The Threat of Radiated Intentional Electromagnetic Interference (IEMI): Deterministic and Statistical Prediction Models for Field Coupling to Cables and Systems

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IEMI

Intentional Electromagnetic Interference

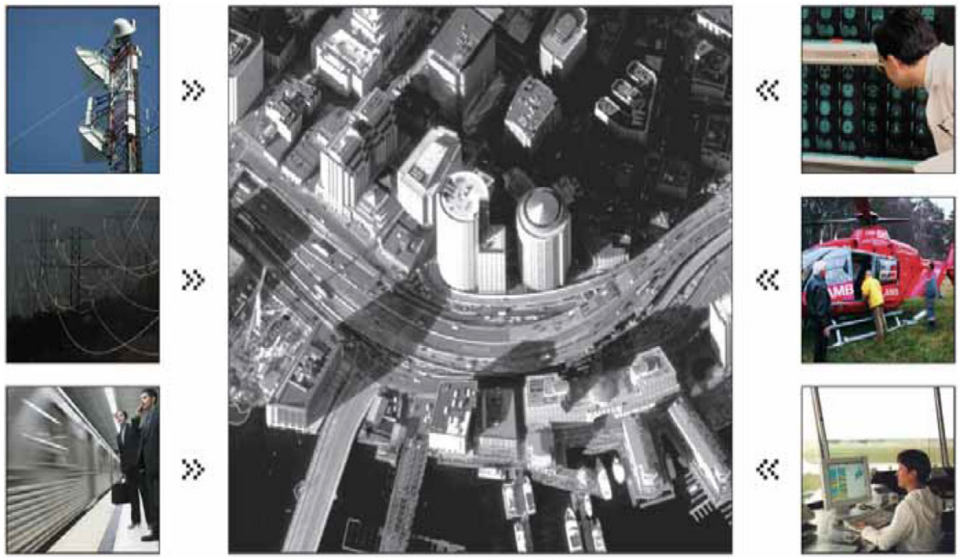
“Intentional malicious generation of electromagnetic energy, introducing noise or signals into electric and electronic systems, thus disrupting, confusing or damaging these systems for terrorist or criminal purposes”

—— IEC 61000-2-13

(originally from a resolution of URSI General Assembly, Toronto, 1999)

Possible Targets:

- (Smart-Grid) Power Networks
- Telecom systems
- Financial systems
- Medical Care
- Radio/TV Broadcasting
- Transport infrastructures
- etc…

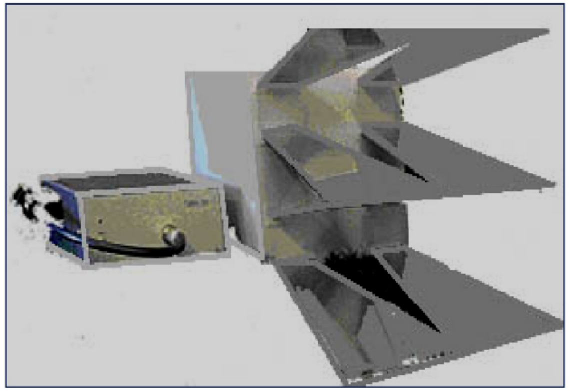


Electromagnetic Environment

Interference mechanisms

- Conducted

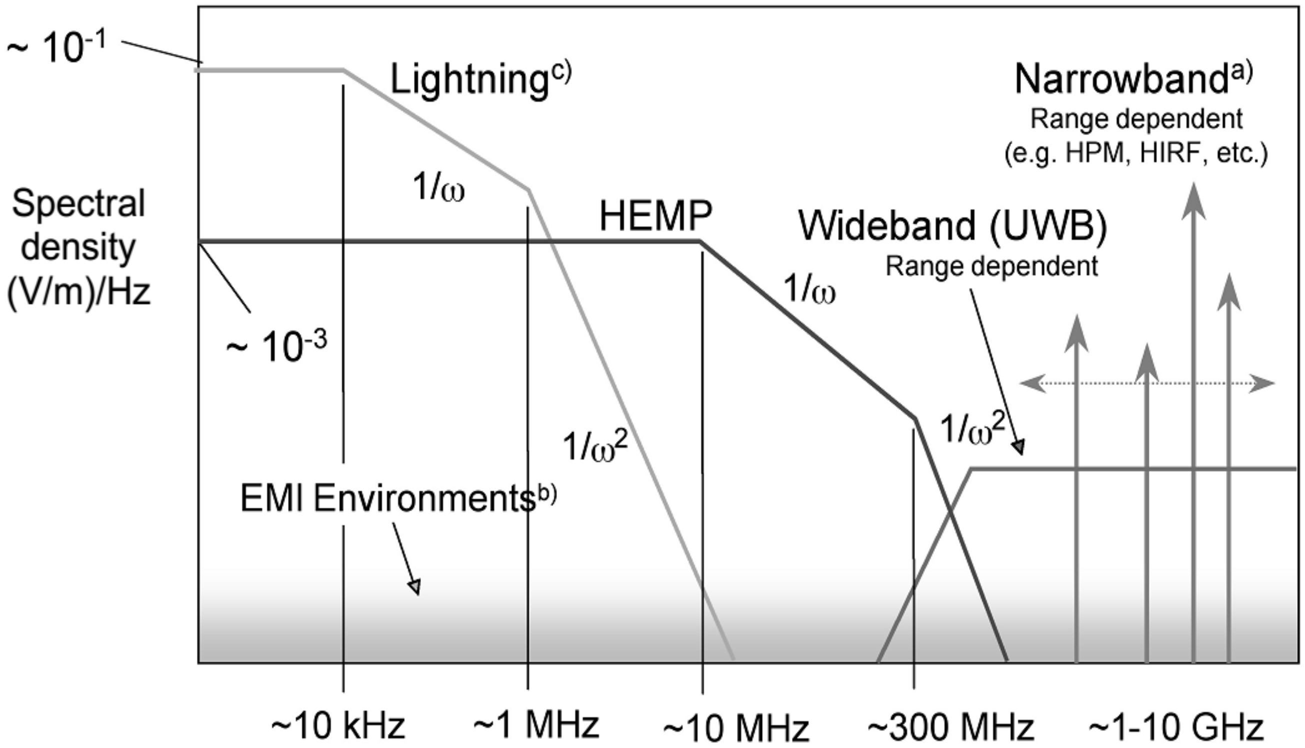
- Radiated



Radiated HPEM field

High power electromagnetics

High-power electromagnetic fields with peak electric field levels that typically exceed 100 V/m



Source: IEC 61000-2-13

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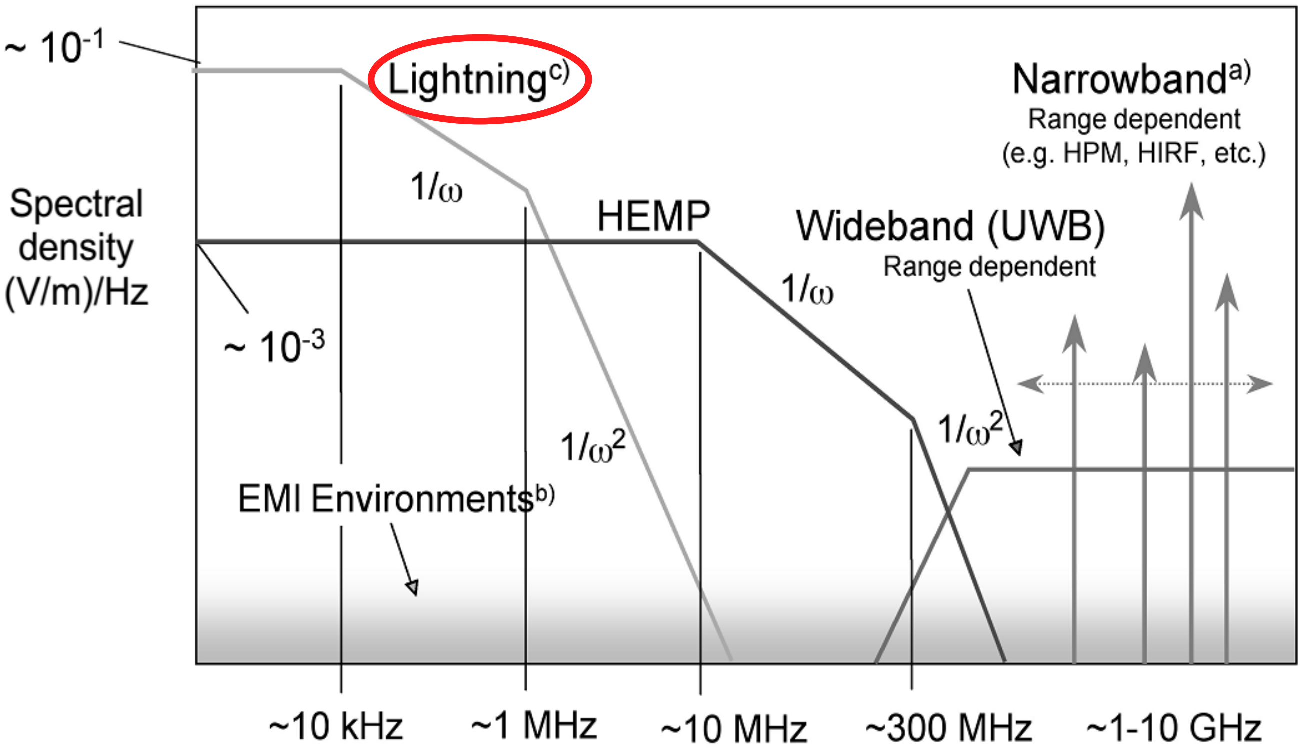

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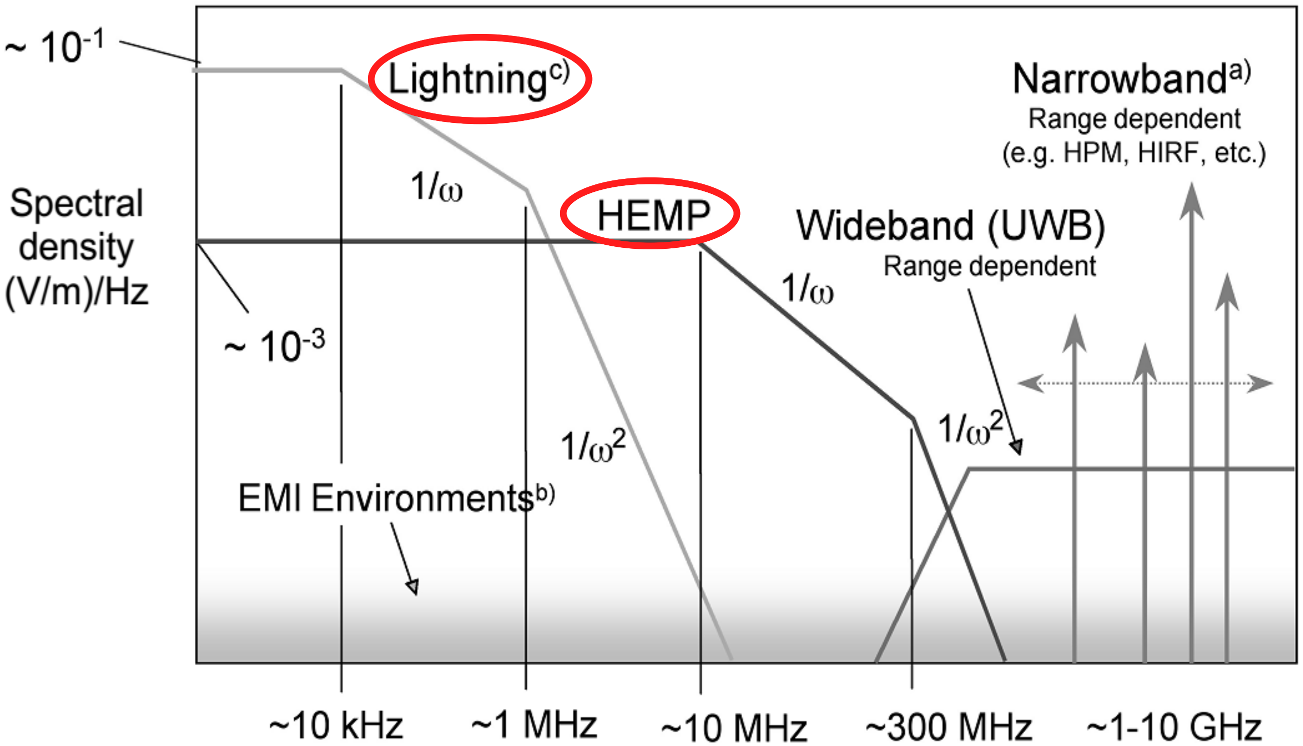

