



CEM DES SYSTÈMES

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SENSIBILISATION AUX PRINCIPES CEM

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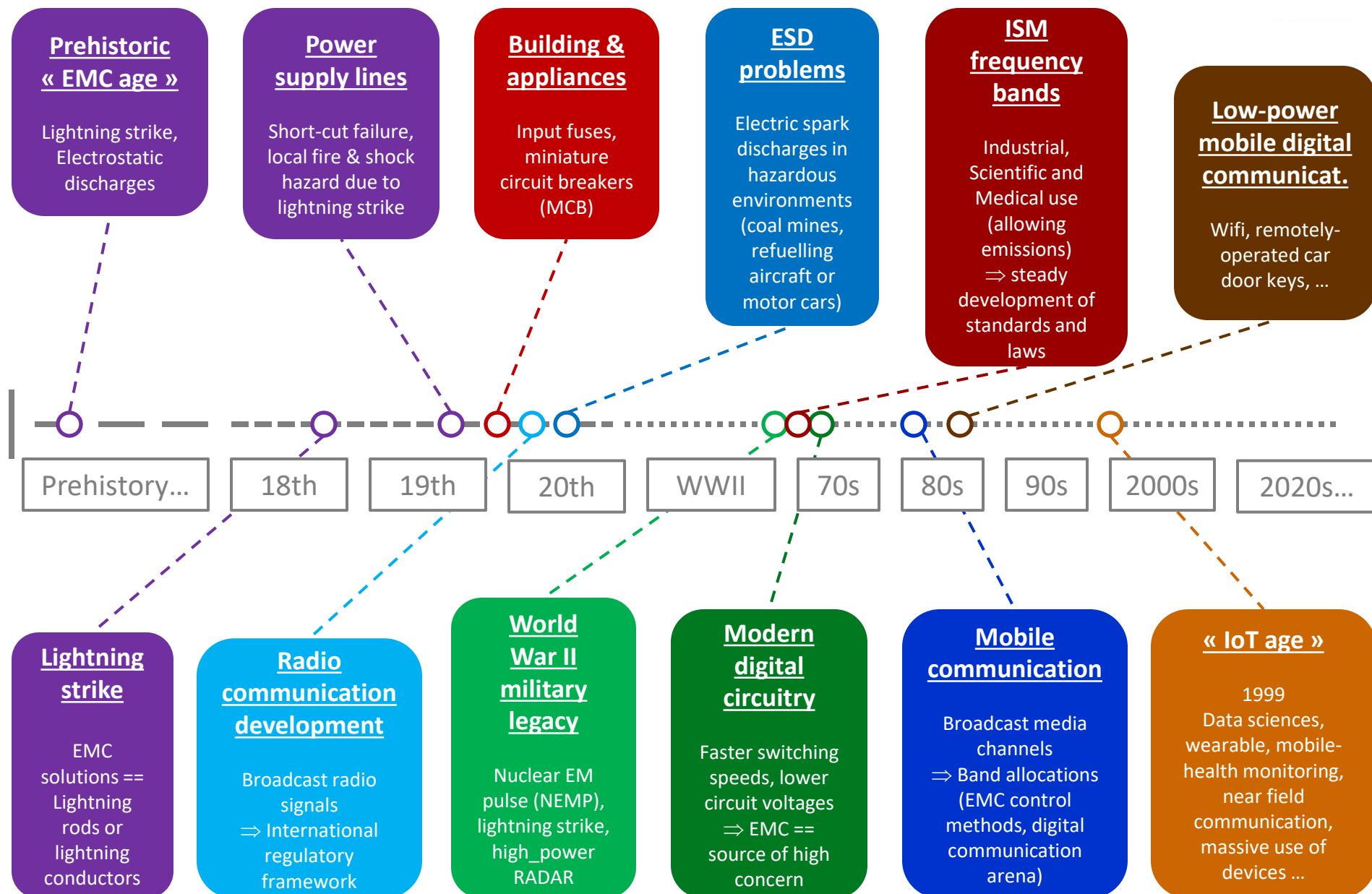


Safran Tech

PLAN

1. Position du problème
 - a) Limiter les interférence EM (EMI) : quel(s) besoin(s) ?
 - b) En quoi l'IoT et les systèmes connectés posent un problème ?
 - c) Normes, spécifications & gestion du spectre EM
2. Attentes des outils de simulation (num. & exp.)
 - a) CEM : quels calculs, quelles interactions ?
 - b) Matériel(s) et méthode(s)
 - c) Cas des différences finies : exemples
3. Caractérisation des composants IoT du point de vue CEM
 - a) Estimation de l'influence « IoT » à l'aide d'outils numériques
 - b) Interférences électromagnétiques « intentionnelles » & IoT
4. Conclusions

1-A/ HISTORIQUE BREF ET NON-EXHAUSTIF DE LA CEM



1-A/ INTERFÉRENCES NON-INTEENTIONNELLES ‘HISTORIQUES’ (1)



USS Forrestal explosion, July 1967

Uncommanded release of munitions that struck a fully armed and fueled fighter on deck
(134 deaths, severe damage on the aircraft carrier and aircrafts)

⇒ Revision of EMC requirements including special considerations for electroexplosive devices

W. Von Achen, The Apache Helicopter: An EMI Case History, Compliance Engineering, 1991

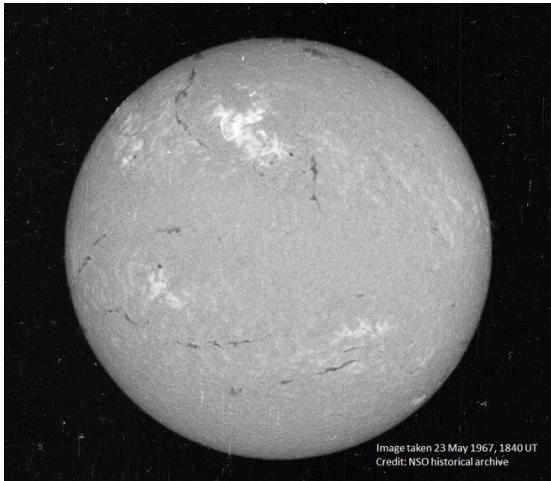
B-52 “in-flight” control system

When adding op-amp-based flight control systems to the B-52 bomber autopilot stability augmentation system, the use of the HF radio was altered. It resulted in the uncommanded activation of all near empennage flight control surfaces.

The wiring system, which had not been changed, was found to be susceptible to HF. This was a case of using new (at the time) technology and introducing a potentially dangerous problem that had not existed before using the new technology.



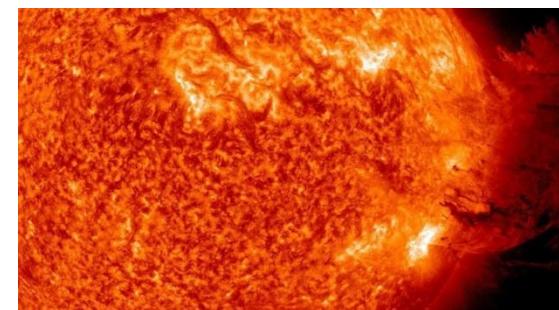
1-A/ INTERFÉRENCES NON-INTENTIONNELLES ‘HISTORIQUES’ (2)



M. Wall, How a 1967 solar storm nearly led to nuclear war, space.com, 2016

Solar storm, May 1967

Solar flares may be powerful enough to cause EM radiation that can interfere with communication systems. A powerful solar storm nearly heated the Cold War up catastrophically a half century ago, a new study suggests. The U.S. Air Force began preparing for war on May 23, 1967, thinking that the Soviet Union had jammed a set of American surveillance radars. But military space-weather forecasters intervened in time, telling top officials that a powerful sun eruption was to blame, according to the study.



Solar storm, August 1972

The extreme space weather events of early August 1972 had significant impact on the US Navy, which have not been widely reported: a nearly instantaneous, unintended detonation of dozens of sea mines south of Hai Phong, North Vietnam. These American mines' magnetic detonators were designed to be set off when a ship passed nearby. The study also notes that additional effects of the storm included radio blackouts, a visible aurora in parts of the UK and Spain, and damage to solar panels to orbiting satellites.



- , A solar storm during the Vietnam War was powerful enough to set off sea mines, qz.com, 2018

1-A/ INTERFÉRENCES NON-INTENTIONNELLES ‘HISTORIQUES’ (3)



Panam Flight 214, 1963

In 1963, a Pan American Boeing 707 crashed due to a lightning strike, causing the death of 81 occupants.

https://en.wikipedia.org/wiki/Pan_Am_Flight_214

<https://www.aerotime.aero/articles/25885-how-dangerous-is-a-lightning-strike-for-an-aircraft>

Vol easyjet, 2022

Un **vol de la compagnie EasyJet** a été forcé de s’arrêter en urgence après que l’avion eut été frappé par la foudre ! Le vol qui devait **relier Milan à Naples** a donc été forcé de s’arrêter après qu’un éclair ait touché l’une des deux ailes. Il faut dire que la **région de Campanie**, dans le sud de l’Italie, a été frappée par de fortes pluies qui ont rendu très difficile l’accès à l’aéroport international de Naples. Les conditions météorologiques défavorables ont entraîné un atterrissage d’urgence à l’aéroport **Karol Wojtyla de Bari**, dans la région des Pouilles (dans le sud de l’Italie).



- **Foudre & aéronefs**
 - Phénomène imprévisible et inévitable
(en moyenne 1 foudroiement par an, i.e. 1500 h de vol)
- **Déclenchement majoritaire de la foudre par l'avion (90%)**
 - Sinon canal de foudre intercepté par l'avion

1-B/ EXEMPLE ILLUSTRATIF : IoT & EMC/EMI (CEM/IEM EN FR)

Keywords search (IoT, EMI, EMC) ⇒ « surprising » / maximum dozen papers!

- Time domain measurements needed due to software cycles
- In-band interferences
- Variations around EM environments
- EMC performance of low cost components
- Criticality with respect to dedicated applications
- Detuning and crosstalks (co-location)
- Specific Absorption Rate (SAR)
- Model based software testing



EMC Challenges for the Internet of Things

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Abstract—The Internet of Things (IoT) is a new paradigm for distributed computing and communication. It is based on the concept of connecting objects and sensors to the Internet. This allows for a wide range of applications such as smart homes, smart cities, and industrial automation. However, the increasing number of connected devices also poses significant challenges for electromagnetic compatibility (EMC). In this paper, we discuss the main EMC challenges for the IoT, including the need for time domain measurements, the criticality of in-band interferences, and the variations around EM environments.

Index Terms—Internet of Things, EMC, time domain measurements, in-band interferences, variations around EM environments.

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Manuscript received April 20, 2017; revised June 15, 2017; accepted July 10, 2017. This work was presented at the 2017 International Symposium on Electromagnetic Compatibility (EMC Europe 2017), Prague, Czech Republic, September 4–7, 2017.

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Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier: 10.1109/ICEM.2017.8051822

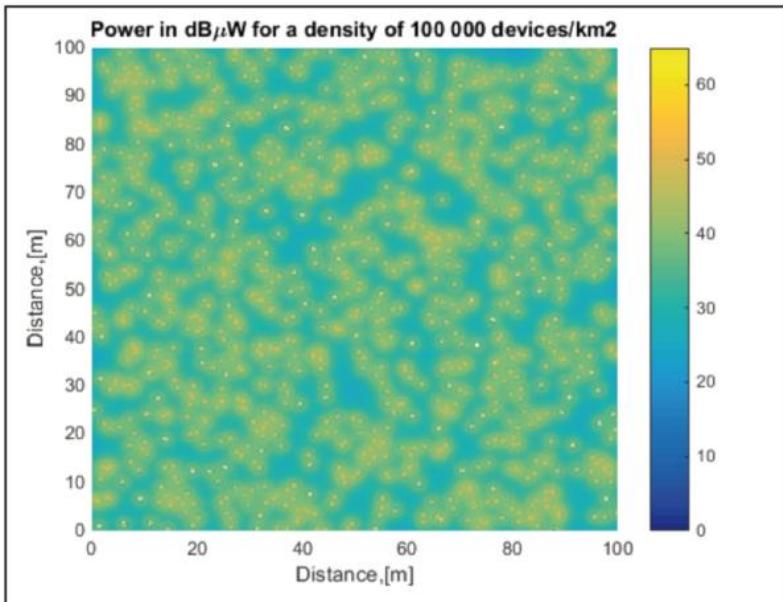
IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY

Volume 59, No. 4, August 2017, pp. 609–616

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10.1109/TEMC.2017.2700000

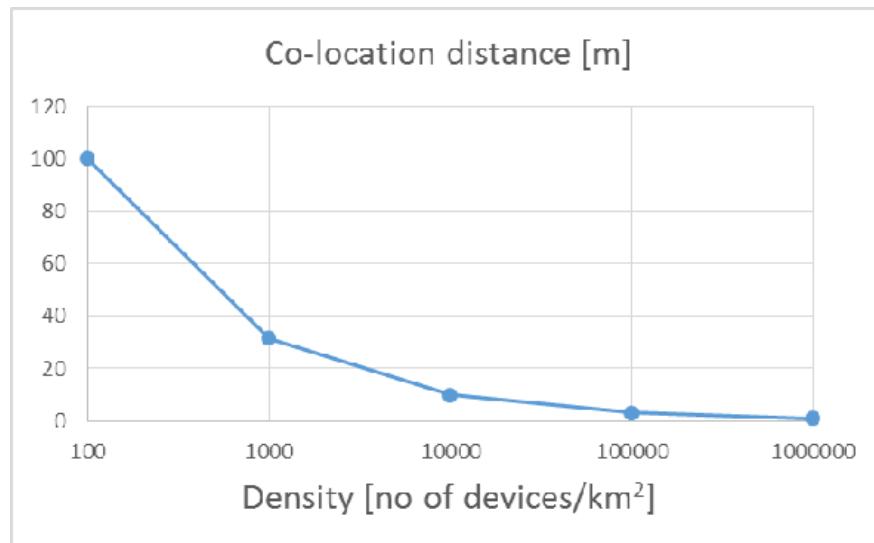
1-B/ IMPORTANCE DE LA DENSITÉ & LOCALISATION DES ÉQUIPEMENTS



Smart cities

Device	Density [# devices / km ²]
Water meters	10,000
Electricity meters	10,000
Gas meters	10,000
Vending machines	150
Bike fleet management	200
Pay-as-you-drive	2,250

K. Wiklundh and P. Stenumgaard, EMC challenges for the IoT, in proc. Int. Symp. On EMC, Angers, France, 2017



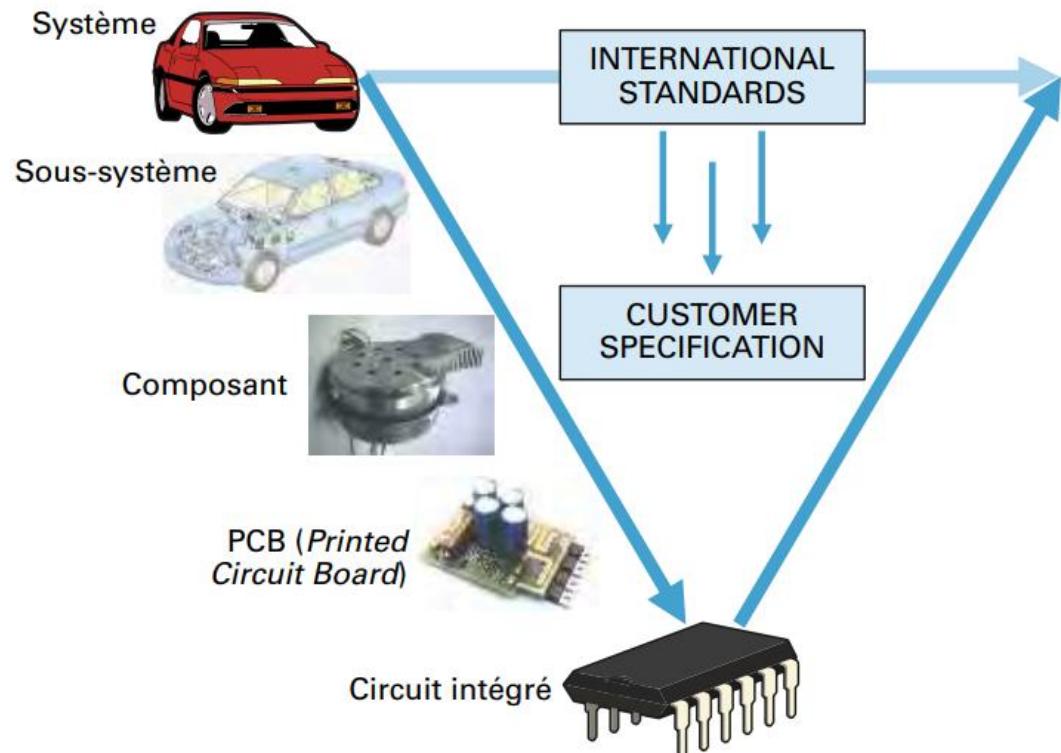
The higher co-location densities,
the most challenging from an
EMC point of view

1-B/ CEM ET CYCLE EN ‘V’ ...

- Processus de développement de produit classique en 2 étapes
 - Spécification (descendante)
 - Validation (montante)

■ Difficulté

- Déclinaison des besoins ‘équipements’
- Pré-évaluation des contraintes par simulation impossible
- Equipements et faisceaux déjà spécifiés



■ Pratique

- Besoin ‘équipement’ défini dans un CdC (règles standards) non forcément adaptées à l’équipement et à sa disposition dans le système

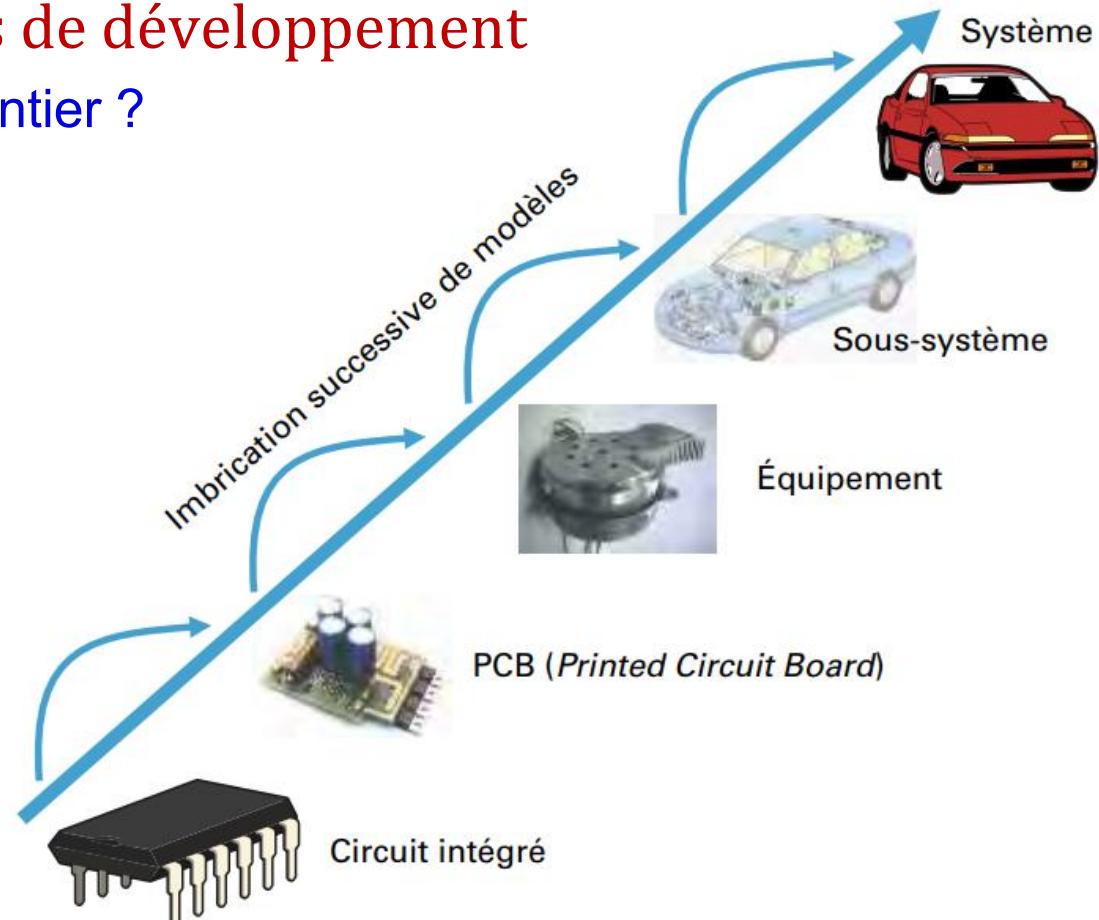
1-B/ ... SOLUTION : APPROCHE 'BOTTOM-UP'

■ Valider les hypothèses de développement

- Charge de l'équipementier ?
- Impact des choix sur intégration successive dans les sous-systèmes et le système

■ Modèles équivalents

- CMS
- Carte PCB
- Équipement
- Sous-système
- Système



But == obtenir rapidement une estimation des risques liés à une implantation particulière d'un équipement

