Electromagnetic Modelling Techniques

Christos Christopoulos FIEEE FREng

Emeritus Professor of Electrical Engineering,

George Green Institute for Electromagnetics Research

University of Nottingham

Nottingham, NG8 2QY, UK

christos.christopoulos@nottingham.ac.uk

www.nottingham.ac.uk/ggiemr

The University of Nottingham

GGIEMR

OUTLINE:

- Introduction
- Numerical Modelling and Physical Experimentation
- Generic Classification of Numerical Methods
- Multiscale problems, Complexity and Uncertainty
- Conclusions and Outlook

Introduction:

- The application of Computational Electromagnetics (CEM) to EMC and other EM design and analysis problems presents specials difficulties: very broadband characterization(TD or FD models); large differences of electrical scale (multi-scale models); changing material properties (f-dependent material models); extreme complexity (embedded models, hybrid models); parameter uncertainty (stochastic models)…
- Experiments at high-frequencies and over a wide bandwidth are also very challenging, as calibration and the impact of environmental factors can affect the accuracy of measurements

Numerical Modelling and Physical Experimentation:

- There is an unfortunate dichotomy between practitioners on the one hand who pride themselves as “practical, based on experience, hands on” and those on the other hand who pride themselves as “theoreticians”

- This, in my view is a false dichotomy. A good “theory” is a very “practical tool” as it encapsulates in a small number of postulates and general principles this essence of numerous experiences. Thus, it provides generality and the capacity to extrapolate from current experiences to future possibilities…a very powerful tool.

- BUT, our capacity to function securely as engineers cannot alone be build on abstractions-we need to temper our theoretical modelling work by observations and careful experiments. The key is to exploit the synergies between experiments and simulation!

Some common aphorisms!

- Everyone believes the results of an experiment except the person who did it!
- No one believes the results of a simulation except the person who did it!

Data alone does not confer knowledge…it is the interpretation of the data and their placement into a wider context (a theory) that extracts meaning and allows us to formulate a proper response.

…We need a broader context, a coherent framework, in which to interpret our experiences…

The formation of an engineer is and must be a multi-faceted affair, a blend of practical, experimental and theoretical "experiences".

Some examples of recurrent problems from EMC are given next:

Issues with EMC tests:

- **Many aspects of the test environment are difficult to control**
- **Screened rooms can never be completely damped but worthwhile improvements can be made**
- **Partially damped rooms are a compromise between cost and accuracy**
- **There are size limitations for TEM and GTEM cells**
- **Open area test sites suffer from environmental problems and must be well designed**
- **Proximity effects influence the calibration of antennas**
- **Near-field effects make extrapolation difficult**

Issues related to EMC Simulations:

- **Relatively easy to isolate factors and establish what is critical in the response of a systems**
- **Possible to do "what if" experiments**
- **You can study system response well before you have a prototype thus anticipating problems**
- **Full diagnostics (a ring-side seat!)**
- **Can do numerical experiment which in real life are too expensive or dangerous to attempt**
- **It is easy to overlook significant factors which affect performance**
- **You can be overwhelmed by information!**

- ***Experimentation and simulation together can improve the understanding of EMC!***

Practical experience is great, except that in science and engineering we are often confronted with unfamiliar things and it is then very easy to make mistakes! We thus need a theoretical framework, a numerical model, to back up or otherwise our intuitions…

But, we must be aware that models are devices for capturing particular insights, not full-proof systems for predicting everything under all circumstances…"

All models are 'wrong', but some are useful!"

The need to control costs, achieve designs right first time, and to minimise time to market, imply a greater use of simulation for certification and compliance.

…relying on numerical models alone is unacceptable

…relying on experiments alone is impractical

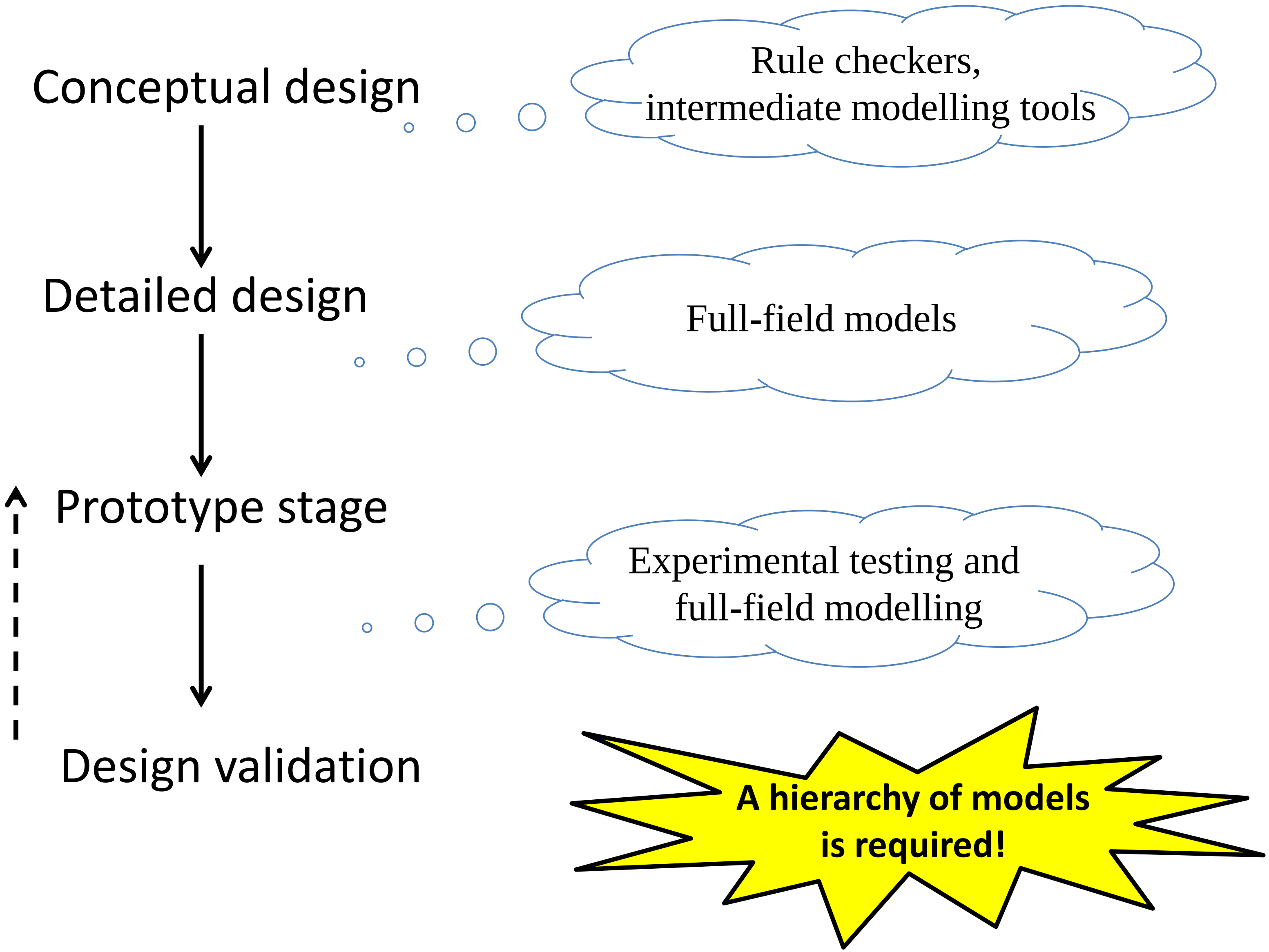
We will increasingly rely more on simulation and we must <u>validate the software</u> against carefully conducted basic experiments AND <u>validate the models</u> against whole system experimental testing

Make full use of ALL available tools…experiments, analytical calculations, numerical models…

We need to observe, experiment, model, and think sometimes abstract thoughts to gain a better understanding of the behaviour of complex systems and to engage in creative design. Sticking with only experiments, or, only simulations is not a good idea…

