf{H}$ to form currents. The distributed-to-lumped map preserves the power balance expressed by Poynting's theorem when extended to include reactive storage associated with inductive and capacitive elements.

$$\frac{\partial u}{\partial t} + \nabla \cdot \mathbf{S} = -\mathbf{J} \cdot \mathbf{E}, \qquad u = \tfrac{1}{2}\left(\mathbf{E} \cdot \mathbf{D} + \mathbf{B} \cdot \mathbf{H}\right), \quad \mathbf{S} = \mathbf{E} \times \mathbf{H}$$

These relations are referenced here as analytic primitives, anchoring the later reductions used for identification, coupling estimates, and mitigation reasoning.

3. Internal Sources of Electromagnetic Compatibility Issues

Internal sources are energized by device functions and are therefore temporally correlated with system activity [11]. Digital transitions at IO drivers and within core logic inject displacement and conduction currents whose spatial distribution is shaped by the return network. Rise and fall times concentrate spectral weight; when return paths are interrupted by splits, sparse stitching, or impedance discontinuities, common-mode conversion results and energy escapes beyond local differential loops. Power converters modulate energy at carrier and sideband frequencies through switch-node waveforms that appear as piecewise-linear voltages and currents. Control loops add low-frequency components that can intermodulate with radio bands depending on harmonic alignment.

A compact representation for interconnect behavior under fast edges is the transmission-line model with per-unit-length parameters that reflect material and geometry. For a uniform line affected by internal switching sources, the telegrapher system relates voltages and currents, and boundary conditions at driver and load determine reflections that can be partly observed as ringing or radiated components.

$$\frac{\partial v(x,t)}{\partial x} = -L' \frac{\partial i(x,t)}{\partial t} - R'\, i(x,t), \qquad \frac{\partial i(x,t)}{\partial x} = -C' \frac{\partial v(x,t)}{\partial t} - G'\, v(x,t)$$

The return distribution is often multi-path rather than confined to a single reference plane. To capture partial returns, partial element equivalent circuit formulations define inductive and capacitive couplings among conductors via integrals of Green's functions with kernel dependences on distance and orientation [12]. The magnetic flux linkage across loops that traverse vias and plane apertures can be encoded in an inductance matrix L and a capacitance matrix C, where off-diagonal entries describe mutual couplings. When a driver current vector $i(t)$ excites the structure, the loop voltages obey

$$L\,\frac{di(t)}{dt} + R\,i(t) + \int_{-\infty}^{t} K(t-\tau)i(\tau)\,d\tau + C^{-1}\int i(t)\,dt = e(t),$$

where K represents dispersive effects associated with skin depth and dielectric loss and $e(t)$ is the effective source voltage. This form emphasizes that even nominally lumped paths carry memory through convolution kernels induced by diffusion and polarization relaxation.

Switched-mode converters introduce internal sources with piecewise-affine dynamics. A canonical buck converter with switch-node voltage $v_s(t)$, inductor current $i_L(t)$, and duty modulation $d(t)$ produces ripple components whose spectra are shaped by the product of the ideal PWM comb and the power-stage transfer. The output impedance seen by subcircuits depends on control bandwidth, compensation zero-pole placement, and parasitic elements. The small-signal model linearized about a periodic orbit can be written in harmonic balance notation by lifting states to Fourier coefficients. For identification, an equivalent envelope description often suffices: [13]

$$\frac{d}{dt}\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_o\end{bmatrix} = A\begin{bmatrix}\tilde{i}_L\\ \tilde{v}_o\end{bmatrix} + B\,\tilde{d}(t) + w(t), \qquad \tilde{d}(t) = \sum_k \alpha_k e^{jk\omega_s t},$$

with $w(t)$ modeling internal noise sources and device-level shot and thermal contributions. The switch node couples capacitively to ground and to heatsinks or chassis, creating common-mode displacement currents proportional to the time derivative of $v_s(t)$. The effective common-mode source amplitude scales with $C_{\mathrm{par}}\,dv_s/dt$, illustrating the sensitivity of radiated emissions to geometry and to the slew control implemented in gate drivers.

Clock distribution networks present another internal source class. Skew between branches drives transient return currents through plane impedances, and simultaneous switching produces broadband impulsive spectra. If N outputs toggle with correlation matrix Γ and each driver injects a current pulse shape $p(t)$ into a shared return network with impedance $Z_{\mathrm{ret}}(\omega)$, the expected power spectral density of the aggregate return current is

$$S_I(\omega) = |P(\omega)|^2 \sum_{m,n=1}^{N} \Gamma_{mn}\,,$$

and the voltage across the return impedance has spectrum $S_V(\omega) = |Z_{\mathrm{ret}}(\omega)|^2 S_I(\omega)$. The conversion to common mode depends on asymmetries and on the modal decomposition of plane currents near apertures and edges. If the plane pair forms a cavity with dimensions comparable to a fraction of the wavelength, cavity modes can be excited; the admittance seen by a local source then exhibits resonant features that can be probed by injecting small currents and measuring local potentials.

Substrate coupling constitutes a further internal path in mixed-signal systems. Junction and well capacitances, substrate resistivity, and guard ring configurations determine how digital edge energy reaches analog nodes. A simplified substrate network models the silicon as a resistive sheet with distributed capacitances to the ground reference [14]. If $V_D(x,y,t)$ denotes the digital substrate potential and $V_A(x,y,t)$ the analog region, a diffusion-like equation captures lateral propagation:

$$\frac{\partial V(x,y,t)}{\partial t} = D\nabla^2 V(x,y,t) - \frac{1}{\tau}V(x,y,t) + S(x,y,t),$$

where D depends on substrate resistivity and capacitance density, τ summarizes vertical leakage to reference, and S represents injection under digital gates. The analog victim sees an integrated exposure over its footprint, filtered by its input network and bias dependencies.