1-c/ BANDES ET GAMMES DE FRÉQUENCES EN CEM

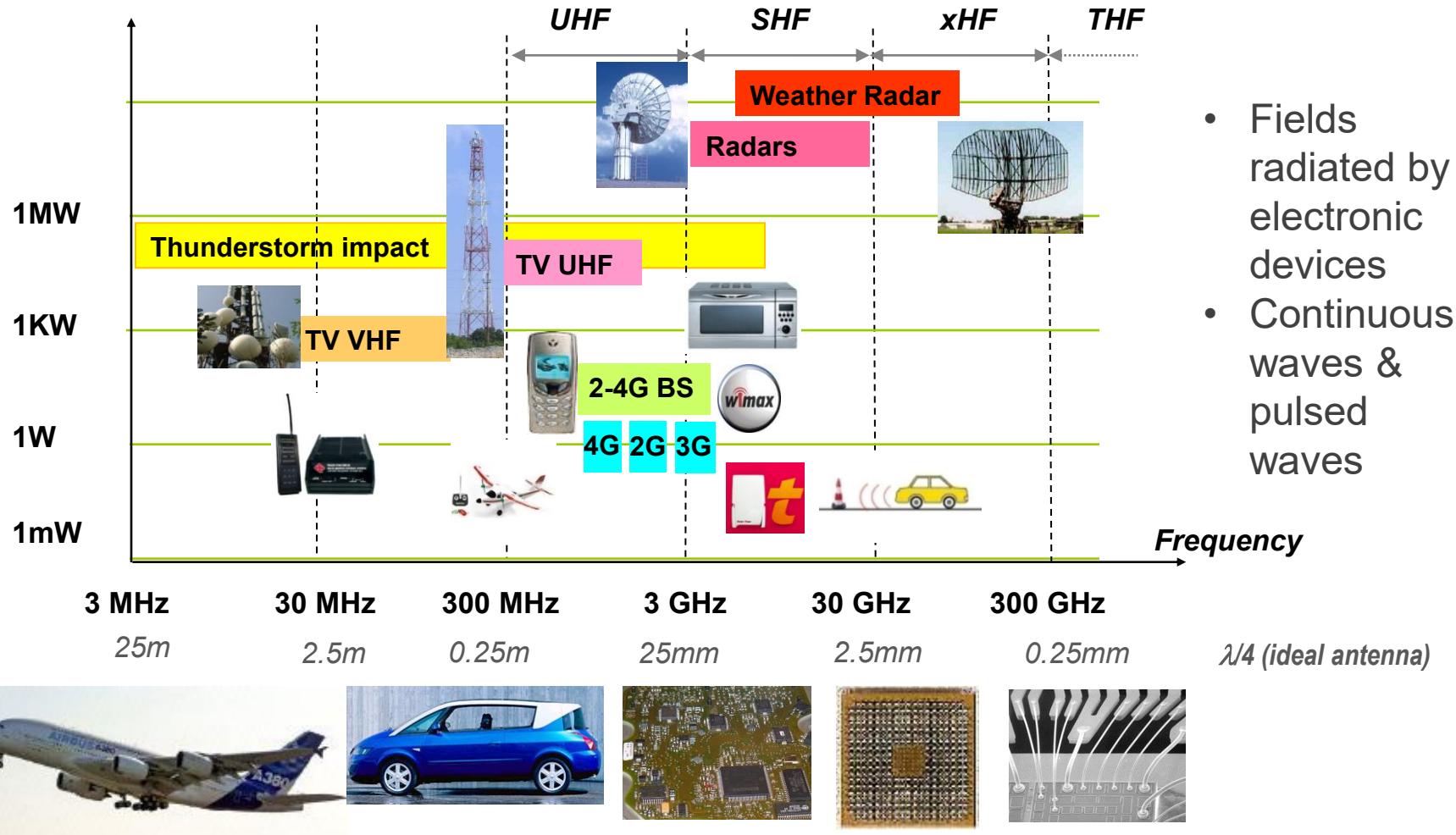
Une grande majorité de problèmes CEM se produisent entre 9 kHz et 6 GHz :

- Les émissions conduites apparaissent en-dessous de 30 MHz
- Les émissions rayonnées apparaissent au-dessus de 30 MHz

Gamme	Dénomination / Bande	Longueur d'onde
3MHz ↔ 30MHz	HF	100m ↔ 10m
30MHz ↔ 300MHz	VHF	10m ↔ 1m
300MHz ↔ 1GHz	UHF	1m ↔ 30cm
1GHz ↔ 2GHz	L	30cm ↔ 15m
2GHz ↔ 4GHz	S	15cm ↔ 7.5cm
4GHz ↔ 8GHz	C	7.5cm ↔ 3.75cm
8GHz ↔ 12GHz	X	3.75cm ↔ 2.5cm
12GHz ↔ 18GHz	Ku	2.5cm ↔ 1.67cm
18GHz ↔ 27GHz	K	1.67cm ↔ 1.11cm
27GHz ↔ 40GHz	Ka	1.11cm ↔ 0.75cm

1-C/ GESTION DU SPECTRE (1)

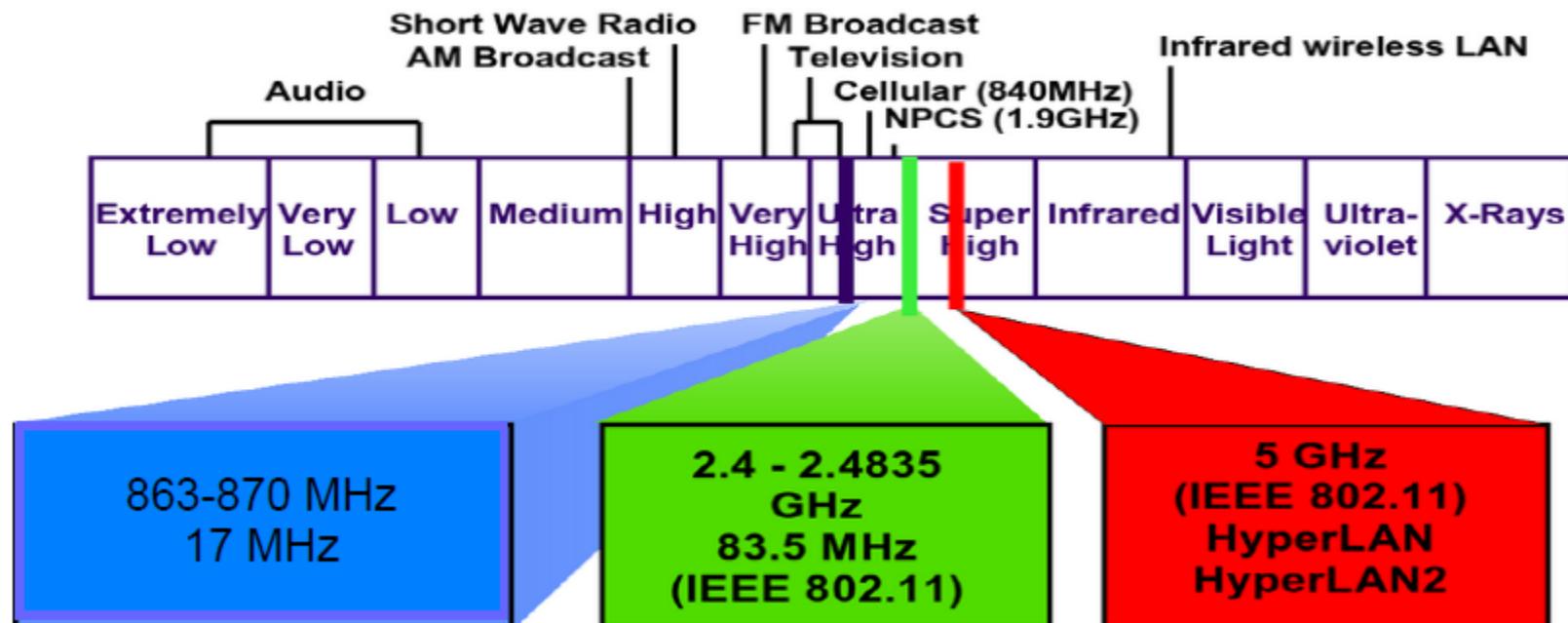
Sources EM majeures listées à l'international



1-C/ GESTION DU SPECTRE (2)

Sources EM internationales et techniques dédiées IoT

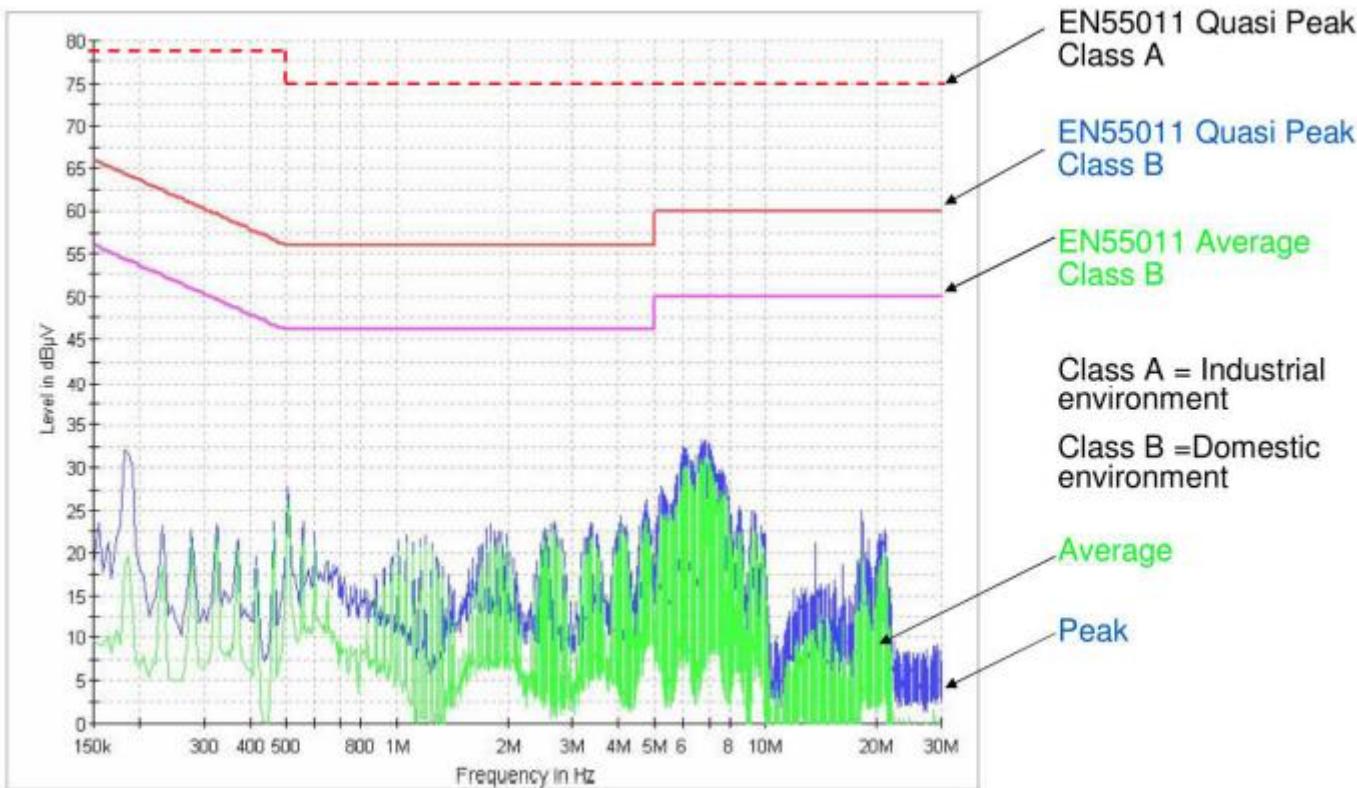
- **GSM dual band:** 880-915MHz (925-960 MHz) & 1710-1785 MHz (1805-1880 MHz)
- **4G LTE:** 700MHz – 800MHz – 1800MHz – 2600 MHz
- **WiFi (IEEE 802.11):** 2400-2483 MHz & 5150 -5850 MHz
- **Bluetooth (IEEE 802.15.1):** 2400-2483,5 MHz
- **ZigBee (IEEE 802.15.4):** 865 – 868,6 MHz
- **RFID (suivant applications):** 140 kHz(badge) 13.56MHz(tag traçabilité)
434MHz & 868MHz (tag logistique) 2450 MHz & 5800MHz (radar)
- **LoRaWan & SigFox:** 865 MHz – 868 MHz



1-C/ BESOINS 'NATURELS' POUR DES NORMES & STANDARDS

Objective == Minimizing EMC related problems

- National & international regulators \Rightarrow EMC standards
- Compliance with EMC standards of new electrical devices is enforced by law (depending on each country)
- Several standard EMC tests exist
- Example: European standard EN 55011 \leftrightarrow Int. standard CISPR 11



1-C/ BASES SUR LES NORMES ET STANDARDS EN CEM

Type	Standard	Test / domaine	Type	Standard	Test / domaine
Commercial	CISPR 11	Equipement ISM	Commercial	IEC 61000-4-11	Variations de tension
	CISPR 22	Equipement ITE		FCC Part 15B	Equipement ITE
	CISPR 16	Méthodes de mesures		ANSI C63.4	Méthodes de mesures
	IEC 61000-3-2	Harmoniques		IEC 60601-1-2	Produits médicaux
	IEC 61000-3-3	Flicker	Automobile	SAE J1113	CEM automobile
	IEC 61000-4-2	Décharges électrostatiques (ESD)		MIL-STD-461F	Tests de qualification CEM
	IEC 61000-4-3	Immunité rayonnée	Aéronautique	DO-160	Test de qualification CEM (aéronef)
	IEC 61000-4-4	Transitoires rapides		SAE ARP5412B	Environnement foudre pour aéronef & Tests de formes d'ondes
	IEC 61000-4-5	Décharge (foudre)		SAE ARP5416A	Méthode de tests d'aéronefs
	IEC 61000-4-6	Immunité conduite			
	IEC 61000-4-8	Immunité magnétique			

1-C/ STANDARDS & PARAMÈTRES CEM BASIQUES (1)

Terme	Signification
Emission	Génération non-souhaitée d'énergie EM
Immunité	Capacité à supporter les interférences EM
Susceptibilité	Opposé d'Immunité (\rightarrow Exercice, reformuler)
Couplage	Chemin à travers lequel les interférences circulent à partir du système source jusqu'au système victime
Couplage par conduction	Couplage entre source et victime formé par un contact direct conductif, e.g. un fil, un câble ou une piste PCB
Couplage inductif	Couplage entre source et victime, séparé par une courte distance, via un champ magnétique (H)
Couplage capacitif	Couplage entre source et victime, séparé par une courte distance, via un champ électrique (E)
Couplage rayonné (ou radiatif EM)	Couplage intervenant quand source et victime sont séparés par une distance importante, via des ondes EM

1-C/ STANDARDS & PARAMÈTRES CEM BASIQUES (2)

Harmonised standards under the EMC Directive (EMCD)

- Emission → EN/IEC 61000-4-1
- Immunity → EN/IEC 61000-4-2

EMCD Emission phenomena to be tested

- Radiated emission (30 – 1000 MHz)
- Radiated emission (1 – 6 GHz)
- Conducted emission (0.15 – 30 MHz)

EMCD Immunity phenomena to be tested

- Radiated immunity (80 – 1000 MHz)
- Conducted immunity (0.15 – 80 MHz)
- Burst & Surge (AC+DC ports)
- ESD (air & contact discharges)
- Voltage dips / interruptions

Radio & Telecommunications Terminal Equipment Directive (RTTE)

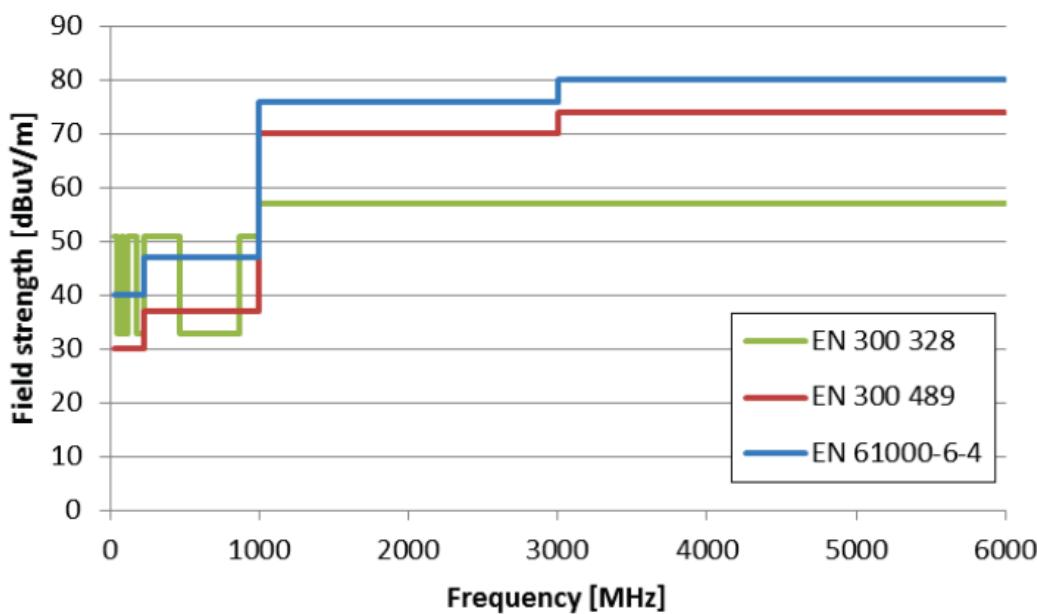
- For products including a radio transceiver
- Radio Equipment Directive (2017)
- Additional EMC requirements (EN 301 489-1 & EN 300 328)

1-C/ STANDARDS & PARAMÈTRES CEM BASIQUES (3)

- RF output power
- Duty cycle and accumulated transmit time
- Hopping sequence, adaptivity & frequency separation
- Occupied channel bandwidth
- Out-of-band and spurious emission
- Receiver blocking & spurious emission
- Geo-location capability

Regulation implies requirements with radio parameters
⇒ EN 61000-6-4 + EN 300 328 & EN 300 489

A. Mynster & P. Thastrup Jensen, *EMC for IoT*, EMC Europe 2016, 2016



Special challenges when testing wireless IoT

- Optical interface via lamps or optical fiber
- Real time clock
- Index numbering or time stamps on internal processing activities
- Detailed internal storage/logging facilities
- Raw data transmissions over wireless link
- Online cloud monitoring
- Internal system check against typical value register

1-C/ BASIQUES DE LA CEM : PARAMÈTRES ANTENNAIRES

Importance of antenna selection

Frequency Efficiency Bandwidth Dimensions



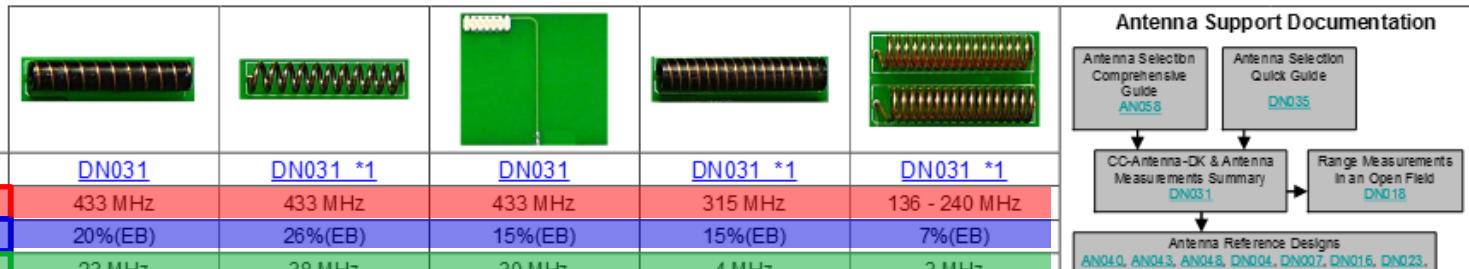
Antenna Selection Quick Guide

DN035

Design / Application Note	DN007 *1	AN043 *2	DN004	DN041	DN024	DN034	AN048
Frequency	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz
Typical Efficiency	80%(EB) 94%(SA)	68%(EB)	80%(EB)	65%(Zlight2)	76%(EB) 94%(SA)	72%(SA)	55%(USB)
Bandwidth@ VSWR 2:0	280 MHz	101 MHz	100 MHz	150 MHz	354 MHz (SA)	497 MHz	150 MHz
Dimensions (mm)	26 x 8	15 x 6	46 x 9	45 x 2.5	38 x 25	150 x 100	7 x 3



Design / Application Note	DN024 *1	DN023	DN031	DN031	DN033	DN031	DN038 *2
Frequency	868 / 915 / 920 MHz	868 / 915 / 920 MHz	868 / 915 / 920 MHz	868 / 915 / 920 MHz	868 / 915 / 920 MHz	868 / 915 / 920 MHz	868 / 915 / 920 MHz
Typical Efficiency	64%(EB) 98%(SA)	80%(SA)	69%(EB)	64%(EB)	48%(EB)	63%(EB)	66%(EB)
Bandwidth @ VSWR 2:0	88 MHz (SA)	40 MHz	62 MHz	56 MHz	56 MHz	6 MHz	40 MHz
Dimensions (mm)	38 x 25	43 x 20	10 x 28	48 x 8	15 x (5 to 29)	10 x 14	19 x 12



						Antenna Support Documentation		
Design / Application Note	DN031	DN031 *1	DN031	DN031 *1	DN031 *1	Antenna Selection Comprehensive Guide AN058	Antenna Selection Quick Guide DN035	
Frequency	433 MHz	433 MHz	433 MHz	315 MHz	136 - 240 MHz	CC-Antenna-OK & Antenna Measurements Summary DN031	Range Measurements In an Open Field DN018	
Typical Efficiency	20%(EB)	26%(EB)	15%(EB)	15%(EB)	7%(EB)			
Bandwidth @ VSWR 2:0	23 MHz	38 MHz	30 MHz	4 MHz	3 MHz	Antenna Reference Designs AN040, AN043, AN048, DN004, DN007, DN016, DN023, DN024, DN031, DN034, DN038, DN041		
Dimensions (mm)	37 x 9	42 x (10 to 29)	15 x (5 to 29)	37 x 9	42 x (22 to 29)		OTA Measurement Reports DN6xx	

EB: SmartRF Evaluation Board

*1 First Choice Recommended Antenna

*2 Second Choice Recommended Antenna

SWRA351A

By Richard Wallace

1-c/ BASIQUES DE LA CEM : ZONAGE / SÉGRÉGATION

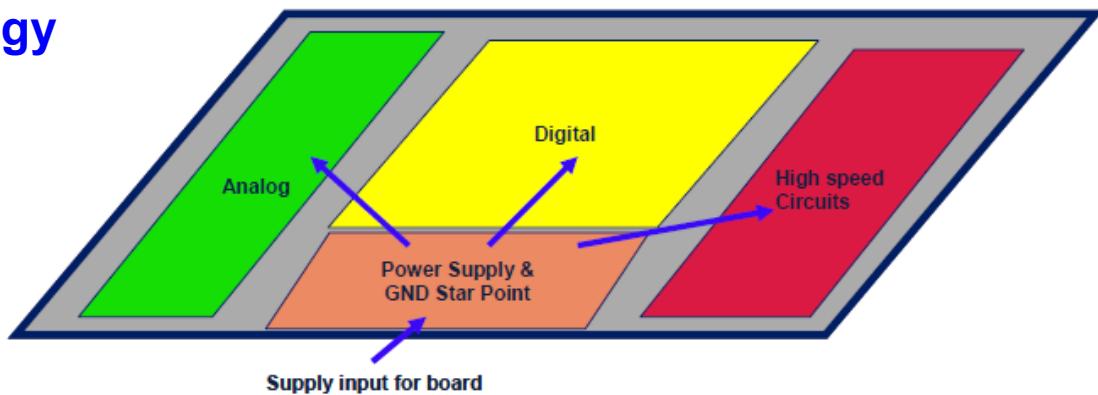
Zoning in functional blocks is a major EMC issue