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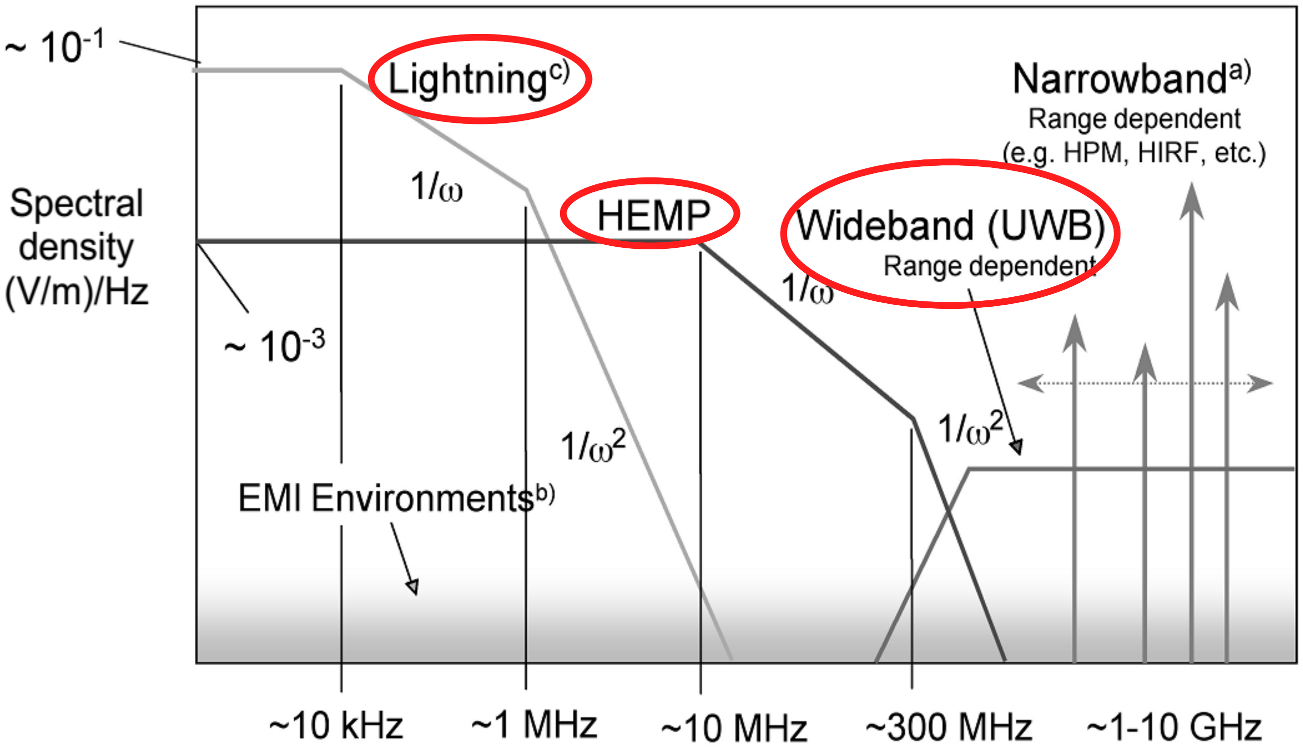

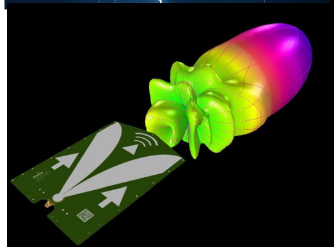

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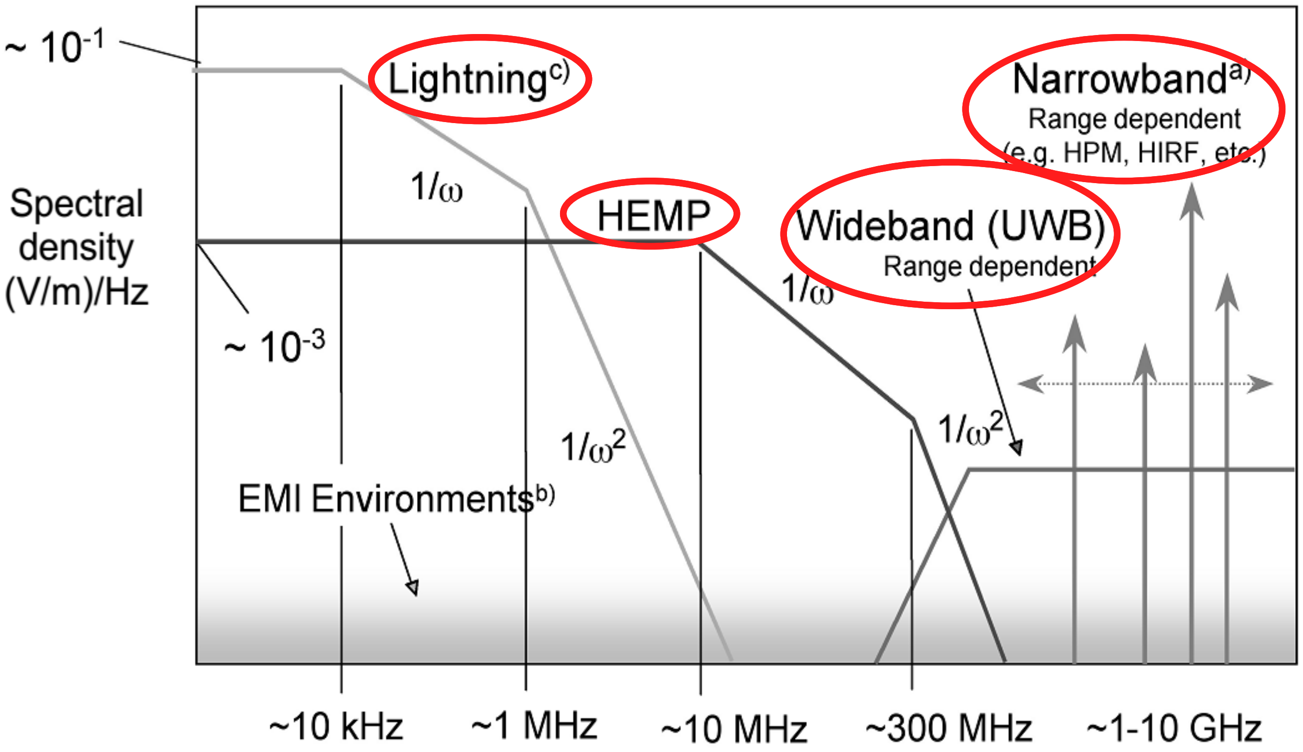
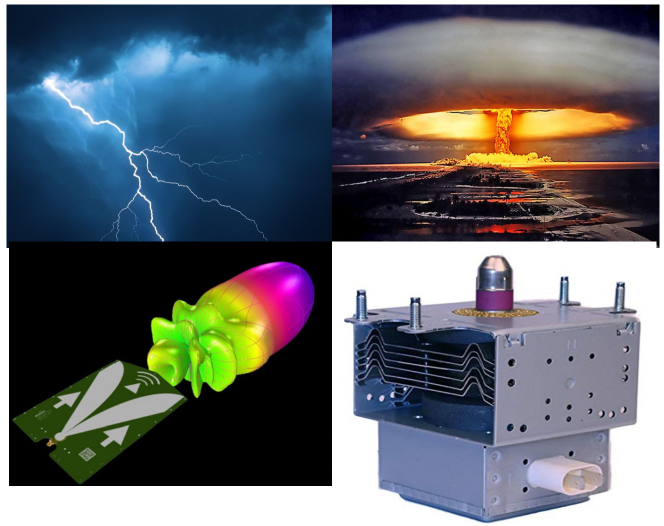
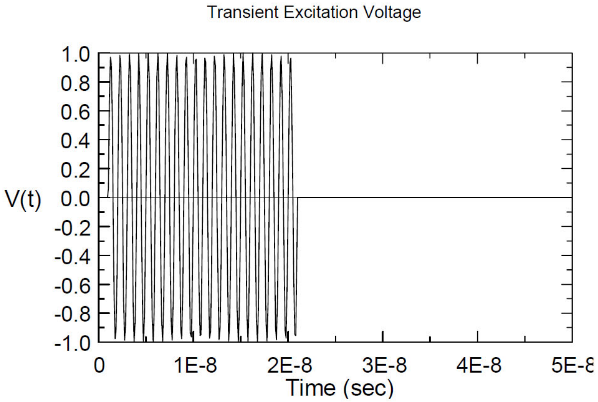
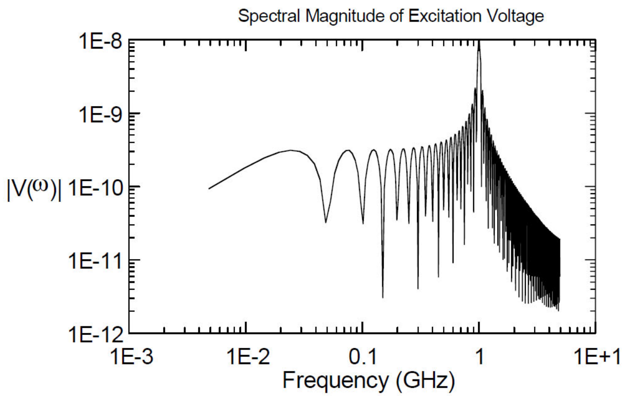