4. External Sources and Coupling Pathways

External sources enter through fields or through conducted paths such as cables, shields, and grounds connected to other equipment. A unifying description treats the device under test as a multiport that exchanges power with the environment through defined ports and through apertures that act as distributed ports. The incident field induces equivalent surface currents over the enclosure, and these currents in turn drive internal conductors. In conducted susceptibility, disturbances propagate along harnesses and couple via connector pin impedances and common reference conductors. The classification into radiated and conducted phenomena is useful for testing but should not obscure the continuity in physical mechanisms; currents flowing along external conductors create fields and vice versa.

For field-to-wire coupling, the transfer can be approximated by the induced electromotive force integrated along conductor paths [15]. If a wire of length ℓ and orientation $\hat{u}$ resides in an incident field $\mathbf{E}_{\text{inc}}(\mathbf{r})$, the open-circuit voltage at its terminals follows

$$V_{\text{oc}}(\omega) = \int_0^{\ell} \mathbf{E}_{\text{inc}}(\mathbf{r}_0 + s\hat{u}) \cdot \hat{u}\, e^{-j\beta s}\, ds,$$

where β accounts for phase accumulation along the wire. When the wire is part of a harness terminated into finite impedances, the induced voltage becomes a source in the network that produces both differential and common-mode currents depending on termination asymmetries. Apertures in enclosures operate as slot antennas; their transmission depends on dimensions relative to wavelength, thickness, and proximity to internal resonant structures. The transmission coefficient of a narrow rectangular slot under a uniform field approximation can be related to its magnetic polarizability, providing a first estimate of coupled power without full-wave simulation.

Conducted external interference often manifests through common-mode currents on harness shields or reference conductors. The conversion into internal differential disturbances occurs at points where symmetry breaks, such as imbalanced filter elements, connector pinouts, or return-path offsets. The chain can be summarized by a cascade of mode converters and transfer impedances. Denote an external common-mode current $I_{\text{cm,ext}}$ and an internal differential voltage response $V_{\text{diff,int}}$; a minimal cascade model writes

$$V_{\text{diff,int}}(\omega) = T_{cd}(\omega)\, Z_{dd}(\omega)\, T_{cc\to dd}(\omega)\, I_{\text{cm,ext}}(\omega),$$

where T_{cd} captures conversion from common to differential at ingress, Z_{dd} encodes the victim differential impedance landscape, and $T_{cc\to dd}$ stands for additional internal conversions. This structure emphasizes parameter identifiability by measurements: each block can be probed by tailored excitations to bound the magnitude of coupling under operating conditions.

When external sources are narrowband, as in communication systems, susceptibility depends on spectral alignment with internal resonances and on nonlinearities that create intermodulation products [16]. If a pair of external tones at ω_1 and ω_2 interacts with a nonlinear transfer $y = a_1 x + a_2 x^2 + a_3 x^3 + \ldots$, internal responses may appear at $2\omega_1 - \omega_2$ or other combinations. The envelope of these products depends on the local power at the nonlinearity and on bias conditions. This mechanism becomes relevant when external fields couple strongly into stages that contain active devices or saturable magnetics.

An impulsive external source, such as electrostatic discharge to an enclosure or cable, injects a broadband current transient that excites enclosure and cable modes. The time profile can be abstracted as a current source with double-exponential form, and fields within the enclosure respond with ringing governed by modal Q-factors and coupling coefficients. The induced waveforms at victim nodes often display distinct early-time components associated with direct coupling paths and late-time components dominated by reverberant energy. Decomposing the measured response into early and late time supports attribution of the dominant path and targets mitigation to either immediate ingress points or energy damping mechanisms.

$$i_{\mathrm{ESD}}(t) = I_0 \left(e^{-t/\tau_1} - e^{-t/\tau_2}\right) u(t), \qquad v_{\mathrm{victim}}(t) = \int_0^t h(t-\tau) i_{\mathrm{ESD}}(\tau) d\tau,$$

where $h(t)$ is the impulse response from the injection point to the victim node, reflecting both direct and cavity-mediated contributions. Frequency-domain analysis of h reveals peaks at enclosure modes and at cable resonances that can be shifted by geometric adjustments or by added loss. [17]

5. Modeling and Quantitative Analysis

Coupling Type	Key Mechanism / Parameter	Main Effect
Field-to-Wire	Induced EMF along conductor; length, orientation	Common/differential currents
Aperture	Slot antenna behavior; aperture size, shape	Internal radiation, resonance
Conducted	Harness/shield imbalance; reference impedance	Mode conversion, ground loops
Nonlinear Mix	External tones + nonlinear devices	Intermodulation products
Impulsive (ESD)	Fast transient, broadband current	Enclosure ringing, transient upset

Table 4. *External interference coupling mechanisms and their effects..*

Model Level	Representation / Quantities	Estimation Method
Field	Surface currents $\mathbf{J}_s$, $\mathbf{M}_s$	Probe data, inversion
Circuit	$Z(\omega)$, $S(\omega)$ relations	VNA / network analysis
Mixed-Mode	Z_{cc}, Z_{dd}, Z_{cd}	Mode tests
Stochastic	λ, A_m, $H(\omega)$	Spectral inference
Optimization	$\Gamma(\omega)$, p_k, R	Analytical bounds

Table 5. *Modeling hierarchy and parameter estimation techniques..*

Source Type	Spectral Form	Preferred Mitigation
Narrowband RF	Stable tones	Shielding, notch filters
Broadband ESD	Fast transient	Ground bonding, absorbers
Switching Noise	Clock-synchronous	Layout, decoupling
Ambient Fields	Nearby transmitters	Enclosure integrity
Mixed Paths	Radiated + conducted	Balanced I/O, CM suppression

Table 6. *External interference types and mitigation focus..*

A modeling framework that supports identification must connect sources to observables through parameterized structures whose elements can be estimated from measurements or constrained by geometry. The field-to-circuit reduction and circuit-to-field reconstruction appear as inverse problems conditioned by incomplete data and by uncertainties in material properties and boundary conditions. The strategy adopted here is to write transfer relations that depend on a small set of lumped or distributed parameters and to bound those parameters with data from non-invasive probes and from known dimensions.

