ELECTROMAGNETIC COMPATIBILITY (EMC) FOR SYSTEM ENGINEERS

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Abstract
Spurious EM interactions within and between systems endanger and may disturb their proper functional performance. The prevention, elimination or suppression of such electromagnetic interference (EMI) to a satisfactory level constitutes the engineering discipline– EMC – ElectroMagnetic Compatibility. Its objective is preservation or recovery of expected performance of electronic systems at minimal cost and minimal disturbance of the systems' development process. The need to provide timely solutions, commensurate with the system state of development, binds EMC tools, methodology and management to efficient approximations, modeling and predictions relying on incomplete knowledge of the system, and efficient measurement sequences. Lessons learned on EMC effort management, and insights gained are reviewed in perspective of 50 years of development of EMC.

Introduction

Electromagnetic engineering is the application of science to useful purposes by utilizing configurations whereby the complexity of interactions is reduced to one that serves the purpose: electrical current flows in wires, charge is accumulated in capacitors, waves propagate in transmission lines and waveguides, and antennas are the gateways for transmission and reception of radiated signals. The residual interactions, negligible within the engineered application, may become significant in another part of the system or in another system, where the spuriously interacted signal exceeds its sensitivity. The analysis of the spurious interactions is by far more complex. It may involve all parts of the systems, and require detailed layout and signal analysis of all the systems potentially interacting, and comprehensive modeling of all possible modes of electromagnetic interactions. Reduction of such a sizeable effort to match the resource allocation within a system development project entails compromising the analysis and measurements just to the fineness required by the system sensitivities and level of reliability, and an efficiently managed, effort-bound, process of risk reduction by curing potential system interferences as they are unveiled along the phases of development of the system concept, design, layout, packaging and operation.

EMC employs reference models and topologies, computation techniques and measurement methods. These are constrained by the *proportionality of the EMC effort* to the system-project effort, the *impact of the EMI on the system functionality*, and by a *progressive/ iterative methodology*, continuously utilizing the accrued knowledge about the system along the development path.

EMC methodologies have evolved in response to the immense growth in density, sensitivity, bandwidth and complexity of electronic systems over the last 50 years, often compactly packaged with high power electronics [1,2,3,4,5,6]. Challenges that are fundamental to major technologies and applications have received due attention, harvesting structured methodologies that blended into their respective engineering: layout of high-speed and RF integrated circuits, integration of interference-handling into the wireless communications' signal management and processing, and others. However, each new integration or co-location of different circuits or systems, or new configuration or packaging, poses challenging risks of interference that need specific attention, even if the system concept is well established and the system project is considered low-risk. This is a challenge of a project-within-a-project, running across the mother project and structured to accommodate the high risk of EMI.

The following sections discuss: *the nature of EMI; the challenge of EMC; EMC management within a project; EMC tools: computations and modeling, measurements, standards and regulations.*

The nature of EMI

EMI - Garbage of Electronics.
The leftovers after engineering approximation to physics.

Interference is generated in a circuit/ system when a benign signal for that circuit propagates through spurious coupling and affects another victim circuit/ system, or when an improper signal is generated in the circuit and then propagates through proper or spurious coupling and affects the victim circuit. Such signals are considered interference only when they affect the system performance. This process is schematically mapped in the interaction map, Figure 1: *sources* generate Interference signals during *events*. These propagate through the system/ between the systems via proper routes (*systems rules*) or improper (*spurious*) paths, and received by respective sensitive *receptors*. Signals received by one or a combination of receptors, exceeding the system sensitivity threshold *("relevant")* create *failure/ disturbance events*.

Relevance is a metric comparing the interference signal at the receptors with the system threshold. The *relevance filters* are:

- Amplitude threshold, in terms of the receptor sensitivity, e.g. voltage, power, energy.
- Frequency correlation.
- Time correlation: single event, logic sequence, phase (in narrow band).

Interference sources and events

Benign signals, coupled through passive, linear, paths, are predictable *events* that can be reliably repeated for detection and modeling. They are detectable and recognized by their known features: frequency, modulation, timing etc. (a good example is the interference from pulsed radar that can be predicted and blanked out by gating the receptors).