Source: IEC 61000-2-13

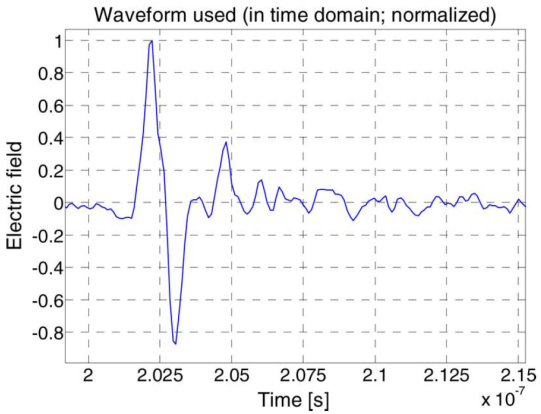
Radiated HPEM Spectrum
Narrowband and Wideband





nearly a single frequency of power delivered over a time frame

Source: IEC 61000-2-13



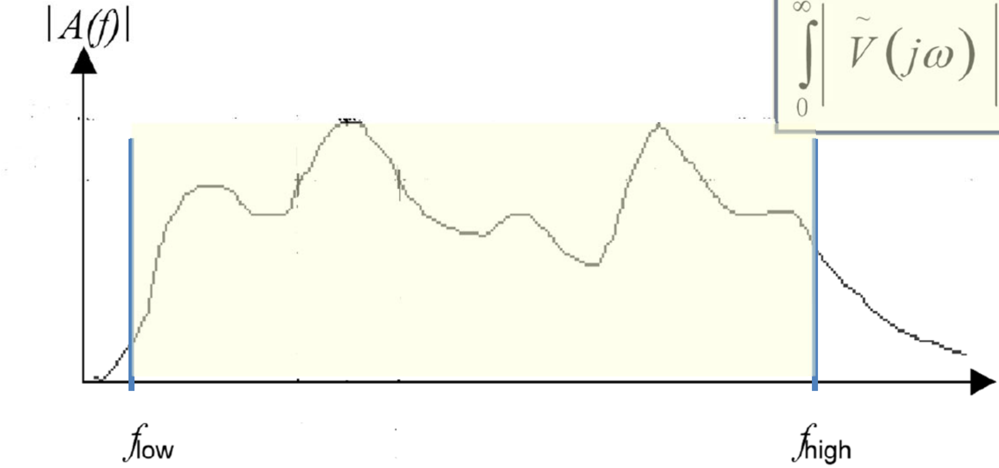
a single pulse

Source: Mansson et al. (2008)

Wideband Radiated HPEM
Definition as per IEC 61000-2-13

Bandwidth [f_{low}, f_{high}] contains
90% of total energy

$$\frac{\int_{f_\ell}^{f_h} \left| \tilde{V}(j\omega) \right|^2 d\omega}{\int_{0}^{\infty} \left| \tilde{V}(j\omega) \right|^2 d\omega} = 0.9$$



Band ratio

$$b_r = \frac{f_{high}}{f_{low}}$$

Category	Band ratio
NARROWBAND	$b_r < 1.01$
MESOBAND	$1.01 < b_r \leq 3$
SUB-HYPERBAND	$3 < b_r \leq 10$
HYPERBAND	$b_r > 10$

WIDEBAND

Uncertainty of IEMI Environments

[…] the standardization process for HPEM environments is more difficult. The recommended approach is to investigate the various types of HPEM environments that have been produced to date and are likely to be feasible in the near future, and then to develop suitable HPEM standard waveforms from such a study. Such HPEM environment standard waveforms can be amended in due course, depending on emerging technologies that make it possible to produce them.

—— *IEC 61000-2-13*

State-of-the-art

What has been done in the past research?

Mostly experimental activities: radiated susceptibility (RS) test for different victim system against canonical HPEM/IEMI

Build a disruptor
Choose a system → Excite system with EM field → Observe effect
Find threshold

State-of-the-art

What has been done in the pas

Mostly experimental activities
different victim system agains

Build a disruptor
Choose a system

Excite system
with EM field

Publication	Victim system	HPEM/IEMI waveform	Testing facility	System effects
Beek 2015 [68]	Radio base station receiver	CW	DCI	• Physical damage • Receiver saturation • Masking signal
Mora 2016 [69]	Communication Raceway	• Bipolar hyperband pulse • CW	• GTEM cell • Reverberation chamber	LVP cable is more susceptible than telephone/Ethernet cable
Nitsch 2004 [64]	• Computers • Microprocessor • Basic ICs	• HEMP • Unipolar & Bipolar UWB • HPM	TEM cell	• Bit error • Lost frames • Breakdown
Camp 2000s [70], [71]	Microcontroller	• UWB • EMPs	TEM cell	• Breakdown • destruction
Mansson 2008 [72]	GPS receiver	• Narrowband • HPM • UWB	Open-area test	• System crash, self-recovery • Loss of function • Permanent damage
Zhou 2010s [73]	Silicon-based amplifier	HPM	DCI	Thermal burndown
Brauer 2019 [67]	COTS IT network	• UWB • DS pulse • HPM pulse	TEM cell	• Disturbance • Data rate decrease • Short interrruption • Total failure (Reset needed) • Destruction
Li 2018 [65]	Computer commnication system	Double exponential pulse	XT-based method	• Bit error • Communication interrupted, restart requried
Kreitlow 2015 [63]	Computer network	Pulse train	Open-area test	• No effect • Speed drop
Lanzrath 2018 [74]	Secondary system of substation	CW HPM	BCI TEM cell	• Communication upset/failure • Prtection failure (recoverable) • Lose of trip record
Przesmycki 2016 [75]	• Computer • Tablet • TEMPEST computer • Router	Transient pulse	Anechoic chamber test	Damage

State-of-the-art

What has been done in the past research?

Mostly experimental activities: radiated susceptibility (RS) test for different victim system against canonical HPEM/IEMI

Build a disruptor Choose a system	➡	Excite system with EM field	➡	Observe effect Find threshold

Common issues:

- lack of general representativeness (results valid only for the specific waveform applied)
- lack of prediction models for assessment
- contradictory conclusions…

overlook of uncertainties involved in coupling link!

Challenge & Research Objective

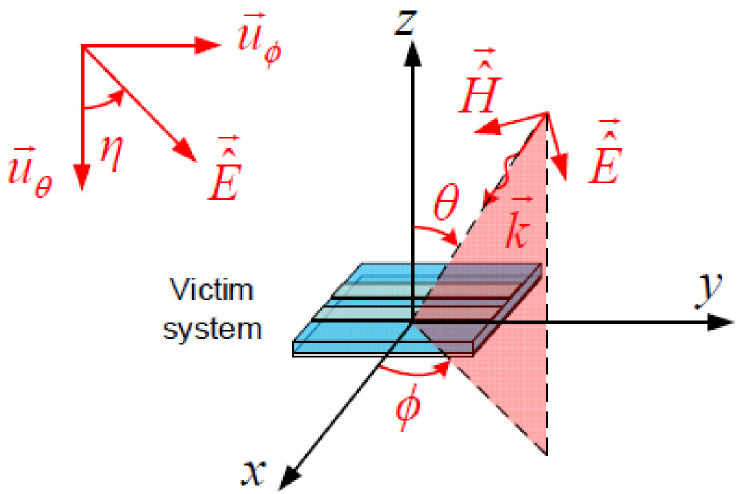
Classification of the uncertainties

Uncertainties involved in the coupling link

- Source: TD/FD waveform
- Coupling path:
  incidence direction (θ,φ) and wave polarization (η)
- Victim system: geometrical and/or electrical parameters

Objective

Assessing the radiated susceptibility of system against radiated HPEM/IEMI, with special attention paid to the uncertainties involved in the coupling link through worst-case and statistical analysis



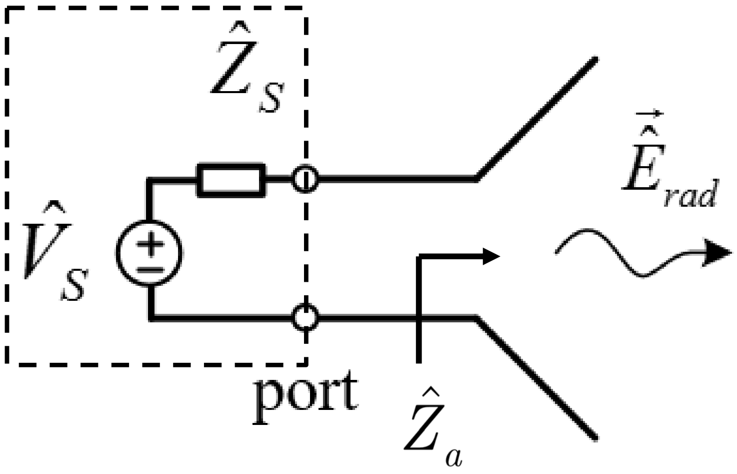
1 Full-wave Field Coupling (FC) Model

Fast evaluation of system response under arbitrary HPEM pulse waveform

Reciprocity-based FC model

- Any linear system is treated as an unintentional antenna

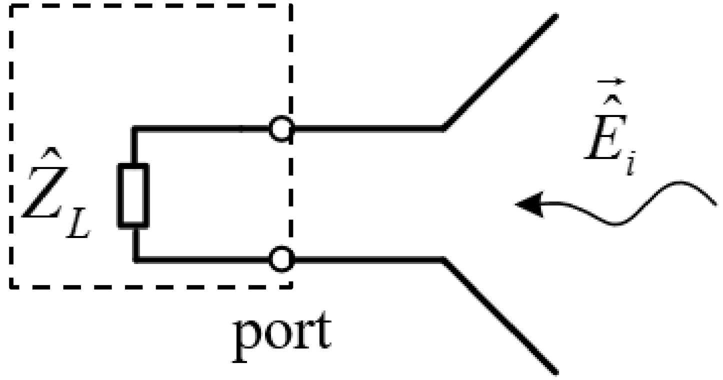
Transmitting mode



By full-wave simulation:

- far-field radiation pattern $\vec{\hat{F}}$
- antenna impedance $\hat{Z}_a$

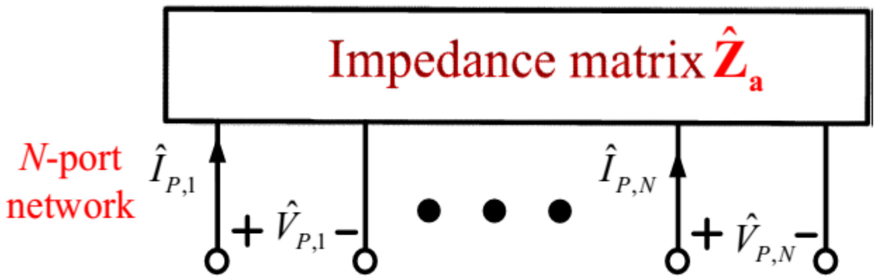
Receiving mode



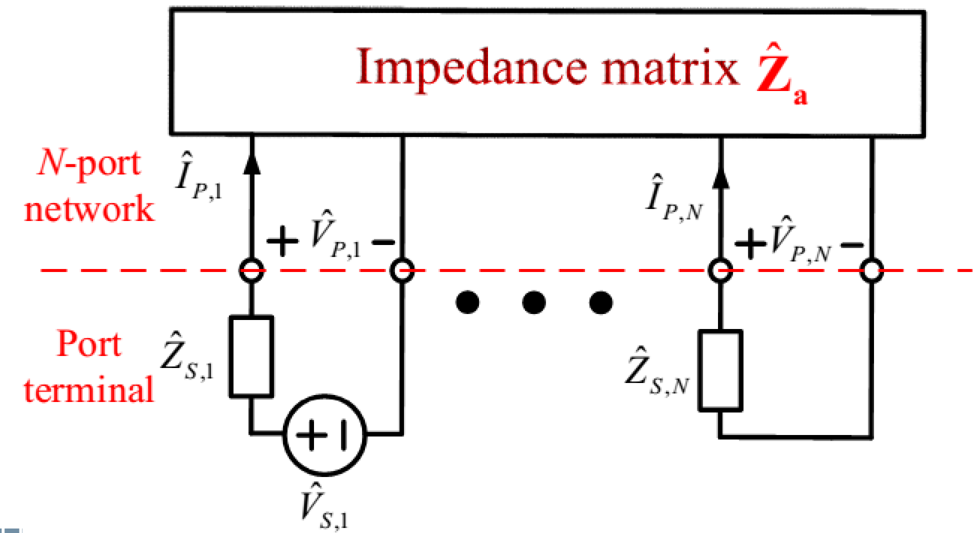
The port voltage/current can be evaluated by post-processing $\vec{\hat{F}}$ and $\hat{Z}_a$