In the near field, probe voltages map approximately to tangential electric fields or magnetic fields depending on probe design. An electric field probe with effective length l_{eff} responds to the local field component as $v_p(\omega) \approx j\omega l_{\text{eff}} E_t(\omega) Z_{\text{in}}/(Z_{\text{in}} + Z_{\text{load}})$ under small loading. A magnetic loop probe with area A_{eff} produces $v_p(\omega) \approx j\omega\mu A_{\text{eff}} H_t(\omega)$ with similar loading considerations. These relations permit reconstruction of equivalent source moments by assuming localized dipole models. For a small current loop of area A carrying current $I(\omega)$, the magnetic dipole moment $\mathbf{m} = I(\omega) A\hat{n}$ generates fields that decay with distance as dipole terms, enabling inversion given probe calibrations and standoff distances.

$$\mathbf{E}(\mathbf{r},\omega) \approx -j\omega\mu \frac{e^{-jkr}}{4\pi r} (\hat{r} \times \mathbf{m}) \times \hat{r}, \qquad \mathbf{H}(\mathbf{r},\omega) \approx k^2 \frac{e^{-jkr}}{4\pi r} (\hat{r} \times \mathbf{m})$$

In the intermediate field and for extended sources, integral-equation formulations provide a more appropriate link. Surface equivalence replaces the physical object by equivalent electric and magnetic surface currents $\mathbf{J}_s$ and $\mathbf{M}_s$ that reproduce the same exterior fields. The fields in the observation region follow from convolution with dyadic Green's functions. For numerical tractability, the surface is discretized, yielding a system $Z\mathbf{x} = \mathbf{b}$, where $\mathbf{x}$ stacks unknown current coefficients and $\mathbf{b}$ contains impressed field terms. Identification then becomes a regularized inversion informed by measurements at limited points [18]. A simplified projection onto a small number of dominant basis functions or modes provides reduced-order models that can be parameterized from sparse observations.

$$\begin{aligned}
\mathbf{E}(\mathbf{r}) &= j\omega\mu \int_S \overline{\overline{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_s(\mathbf{r}')\, dS' - \nabla \times \int_S \overline{\overline{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{M}_s(\mathbf{r}')\, dS', \\
\mathbf{H}(\mathbf{r}) &= j\omega\varepsilon \int_S \overline{\overline{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{M}_s(\mathbf{r}')\, dS' + \nabla \times \int_S \overline{\overline{G}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_s(\mathbf{r}')\, dS'
\end{aligned}$$

At the circuit level, multiport network descriptions capture conducted interactions. The scattering matrix $S(\omega)$ or the impedance matrix $Z(\omega)$ relates port voltages and currents, and mode decomposition separates common and differential excitations. When internal and external sources coexist, superposition yields the net response. Within this view, identification reduces to estimating a small set of transfer parameters between defined aggressor and victim ports. To bound radiated contributions, one can introduce ports that represent equivalent apertures or distributed return paths, acknowledging that their physical interpretation is approximate but operationally useful.

$$\begin{bmatrix} \mathbf{V} \\ \mathbf{I} \end{bmatrix} = \begin{bmatrix} Z(\omega) & 0 \\ 0 & Y(\omega) \end{bmatrix} \begin{bmatrix} \mathbf{I} \\ \mathbf{V} \end{bmatrix} + \begin{bmatrix} \mathbf{V}_s \\ \mathbf{I}_s \end{bmatrix}, \qquad \mathbf{b} = T(\omega)\,\mathbf{a}$$

where $\mathbf{a}$ and $\mathbf{b}$ denote incident and reflected wave vectors in a scattering description, and T is the transmission submatrix. Mode conversion can be represented by off-diagonal blocks in a mixed-mode matrix. When only partial port access is available, parameter extraction relies on selective terminations and on measurements at different configurations to overconstrain unknowns.

Stochastic models complement deterministic transfer descriptions by capturing variability and impulsive phenomena [19]. Broadband impulsive interference can be modeled as a compound Poisson process with rate λ and pulse shape $h(t)$, resulting in a second-order spectrum that is flat above the pulse width reciprocal but modulated by the pulse spectrum. Narrowband interference can be represented as a random-phase tone with slowly varying amplitude. Superposing these components yields an environment model against which internal sources are compared. Separation between internal and external contributions can exploit differences in cyclostationary structure; internal switching tied to clocks exhibits cyclic spectra at multiples of the clock, whereas external contributions may lack such structure unless they are themselves modulated.

$$x(t) = \sum_k a_k h(t-t_k) + \sum_m A_m \cos(\omega_m t + \phi_m), \qquad S_x(\omega) = \lambda |H(\omega)|^2 + \tfrac{1}{2} \sum_m A_m^2 \left[\delta(\omega - \omega_m) + \delta(\omega + \omega_m)\right]$$

Optimization concepts enter when designing mitigation under bandwidth and geometry constraints. Matching and filtering obey causality bounds that limit achievable attenuation over specified bands given source and load impedances. The Fano limit provides an integral constraint on reflection achievable by passive, lossless networks, guiding expectations about how much common-mode suppression can be obtained without significant volume or loss. For a real, positive rational load $Z_L(s)$ with certain pole-zero structure, the integral of $\ln(1/|\Gamma(\omega)|)$ over frequency is bounded, providing a measure of the trade between bandwidth and mismatch.

$$\int_0^{\Omega} \ln \frac{1}{|\Gamma(\omega)|}\, d\omega \leq \frac{\pi}{R} \sum_k \mathrm{Re}(p_k) - \epsilon(\Omega),$$

where p_k are the right-half-plane zeros of $Z_L(s)$ and R is a reference resistance, with ϵ shrinking as Ω grows [20]. This inequality tempers expectations for broadband filters applied to common-mode paths and suggests distributing suppression across multiple structures with staggered resonances.