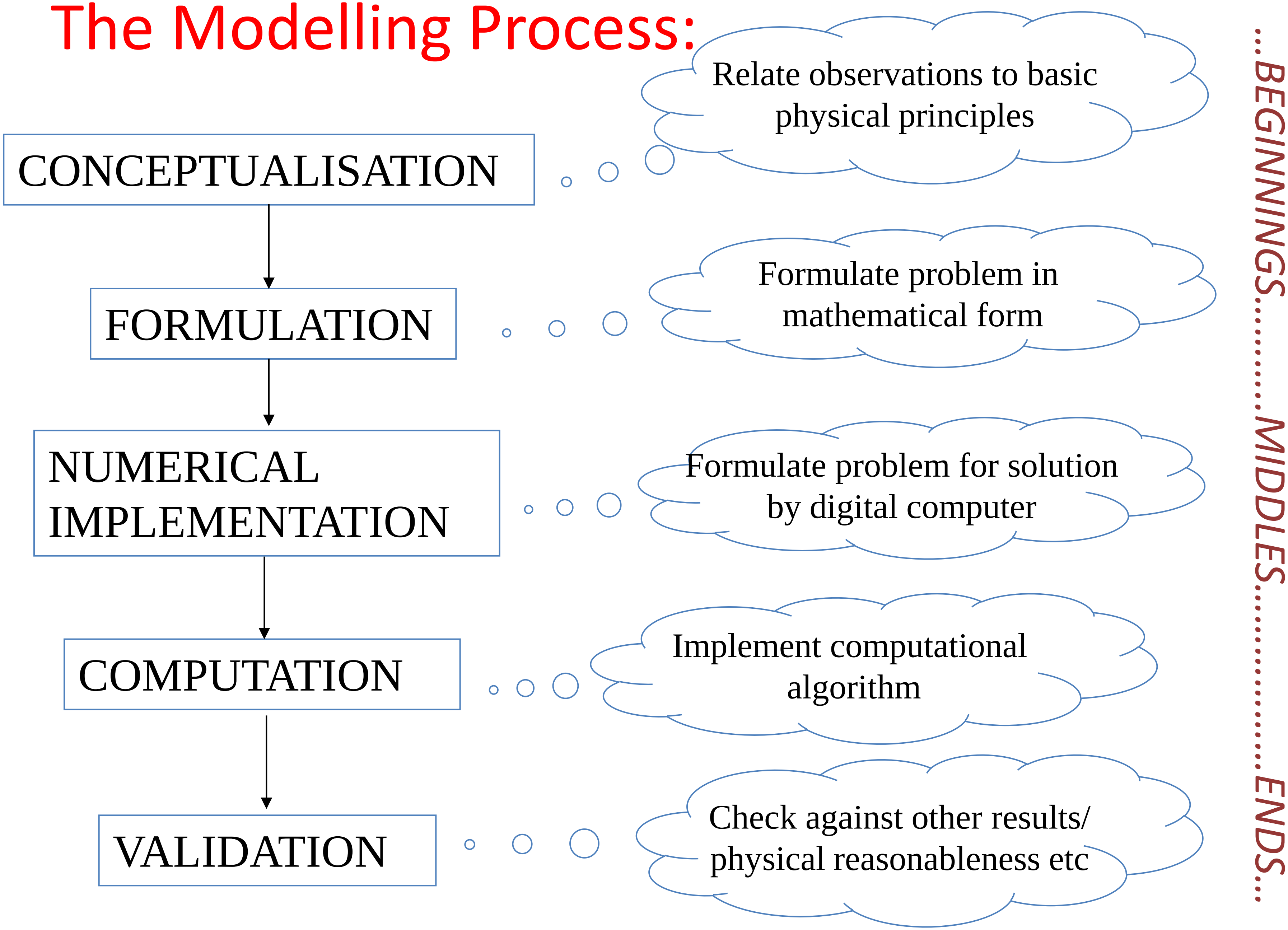
Goethe…
“Thought expands, but lames; action animates, but narrows”

The Design Process:

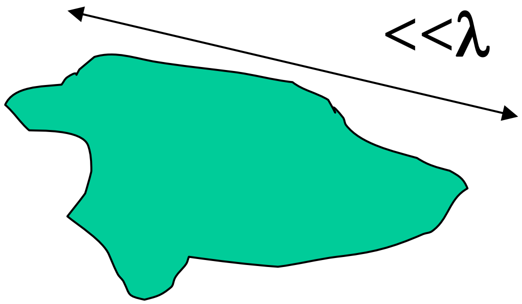


...BEGINNINGS........MIDDLES..............ENDS...

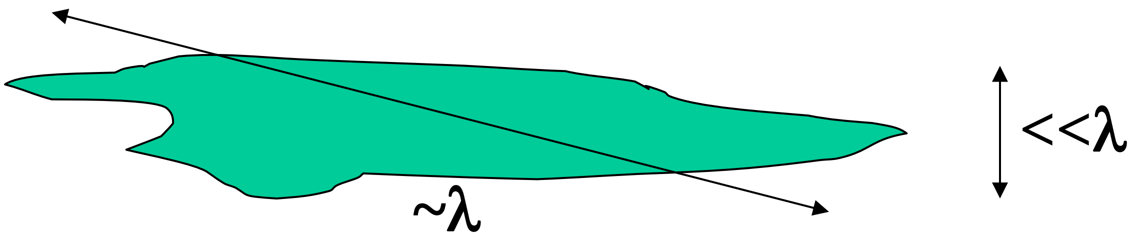
The Modelling Process:



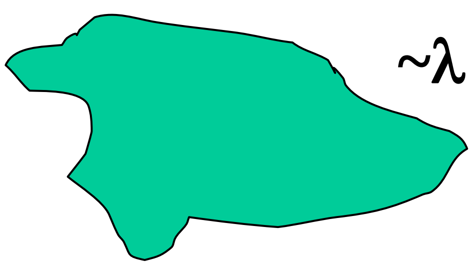
All models are not the same!...



Network approach
(KVL, KCL)



Transmission line theory may be adequate (Telegrapher’s equations)



Full-field theory (Maxwell’s equations)

Generic Classification of Numerical Methods:

- Time/frequency domain techniques
- Integral/differential equation techniques
- Some other very high frequency techniques (e.g. ray methods)

Classification Criteria:

- according to the domain of the operator (differential DE, integral IE)
- according to the domain of the variable (time TD, frequency FD)
- other categories (e.g. ray methods)

Example of a formulation in the time- and frequency-domains:

Consider and R-L series circuit. Its solution can be tackled into different ways.

Time-domain differential equation formulation

$$V_0 \cos(\omega t) = i(t)R + L\frac{di(t)}{dt}$$

Frequency-domain formulation

$$V_0 = \bar{I}(R + j\omega L)$$

Example of formulation in integral- and differential form:

Consider the solution of an electrostatic problem. It can be formulated in two different ways.

Either using Gauss's Law

$$\int_S \overline{D} d\bar{s} = \int_V \rho dv$$

Or, using Poisson's equation

$$\nabla^2 \varphi = -\rho / \varepsilon$$

INTEGRAL METHODS:

Good!

- open boundary problems
- only active region is discretised
- wire-like electrically long geometries

Not so good!

- Dielectrics, lossy materials
- large matrix manipulations
- complex electrically small conductors and thin plates

DIFFERENTIAL METHODS:

Good!

- highly inhomogeneous media
- highly complex electrically small conductors and thin plates
- time-varying problems, non-linear media

Not so good!

- entire problem space must be discretised
- open-boundary problems

Generic Solvers(1)

- *Method of Moments (MoM)*

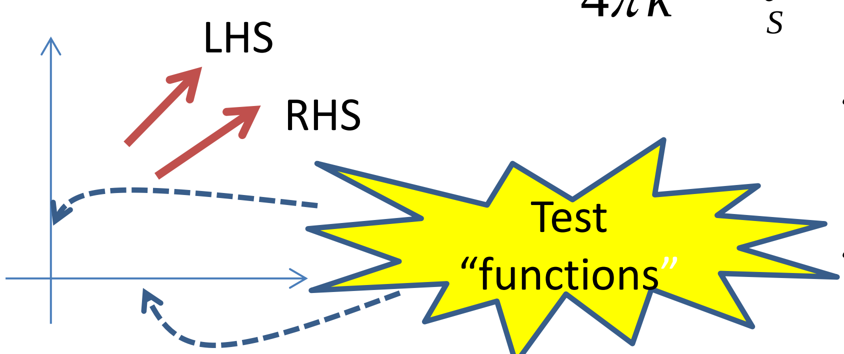
Well established technique, belonging to the class of frequency-domain, integral methods. Used as standard for checking other methods. Good for problems with wire-like structures. Common commercial package is NEC. Uses known expansion functions with unknown coefficients to approximate unknown fields.

$$\hat{n}\times\left(\underline{\vec{E}}^{i}+\underline{\vec{E}}^{s}\right)=0 \Rightarrow \frac{j\eta}{4\pi k}\hat{n}\times\int_{S}\underline{\vec{J}}\left(\vec{r}'\right)\bullet\left(k^{2}\left[I\right]+\nabla\nabla\right)\frac{e^{-jk\left|\vec{r}-\vec{r}'\right|}}{\left|\vec{r}-\vec{r}'\right|}dS'=\hat{n}\times\underline{\vec{E}}^{i}\left(\vec{r}\right)$$

$$\mathcal{L}\left\{\underline{\vec{J}}\left(\vec{r}\right)\right\}=\hat{n}\times\underline{\vec{E}}^{i}\left(\vec{r}\right)$$

EFIE

$$\mathcal{L}\left\{\sum_{j=1}^{N}\alpha_{j}\underline{\vec{J}}_{j}\left(\vec{r}'\right)\right\}=\hat{n}\times\underline{\vec{E}}^{i}\left(\vec{r}\right)$$



Generic Solvers(2)

- *Finite Element Method (FEM)*

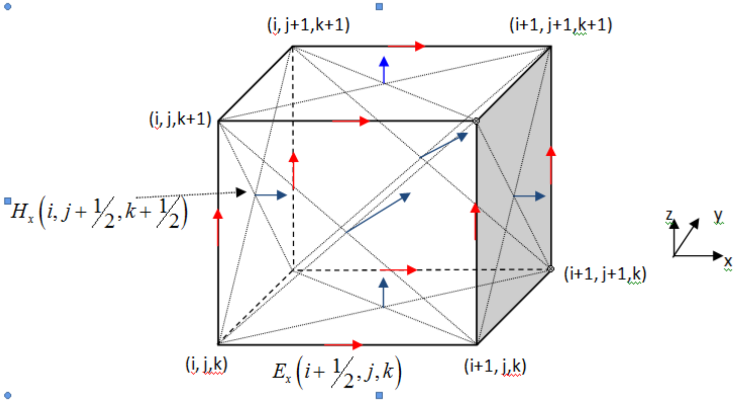
Well established technique, belonging to the class of frequency-domain, integral methods. A variation of this technique is the Boundary Element Method (BEM) which uses discretisation on surfaces only. Very popular technique especially at low frequencies. Many commercial packages available. Uses energy minimisation principles to arrive at solutions.

