Electromagnetic compatibility of Integrated Circuits

INSTITUT NATIONAL DES SCIENCES APPLIQUÉES TOULOUSE

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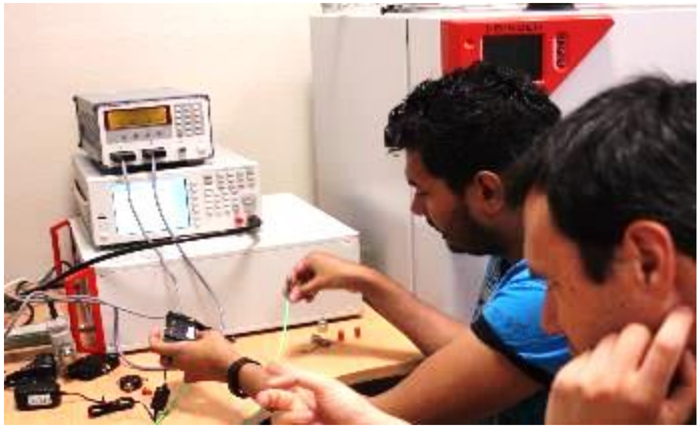
www.ic-emc.org

Objectives

- **Understand parasitic emission mechanisms**
- **Introduce parasitic emission reduction strategies**
- Give an overview of emission and susceptibility measurement standards
- Power Decoupling Network modelling
- **Basis of conducted and radiated emission modelling**
- Basis of immunity modelling
- Hands-on experience in IC emission and immunity measurements



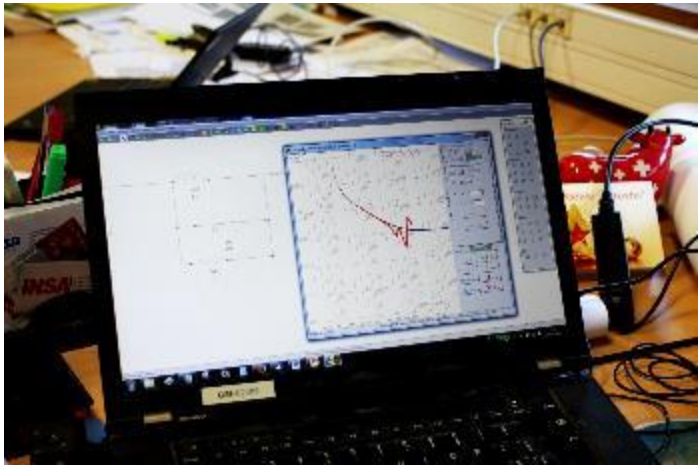
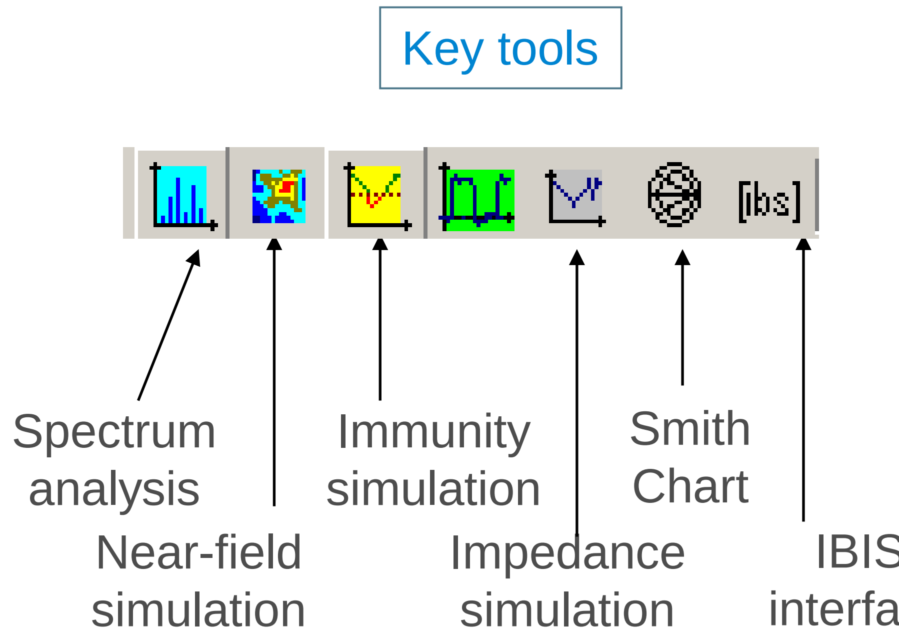
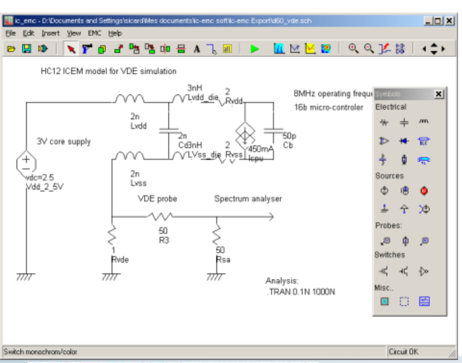


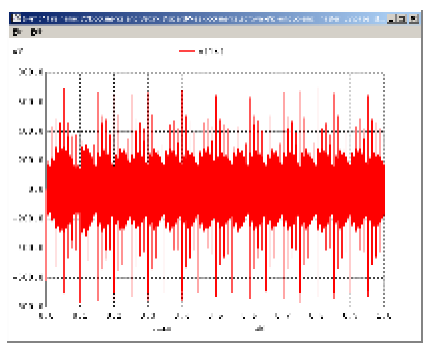
Illustration with IC-EMC

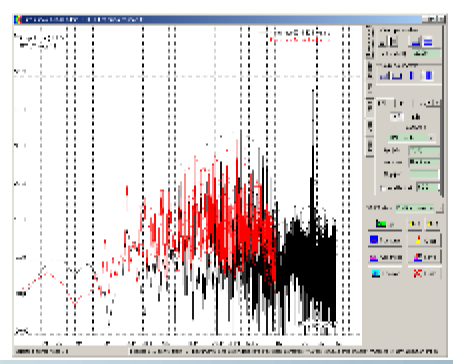
IC-EMC - A TOOL FOR EMC PREDICTION AT IC LEVEL

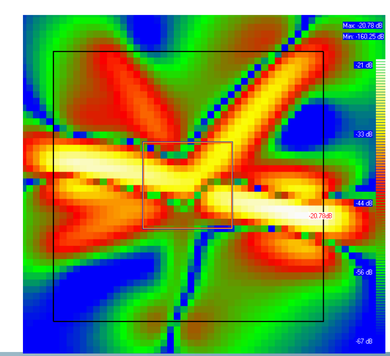
- A schematic editor
- An interface to WinSpice
- A post-processor to compare simulated with measured spectrum
- An Electromagnetic solver for radiated field
- Freeware, online
- 250 pp documentation, 15 case studies





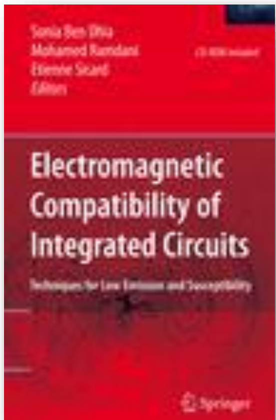


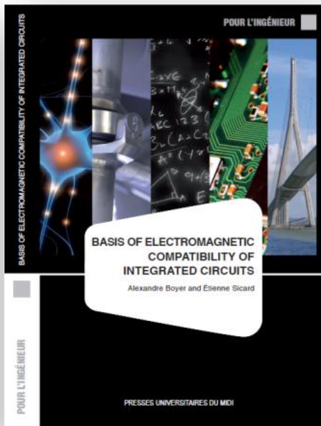


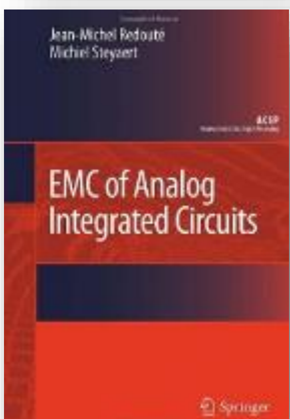


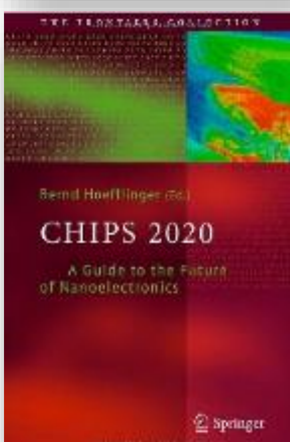
References

Books





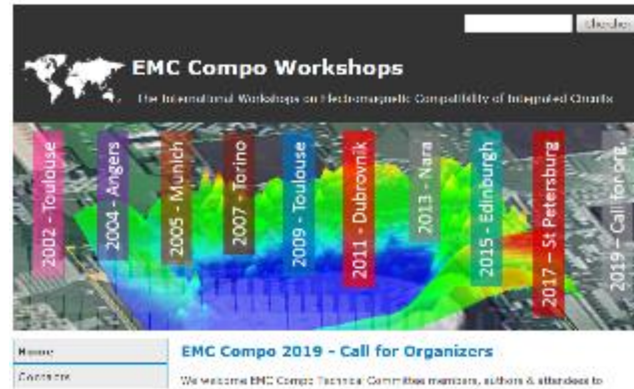




Freeware

www.ic-emc.org

Workshops



www.emccompo.org

Standards www.iec.ch

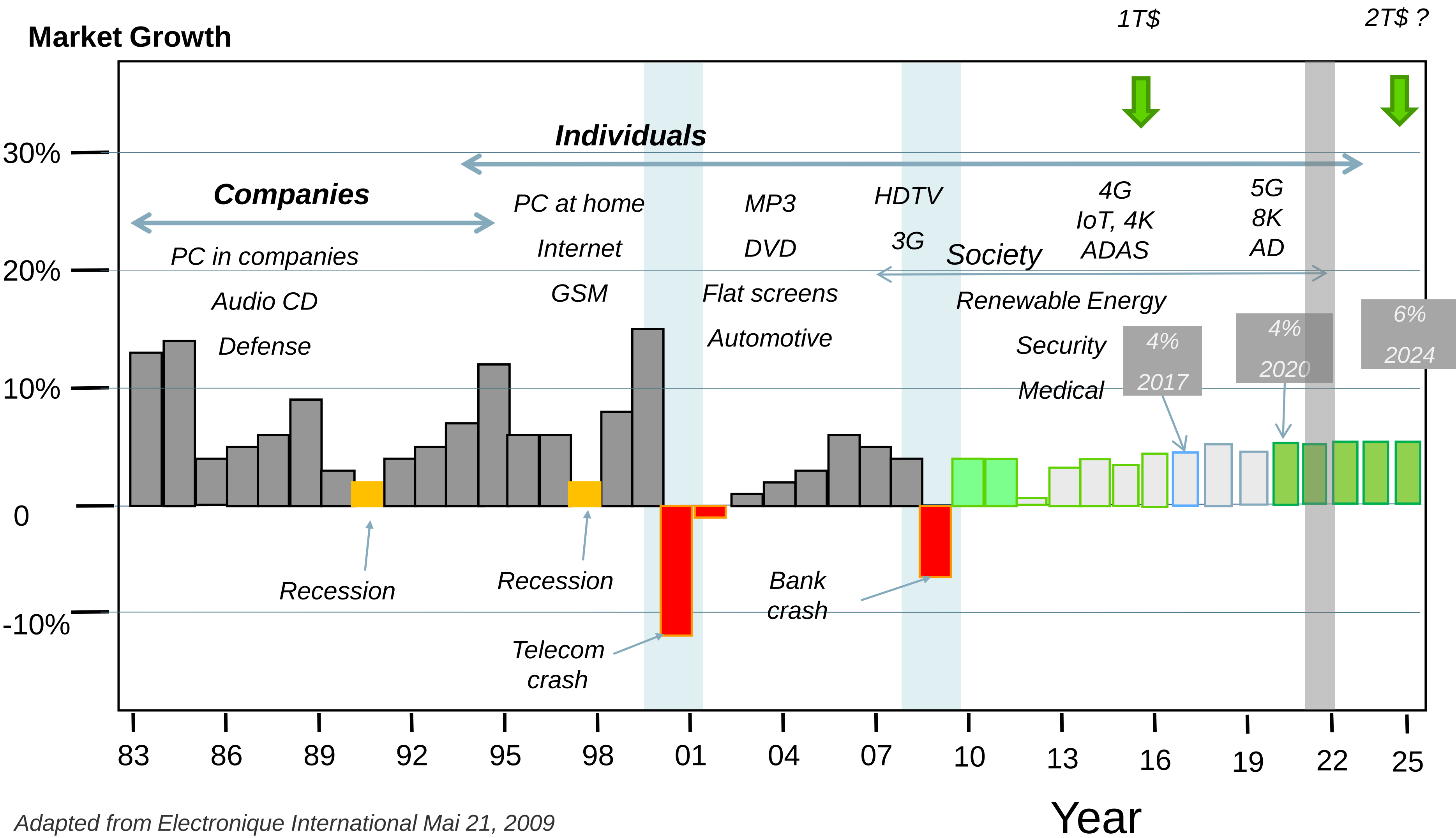
- IEC 61967, 2001, Integrated Circuits Emissions
- IEC 62132, 2003, Integrated circuits Immunity
- IEC 62433, 2008, Integrated Circuit Model

1. EMC of ICs
An overview

Outlines

- Electronic Market Growth
- Electromagnetic interference
- What is EMC
- Technology scale down
- Going 3D
- Origin of parasitic emission
- Trends towards higher emission
- Origin on susceptibility
- Emission issues
- Susceptibility issues
- EMC issues
- Conclusion

Electronic Market Growth



Adapted from Electronique International Mai 21, 2009

Electronic Market Growth

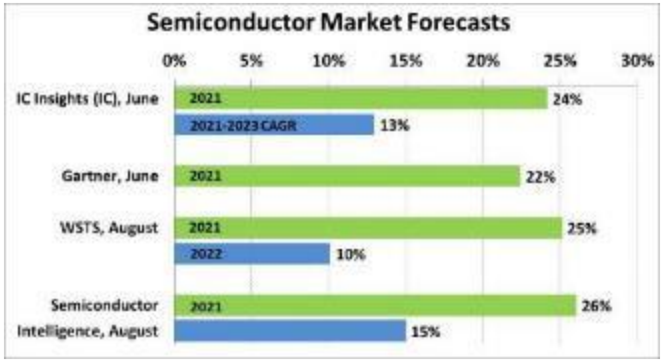
https://www.semiconductorintelligence.com/semiconductor-growth-to-continue-in-2022/

Top Semiconductor Companies' Revenue

Change versus prior quarter in local currency

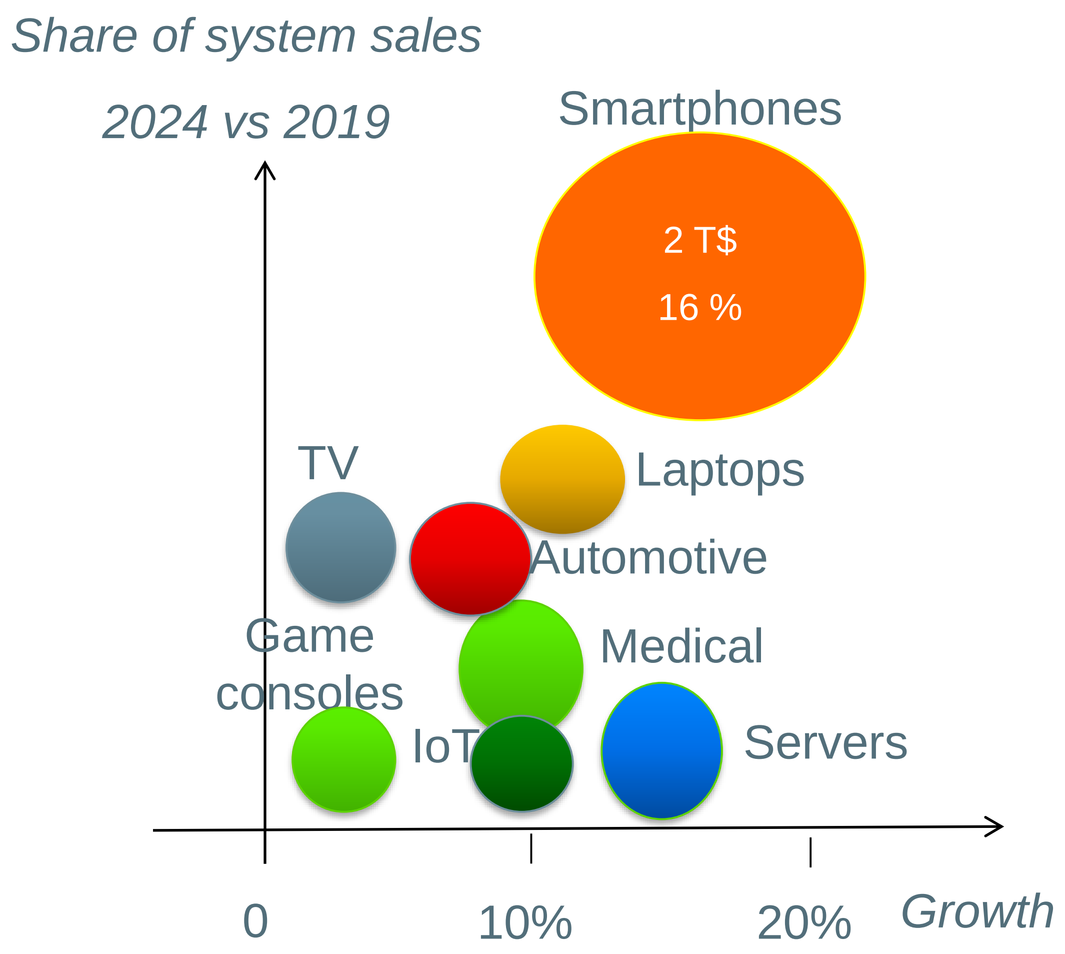
Rank	Company	$Billion 2Q21		Reported 2Q21	Guidance 3Q21	Comments on 3Q21 revenue
1	Samsung SC	20.3		19.6%	n/a	strong demand for server/PC
2	Intel	19.6		-0.2%	-2.7%	supply constrained
3	SK Hynix	9.2		21.5%	n/a	strong demand for 5G & server
4	Micron Technology	7.4		19.0%	10.5%	memory supply below demand
5	Broadcom	6.8	*	2.1%	n/a	* 2Q21 is guidance from 1Q21
6	Qualcomm (IC)	6.5		3.0%	12.0%	strong handset growth
7	Nvidia	6.3	*	11.3%	n/a	* 2Q21 is guidance from 1Q21
8	Texas Instruments	4.6		6.8%	0.0%	capacity limited
9	MediaTek	4.5		16.3%	2.5%	strong 5G market
10	AMD	3.9		11.8%	6.5%	growth in data center & gaming
11	Infineon Technologies	3.3		0.8%	6.5%	recovery in smartphones
12	STMicroelectronics	3.0		-0.8%	7.0%	improved pricing & volume
13	Kioxia	3.0		11.8%	n/a	strong SSD & 5G demand
14	NXP Semiconductors	2.6		1.1%	9.8%	strong demand across markets
	Total of above companies			10%		
	Memory Companies (US$)			22%		Samsung, SK Hynix, Micron, Kioxia
	Non-Memory Companies			3%	2%	companies providing guidance

2021 2022



Electronic Market Growth

- **Vision 2024**
  - **Increasing disposable income,**
  - **expanding urban population,**
  - **growing internet penetration and**
  - **availability of strong distribution network**



INSA NATIONAL INSTITUTE OF APPLIED SCIENCES TOULOUSE
DEPARTMENT OF COMPUTER & ELECTRICAL ENGINEERING

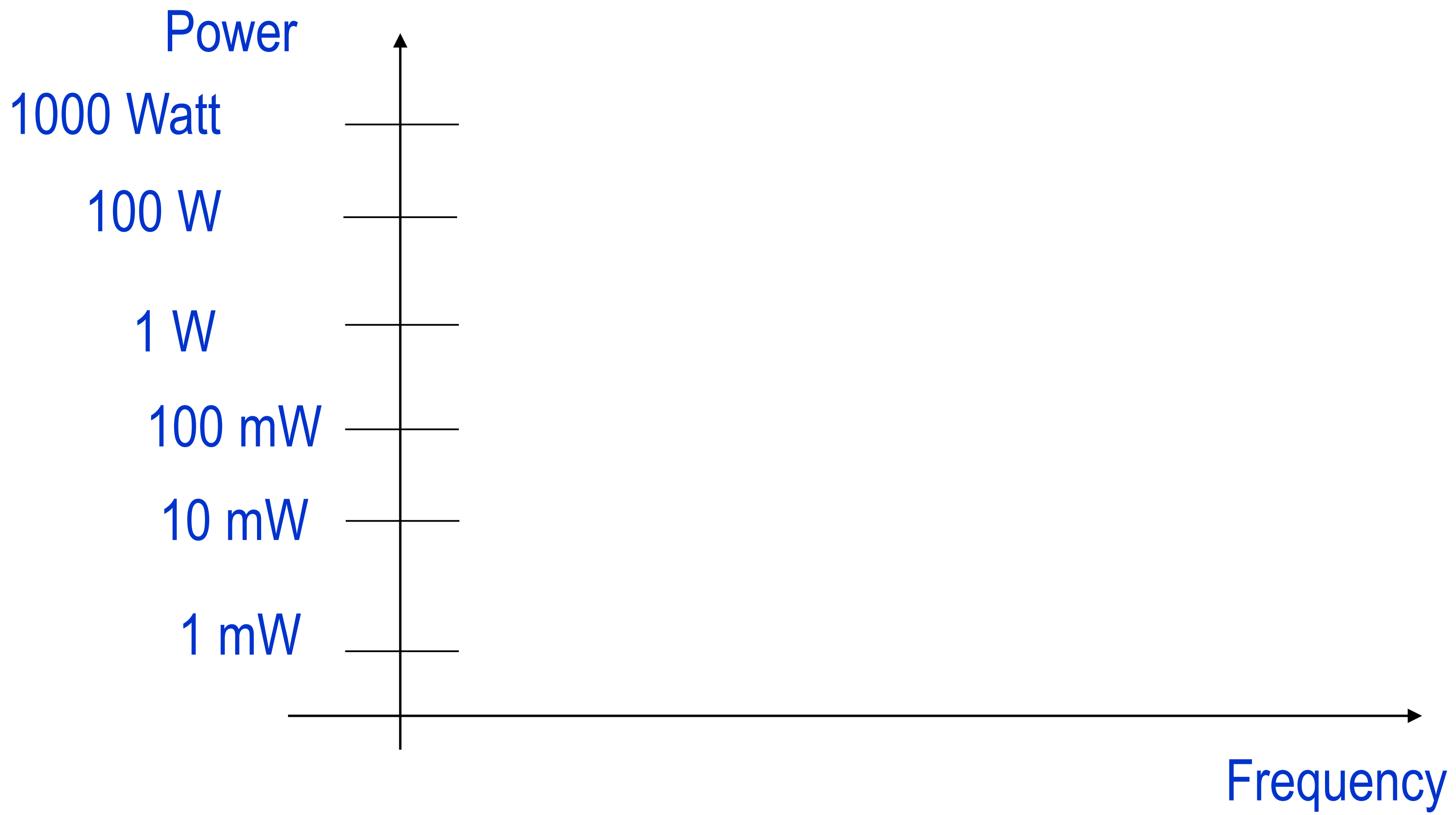
Electromagnetic Interference

EMI ISSUES IN WIRELESS DEVICES

- Numerous interference cases reported over the ISM band 2400 – 2483.5 MHz.
- From Cisco, « 20 Myths of WiFi Interference », White Paper, 2008:
  - “Interference contributes to 50 % of the problems on the customer’s Wi-Fi network. “
  - “In a recent survey of 300 of their customers, a major Wi-Fi tools provider reported that “troubleshooting interference won ‘top honors’ as the biggest challenge in managing a Wi-Fi network.””
  - “67 percent of all residential Wi-Fi problems are linked to interfering devices, such as cordless phones, baby monitors, and microwave ovens.”
  - “At 8m, a microwave oven degrades data throughput by 64%.”

Electromagnetic Interference

- **Wifi & Microwave**



Electronic Market Growth

GSMA Intelligence

TOTAL CELLULAR CONNECTIONS	UNIQUE MOBILE SUBSCRIBERS	ARPU/MONTH
Including licensed cellular IoT - Q1 2022	Q1 2022	FY 2020/21
10 461 122 395	5 298 158 087	$8.08
▲ 6.57%	▲ 1.74%	▼ -0.12%

SIX YEARS AGO… (OCT. 2016)

GLOBAL DATA

Mobile connections, including M2M Oct 2016	Unique mobile subscribers Oct 2016	Revenue/year FY 2015	ARPU/month FY 2015
7,802,658,518	4,752,110,923	$1.06T	$10.25
▲ 4.70%	▲ 4.76%	▲ 2.18%	▼ -2.78%

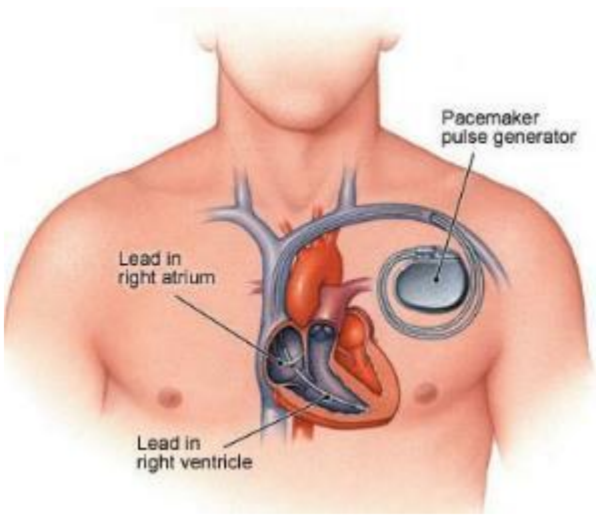
https://www.gsmaintelligence.com/data/

Electromagnetic Interference

EMI ISSUES IN MEDICAL DEVICES

Interference Technology – June 2015

ITEM™ interference technology
THE INTERNATIONAL JOURNAL OF ELECTROMAGNETIC COMPATIBILITY



"Pacemakers can mistakenly detect electromagnetic interference (EMI) from smartphones as a cardiac signal, causing them to briefly stop working. This leads to a pause in the cardiac rhythm of the pacing dependent patient and may result in syncope." Dr. Lennerz

"For implantable cardioverter defibrillators (ICDs) the external signal mimics a life threatening ventricular tachyarrhythmia, leading the ICD to deliver a painful shock" Dr. Lennerz

http://www.interferencetechnology.com

Electromagnetic Interference

EMI ISSUES IN AVIATION

Interference Technology – January 2013

FAA said Wi-Fi systems may interfere with the Honeywell phase 3 display units aboard 157 Boeing airplanes in use by various U.S. airlines. These display units are critical for flight safety, providing crewmembers with information such as airspeed, altitude, heading, and pitch and roll [..] the issue was discovered two years ago during testing to certify a Wi-Fi system for use on Boeing 737 Next Generation.

Electromagnetic Interference

EMI ISSUES IN AUTOMOTIVE

http://incompliancemag.com/2-12-million-vehicles-recalled-for-airbag-issues

In Compliance, 2015

IN COMPLIANCE

2.12 Million Vehicles Recalled For Airbag Issues

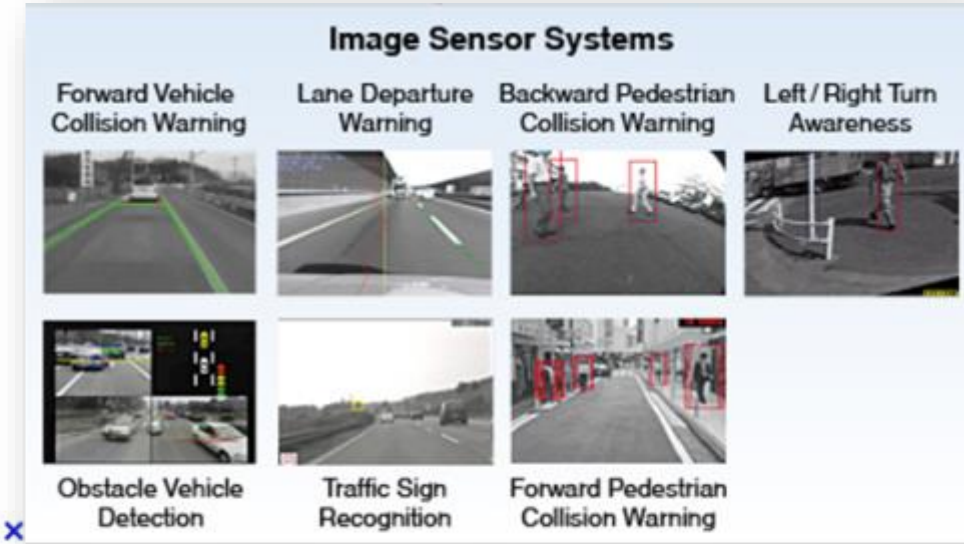
POSTED BY IN COMPLIANCE NEWS ON FEBRUARY 2, 2015 IN ENGINEERING NEWS, PRODUCT RECALLS | LEAVE A RESPONSE

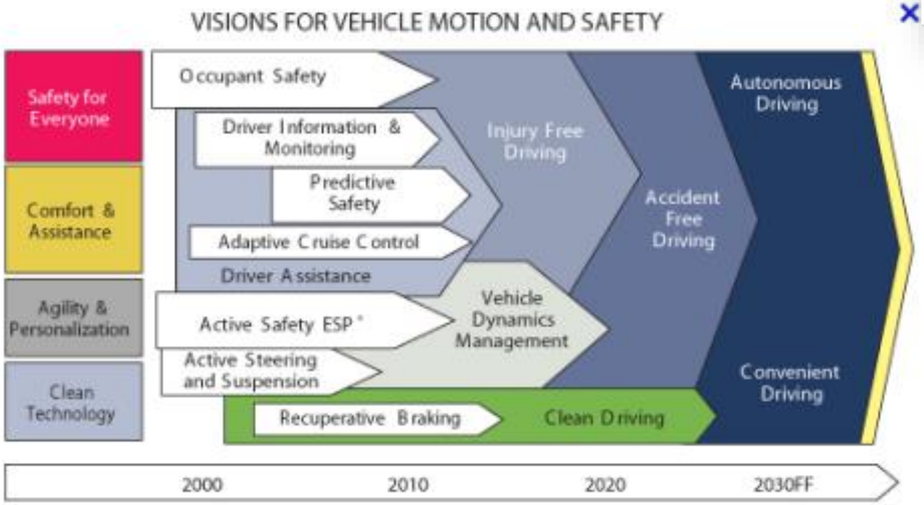
The National Highway Traffic Safety Administration (NHTSA) announced this weekend that Chrysler, Honda, and Toyota are recalling 2.12 million cars because a previous attempt to resolve an issue with faulty electrical components in airbags does not completely solve the problem. The new recalls include the following models from the early 2000s: Acura MDX, Dodge Viper, Jeep Grand Cherokee and Liberty, Honda Odyssey, Pontiac Vibe, Toyota Corolla, Toyota Matrix and Toyota Avalon.

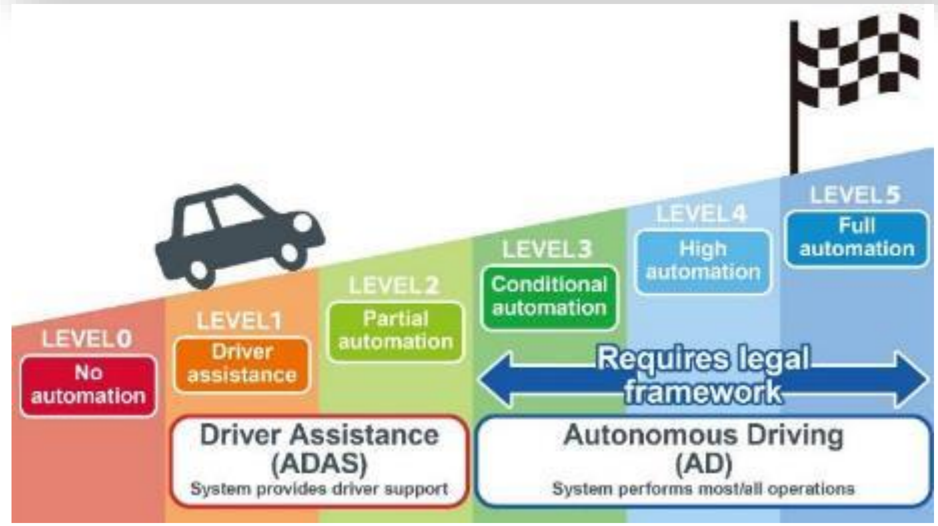
Electromagnetic Interference

EMI ISSUES IN AUTOMOTIVE

- ADAS - Advanced Driver Assistance Systems in 2020
- AD - Autonomous driving in 2030
- Much more sensors, cameras, embedded calculators & security





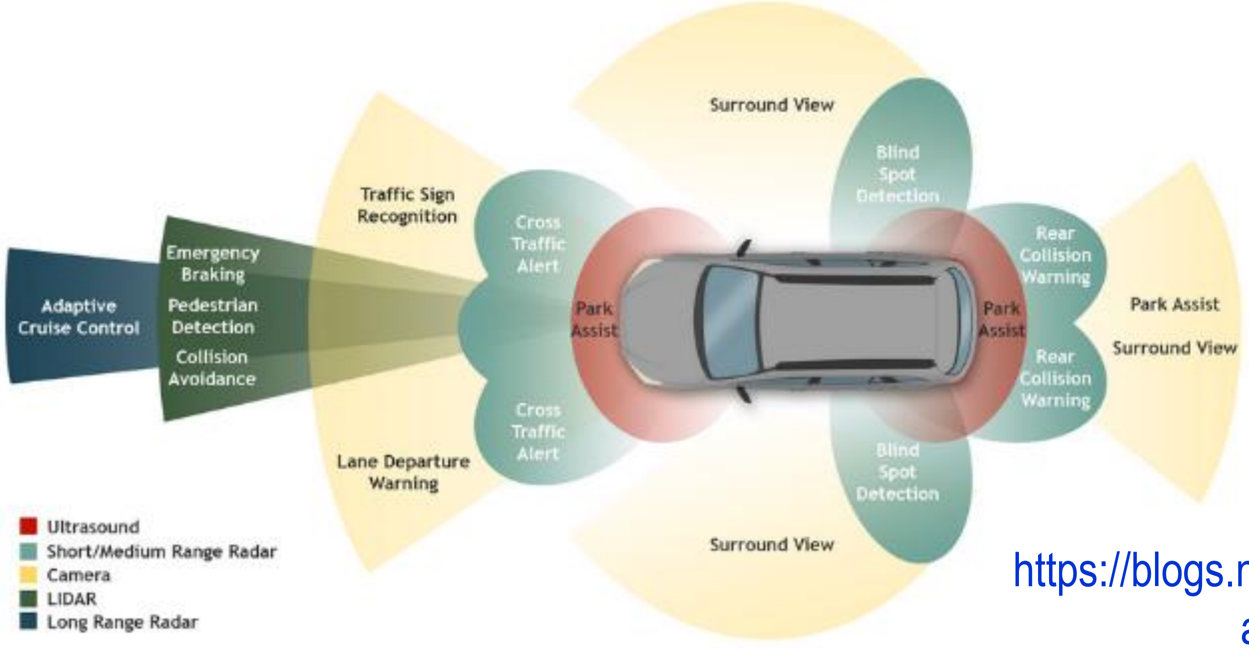


Electromagnetic Interference

EMI ISSUES IN AUTOMOTIVE

ADAS automobile : 100 million lines of software code, 100 microprocessor-based electronic control units (ECUs) networked throughout the body of the car.