6. The Role and Limits of Full-Wave Simulation in EMC Root-Cause Analysis

Full-wave electromagnetic simulation occupies a central position in the analysis toolbox for complex circuits because it respects the governing equations over realistic geometries and material stacks, resolving currents and fields without presupposing a partition into lumped elements. In multilayer boards with enclosure interactions and external harnesses, this promise is especially appealing: the capacity to visualize current return densities around apertures, to quantify cavity modes interacting with switching edges, and to compare how small geometric changes alter radiated signatures across bands. However, the same completeness that grants fidelity also imposes computational and interpretive burdens that make the raw outputs difficult to translate into decisions about layout edits, filtering placements, and return-stitch planning. The observation that costly field solves do not automatically identify the few parameters that govern the emergence of a given electromagnetic compatibility symptom has been noted by a range of authors, including accounts that emphasize resource intensity and limited direct actionability in the context of root-cause attribution (e.g., Tsintsadze et al., 2024) [21].

External Source Type	Spectral Character	Mitigation Focus
Continuous Narrowband (RF)	Discrete tones, stable carriers	Shielding, notch or band-stop filters
Broadband Impulsive (ESD)	Fast transient, wideband spectrum	Ground bonding, transient absorbers
Periodic Switching Noise	Clock-synchronous harmonics	Layout symmetry, decoupling, filtering
Environmental Fields	Ambient or nearby transmitters	Enclosure integrity, cable management
Mixed Field–Conducted	Coupled radiated/conducted paths	Balanced interfaces, CM suppression

Table 7. *External interference categories and preferred mitigation priorities..*

The computational burden of full-wave methods follows from well-understood scaling with electrical size and material dispersion. In finite element and method of moments discretizations, the number of unknowns grows roughly with the volume or surface area measured in cubic or quadratic cells per wavelength, so that a domain with characteristic length L at wavenumber $k = 2\pi/\lambda$ yields an unknown count $N \approx \alpha(kL)^p$, with $p \in \{2, 3\}$ depending on whether a surface or volumetric scheme is used and with α capturing mesh quality and curvature resolution. Time-harmonic solves with direct factorizations then inherit complexity that scales as $O(N^{1.5})$ to $O(N^3)$ depending on sparsity and ordering, while iterative Krylov methods experience iteration counts that increase with condition number and with the spectral features of the operator. In time-domain schemes such as finite-difference or finite-integration methods, stability and accuracy constraints couple spatial resolution Δx to time step Δt through Courant limits, $\Delta t \leq \beta \Delta x / c$, making long-duration transients expensive when narrow resonances require small losses and slow decay. When analysis spans a frequency decade with fine spectral sampling to capture narrow peaks and deep notches, the burden compounds, and the naive aggregation of parametric sweeps across tens of geometric and material variables becomes impractical even with high-performance computing. [22]

Yet computational cost alone is not the main obstacle to actionability. What designers need is a mapping from candidate interventions—moving a stitching via, reorienting a choke, enlarging a copper pour, modifying a slot seam, altering a gate-drive slew rate—to predicted changes in relevant figures of merit such as common-mode currents on a harness, mixed-mode S-parameters at a connector, or integrated radiated power within a regulated band. Full-wave solutions yield field distributions and port responses under an existing configuration; turning those into directional advice requires sensitivity structure. If the figure of merit is denoted $J(\boldsymbol{\theta})$, where $\boldsymbol{\theta}$ collects geometric and electrical parameters, then efficient decision support needs $\nabla_{\boldsymbol{\theta}} J$ and credible bounds for ΔJ under manufacturing variability. In principle, adjoint methods deliver gradients at the cost of one forward and one adjoint solve, but implementing shape derivatives through meshing pipelines and material models is a delicate exercise in industrial settings where geometries come from heterogeneous CAD sources. Without gradients, design-of-experiments based on one-factor-at-a-time perturbations lacks statistical power and risks misattributing effects when interactions are present.

Hybridization with circuit descriptions brings the analysis closer to the levers that practitioners can actuate. Rather than simulating an entire board, enclosure, and cable assembly in a monolithic field solve, one may represent localized regions of strong field interaction with full-wave accuracy while replacing the rest by ports connected to lumped or reduced-order networks extracted from measurement. In such a partition, the enclosure and its dominant apertures become a multiport whose scattering matrix is either computed once or measured, and subcircuits attach through mode-converting interfaces that separate common and differential contributions. The response at a victim node then reads as a chain of transfer blocks whose elements lend themselves to identification and tuning, $V_{\text{victim}}(\omega) = H_{ed}(\omega)\, H_{dc}(\omega)\, H_{ce}(\omega)\, U_{\text{source}}(\omega)$, where H_{ce} captures field-to-enclosure coupling, H_{dc} enclosure-to-differential conversion at penetrations, and H_{ed} the electrical path inside the board. This factorization can be parameterized from a small number of well-chosen full-wave runs combined with bench measurements using current clamps, near-field probes, and mixed-mode S-parameters, drastically reducing the dimensionality of the problem while preserving the physics that matters for the symmetry breaks and resonances that create the symptom.