Generic Solvers(3)

- *Finite Difference Time Domain Method (FDTD)*

  Well established technique , belonging to the class of time-domain, differential methods. Very popular technique especially at high frequencies. Many commercial packages available (also FIT).

  Approximates derivatives by differences and uses marching in time algorithm to arrive at solutions.



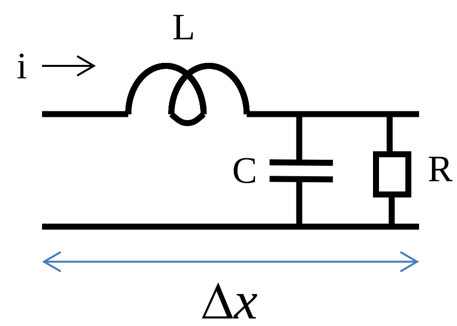
- E, calculated at nΔt, H at (n+1/2 Δt)
- Also displacement in space
- Stability, $\Delta t \le \dfrac{\Delta \ell}{c\sqrt{3}}$

Generic Solvers(4)

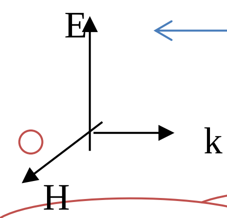
- *Transmission-Line Modelling (or Matrix) Method (TLM)*

  Well established technique, belonging to the class of time-domain, differential methods. Popular technique especially at high frequencies. Example of a commercial package is Micro-Stripes. Uses circuit equivalents to model fields.

$$\frac{\partial^2 i}{\partial x^2} = \frac{LC}{(\Delta x)^2}\frac{\partial^2 i}{\partial t^2} + \frac{L}{(\Delta x)^2 R}\frac{\partial i}{\partial t}$$

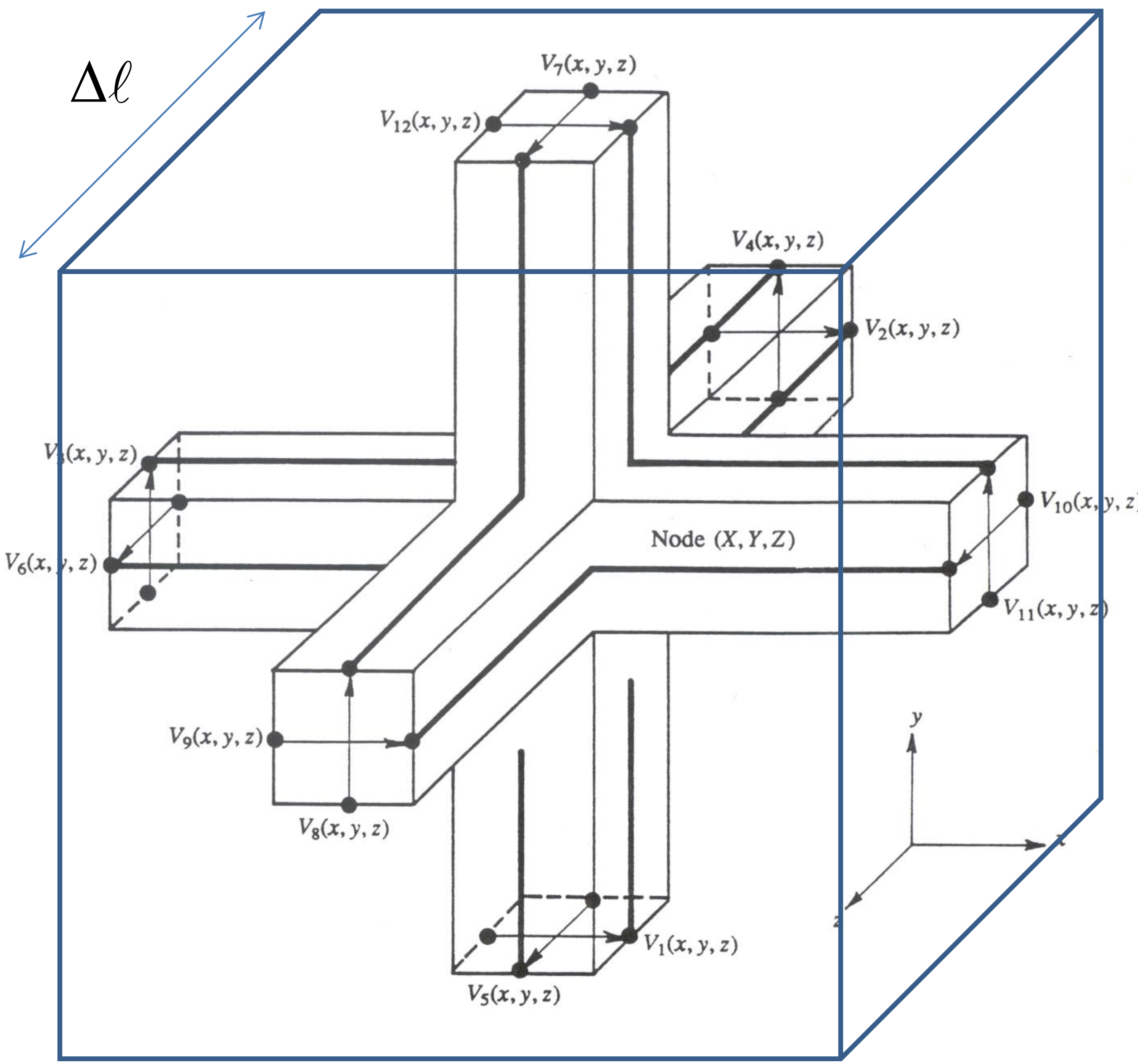


$$\frac{\partial^2 j}{\partial x^2} = \mu\varepsilon\frac{\partial^2 j}{\partial t^2} + \mu\sigma\frac{\partial j}{\partial t}$$



Equations are isomorphic!

TLM(4)-continued: 3D node and associated cell



Scattering:

$$V^r = [S]V^i$$

Connection:

$$_{k+1}V^i = [C]_k V^r$$

$$\Delta t = \frac{\Delta\ell}{2c}$$

$$\Delta\ell \leq \frac{\lambda_{\min}}{10}$$

Generic Solvers(5)

- *Semi-Analytical Methods*

  Examples are, the Method of Lines, Mode Matching etc. They are efficient and accurate but only suited to problems with some degree of symmetry.

Generic Solvers(6)

- *Hybrid Methods*

  Combine the best features of two methods e.g. finite difference and integral methods. Can be very efficient but not many commercial versions are available.

The mule syndrome!

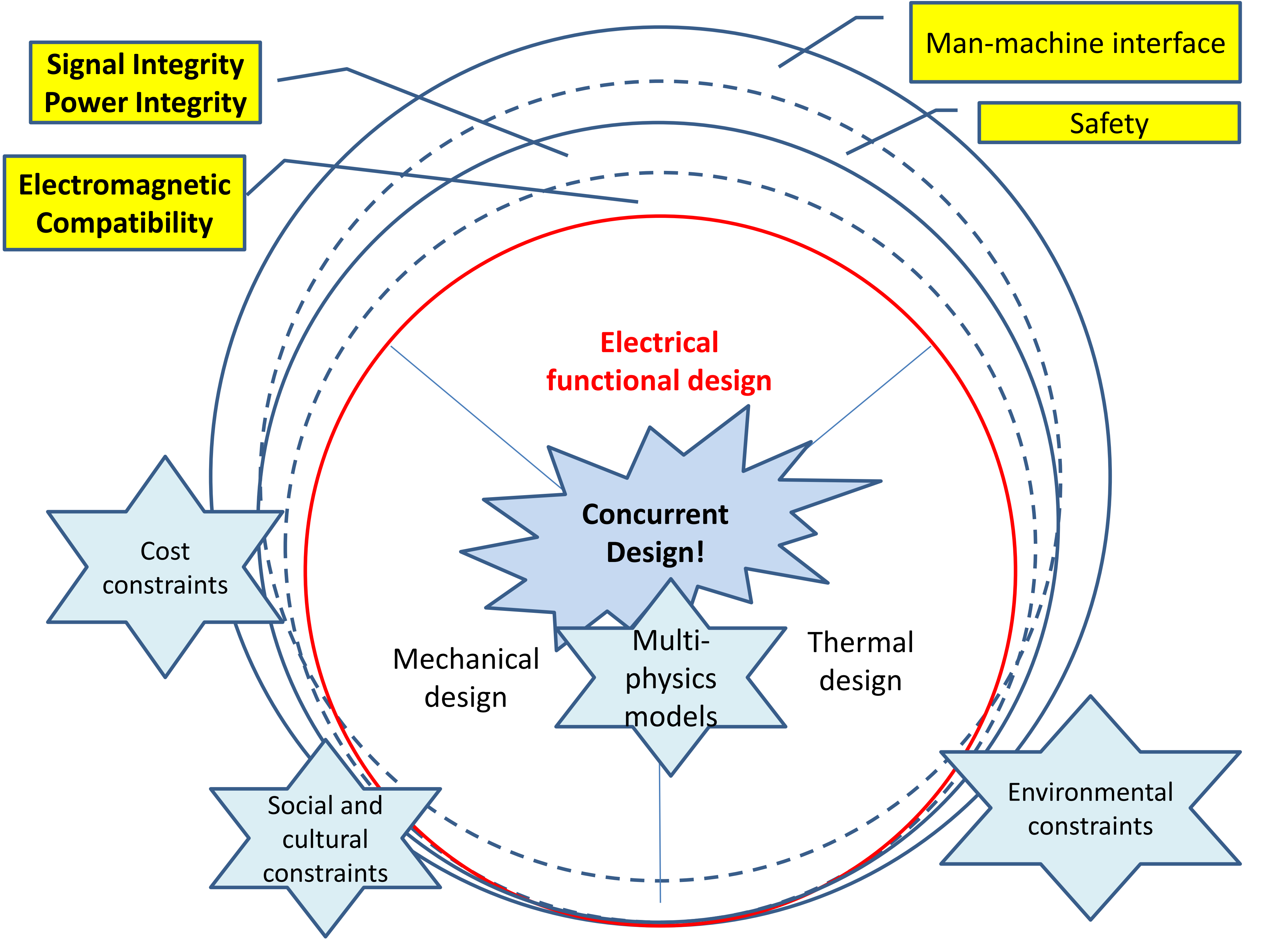
Aficionados of the mule claim that they are *"more patient, sure-footed, hardy and long-lived than horses, and they are considered less obstinate, faster, and more intelligent than donkeys.“.*
However, I do know of several cases of Greek men who have lost their manhood to stroppy kicking mules! I read further in Wikipedia that *“Mules are highly intelligent. They tend to be curious by nature. A mule generally will not let the rider put it in harm's way”*. There is a clue in the last sentence- mules can be awkward animals-you can flog a horse to death but you cannot do this to a mule.
Hybrid numerical methods have great advantages but are difficult to apply and make them do exactly what you want …

The simpler the model the better it is!
It is never the “real thing” and it should not be.