Don't do that and you'd be in trouble

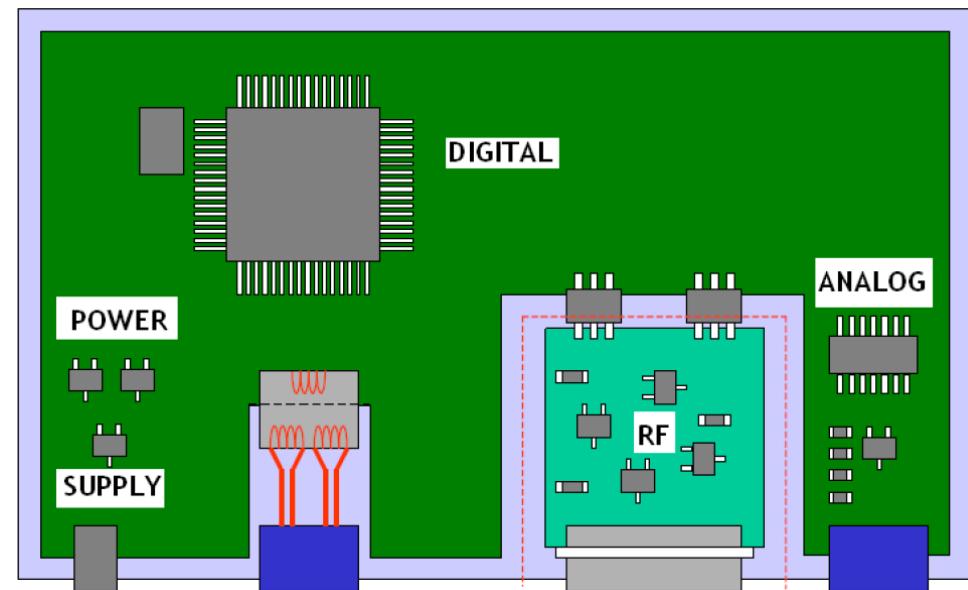
Regroup same kind of technology

Need to know

Sensitive parts
Emissive parts



Block type	Emission	Susceptibility
1. DC/DC converter	+	++
2. Power switch output	++	--
3. Charge pump	++	--
4. Oscillator / PLL / Clock circuitry	++	++
5. Fast digital I/O	++	-
6. Digital block supply	+	-
7. Analog input/supply	--	++
8. RF front end	+	++

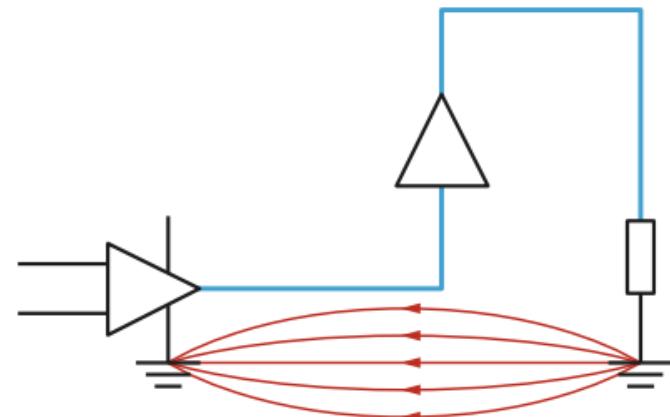
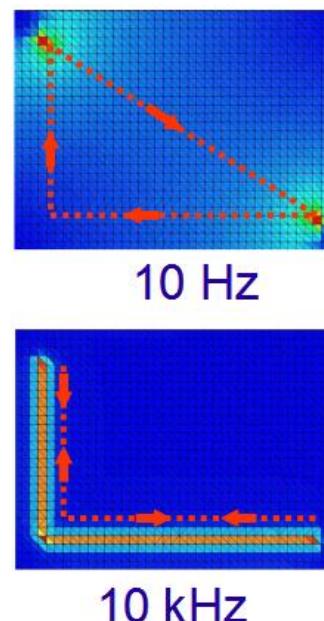
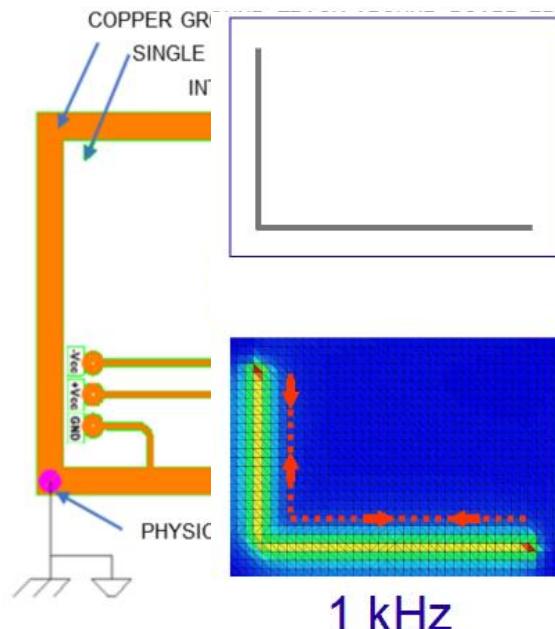


1-c/ BASIQUES CEM : CHEMINS DE RETOURS DE COURANTS

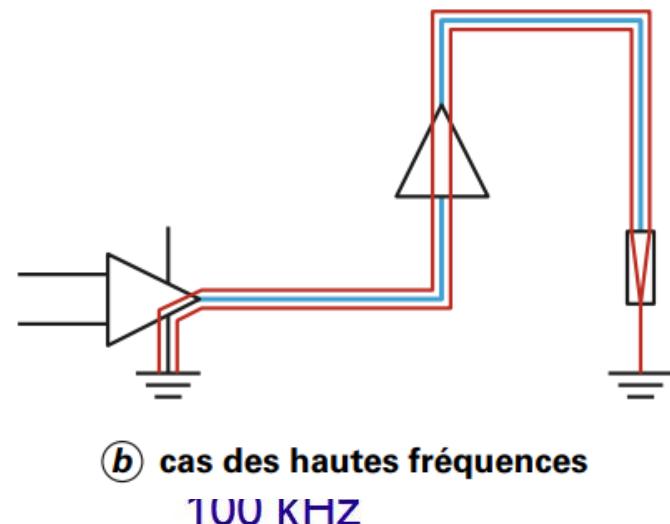
Ensure a short and controlled return current path

Don't do that and
you'd still be in trouble

- Place a full ground plane on microstrip border line
- Avoid slot in return plane (ground plane)
- Keep a symmetry (avoid unbalance in the return current path)
- Avoid routing of critical signals along board edge
- Avoid 90° angle on tracks...



a cas des basses fréquences



b cas des hautes fréquences
100 KHz

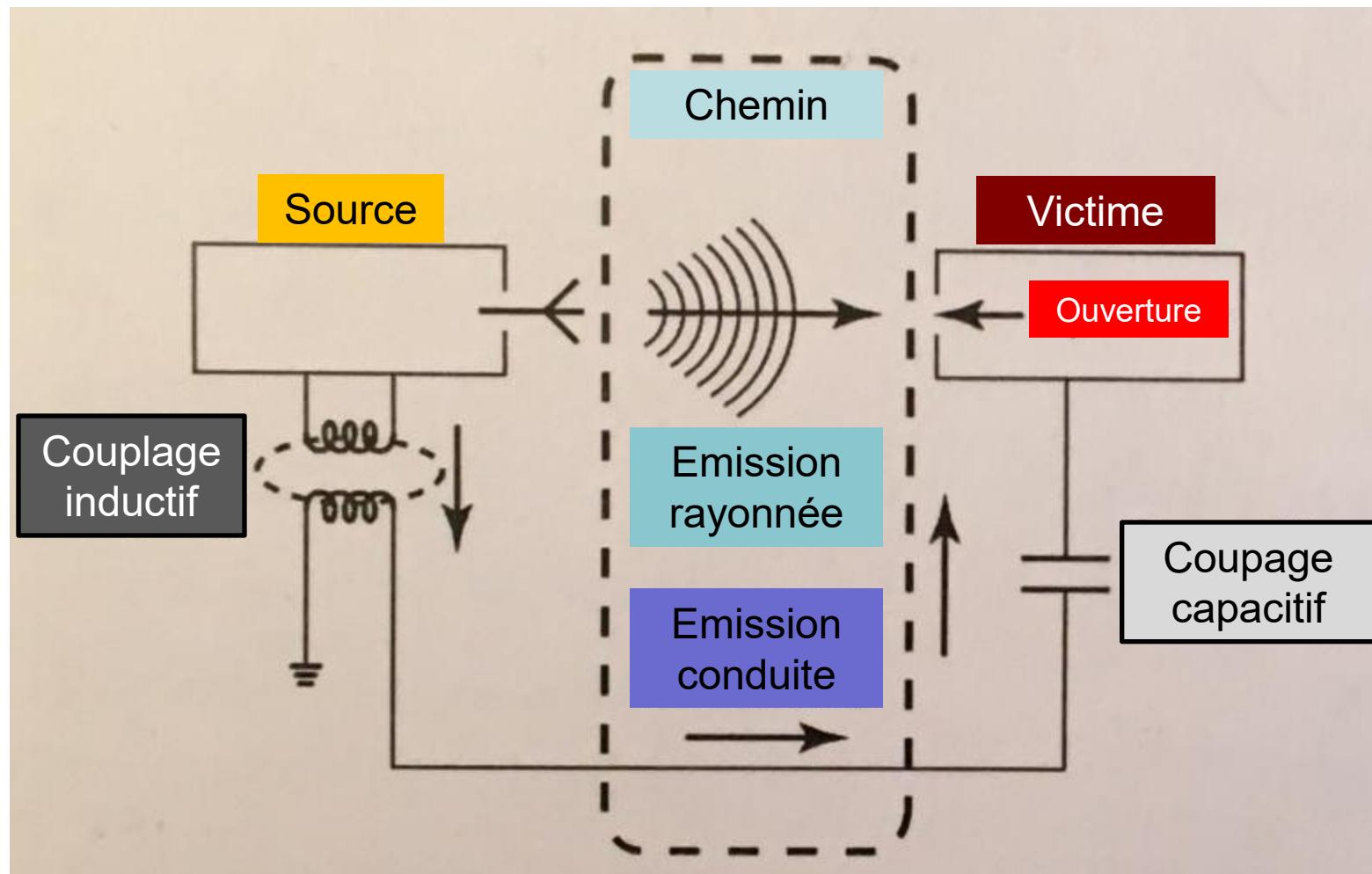
PLAN

1. Position du problème
 - a) Limiter les interférence EM (EMI) : quel(s) besoin(s) ?
 - b) En quoi l'IoT et les systèmes connectés posent un problème ?
 - c) Normes, spécifications & gestion du spectre EM
2. Attentes des outils de simulation (num. & exp.)
 - a) CEM : quels calculs, quelles interactions ?
 - b) Matériel(s) et méthode(s)
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3. Caractérisation des composants IoT du point de vue CEM
 - a) Estimation de l'influence « IoT » à l'aide d'outils numériques
 - b) Interférences électromagnétiques « intentionnelles » & IoT
4. Conclusions

2-A/ CEM : QUELS CALCULS ?

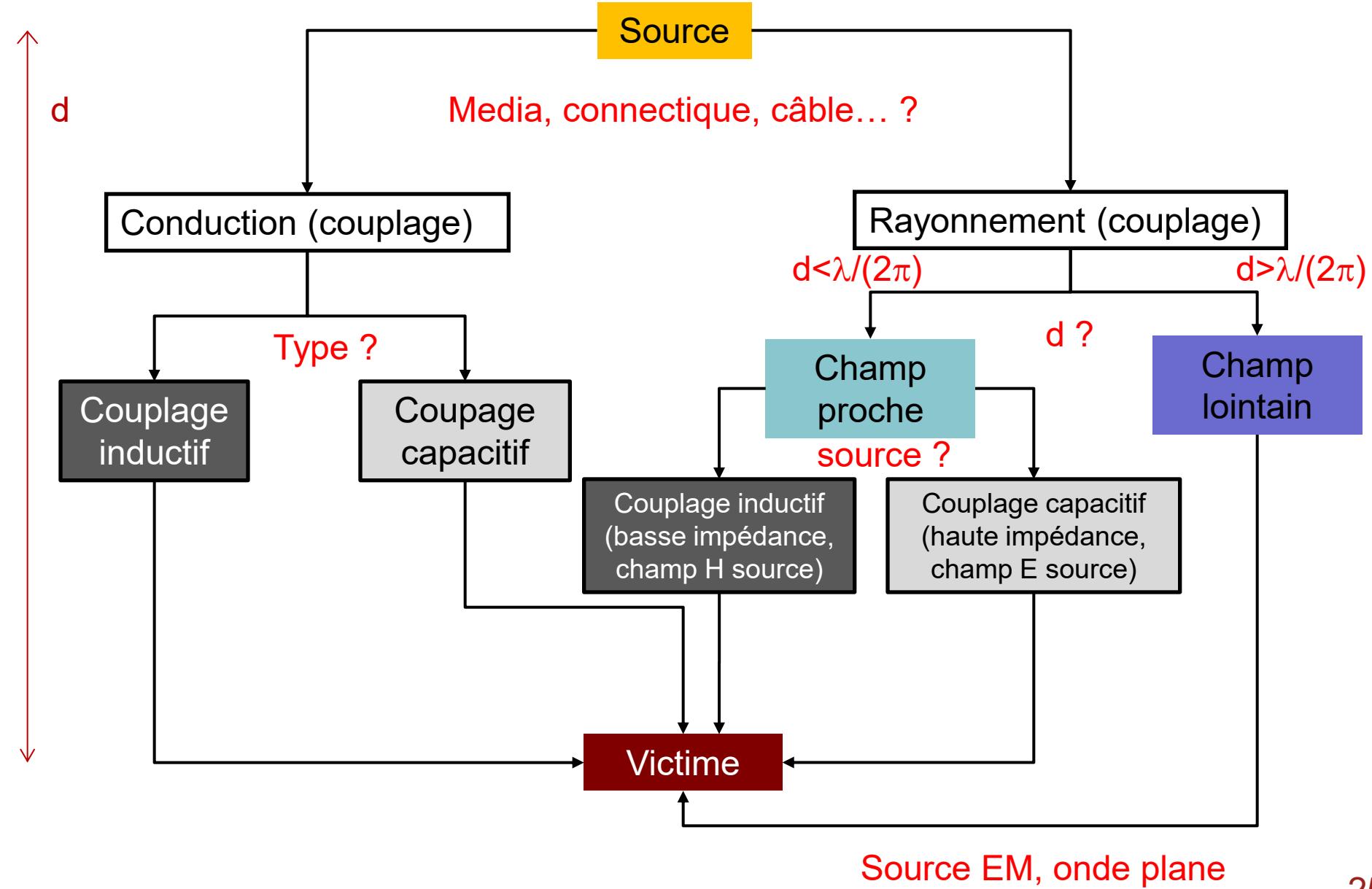
- Calculs circuits mais pas que ...
 - Avantage aux électroniciens, aide de logiciels de circuits comme SPICE, SABER, QUCS Studio, etc.
 - « ou » utiliser des logiciels de mathématiques comme Scilab, Octave, Matlab, Python, etc.
 - MAIS CEM \Rightarrow calculs d'interactions entre des grandeurs comme : courants, tensions, champs électromagnétiques
- Utilisation des outils commerciaux
 - Utile : HFSS, CST, etc. (voir dans la suite)
 - Mais attention : besoin de se référer au besoin physique et matériel visé (compréhension des phénomènes)
 - Sinon : résultats et interprétation erronés ... restons prudents ...
- Temps / Fréquence
 - Majoritairement domaine fréquentiel (norme, mesures, ...)
 - Mais : dimension temporelle importante des phénomènes ...

2-A/ CEM : QUELLES INTERACTIONS ? ... COUPLAGES ? (1)



Remarque : Les couplages capacitifs et inductifs existent également pour le mode de couplage rayonné.

2-A/ CEM : QUELLES INTERACTIONS ? COUPLAGES ... ? (2)



2-A/ CONTEXTE IoT : OUTILS NUMÉRIQUES POUR LA CEM

Variety of EM simulation tools & softwares

- Altair HyperWorks (Flux, FEKO)
- Ansys© HFSS©
- COMSOL© Multiphysics
- Dassault Simulia (CST©)
- Keysight Technologies (ADS, EM Pro, Genesys, GoldenGate)
- Remcom®
- SEMCAD-X
- Sonnet® Software
- WIPL-D
- Spice, Qucs Studio



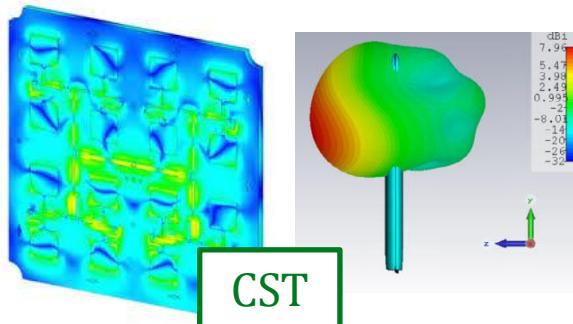
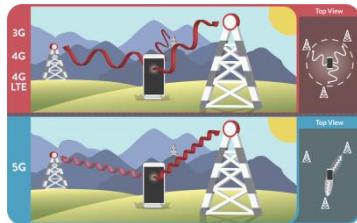
Applications directly or indirectly linked to EMC requirements for IoT



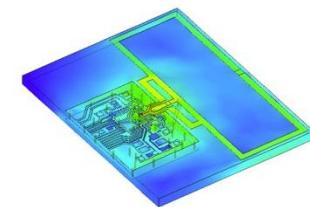
- Antenna design, Reflector antennas, Antenna placement
- Arrays & radomes (antennas)
- Radar Cross Section / EM waves scattering
- Microwave applications & Circuits modeling
- Electromagnetic interference & EMC
- Low frequency / magnetic field
- Dosimetry, bioelectromagnetism

2-A/ DIVERSITÉ DES APPLICATIONS & MÉTHODES NUMÉR. (1)

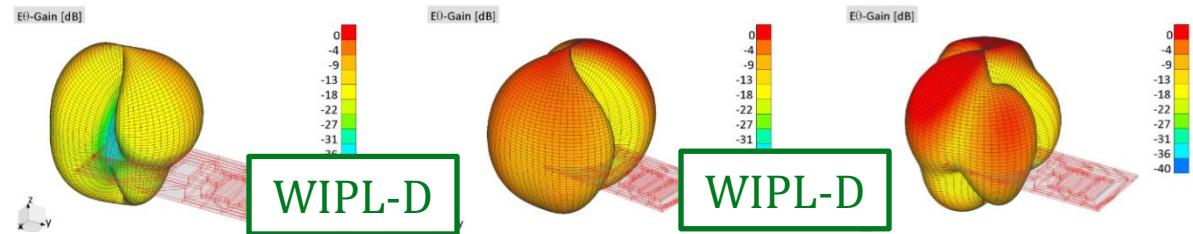
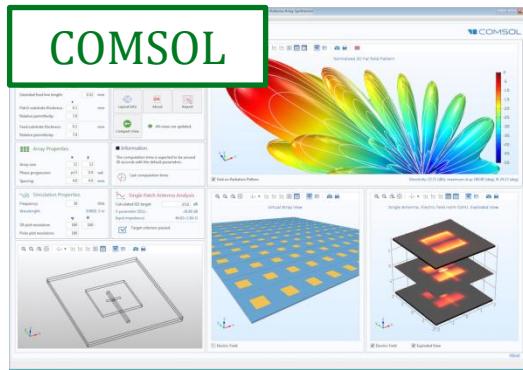
Antenna design



Altair FEKO

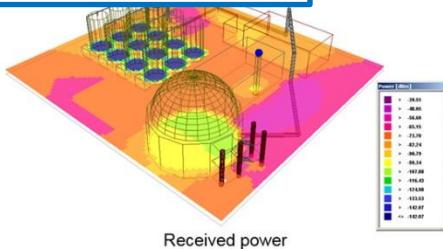


COMSOL

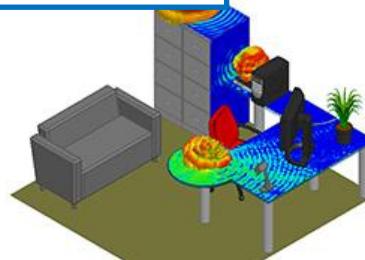


Propagation, Scattering & Location of antennas

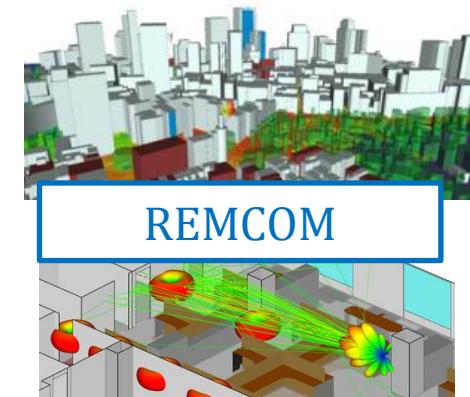
Altair WinProp



Ansys HFSS

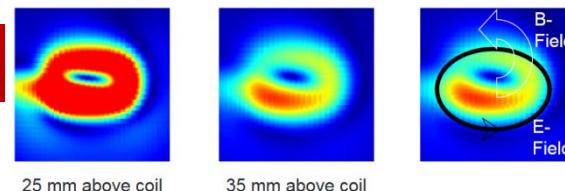
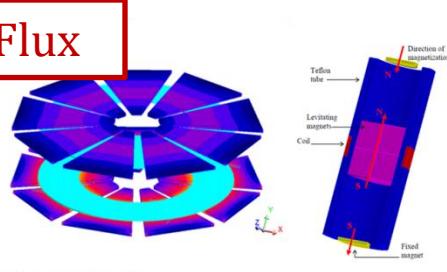
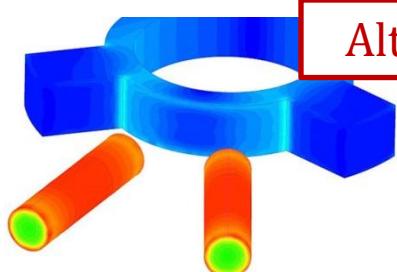


REMCOM

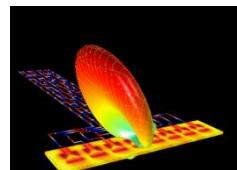
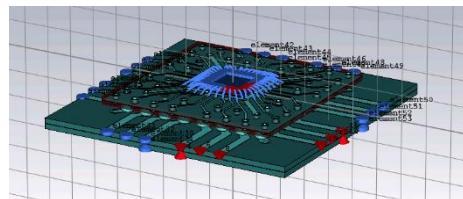
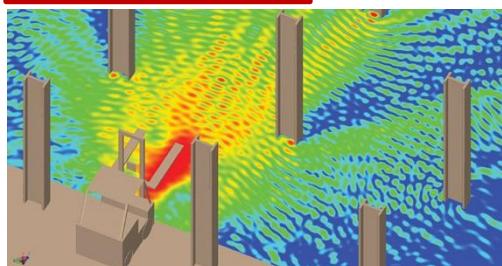


2-A/ DIVERSITÉ DES APPLICATIONS & MÉTHODES NUMÉR. (2)

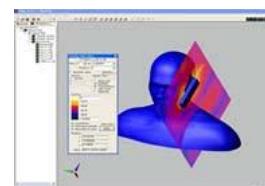
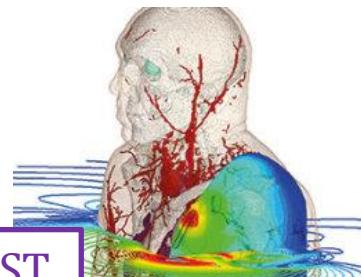
Low frequency (probing, H-field, RFID, WPT, circuits)



Altair FEKO



High frequency & BioEM



Altair FEKO



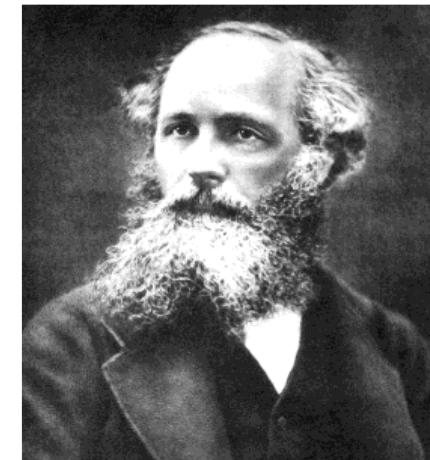
2-B/ MÉTHODES NUMÉRIQUES : FORMULATION DU PROBLÈME (1)

■ Equations de (James Clerk) Maxwell

- Deux équations (historiques)
+ équations constitutives des matériaux

$$\frac{\partial \mathbf{E}}{\partial t} = \frac{1}{\epsilon_0} \nabla \times \mathbf{H} \quad \frac{\partial \mathbf{H}}{\partial t} = -\frac{1}{\mu_0} \nabla \times \mathbf{E}$$

■ Equation d'onde homogène



$$\nabla^2 \mathbf{F} + k^2 \mathbf{F} = 0 \quad (1)$$

avec ∇^2 opérateur de Laplace qui implique les dérivées spatiales de \mathbf{F} et dont l'expression dépend du système de coordonnées utilisé,

k nombre d'onde du milieu.