Equivalence principles enable further reduction by collapsing distributed radiators to compact sources that reproduce the exterior field, thereby allowing what-if reasoning without remeshing the interior. If a switching node and its heatsink generate a dominant common-mode pattern, an equivalent dipole or triplet of dipoles with fitted moments can stand in for the detailed geometry. The fit proceeds by minimizing discrepancy between measured or simulated fields $\mathbf{E}_{\text{obs}}(\mathbf{r}_m)$ at points $\mathbf{r}_m$ and the fields of a source ansatz, leading to a least-squares system that is small enough to solve robustly even in the presence of noise and moderate probe loading. Once fitted, pattern transformations under rotations, small translations, and changes in local boundary conditions can be obtained analytically. This approach shifts the design conversation from case-specific volumetric fields to a few source parameters and a coupling matrix to ports and apertures, which is closer to the way mitigations such as shield bonds and cable terminations are implemented.

A precondition for pragmatic reduction is a disciplined use of modal language that separates differential and common-mode content and recognizes the role of cavity and transmission-line modes in structuring the spectrum of interest. The mixed-mode decomposition of S-parameters at connectors and the computation of dominant enclosure eigenmodes at frequencies of concern provide a vocabulary in which mitigation can be discussed without re-running broad-band full-wave solves for every hypothesis. When return paths are well distributed and cavity Q-factors are moderate because of material losses and contact resistances, small topological edits can produce large modal shifts. In such contexts, qualitative insights about where a given mode stores energy—edges, seams, apertures, cable entries—can be decisive, whereas the precise field map at sub-millimeter resolution is not. [23]

Uncertainty quantification deserves prominence because the gap between simulated and realized behavior is often driven less by mesh density than by tolerances in contact impedances, seam gapping, cable routing, and material dispersion. Representing these uncertainties explicitly transforms the problem from point predictions to distributional statements. A practical strategy is to combine sparse full-wave runs at anchor points with surrogate models such as polynomial chaos expansions or Gaussian process regressions that map stochastic parameters to figures of merit. If $J(\boldsymbol{\theta})$ is approximated by a surrogate $\tilde{J}(\boldsymbol{\theta})$ trained on M carefully selected samples, then marginal effects and pairwise interactions can be quantified through Sobol indices computed cheaply on the surrogate. This supports a ranking of parameters by influence, concentrating attention on those that determine the tails of the distribution—often contact conductances and cable placements rather than dielectric constants or trace widths. Such analysis informs robust design, where the goal is not to maximize nominal compliance margin but to minimize the probability of excursion under field or conducted tests given manufacturing and usage variability.

Adjoint and gradient-free sensitivity methods provide complementary routes to actionability. When adjoints are infeasible due to meshing or proprietary solver constraints, derivative-free methods that exploit smoothness in a low-dimensional active subspace can still deliver effective search directions. If samples of J exhibit a dominant low-rank structure in the parameter space, a projection onto the leading eigenvectors of the sample covariance of gradients—or their finite-difference approximations—identifies combinations of parameters that matter. Even approximate gradients obtained by coarse-mesh solves can serve to identify this subspace, after which high-fidelity evaluations need only be performed along a small number of composite directions [24]. In this manner, the engineering workflow uses full-wave computation as a probe to reveal structure rather than as the sole vehicle for prediction.

Time-frequency structure of internal and external sources supplies additional leverage. Internal switching tied to clocks produces cyclostationary signatures that are sparse on cyclic spectra; external narrowband fields appear as isolated tones; impulsive events have concentrated early-time energy followed by modal reverberation. Figures of merit constructed to be sensitive to these structures—for example, the energy in a narrow cyclic frequency bin or the ratio of early- to late-time energy at a victim node—are easier to predict and to control than broadband integrals. Full-wave time-domain solves that are expensive over long horizons can be restricted to windows that capture strong coupling intervals identified by measurement. Envelope and multirate schemes are likewise attractive: if the essential interaction involves a slowly varying envelope modulating a high-frequency carrier, the governing partial differential equations can be averaged in phase to reduce the stiffness of the time stepping. The result is not only a speedup but a model whose parameters map more directly to control variables such as duty perturbations and edge-rate limits.

Port reduction and model order reduction connect full-wave richness to circuit-level decision variables. In many enclosures the number of ports across which significant power exchange occurs is small compared to the number of mesh unknowns [25]. Projection-based techniques such as Krylov subspace methods, balanced truncation, and passivity-preserving rational fitting compress the transfer matrix $H(\omega)$ into a reduced model $\hat{H}(\omega)$ with guaranteed stability and accuracy over bands of interest. If $\hat{H}$ retains the leading residues associated with dominant poles near aperture and cavity resonances, then circuit simulators can embed $\hat{H}$ as a rational macromodel and co-simulate with nonlinear device models and control loops. This allows exploration of controller bandwidth changes, gate driver modifications, and decoupling schemes with more realism than pure lumped approximations but at a computational cost orders of magnitude lower than repeated full-wave solves. Passivity constraints are central, since non-passive fits can cause non-physical energy generation when connected to active circuits; enforcing positive realness during fitting secures well-behaved simulations under port interconnections.

The interface between measurement and simulation is where actionability becomes testable. Treating measurements as operators acting on underlying fields and currents enables data assimilation with honest accounting of probe influence and noise. If $y = \mathcal{H}(x) + \eta$ models the measurement of an unobserved field or port response x through a forward operator $\mathcal{H}$ and noise η, then Bayesian inference with priors informed by reduced models produces posterior distributions over parameters that drive mitigation. In practice one may use a linearization about a nominal state, $y \approx H\theta + \eta$, to compute a maximum a posteriori estimate $\hat{\theta}$ for a small set of influential parameters such as seam conductance, cable bond quality, and return via inductance. The updated parameters then calibrate the reduced model that is used for what-if reasoning. The computational expense resides in evaluating H and propagating covariance; both tasks are much cheaper when full-wave models are used only to generate calibration data for a reduced representation rather than to predict end quantities at every iteration.