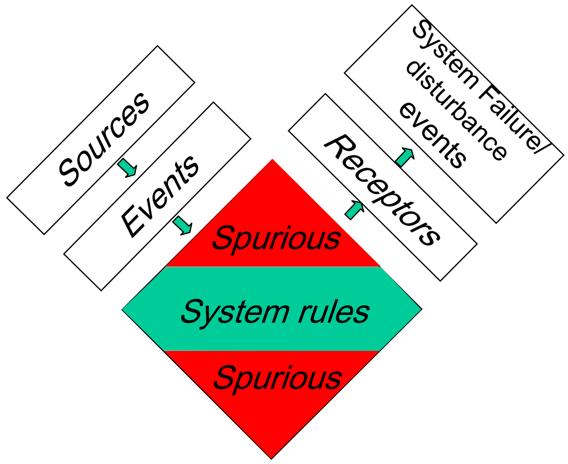


Figure 1: The interaction map

Signal generation through a non-linear process (e.g. signal multiplication and generation of new frequency products, or generation of harmonics of a benign signal) may occur in circuit elements that are driven away from their proper working point (e.g. by a voltage surge) or in corroded connections along the transmission path. Detection of such spurious signals requires a search in the spectral domain.

Least predictable are transient signals. These occur during a change of state of a circuit (e.g. switching), an inadvertent correlation of a series of events with the victim-system clock or logic, or a failure of a circuit or a component. Transients may have an impact by a discharge/ avalanche or excessive heat effect in the victim circuit/ component either per event or by charge or energy accumulation through a series of transients. These are the least predictable events and hardest to intercept and model.

Interference propagation/ coupling

The electromagnetic forces act at a distance. Engineering applications utilize materials and configurations that capture the dominant fields or their effects: wires carrying current and subject to voltage difference, lumped components (capacitors, inductors, resistors), transmission lines, etc. The residual fields (e.g. distributed induction and capacitance between wires, radiation through imperfect shield, etc.) that have negligible impact on the operation of the source circuits may propagate and be relevant to sensitive receptors in other parts of the system. Their modeling is by far more complex: inductive, capacitive and radiative

interactions may be involved in an environment hardly lending itself to separation of "building blocks". The EMI topology has to be *conjectured* to canonical EM interaction configurations, based on judicious approximations of the specific layout involved –and then verified by measurements.
EMI interaction is primarily classified to these groups of propagation topology:

Interference between wireless transmissions of structured signals. The means of transmission are antennas. The interaction filters are space (directional and polarization selectivity, and path attenuation), frequency, time, modulation, code, etc. Such interference between wireless services is regulated by regulating bodies, national and ITU. The analysis, modeling and mitigation of wireless interference are part of the hard core of communications, radar and remote sensing engineering and are not salient to EMC.

Emission/ reception of open space radiation other than through antennas. Radiation coupled to wires and penetrating through slots in shields (conducting, magnetic or absorptive surfaces). A major analysis and modeling thrust was undertaken during the 80s to counter the threat of EMP (Electromagnetic Pulse) and then HPM (High Power Microwave), led by the US Air Force and culminating in the series of Interaction Notes. A comprehensive Electromagnetic Topology ("EMT") was formulated, anchored on the BLT (Baum-Liu-Tesche) equation that formulates a generalized scattering/ transmission equation for complex structures encapsulated in layered shields [7,8]. The practicality of this formulation to actual systems is discussed below.

Electrostatic discharge (ESD). Electrostatic charges may accumulate between the system and its environment, or between parts of the system, and then discharge when the voltage reaches the breakdown point, creating a transient signal. Microelectronic circuits are ESD-prone during close contact with human or machine handling. High-voltage discharge, reaching hundreds of KV, are prevalent with aircraft, discharging to the ambient air, or to the ground upon landing, vehicles accumulating charge through friction with the road, etc[9,10].

Intra-system interference. Both the sources and the receptors of the interference are internal to the system. Compactly packed systems lend themselves to such interactions. Such systems may be

– Coherent system: the EM signals generated in the system are inter-related to produce system's functions according to the system rules.
– Heterogeneous systems: multiple EM-coherent systems, packaged together, that are EM-independent but have functional system relations (e.g. manned vehicles, manned aircraft).

This is the most complex interference challenge. No single spurious interaction mode is known a-priori to have dominance. The observation, analysis and modeling into an effective topology may incorporate both a top-down approach, observing the system effect and seeking its propagation path – and bottom-up, trying to suit interaction modes to cascaded blocks along the path[2,7,8].

The EMC challenge

The objective of EMC is reducing the spurious interactions within and between systems below the threshold of interfering to the systems' functions and performance. This undertaking may take the form of a *stand-alone project* or of an *adjunct project* within the system-development project.