Elle s'écrit dans le domaine temporel et pour un milieu sans pertes de la façon suivante :

$$\nabla^2 \mathbf{F} + \mu \epsilon \frac{\partial \mathbf{F}}{\partial t^2} = 0 \quad (2)$$

avec μ et ϵ respectivement la perméabilité et la permittivité du milieu.

2-B/ MÉTHODES NUMÉRIQUES : FORMULATION DU PROBLÈME (2)

■ Equation intégrale

$$\mathbf{A}(\mathbf{r}) = -\mu \int \mathbf{J}(\mathbf{r}') G(\mathbf{r}, \mathbf{r}') d\mathbf{v}' \quad (3)$$

Sur tout
le volume
de courant

dans laquelle μ est la perméabilité du milieu (supposé linéaire, isotrope et sans pertes), $G(\mathbf{r}, \mathbf{r}')$ est la fonction de Green de l'espace libre donnée par :

$$G(R) = -\frac{e^{-jkR}}{4\pi R} \quad (4)$$

avec $k = \omega/c$ nombre d'onde,
 ω pulsation,
 c vitesse de la lumière dans le milieu,
 $R = \|\mathbf{r} - \mathbf{r}'\|$ distance entre le point d'observation en \mathbf{r} et la position de l'élément infinitésimal de la source en \mathbf{r}' (voir figure 1).

2-B/ MÉTHODES NUMÉRIQUES : FORMULATION DU PROBLÈME (3)

■ Approche variationnelle

- Principe == plutôt que de résoudre directement (analytiquement ou numériquement) une équation différentielle
⇒ rendre stationnaire une expression fonctionnelle associée au problème original (méthode variationnelle) ; ex. équation de Laplace

■ Approche semi-analytique

- Grand nombre de méthodes
- Exemple : solutions de l'équation d'onde sous forme modale, fonctions harmoniques, ondes planes

■ Formes asymptotiques

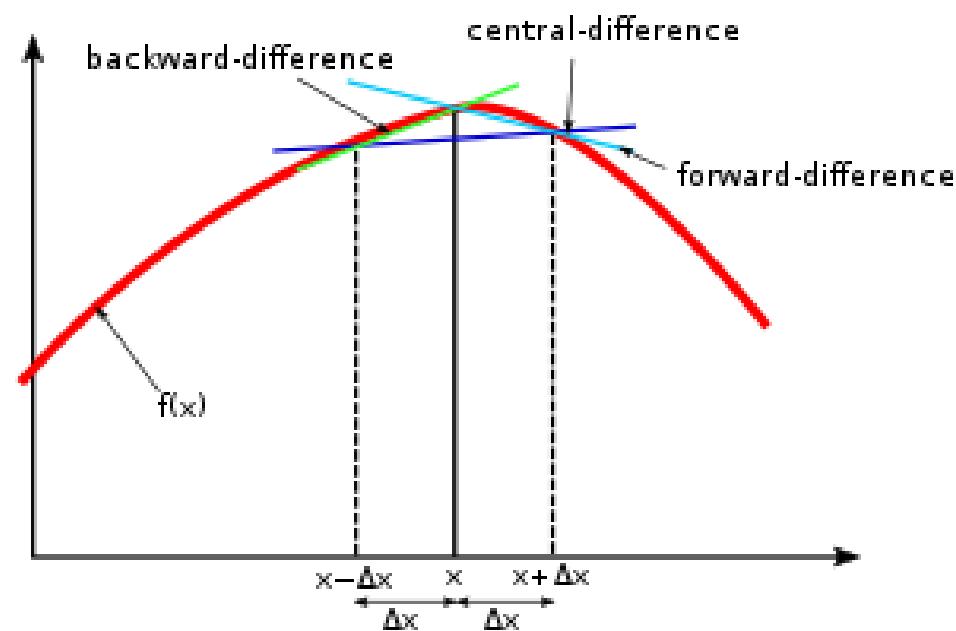
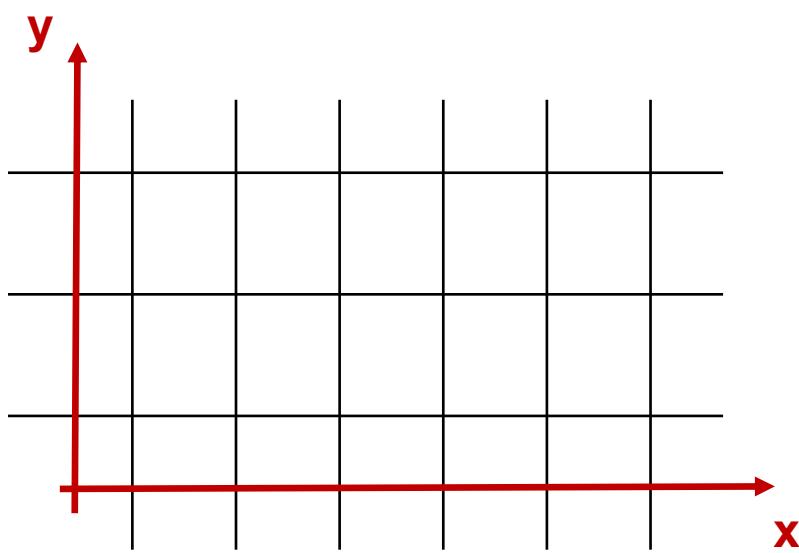
- Nécessite de discréteriser le domaine de calculs
- Problème au-delà de 10 longueurs d'onde
⇒ Nécessité d'hypothèses simplificatrices (ex. : optique avec le concept de rayons ou tubes de rayons – faisceaux)

2-B/ MÉTHODES NUMÉRIQUES : FORMULATION DU PROBLÈME (4)

- Approches ‘rigoureuses’ / ‘Full-wave’
 - **Volumes finis**
 - ⇒ Intégration sur des volumes élémentaires de formes simples des équations écrites sous forme conservative (ex. équations de la mécanique des fluides, de l’acoustique, ... de l’EM)
 - ++ : géométries complexes, conditions aux limites facilitées
 - : peu de résultats théoriques de convergence
 - **Eléments finis**
 - ⇒ Mettre en œuvre le principe de résolution dans un sous-espace de dimension finie d’un problème écrit sous forme variationnelle (minimum d’énergie en général). Solution approchée donnée par l’expression d’une fonction en certains points ou nœuds du maillage
 - ++ : géométries complexes, nombreux résultats sur la convergence
 - : complexité de mise en œuvre et grand coût de calcul et mémoire
 - **Différences finies**
 - ⇒ Remplacer les dérivées partielles par des différences divisées ou combinées de valeurs ponctuelles de la fonction en un nombre fini de points discrets ou nœuds du maillage
 - ++ : grande simplicité d’écriture et faibles coûts de calculs
 - : limitations des géométries (simples, grille continue, aliasing), difficultés de prise en compte des conditions aux limites

2-c/ MÉTHODE DES DIFFÉRENCES FINIES (DF)

- Définition
 - Méthode de recherche de solution approchée de solution d'équations aux dérivées partielles (EDP)
- Méthode des différences finies
 - Approximation (droite tangente)
- Discrétisation du domaine de calculs



2-c/ DF POUR L'OPÉRATEUR DE LAPLACE (1)

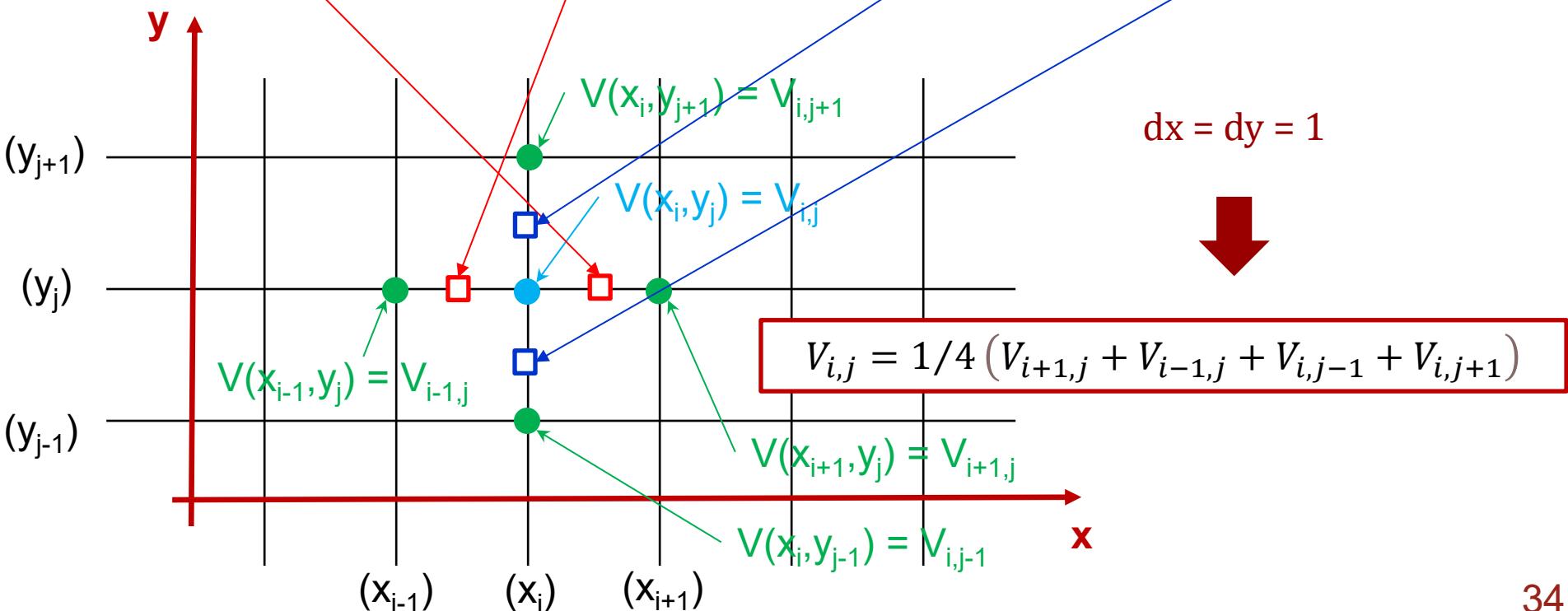
- Equation de Laplace $\partial^2 V / \partial x^2 + \partial^2 V / \partial y^2 = 0$

$$\Delta V = 0$$

$$\frac{\partial}{\partial x} \frac{\partial V}{\partial x} + \frac{\partial}{\partial y} \frac{\partial V}{\partial y} = 0$$

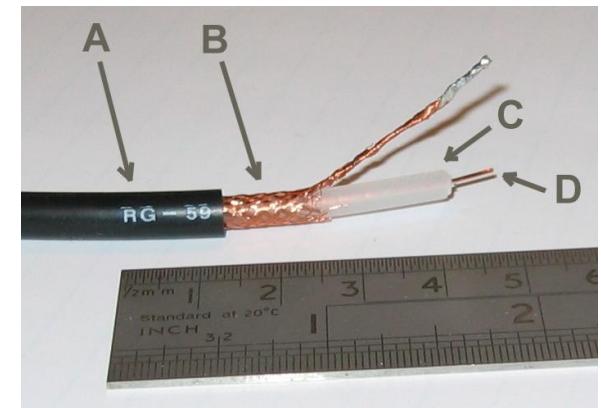
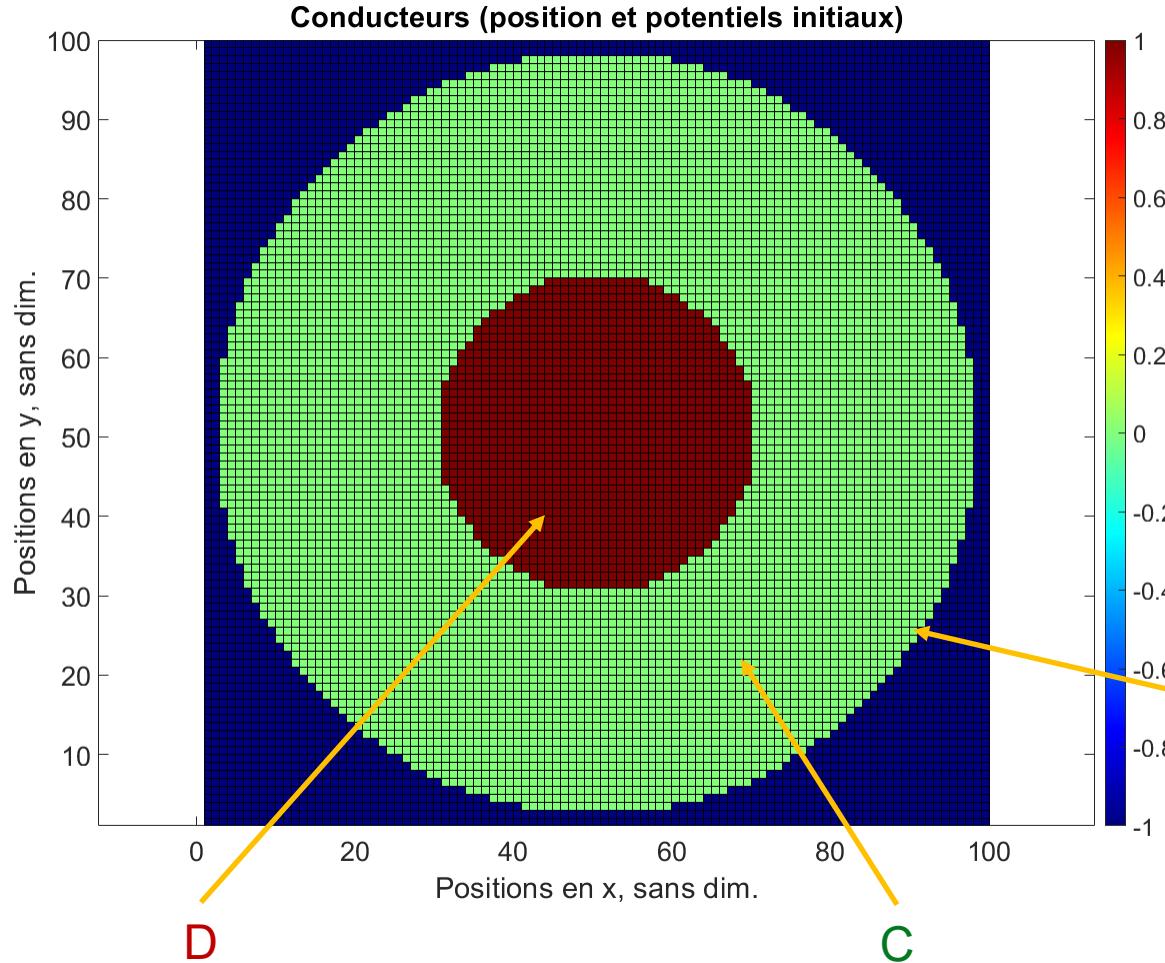
- Discrétisation DF

$$\frac{1}{dx} \left[\frac{1}{dx} (V_{i+1,j} - V_{i,j}) - \frac{1}{dx} (V_{i,j} - V_{i-1,j}) \right] + \frac{1}{dy} \left[\frac{1}{dy} (V_{i,j+1} - V_{i,j}) - \frac{1}{dy} (V_{i,j} - V_{i,j-1}) \right] = 0$$



2-c/ DF POUR L'OPÉRATEUR DE LAPLACE (2)

- Exemple d'application : câble coaxial
 - A=gaine extérieure / B=blindage / C=diélectrique / D=âme centrale

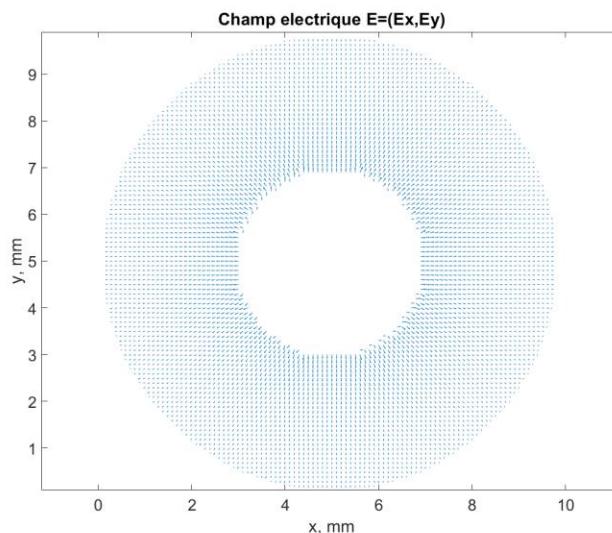
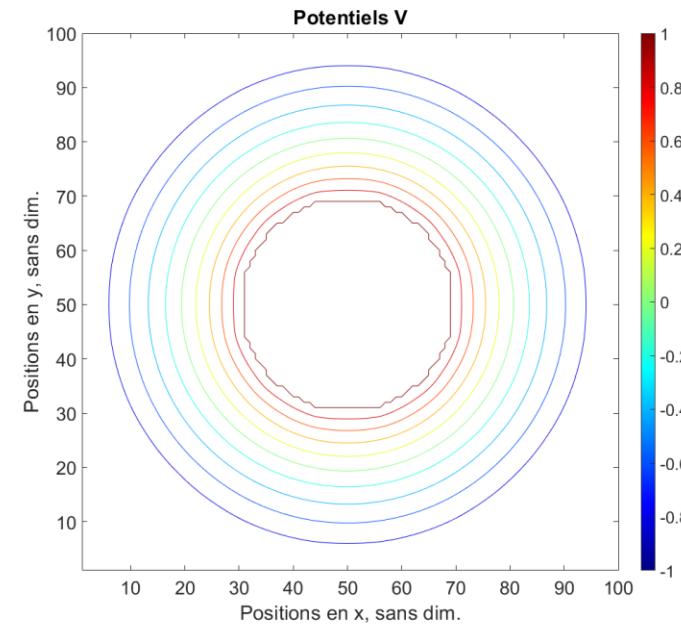
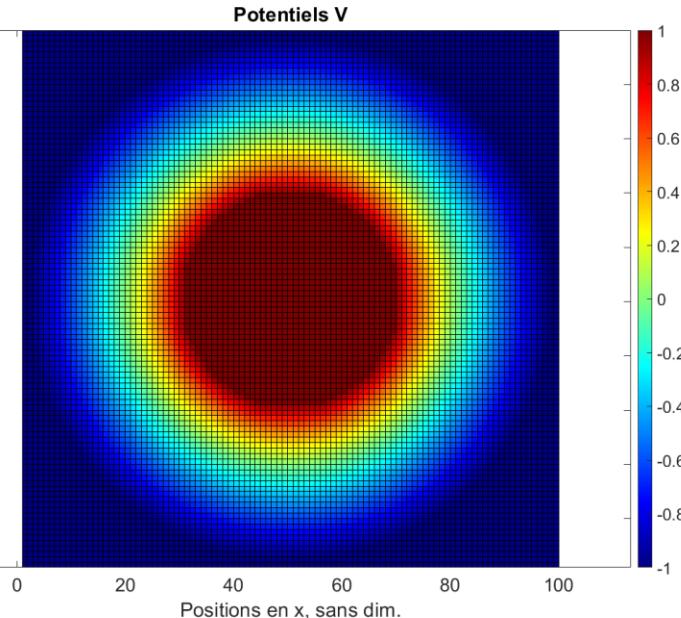


Rayon interne : $a = 2\text{mm}$
Rayon externe : $b = 4,8\text{mm}$

B

2-c/ DF POUR L'OPÉRATEUR DE LAPLACE (3)

- Potentiels, champs électriques, capacités



$$C_{th} = \frac{2\pi\epsilon_0}{\ln \frac{b}{a}}$$

C_th = 63 pF

C_laplace = 62 pF (+ Théorème de Gauss)

Cœur d'outils numériques variés : COMSOL, ...