It should be accurate enough and simple so as to manipulate easily.

Ideally, it should be one that we can sketch on the back of an envelope and experiment with it while on the bus home after work!

But alas, our systems are far too complex to even approach this ideal!

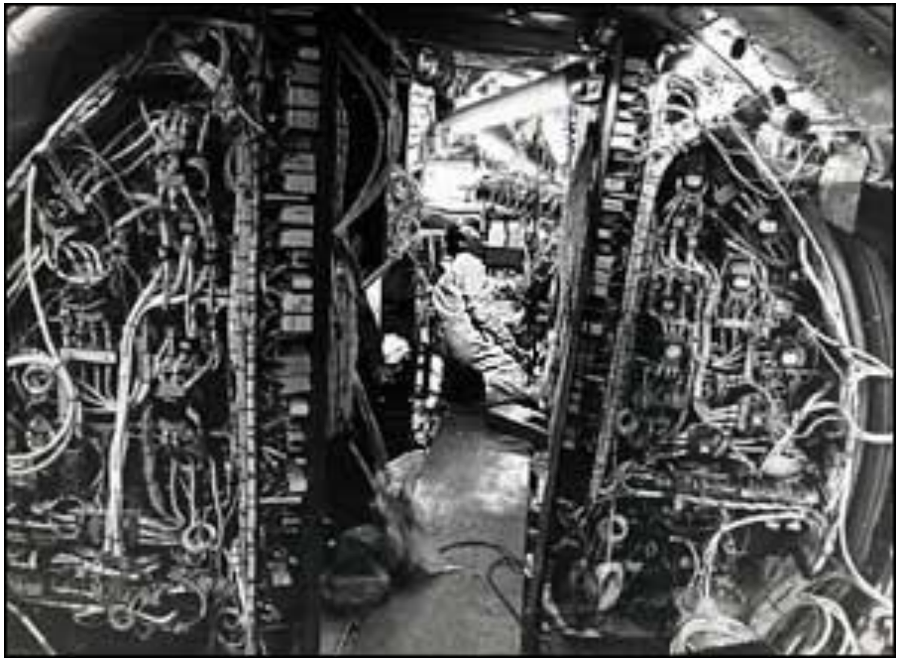


Signal Integrity
Power Integrity
Man-machine interface
Safety
Electromagnetic Compatibility
Electrical functional design
Concurrent Design!
Cost constraints
Mechanical design
Multi-physics models
Thermal design
Social and cultural constraints
Environmental constraints

Multiscale problems, Complexity and Uncertainty:

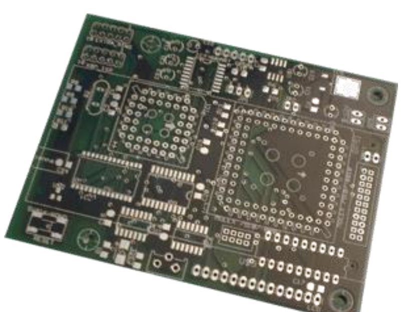
- EMC and Signal Integrity (SI) are studied in an environment where high repetition frequency short transition-time pulses propagate. A deep understanding of the relevant interactions required characterization and analysis in the time domain (TD) and inherently over a very wide range of frequencies. Models of materials over a wide frequency range are required and TD simulation codes are essential tools for such studies.
- Probably 75% of simulations in EMC are done in the time domain (TD). Naturally, practice differs in say electrical machine design.
- Material characterization from DC to at least 6 GHz must account for changing properties. New artificial materials with intricate geometrical details and frequency-dependent properties must be <u>efficiently</u> modelled in simulations

A panorama of complexity!



Concord wiring!

JSF wiring (28km wiring, 20k connectors)!

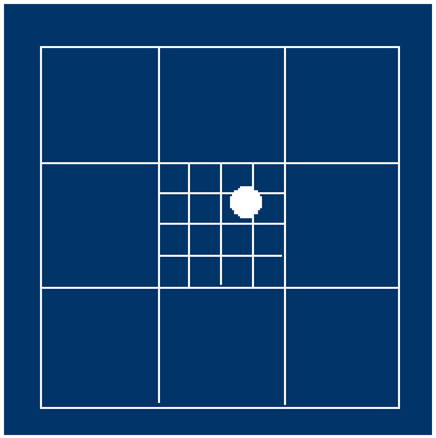


Typical PCB!

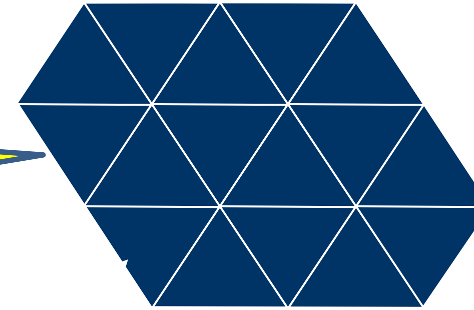
We are not dealing with "canonical" problems!... de-featuring?

Example: Distort!

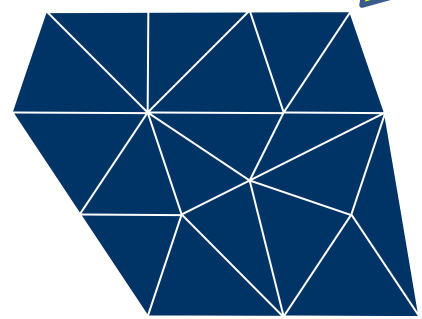
Multi-grid mesh



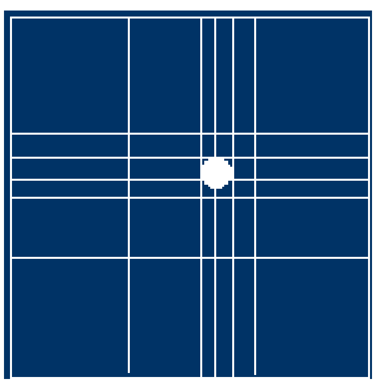
Structured mesh

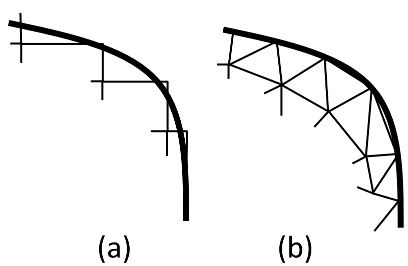


Un-structured mesh (number of neighbours varies according to demands of the problem)



Hybrid mesh

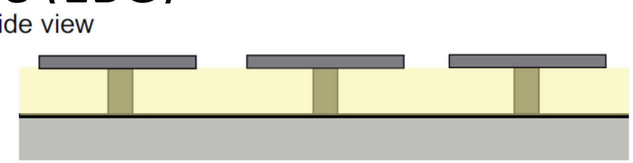


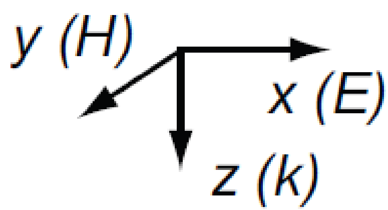


Conformal boundaries (best described by an unstructured mesh)