The decision to deploy full-wave solvers should follow a triage that identifies the coupling class and the scale of geometric interactions. When the symptom is tied to a discrete aperture or a specific slot seam, a localized full-wave submodel that includes the immediate neighborhood and treats the rest as ports is often sufficient and aligns naturally with mitigation options such as gasketing or bond reinforcement. When the symptom involves large-scale cavity modes interacting with cable common-mode currents, a macromodel of the enclosure that captures a handful of dominant modes and their coupling to cable terminations provides the needed insight and invites experiments where cable routing is systematically varied to measure sensitivity [26]. Conversely, when the symptom is a narrow conducted emission line whose amplitude correlates with control-loop parameters, a field solve offers little added value compared with mixed-mode network analysis and time-domain measurements performed under controlled toggling of internal activity.

Practical constraints such as CAD availability, meshing robustness across fillets and chamfers, and proprietary material stacks weigh heavily in tool choice. The introduction of generic seams or homogenized anisotropic sheets to stand in for complex perforations can be justified if the surrogate parameters are calibrated once per technology and reused across programs. That approach amortizes the cost of a high-fidelity campaign and delivers models that can be exercised in design phases where geometry is fluid. It also keeps the analysis anchored to parameters that sourcing and manufacturing can influence: seam pressure, plating thickness, gasket compression, and bonding circumference. Full-wave computation plays a crucial role in the initial calibration, providing the data from which a compact parametric description is distilled.

It is important to recognize that field detail can seduce decision makers into overconfident interpretations. Colorful plots of surface currents and electric fields stress features that may not govern the observed figure of merit, especially when post-processing thresholds and dynamic ranges are chosen for visual appeal. Actionable analysis resists that temptation by tying every plot to a quantifiable transfer pathway: how much of the measured common-mode current on a cable can be attributed to a particular seam under a given excitation; how the movement of a return via by a few millimeters changes the mode conversion at a specific connector; how a reduction in gate-slew rate alters the fitted equivalent dipole moment at a switch node and, through the enclosure macromodel, the far-field level in a regulatory band [27]. The currency of argument becomes sensitivities and contributions, not isolated images.

Finally, the role of prior literature is to point out recurring patterns rather than to dictate a single method. Analyses that document the resource intensity of full-wave methods and their limited direct actionability in root-cause attribution have encouraged the turn toward hybrid and reduced approaches, but those observations are only one input among many that motivate a workflow where measurement, reduced modeling, and targeted simulation interact. In a mature practice, full-wave simulations are commissioned with precise questions: to identify whether an aperture couples predominantly to a given cavity mode and to quantify the coupling coefficient; to compute the scattering matrix of a connector neighborhood under a small set of cable terminations; to validate the passivity and accuracy of a macromodel over a specified band. Everything else—ranking of mitigations, robustness under variability, mapping of design knobs to outcomes—leans on models whose dimensionality and structure reflect the few degrees of freedom that matter for the phenomenon. By approaching the problem in this way, the analysis remains tractable, the conclusions become testable with limited experiments, and the flow from hypothesis to edit acquires a clarity that is often missing when inspection of full-wave fields is used as a primary diagnostic, as several studies over recent years have underscored in diverse settings.

7. Measurement and Diagnostics

Measurements aimed at identifying EMC sources must contend with probe loading, calibration stability, fixture resonances, and the limited spatial and spectral sampling achievable under time constraints. A diagnostic plan gains reliability when it explicitly acknowledges these imperfections and treats measurements as operators acting on underlying currents and fields rather than as direct readouts. The operator viewpoint encourages the use of multiple probe types and positions to triangulate equivalent sources through redundancy. [28]

Near-field scanning furnishes spatially resolved signatures that can be compared with current or field maps predicted by models. A coarse-to-fine scan strategy allocates measurement density proportional to observed gradients, improving coverage without undue time. To relate probe outputs to equivalent source quantities, one may apply deconvolution using known probe transfer functions. In practice, robust estimation that penalizes high spatial curvature in the reconstructed fields helps manage noise amplification. If $\mathbf{y} = H\mathbf{x} + \mathbf{n}$ represents discretized measurements with forward operator H, a Tikhonov-regularized estimate of equivalent current coefficients $\hat{\mathbf{x}}$ can be obtained by minimizing $\|\mathbf{y} - H\mathbf{x}\|_2^2 + \alpha\|\mathbf{L}\mathbf{x}\|_2^2$ where $\mathbf{L}$ encodes smoothness.

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \left(\|\mathbf{y} - H\mathbf{x}\|_2^2 + \alpha\|\mathbf{L}\mathbf{x}\|_2^2 \right), \qquad (H^*H + \alpha L^*L)\,\hat{\mathbf{x}} = H^*\mathbf{y}$$

Conducted measurements with current probes and LISNs are subject to clamp transfer uncertainty and fixture parasitics. Calibration traces recorded before and after a measurement run can be used to bound drift. When possible, in-situ two-tone or swept-sine excitations help estimate transfer functions between candidate aggressor nodes and victim nodes. A vector network analyzer configured for mixed-mode S-parameters supports separation between common and differential responses, although adapter and cable effects must be de-embedded [29]. The chain is represented by a cascade of two-ports; logarithmic magnitude addition is not valid due to interactions, so one must compute the resulting S-matrix or Z-matrix of the assembled network.