ISP (image signal processor), VPU (video processing unit), PVA (programmable vision accelerator), DLA (deep learning accelerator), CUDA GPU, and CPU

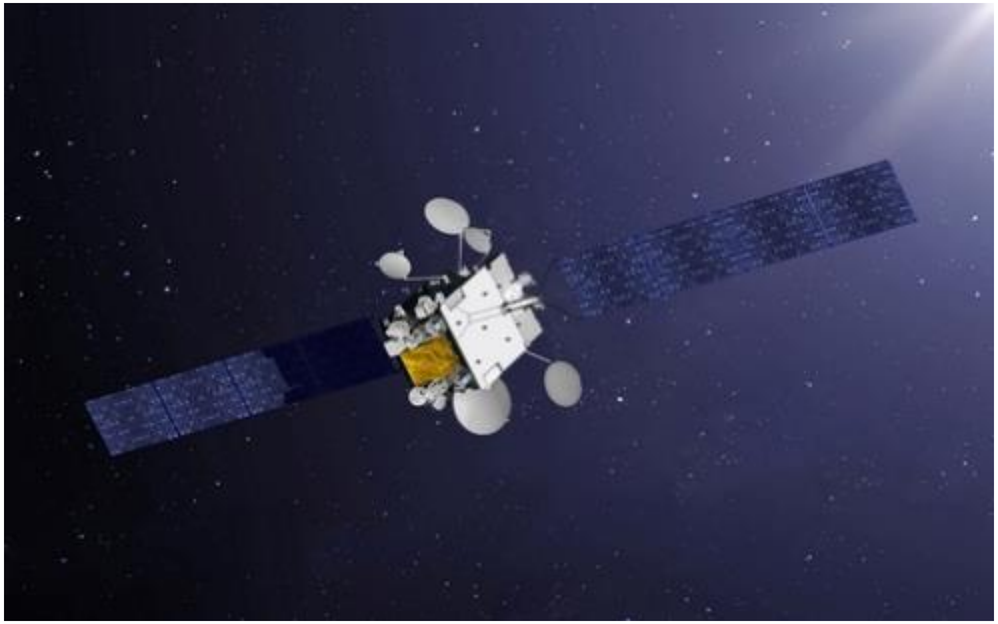


https://blogs.nvidia.com/blog/2018/05/23/xavier-architected-for-safety/

Electromagnetic Interference

Lancement réussi pour Syracuse 4A, un satellite militaire de dernière génération

- **25/10/2021 - “Maîtriser l’espace est essentiel pour la souveraineté de notre défense et la sécurité nationale. Encore faut-il savoir se défendre, à des milliers de kilomètres au-dessus de nos têtes. Aussi, le satellite est muni de dispositifs de surveillance pour détecter l’approche de débris ou de satellites « butineurs », qui viendraient se placer dans le rayon d’émission pour tenter de capter les communications. Surtout, Syracuse 4A est doté d’une meilleure résistance au brouillage, à l’interception et aux attaques cyber. »**



https://www.defense.gouv.fr/portail/actualites2/lancement-reussi-pour-syracuse-4a-un-satellite-militaire-de-derniere-generation

Electromagnetic Interference

- **EMC JAMMING**

“criminals, rogue employees and even otherwise law-abiding citizens are using illegal “jamming” devices to overpower GPS, cellphone and other electronic signals in localized areas.”

https://interferencetechnology.com/gps-interference-attack/

What is EMC ?

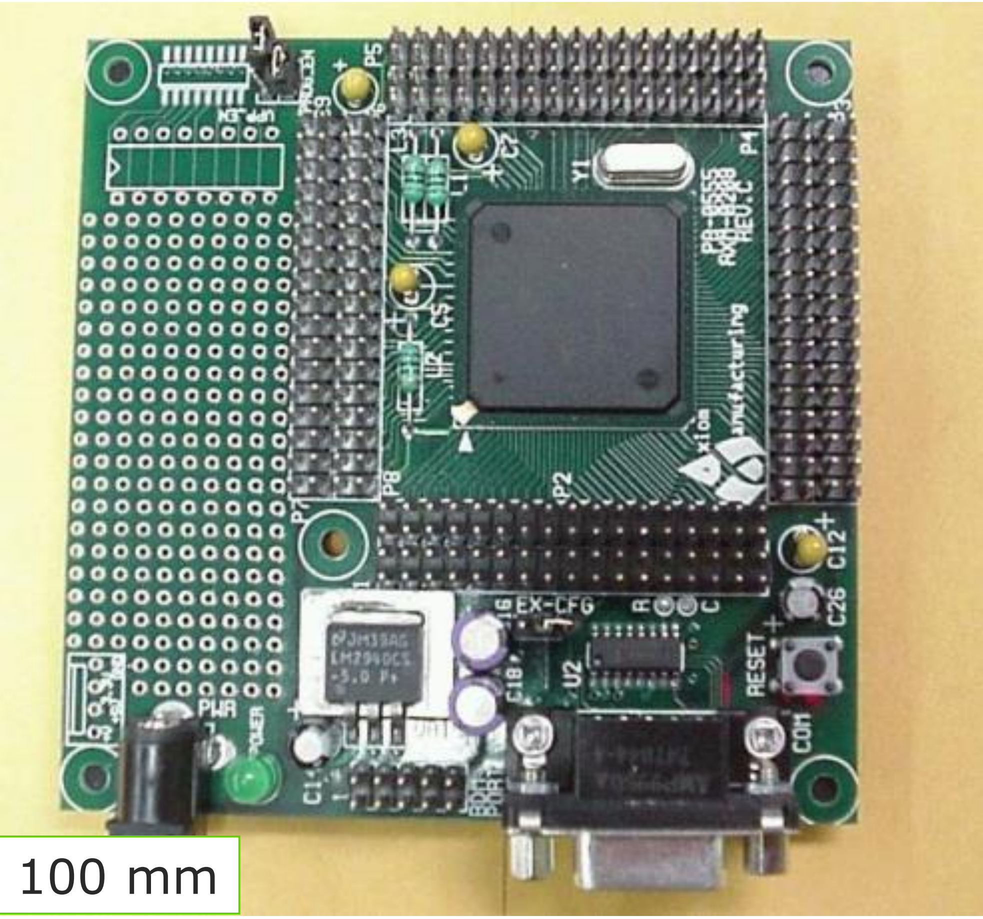
DEFINITION

« The ability of a component, equipment or system to operate satisfyingly in a given electromagnetic environment, without introducing any harmful electromagnetic disturbances to all systems placed in this environment. »

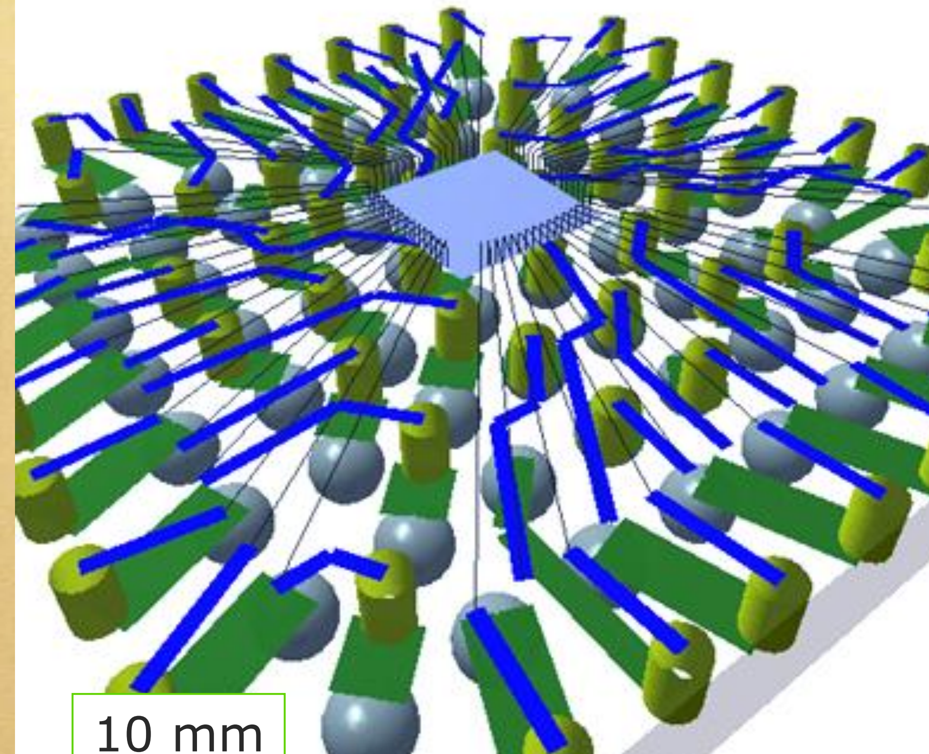
- ✓ Essential constraint to ensure functional safety of electronic or electrical applications
- ✓ Guarantee the simultaneous operation of every electrical or electronic equipment in a given electromagnetic environment
- ✓ Reduce both the parasitic electromagnetic emission and the sensitivity or susceptibility to electromagnetic interferences.

What is EMC?

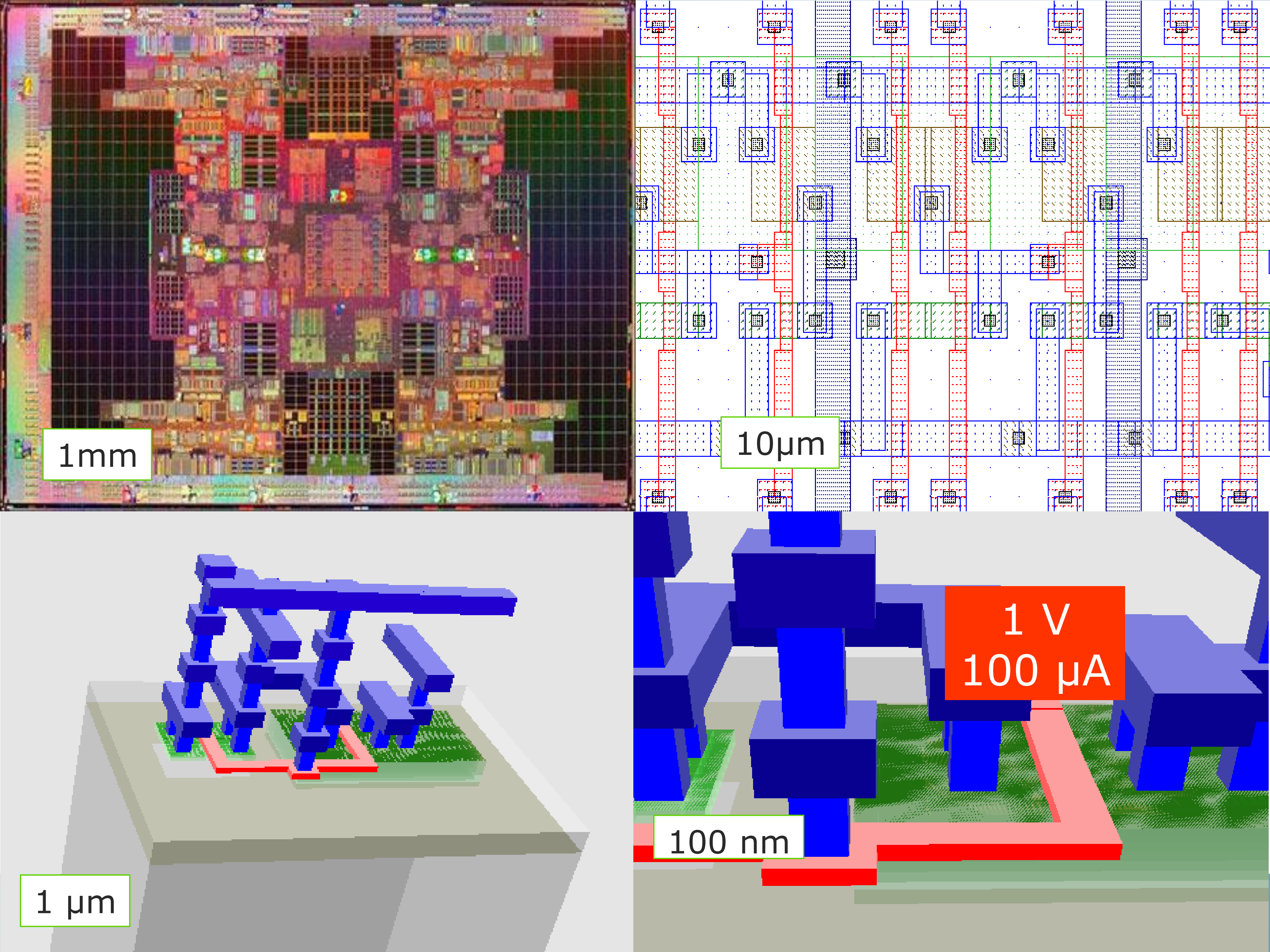
ZOOM AT DEVICES



100 mm



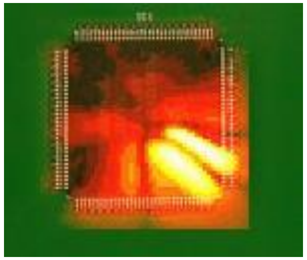
10 mm

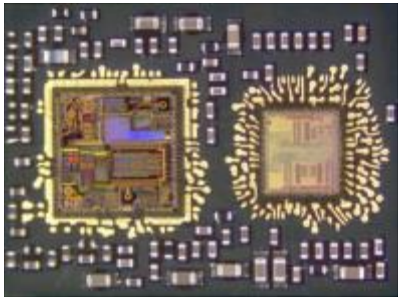

1mm
10μm
1 μm
1 V
100 μA
100 nm

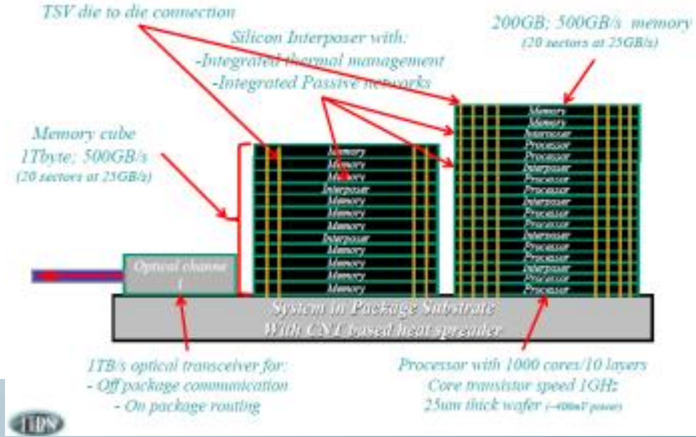
What is EMC?

WHY EMC OF IC ?

- Until mid 90’s, IC designers had no consideration about EMC problems in their design..
- Starting 1996, automotive customers started to select ICs on EMC criteria
- Starting 2005, mobile industry required EMC in System in package
- Massive 3D integration will require careful EMC design



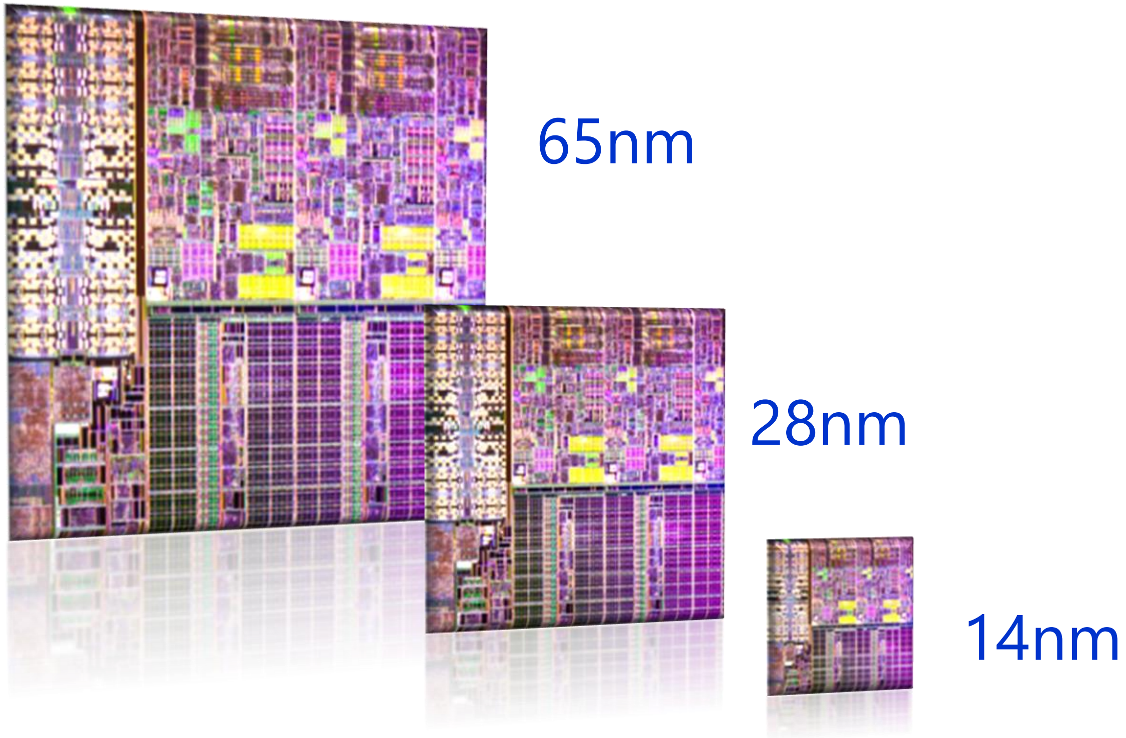


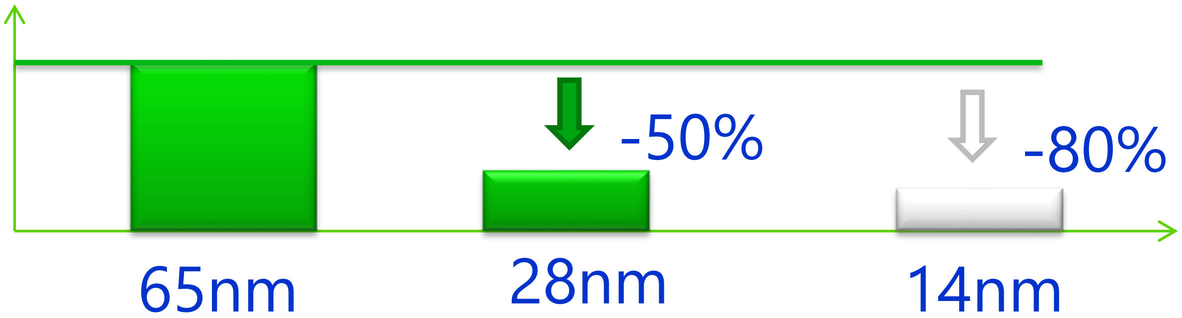


Technology scale down

Scale down benefits

- ..
- ...
- ...



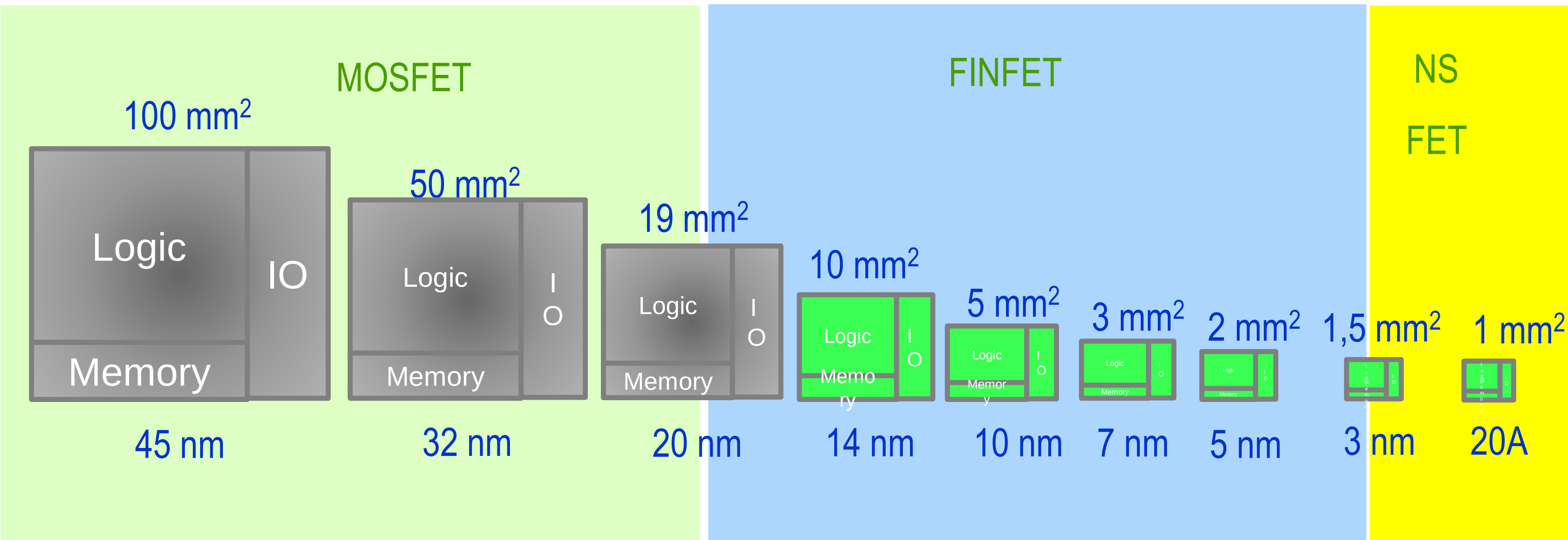


What is EMC?

Embedded blocks				
	Core+ DSP 1 Mb Mem	Dual core Dual DSP RF Graphic Process. 100 Mb Mem Sensors	Octa Core Octa DSP 3D Image Proc Crypto processor IA, 0.4-26 GHz Gb Memories Multi-sensors	

Technology scale down

- **Drastic reduction of the silicon area**

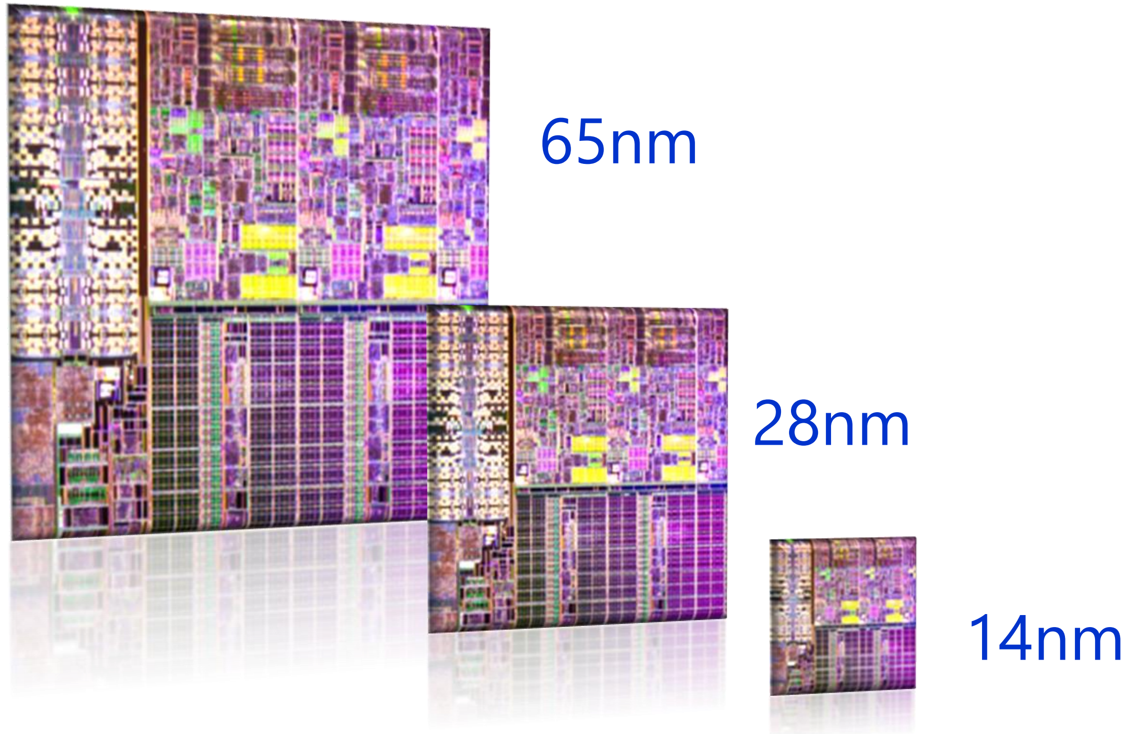


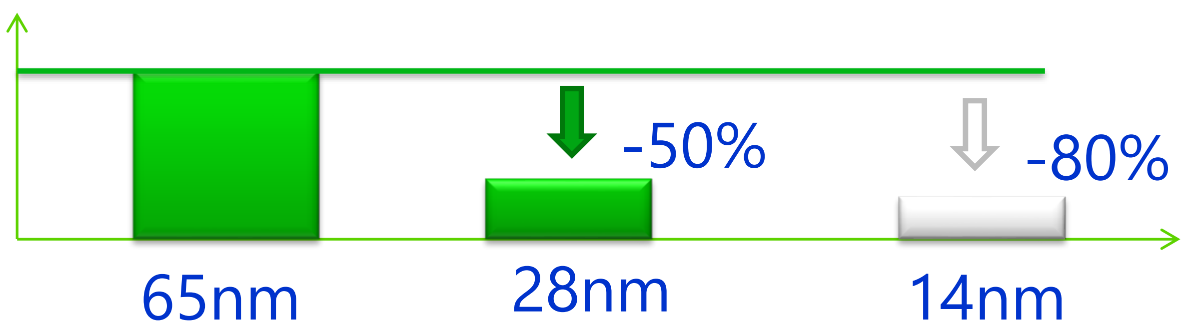
Adapted from Mistry, K. (2017). 10 nm technology leadership, Technology and Manufacturing Day, Intel. 2017.

Technology scale down

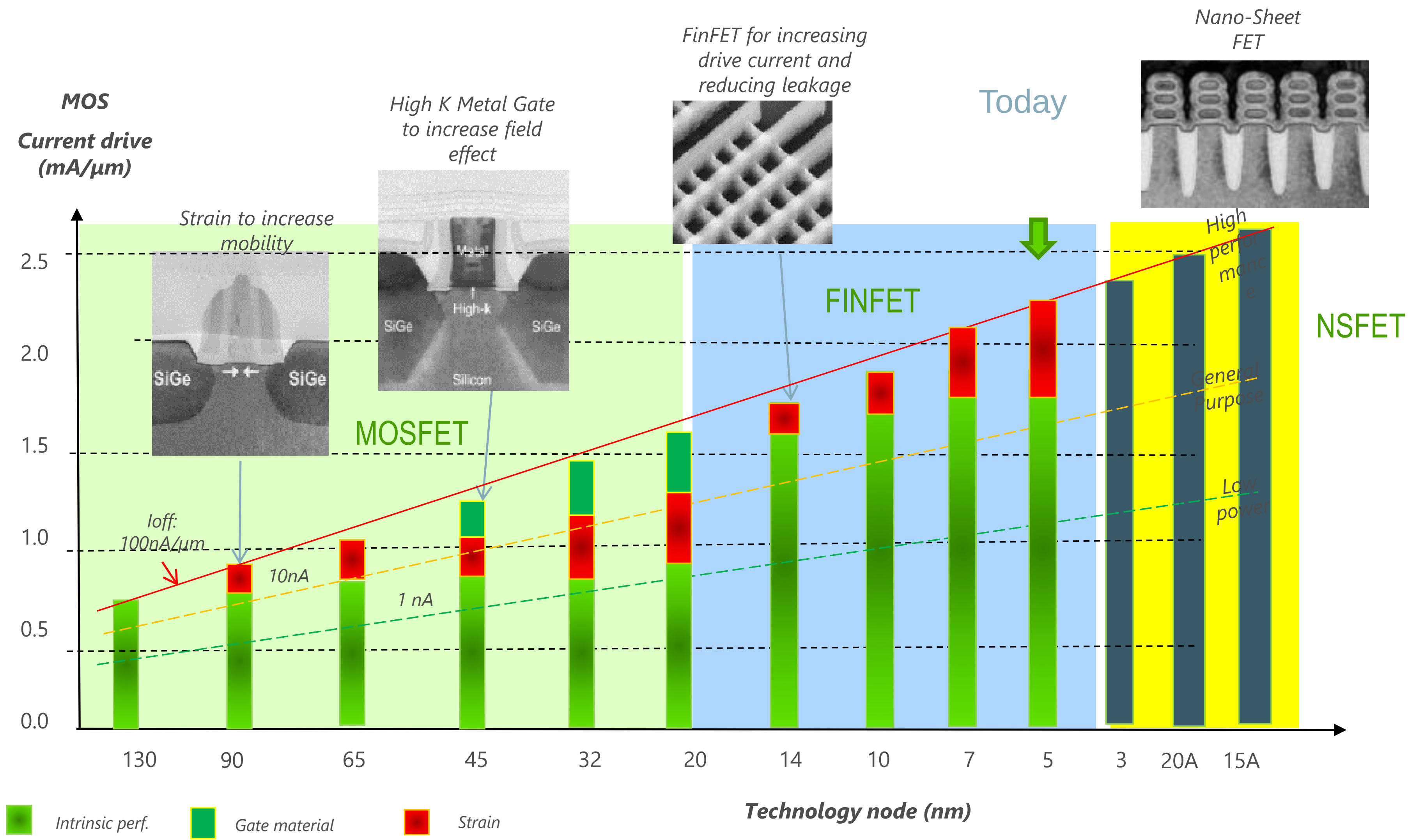
Scale down benefits

- ..
- …
- …

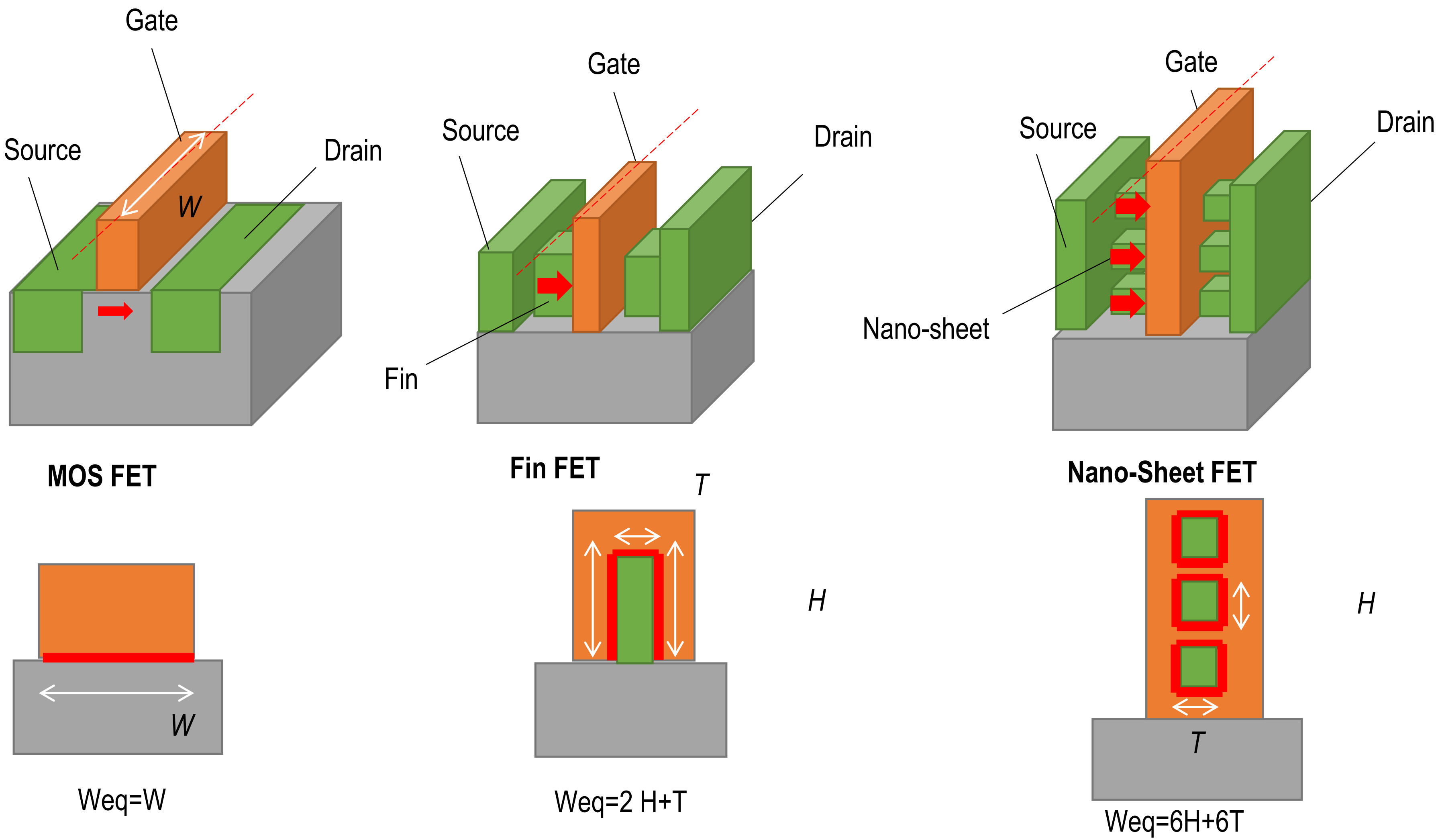




Technology scale down



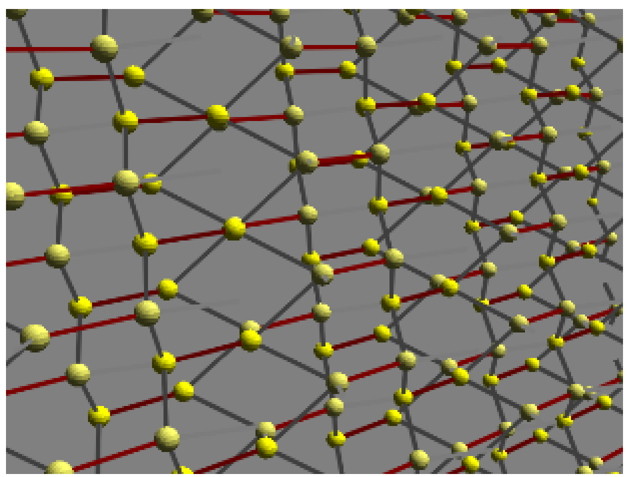
Technology scale down



Technology scale down

TSMC 3-nm A16 Apple processor

Samsung 3-nm Qualcomm Snapdragon 898



Si lattice: ___ nm

Technology scale down

TSMC to build a $12 billion advanced semiconductor plant in Arizona with US government support

Catherine Shu @catherineshu / 5:22 AM GMT+2 • May 15, 2020

2020

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Home > Samsung Foundry

Samsung Foundry: New $17 Billion Fab in th by Late 2023

by Anton Shilov on February 10, 2021 11:00 AM EST

Posted in Samsung Foundry | Samsung | process technology | 3nm

2021

TECH

Intel is spending $20 billion to build two new chip plants in Arizona

PUBLISHED TUE, MAR 23 2021 4:59 PM EDT | UPDATED WED, MAR 24 2021 7:38 AM EDT

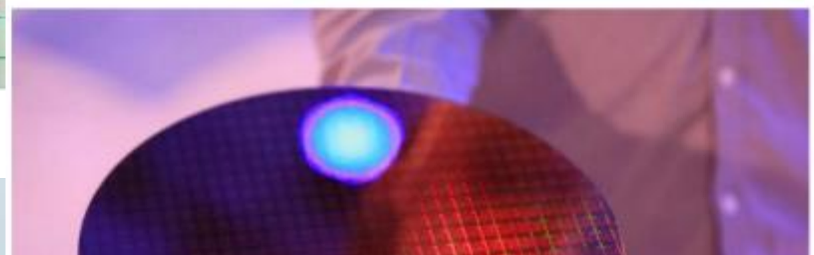
Kif Leswing @KIFLESWING

SHARE

2021

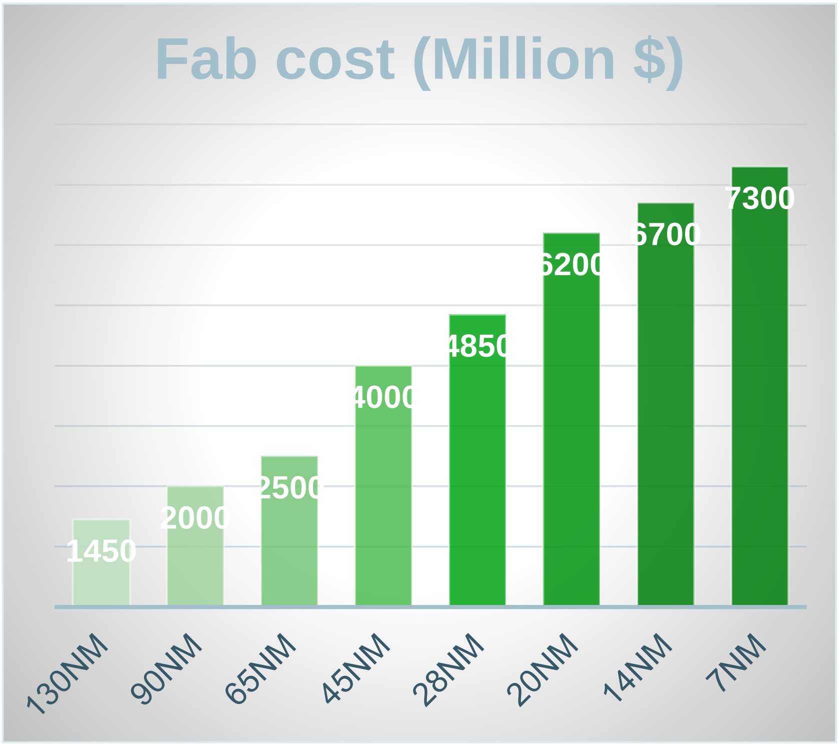
KEY POINTS

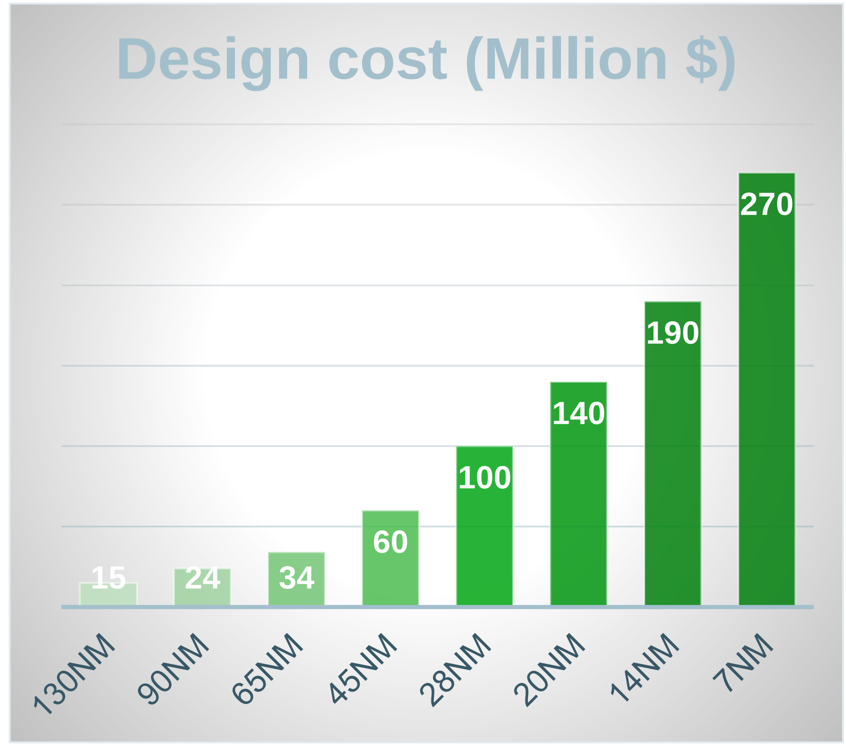
- Intel announced on Tuesday that it will spend $20 billion to build two major factories in Arizona.
- The news comes amid a worldwide chip shortage that is snarling industries from automobiles to electronics and worries the U.S. is falling behind in semiconductor manufacturing.
- The announcement signals that Intel will continue to focus on manufacturing.