Multi-port formulation

- The victim system is treated as a linear multi-port network



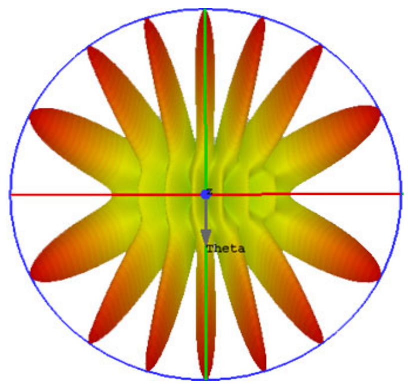
- Transmitting mode (*N* full-wave simulations)



$$\hat{\vec{F}}_{R,n}(\omega,\theta,\phi) = r e^{jkr} \hat{\vec{E}}_{r,n}(\omega,r,\theta,\phi)$$

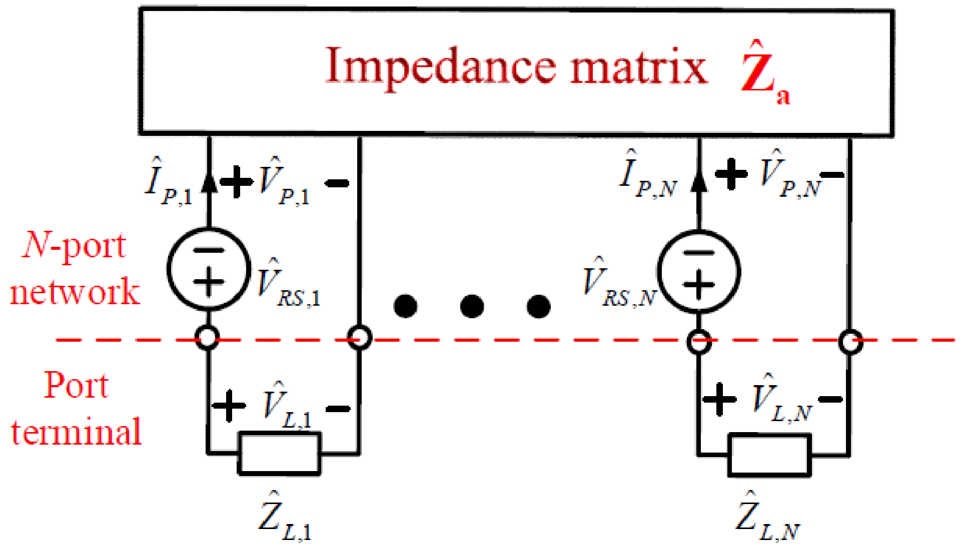
$$\hat{\vec{\mathbf{F}}}_{\mathbf{R}} = \left[\hat{\vec{F}}_{R,1}, \hat{\vec{F}}_{R,2}, \cdots, \hat{\vec{F}}_{R,N}\right]^{\mathrm{T}}$$

complex-valued radiation patterns



Coupling Length

- Receiving mode



$$\hat{\mathbf{L}} = -\frac{2j\lambda_0}{Z_0}\hat{\mathbf{Z}}_L\left(\hat{\mathbf{Z}}_a + \hat{\mathbf{Z}}_L\right)^{-1}\left[\hat{\mathbf{F}}_\vartheta \cos\eta + \hat{\mathbf{F}}_\phi \sin\eta\right]$$

Coupling length (SI: meter)

$$\hat{\mathbf{L}} = \left[\hat{L}_1, \cdots, \hat{L}_i, \cdots \hat{L}_n\right] = \frac{\hat{\mathbf{V}}_L}{\hat{E}_i}$$

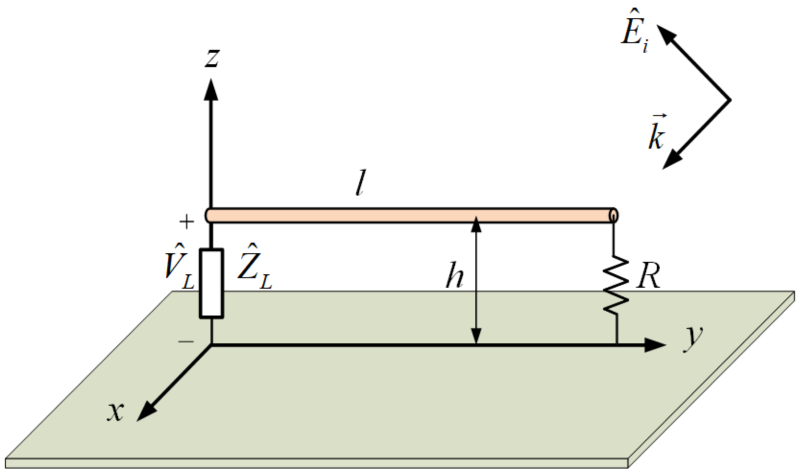
Expressed as function of:
- Input impedance matrix
- Complex radiation patterns

For any possible θ, ϕ, η and terminal loads

- G. Spadacini, T. Liang et al., IEEE Trans. on EMC, vol. 60 , no.5 , 2018.
- T. Liang et al., IEEE Access, vol.7, 2019

Computational advantage
Example

- One port system
- 10^5 sets of incidence & polarization angles
- Full-wave solver: FIT



Classic full-wave approach

$$T_{(fullwave)} \times N_{samples}$$

$$\approx 20\,\text{min} \times 10^5$$

$$\approx 3.8\ \text{years}\,!$$

Reciprocity-based approach

$$T_{(fullwave)} + T_{(postprocess)}$$

$$\approx 20\,\text{min} + 10\,\text{min}$$

$$\approx 30\,\text{min}\,!$$

2 Solving the uncertainty of IEMI Source: Worst-Case Coupling Analysis

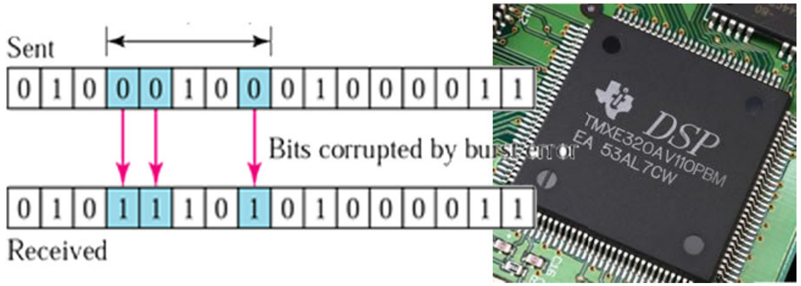
Accounting for the uncertainties of HPEM source waveforms

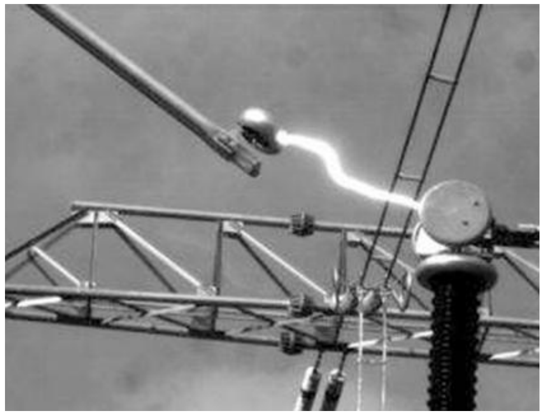
Worst-case HPEM coupling analysis

What is the worst-case scenario?

A set of different attributes (norms) of induced waveform *f(t)* are correlated to susceptibility effect of electronic system.

Figure of merits	Norm	Param	Susceptibility effects
$\lvert f(t)\rvert_{\max}$	∞-norm	Peak	Bit error / overvoltage breakdown
$\int_{-\infty}^{+\infty} \lvert f(t)\rvert^2\,dt$	squared 2-norm	Energy	Overheat / Burnout
$\int_{-\infty}^{+\infty} \lvert f(t)\rvert\,dt$	1-norm	Rectified Impulse	Dielectric puncture
Rising speed, repeat rate, pulse polarization, … Other norms and non-norm attributes…			





• D. V. Giri, *High-power Electromagnetic Radiators: Nonlethal Weapons and Other Applications*. Cambridge, MA, USA: Harvard University Press, 2004.

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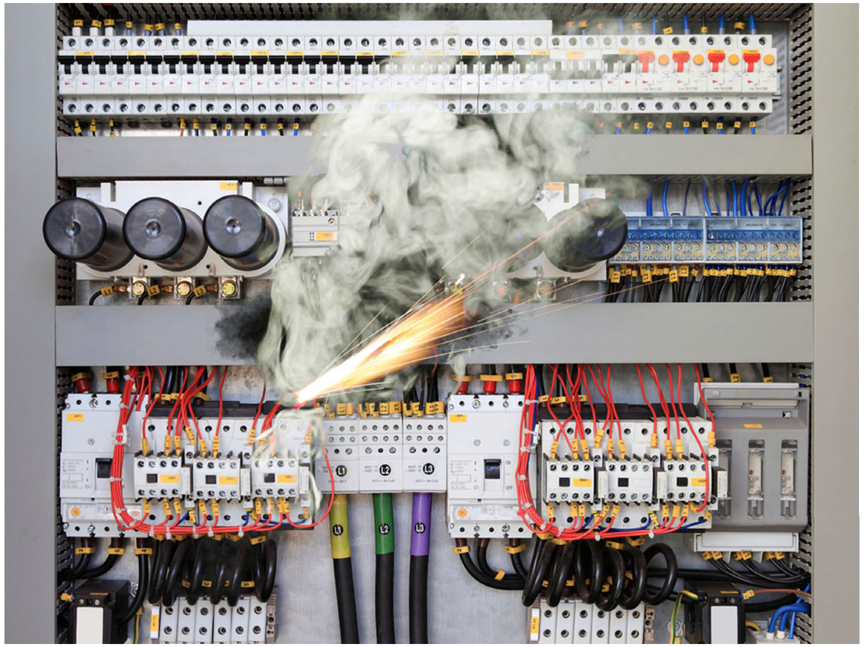