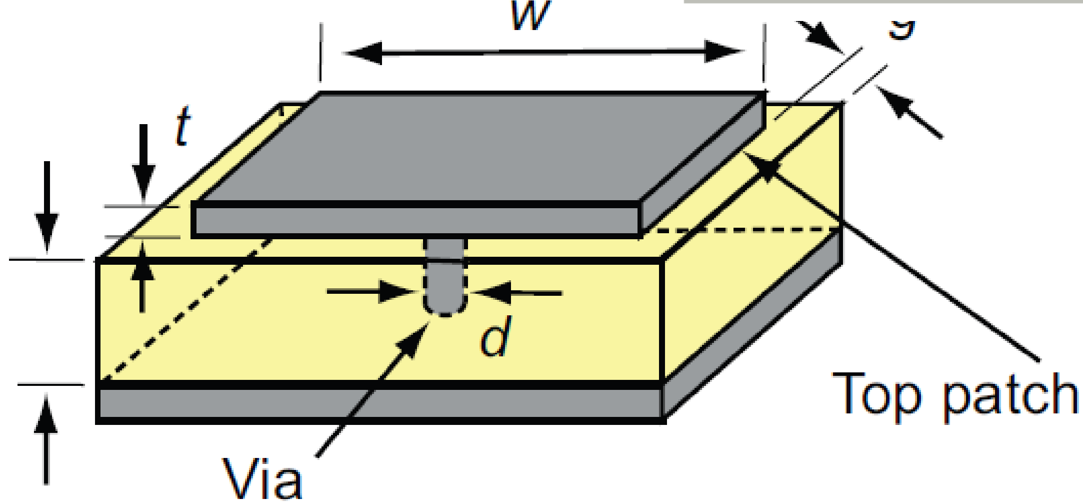
Example: Digital filter interface

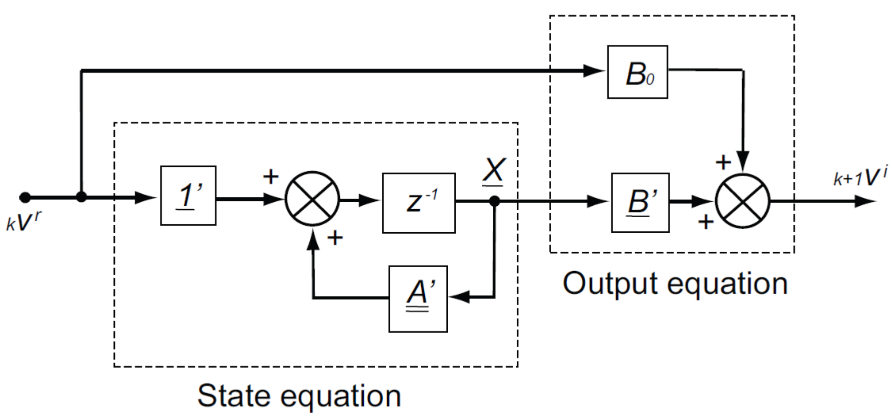
Extraction of the reflection coefficient from a boundary covered by an electronic bandgap structure (EBG)





w	4.0 [mm]
d	0.8 [mm]
t	0.1 [mm]
h	1.5 [mm]
g	0.2 [mm]





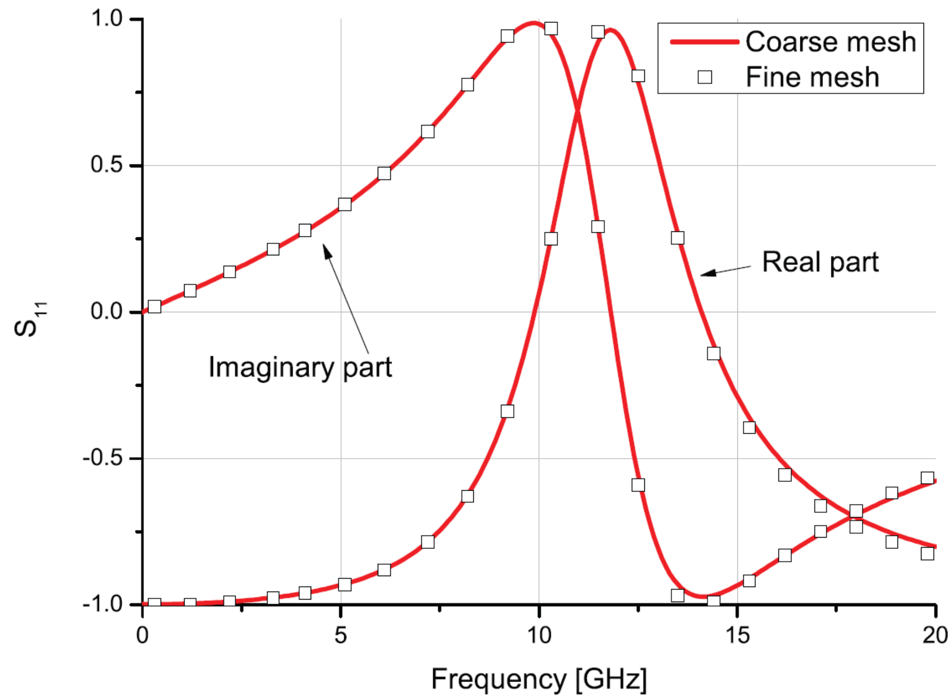
General form of DF to account for the details of the EBG(the parameters are extracted from the Padé form-see over)

Fine mesh resolution 0.1mm; Coarse mesh resolution 1.0mm
The coarse mesh is supplemented with the DF algorithm (2 poles) to account for the EBG

Padé form of reflection coefficient:

$$F(s) = \frac{b_0 + b_1 s + b_2 s^2}{a_0 + a_1 s + s^2}$$

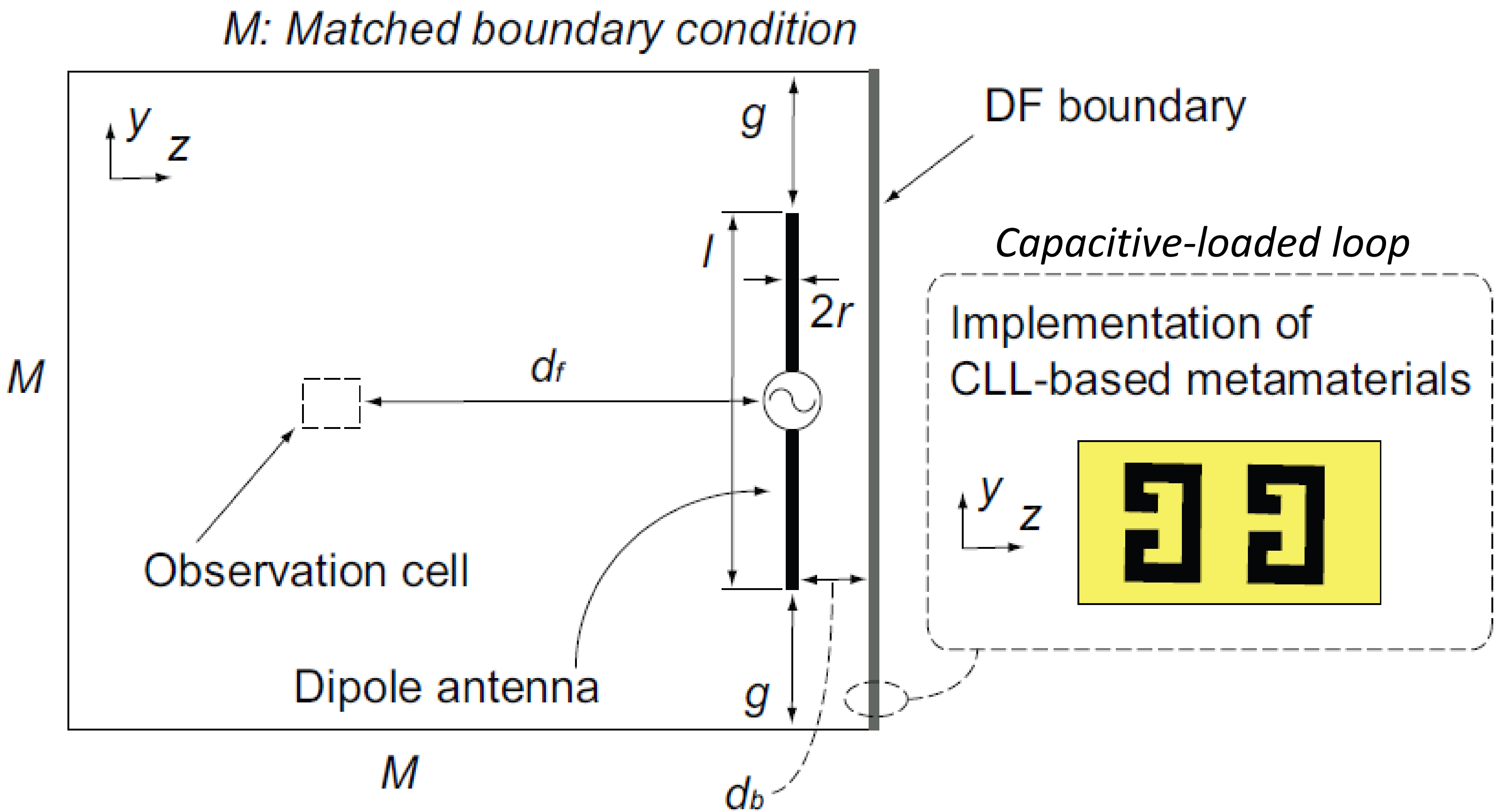
i	a_i	b_i
0	5.50562×10^{21}	-5.49485×10^{21}
1	2.69504×10^{10}	2.59674×10^{10}
2		-9.92844×10^{-1}



Efficiency gains!