Technology scale down

TECHNOLOGY INNOVATION & COST

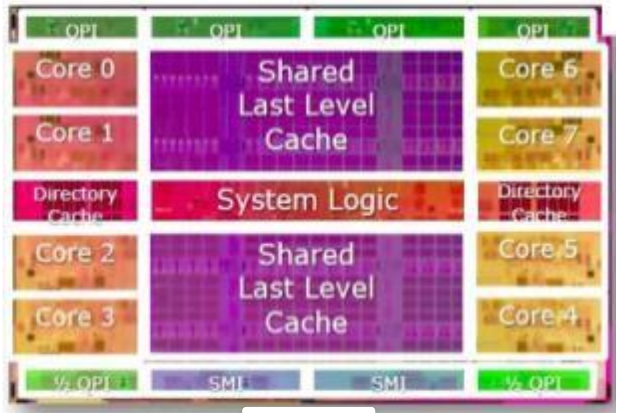




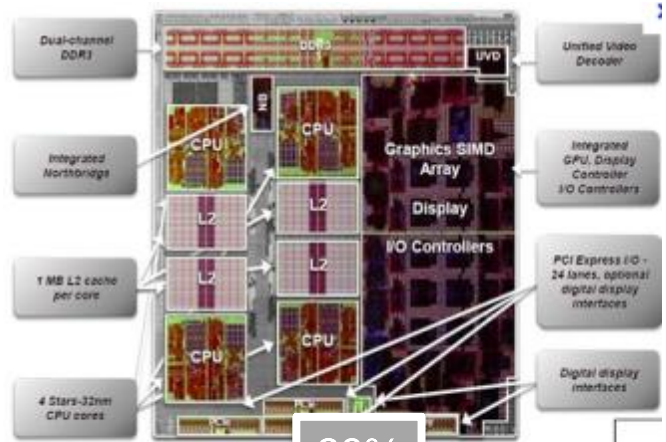
- Strain, eSiGe,
- High-K, low-K dielectric, Airgap
- Metal gate
- FinFET/ Gate-All-Around FET
- Double, quad patterning

Technology scale down

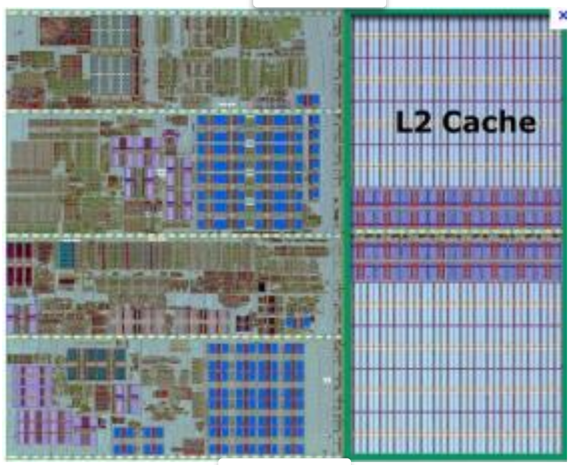
IMPORTANCE OF MEMORY



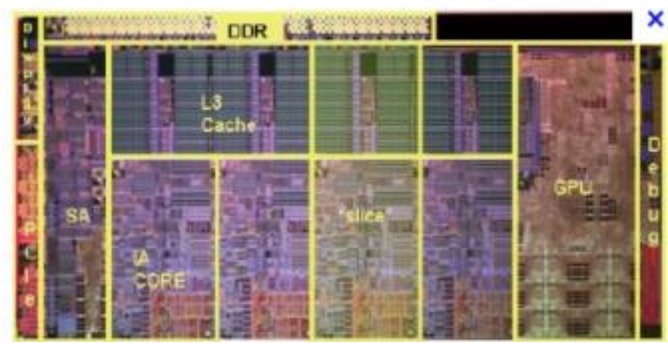
50%



20%



55%

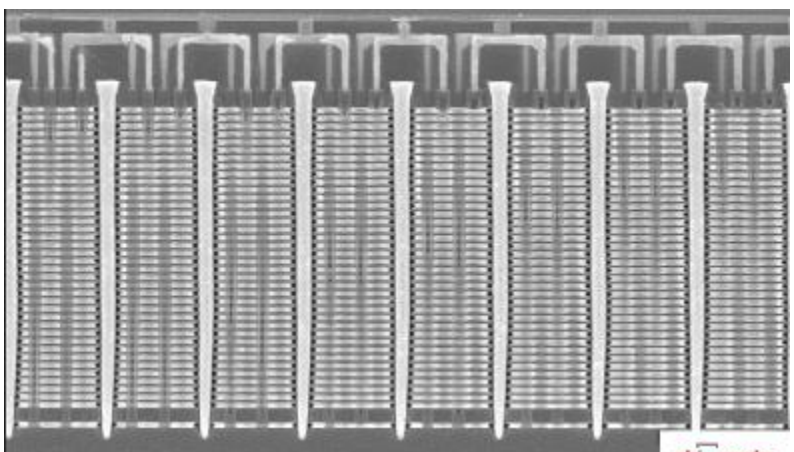


35%

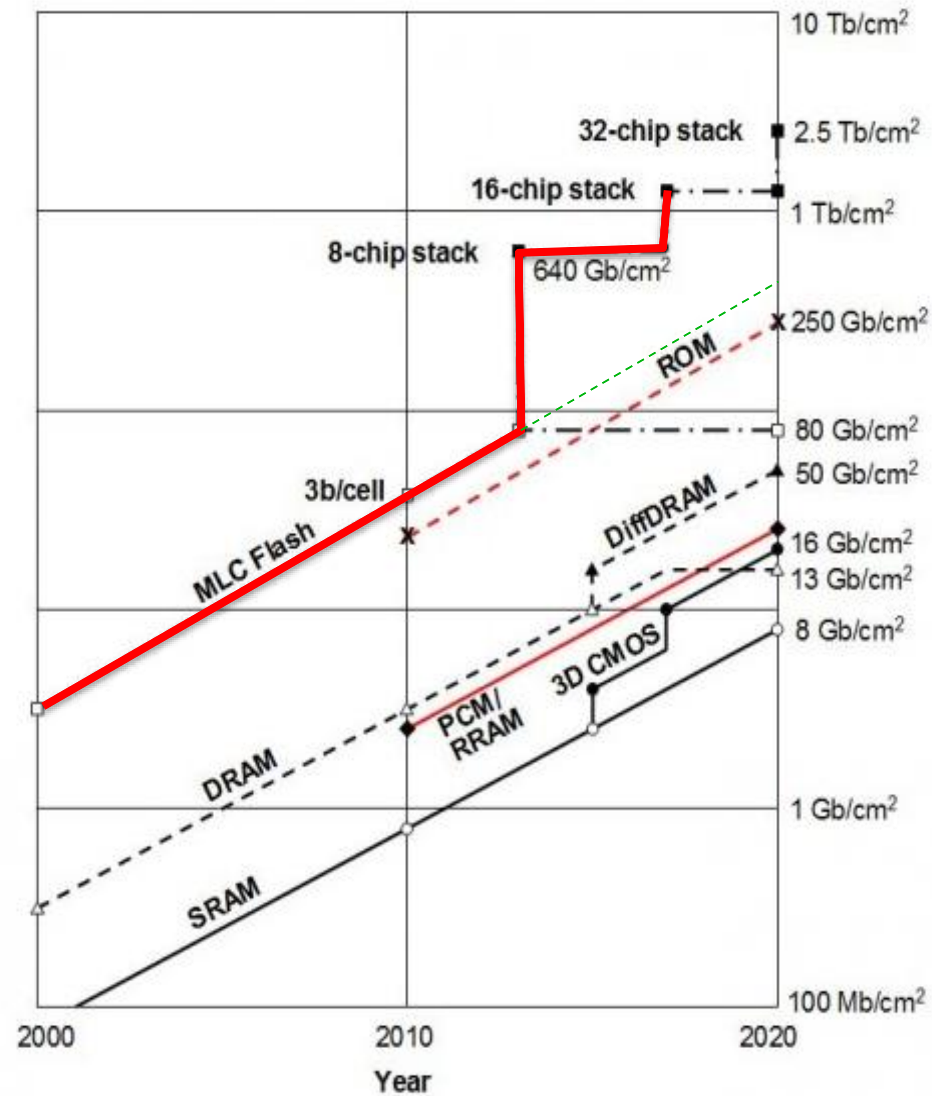
Going 3D

Stacked process layers

- 8, 16, 32 layers of active devices
- 1 tera-bit/cm2 achieved 5 years ahead from roadmaps

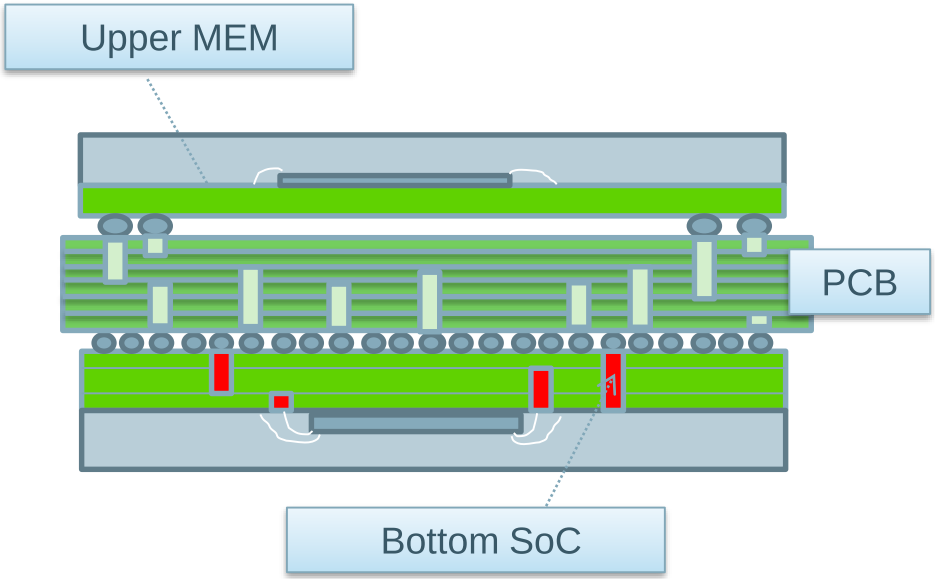


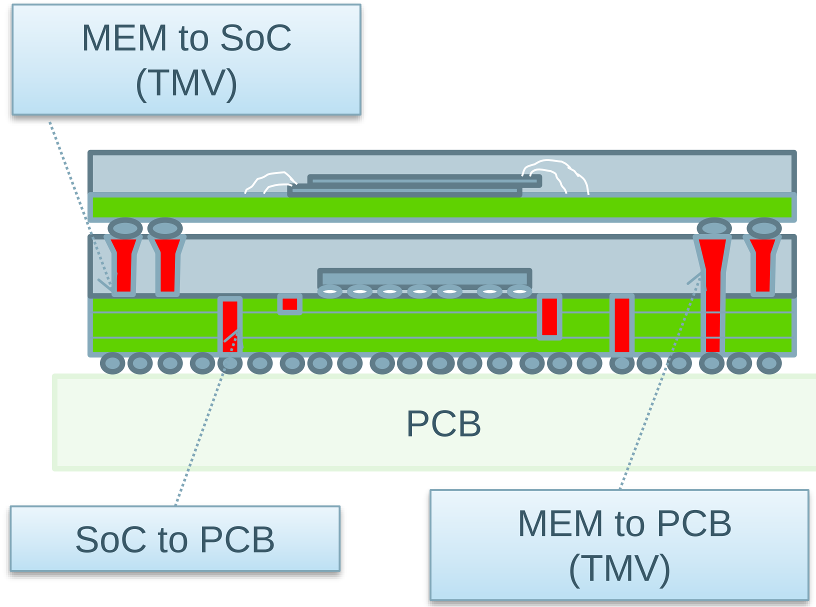
Close-up image of V-NAND flash array

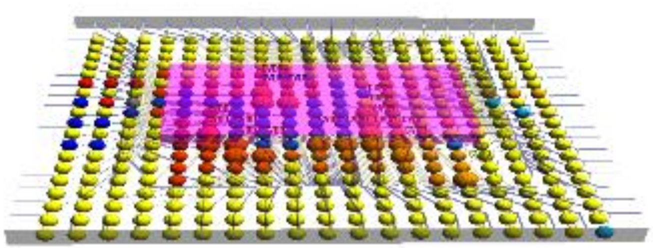


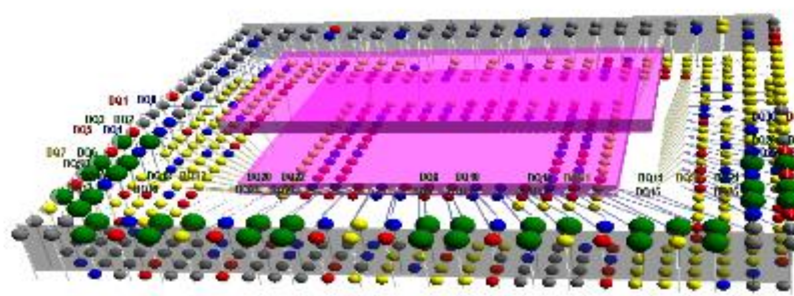
Processor to memory

Package-on-package (PoP)





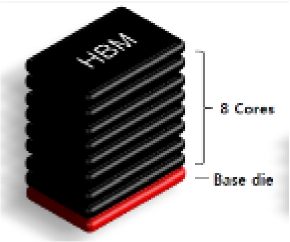




E. Sicard, EMC performance analysis of a Processor/Memory System using PCB and Package-On-Package, EMC Compo 2015 Edinburgh

Processor to memory

- Increased memory/ processor bandwidth
  - ➔ High performance computing & AI
  - ➔ Mobiles & high resolution games
  - ➔ Servers & Security



High Performance Computing & Networking

High Bandwidth Memory

Mobile

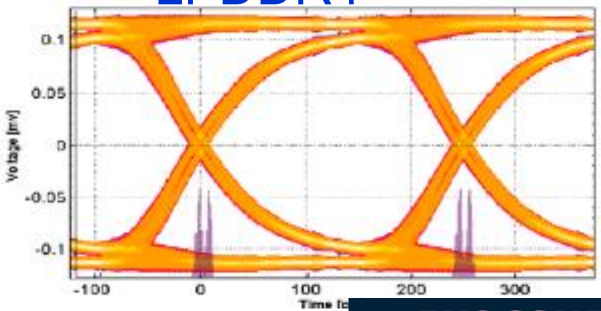
Low Power DDR5

Graphics

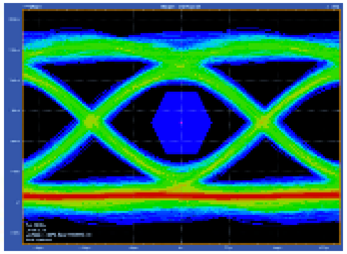
Graphics DDR6

Processor to memory

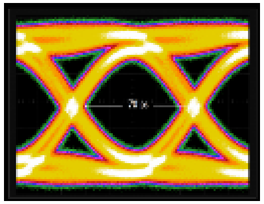
LPDDR4



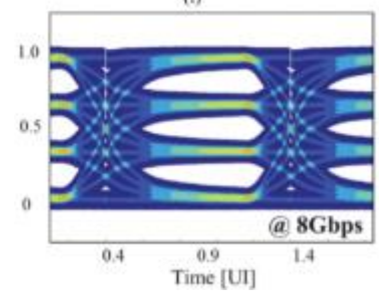
LPDDR5



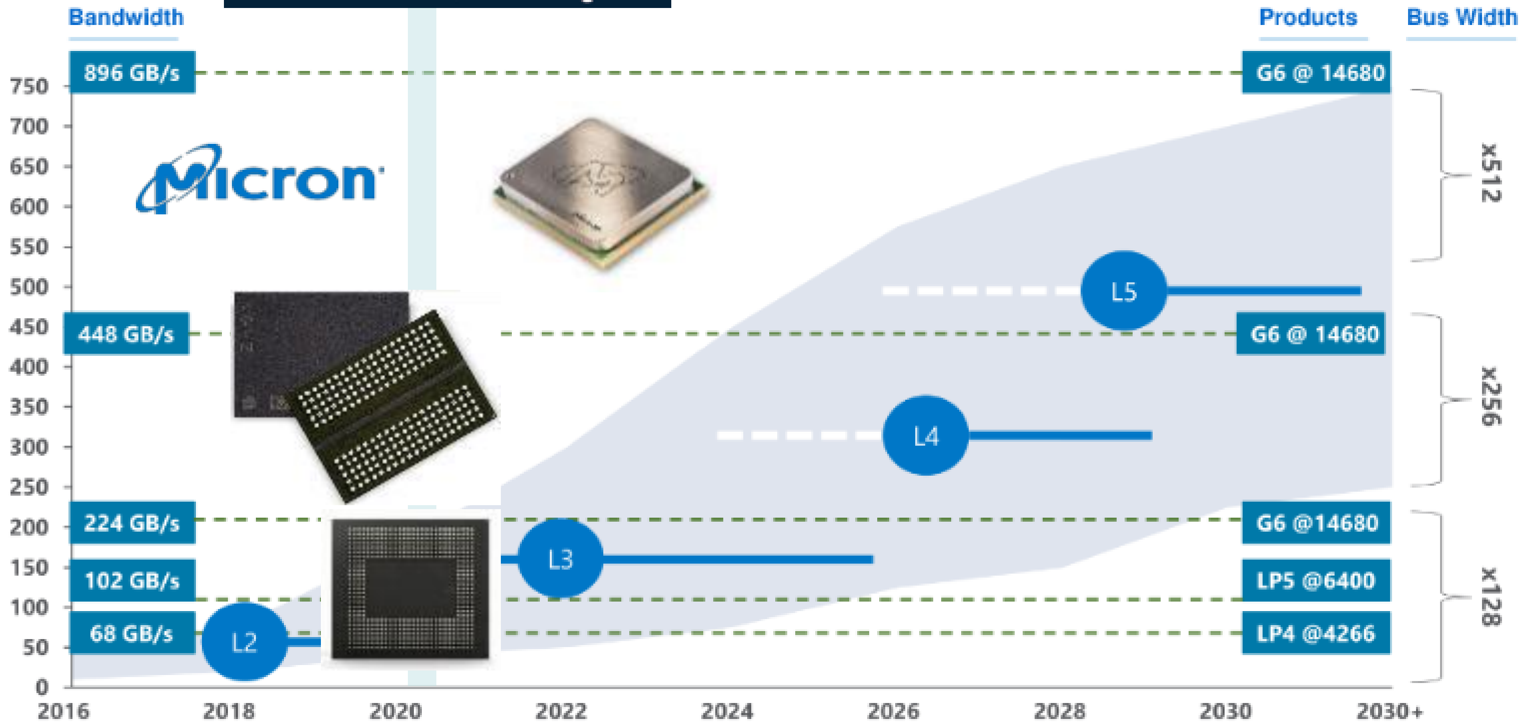
GDDR6



HMC



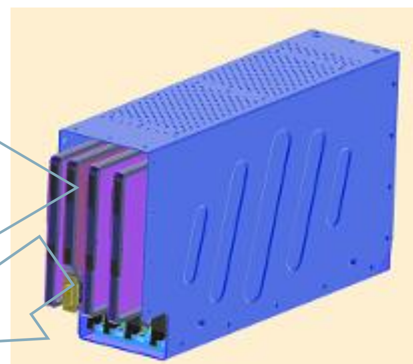
EMC COMPO 2019
Oct 21-23, Haining

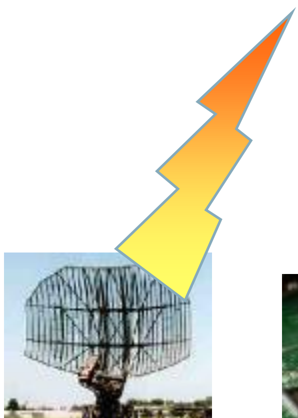


EMC at IC Level

- **SUSCEPTIBILITY**

Equipment





Boards

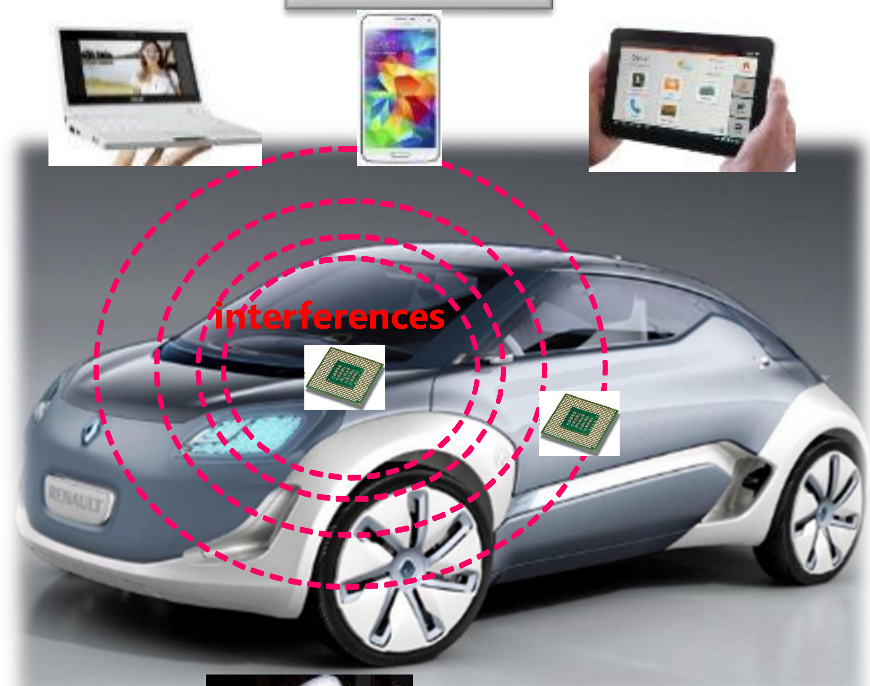
Radar

Components

Hardware fault
Software failure
Function Loss

- **EMISSION**

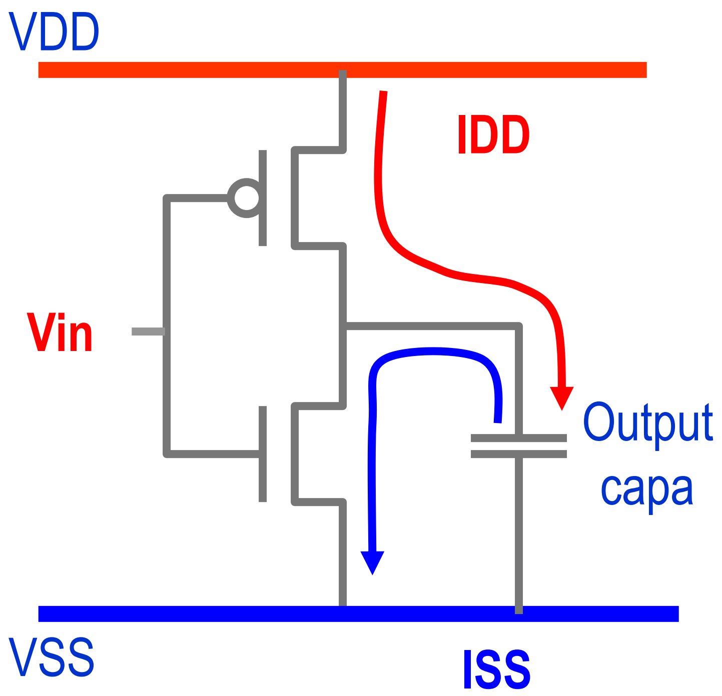
Personal Devices



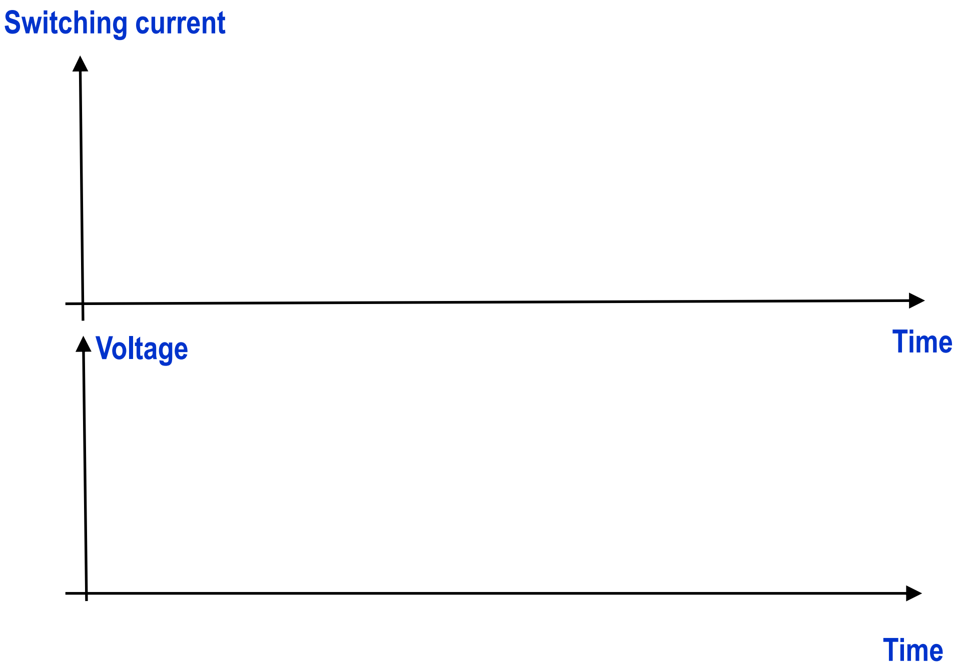
Safety systems

Origin of Parasitic Emission

BASIC MECHANISMS FOR CURRENT SWITCHING



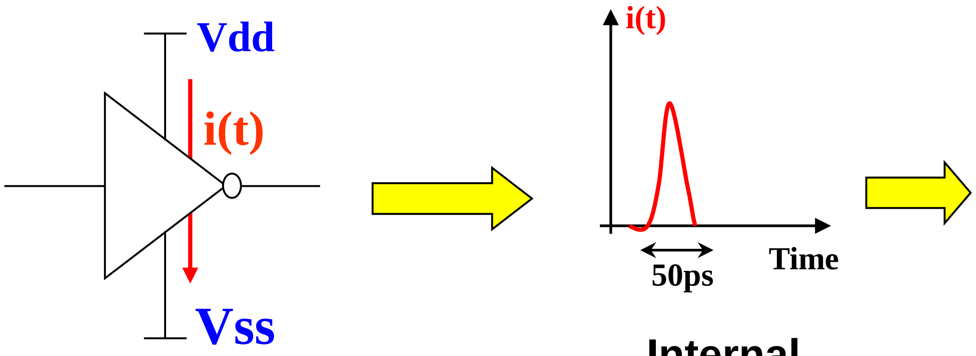
CMOS inverter exemple



Question: waveform, amplitude?