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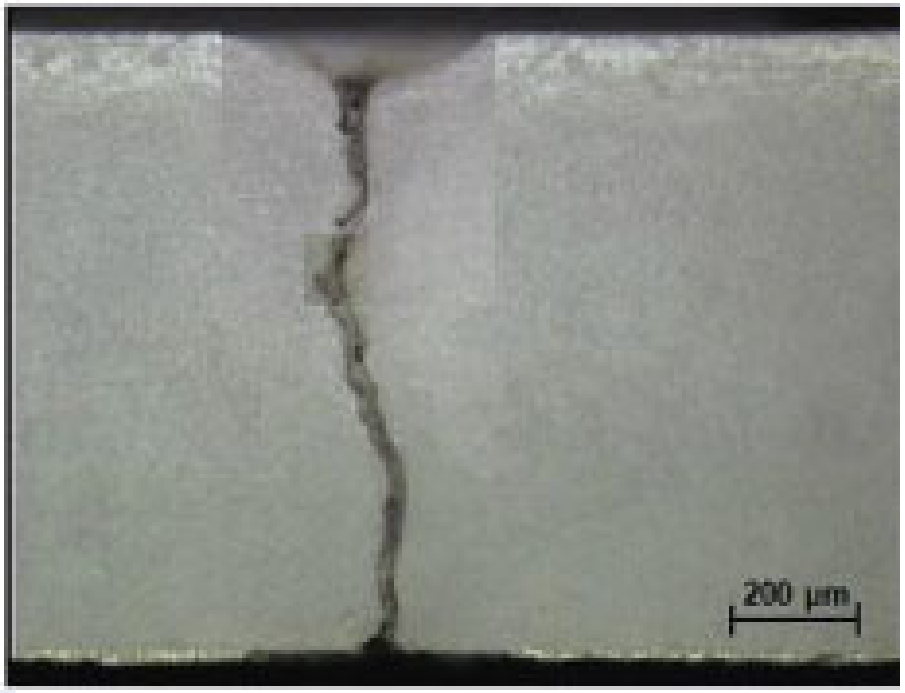

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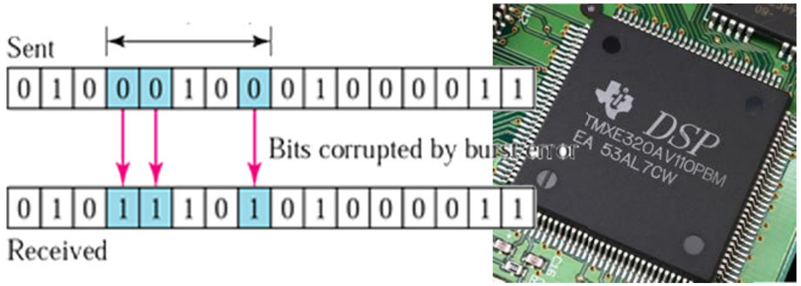

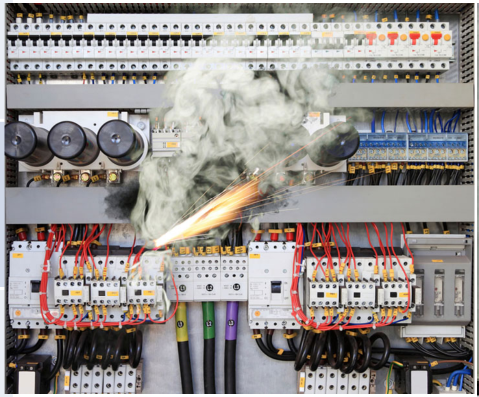

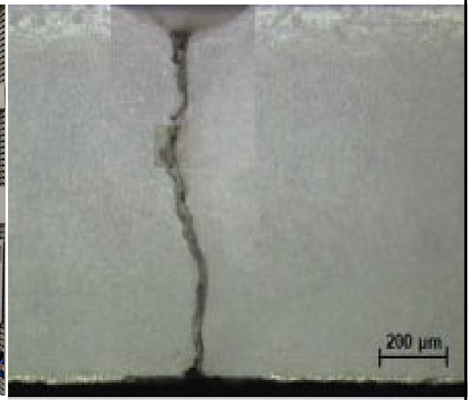

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Worst-case HPEM coupling analysis

What is the worst-case scenario?

Worst-case scenario: Victim system is subject to a particular HPEM field whose waveform is capable to maximize certain norms of the induced voltage/current.

Worst-case peak scenario → Maximizing waveform peak (∞-norm)

Worst-case energy scenario → Maximizing dissipated energy (2-norm)

Worst-case rectified-impulse scenario → Maximizing rectified-impulse (1-norm)

Constraints on the electric field waveform/spectrum:

1. Band-limited $\hat{E}_i(\omega) = 0,\ \omega \in [\omega_1, \omega_2]$
2. Energy bounded $\frac{1}{2\pi Z_0}\int_{-\infty}^{+\infty}\left|\hat{E}_i(\omega)\right|^2 d\omega = W_E$

- G. Spadacini, T. Liang et al., IEEE Trans. on EMC, vol. 60 , no.5 , 2018.
- T. Liang et al., IEEE Access, vol.7, 2019

Worst-case peak scenario

The optimization

Constrained optimization:

$$\begin{cases} \max : J = V_{LP} = \dfrac{1}{2\pi}\displaystyle\int_{-\infty}^{+\infty} \hat{L}(\omega)\hat{E}_i(\omega)e^{j\omega t_0}\,d\omega \\ s.t. : \dfrac{1}{2\pi Z_0}\displaystyle\int_{-\infty}^{+\infty} \left|\hat{E}_i(\omega)\right|^2 d\omega = W_E \end{cases}$$

⇦ IFT to obtain the TD voltage at t_0

⇦ Constraint of field energy

Solution in closed form

Worst-case field

$$\hat{E}_i(\omega) = \sqrt{\frac{\pi Z_0 W_E}{\int_{\omega_1}^{\omega_2}\left|\hat{L}(\omega)\right|^2 d\omega}}\,\hat{L}(\omega)^* e^{-j\omega t_0}$$

Worst-case load voltage peak

$$V_{LP} = \sqrt{\frac{Z_0 W_E}{\pi}\int_{\omega_1}^{\omega_2}\left|\hat{L}(\omega)\right|^2 d\omega}$$

$$\left|\hat{E}_i(\omega)\right| \propto \left|\hat{L}(\omega)\right|$$

Magnitude is proportional to the magnitude of coupling length, so to favor frequencies of good receiving properties

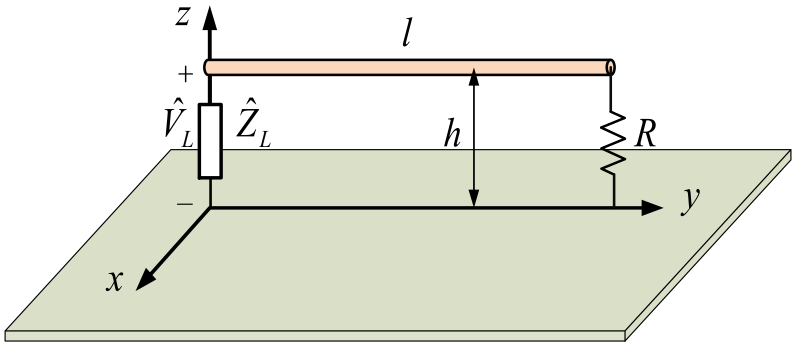
$$\angle\hat{E}_i(\omega) = -\left(\angle\hat{L}(\omega) + \omega t_0\right)$$

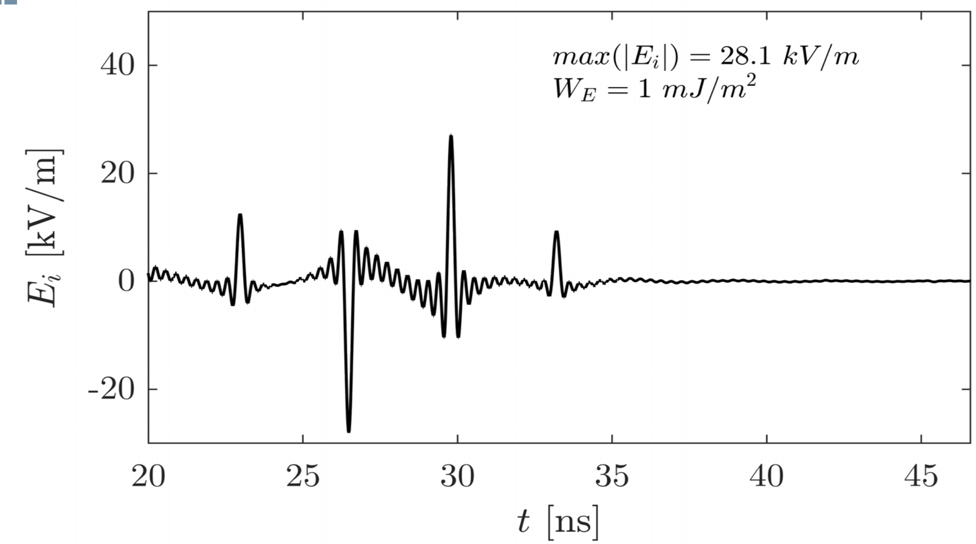
phase is opposite to the phase of coupling length to compensate delay, plus an angle ωt_0 to position the peak at desired time t_0.

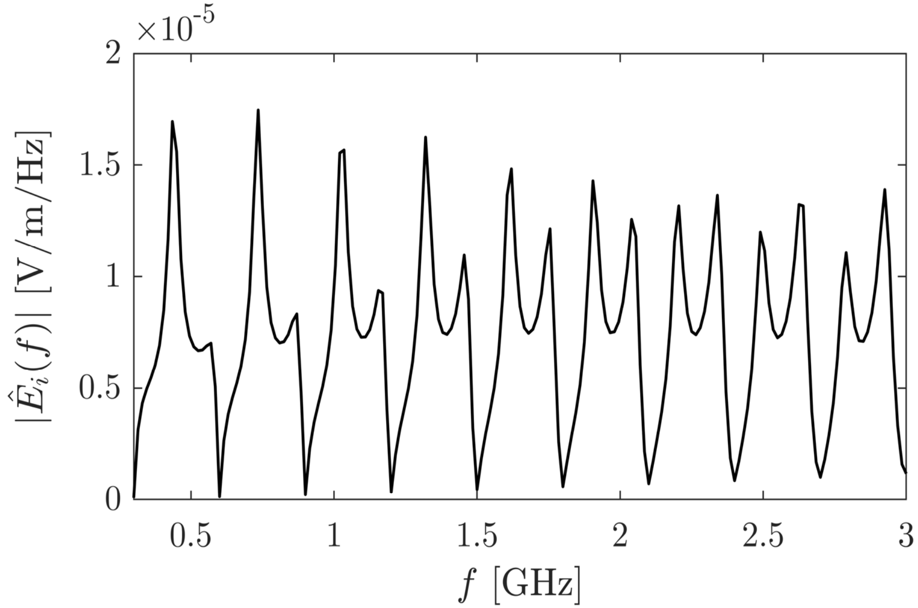
Worst-case peak scenario

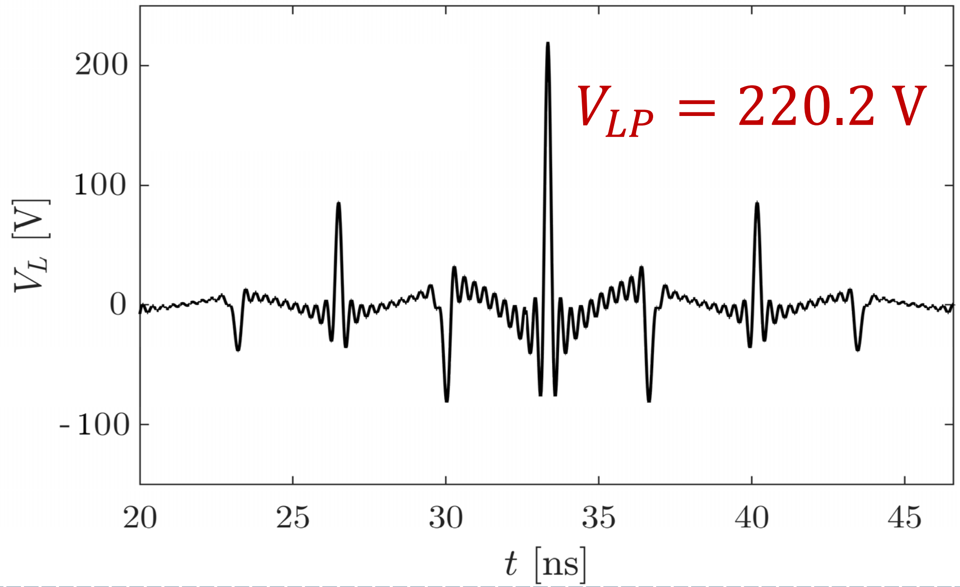
What does the field/load waveform look like?