The development of a generic EMC solution to a class of systems (e.g. design rules for integrated circuits) warrants a major stand-alone effort whose cost is justified by the savings thereafter[9,10]. However, a recovery effort for an (operating) system that is already EMI-infected and requires changes in order to reach its full performance – is highly cost sensitive. The cost of such an effort is proportional to the system's complexity. It entails diagnosis, analysis, measurements, changes in architecture, signal design and routing, layout and packaging.

The cost of synchronizing the EM compatibility effort with the system development process, from the conception phase on, accrues proportionate to the accrued cost of the system development. The rate of interference-risk reduction is proportional to the resources allocated and disruption of the project. These amount to the equation of the project burn-rate due to EMI mitigation:

$$BR_{EMC} \propto -C\big|_t \frac{dR_{EMI}}{dt} \qquad (1).$$

Here BR_{EMC} is the burn-rate of the project due to EMI mitigation
$C/_t$ is the accrued cost of the system project
R_{EMI} is the risk of system failure due to EMI.

While the accrued cost derives from the project strategy, the second term depends on the EMC strategy: a posteriori fix approach penalizes the project in high cost and in delay. A reduced risk approach by over-designing the EM isolation between circuits may cost in system performance, weight and cost. An attempt to achieve compatibility by adaptively tailoring the design, layout and signals' structure of the system constituents, requires an interactive diligent effort across the project working groups and throughout the project development.

The rate of reducing EMI risk, dR_{EMI}/dt, is bounded not only by the level of effort but by the shear lack of information on potential spurious interactions. Possible spurious interactions in the system are not known at the onset. Only interactions anticipated from the conceptual architecture can be inferred during the conception phase. More information can be extracted during validation, when critical tests are carried out. The signal paths and system configuration, as developed through the project, also create further spurious interactions. Late unveiling and mitigation of these cost a higher already-committed effort (lost cost), as portrayed in Figure 2. The interactive EMC effort is fed by the project available design information and samples to test, and feeds back recommended changes in system block diagram, signal flow, layout and packaging. Early EMI unveiling and mitigation obviously reduce the cost of any changes needed and disruption of the project pace[2,4].

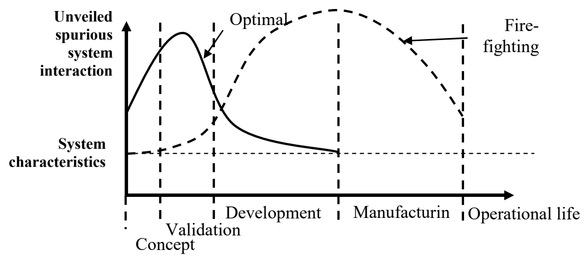


Figure 2: unveiled spurious system interactions

Management of EMC in System Development

A project, according to [11], is "a temporary endeavor undertaking to create a unique product or service". A certain value is perceived to be gained upon completion, and resources are planned toward this goal (cost of project). The process of project planning is analytic: sub-projects (phases) are defined and work packages organized and are inter-related by progress and by resource allocation. The progress is measured by the accomplishment – increasing the value toward the objective. However, if such an achievement depends on reducing the risks ahead it is not actually an achievement rather a risked expenditure (in cost and in time). A true measure of progress is thus the reduction of risk to achieve the project value[12]. The optimal rate of risk reduction in the project from its onset to completion is obtained considering the concurrent rate of change of the project expenditure – its burn-rate. The cost lost during an incremental time (as in the dashed brackets in Figure 3) is the product of the risk and the project burn-rate, $R(t)\bullet BR(t)\Delta t = \Delta\left[Lost\ \cos\ t\right]$. Minimizing the lost cost over the project (Eq. 2) entails a concave risk-reduction curve and an escalating burn-rate curve accordingly.

$$\int_0^T R(t)\bullet BR(t)\bullet dt = Lost\ \cos\ t \Rightarrow \min \qquad (2)$$