	Coarse mesh	Fine mesh
Cell size [mm^3]	$1.0 \times 1.0 \times 1.0$	$0.1 \times 0.1 \times 0.1$
Analysis space size ($N_x \times N_y \times N_z$)	$(5 \times 5 \times 44)$	$(44 \times 44 \times 60)$
Calculation time	< 1 minute	3 hours

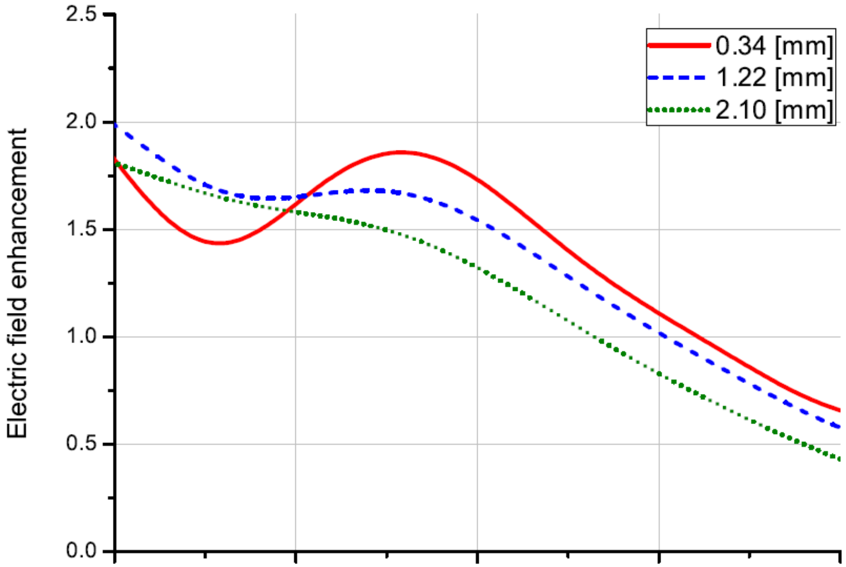
Note: Implementation in the TD is done by deriving an equivalent DF algorithm (e.g. using bilinear transform). Frequency-dependent materials dealt with in a similar way.



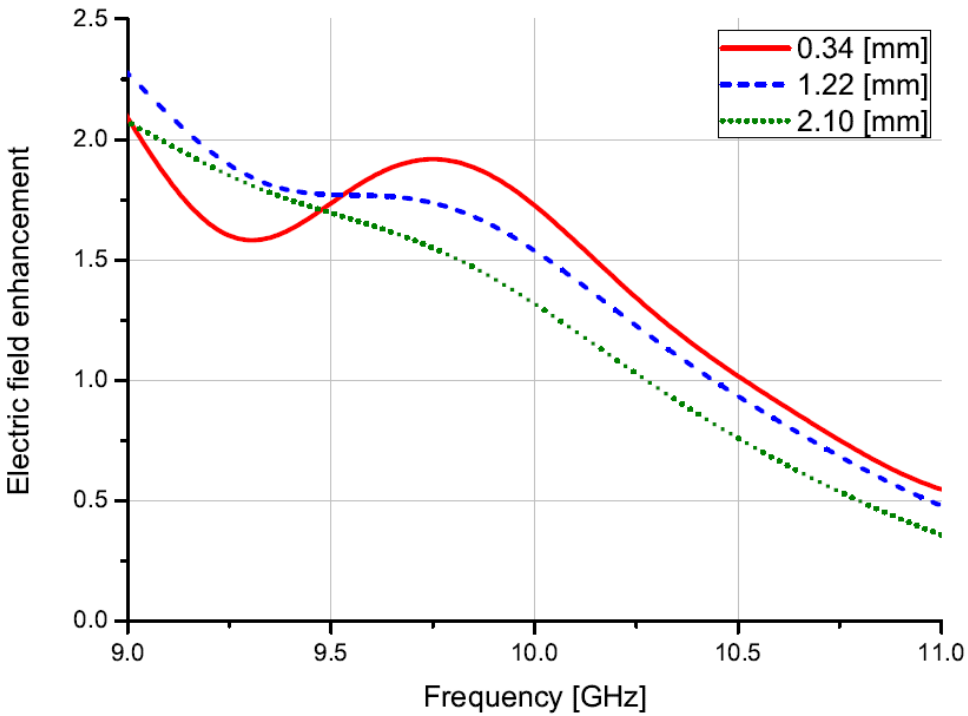
Cylindrical antenna is modelled using a "thin-wire" formulation

s

TLM unit cell size	$0.88 \times 0.88 \times 0.88$ [mm^3]
d_f	3.86 [mm]
d_b	0.34, 1.22 or 2.10 [mm]
g	7.04 [mm]
r	0.10 [mm]
l	9.68 [mm]
Resistance of centre cell of antenna	50.0 [Ω]



electric field with meta-material wall/electric field with absorbing wall



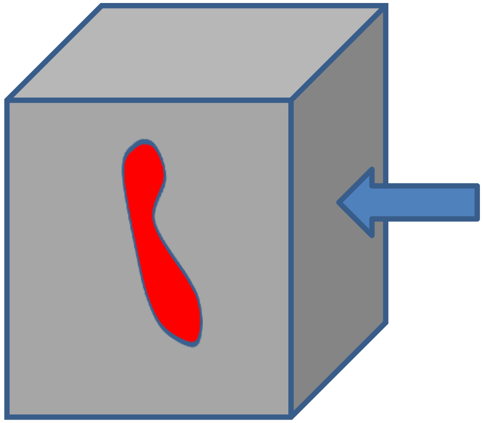
electric field with meta-material wall/electric field with PEC wall

Example: Embed a cell using modal decomposition

How do we deal with a cell which contains an unusual object?

Reducing the size of the cell so that we can map directly the geometrical shape of the unusual object is not practical (excessive computational resources required, tedious mapping etc).

The alternative is to deal with this cell in an entirely different way (as a **sub-cell, macromodel**). We need to know the "impedance" seen by signal impinging on each face of the cell so that the rest of the computation encounters there a boundary condition.

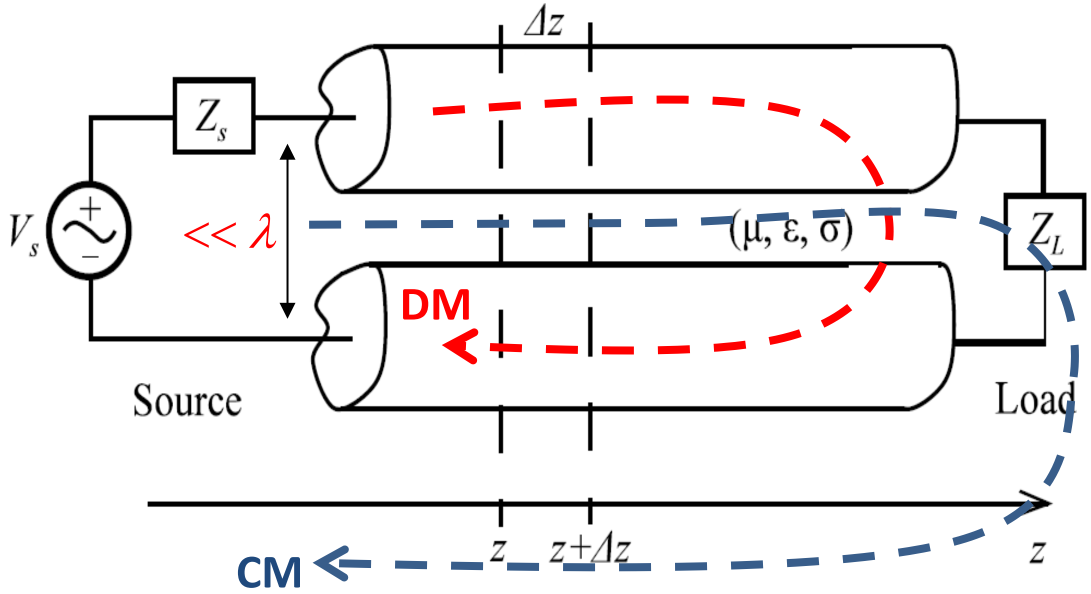


The difficulty here is that the impedance seen on each face depends on the entire 3D environment as there is coupling between all signals impinging on the six facets of the cell.

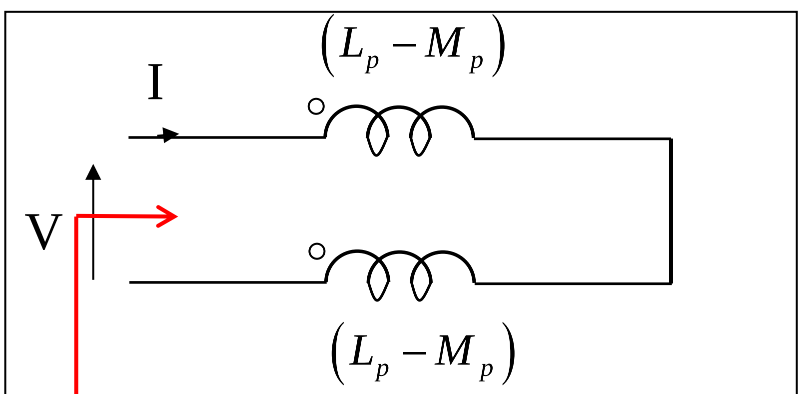
The calculation becomes far easier if incident signals are decomposed into components which are independent and see a well defined impedance at each face. These components are what we call **"modes".**

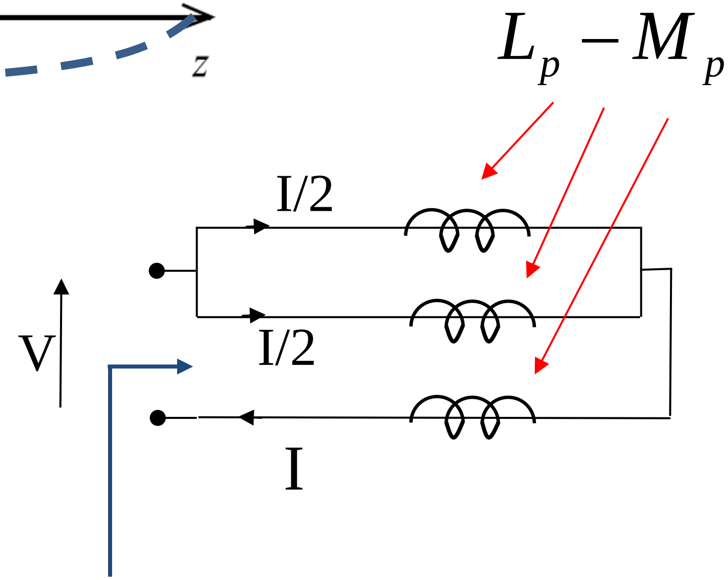
$$\bar{V}^i = [U]\bar{X}^i$$

$$\bar{V}^r = [U]\bar{X}^r \qquad [U], \text{ eigenvector matrix}$$



What are “modes” ?