2-c/ DF POUR LA PROPAGATION DES ONDES

- Equations de Maxwell

$$\frac{\partial \mathbf{E}}{\partial t} = \frac{1}{\epsilon_0} \nabla \times \mathbf{H}$$

$$\frac{\partial \mathbf{H}}{\partial t} = -\frac{1}{\mu_0} \nabla \times \mathbf{E}$$

$$\nabla \times \mathbf{E} = \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E_y & E_z \end{vmatrix}$$

$$\begin{bmatrix} \frac{\partial E_x}{\partial t} \\ \frac{\partial E_y}{\partial t} \\ \frac{\partial E_z}{\partial t} \end{bmatrix} = \frac{1}{\epsilon_0} \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ H_x & H_y & H_z \end{vmatrix} = \frac{1}{\epsilon_0} \begin{bmatrix} \frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \\ \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \\ \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \end{bmatrix}$$

$$\begin{bmatrix} \frac{\partial H_x}{\partial t} \\ \frac{\partial H_y}{\partial t} \\ \frac{\partial H_z}{\partial t} \end{bmatrix} = -\frac{1}{\mu_0} \begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ E_x & E_y & E_z \end{vmatrix} = -\frac{1}{\mu_0} \begin{bmatrix} \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} \\ \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} \\ \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \end{bmatrix}$$

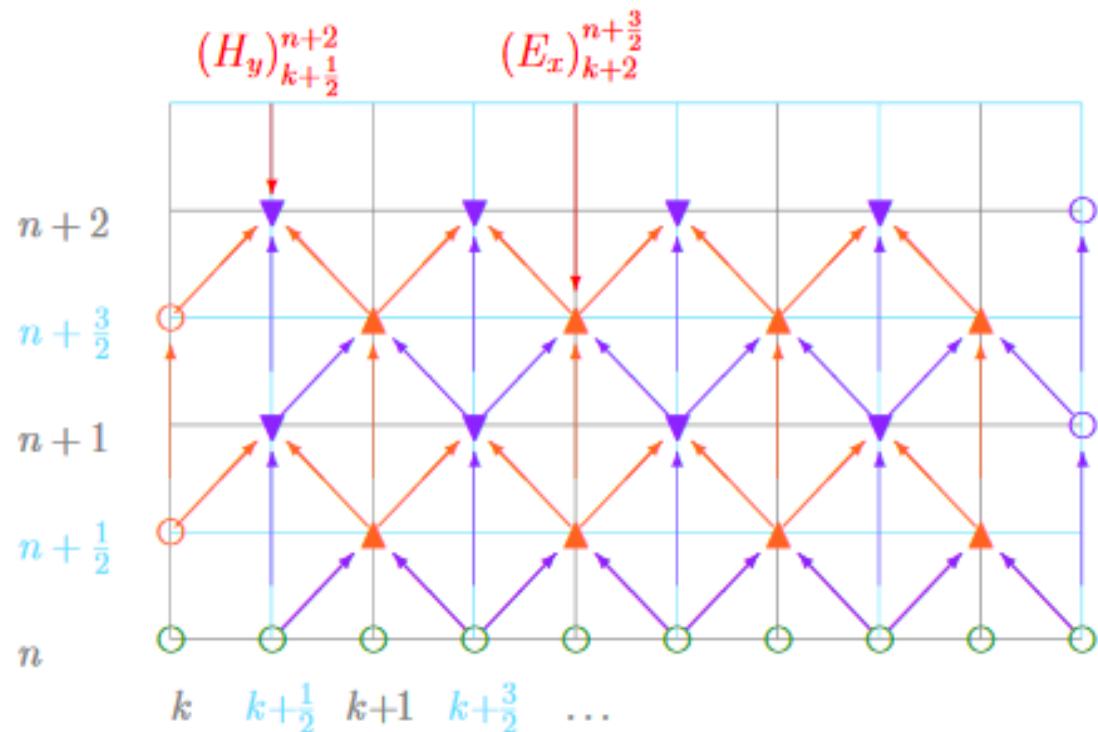
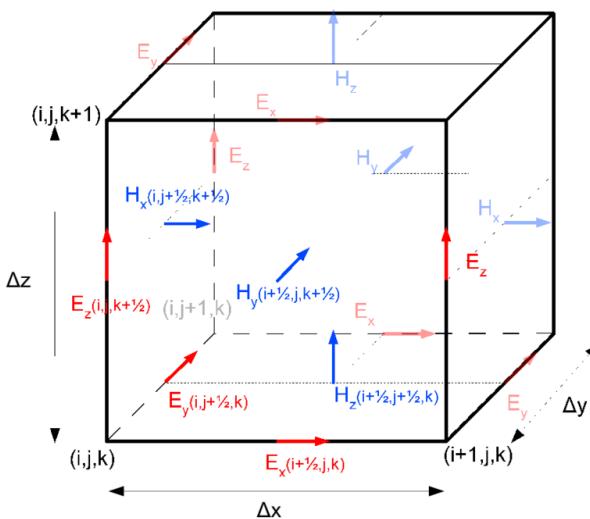
Problème particulier concernant la propagation d'une onde selon l'axe « z ». On prendra pour hypothèse que la composante E_y est nulle (tout comme E_z) et on a : $\mathbf{E} = (E_x, 0, 0)$. Ceci impose que la seule composante pour \mathbf{H} non nulle est H_y ici.

$$\frac{\partial E_x}{\partial t} = -\frac{1}{\epsilon_0} \frac{\partial H_y}{\partial z}$$

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0} \frac{\partial E_x}{\partial z}$$

2-c/ DF POUR LA PROPAGATION DES ONDES

- Grille d'approximation du schéma FDTD
 - n , en ordonnée, pour le temps
 - k , en abscisse, pour l'espace, et pour les champs E et H
 - Cellules entre-croisées (champ E et H)
=> Cellule de Yee



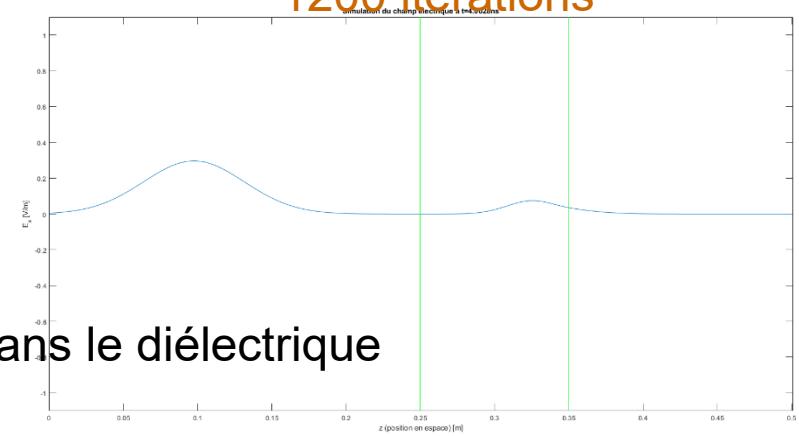
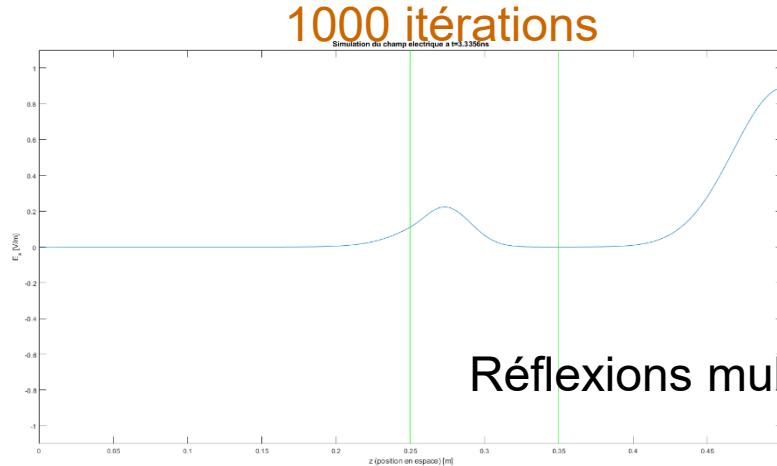
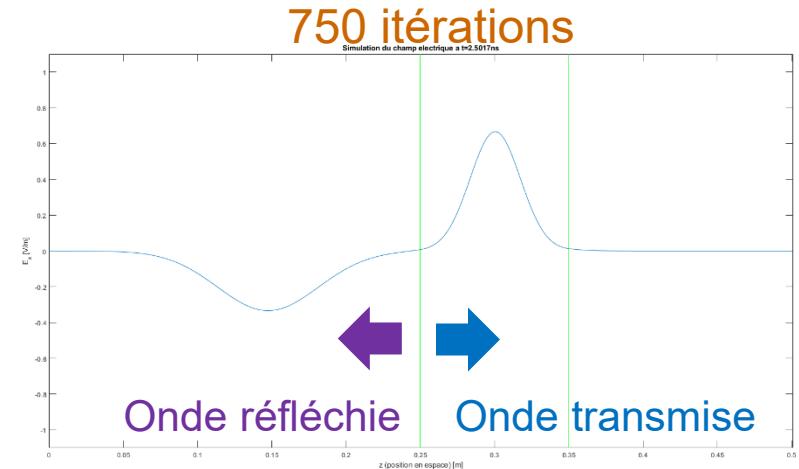
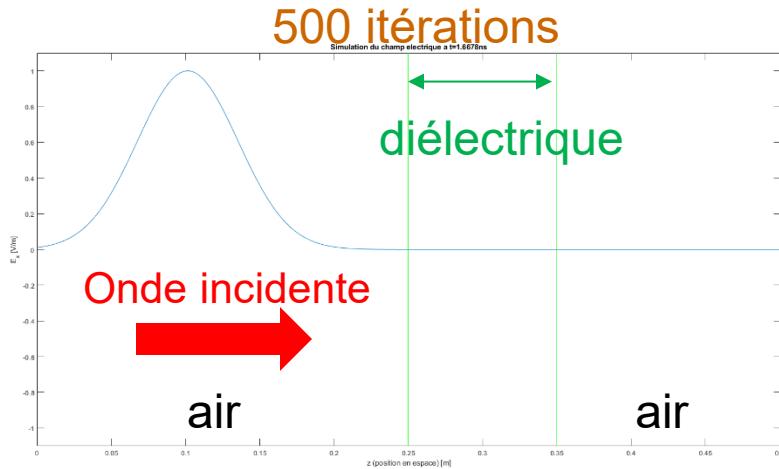
$$\frac{(E_x)_k^{n+1/2} - (E_x)_k^{n-1/2}}{\Delta t} = -\frac{1}{\epsilon_0} \frac{(H_y)_{k+1/2}^n - (H_y)_{k-1/2}^n}{\Delta z}$$

$$\frac{(H_y)_{k+1/2}^{n+1} - (H_y)_{k+1/2}^n}{\Delta t} = -\frac{1}{\mu_0} \frac{(E_x)_{k+1/2}^n - (E_x)_{k-1/2}^n}{\Delta z}$$

2-c/ DF POUR LA PROPAGATION : APPLICATION 1-D

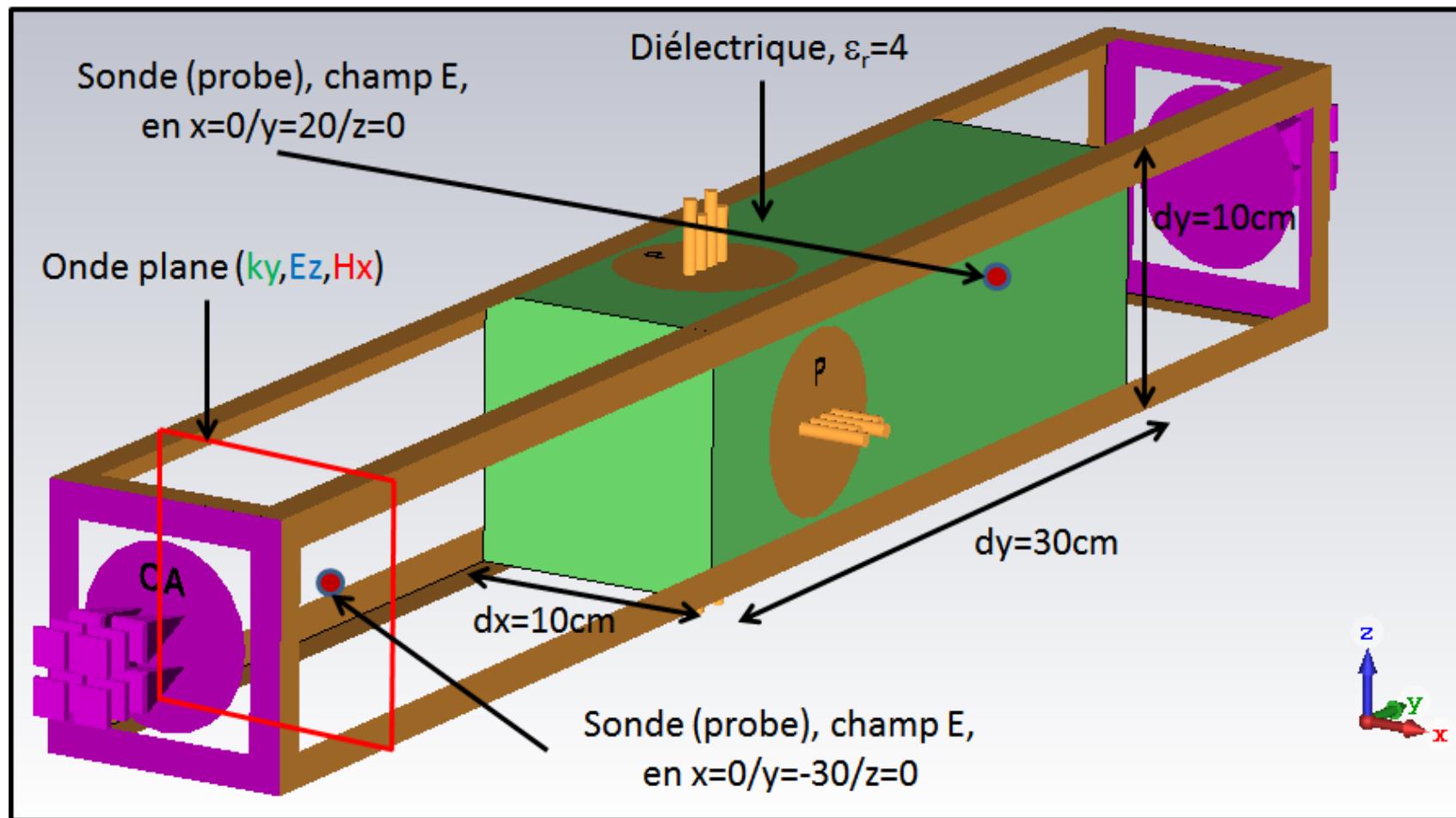
■ Propagation 1-D d'une onde plane

- Domaine : $Lz=0.5$ m
- Sens de propagation / réflexion et transmission sur un diélectrique



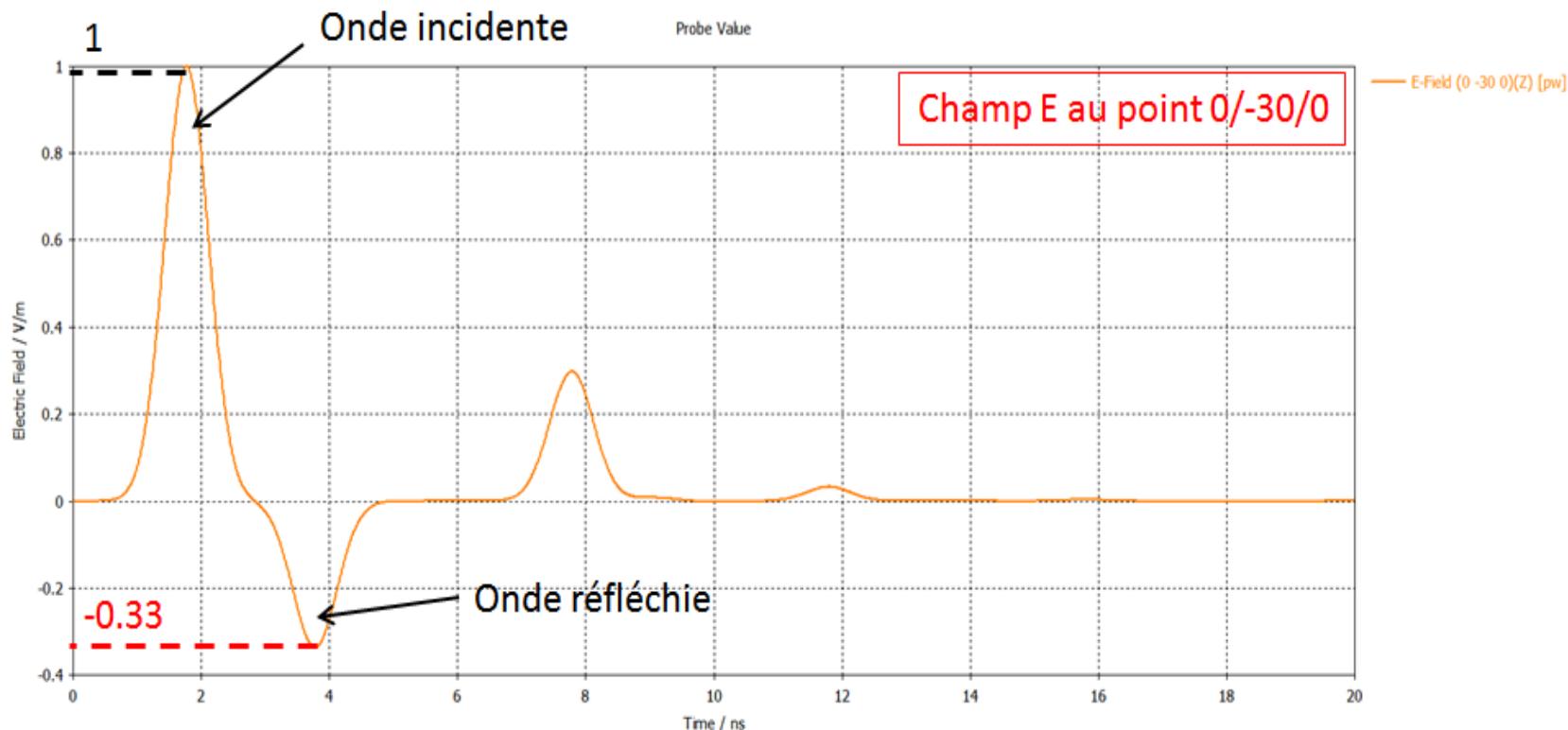
2-c/ DF POUR LA PROPAGATION : APPLICATION 3-D (1)

- Example illustratif : CST (Suite logicielle Dassault Simulia)



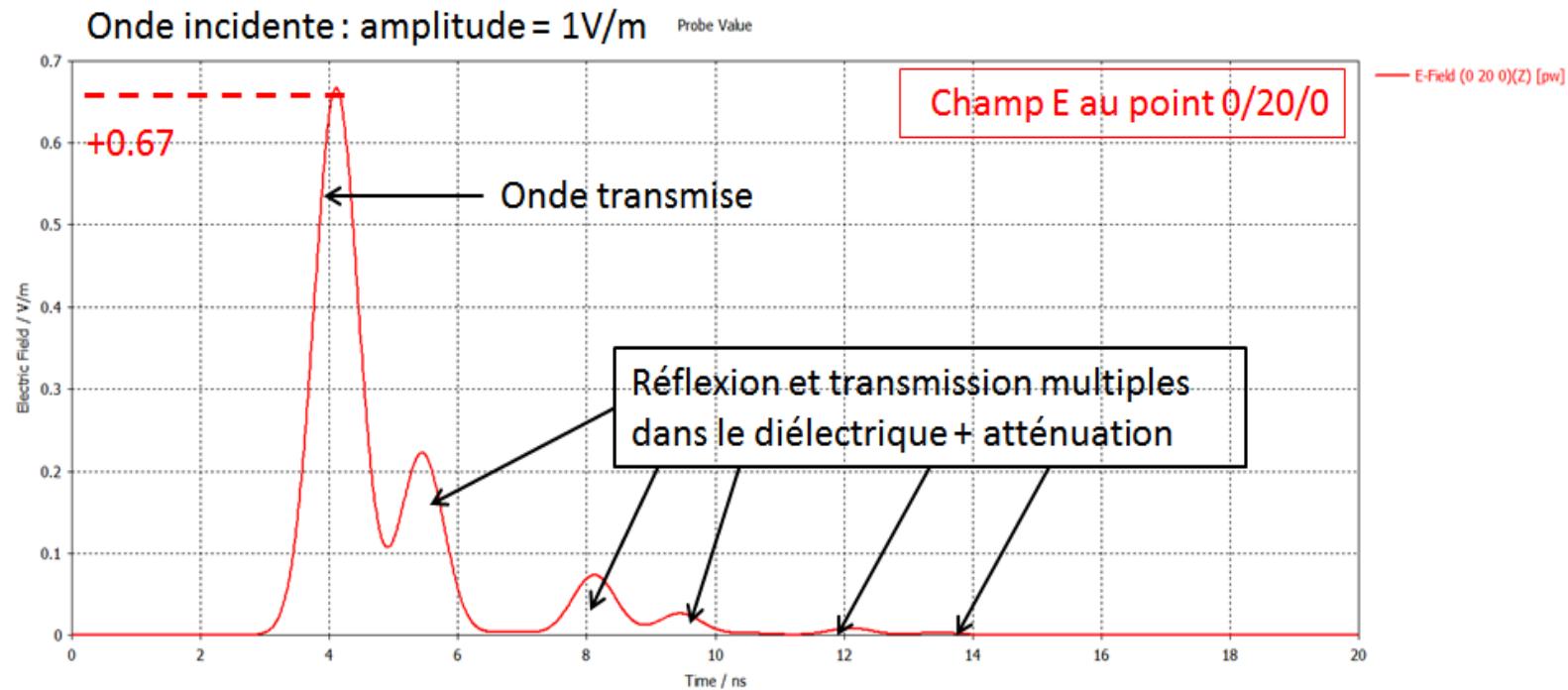
2-c/ DF POUR LA PROPAGATION : APPLICATION 3-D (2)

- Example illustratif : CST (Suite logicielle Dassault Simulia)