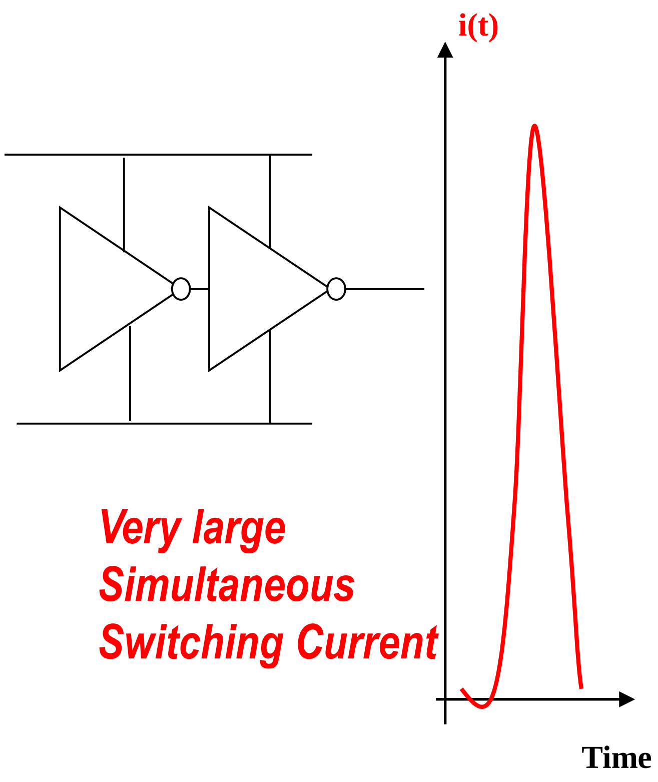
Origin of Parasitic Emission

STRONGER SWITCHING CURRENT:



Switching gates

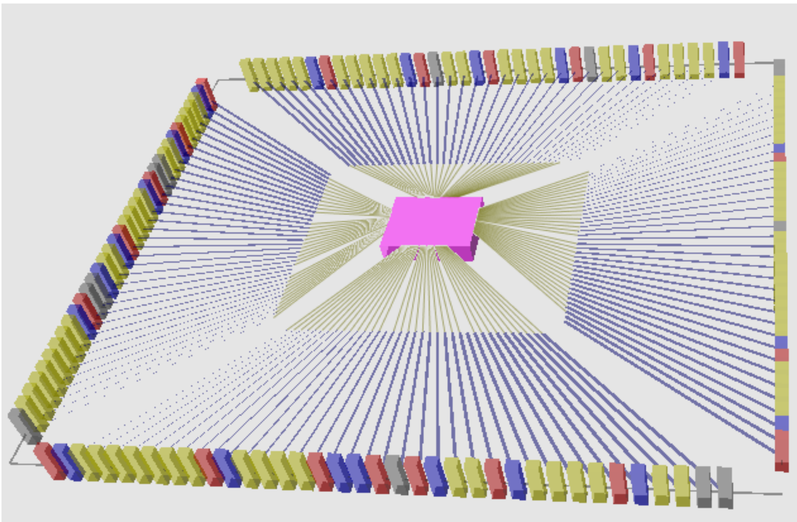
Internal switching current

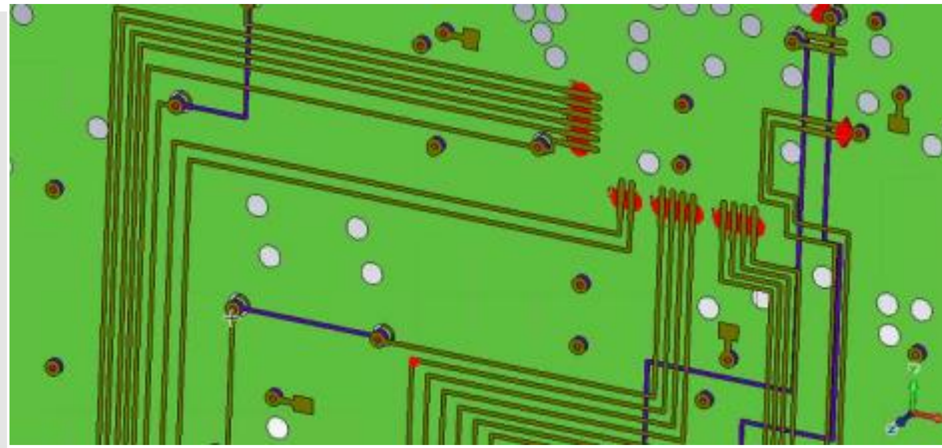


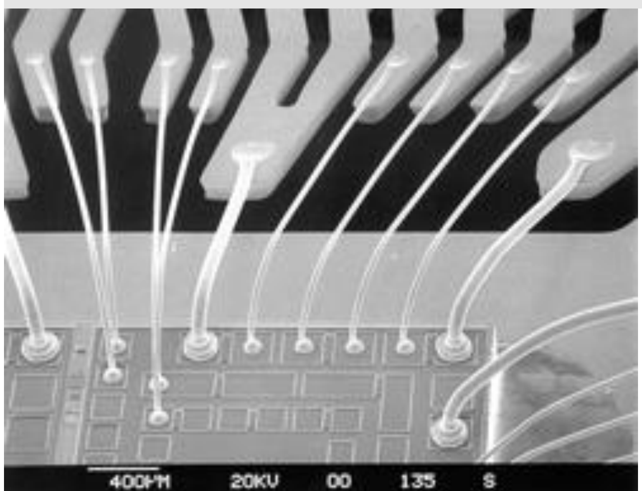
- ✓ Low power processor: 1A @ 100 MHz
- ✓ Medium power processor : 10 A @ 500 MHz
- ✓ High performance processor : 100 A @ 1 GHz

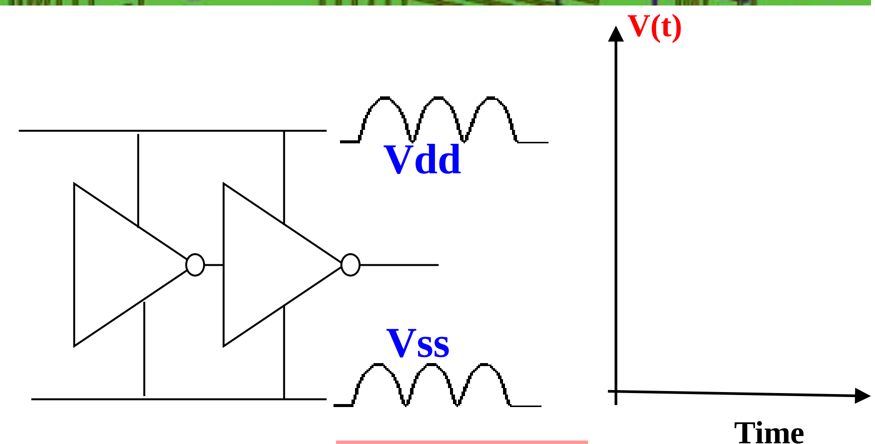
Origin of Parasitic Emission

Wires act as antennas









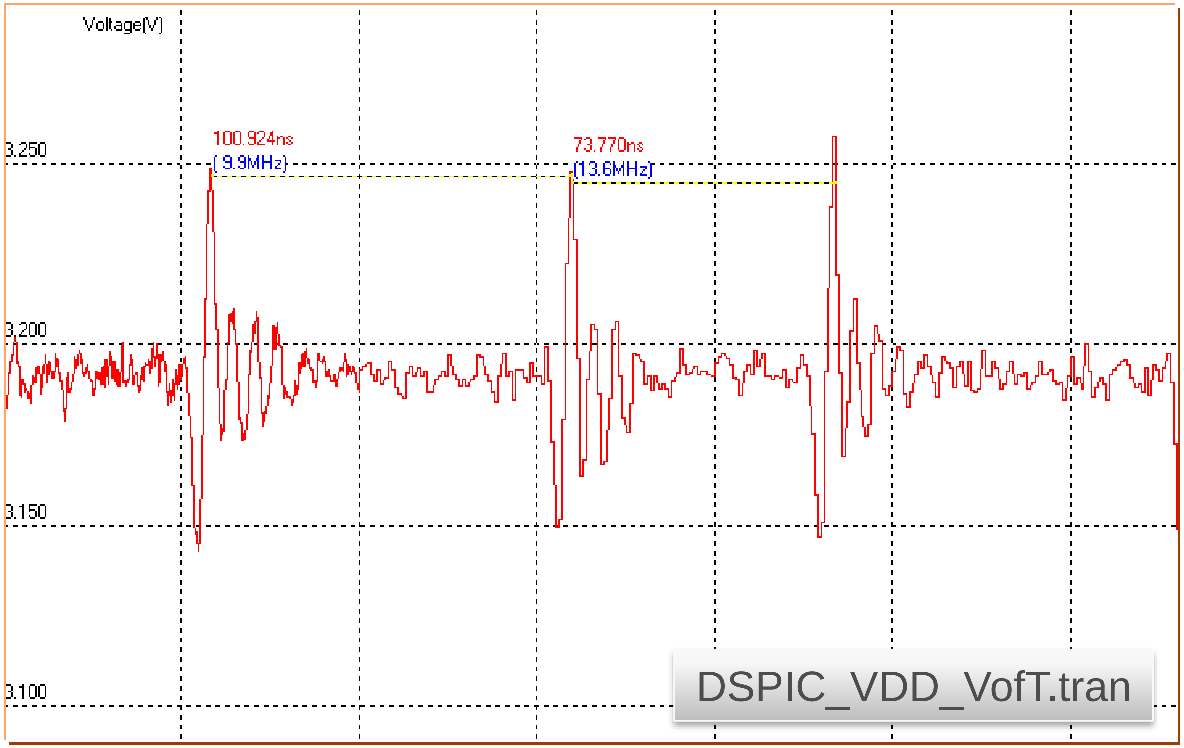
$$L = \_\, nH / mm$$

$$\Delta V = \_\, -$$

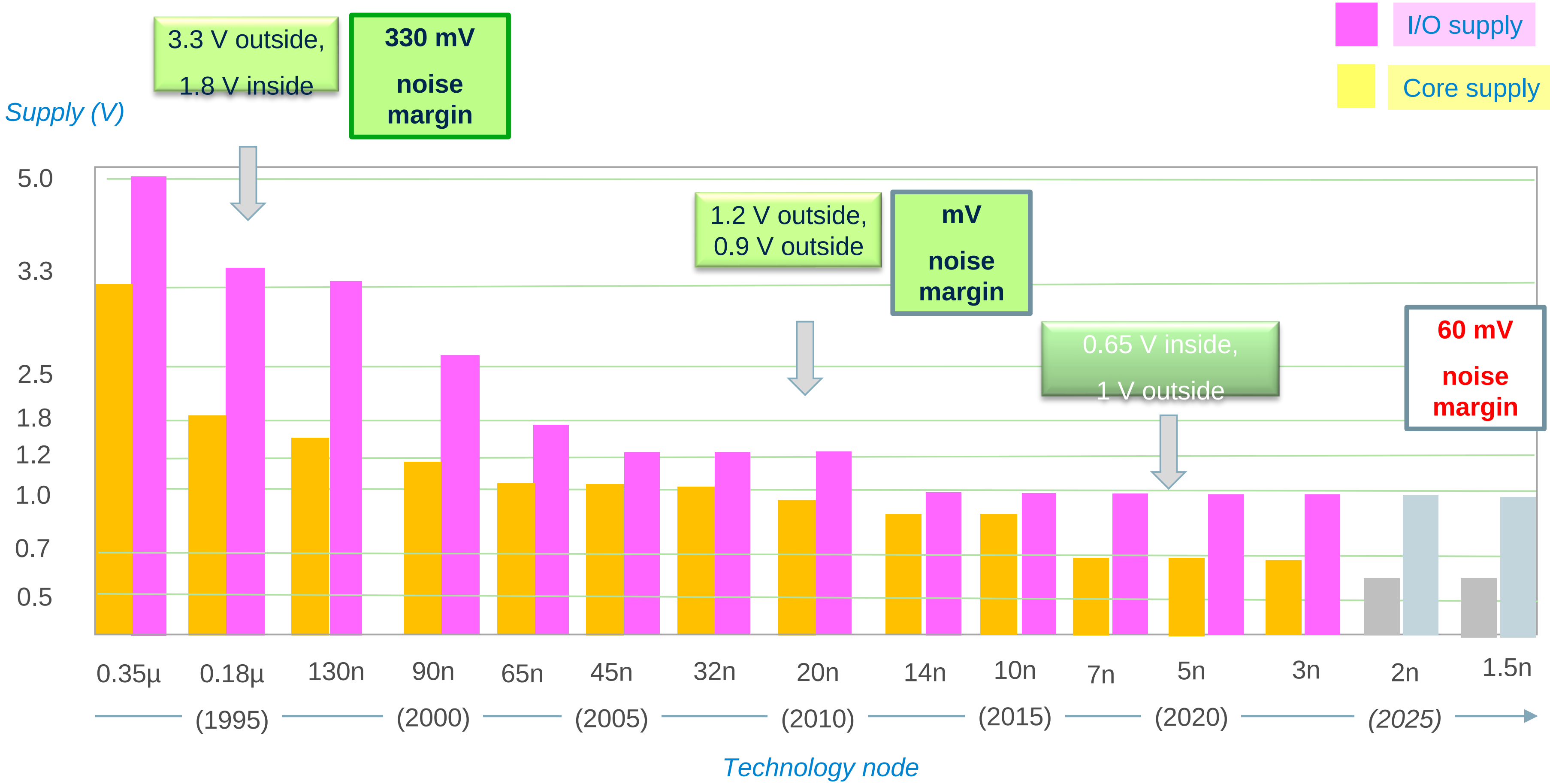
Origin of Parasitic Emission

WIRES+CURRENT = NOISE

- DSPIC33F noise measurement with active probe on X10
- Activation of the core by a 40 MHz internal PLL
- Synchronous ADDR0..15 bus switching 0x0000, 0xFFFF

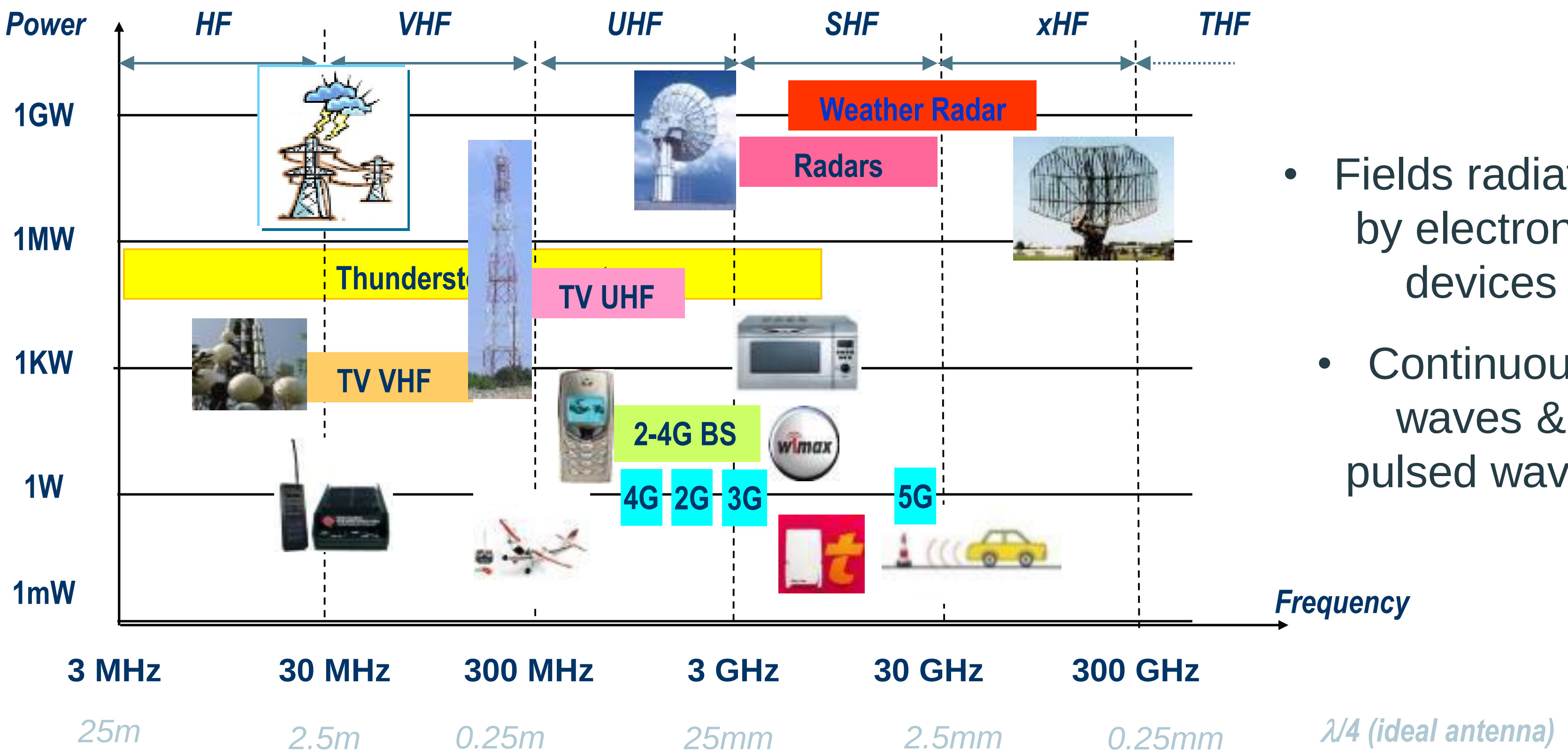


Susceptibility Issues



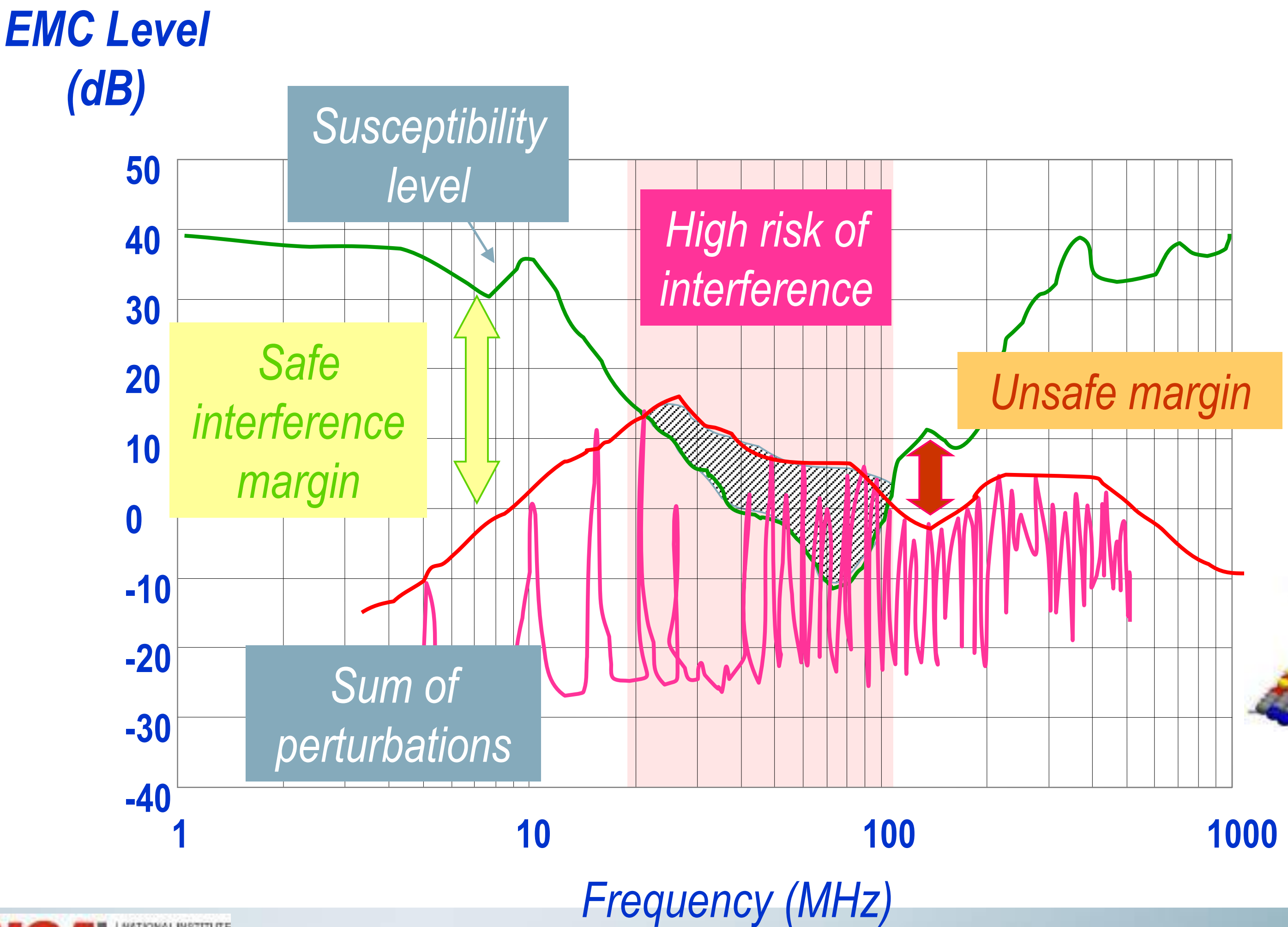
Susceptibility Issues

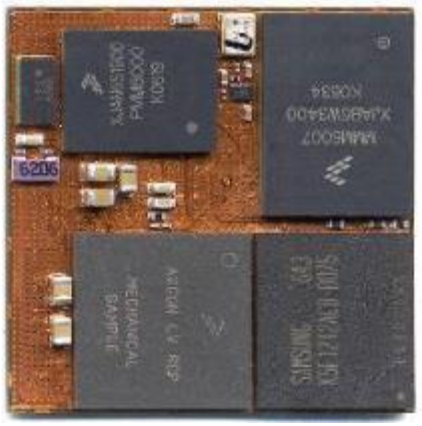
UNINTENTIONAL ELECTROMAGNETIC SOURCES

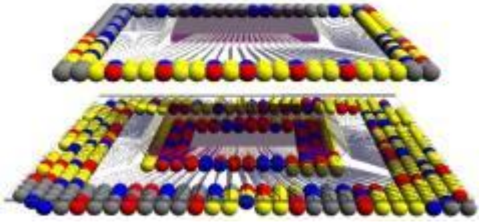


- Fields radiated by electronic devices
- Continuous waves & pulsed waves

SYSTEM-ON-CHIP, 3D STACKING: DANGER







Susceptibility Issues

Large cells

Low data rate

Medium cells

Medium Data rate

5G 700

4G 800

2-3G 900

2-4G 1 800

3G 1 900

4G 2 600

1 GHz

2 GHz

3 GHz

5G 3 400

5G 26 000

6G 116 000

6G 174 000

6G 244 000

Small cells

High data rate

Conclusion

- EMI reported in all kinds of devices
- IC involved in many EMI problems
- IC technology evolution towards higher complexity
- On-chip switching currents in the 10-100 A range
- ICs are good antennas in the GHz range
- Increased switching noise
- Increased emission issues
- Reduced noise margins
- System-on-chips, systems-in-package rise new EMC issues

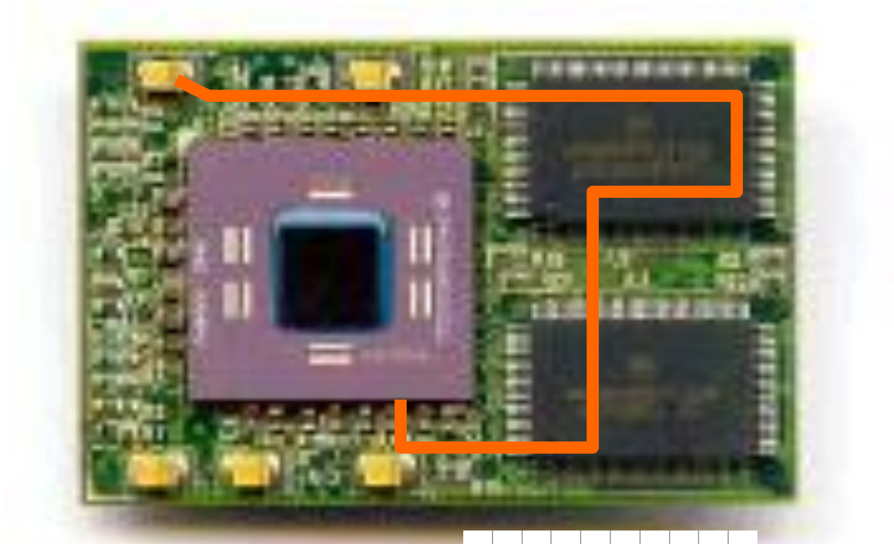
2. EMC Basics concepts

Summary

Basic principles

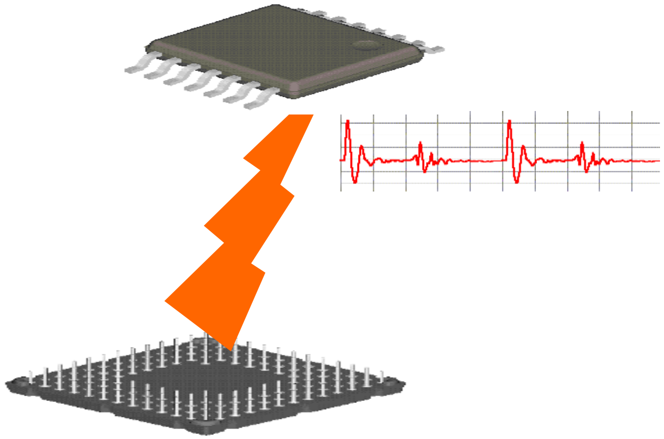
CONDUCTED AND RADIATED EMI

Conducted mode



The VDD supply propagates parasits

Radiated mode



The EM wave propagates through the air

Power Integrity (PI)

Electromagnetic Interference (EMI)

Specific Units

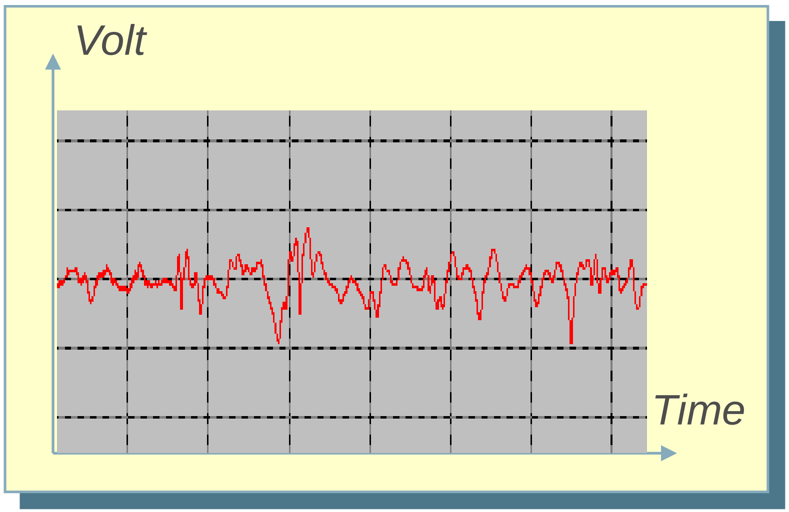
THE "EMC" WAY OF THINKING

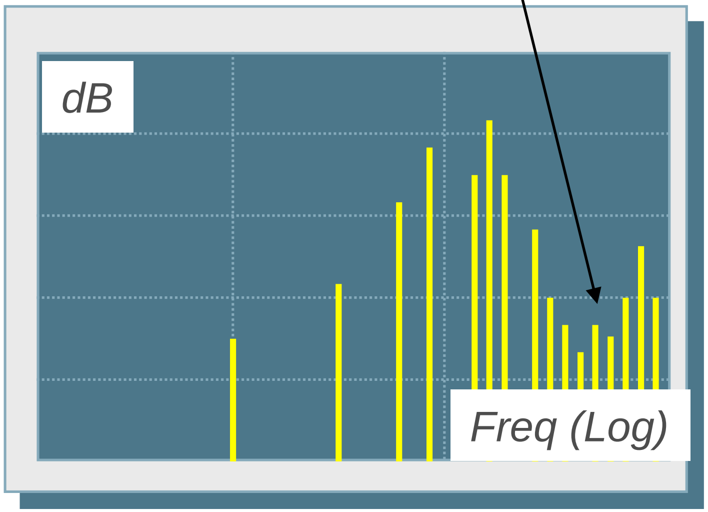
Electrical domain	*Electromagnetic domain*
Voltage V (Volt)	
Current I (Amp)	
Impedance Z (Ohm)	
Z=V/I	
$P=I^2 \times R$ (watts)	

Specific units

AMPLITUDE IN DB VS. FREQUENCY IN LOG

Distinguish contributions of small harmonics





Cover very large bandwidth

Time domain measurement

Fourier transform

Frequency measurement

Oscilloscope

Spectrum analyser

Specific units

EMISSION AND SUSCEPTIBILITY LEVEL UNITS

Voltage Units

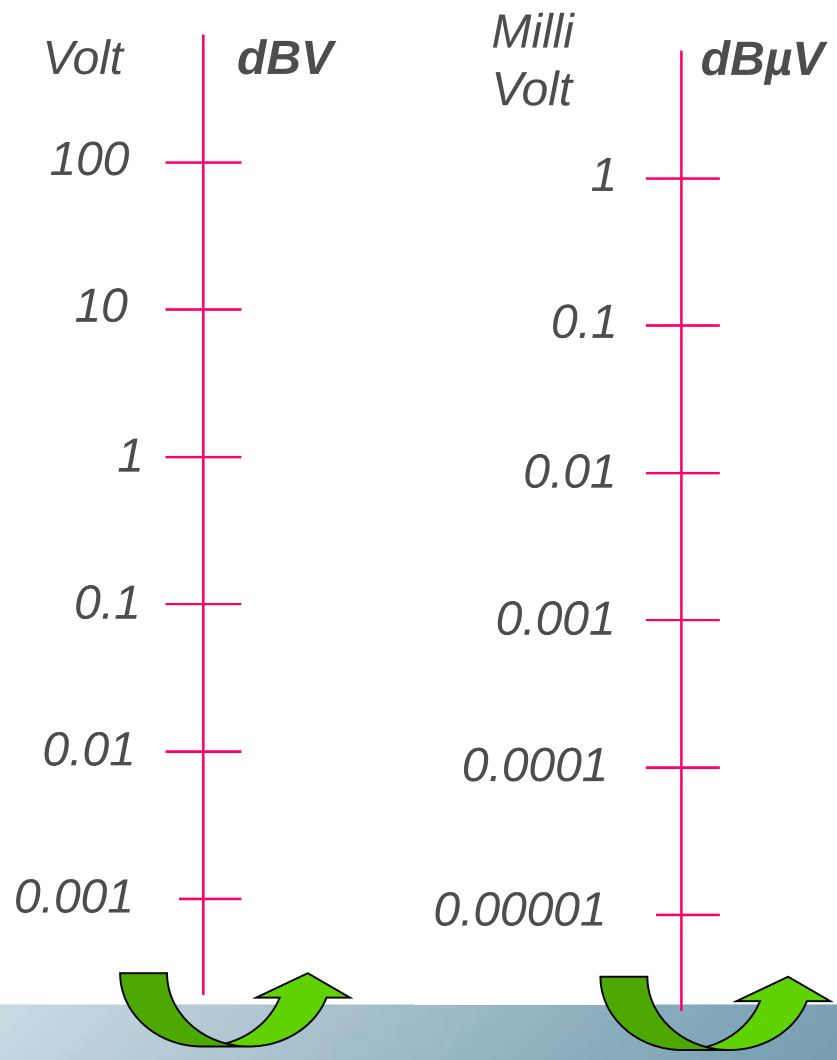
Wide dynamic range of signals in EMC → use of dB (decibel)

For example dBV, dBA :

$$dBV = 20 \times \log(V)$$
$$dBA = 20 \times \log(A)$$

Extensive use of dBµV

$$V_{dB\mu V} = 20 \times \log\left(\frac{V}{1\mu V}\right) = 20 \times \log(V) + 120$$



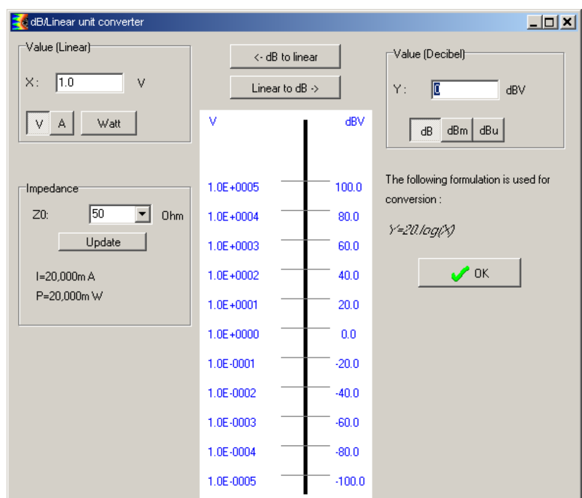
Specific units

EMISSION AND SUSCEPTIBILITY LEVEL UNITS

Power Units

The most common power unit is the "dBm" (dB milli-Watt)

$$P_{dBmW} = 10 \times \log\left(\frac{P_W}{1mW}\right) = 10 \times \log(P_W) + 30$$



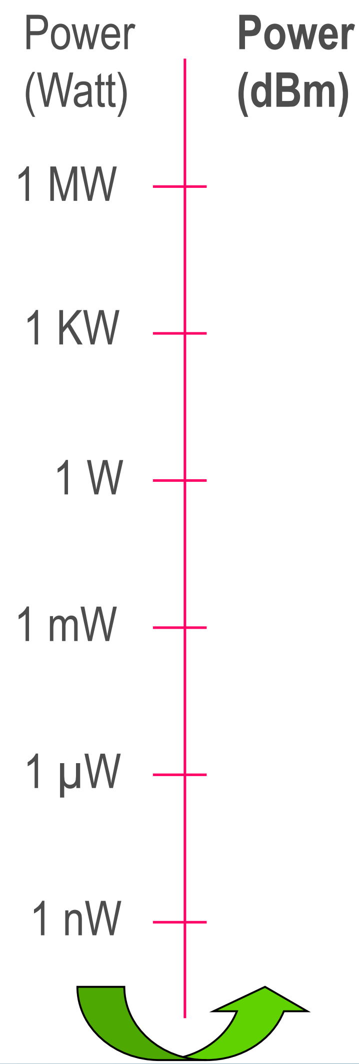
Exercise: Specific units

1 mV = ___ dBµV

1 W = ___ dBm

IC-EMC: 0dbm in 50 Ω

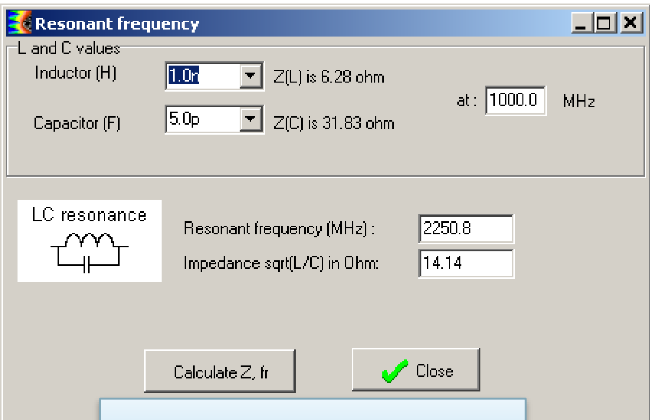
Tools > dB/Unit converter



LC Resonance

THE CHIP IS A LC RESONATOR

- DSPIC33F DIE ALONE

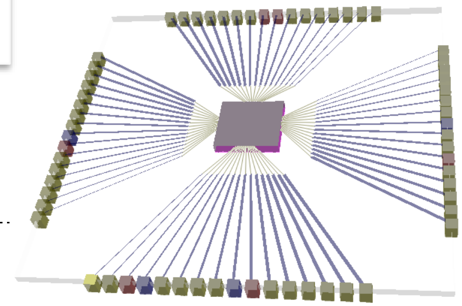


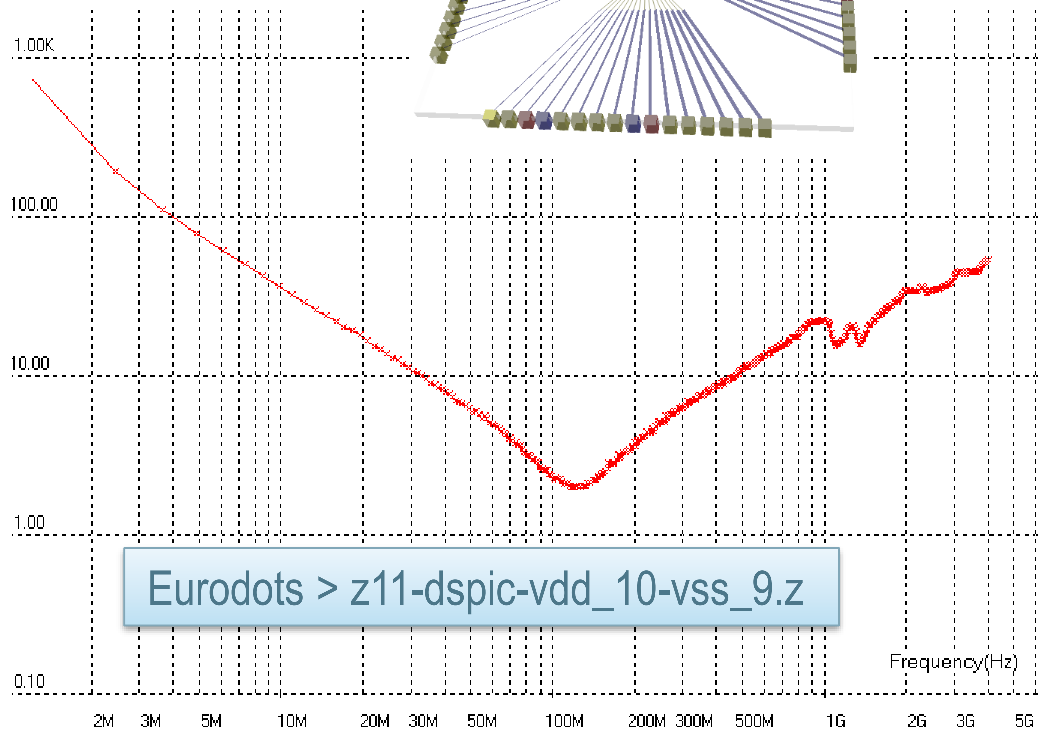
Tools > LC resonance

Impedance measurement between Vdd and Vss

f= ___

Impedance (Ω)





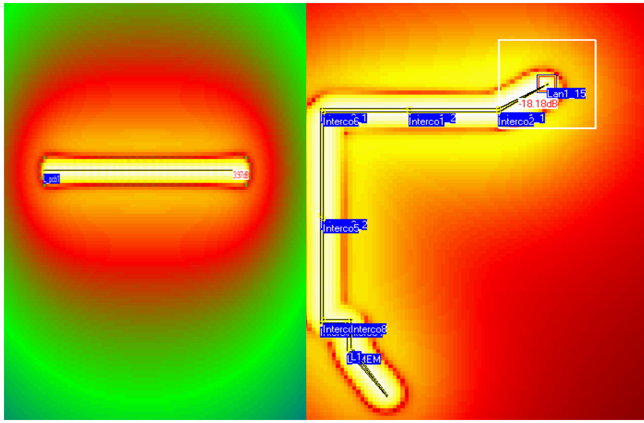
Eurodots > z11-dspic-vdd_10-vss_9.z

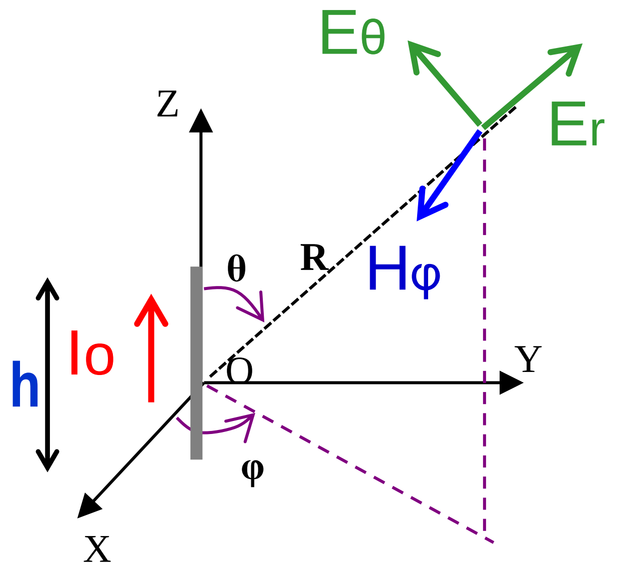
Frequency (Hz)