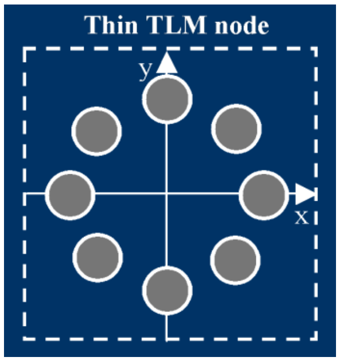
$2(\mathbf{L_p} - \mathbf{M_p})$ DM impedance

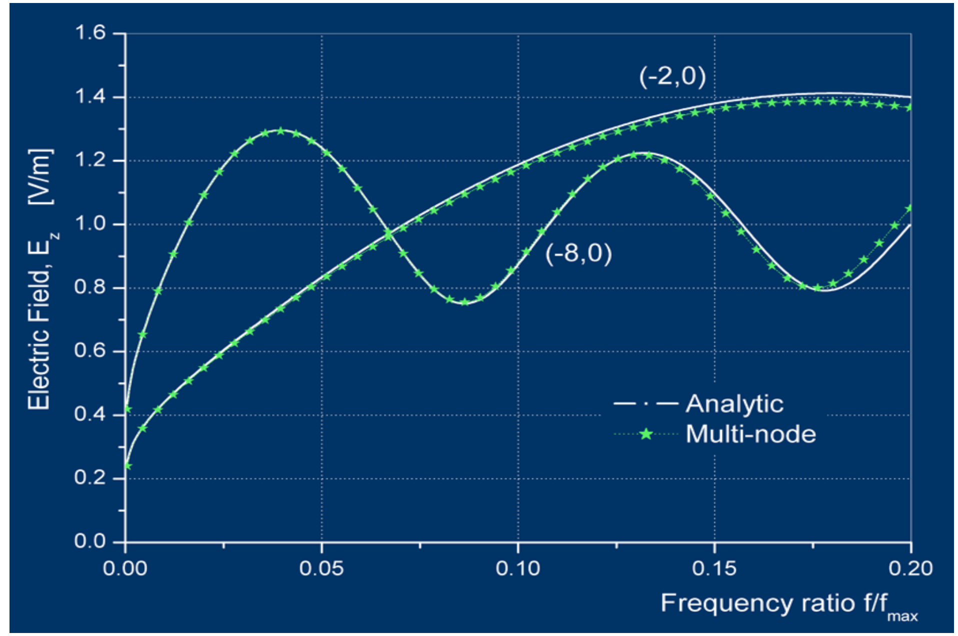
$\frac{3}{2}(\mathbf{L_p} - \mathbf{M_p})$ DM impedance

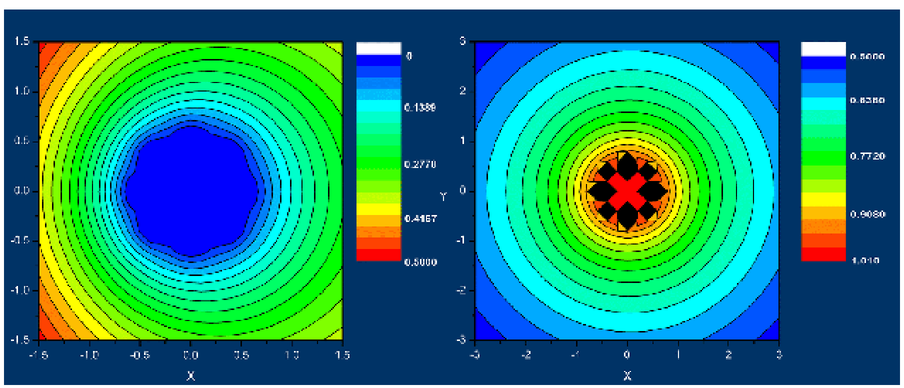
Embed!

Modal Expansion Techniques

wire shield







Total Field

Scattered Field

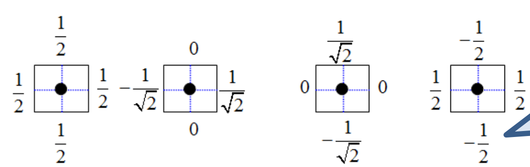
The parameters:

Number of wires = 8,

a = 0.003125m, r= 0.0125m,

θ= 0°, 45°, 90°, 135°, 180°,

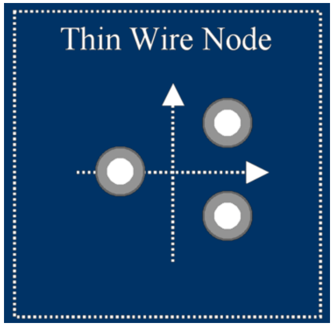
225°, 270°, 315°

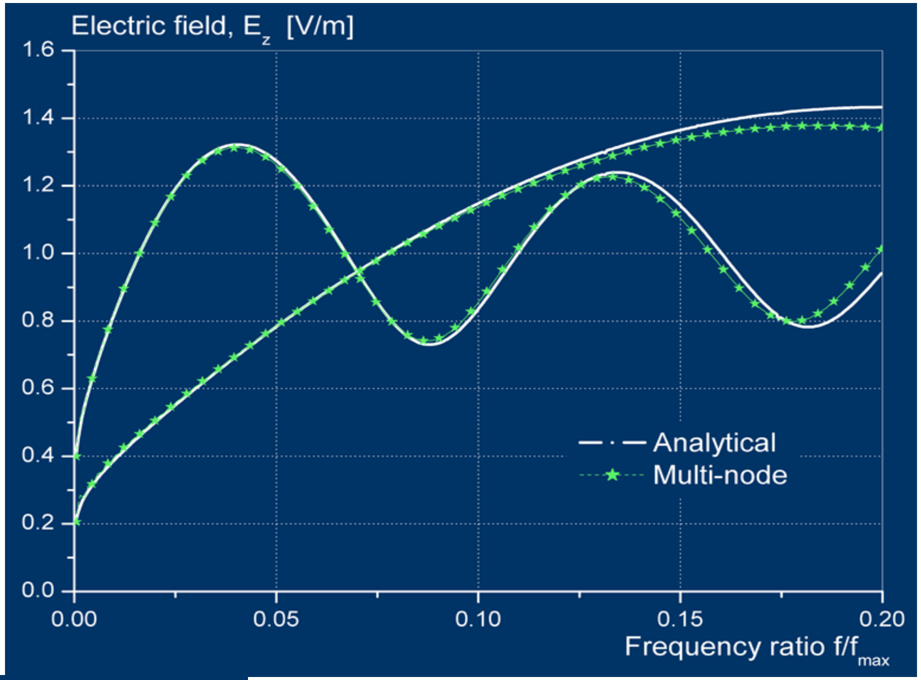


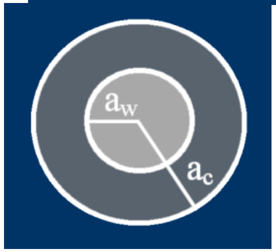
Simplified example of modal decomposition

Modal Expansion Techniques

Dielectric coated wires







Parameters:

Dielectric constant =100
Number of wires = 3
a_{w1} = 0.005m,
a_{w2} = 0.00625m,
a_{w3} = 0.0075m,
a_{c1}=a_{c2} =a_{c3} = 0.0125m
r_1 = 0.01, r_2 = 0.01125,
r_3 = 0.0125
θ_1= 45°, θ_2=-45°, θ_3=180°
node size = 0.05m,
total mesh area 60m by 60m

Uncertainty:

- Complex systems in particular are characterized by uncertainties in parameter values which make the prediction of their response problematic. The normal deterministic studies are useful, but they fail to bring out the full range of potential responses and to take account of the risks involved and the confidence that can be attached to predictions

- Monte-Carlo studies require numerous simulations to span the parameter space and hence are unrealistic in situations where a single simulation requires major computational resources

- A stochastic approach to modelling is based on extracting the first few moments (mean and standard deviation, or even the entire pdf) from a relatively small number of simulations…(see the Unscented Transform UT)…

For an output g(x) which depends on a random variable $x = \bar{X} + \hat{x}$ where $\hat{x}$ is a zero mean Gaussian random variable we need 3 simulations at

Example of the applications of UT

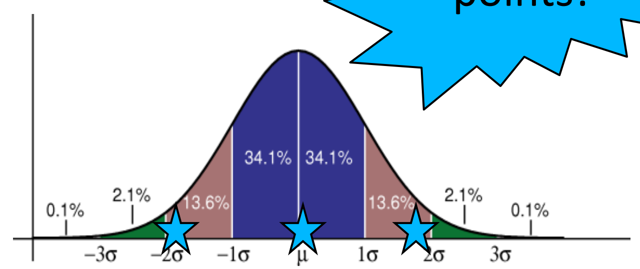
$$\bar{X}, \quad \bar{X} + \sigma\sqrt{3}, \quad \bar{X} - \sigma\sqrt{3}$$

Where σ is the standard deviation of $\hat{x}$

The results of the 3 simulations are: $g\left(\bar{X}\right), \quad g\left(\bar{X} + \sigma\sqrt{3}\right), \quad g\left(\bar{X} - \sigma\sqrt{3}\right)$

Sigma points!