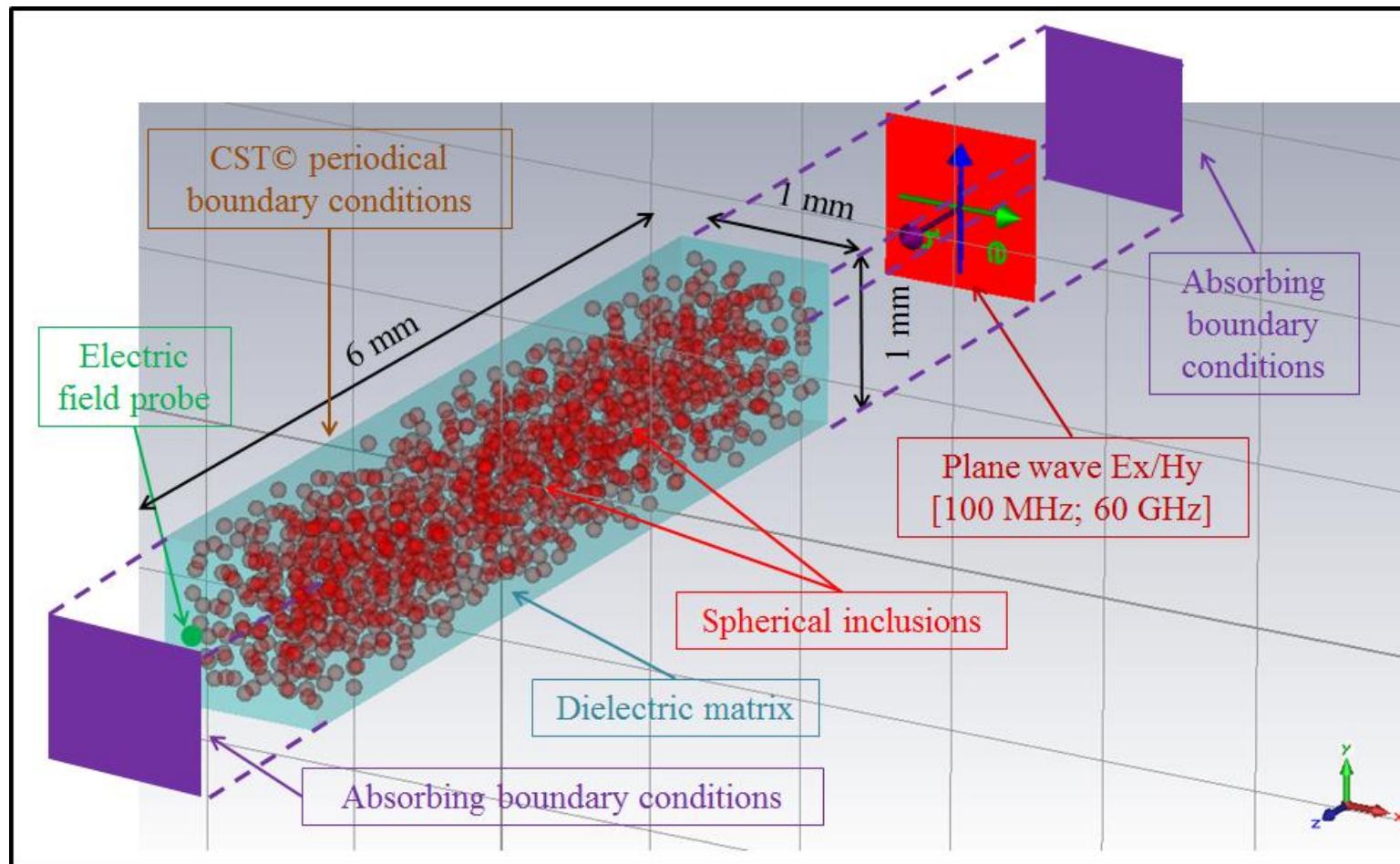
2-c/ DF POUR LA PROPAGATION : APPLICATION 3-D (3)

- Example illustratif : CST (Suite logicielle Dassault Simulia)

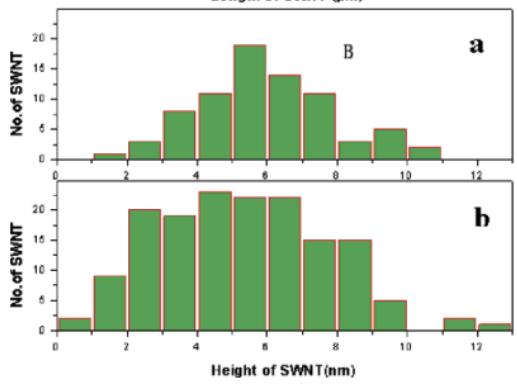
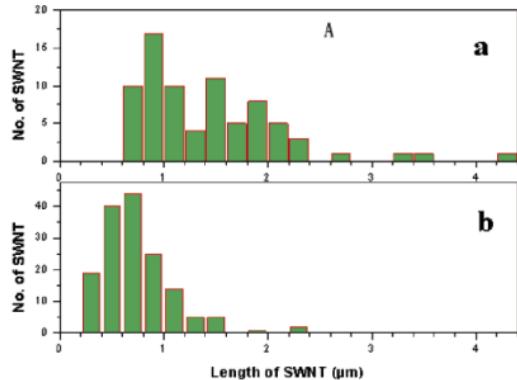


2-c/ DF POUR LA PROPAGATION : COMPOSITES

- Prise en compte de la nature ‘statistique’ des composites
 - Matériaux, inclusions conductrice, ...
 - Gaz / Liquide, blindage, ...

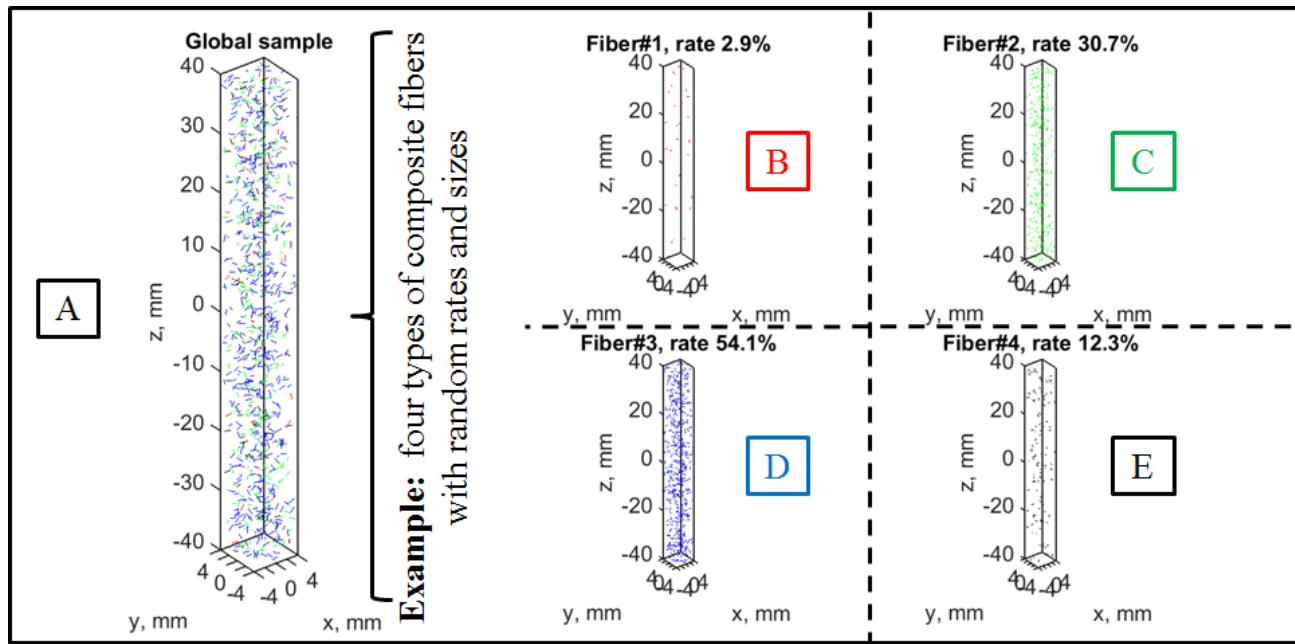


2-C/ GÉNÉRATION D'ÉCHANTILLONS : « NANORODS » FINS



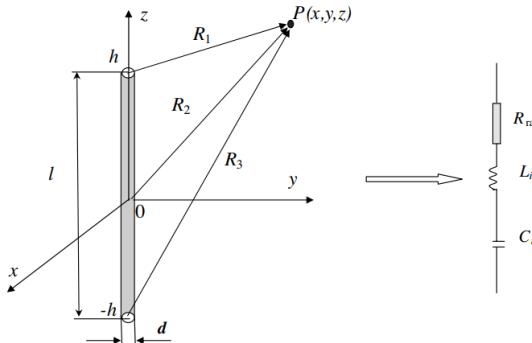
N. Li et al., *EM interference (EMI), shielding of single-walled carbon nanotube epoxy composites*, China NanoLetters, 2006

Illustration with 4 bins per composite sample

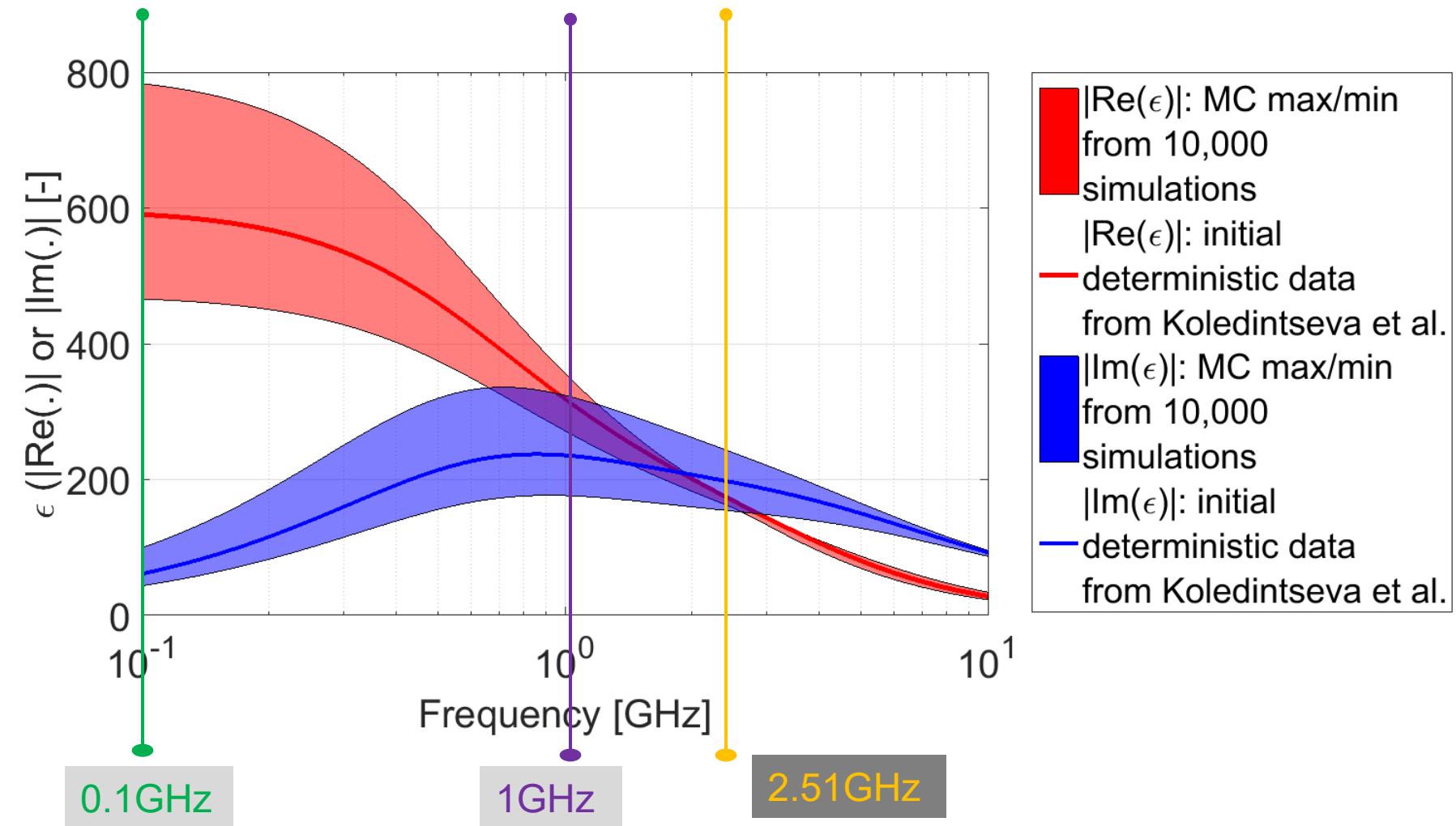


⇒ 10,000 MC samples and SE computation

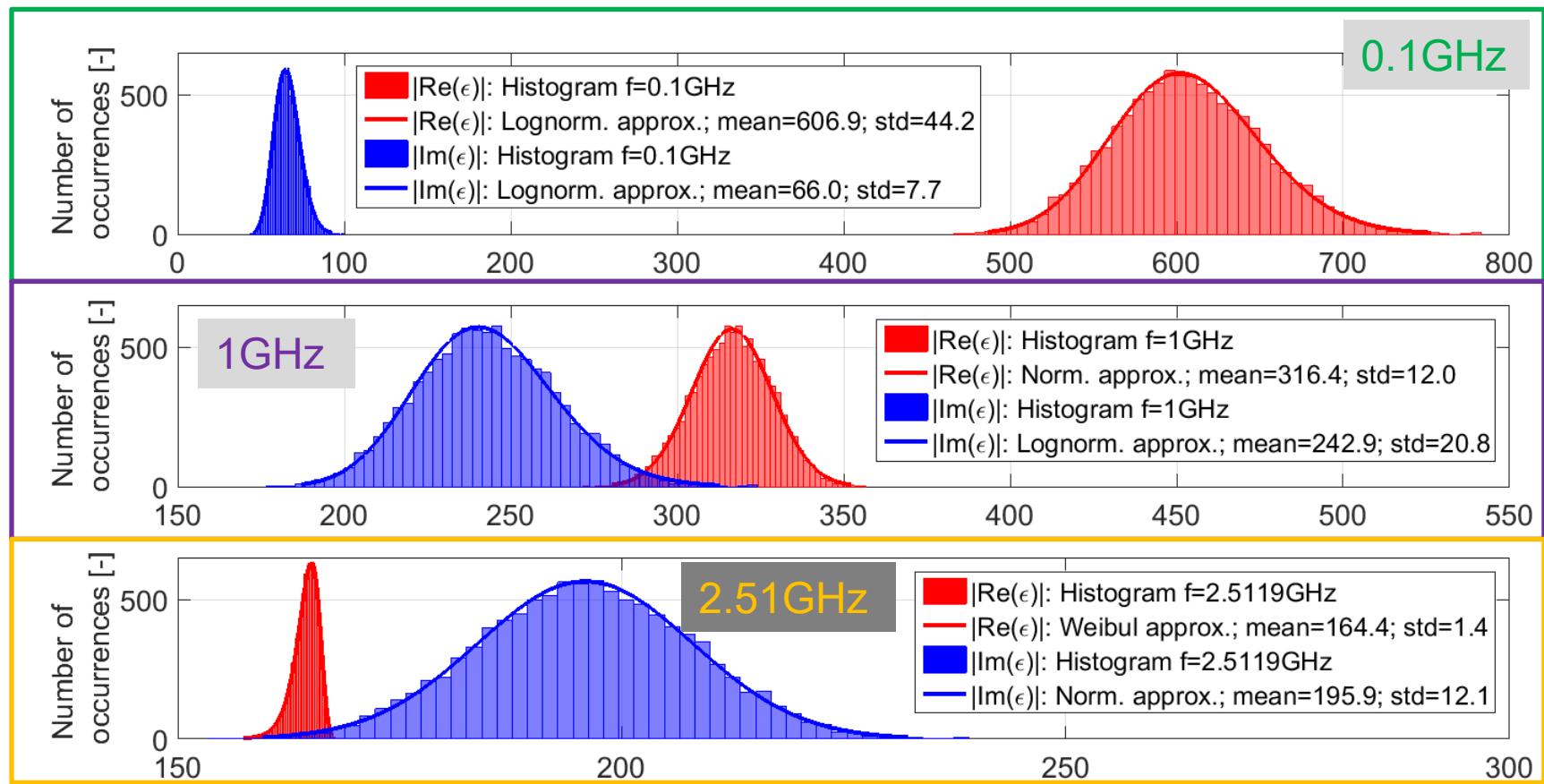
Analogy between composite nanorod and dipole antenna



2-c/ PROPRIÉTÉS ÉQUIVALENTES DIÉLECTRIQUE: DISPERSION STATISTIQUE (1)

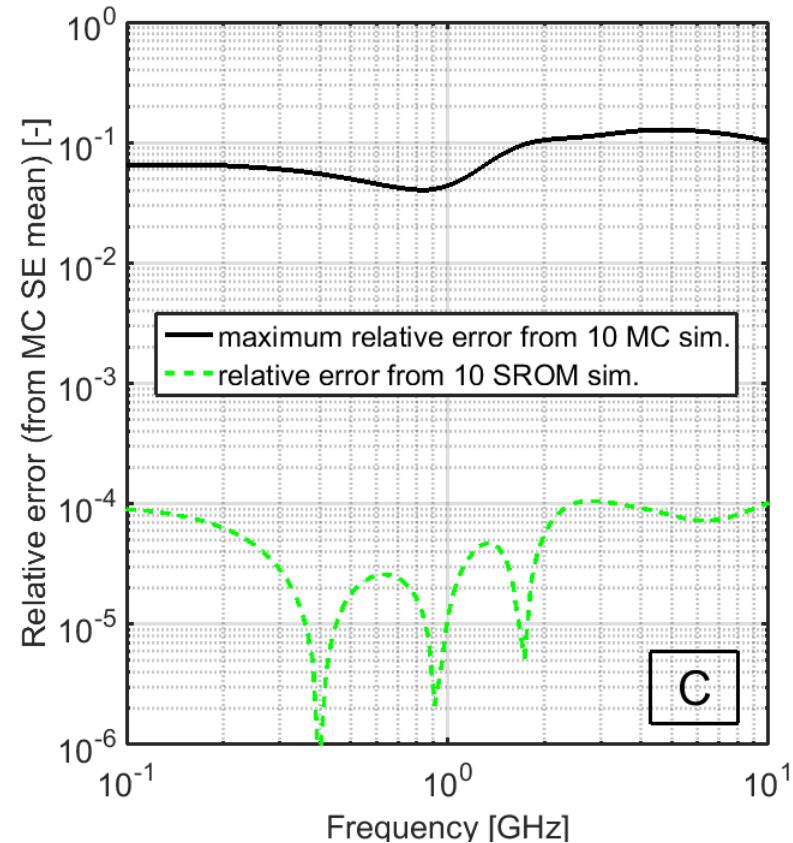
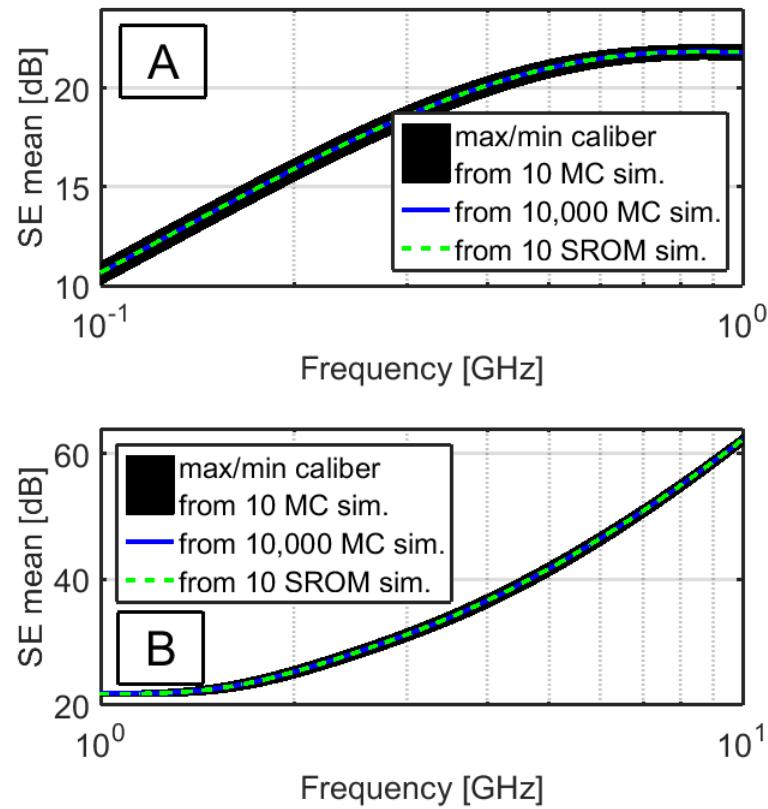


2-c/ PROPRIÉTÉS ÉQUIVALENTES DIÉLECTRIQUE: DISPERSION STATISTIQUE (2)



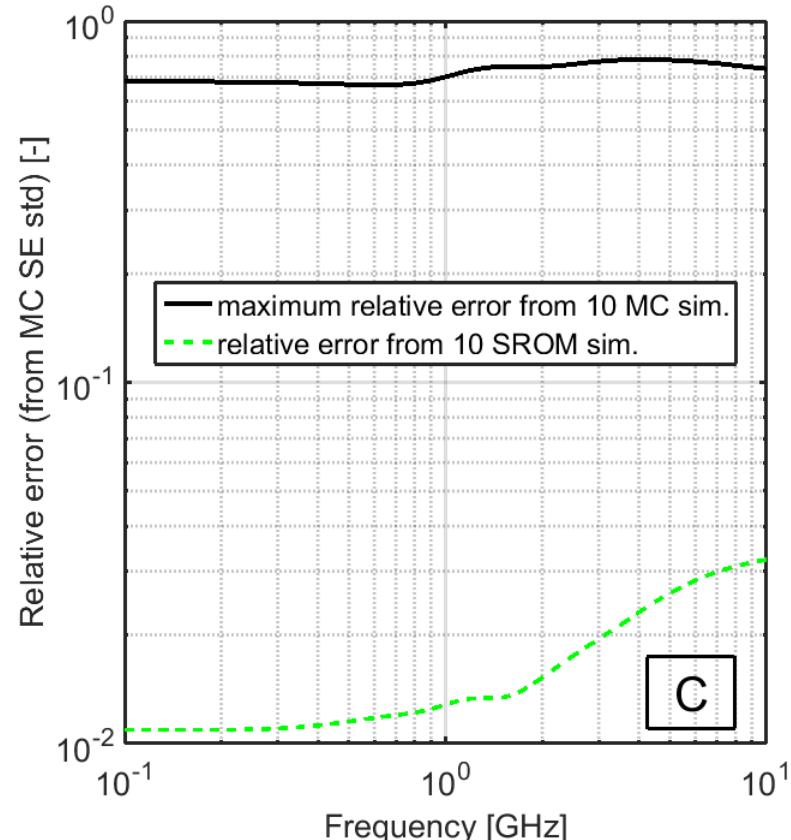
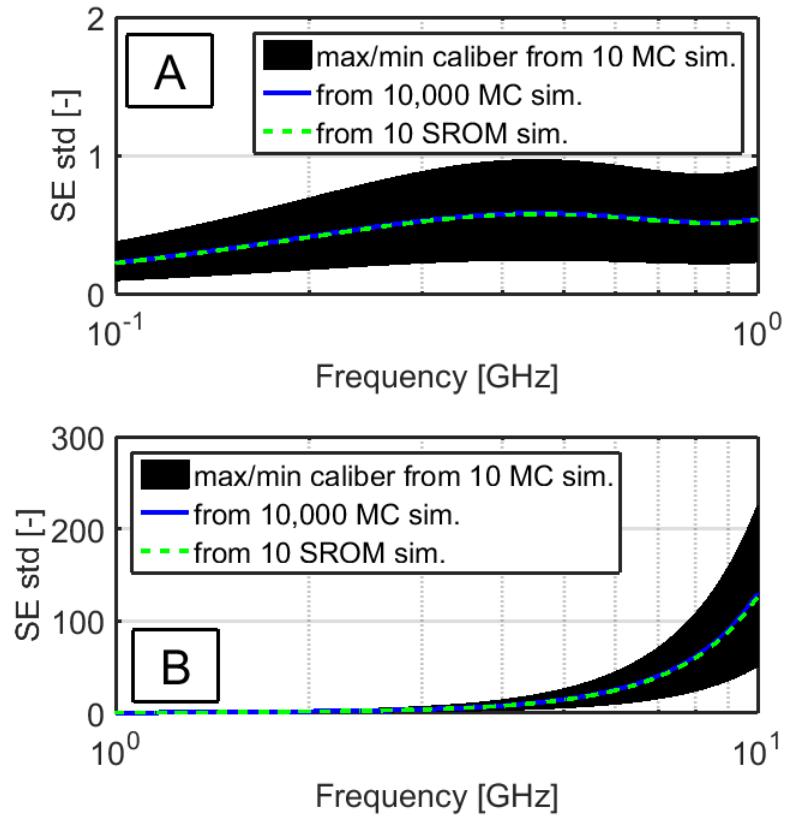
⇒ Assessing probabilistic distributions with respect to frequency?