UHF, W_E=1 mJ/m², $\theta=30°, \phi=0°, \eta=45°$









Worst-case energy scenario

The optimization

Constrained optimization:

$$\max : \; W_L = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \frac{1}{\hat{Z}_{L,i}^{*}} \left|\hat{V}_L\right|^2 d\omega$$

$$s.t. : \quad \frac{1}{2\pi Z_0}\int_{-\infty}^{+\infty} \left|\hat{E}_i(\omega)\right|^2 d\omega = W_E$$

Solution

$$W_L \le \frac{1}{\pi}\int_0^{+\infty} \left|\hat{E}_i\right|^2 \max\left\{\mathrm{Re}\left(\hat{Z}_L^{-1}\right)\left|\hat{L}\right|^2\right\} d\omega$$

$$= \max\left\{\mathrm{Re}\left(\hat{Z}_L^{-1}\right)\left|\hat{L}\right|^2\right\}\frac{1}{\pi}\int_0^{+\infty}\left|\hat{E}_i\right|^2 d\omega$$

$$= Z_0 W_E \max\left\{\mathrm{Re}\left(\hat{Z}_L^{-1}\right)\left|\hat{L}\right|^2\right\}$$

- The worst-case for dissipated energy is a narrowband HPEM pulse tuned into the frequency for which the coupling length exhibits maximum value
- The narrower the pulse, the higher the energy, with an asymptote in

$$W_L = \frac{Z_0 W_E}{R_L}\max\left\{\left|\hat{L}\right|^2\right\}$$

- In practical term, a bandratio as low as 1.001 could approach this limit

Worst-case rectified-impulse scenario

The optimization

Constrained optimization:

$$\max: \qquad J_{L,n} = \int_{-\infty}^{+\infty} \left| V_{L,n}(t) \right| dt$$

$$\text{constraint}: \frac{1}{2\pi Z_0} \int_{-\infty}^{+\infty} \left| \hat{E}_i(\omega) \right|^2 d\omega = W_E$$

Hölder's inequality

$$\left\| s_1(x) s_2(x) \right\|_1 \leq \left\| s_1(x) \right\|_p \left\| s_2(x) \right\|_q ;$$

$$\frac{1}{p} + \frac{1}{q} = 1$$

$$J_L \geq \frac{\left\| V_L(t) \right\|_2}{\left\| V_L(t) \right\|_\infty} = \frac{\left\| V_L(t) \right\|_2}{V_{LP}}$$

- The rectified impulse can be made arbitrarily large by reducing the bandwidth
- If the center frequency of the narrowband signal was optimally tuned, a worst-case condition for energy would be simultaneously reached.

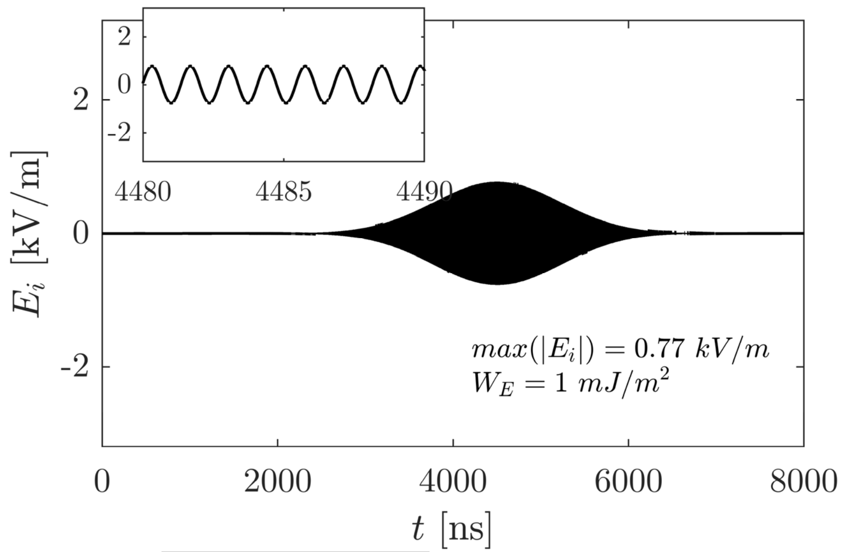
No solution possible

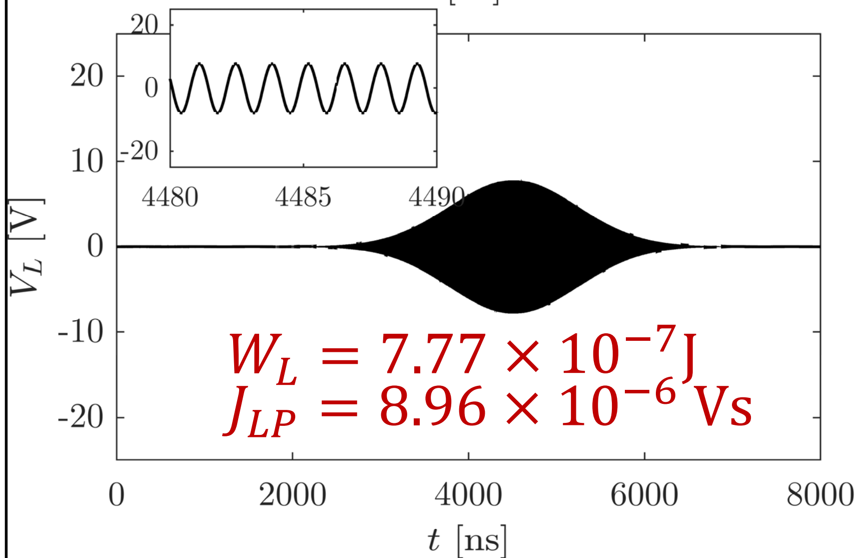
$$J_L \to \infty \text{ as } \omega_2 / \omega_1 \to 1^+$$

Worst-case energy/rectified-impulse

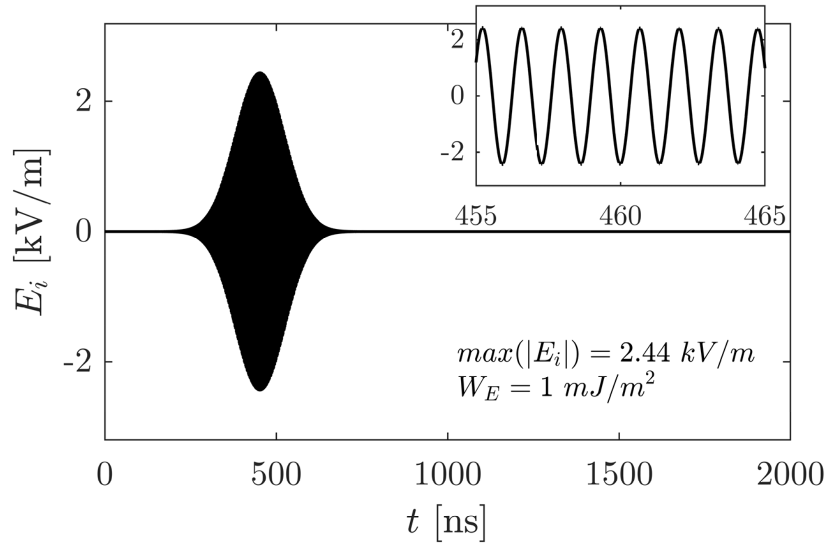
What does the field/load waveform look like?