Radiating Element

RADIATED EMISSION

- Elementary "Hertz" current dipole.
- Short wire with a length << λ , crossed by a sinusoidal current with a constant amplitude Io





$$\vec{E}_r = 2\frac{\eta\beta^2 I_o h}{4\pi}\cos\theta\left(\frac{1}{\beta^2 r^2} - \frac{j}{\beta^3 r^3}\right)e^{-j\beta r}$$

$$\vec{E}_\theta = \frac{\eta\beta^2 I_o h}{4\pi}\sin\theta\left(\frac{1}{\beta^2 r^2} + \frac{j}{\beta r} - \frac{j}{\beta^3 r^3}\right)e^{-j\beta r}$$

$$\vec{H}_\varphi = \frac{\beta^2 I_o h}{4\pi}\sin\theta\left(\frac{1}{\beta^2 r^2} + j\frac{1}{\beta r}\right)e^{-j\beta r}$$

$$\vec{E}_\varphi = \vec{H}_r = \vec{H}_\theta = \vec{0}$$

Radiating Element

NEAR FIELD/FAR FIELD

- Close to the antenna

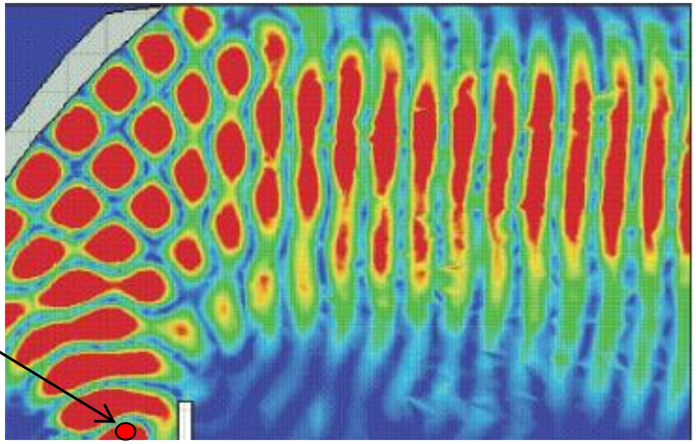
$$\beta R << 1 \Rightarrow R << \frac{\lambda}{2\pi}$$

$$R_{limit} = \frac{\lambda}{2\pi}$$

- Far from the antenna

$$\beta R >> 1 \Rightarrow R >> \frac{\lambda}{2\pi}$$

Near-field region



Far-field region

- ✓ Non radiating field (non TEM wave)
- ✓ E and H decreases rapidly in $1/r^3$

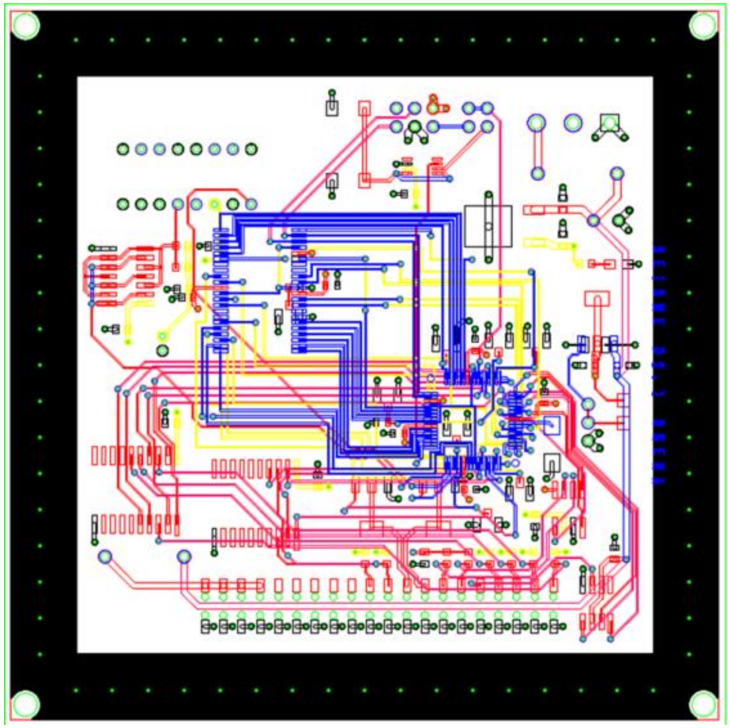
- ✓ Radiating field (TEM wave)
- ✓ E and H decreases in 1/r

100 MHz : Rlimit =_____

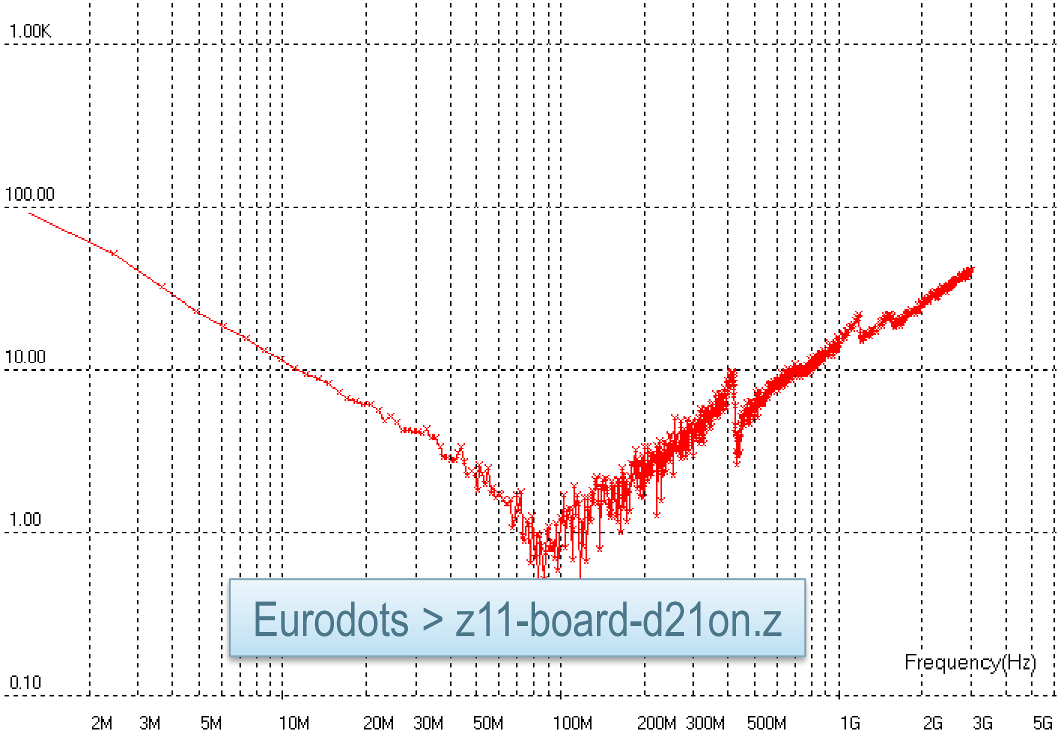
LC Resonance

THE BOARD IS A RESONATOR

- The VDD/VSS plate acts as a capacitor



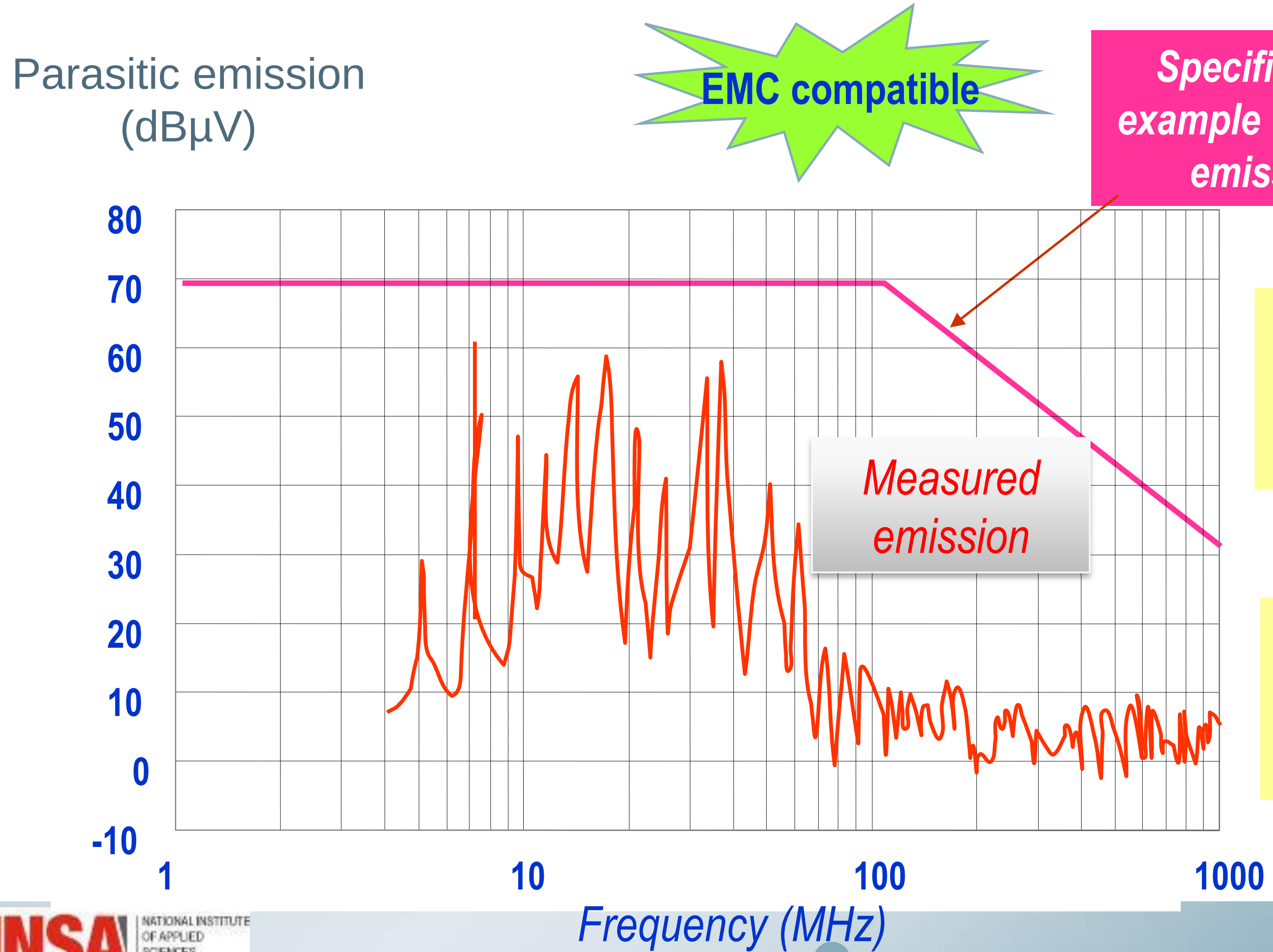
Impedance (Ω)



Frequency (Hz)

Emission spectrum

EMISSION LEVEL VS. CUSTOMER SPECIFICATION



IC-EMC: load

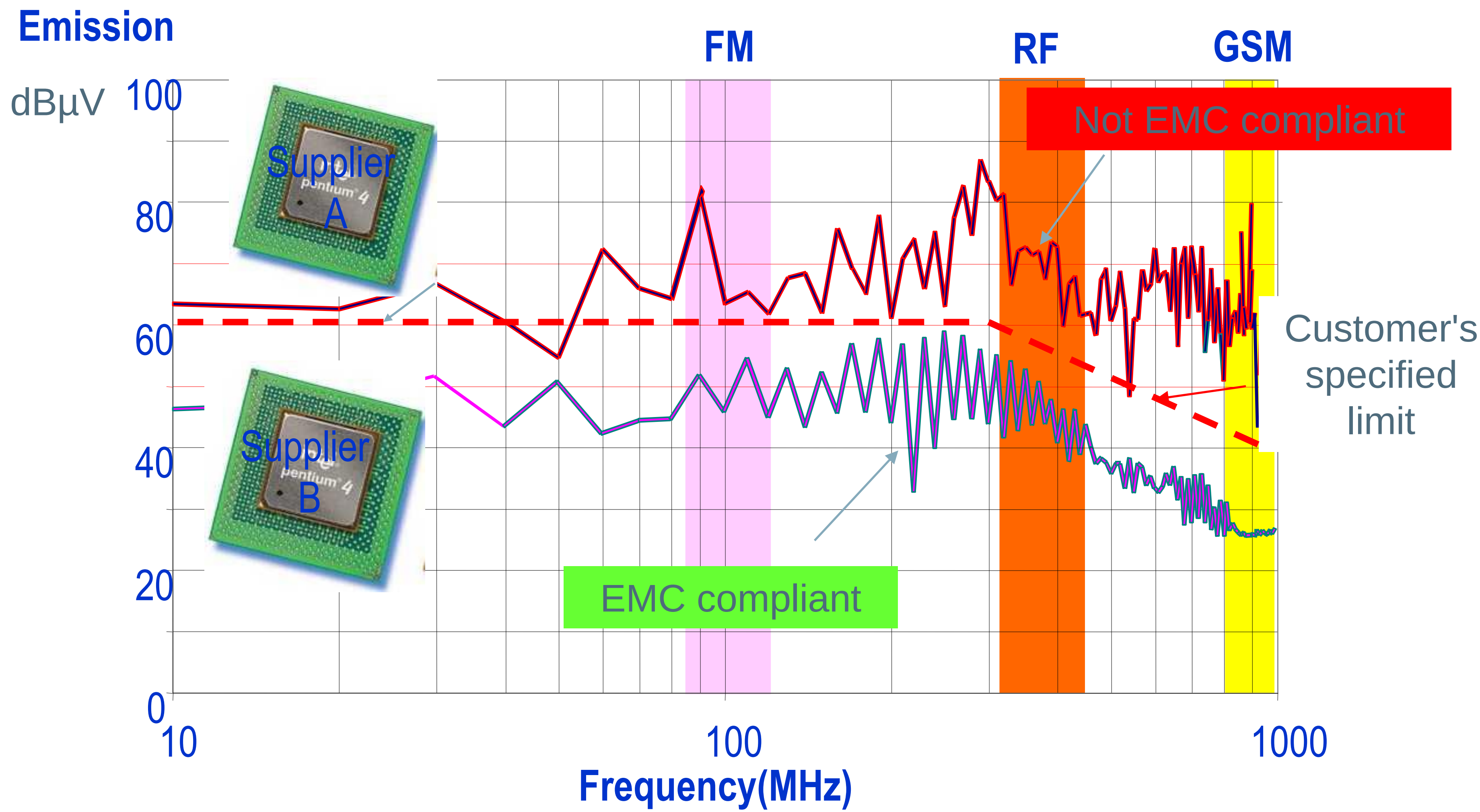
Emission > d60 > d60_vde.tab

IC-EMC: load

Getting started > mpc > mpc_vde.tab

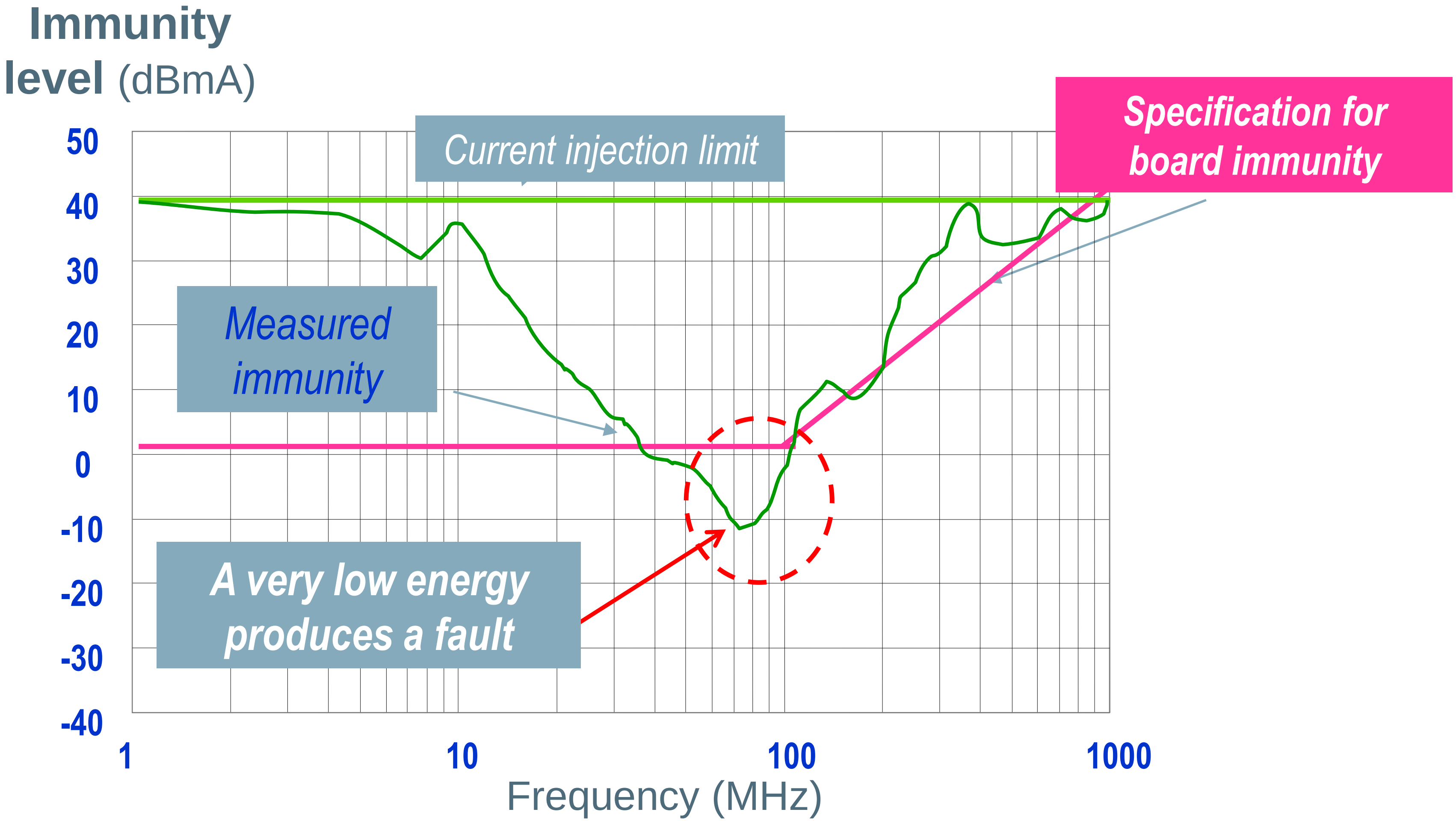
Emission spectrum

LOW PARASITIC EMISSION IS A KEY COMMERCIAL ARGUMENT



Susceptibility spectrum

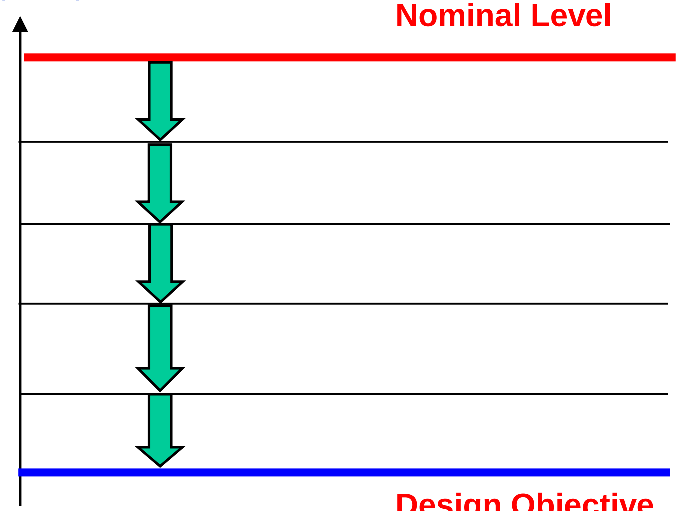
IMMUNITY LEVEL HAS TO BE HIGHER THAN CUSTOMER SPECIFICATION



Notion of margin

WHY A MARGIN ?

- To ensure low parasitic emission ICs supplier has to adopt margins



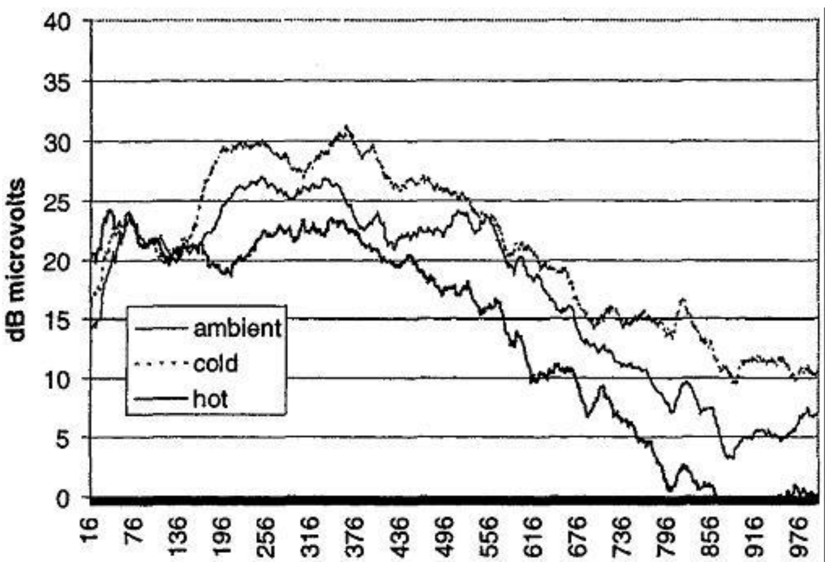
- Margin depends on the application domain

Domain	Lifetime	Margin
Aeronautics		
Automotive		
Consumer		

Notion of margin

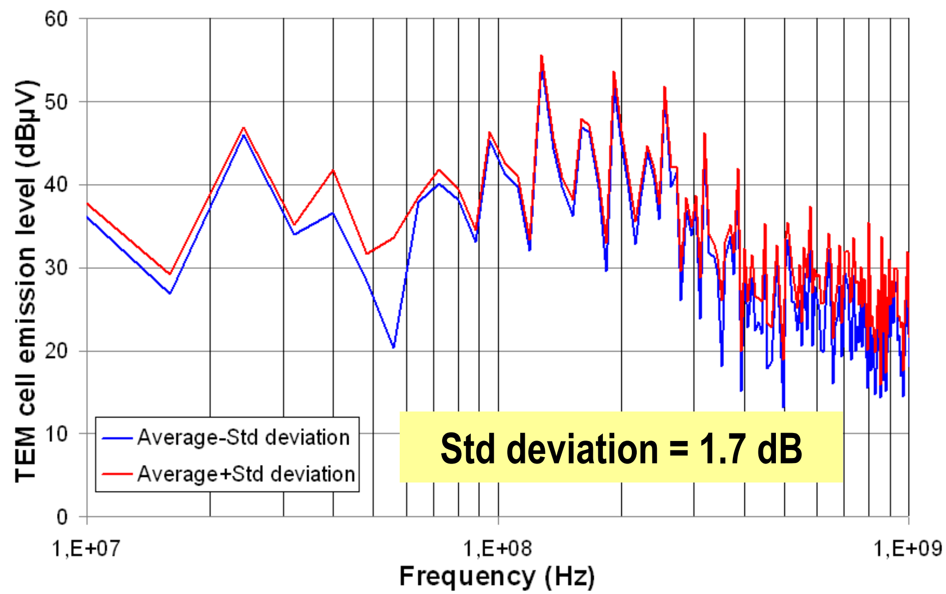
INFLUENT PARAMETERS ON IC EMC

- The temperature of a circuit has a direct impact on the switching time of internal devices. When temperature increases, the high frequency content of the emission spectrum tends to be reduced.



K. P. Slattery et al., "Modeling the radiated emissions from microprocessors and other VLSI devices", IEEE Symp. on EMC, 2000.

- The variability between components induce a dispersion of emission and susceptibility level. Radiated emission in TEM cell of a 16 bit microcontroller PIC18F2480. Measurement of 12 samples and extraction of emission level dispersion.

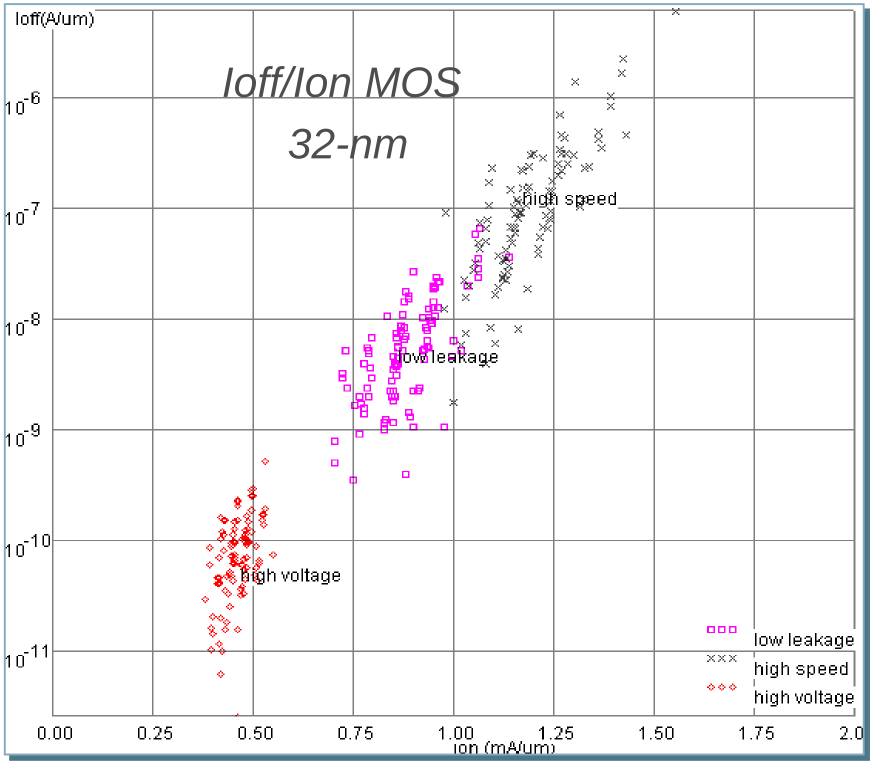


H. Huang and A. Boyer (LAAS-CNRS)

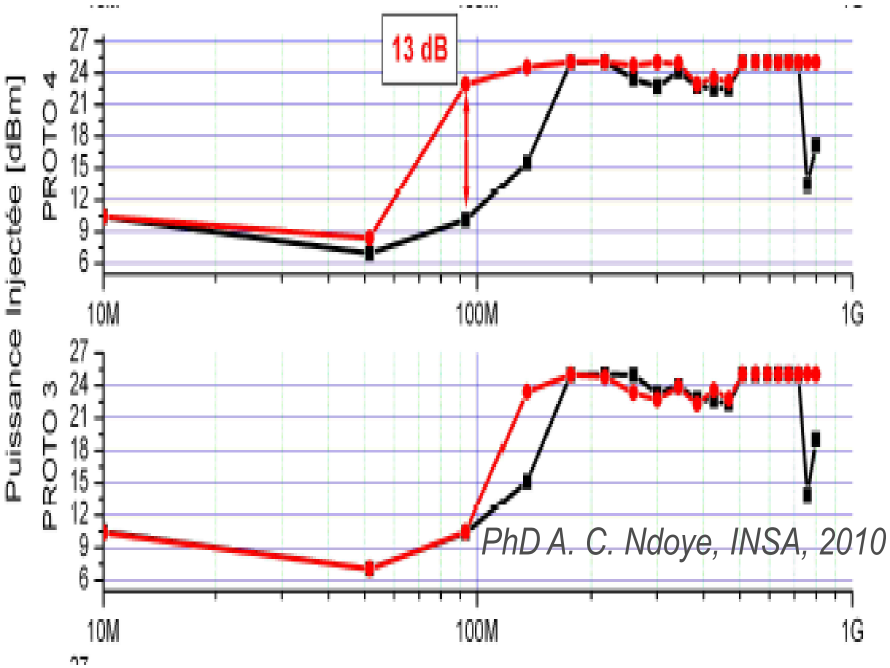
Notion of margin

INFLUENT PARAMETERS ON IC EMC

- MOS device characteristics fluctuate by +/- 30 %



- Ageing may significantly alter EMC performances



Immunity vs. ageing (LTOL)

Impedance

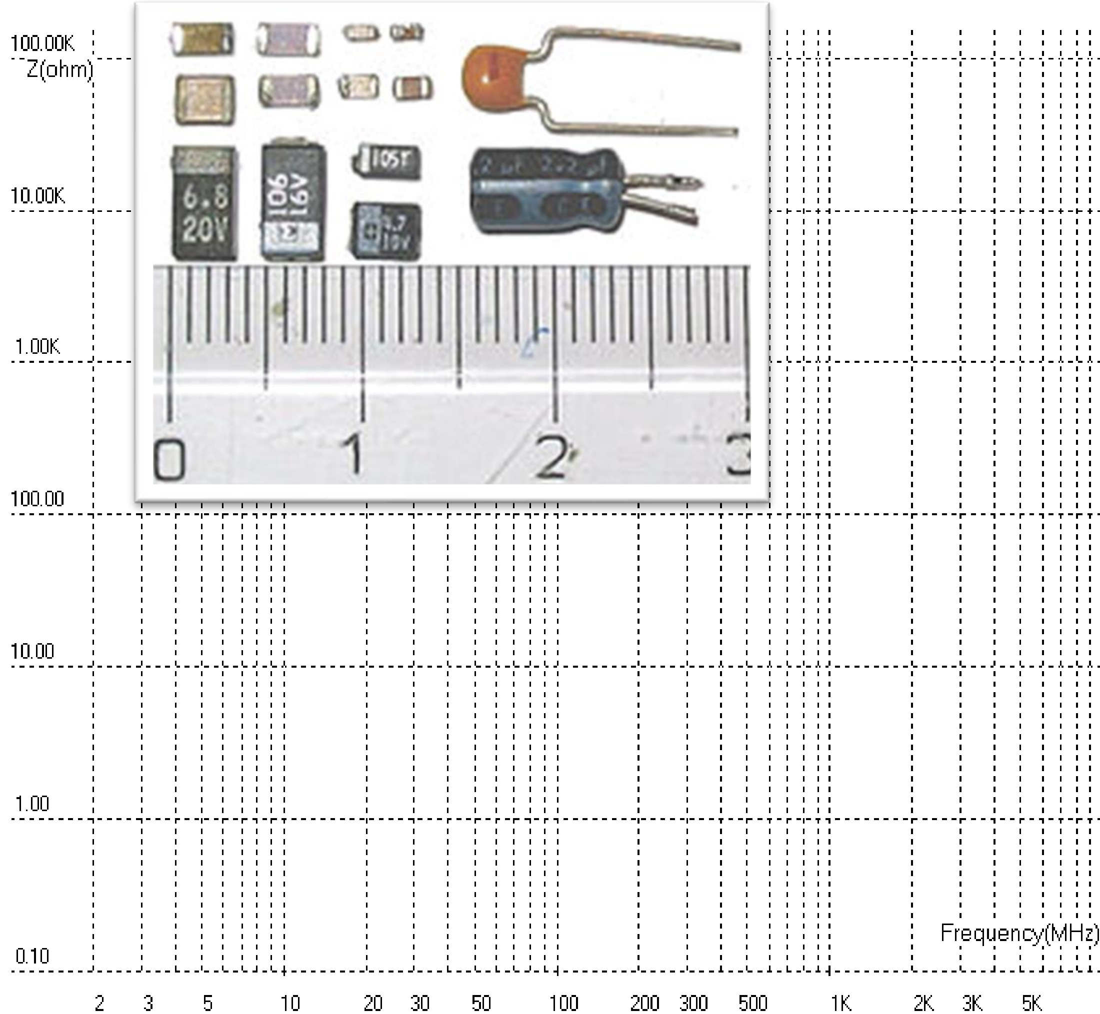
R,L,C VS. FREQUENCY

Impedance profile of:

- 1 Ω resistor (z11-1Ohm_0603.z)
- 0603 = 1.6 x 0.8 mm

comparison	Metric code	Imperial code	comparison
0.1x0.1 mm	0402	01005	0.01x0.01 in (10x10 mils)
	0603	0201	
	1005	0402	
	1608	0603	
1x1mm	2012	0805	0.1x0.1 in (100x100 mils)
	2520	1008	
	3216	1206	
	3225	1210	
	4516	1806	
	4532	1812	
	5025	2010	
1x1 cm	6332	2512	0.5x0.5in (500x500 mils)

Actual size



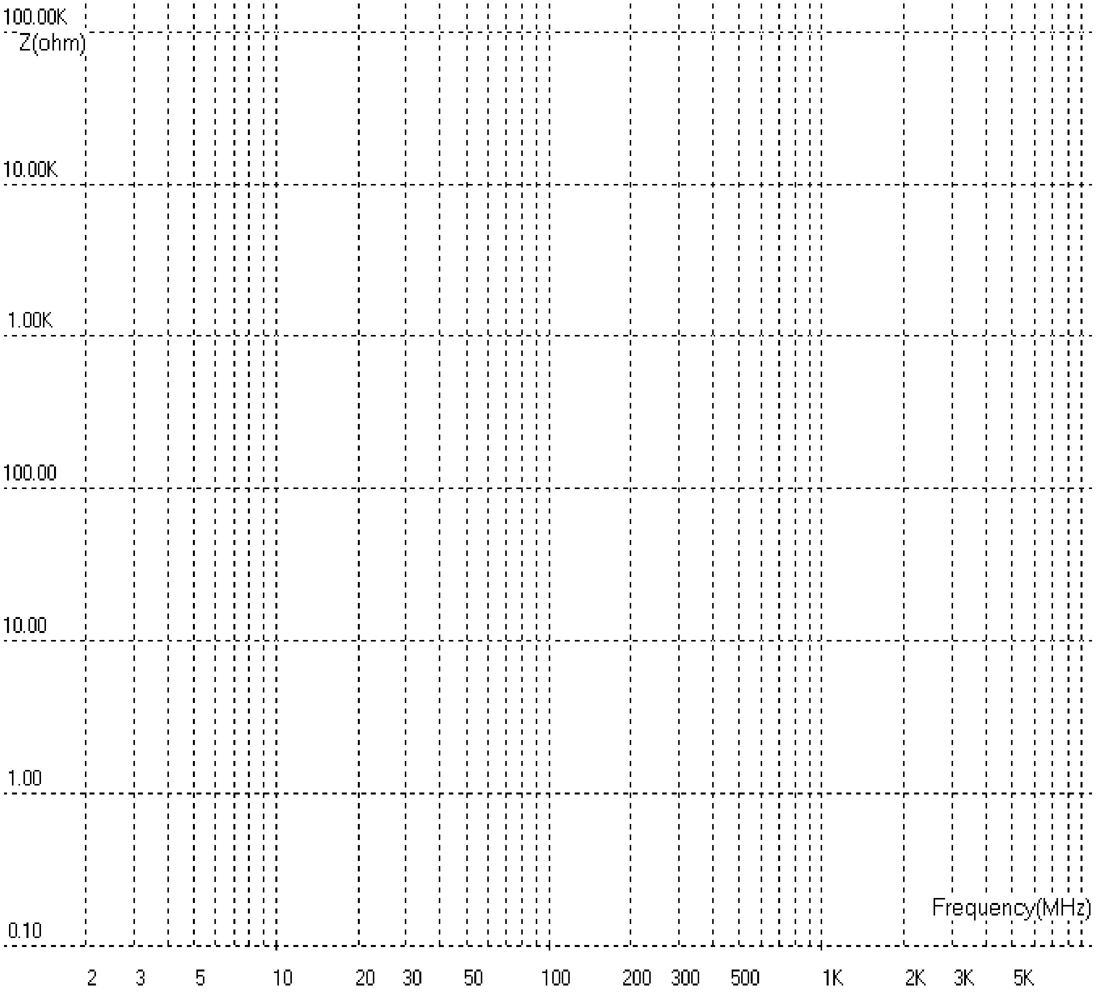
Impedance

R,L,C VS. FREQUENCY

Impedance profile of:

- 1 nF capacitor (z11-C1nF_0603.z)

Schematic diagram:



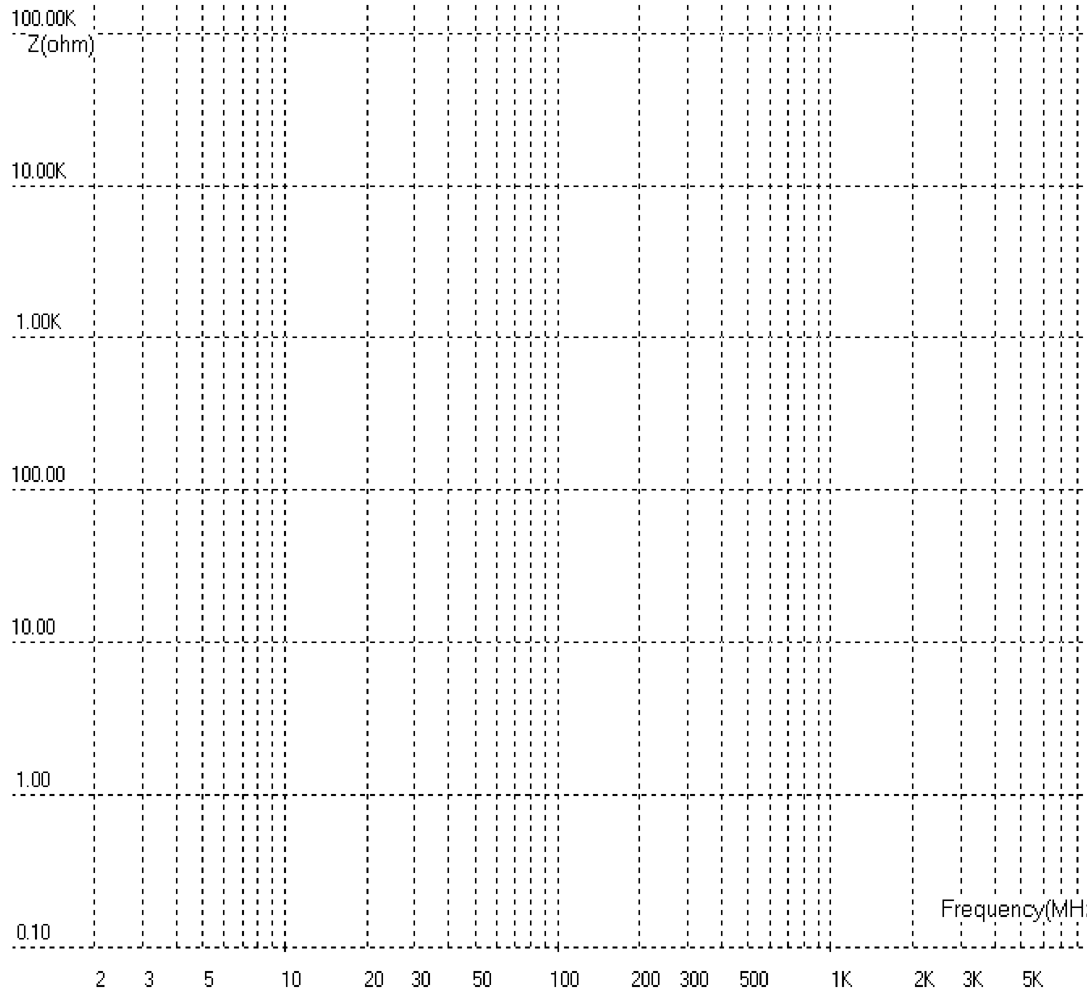
Impedance

R,L,C VS. FREQUENCY

Impedance profile of:

- Inductance 47 µH (Zin_L47u.s50)

Schematic diagram:

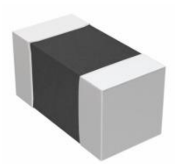


Impedance

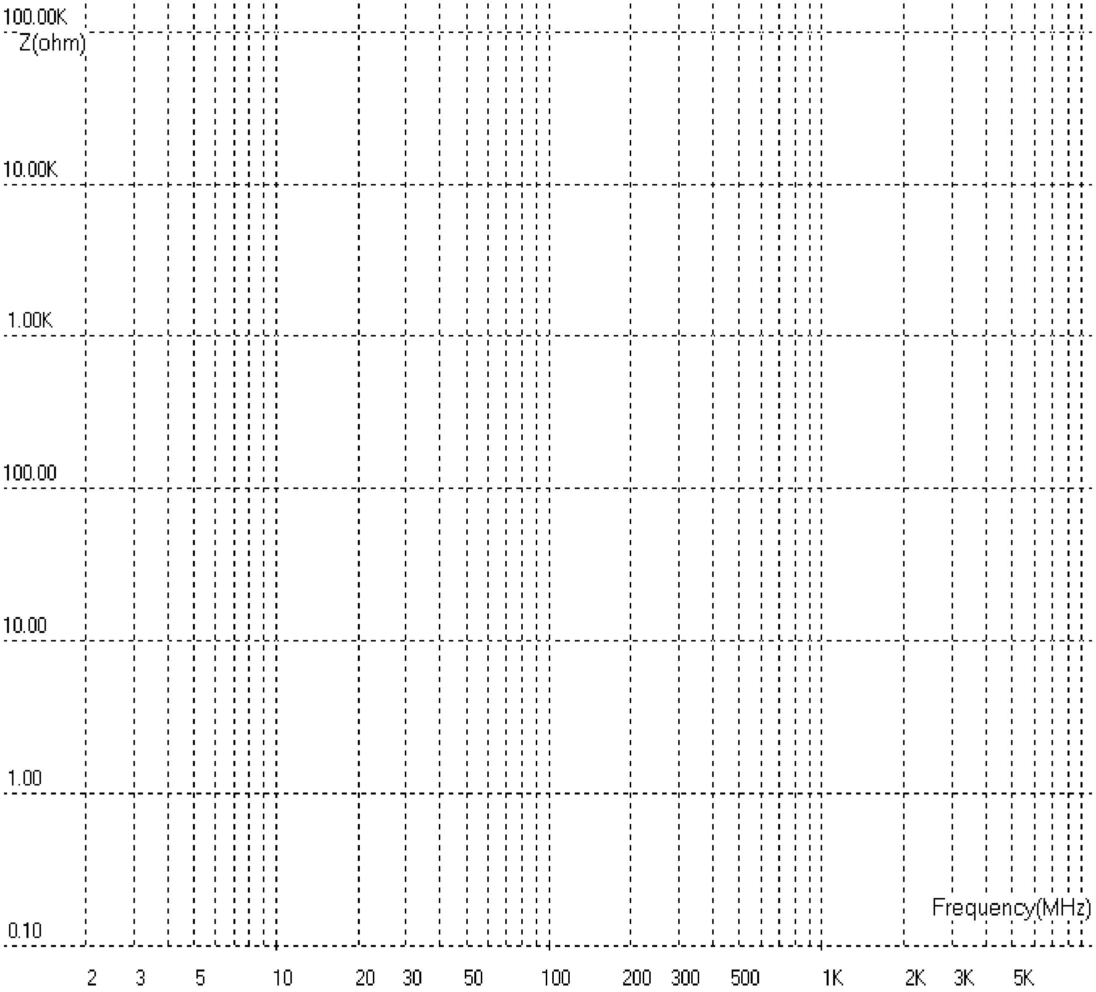
R,L,C VS. FREQUENCY

Impedance profile of:

- Ferrite (Zin_FerriteBLM18HK102SN1.s50)



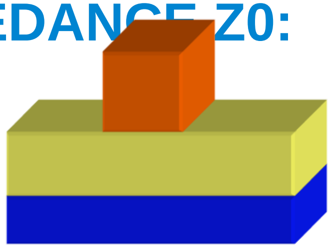
Schematic diagram:



Characteristic Impedance

CONDUCTOR IMPEDANCE OR CHARACTERISTIC IMPEDANCE Z0:

Coaxial line



Microstrip line

- **From the electromagnetic point of view:**

$$Z_0 = \frac{E}{H}$$

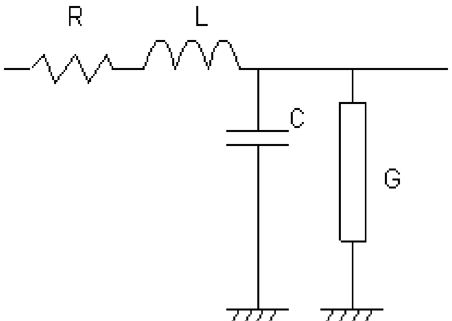
→ Link to conductor geometry and material properties

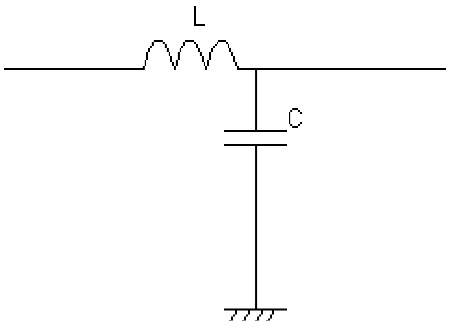
- **From the electric point of view :**

$$Z_0 = \sqrt{\frac{R + jL\omega}{G + jC\omega}}$$

→ **lossless conductor**

$$Z_0 \approx \sqrt{\frac{L}{C}}$$

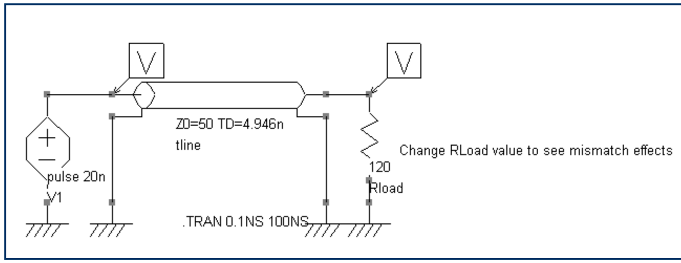




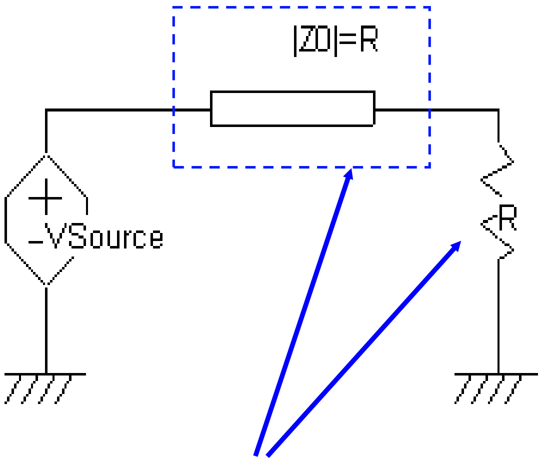
Equivalent electrical schematic

Characteristic Impedance

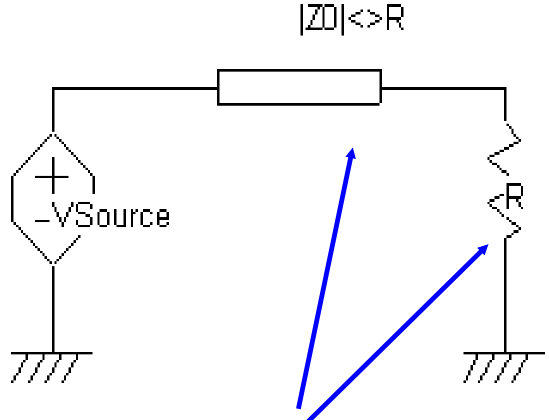
IMPEDANCE MATCHING



Why impedance matching is fundamental ?



Adapted:



Not adapted:

IC-EMC

Impedance>

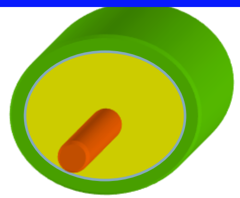
impedance_mismatch.sch

Characteristic Impedance

CHARACTERISTIC IMPEDANCE Z0:

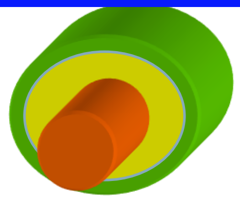
What is the optimum characteristic impedance for a coaxial cable ?

Small conductor



Or ?

Large conductor



	Small conductor	Large conductor
Power handling		
Bending		
weight		
Low loss		
Small capacitance		
Small inductance		
Low Impedance		

Ideal values:

- Maximum power : Z0 = ___Ω
- Minimum loss: Z0 = ____ Ω

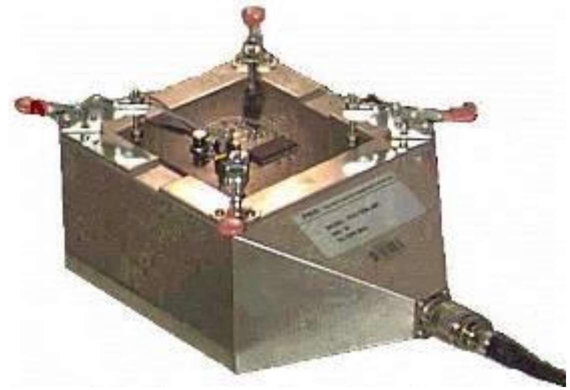
Cable examples:

- EMC cable (compromise between power and loss) : Z0 = ___ Ω
- TV cable : Z0 = ___ Ω
- Base station cable : Z0 = ___ Ω

Characteristic Impedance

50 OHM ADAPTED SYSTEMS

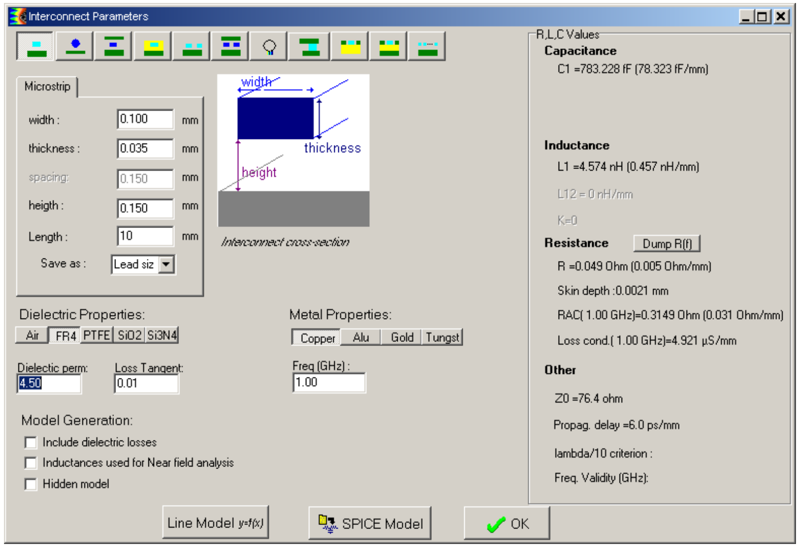
Spectrum analyzer



Tem cell

Waveform generator

Amplifier



Tools > Interconnect parameters

Conclusion

- Specific units used in EMC have been detailed
- The current dipole is the base for radiated emission
- The Emission Spectrum has been described
- Susceptibility Threshold, margins have been discussed
- The notion of impedance has been introduced
- Characteristic impedance of cables lead to specific values
- Discrete components used in the experimental board have been modeled up to 1 GHz

Classroom experiments - EMC issues

Purpose

1. **Clarify basic concepts for EMC by hands-on experiments**

2. **Present some measurement equipments for EMC of electronic devices and equipments**

3. **Provide simple tools to evaluate EMC issues**

Summary

1. **Susceptibility of circuits to electromagnetic disturbances**
2. **Spectrum analyzer – Spectral content evaluation**
3. **Observing typical antenna at PCB/IC level**
4. **Crosstalk**
5. **DM vs CM current – radiation from cables**

Susceptibility of circuits to electromagnetic disturbances – An example

Susceptibility of circuits

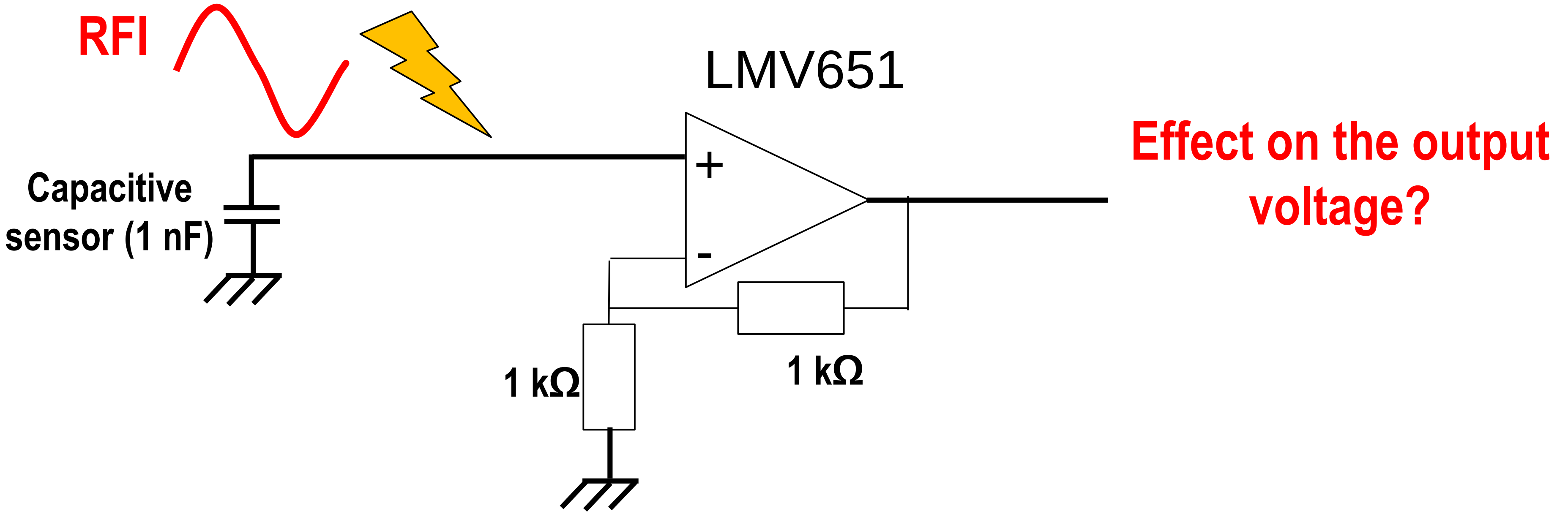
Effect of IC malfunction due to EM disturbance – Real examples

- **Striking of berth by Coastal Inspiration, 20th dec 2011, Nanaimo, British Columbia, Canada.**
- **A problem of an amplifier, due to EM disturbances, leads to a failure in speed reduction command.**

- **Other example: Cell phone interference with speaker**

Susceptibility of circuits

Susceptibility of op-amp

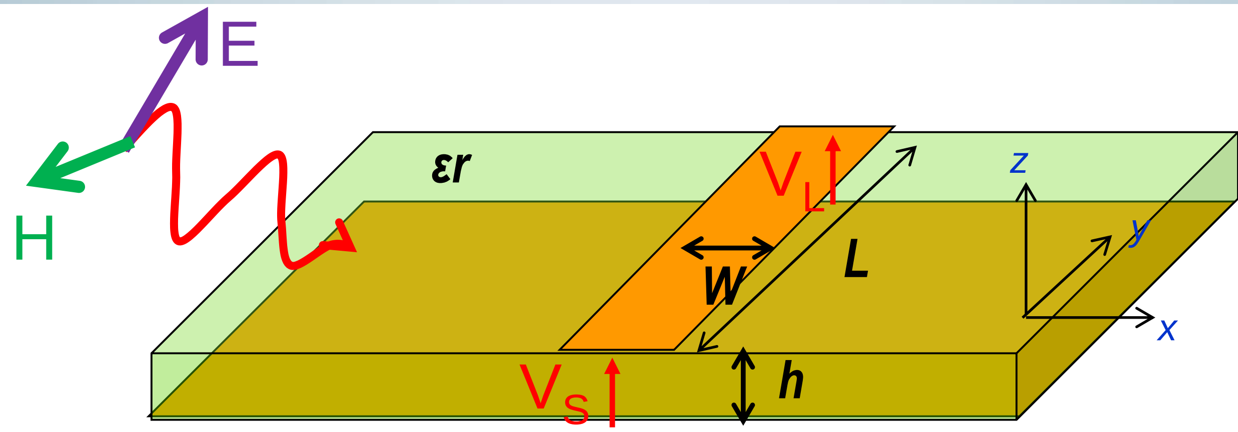


- Couple on the circuit a sine wave electromagnetic disturbance
- Observe the effect on the output voltage

Simple radiated emission/susceptibility model

Far-field coupling

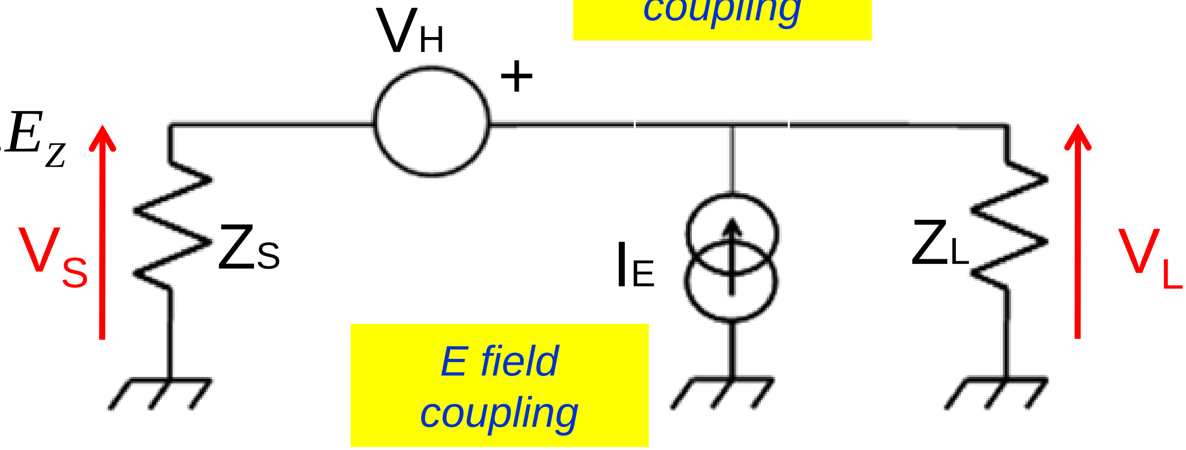
- Illumination of a microstrip line by an uniform plane wave



- Worst-case model (transmission line effect neglected)

$$V_H(\omega) = j\omega\mu_0 h.\min\left(L,\frac{\lambda}{4}\right).H_x$$

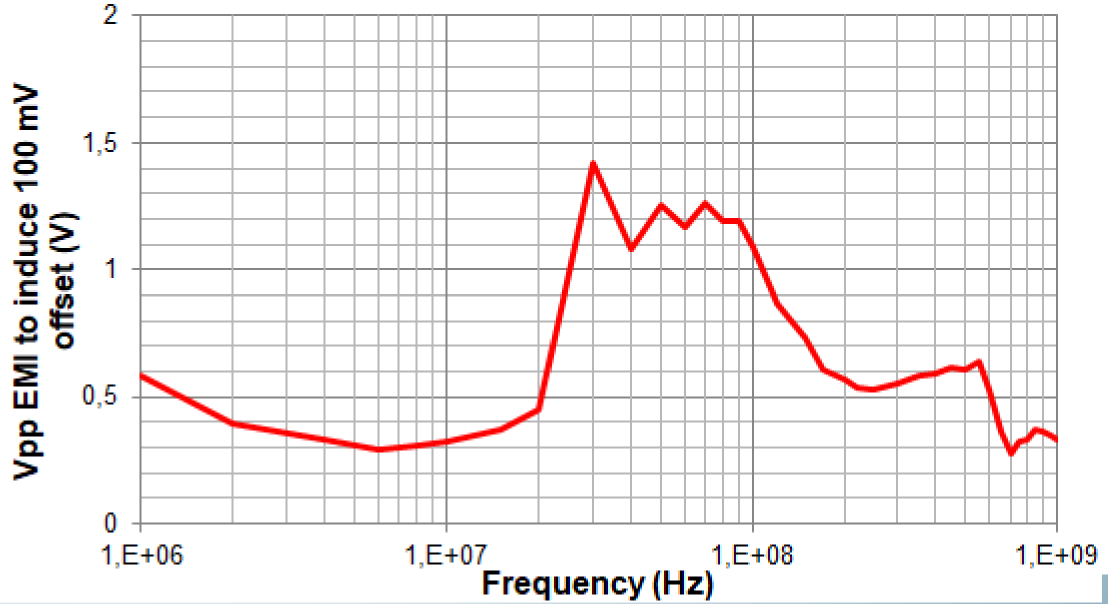
$$I_E(\omega) = j\omega c_{line} h.\min\left(L,\frac{\lambda}{4}\right).E_Z$$



Susceptibility of circuits

Estimation of the radiated susceptibility of op-amp

- **Radiated susceptibility at 900 MHz ?**
- **Let consider:**
  - ➔ **LMV651 connected to a high-Z sensor by a 50 mm long trace routed at 1.6 mm above a ground plane.**
  - ➔ **Let consider identical load on each termination of the line.**
  - ➔ **Peak-to-peak voltage applied on V+ to induce 100 mV offset:**



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Susceptibility of circuits

Estimation of the radiated susceptibility of op-amp

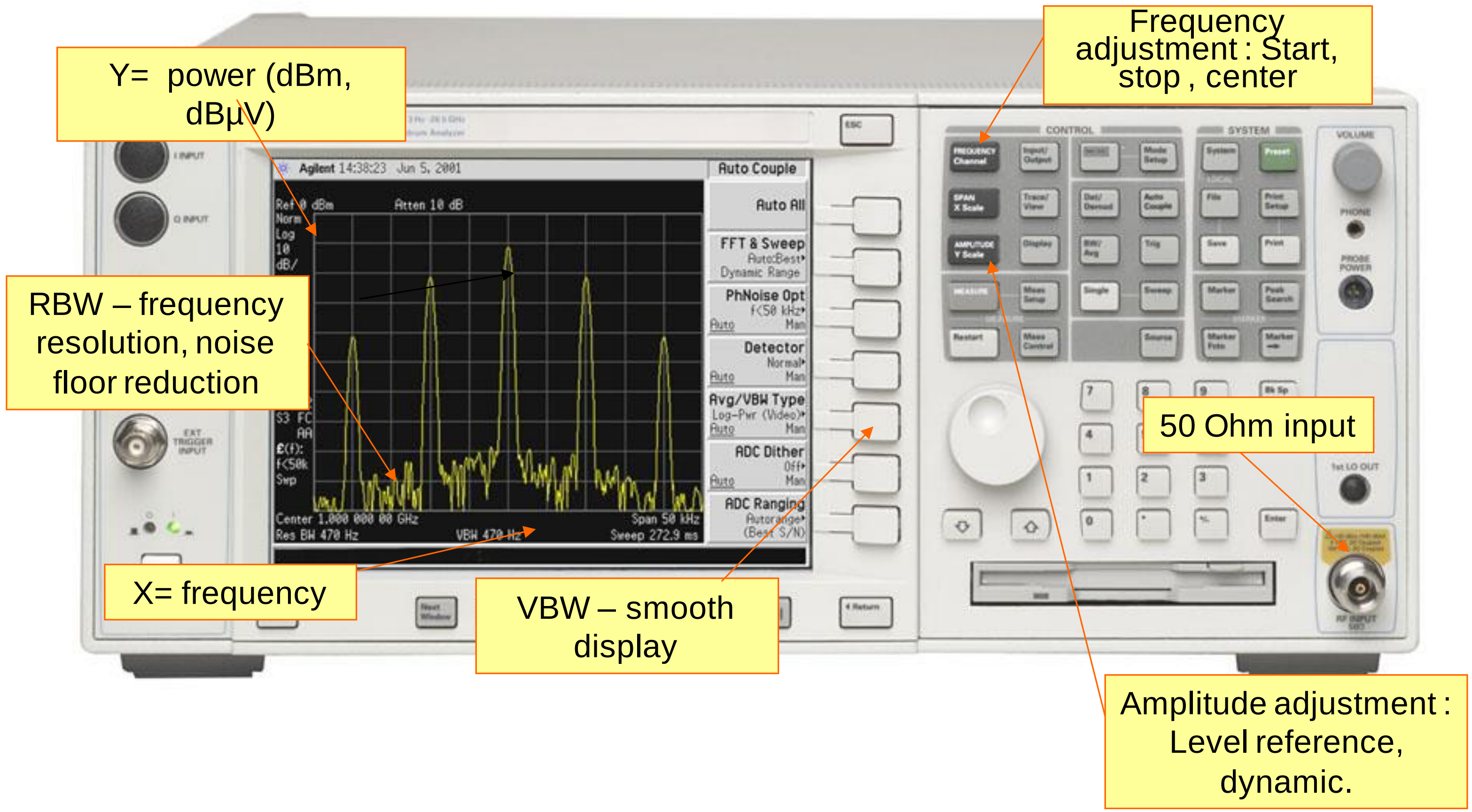
- **Solutions ?**

Classroom experiments

Spectrum analyzer – Spectral content evaluation

Spectrum analyzer

Spectrum Analyser (EMI receiver)

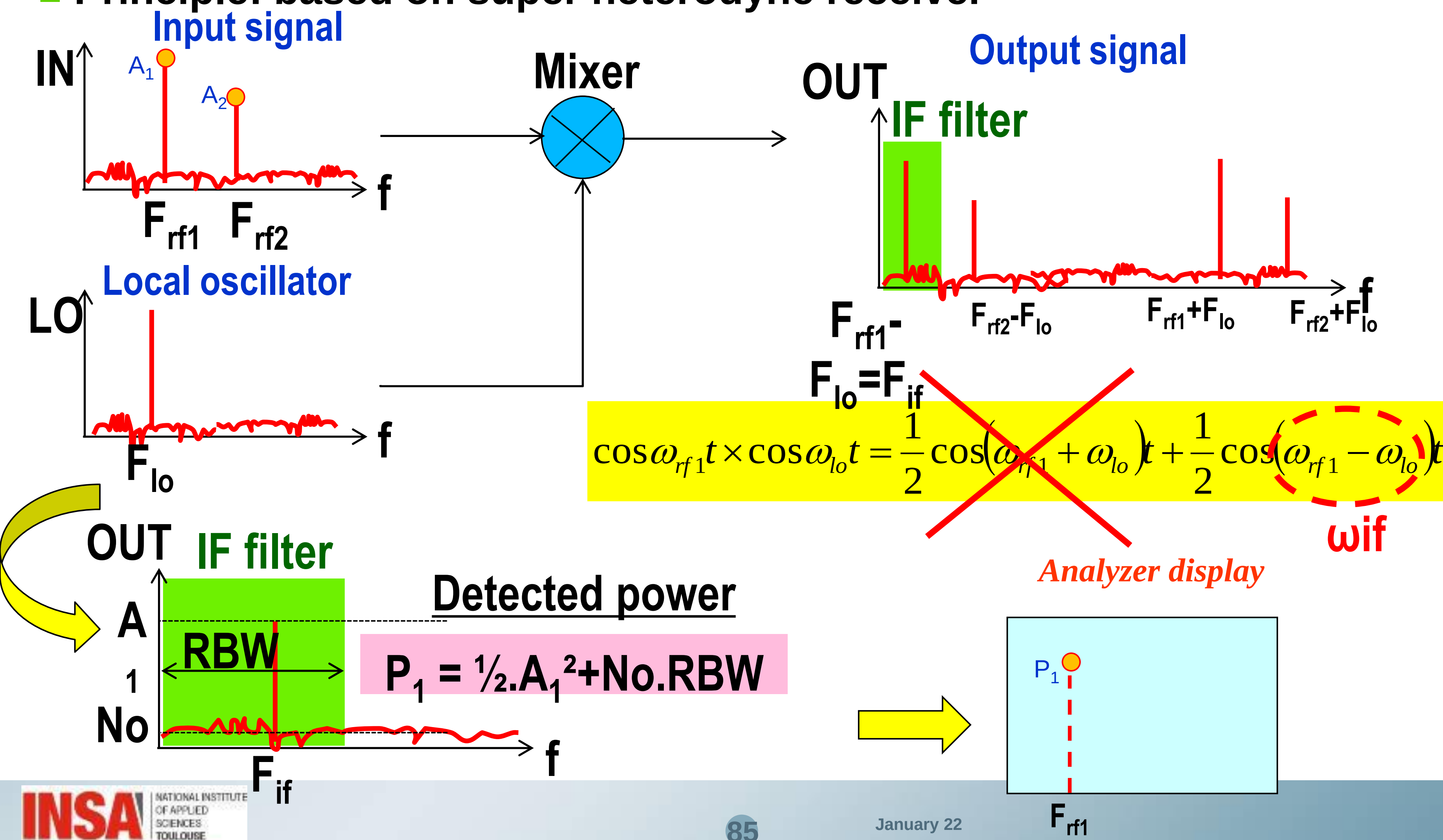


- **Main measurement equipments for emission test**
- **Emission tests require large bandwidth (> 1 GHz) and high sensitivity (typ. 10 dBµV)**

Spectrum analyzer

Spectrum Analyser (EMI receiver)

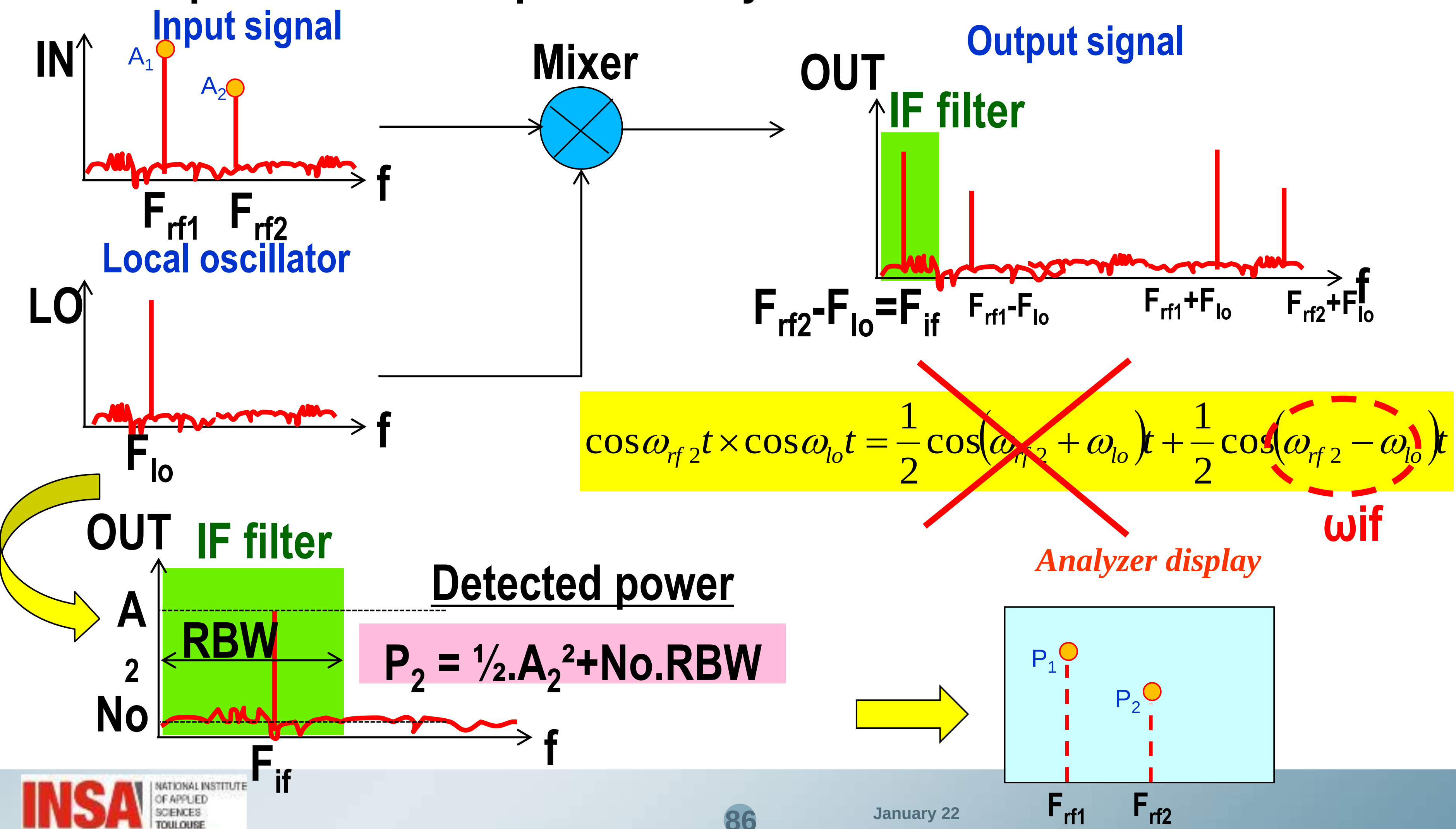
- **Principle: based on super heterodyne receiver**