2-c/ MOYENNE DE L'EFFICACITÉ DE BLINDAGE (SE)



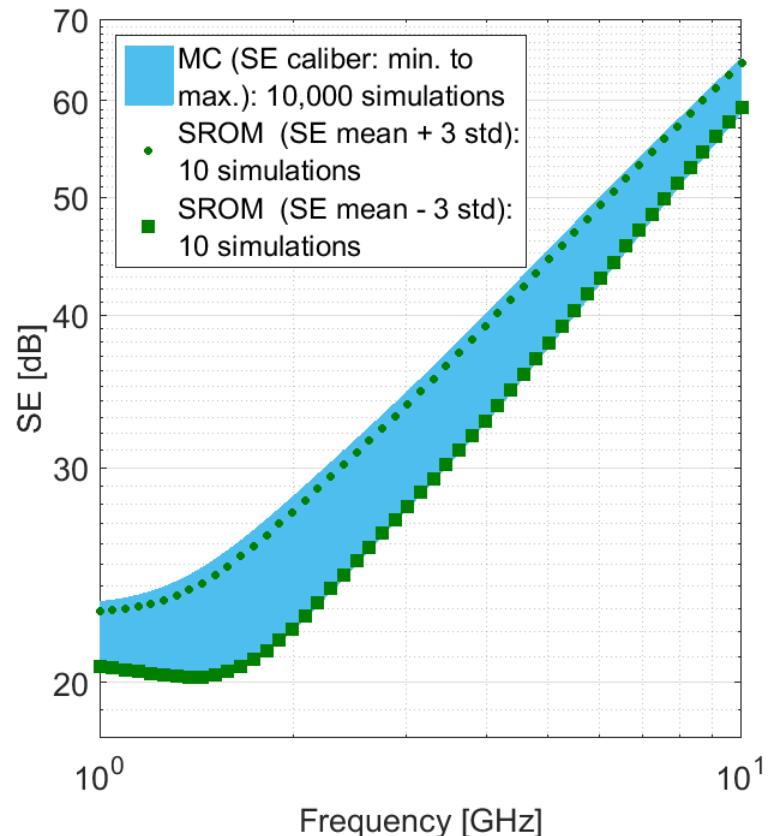
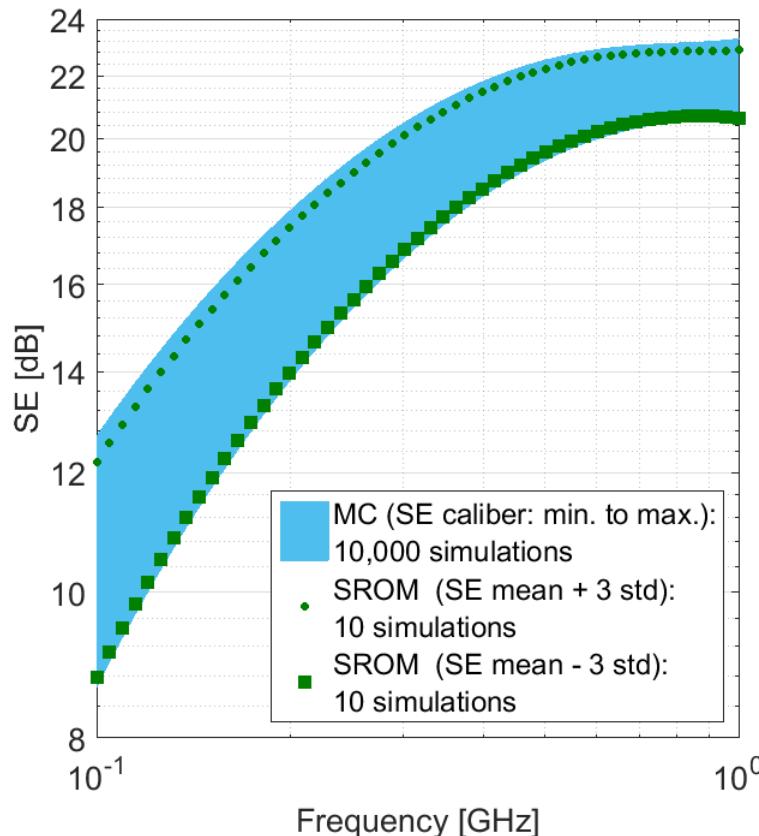
⇒ Excellent agreement between results from 10 SROM simulations and MC
⇒ Relative error: MC random choices error $\approx 4\text{-}10\%$ / SROM error $< 0.01\%$

2-c/ EVALUATION DE L'ÉCART-TYPE (EFFICACITÉ DE BLINDAGE)



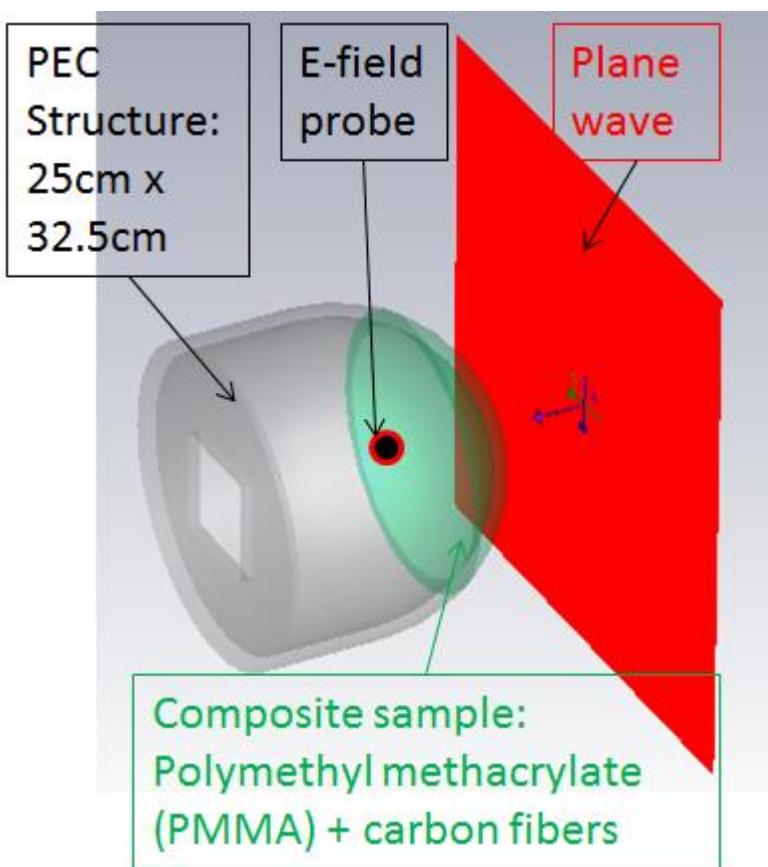
⇒ Excellent agreement between results from 10 SROM simulations and MC
⇒ Relative error: MC random choices error $\approx 70\%$ / SROM error $\approx 1\text{-}3\%$

2-C/ ESTIMATIONS DES EXTREMES (MINIMUM / MAXIMUM)



⇒ Good agreement between results from MC (entire population) and caliber given from $\text{mean}(\text{SE}) \pm 3 * \text{std}(\text{SE})$

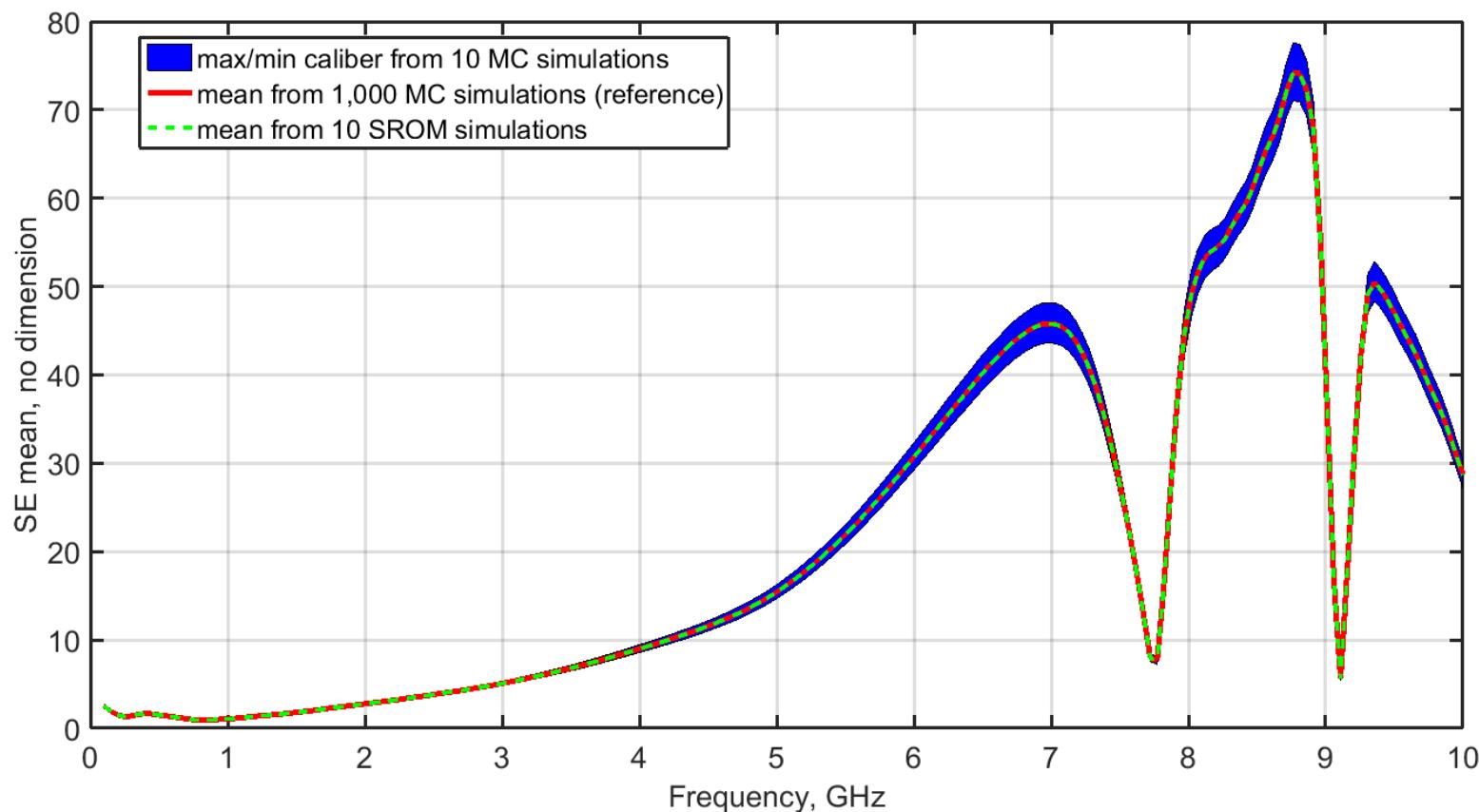
2-c/ SIMULATIONS 3-D « FULL-WAVE » : IMPACT SYSTÈME (1)



	koledin_nmc1000_u1.txt	koledin_nmc1000_u2.txt	koledin_nmc1000_u1000.txt
1	1.0000000e+08	4.7119263e+02	4.3668876e+01
2	1.0990000e+08	4.7007013e+02	4.7823460e+01
3	1.1980000e+08	4.6885210e+02	5.1932128e+01
4	1.2970000e+08	4.6754114e+02	5.5991667e+01
5	1.3960000e+08	4.6613991e+02	5.9999072e+01
6	1.4950000e+08	4.6465107e+02	6.3951495e+01
7	1.5940000e+08	4.6307734e+02	6.7846201e+01
8	1.6930000e+08	4.6142153e+02	7.1680546e+01
9	1.7920000e+08	4.5968654e+02	7.5451984e+01
10	1.8910000e+08	4.5787541e+02	7.9158107e+01
11	1.9900000e+08	4.5599130e+02	8.2796668e+01
12	2.0890000e+08	4.5403748e+02	8.6365616e+01
13	2.1880000e+08	4.5201730e+02	8.9863101e+01
14	2.2870000e+08	4.4993418e+02	9.3287485e+01
15	2.3860000e+08	4.4779154e+02	9.6637338e+01
16	2.4850000e+08	4.4559284e+02	9.9911436e+01
17	2.5840000e+08	4.4334155e+02	1.0310875e+02
18	2.6830000e+08	4.4104109e+02	1.0622844e+02
19	2.7820000e+08	4.3869488e+02	1.0926986e+02
20	2.8810000e+08	4.3630631e+02	1.1223252e+02
21	2.9800000e+08	4.3387871e+02	1.1511613e+02
22	3.0790000e+08	4.3141535e+02	1.1792052e+02
23	3.1780000e+08	4.2891946e+02	1.2064571e+02
24	3.2770000e+08	4.2639419e+02	1.2329186e+02
25	3.3760000e+08	4.2384261e+02	1.2585924e+02
26	3.4750000e+08	4.2126773e+02	1.2834828e+02
27	3.5740000e+08	4.1867245e+02	1.3075952e+02
28	3.6730000e+08	4.1605961e+02	1.3309362e+02
29	3.7720000e+08	4.1343195e+02	1.3535133e+02
30	3.8710000e+08	4.1079208e+02	1.3753353e+02
31	3.9700000e+08	4.0814257e+02	1.3964116e+02
32	4.0690000e+08	4.0548586e+02	1.4167525e+02

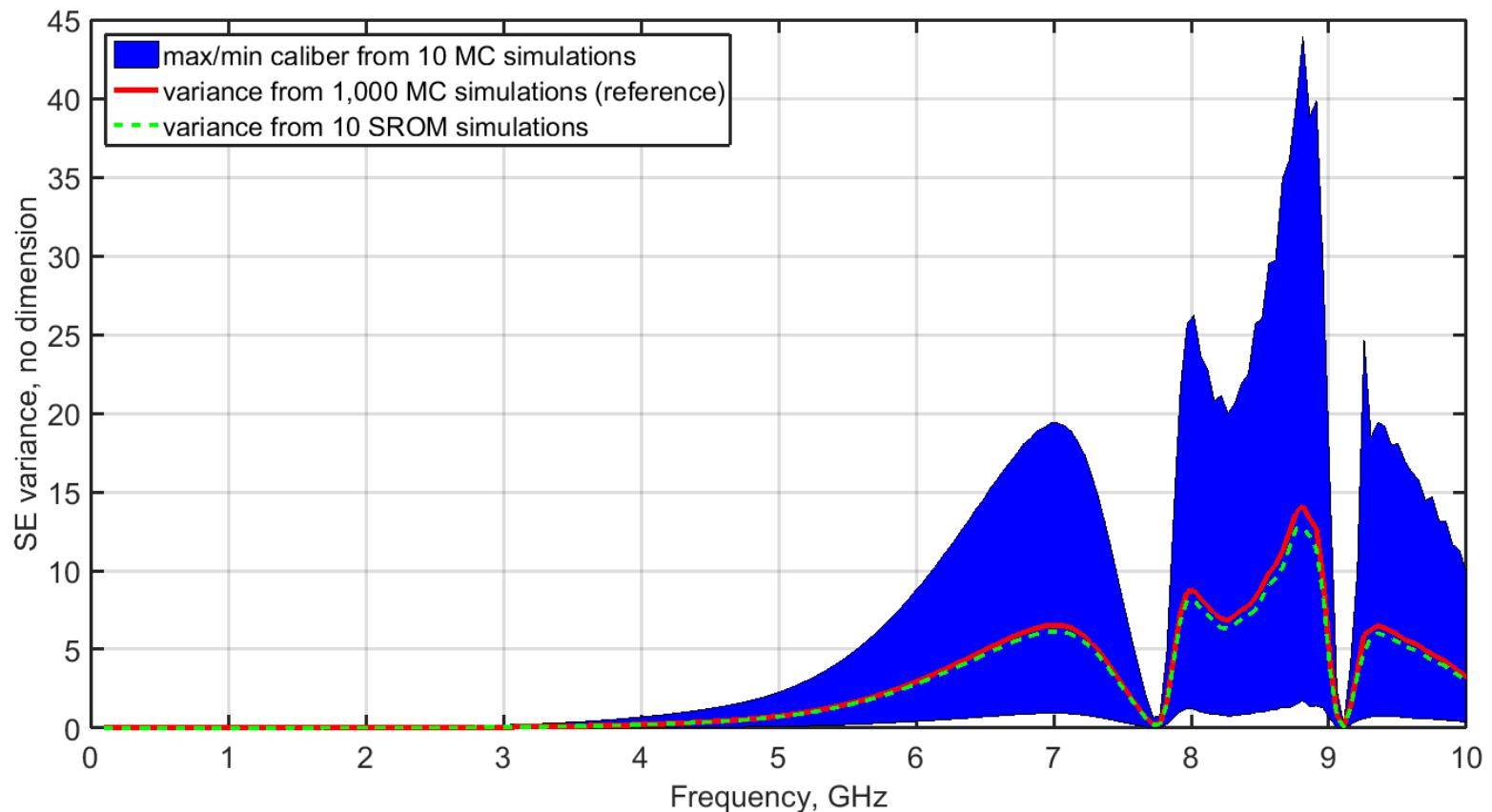
- 1,000 composite samples → 1,000 mixture equivalent dielectric properties
- Probing E-field transmitted inside device
- 35 minutes per simulation

2-c/ SIMULATIONS 3-D « FULL-WAVE » : IMPACT SYSTÈME (2)



Evaluation du pouvoir de protection EM du matériau (moyenne)

2-C/ SIMULATIONS 3-D « FULL-WAVE » : IMPACT SYSTÈME (3)



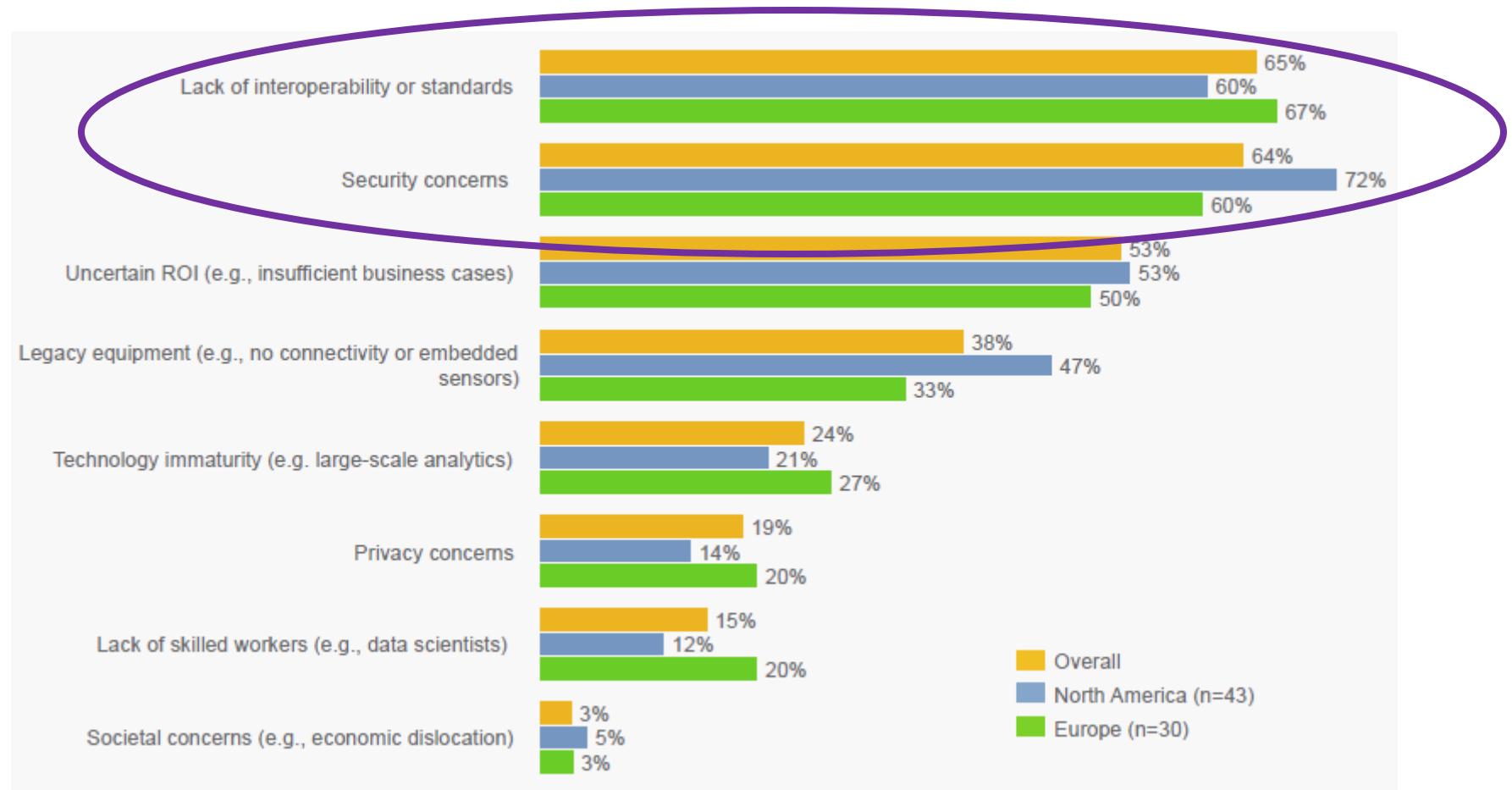
Evaluation du pouvoir de protection EM du matériau (variance)
⇒ Ouverture vers l'analyse de sensibilité, l'optimisation, les méthodes avancées (IA, metamodèles, fiabilité, risque, ...)

PLAN

1. Position du problème
 - a) Limiter les interférence EM (EMI) : quel(s) besoin(s) ?
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4. Conclusions

3-A/ PRÉOCCUPATIONS SOCIÉTALES & FINANCIÈRES (IoT)

Q: What are the greatest barriers inhibiting the adoption of IoT?