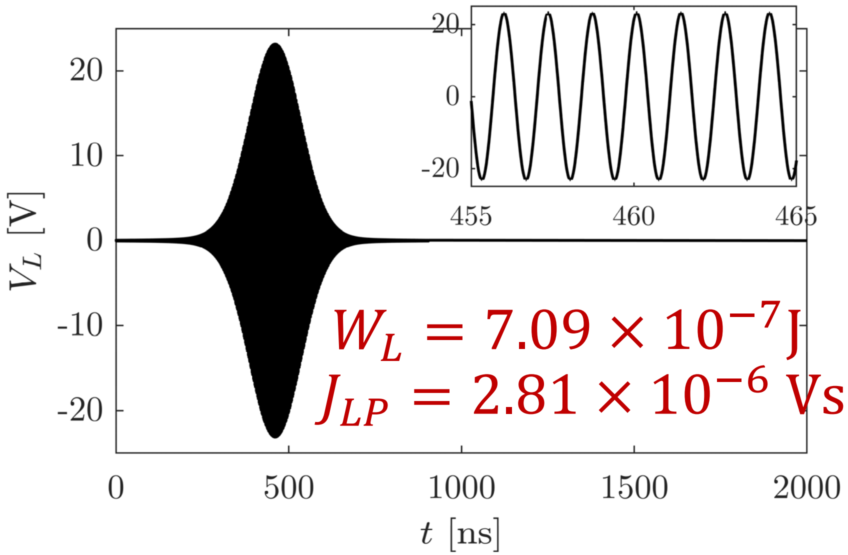
$b_r = 1.001, f_c = 735$ MHz





$b_r = 1.01, f_c = 735$ MHz

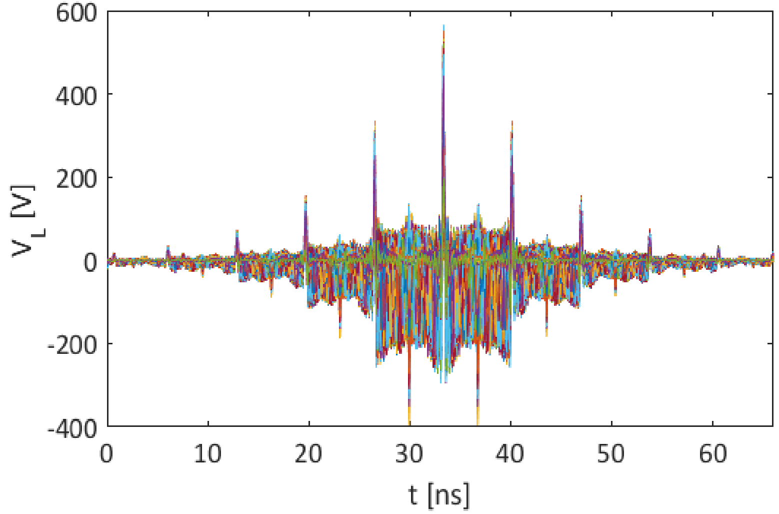


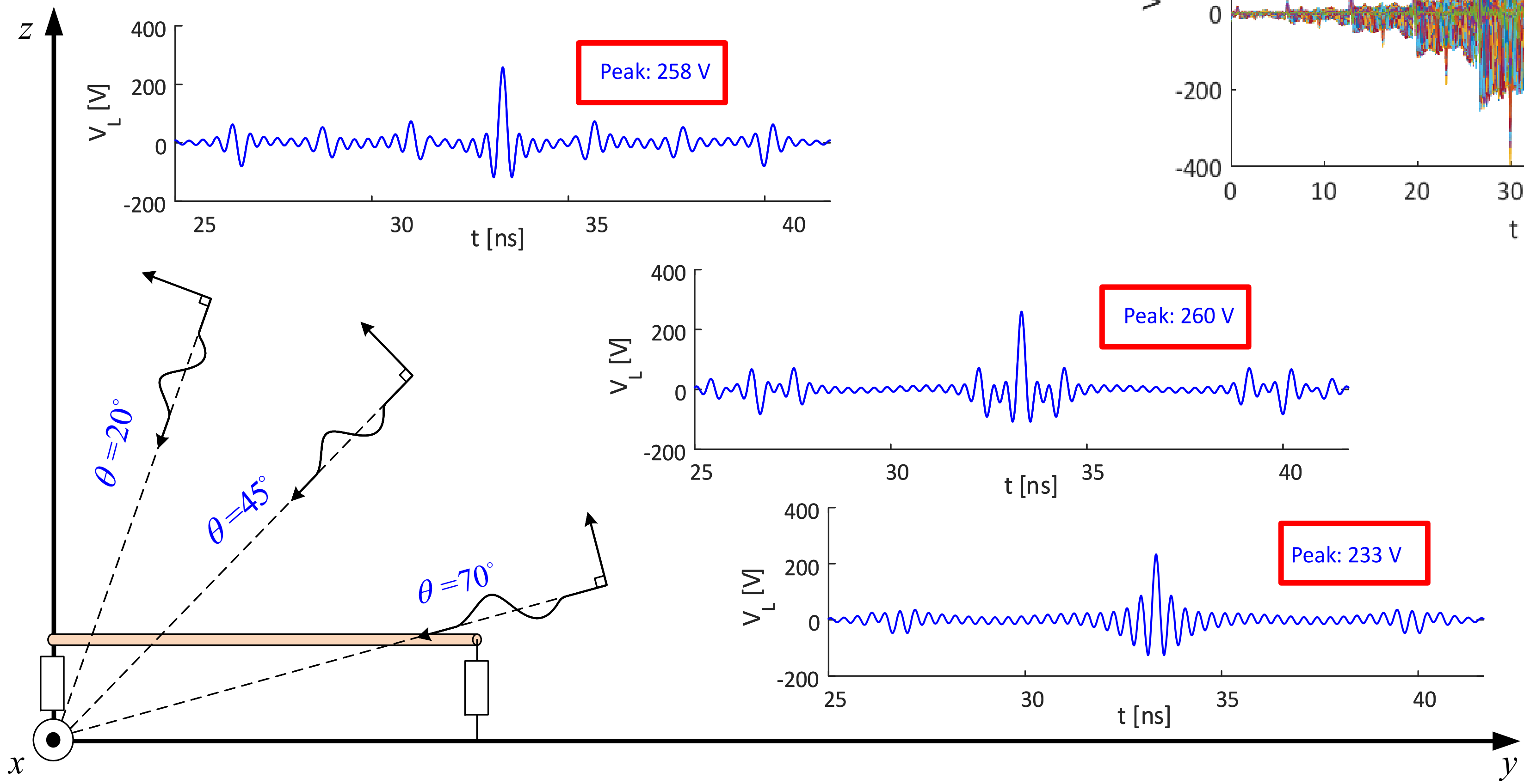


3 Including the uncertainty of coupling path: Combined Worst-Case Statistical Analysis

Angle dependence

Worst-case peak waveforms are dependent on θ, ϕ, η





Statistical Analysis

Assuming unknown field direction/polarization as random variable with Uniform Distribution

$$\underbrace{\theta \sim \mathrm{U}\left[0, 90^\circ\right], \phi \sim \mathrm{U}\left[0, 360^\circ\right]}_{\text{Upper hemisphere}}, \eta \sim \mathrm{U}\left[0, 360^\circ\right]$$

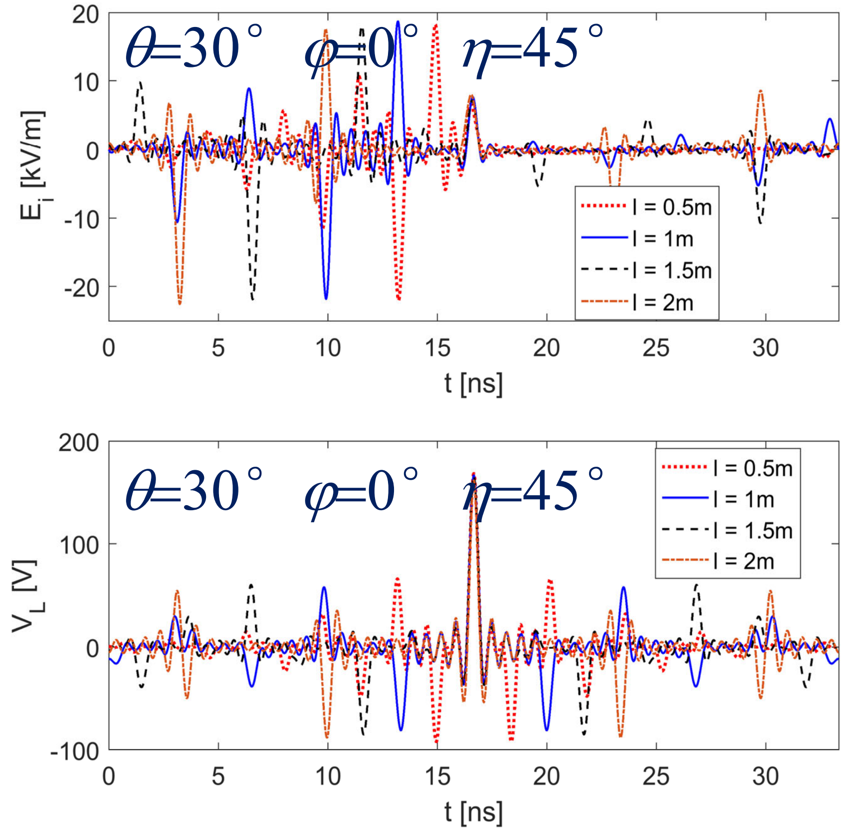
All possible polarization angle

- Evaluate by Monte Carlo simulation the Cumulative distribution function (CDF) of *worst-case norms (e.g. peak)*

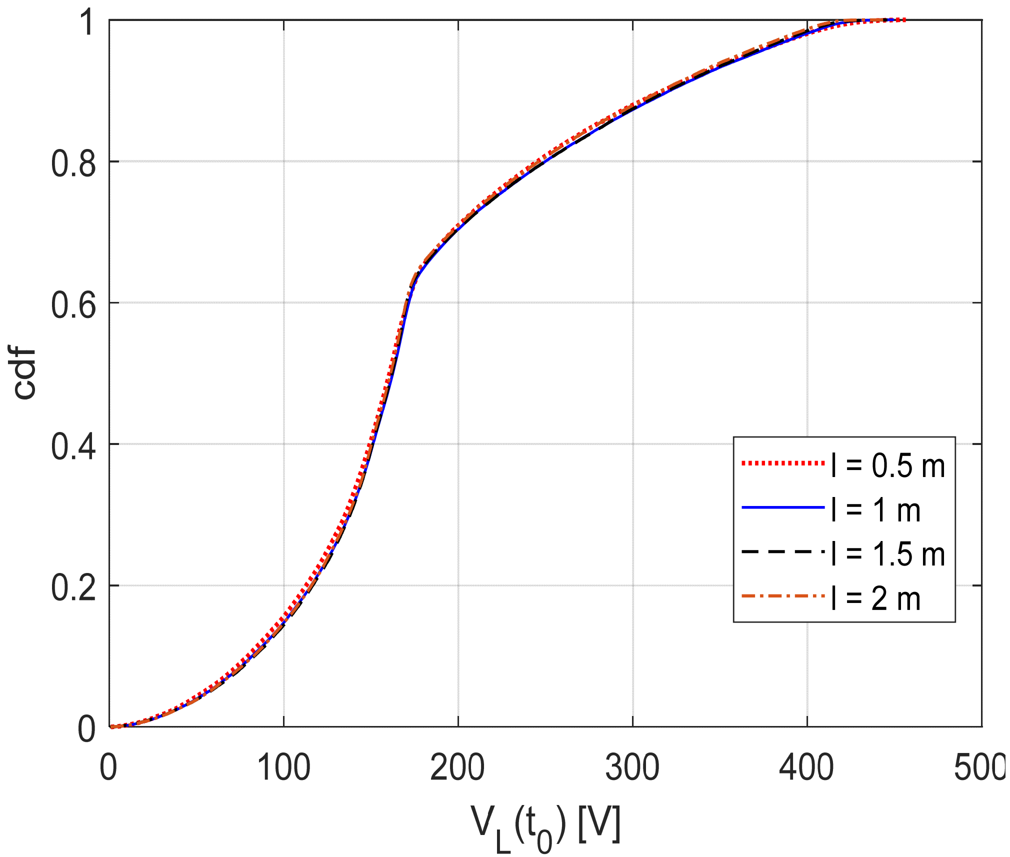
- Impact of system parameters (impedances, length, height, etc.) by parametric analysis