Spectrum analyzer

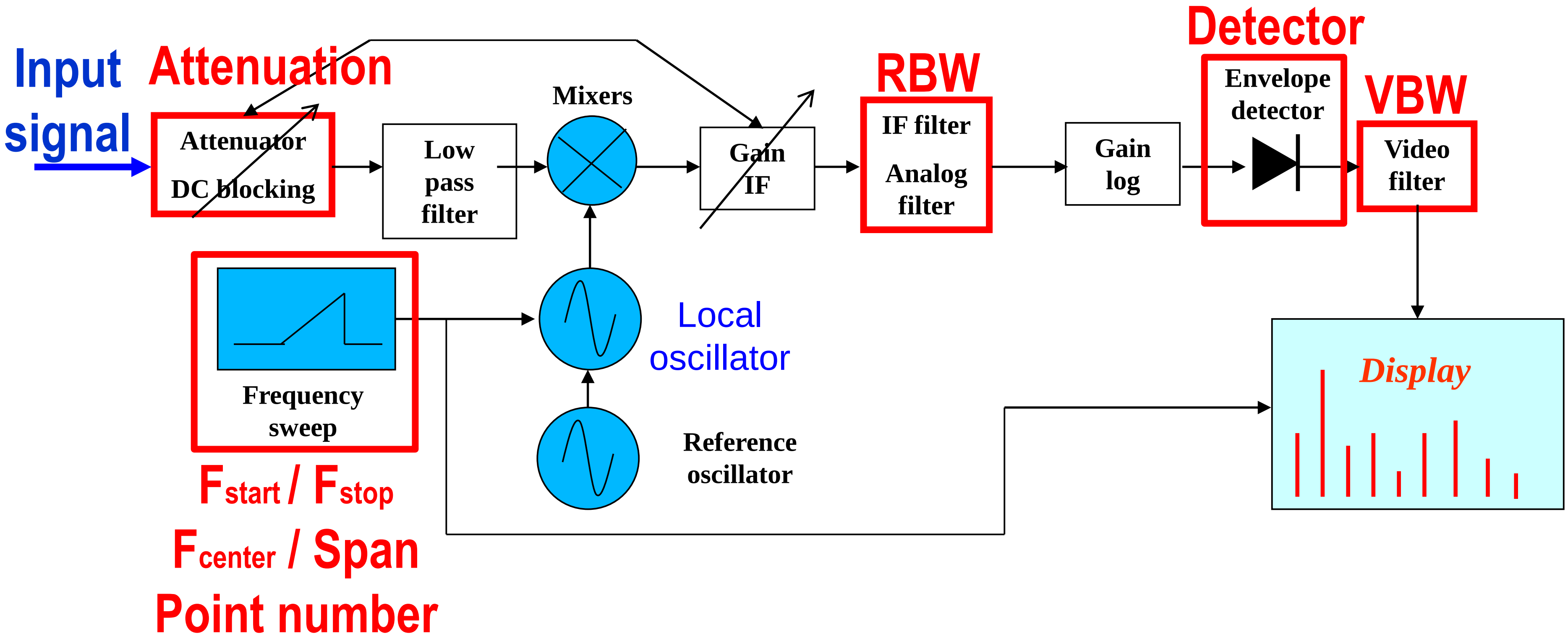
Spectrum Analyser (EMI receiver)

- Principle: based on super heterodyne receiver



Spectrum Analyser (EMI receiver)

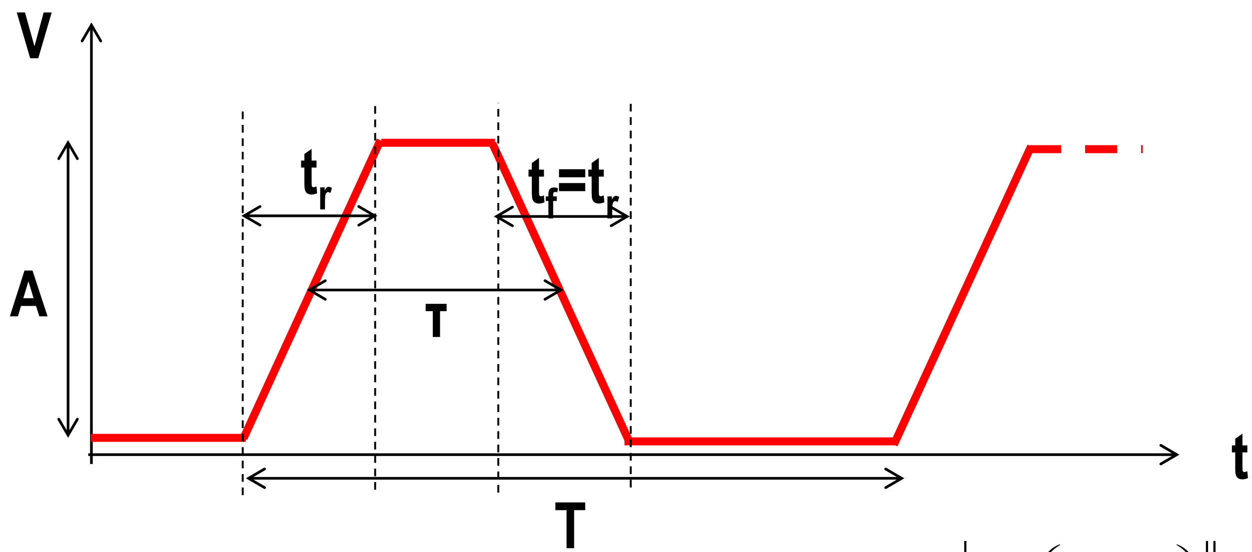
- **Building blocks and adjustable elements:**



Spectral content evaluation

Spectral contents from unintentional emission of electronic devices

- **Periodical pulse series:**



Frequency content ?

Fourier coefficient n:

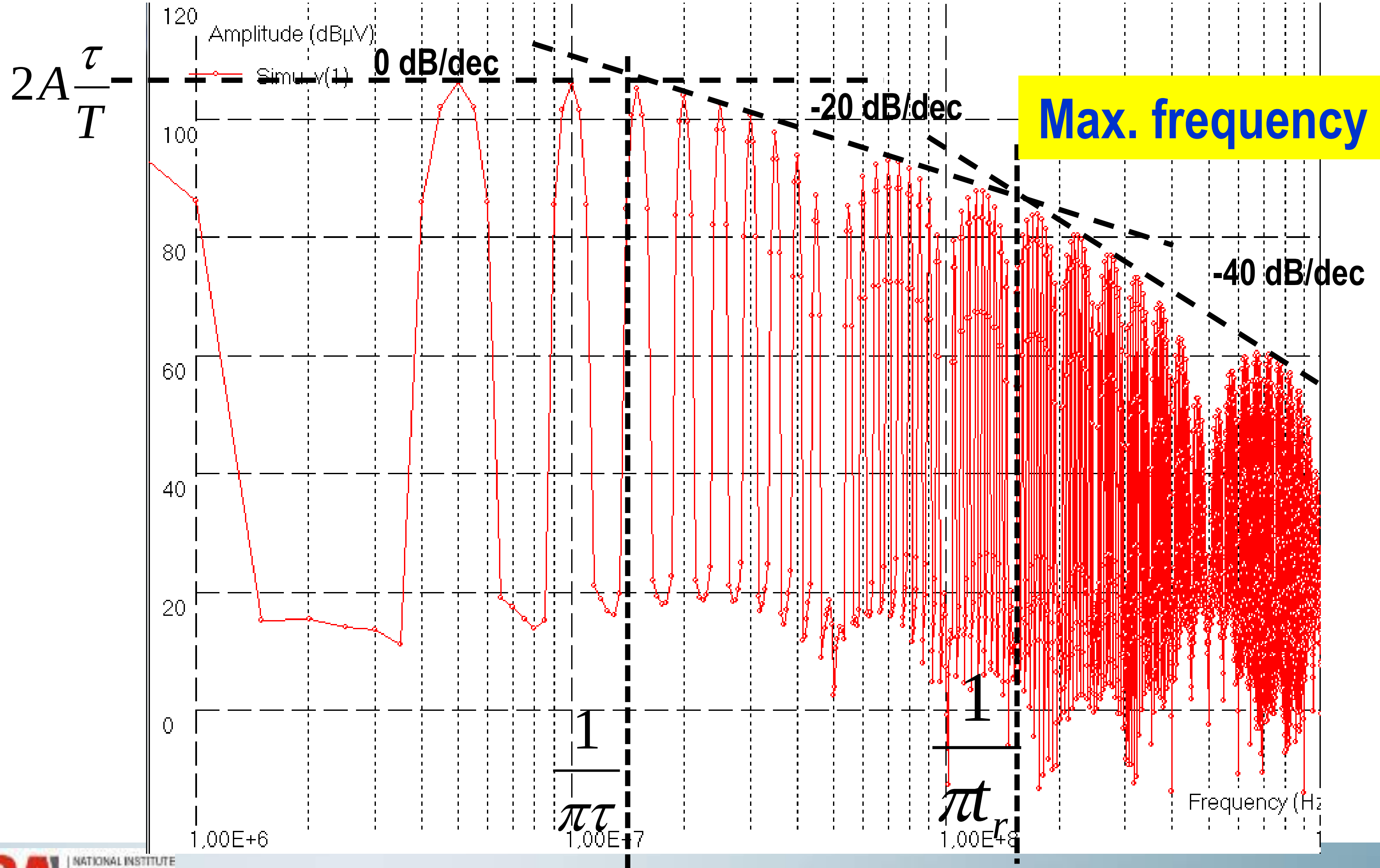
$$\left|c_n^+\right| = \frac{2A\tau}{T}\left|\frac{\sin\left(n\pi\frac{\tau}{T}\right)}{n\pi\frac{\tau}{T}}\right|\left|\frac{\sin\left(n\pi\frac{t_r}{T}\right)}{n\pi\frac{t_r}{T}}\right|, n > 0$$

$$c_0 = \frac{A\tau}{T}$$

Spectral content evaluation

Spectral contents from unintentional emission of electronic devices

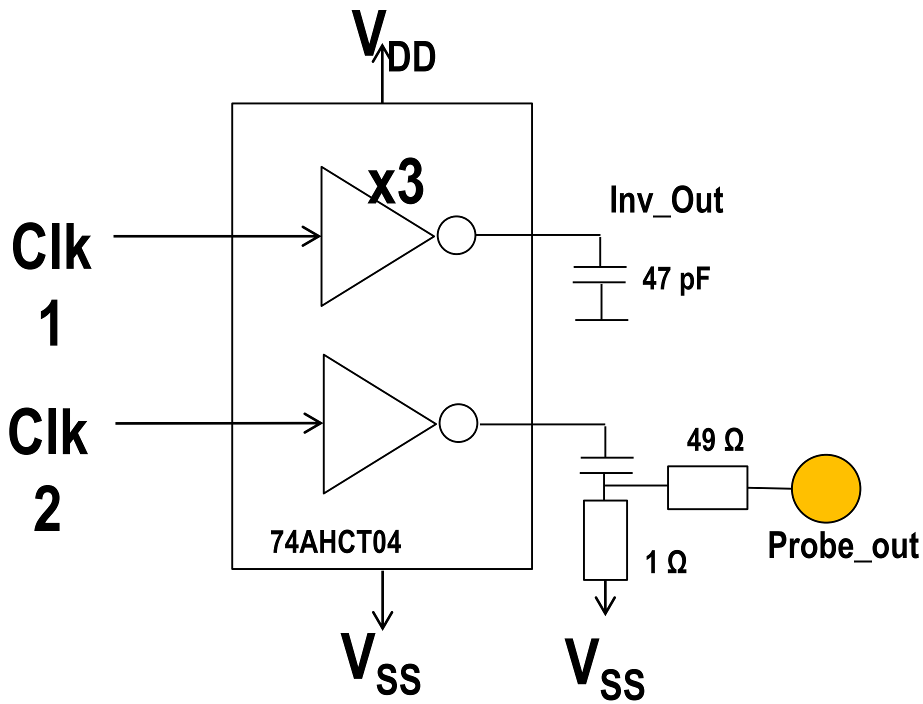
- **Example: A = 1 V, T = 200 ns, τ = 20 ns, tr = tf = 2 ns**

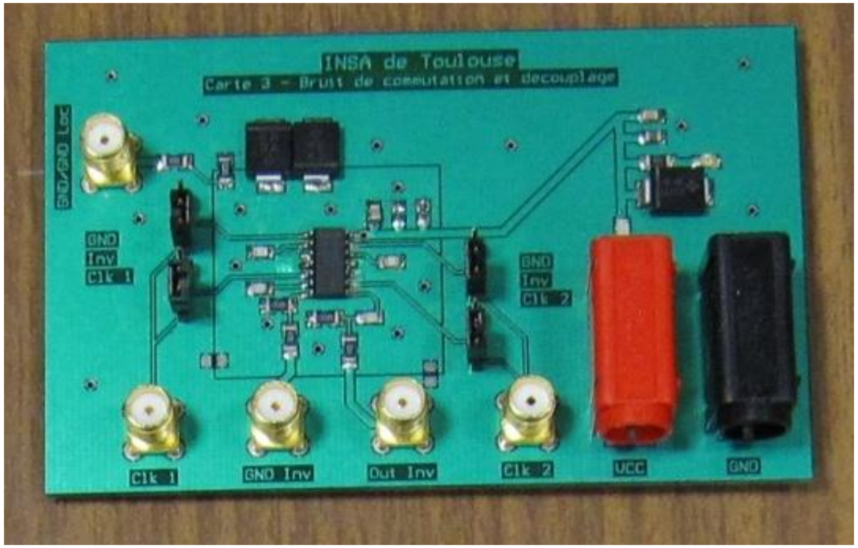


Spectral content evaluation

Spectral contents from unintentional emission of electronic devices

- Example: Hex inverter 74AHCT04





- What is measured on Probe_Out ?
- With oscilloscope, observe Probe_Out and Inv_Out.
- Measure transition times of Inv_Out signal.

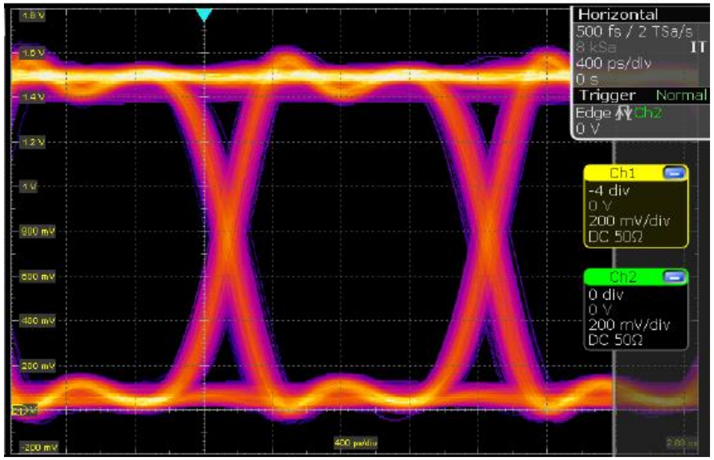
- Connect Probe_out to the spectrum analyzer and observe the spectrum
- Is there a relationship between transition time and spectral occupancy ?

Spectral content evaluation

Spectral contents from unintentional emission of electronic devices

- **Maximum frequency of emission from the following interfaces:**

Technology	**Typ. Rise time**	**Max. freq**
High speed CMOS	1.5 ns	
Ethernet 1000 base-t	400 ps	
USB 2.0 high speed	800 ps	
USB 3.0	80 ps	
DDR3	300 ps	

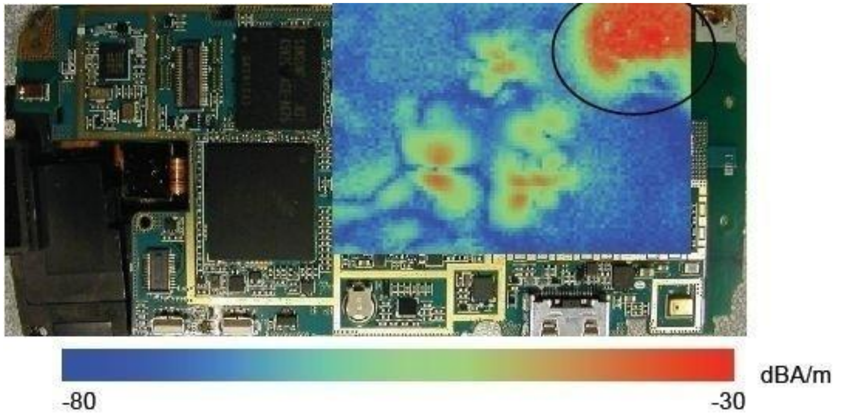


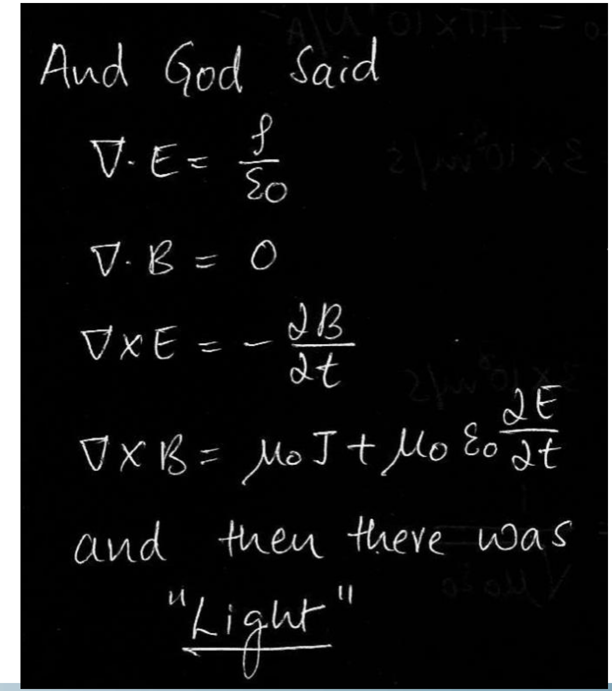
Observing typical antenna at PCB/IC level

Antenna at PCB/IC level

Radiation

- Any conductor crossed by a transient current or excited by a transient voltage can produce electromagnetic fields and radiation.
- Field distribution is determined by Maxweel equations.
- Any IC conductor, PCB traces, connectors, … may be a « parasitic antenna ».
- Radiation depends on excitation source and characteristics of the parasitic antenna.





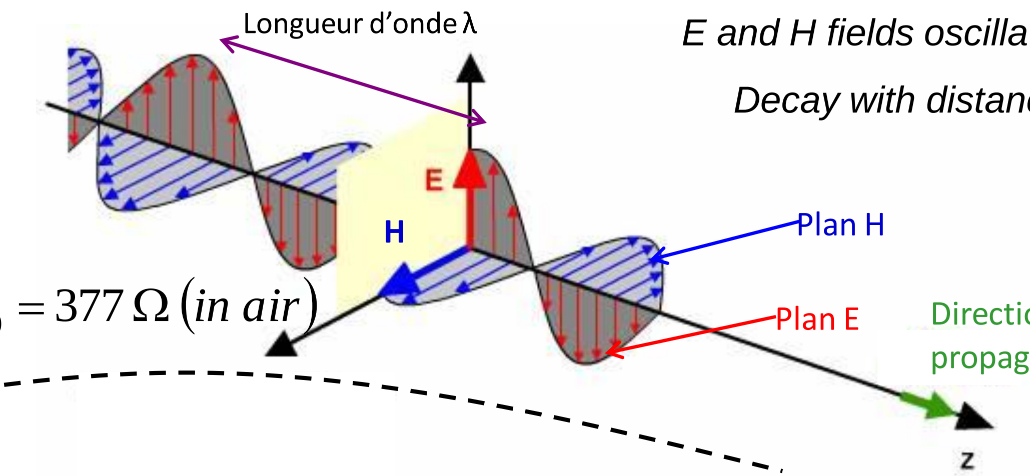
Antenna at PCB/IC level

Radiation

r

Far-field

Plane wave



$$\left|\frac{E}{H}\right| = \eta_0 = 377\,\Omega\,(in\ air)$$

E and H fields oscillate in phase

Decay with distance in 1/r

Near-field

Dominant E or H field

Complex distribution

Decay rapidly with distance ($1/r^3$)

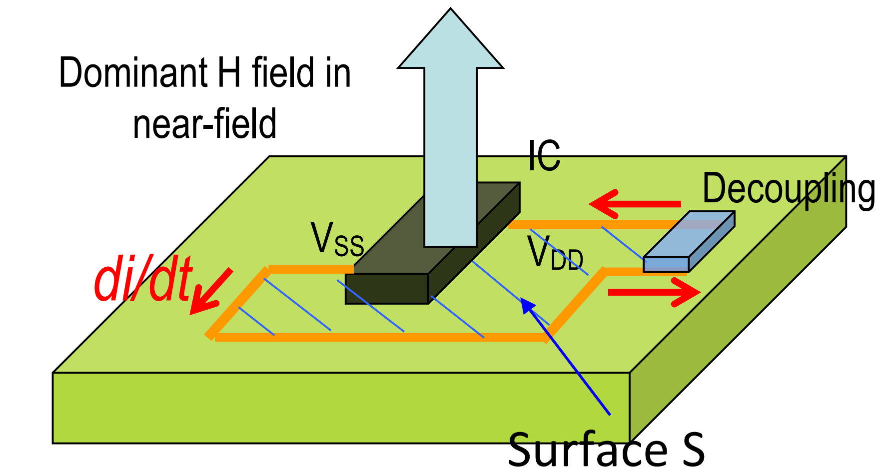
Sources (dv/dt, di/dt)

Antenna at PCB/IC level

Electric vs. magnetic antenna

- At IC or PCB level, two types of basic antenna can be distinguished:

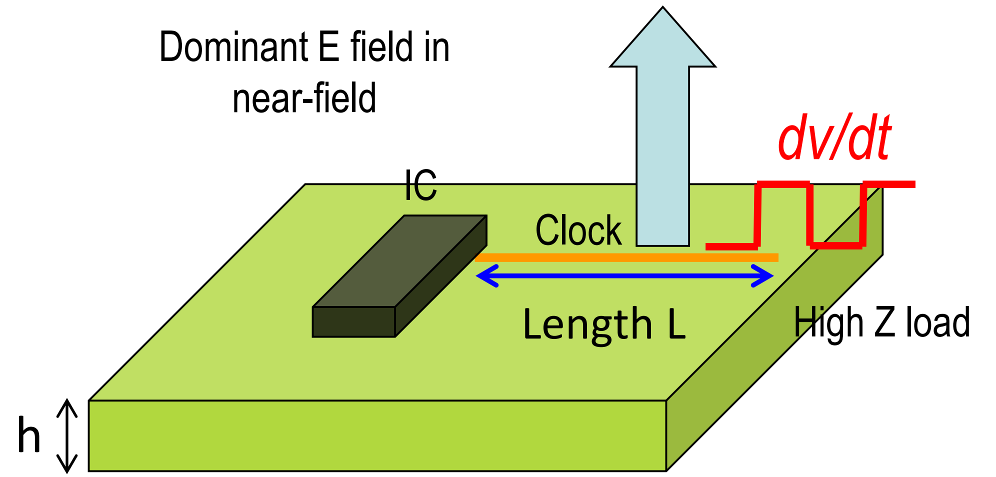
Magnetic antenna (low impedance loop)



In far-field:

$$E_{\max} = \frac{1.32.10^{-14} f^2 S I}{r}$$

Electric antenna (High impedance trace)



In far-field:

$$E_{\max} = 8.27.10^{-14} \frac{V L h C_{line} f^3}{r}$$

$$L = \frac{\lambda}{4} \; si \; f > \frac{c}{4L}$$

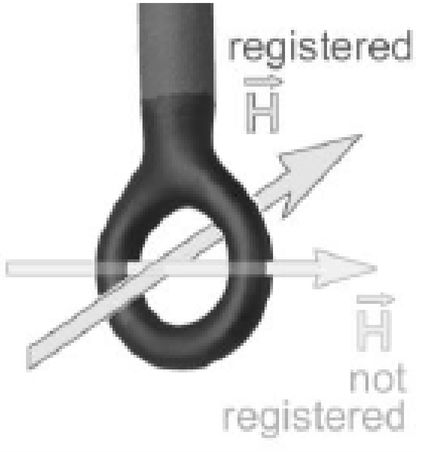
Antenna at PCB/IC level

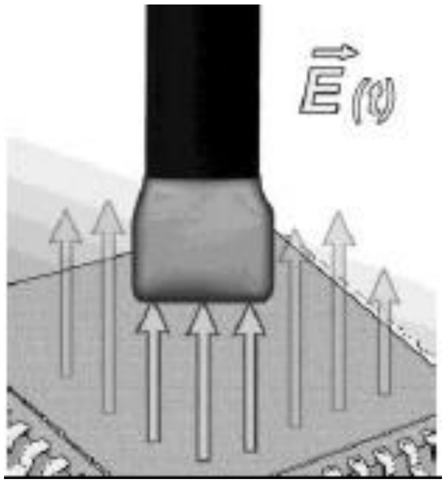
Electric vs. magnetic antenna

- Near-field probes use to sense local electric or magnetic fields

- Excite a microstrip line with a square waveform and connect various types of electrical load (short, open, 50 Ω)
- With near-field probes, observe the distribution of E and H field around the trace. Determine the orientation of H field.

- What is the infliuence of the trace load on the dominant field around the trace ?





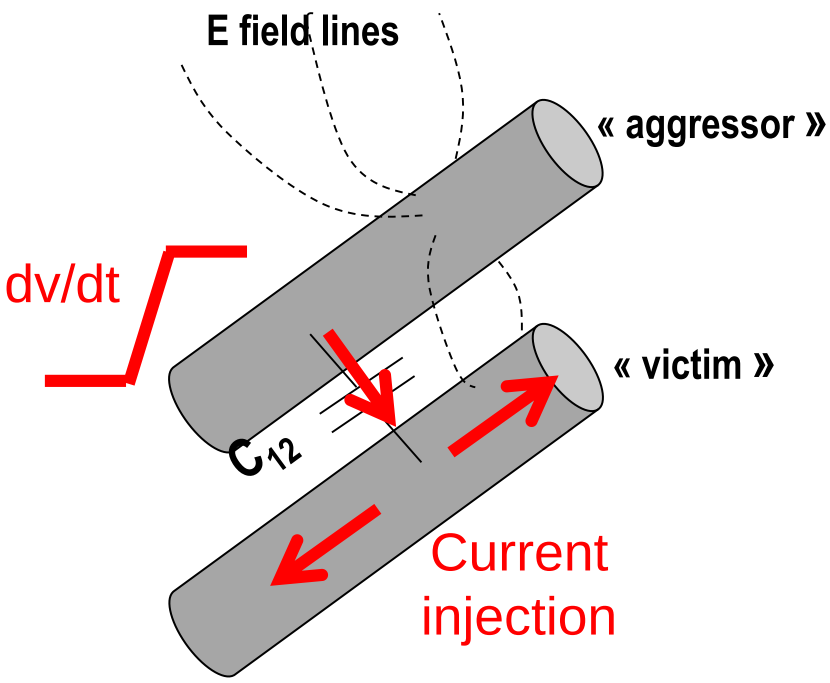
Crosstalk between two nearby traces

Crosstalk

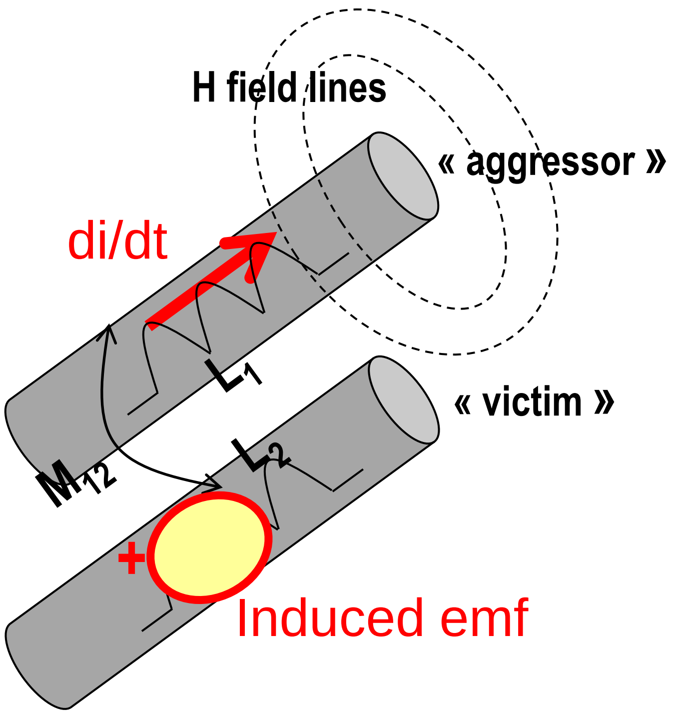
Electric vs. magnetic coupling

- Two types of coupling between two nearby lines:

Electric coupling



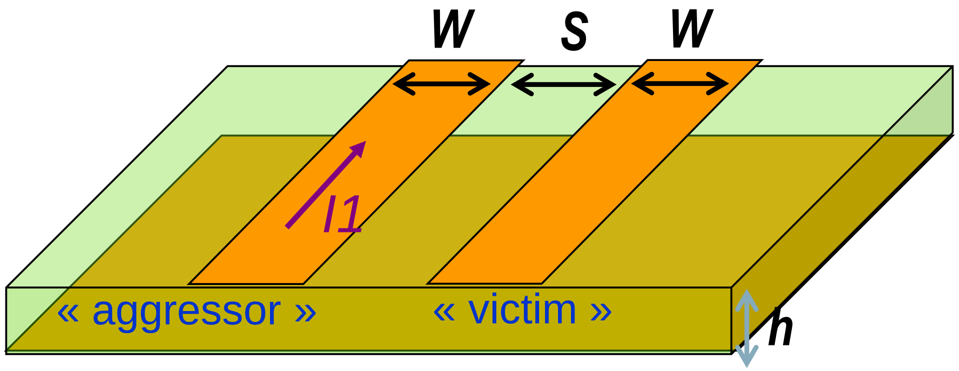
Magnetic coupling



Crosstalk

Electric vs. magnetic coupling

- Two nearby microstripl ines:
  - W = 0.65 mm
  - Separation = 0.15 mm ou 1.65 mm (3W)



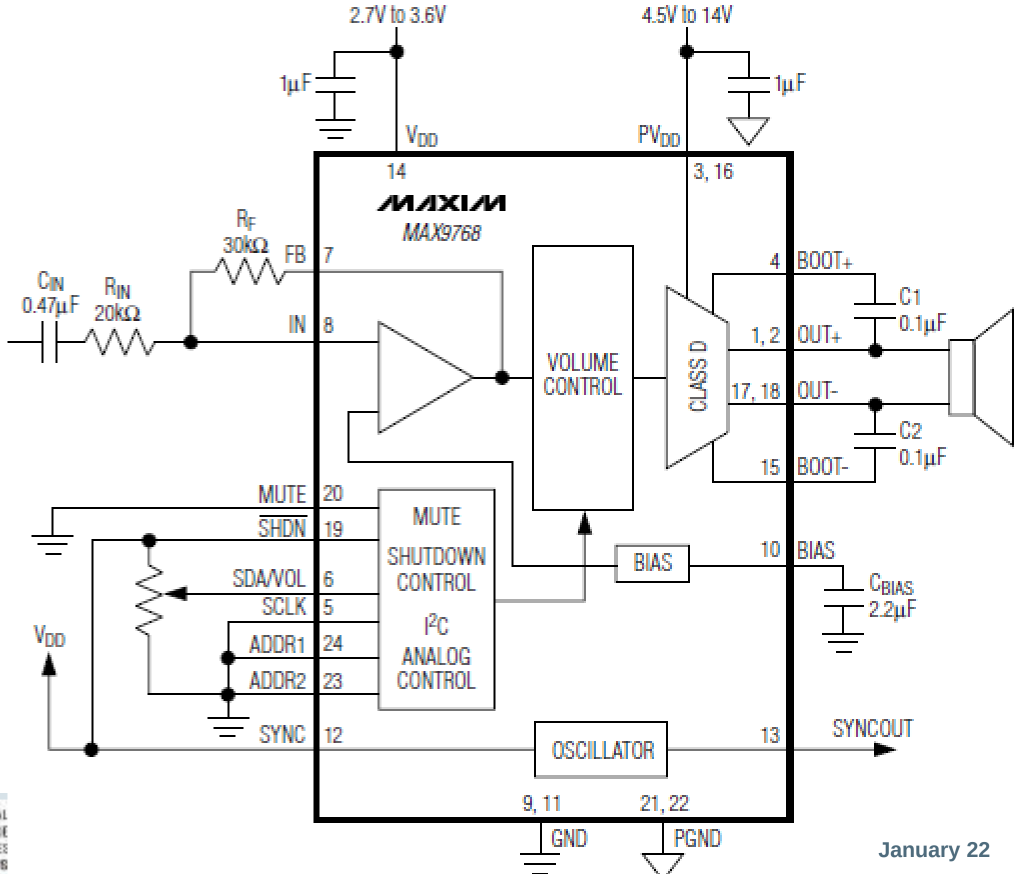
- Apply a square waveform on the input of « aggressor » line. Observe the voltage induced on both terminals of « victim » line (near and far ends).
- Observe the effect of « agressor » line termination (short, open and 50 Ω).
- Propose a basic electrical model to explain observations.
- 3W rule: what is the effect of trace separation ?