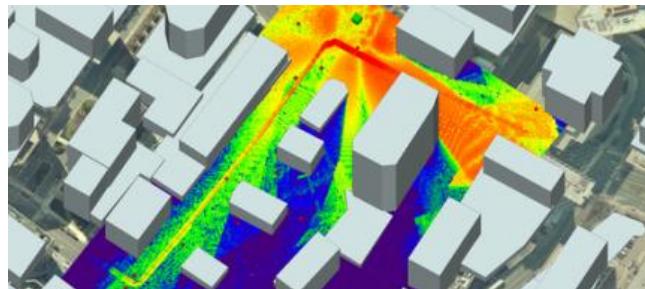


- , *Industrial Internet of Things – Unleashing the potential of connected products and services*,
World Economic Forum, 2015

3-A/ AUGMENTATION DES NIVEAUX D'INTERFÉRENCES EM (1)

Increasing EMC interest?

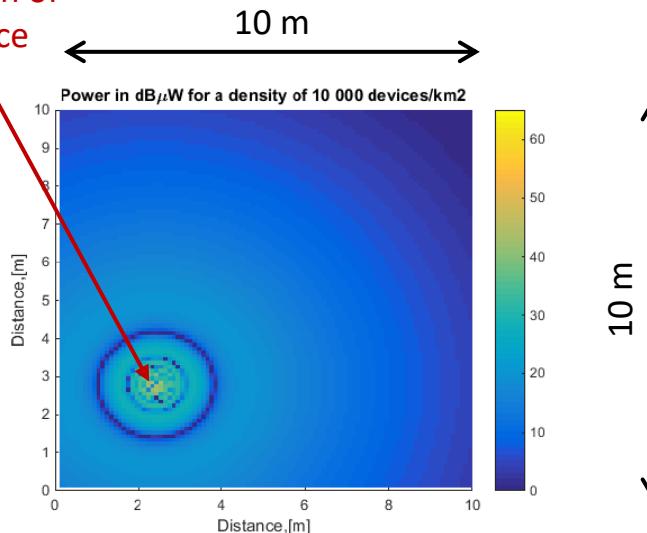
- High density of IoT devices \Rightarrow Increased EM fields?
- ISM frequency of interest: 433 MHz, 868 MHz, 5.8 GHz



Frequency	Transmit power
433 MHz	10 mW
868 MHz	25 mW
5.8 GHz	200 mW

Random location of source

- $f=433 \text{ MHz} / Pt=10 \text{ mW}$
- 10,000 devices per km^2



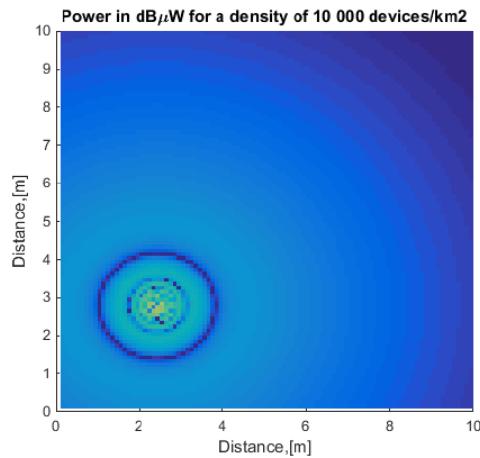
$$P_r \approx 4 \frac{P_t A_m}{4\pi r^2} \sin^2 \left(\frac{2\pi h_1 h_2}{\lambda r} \right)$$

- h_1 == average height (emitting device)
- h_2 == average height (receiving device)
- P_t == transmitted power
- A_m == effective antenna area, depending on frequency
- λ == wavelength
- r == distance between (E) and (R) devices

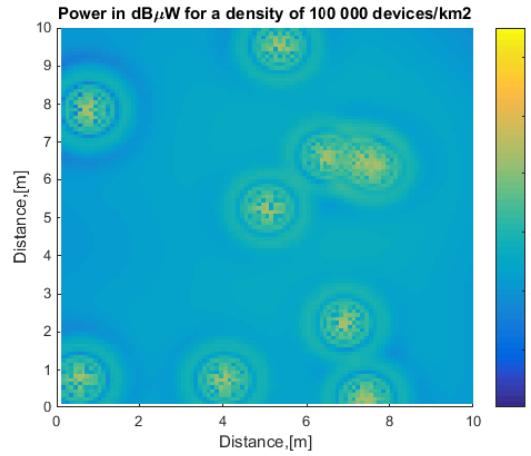
3-A/ AUGMENTATION DES NIVEAUX D'INTERFÉRENCES EM (2)

Increasing EMC interest?

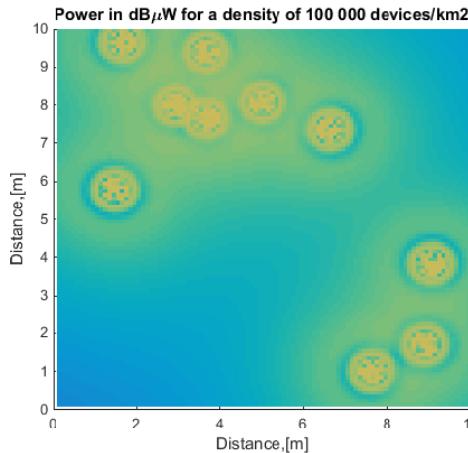
- High density of IoT devices \Rightarrow Increased EM fields?
- ISM frequency of interest: 433 MHz, 868 MHz, 5.8 GHz



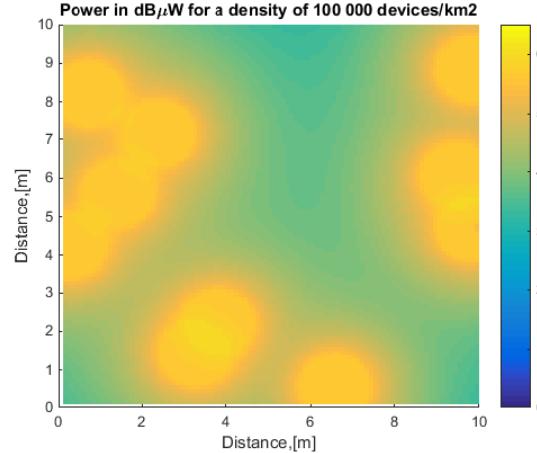
• $f=433 \text{ MHz} / Pt=10 \text{ mW}$
• 10,000 devices per km 2



• $f=433 \text{ MHz} / Pt=10 \text{ mW}$
• 100,000 devices per km 2



• $f=868 \text{ MHz} / Pt=25 \text{ mW}$
• 100,000 devices per km 2



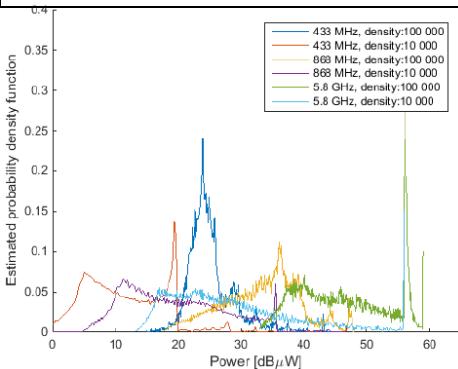
• $f=5.8 \text{ GHz} / Pt=200 \text{ mW}$
• 100,000 devices per km 2

3-A/ AUGMENTATION DES NIVEAUX D'INTERFÉRENCES EM (3)

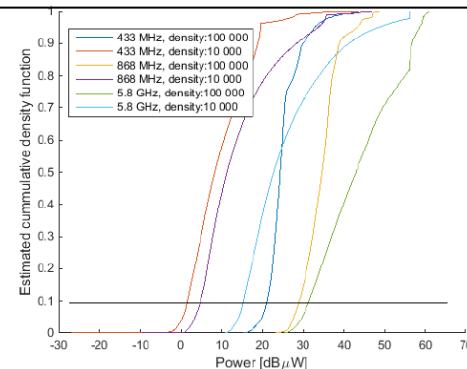
Increasing EMC interest?

- High density of IoT devices \Rightarrow Increased EM fields?
- ISM frequency of interest: 433 MHz, 866 MHz, 5.8 GHz

Probability density function (PDF)



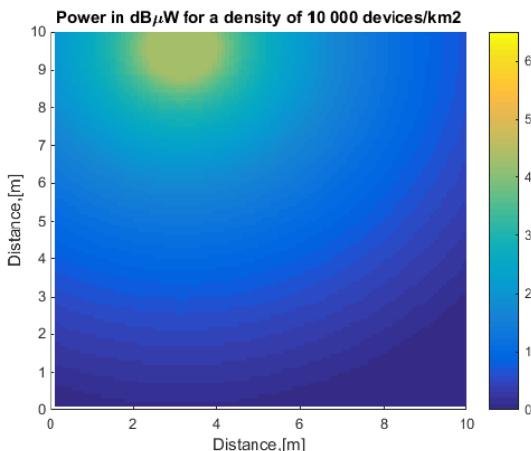
Cumulative density function (PDF)



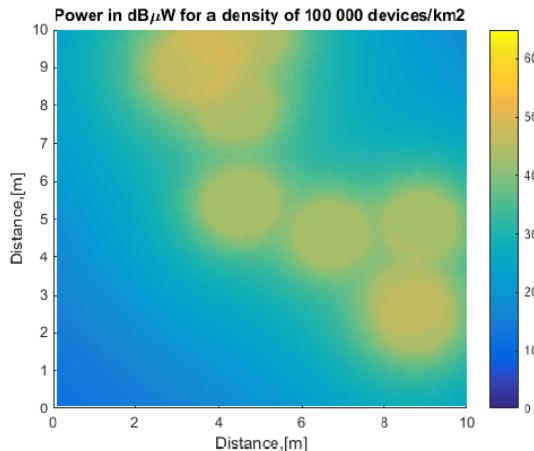
IoT towards tens of GHz?

- Still prospective work towards 30 GHz wifi \Rightarrow Potential effects?

$f=30 \text{ GHz} / Pt=10 \text{ mW} / 10,000 \text{ devices per } \text{km}^2$



$f=30 \text{ GHz} / Pt=10 \text{ mW} / 100,000 \text{ devices per } \text{km}^2$



3-B/ INTERFÉRENCE EM INTENTIONNELLE (IEMI) (1)

Intentional EMI:

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

from URSI (Union RadioScientifique Internationale)
General Assembly, Toronto, 1999

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URSI Commision E (EMC and interferences)
URSI Internat. => Vice-Chair == V. Deniau (IFSTTAR)
URSI France => Chair == S. Lalléchère (UCA)



Possible targets

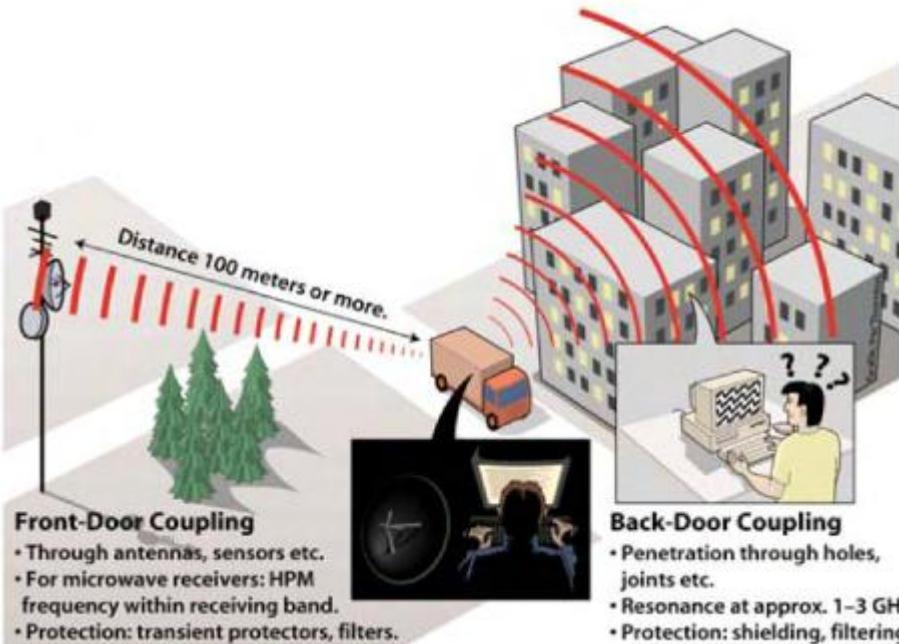
- Power networks
- Telecom systems
- Financial systems
- Computer networks
- Medical care
- Industrial plants
- Radio/TV networks
- Traffic control systems
- Food & Water Supply



- High power microwaves
- Pulse injection on signal/power cables
- Jammers (radio communicat. disruption)
- Nuclear EMP

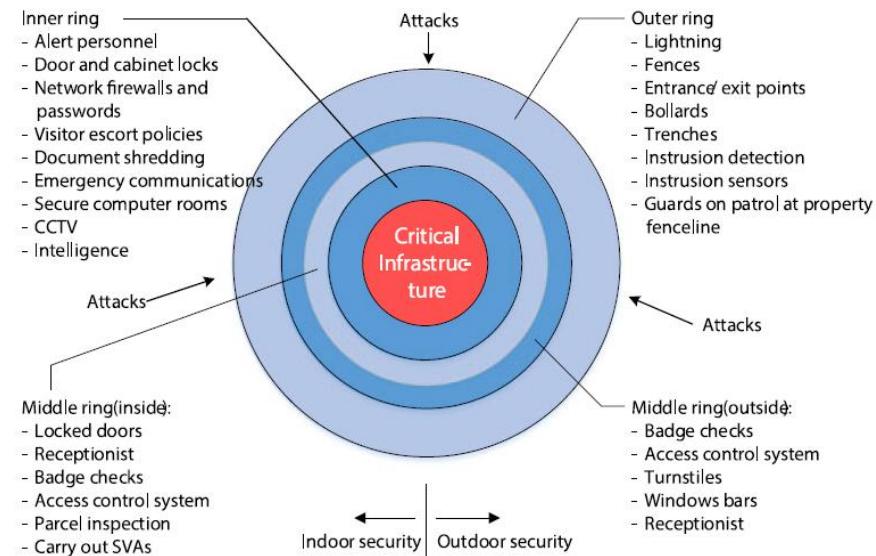
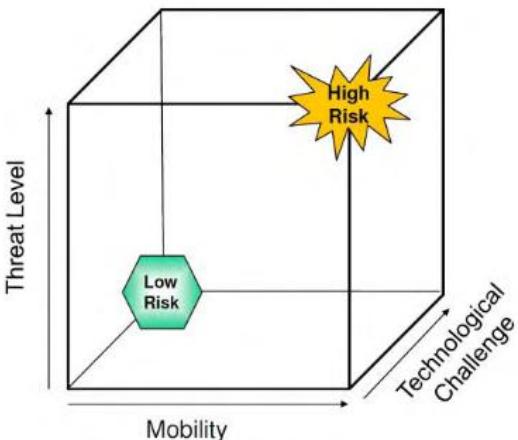
IEMI means

3-B/ INTERFÉRENCE EM INTENTIONNELLE (IEMI) (2)

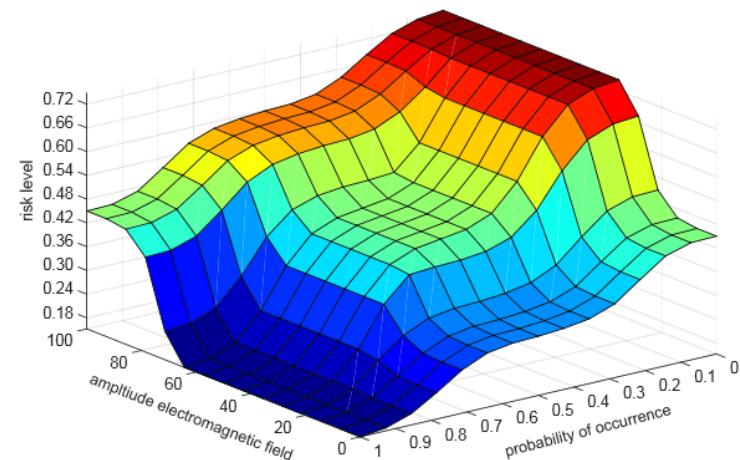


F. Sabath & H. Garbe, Risk potential of radiated HPEM environments, 2009

Risk assessment cube for HPEM environments with extreme regions of special interests



T. Peikert et al., A fuzzy approach for IEMI risk analysis of IT-Systems with respect to transient disturbances, 2015

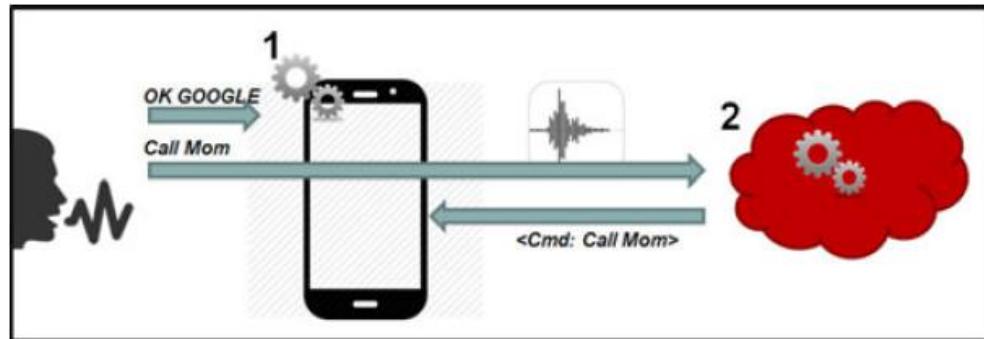


3-B/ IEMI : UNE ILLUSTRATION (1)

C. Kasmi & J. Lopes Esteves, *IEMI threats for information security: remote command injection on modern smartphones*, IEEE TEMC, 2015

Front-door coupling on smartphone headphones cables

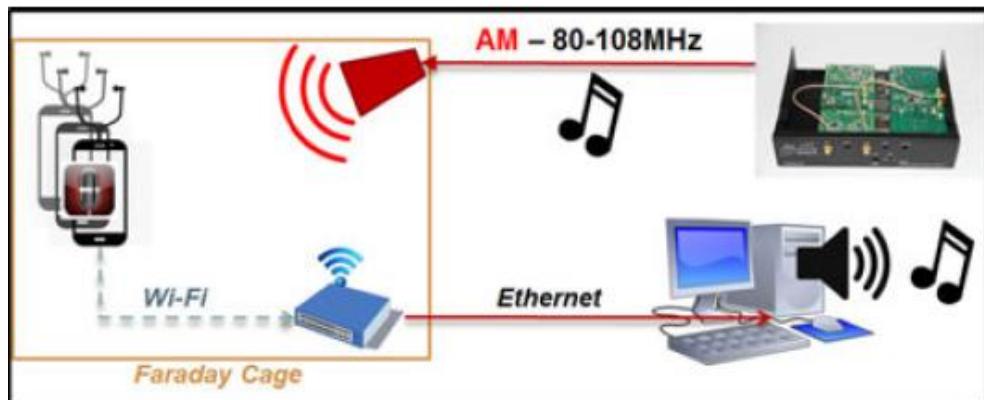
- Electronic warfare
- Information security
- Voice command on smartphones (S-voice, Siri, Jelly bean, Cortana ...)



Two-step procedure for audio signal processing for command execution

Experimental test setup

- Headphones == FM antenna
- Faraday cage (ERC)
- Wireless access point
- Wifi link set up (normal use of the smartphone)

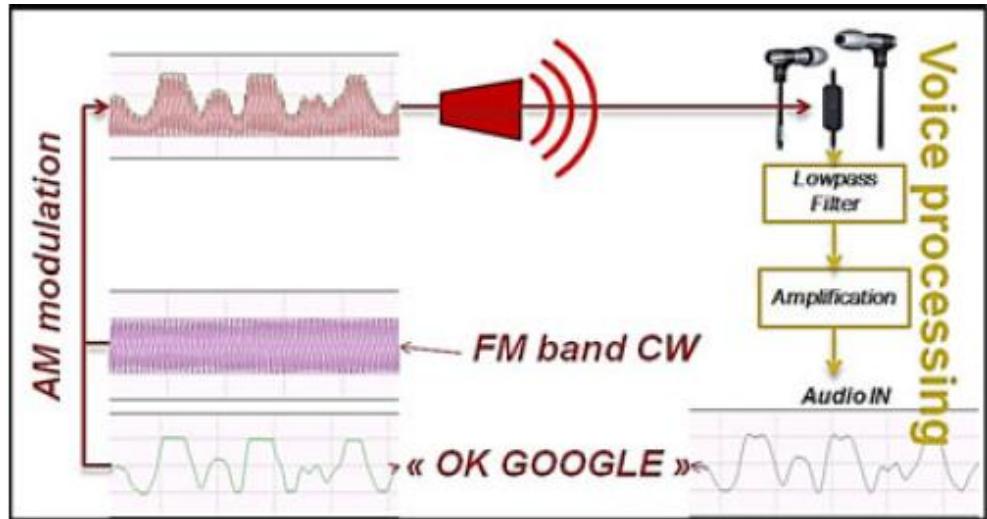


3-B/ IEMI : UNE ILLUSTRATION (2)

C. Kasmi & J. Lopes Esteves, *IEMI threats for information security: remote command injection on modern smartphones*, IEEE TEMC, 2015

Command injection with smart IEMI

- Experimental setup (E-field probe, 50 W amplifier, software signal processing framework)
- Two major scenarii:
Permanent activation
+ User activation
- Minimal field required == 25-30 V/m
(immunity level == 3 V/m)
- Frequency 80-108 MHz



Schematic of the emitted AM modulated signal and the induced signal envelop at the audio interface of the smartphone

Attack scenarii

- Tracking
- Audio spying
- Paid services
- Reputation and phishing
- Advanced compromising

Counter measures (EMC, ...)

- Hardware improvement (audio front-end to reduce the sensitivity of the input interface)
- User voice identification
- Configuration settings (choosing keyword)
- Unusual EM activity detection

PLAN

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4. Conclusions

EMC & systems

- EMC & systems are naturally linked topics
- Various domains are of interest: antennas, coupling paths, sources, power, circuit design, dosimetry, ...
- Density (# of devices per km²) and co-location distances have to be considered very carefully
- Considerably higher frequencies (tens of GHz) VS EMC guidelines (up to 18 GHz)
- Conflicting requirements: frequency range, battery life, bandwidth, density, operational cost, wide-area networks, ...

EMC prospects

- Unlicensed (ISM) VS licensed (e.g. telecommunications operators) frequency bands
- **Need for original interference models**
 - Systems: Unpredictable EMC environment ⇒ Statistical description (# users, ...)
 - Mass increase of low power wireless networks ⇒ Larger vulnerability to EMI
 - Extension of frequency ranges ⇒ Increase for EMC emission and immunity tests
 - Massive use of IoT in daily life ⇒ Unlicensed frequency needs special care
 - Scenarios imply high dynamics, flexible and non-predictable environments
 - ⇒ **Consumer habits have to be modelled**
 - ⇒ **Artificial intelligence tools**

4-B/ REMERCIEMENTS ... QUESTIONS ...

Merci !