$$S_{\mathrm{tot}} = S_3 \star S_2 \star S_1, \qquad \star: \text{ Redheffer star product}, \qquad Z_{\mathrm{tot}} = (Y_1 + Y_2)^{-1} \text{ in parallel topologies}$$

Time-domain reflectometry aids localization of discontinuities in return paths and shields. A fast step launched into a return reference and sampled at sensitive nodes reveals reflections whose timings map to physical distances. The conversion between time and distance depends on effective permittivity; measurement of rise-time spreading along known traces can calibrate the local velocity.

$$z = \frac{c\,t}{\sqrt{\varepsilon_{\mathrm{eff}}}}, \qquad \varepsilon_{\mathrm{eff}} = \frac{\ell}{c}\left(\frac{t_2 - t_1}{\Delta z}\right)^{-1}$$

Electrostatic discharge diagnostics benefit from wideband current monitoring at entry points combined with field probes inside enclosures. By aligning the timing of current peaks and field maxima, one can discriminate direct injection from secondary excitation of enclosure modes. Wavelet transforms provide joint time-frequency views that isolate early transients from late reverberations. Parameter fits of double-exponential source models to measured waveforms yield coefficients that then drive simulations or reduced models used to predict victim voltages under altered configurations.

Statistical repeatability is a practical concern [30]. Environmental variations, loose cable positioning, and temperature affect measured amplitudes and phases. Reporting results as ranges, medians, and interquartile spans communicates robustness without overstating precision. When separating internal and external contributions, controlled toggling of internal activity while monitoring emissions or susceptibility under fixed external conditions allows differential attribution. For instance, gating a converter or forcing IO pins to a static state can reveal background external coupling that persists independent of internal switching.

8. Mitigation and Design Strategies

Mitigation strategies are most effective when tied to characterized source-path-victim relations. Without attribution, interventions risk masking problems in one condition while exacerbating them in another. Layout adjustments that minimize loop areas and align return stitching to crossing traces reduce differential emissions and conversion to common mode. Placement of filters at impedance breaks intercepts currents before conversion occurs deeper in the system. Shielding modifies boundary conditions experienced by internal and external fields, but gaps, seams, and penetrations can create apertures that must be managed with bonding and gasket practices tuned to target frequencies. [31]

Return-path integrity is a lever that affects both internal and external coupling. Stitching capacitors and vias across splits enable high-frequency displacement current closure. The spacing and value distribution should align with the spatial spectrum of return currents inferred from measurements or models. A rough design rule is to place stitching features at intervals shorter than one-tenth of the shortest wavelength of concern along likely return corridors, with values chosen to keep the impedance of the stitching network below the desired threshold across the band of interest. While such rules provide starting points, measurements of local impedance using a two-port probe that injects current between areas and senses voltage inform the tuning of placements.

$$Z_{\text{bridge}}(\omega) = \frac{1}{j\omega C_{\text{stitch}}} + j\omega L_{\text{via}} + R_{\text{ESR}}, \qquad |Z_{\text{bridge}}(\omega)| \ll |Z_{\text{return}}(\omega)| \text{ over target band}$$

Common-mode chokes on cable interfaces address external conducted ingress and egress by raising common-mode impedance while leaving differential signals comparatively unaffected. Their effectiveness depends on the distribution of leakage and on the presence of parasitic capacitances to local ground near the choke. If parasitic capacitance shunts common-mode currents around the choke, the net attenuation diminishes. Distributed filtering that combines a choke with series resistors or RC shunts at points of mode conversion can produce broader suppression than a single element [32]. The choke's impedance magnitude and phase across frequency should be measured or modeled under bias and temperature to verify alignment with the spectral content of identified common-mode currents.

Power distribution design manages internal converter-driven sources by shaping the impedance seen by loads and by confining energy within the plane pair. The target impedance concept guides decoupling networks; the objective is to keep the PDN impedance below a limit over the frequency range where load current transients occur. Placement of capacitors near switching nodes and at load clusters reduces loop sizes and helps avoid exciting plane resonances. However, the addition of capacitors alters the modal landscape, sometimes introducing anti-resonances that create peaks in impedance. Damping with series resistors or lossy capacitors can reduce Q-factors at the cost of additional dissipation.

$$Z_{\text{PDN}}(\omega) = \left(j\omega L_{\text{pkg}} + \sum_k \frac{1}{j\omega C_k + \frac{1}{R_k} + j\omega L_k} + \frac{1}{j\omega C_{\text{plane}}} \right)^{-1}, \qquad Z_{\text{PDN}}(\omega) \le Z_{\text{target}}$$

Shielding treatments consider not only material conductivity and permeability but also the bonding of seams and the treatment of apertures and penetrations. The shielding effectiveness of a panel with finite conductivity depends on skin depth relative to thickness, while seams behave as slot arrays whose transmission accumulates across lengths. Adding fingerstock gaskets or conductive elastomers reduces gap admittance but may introduce contact nonlinearity under vibration [33]. Cable penetrations should be bonded circumferentially where possible to prevent currents from traversing long pigtails that radiate; where circumferential bonding is impractical, ferrules and clamps can shorten the effective length of pigtails and increase local loss.

Grounding strategies mediate both safety and EMC considerations. Single-point concepts provide intuitive control of low-frequency currents but are fragile at high frequencies where parasitics render paths multi-point by necessity. An equipotential reference realized by wide, closely spaced return conductors and by numerous stitching points behaves more predictably across frequency. The language of impedance rather than topology is helpful: paths that appear single-point in schematic become low-impedance meshes through distributed capacitance and inductance. Characterization of these impedances by measurement helps avoid misinterpretation of layout features that, although well-intended, create unexpected resonances.