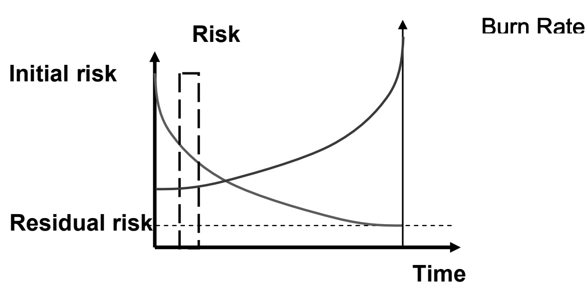
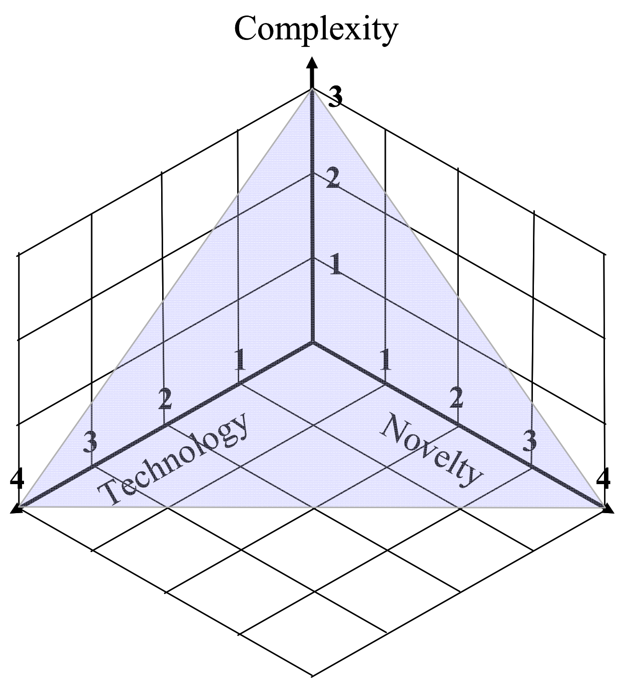


Figure 3: minimizing project cost

This model advocates expediting the reduction of risks before launching high-cost investments. The direct consequence is that the project pace is bounded by the remaining risk, and is not an independent parameter. Time-squeezing techniques of project management (as in CPM – Critical Path Method) are then effective only for low risk projects or phases thereof.

The impact of project risks in complexity, novelty (in system integration and application) and technology uncertainty on their management style have been shown by Shenhar and Bonen [13]. This is portrayed in Figure 3. (The triangular pyramid marks the reasonable risk zone)[1].



	1	2	3	4
Complexity	Sub-system	System	Array of systems	
Novelty Technology	Minor engineering modifications	Derivative of previous version	Known feasibility, no details	No feasibility known

Figure 3: The dimensions of Project Management

EMI risk may be mapped by the same dimensions. The meanings of these axes are different, however. The EMI risk lies in the system implementation: signals' generation, structure and paths, system layout and packaging. It may be high for otherwise low-risk project. The cost of its mitigation is typically a small fraction of the project cost, but its share in the project risk may be high. The synchronization of the EMC effort into the project management has to consider

[1] Shenhar &Dvir [14] proposed a four-dimensional project management model (the "diamond model") adding the project pace as an independent axis. It can be argued from Eq. 2 and thereafter that pace is an independent parameter only for low-risk projects.

both maps and their respective management styles. Early address of the EMI risk, while deferring high-cost project activities until EMI mitigation is underway, appears to optimize cost and time of the project. This is portrayed in Figure 3, exemplifying Equations (1,2).

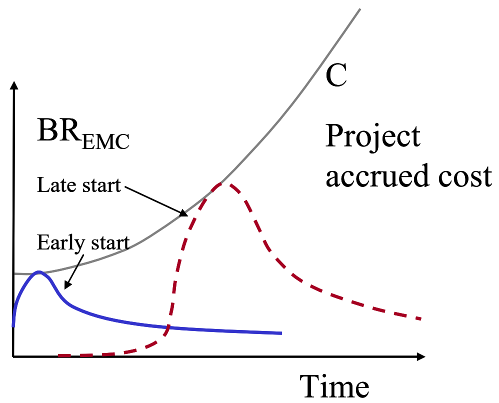


Figure 4: The EMC-effort Burn-Rate

A major part of the EMC project is unveiling of the failure/ disturbance modes and ranking the interaction map by probability of failure, then mitigating failure modes according to the project policy of reliability. The techniques for mitigating known interactions are within good engineering practice in most cases and do not constitute substantial risk. The changes required in the system may be costly, however, and delay the project. The logical sequence of the EMC activity is:

- Data gathering and creating a gross interaction map.
- Analysis, assuming topology, modeling the interactions and simulating.
- Ranking the interference map (by assumed hierarchy).
- Measurements on prototypes.
- Redrawing a reduced interaction map.
- Design and apply EMC changes.
- Validation tests on prototypes.
- Evaluation/ qualification.