We combine the 3 simulations as shown below to get the expected value and variance of the output g.



Variance of the output

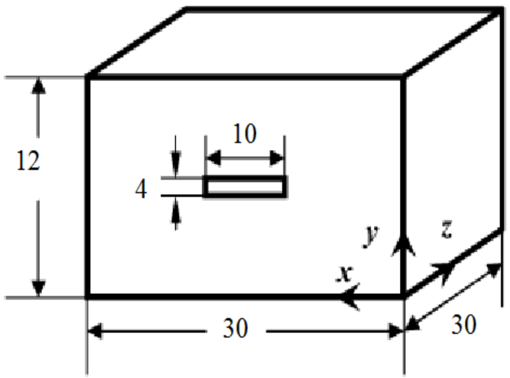
Expected value of output

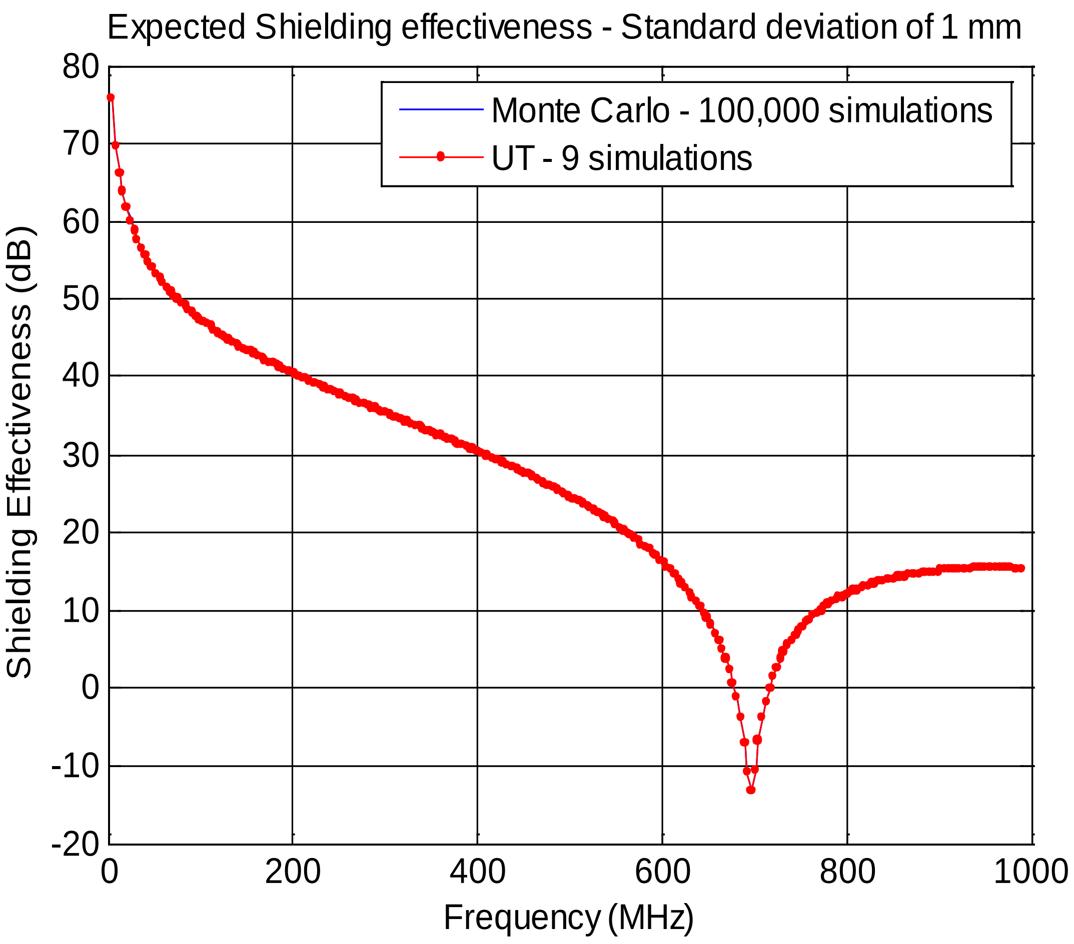
$$\tilde{\bar{g}} = E\left\{g\left(\bar{X} + \hat{x}\right)\right\} = \frac{2}{3} g\left(\bar{X}\right) + \frac{1}{6} g\left(\bar{X} + \sigma\sqrt{3}\right) + \frac{1}{6} g\left(\bar{X} - \sigma\sqrt{3}\right)$$

$$\tilde{\sigma}_g^2 = \frac{2}{3}\left[g(\bar{X}) - \tilde{\bar{g}}\right]^2 + \frac{1}{6}\left[g(\bar{X} + \sigma\sqrt{3}) - \tilde{\bar{g}}\right]^2 + \frac{1}{6}\left[g(\bar{X} - \sigma\sqrt{3}) - \tilde{\bar{g}}\right]^2$$

Example : Shielding Effectiveness – Metal Box

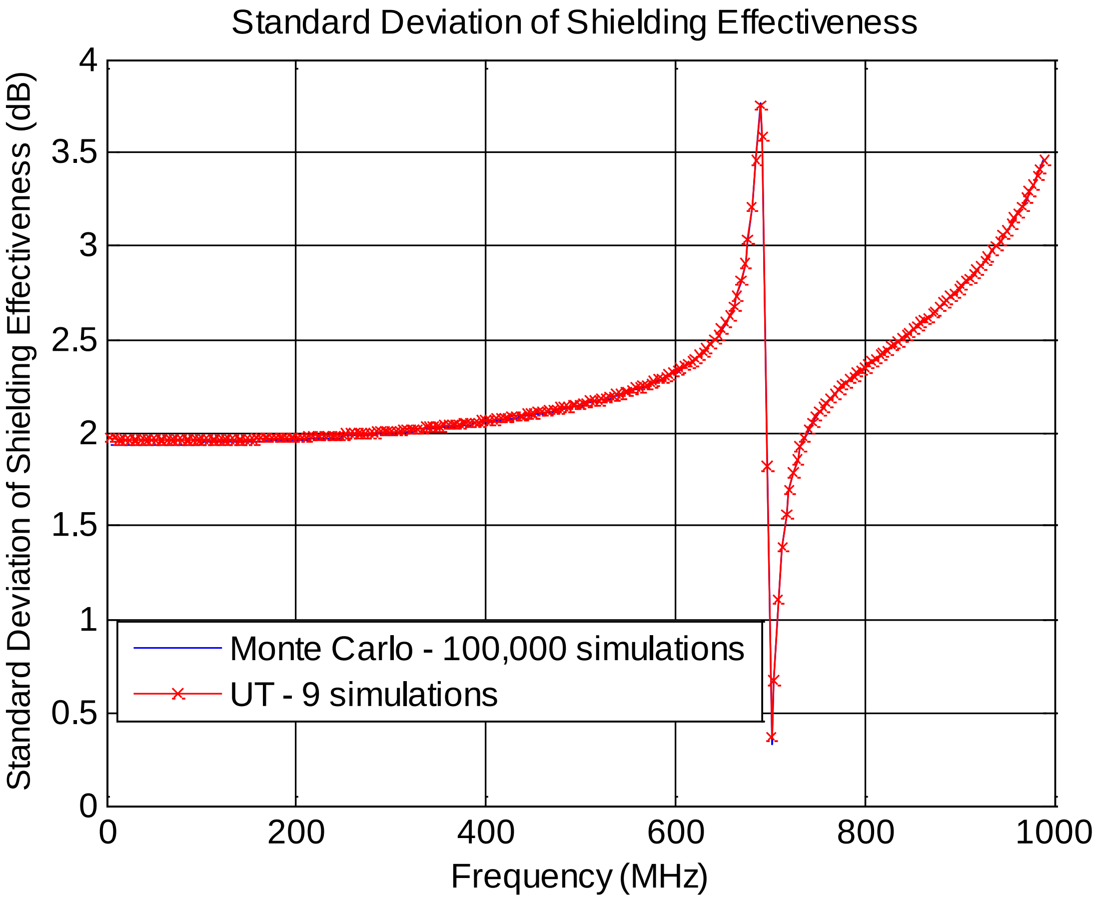
- Analytical formulation – size of the aperture (2 RVs, width and length, Gaussian distribution, std deviation 1mm)





Example : Shielding Effectiveness – Metal Box (cont.)

- Analytical formulation – size of the aperture (as in previous slide)



Conclusions and Outlook:

- EMC and HF modelling in general makes severe demands on CEM
- Broadband responses, multi-scale problems, complexity and uncertainty require innovative approaches to simulation and not just a larger faster computer!
- Combining the best features of individual models into an efficient whole is a powerful approach which is capable of scaling up modelling capabilities to meet practical needs

GGIEMR

- We will increasingly rely on numerical models BUT we must exploit fully synergies and complementarity between simulations and testing
- Need to characterise materials and sub-systems over a wide frequency range in a form suitable for embedding into whole system models
- De-featuring, complexity reduction, parametrised models and physically transparent models to aid creativity are needed!

Contact

Christos CHRISTOPOULOS FREng, FIEEE

Emeritus Professor of Electrical Engineering
George Green Institute for Electromagnetics Research (GGIEMR)
Dept. of Electrical and Electronic Engineering
Faculty of Engineering
University of Nottingham
Nottingham
NG7 2RD
UK
Tel: +44 (0)115 84 68296 (Secr.)
Tel: +44 (0)115 951 5580 (direct)
Fax: +44 (0)115 951 5616
christos.christopoulos@nottingham.ac.uk
www.nottingham.ac.uk/ggiemr/