Device-level controls such as edge-rate limiting and spread-spectrum modulation influence internal source spectra. Slower edges reduce high-frequency content in principle, yet the interaction with return impedances can shift energy into lower bands where regulatory limits may be tighter [34]. Spread-spectrum techniques expand monotonic lines into skirts that may or may not improve compliance depending on detector time constants and limit curves. Quantifying these tradeoffs within the modeling framework described earlier keeps expectations grounded and avoids relying on heuristics divorced from observed parameters.

9. Conclusion

The identification and characterization of internal and external sources of electromagnetic compatibility (EMC) issues in complex circuits depend on a balanced treatment of fields, circuits, and measurements. In practice, this balance arises from the recognition that electromagnetic energy does not confine itself neatly to one domain. Fields radiated from traces and planes are inseparable from the currents and voltages that sustain them, and measurements that capture emissions or susceptibilities inevitably reflect both. Internal sources arise from switching actions, clock distributions, power conversion, and substrate interactions, each producing characteristic temporal and spectral signatures. Their behavior is shaped by return-path impedances, parasitic capacitances, and geometric resonances embedded within the interconnect and packaging structure. When clock or switching edges propagate along paths that do not provide well-defined return currents, the resulting voltage differentials can excite cavity modes within the printed circuit board or the enclosure, leading to radiated emissions whose spectral content extends far beyond the fundamental switching frequency. These same mechanisms can modulate sensitive analog or RF circuits through shared supplies or substrate coupling, introducing jitter, noise, or intermodulation distortion. [35]

External sources, by contrast, couple into systems through both radiated and conducted mechanisms. Radiated coupling occurs when electromagnetic fields from nearby transmitters, switching power equipment, or other electronics induce currents in cables, traces, or structural apertures. Conducted coupling arises when disturbances enter through power or signal connections, propagating along shared conductors into internal circuitry. The effectiveness of such coupling depends strongly on geometry—apertures in shields, cable lengths, harness terminations, and discontinuities in ground or return planes. Symmetry breaks are particularly influential, as they convert common-mode energy, which ideally would circulate harmlessly, into differential disturbances that affect circuit operation directly. Even subtle asymmetries, such as mismatched trace lengths or unbalanced cable shields, can create significant mode conversion. Understanding and mitigating these effects require both geometric modeling of field distributions and circuit-level representation of the corresponding impedances.

A modeling perspective that admits both distributed and lumped representations and that respects parameter identifiability provides a path toward practical attribution. Distributed models capture wave propagation, resonant behavior, and field coupling; lumped models capture localized interactions such as device-level switching, component parasitics, and return impedances [36]. Combining these representations within a unified framework allows engineers to interpret measurements and simulations coherently. However, such hybrid modeling must confront the issue of identifiability—only certain parameters can be inferred from available data without ambiguity. For instance, measuring an emission spectrum does not uniquely determine whether the underlying source is current-driven or voltage-driven, nor does observing a voltage waveform at a single point reveal the full current distribution. Therefore, any modeling approach must incorporate constraints based on physical reasoning, known topology, and controlled experimentation.

Measurements play a central role when interpreted as operators acting on underlying sources. Each measurement configuration—be it a near-field probe, current clamp, or network analyzer—can be viewed as applying a known operator that transforms the physical sources into observable quantities. By systematically varying these operators and applying regularized inversions, one can infer the distributions of currents and voltages responsible for observed emissions or susceptibilities. Regularization is essential because inverse problems in electromagnetics are typically ill-posed: small errors in measurement can lead to large deviations in reconstructed sources. Techniques such as Tikhonov regularization, Bayesian inference, or sparsity-based optimization constrain the solution space, ensuring that inferred parameters remain physically meaningful [37]. Mixed-mode network analysis extends this principle to multiport systems by decomposing signals into differential and common-mode components. Measuring and modeling the corresponding S-parameters allow quantitative linkage between aggressor and victim paths, enabling prediction of coupling strengths under varying configurations.

This analytical foundation supports mitigation strategies that are both targeted and stable. When return paths are identified explicitly, design strategies can focus on closing these paths to minimize loop area and suppress magnetic coupling. Controlling mode conversion requires maintaining symmetry wherever possible and inserting filters or chokes at known imbalance points. Power distribution impedance must be tuned across frequency so that switching currents find low-impedance routes back to their sources without spreading through sensitive domains. Apertures and penetrations, whether in shielded enclosures or multilayer structures, must be addressed as coupled field-circuit interfaces rather than isolated mechanical features. The quantitative linkage of sources and paths allows designers to predict how modifications—such as adding decoupling capacitors, rerouting traces, or adjusting grounding schemes—will affect overall electromagnetic behavior before fabrication or testing.

Crucially, the approach described here avoids single-method prescriptions [38]. Rather than asserting that filtering, shielding, or grounding alone will solve a problem, it emphasizes consistency of parameters and transfer relations that connect observation to cause. By maintaining a common framework across measurement, modeling, and design, each step reinforces the others. For example, a measured transfer impedance between a noisy converter and a sensitive analog node can be validated against simulated coupling paths; if discrepancies arise, they indicate missing elements in the model rather than measurement error. Over time, this consistency builds predictive capability that transcends specific projects or technologies.

Within this framework, mitigation becomes not a collection of independent remedies but a logical consequence of identified coupling. When the physical origins of interference are known, countermeasures can be chosen to interrupt those specific pathways rather than applied generically. A ferrite bead becomes not a mysterious cure but a defined impedance element inserted to attenuate a particular mode; a ground stitch is not an arbitrary addition but a closure of a recognized return loop. Because these design decisions rest on measurable parameters and transfer functions, they remain valid across operating conditions and product variations. Environmental changes, component substitutions, or mechanical modifications may alter details but not invalidate the fundamental relations among sources, paths, and victims [39].

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