CM vs DM current – Cable radiation

CM vs DM current – Cable radiation

Electromagnetic emission from a class-D amplifier

- **MAX9768 – 10 W mono class D speaker amplifier, EN55022 class B compliant.**
- **Applications: low power portable application (notebook computer, Multimedia monitor, GPS navigation system…)**



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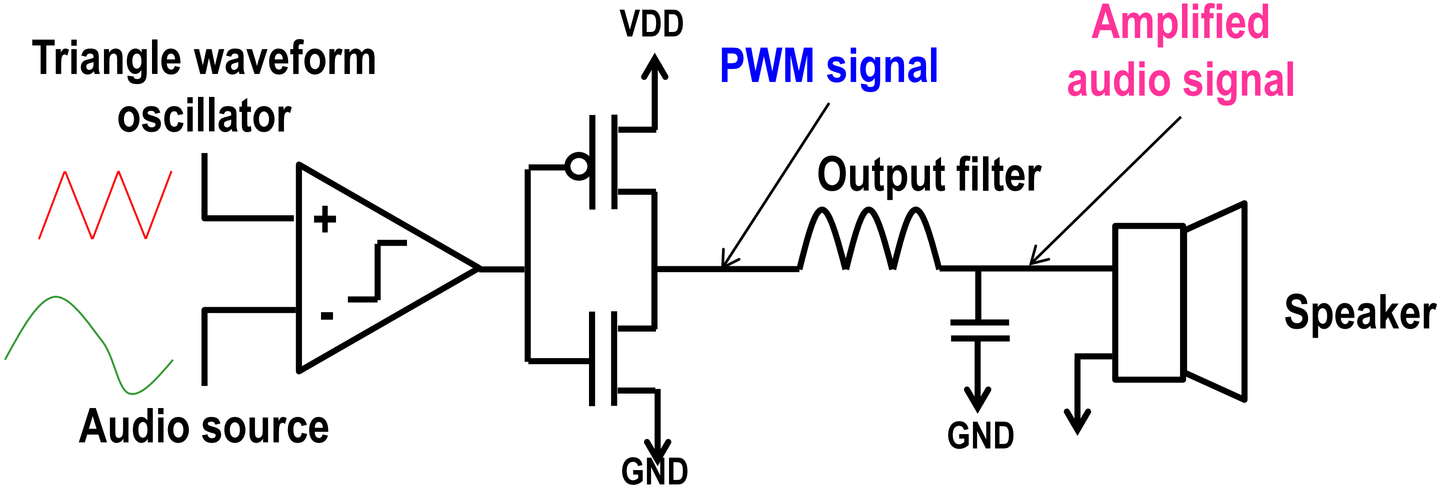
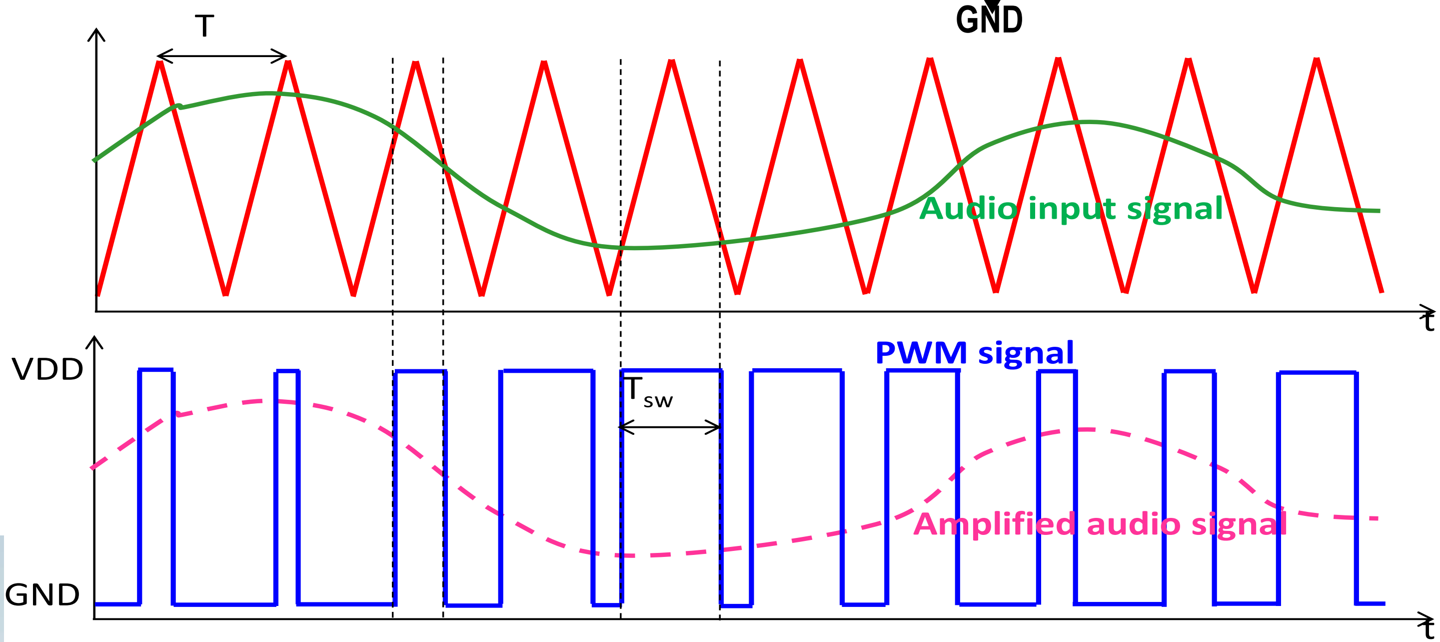
CM vs DM current – Cable radiation

Electromagnetic emission from a class-D amplifier

- **Class D amplifier principle (half-bridge):**





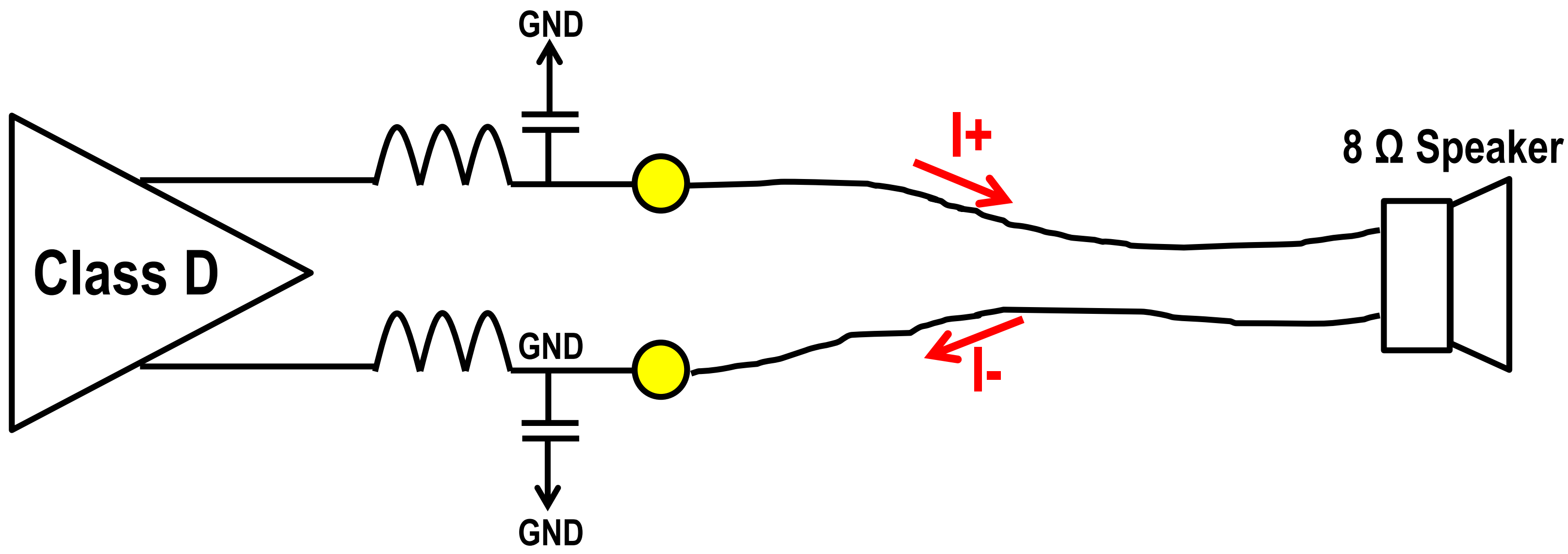
$$out(t) = V_{DD} \frac{T_{SW}(t)}{T}$$

CM vs DM current – Cable radiation

Electromagnetic emission from a class-D amplifier

- **Measure and compare the currents circulating on wires OUT+ and OUT- of the speaker cable.**

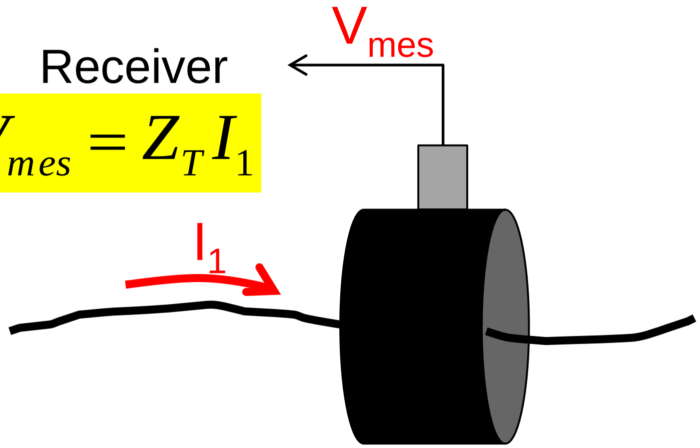
- **Are they perfectly balanced ?**



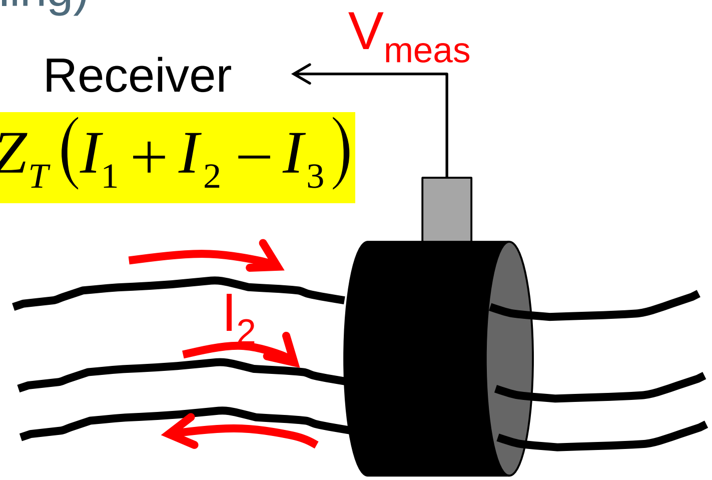
Differential and common-mode current

Differential vs. common mode current measurement

- Transducer current → voltage (magnetic coupling)
- Diagnosis of current circulating on cables

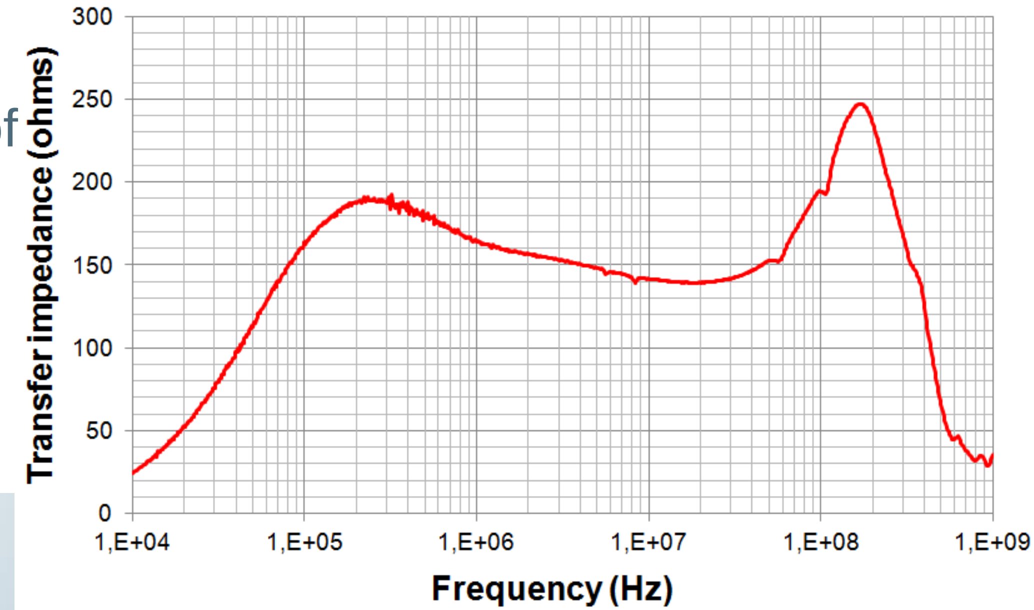


$$V_{mes} = Z_T I_1$$



$$V_{mes} = Z_T\left(I_1 + I_2 - I_3\right)$$

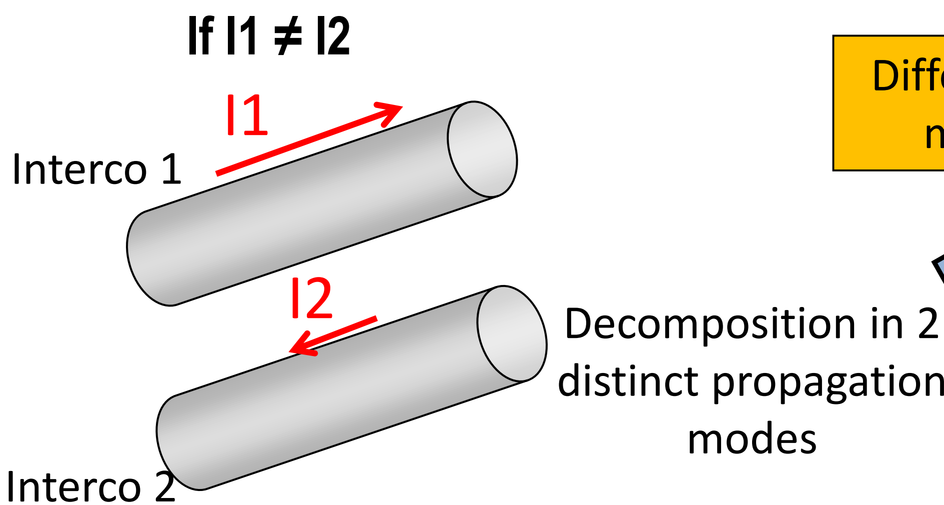
- Example: transfer impedance of TESEQ MD4070 :

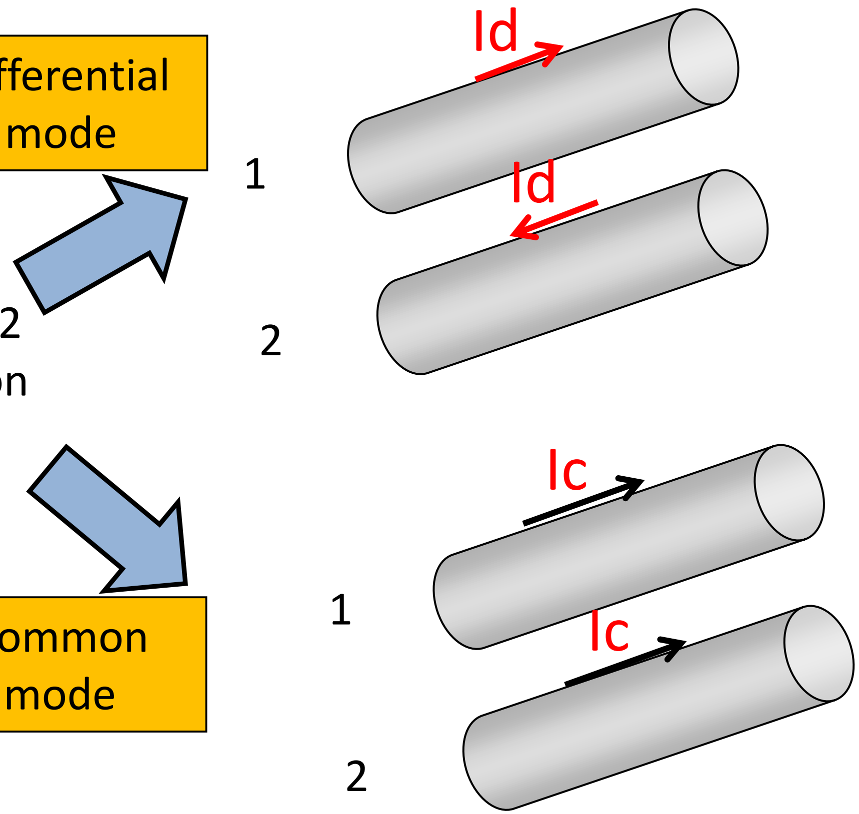


Differential and common-mode current

Differential vs. common mode currents

- **Common mode appears when the return current path is not perfectly defined or differential driver and load are not perfectly balanced.**





$$\vec{I}_D = \frac{\vec{I}_1 - \vec{I}_2}{2}$$

$$\vec{I}_C = \vec{I}_1 + \vec{I}_2$$

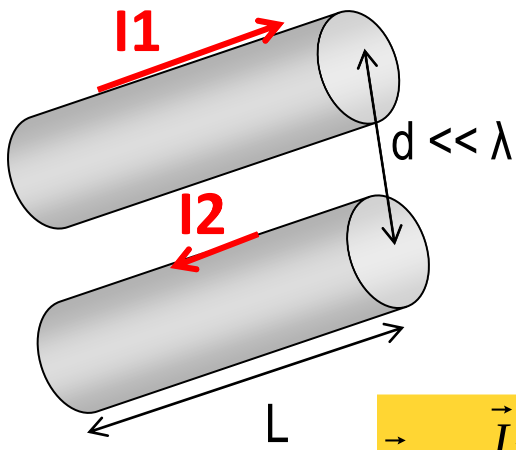
$$\vec{I}_1 = \frac{\vec{I}_C}{2} + \vec{I}_D$$

$$\vec{I}_2 = \frac{\vec{I}_C}{2} - \vec{I}_D$$

Simple radiated emission model

Cable radiation: Differential vs. Common-mode radiation

- Simplified model of worst-case radiation of a two conductor cable

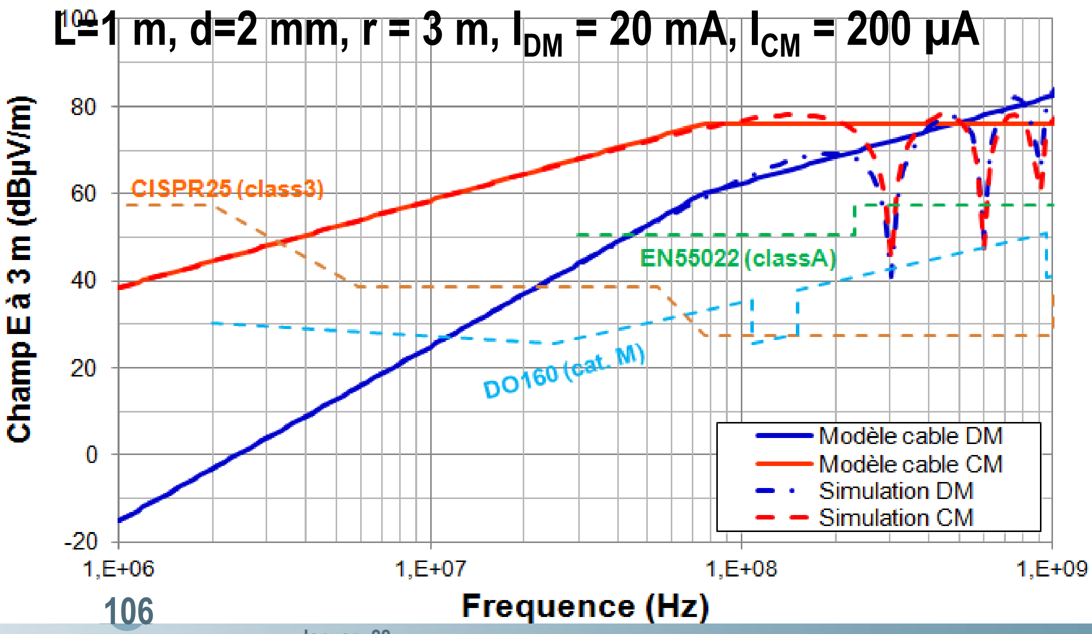


$$\left|E_D\right|_{max} = 1.316.10^{-14}\frac{L.d.f^2}{r}I_D,\ L = \min\left(Long, \frac{\lambda}{4}\right)$$

$$\left|E_C\right|_{max} = 1.257.10^{-6}\frac{L.f}{r}I_C,\ L = \min\left(Long, \frac{\lambda}{4}\right)$$

$$\vec{I}_D = \frac{\vec{I}_1 - \vec{I}_2}{2}$$

$$\vec{I}_C = \vec{I}_1 + \vec{I}_2$$

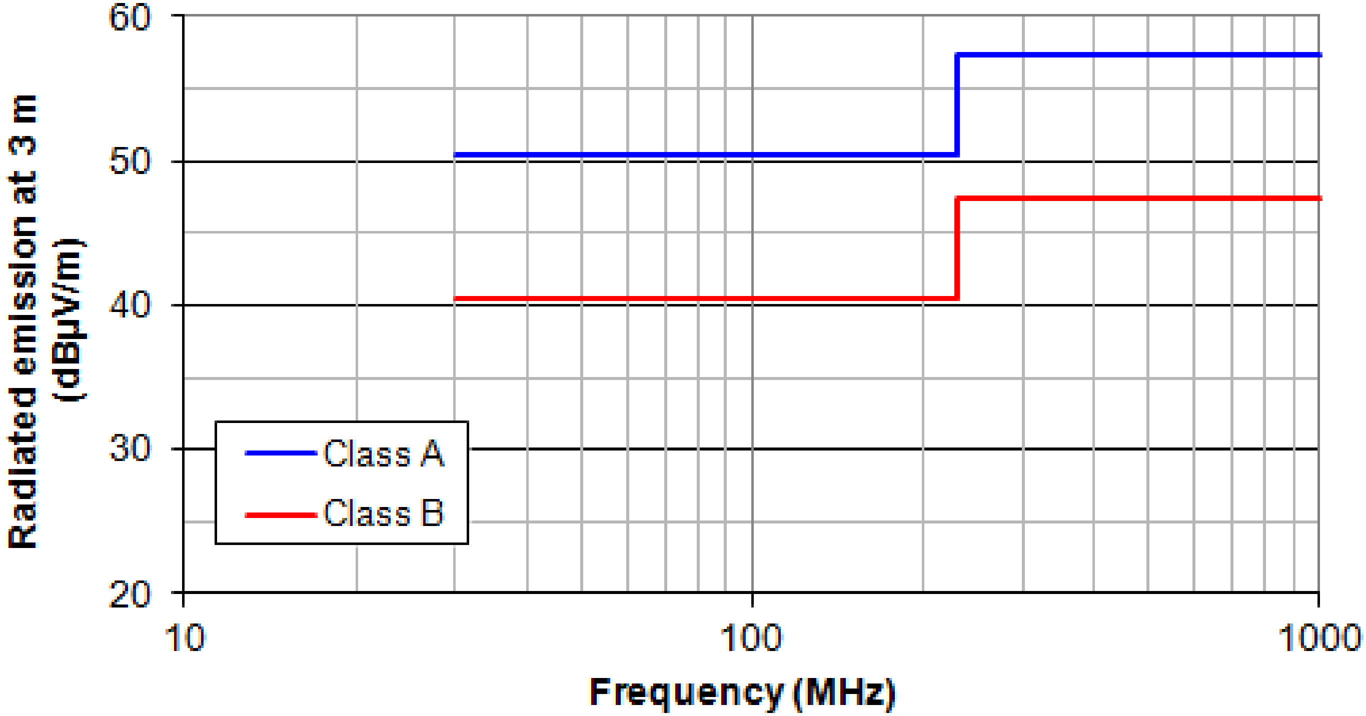


- In electronic equipment, cables are usually the main antennas, especially due to common-mode current.

CM vs DM current – Cable radiation

Electromagnetic emission from a class-D amplifier

- **Evaluate the differential and common-mode radiation at 3 m produced by the speaker cable.**
- **Does it comply with EN55022 class B standard ?**



CM vs DM current – Cable radiation

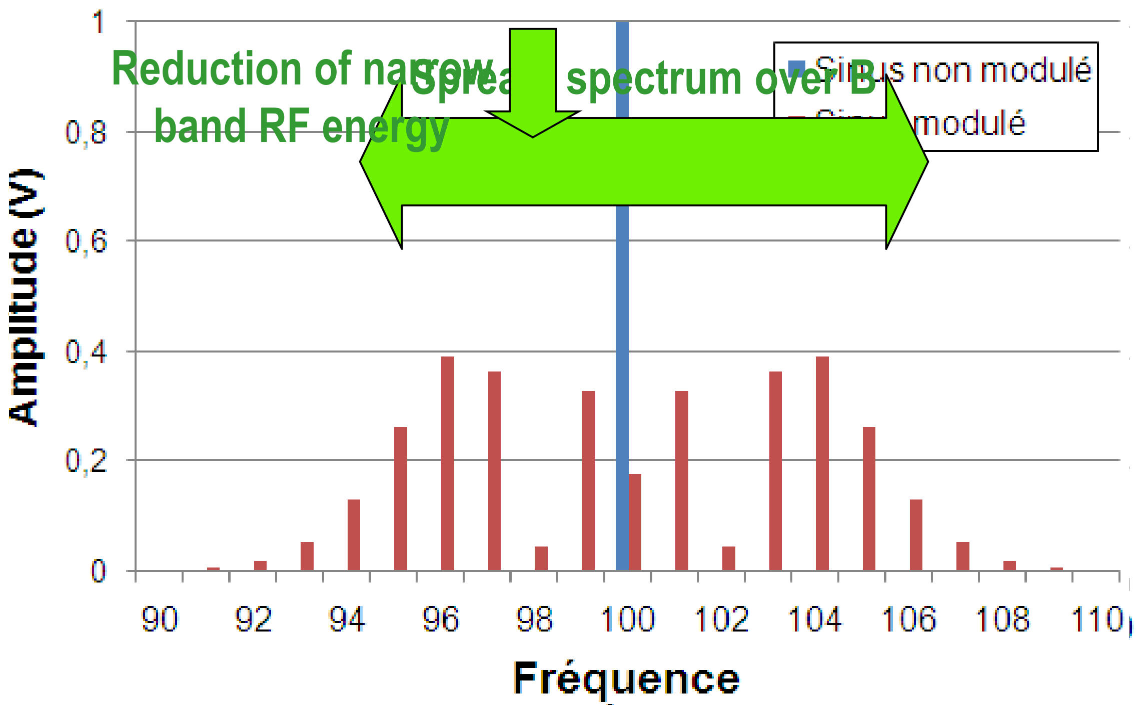
Electromagnetic emission from a class-D amplifier

- **Solutions ?**

Spread spectrum frequency modulation

Frequency modulation

- Frequency modulation spreads the spectrum of a signal
- Example : sinus clock at Fc = 100 MHz vs modulated sinus clock:



Carrier frequency Fc = 100 MHz

Modulation frequency FM = 1 MHz

Frequency excursion dF = +/- 5 MHz

→ Modulation index md = 5

$$S_{FM}(t) = \cos\left(\omega_C t + \frac{df}{F_M}\cos\omega_M t\right)$$

$$S_{FM}(t) = \cos(\omega_C t + md\cos\omega_M t)$$

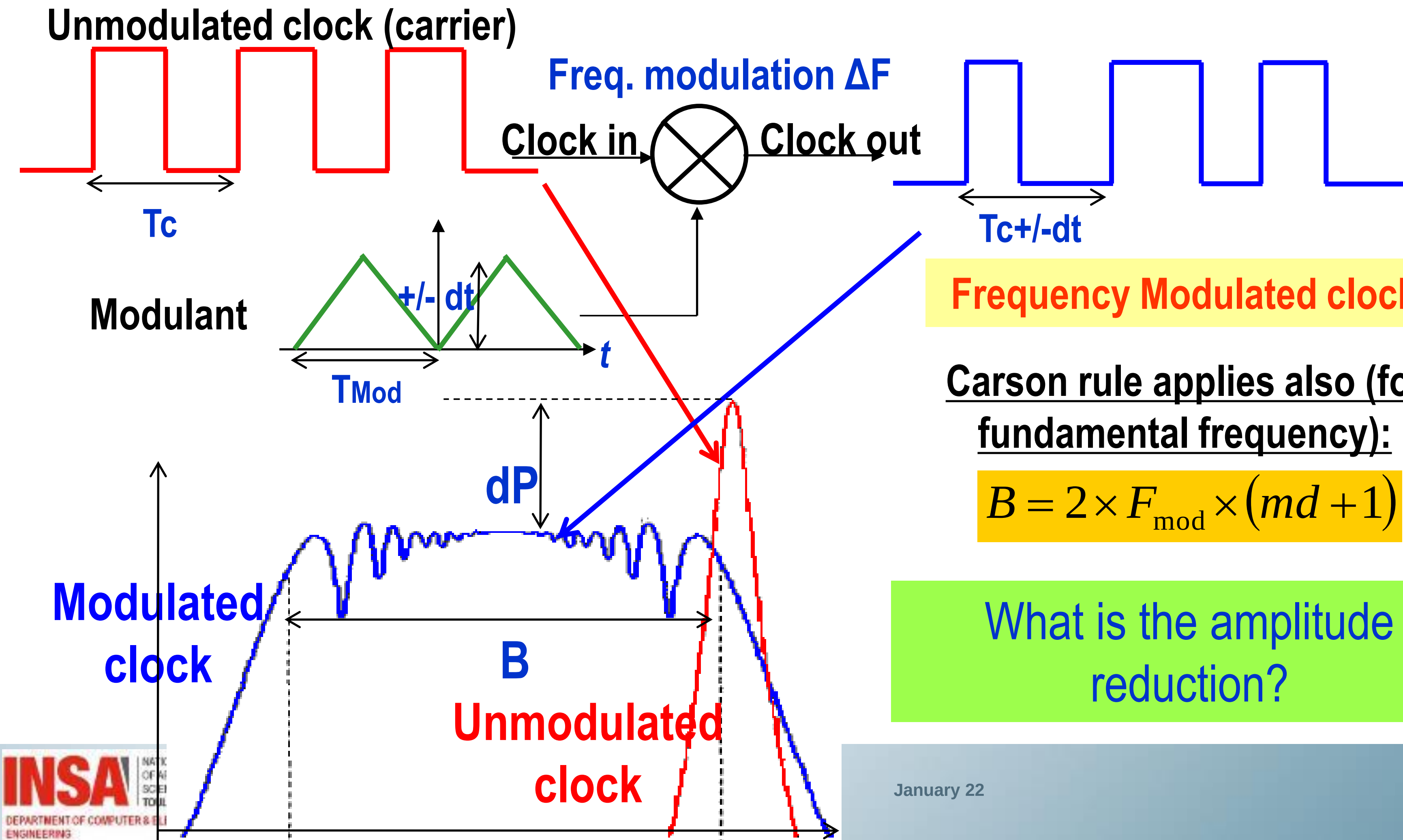
Carson rule:

$$B = 2 \times F_M \times (md + 1)$$

Spread spectrum frequency modulation

Principle

- Emission from clock or PWM signal can be reduced by using spread spectrum frequency modulation (SFFM)



Carson rule applies also (for fundamental frequency):

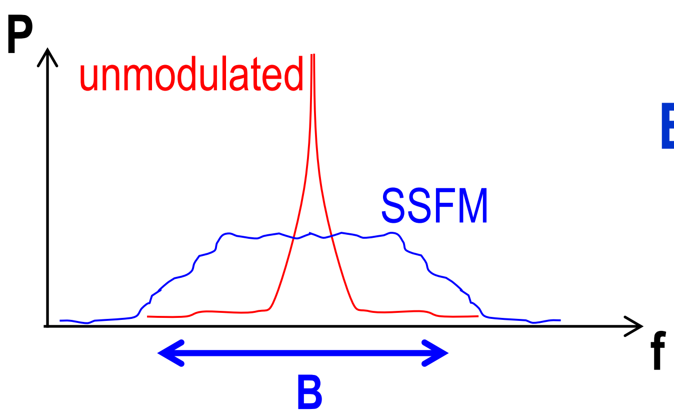
$$B = 2 \times F_{mod} \times (md + 1)$$

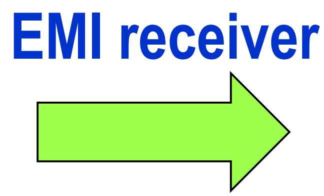
What is the amplitude reduction?

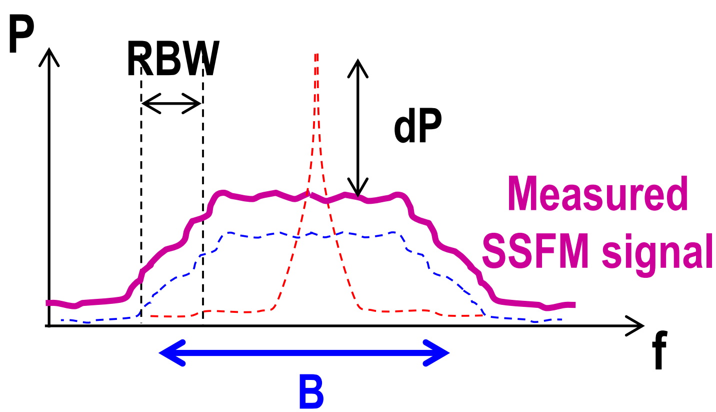
Spread spectrum frequency modulation

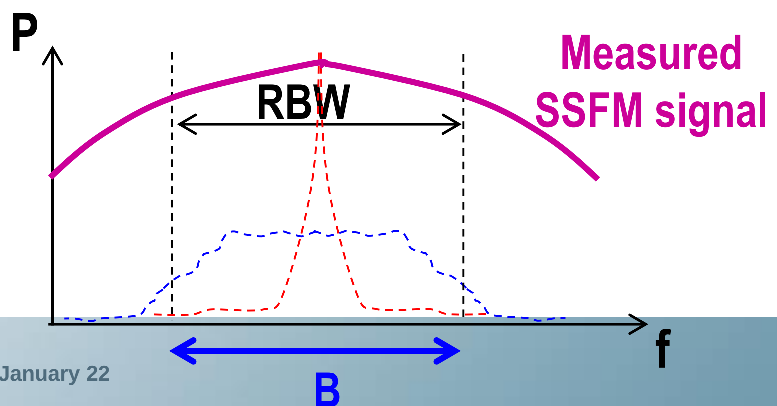
Emission improvement

- The reduction of spectrum amplitude depends on:
  - Parameters of the modulation (md and Fm)
  - The modulant waveform (selection of a waveform that makes the spectrum as flat as possible)
  - Receiver bandwidth RBW:









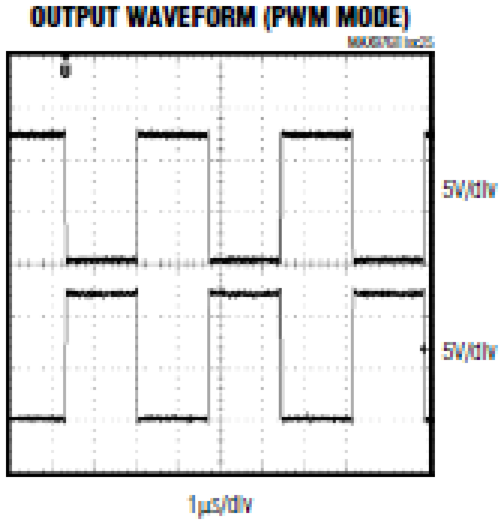
$$dP(dB) \approx 10\log\left(\frac{B}{RBW}\right)$$

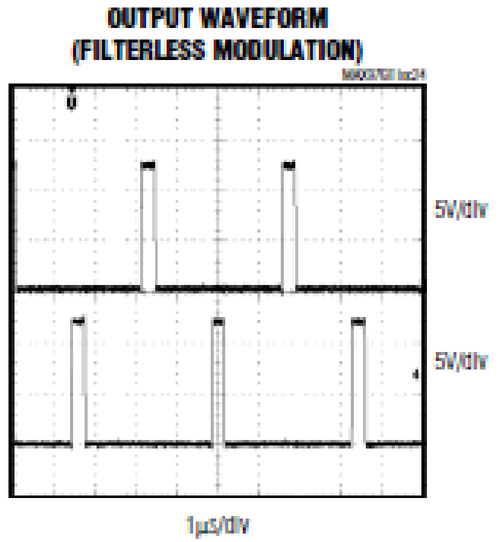
Spread spectrum frequency modulation

Case study – Class-D amplifier MAX9768

- Two output modulations:
  - Classic PWM mode
  - Filterless modulation mode

- Three operating modes:
  - Fixed frequency (300 or 360 kHz)
  - SSFM (Fc = 300 kHz, df = +/- 7.5 kHz)
  - External clock (1 to 1.6 MHz)





Spread spectrum frequency modulation

Case study – Class-D amplifier

- Observe the effect of the internal SSFM on the fundamental frequency of the common-mode noise which propagates along the speaker cable. Use a narrow RBW.

- Observe the effect of the internal SSFM on the spectrum of the common-mode noise which propagates along the speaker cable. Use a narrow RBW.

- EN55022 recommends the following RBW:
  - 9 kHz from 150 kHz to 30 MHz
  - 120 kHz from 30 MHz to 1 GHz
- What is the effect of the internal SSFM on the conducted emission?