The sequence may then re-iterate when further information is unveiled along the system development.

EMC activity impacts the project in each of these phases. It interacts across the project’s work groups and creates unpredicted dependencies between them. Frequent information update across the project is needed. System/ sub-systems and simulators have to be made available for observation tests, model verification tests and then validation tests. Changes in the system may have to be implemented along the development path. The management of synchronizing these with the project depends on the project characteristics and risk level. Low-risk projects are planned to optimize resource allocation. Risks are mainly logistical and their probability is calculated based on statistics of past experience. The EMI risk, however, is lack of knowledge of the nature of the potential problem [15] .The knowledge-gap does not lend itself to statistical assessments and to a-priori synchronizing the EMC into the project work packages and logical structure.

High complexity projects tend to have a respective complex project structure. The dimensions of the interaction map grow exponentially with the complexity of the system. System prototype have to be made available for both data gathering phase and then validation phase, which may have more than one iteration. The dynamic synchronization of the effort necessitates a formal coordinator at the project management level.

Highly novel projects incorporate a new architecture, and the whole interaction map has to be built. The project is risk-prone and its structure is multi-phase, blending the EMI effort more naturally into the review cycles.

Technology uncertainty affects the project management where the uncertainty applies. Generic EMC effort may be needed on applying new technology, in order to characterize interference models typical to the technology.

EMC Tools

The interaction map relates interference sources to failure events. The initial map, listing all potential sources and failure events, forms a huge matrix, whose reduction to a verifiable true interaction map is an insurmountable task within the context of a system development project. The reduction process is a combination of observations, analysis, modeling and measurements [16,17]. Acknowledging the system rules, the spurious interactions are ranked by probability of failure event by filtering possible links in the amplitude, frequency, time and logic domains. This rough sorting is further refined by modeling propagation of the interference signals. The complexity, and in most cases also lack of detailed information, hinders the development of a comprehensive electromagnetic model. Judicious assumptions based on available observations may allow for structuring local hierarchies and thereupon a topology for EM interaction through the system. This whole process is based on assumptions and needs verification by measurements. Interactive progress through modeling and measurements proves to be cost-effective [18,19,20,21].

EM modeling

A model has to represent the interactions within the system and predict the response to specified excitations, with acceptable accuracy and reliability. It has to be formulated by measurable entities, testable for functional relations between them and other system-measurable parameters. Good models provide both trends and bounds [5].

Topology is a reduction of the global EM interaction problem to an ordered network, based on the hierarchy of the interactions. The system elements are segmented into groups by hierarchy of coupling, and topology orders the interaction between the groups. A comprehensive effort to formulate a generic Electro-Magnetic Topology (EMT) was first conceived by C.E. Baum [7,22] and then pursued intensively by the US Air-force under the High altitude Electromagnetic Pulse (HEMP) program, and published in a series of Interaction Notes. The threat covered by that program is a high intensity electromagnetic field, generated by a source located at high altitude, and thus forming a large-scale plane wave on the ground and on remote targets. The spectrum of the pulse covers UHF to about S band. The major underlying assumption in Baum's EMT is the existence of layers of "good shields" within the victim system allowing for subdividing the volume where EM interaction takes place into a multitude of smaller volumes, isolated from each other by the shields[23,24]. Interaction between volumes then takes place only through a small number of links ("tubes"): wire harnesses, or inductive or radiative coupling through apertures. The network thus formed is formulated by the BLT equation [7,8,25], a "super-scattering equation" connecting the voltages at the ports of each of the shielded volumes.

The neat formulation of the overall system's EM interactions encounters shortfalls, however, in gaining credibility for EMC:

– It is attuned to HEMP scenario[26,27], not so much to intra-system interference where the layering of shields is ambiguous.
– The Good Shield Approximation (GSA) that forms the basis for subdividing the interaction into separate volumes – is an assumption that is far from being test-proof and is not valid in many classes of systems.
– The "tubes" between the shields (multi-wire harnesses or alike) – are not always uniform and not repeatable from one to another. Their analysis reduces to estimating Norms (max interference) rather than values, sometimes too coarse for the purpose[28].