Impact of harness length *l*

Negligible impact on the worst-case peak CDF

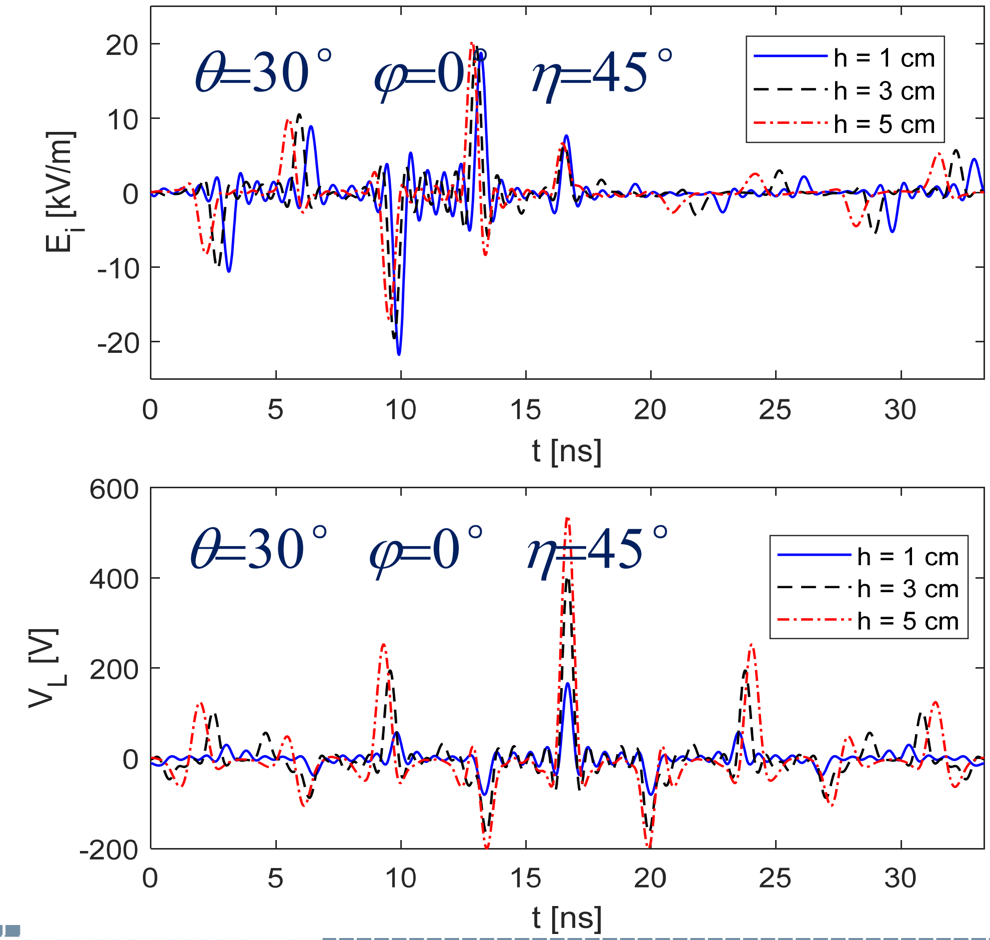


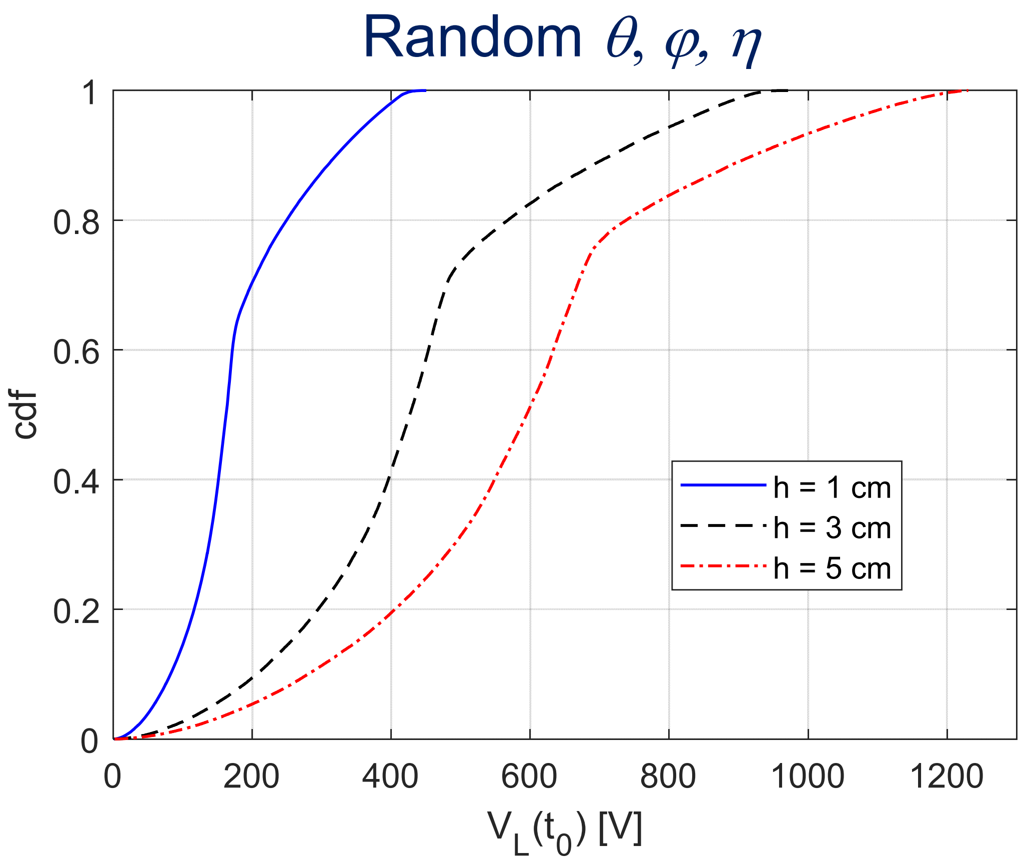
Random θ, φ, η



Impact of height h

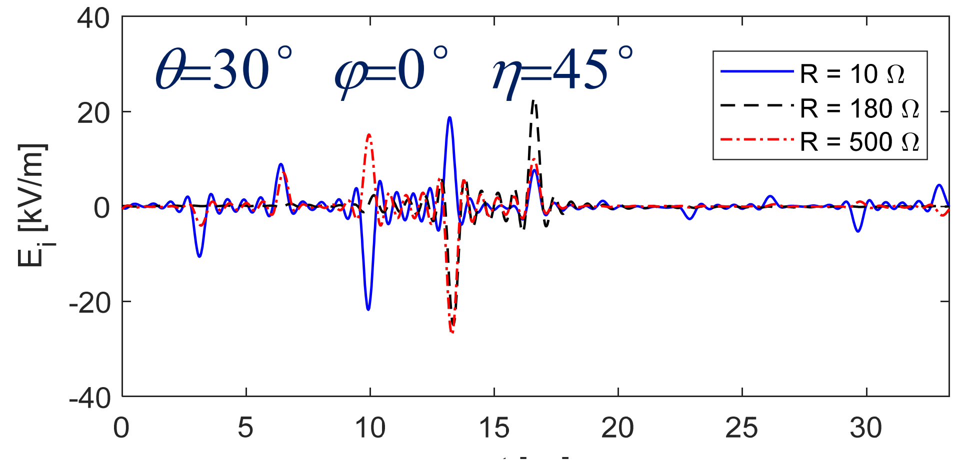
Larger height, larger CDF quantiles

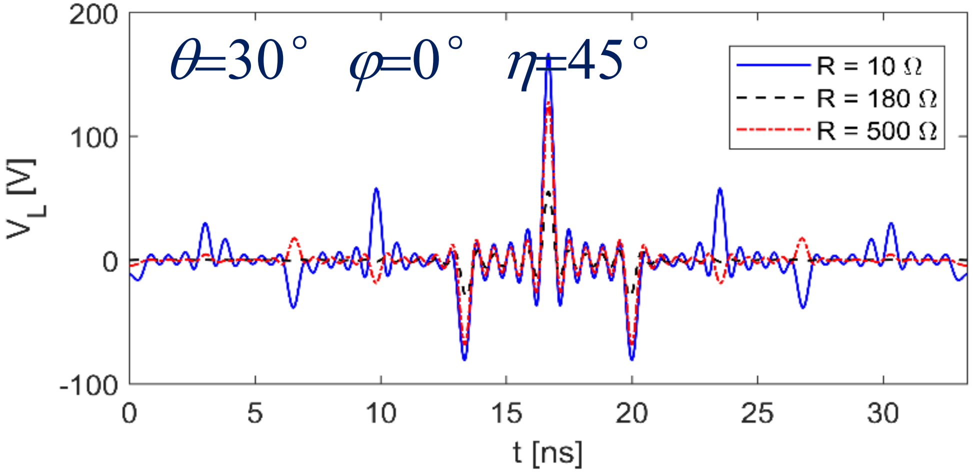


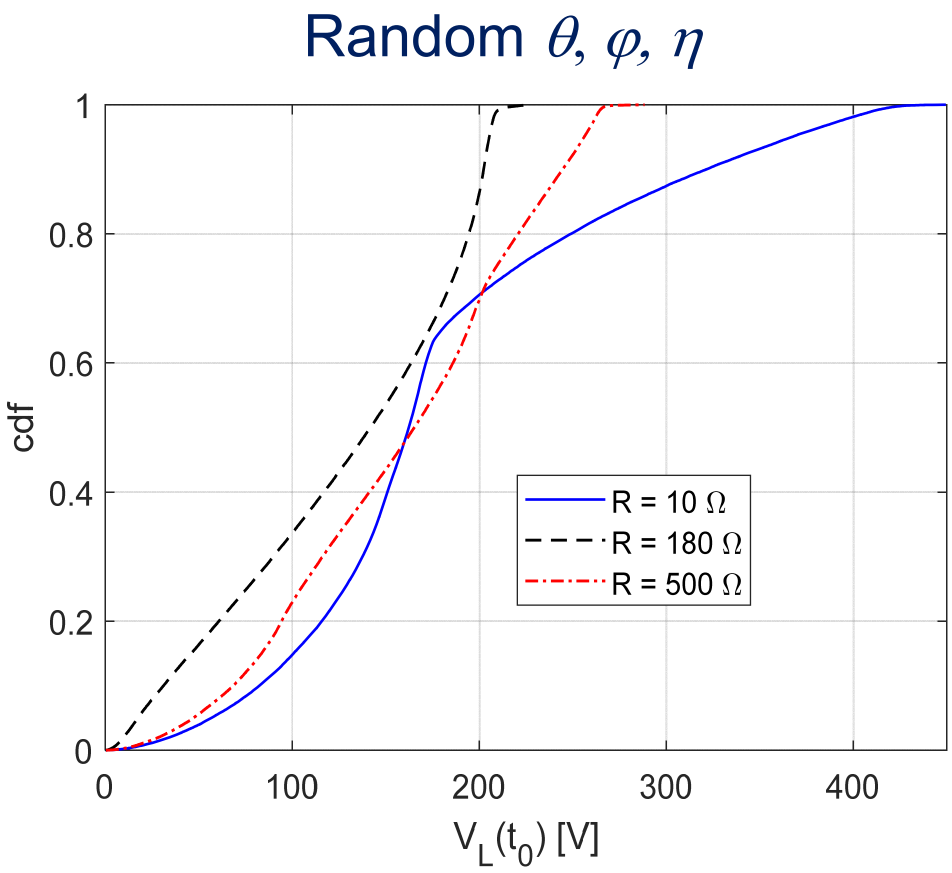


Impact of terminal load R

TL mismatching (Zc = 180 Ω) implies larger quantiles







Conclusion

Assessment methodology for IEMI

- Multiport coupling model based on full-wave simulations
  - Exploiting reciprocity to save computational time related to the need of repeated computations for different incidence and polarization angles
  - Evaluating the “coupling length” transfer function

- Prediction of Radiated IEMI effects
  - Uncertainty of spectral properties of the field through worst-case norms
    - Induced-voltage peak $\rightarrow$ wideband waveform
    - dissipated energy & rectified impulse $\rightarrow$ narrowband tuned waveform
  - Uncertainty of coupling link (incidence, polarization) by statistical and parametric analysis
  - Results expressed as cumulative distribution functions of worst-case norms

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Many Thanks for Your Attention!