The European Community launched in 2000 an EMC modeling effort for the car industry – GEMCAR[29,30]. Application of the Baum's EMT proved useful as initial conceptual guidelines only. A practice adhered to is typifying each system class by its characteristic initial topology, refined thereafter by further measurements and analysis [31,32]. Types of signals and operational sequences, and configuration and packaging, serve for this classification. The following classes are recognized in the car industry:

– Communications (dominated by external radiation)
– Automotive functions (dominated by internal conductive coupling)
– Hybrid/ electric (high power low frequency)
– Safety (radar etc.).

Intensive modeling efforts took place in the computer industry – both at the PCB level and the packaging levels[33].

Computation tools for EMC

The tremendous advancement in computation complexity and in computers' volume and speed of processing - offer a variety of powerful tools for EM modeling. These are tempting for addressing EMI problems that are most complex and encapsulate the whole system and its EMI interactions. This goal proves yet to be too ambitious. Highly detailed description of the configuration may be needed for computing local interactions, including slots (whether intentional or caused by loose screws), material properties, etc. The amount of data required is insurmountable, and so is the complexity of computation of the required fine mesh. Advances in computational EMC are reported in the following classes [28,30,34,35,36]:

– Multiwire harnesses networks and interaction - CRIPTE code [37,17,20, 38,39].
– 3D codes for external radiation problems [40, 34]
– Printed and integrated circuits [33,41,42,43]
– System topology simulation [20,28, 30,44]

EMI measurements

Measurements serve throughout the life cycle of the system: in diagnostics, validation, compliance/ verification and regulatory compliance. The nature of scope of measurements varies with the application. Regulatory compliance is a well defined measurement procedure in terms of the test configuration, test equipment, measured parameters and threshold values. Diagnostic, validation and verification measurements are system-specific, tailored to the system complexity and state of knowledge. They sample parameters of the system state between the measurement probes, and serve to build models that describe the system and relate excitations to responses [45].

The initial interaction map, listing all potential EMI-related sources-to failure modes coupling, represents the lack of models to predict system response. The respective scope of measurements required for characterizing the spurious interactions/ failure modes - is substantial, and its reduction ("culling") is essential. It is obvious that Monte-Carlo sampling the measurement ports does not increase reliability of any element that was not tested, and is not a viable testing model. A model-based culling employing an iterative sequence of measurements and analysis has been applied successfully, reducing the matrix size by two orders of magnitude [18,19]. Alternative models were tested computationally for their response to a structured excitation (e.g. swept frequency, shaped pulse), and compared to measurements. The measurements were used for choosing the models for each interaction, thus gaining a hierarchical topology based on dominant interaction models. This verified topology is then used to cull the weak interactions and schedule the measurements accordingly.

The measurement program is a significant effort that requires preparation and coordination with the project activity. The system under development has to be made available, including the respective labor for its operation. The higher the innovation in the system, the more measurement phases may be needed. High complexity necessitates the tests of more layers (subsystems) and their combination.

Major test facilities [46] for exposing systems to external radiation, serve to test global susceptibility and system qualification. They are not effective for diagnosis, where local interactions (e.g. skin penetration) are sought. This requires local probing [47].

Standards and regulation

EMI is an interactive coupling between circuits and systems that depends on the specific configuration of the systems and their neighborhood. *Interface specifications*, *standards* and *regulations* are protective measures aimed at reducing the risk of EMI within classes of configurations. They refer to, and tested according to, specified configurations and conditions, considered as references for each class. They do not guarantee immunity against EMI, but reduce the risk, to the extent that the system configuration within its environment resembles the reference[48].

Standards are classified into product standards, for specific products' classes, and generic standards, relating to the EM environment. They further specify conductive(grounding and power lines), inductive (cables) and radiated interference, and according to low frequency (mainly power systems) and RF. International standards and regulations specify levels and measurement procedures per frequency band. There are national and international regulatory bodies for EMI control. IEC **-** International Electrotechnical Commission is the international standards and conformity assessment body for all fields of electrotechnology. Its members are national committees and other interested bodies. CISPR – International Special Committee for Radio Interference, is a special committee of IEC.

Compliance with specification and standards may reduce the EMC engineering effort during systems' development, but a price of excessive weight and system cost, and potentially limited performance. Judicious use of these standards should suit the configuration and environment destined for the system, and no more.

Epilog

EMC is a system engineering discipline. The EMC wisdom lies in diagnosis of relevance, topology and hierarchy of interference, and balance of cost-effectiveness in its mitigation. "Green" techniques of cautious utilization of resources, and adaptive techniques for optimizing the performance of systems in the cluster, utilizing sensing/ cognition and adaptation, are envisioned to improve overall performance and use of common resources.

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