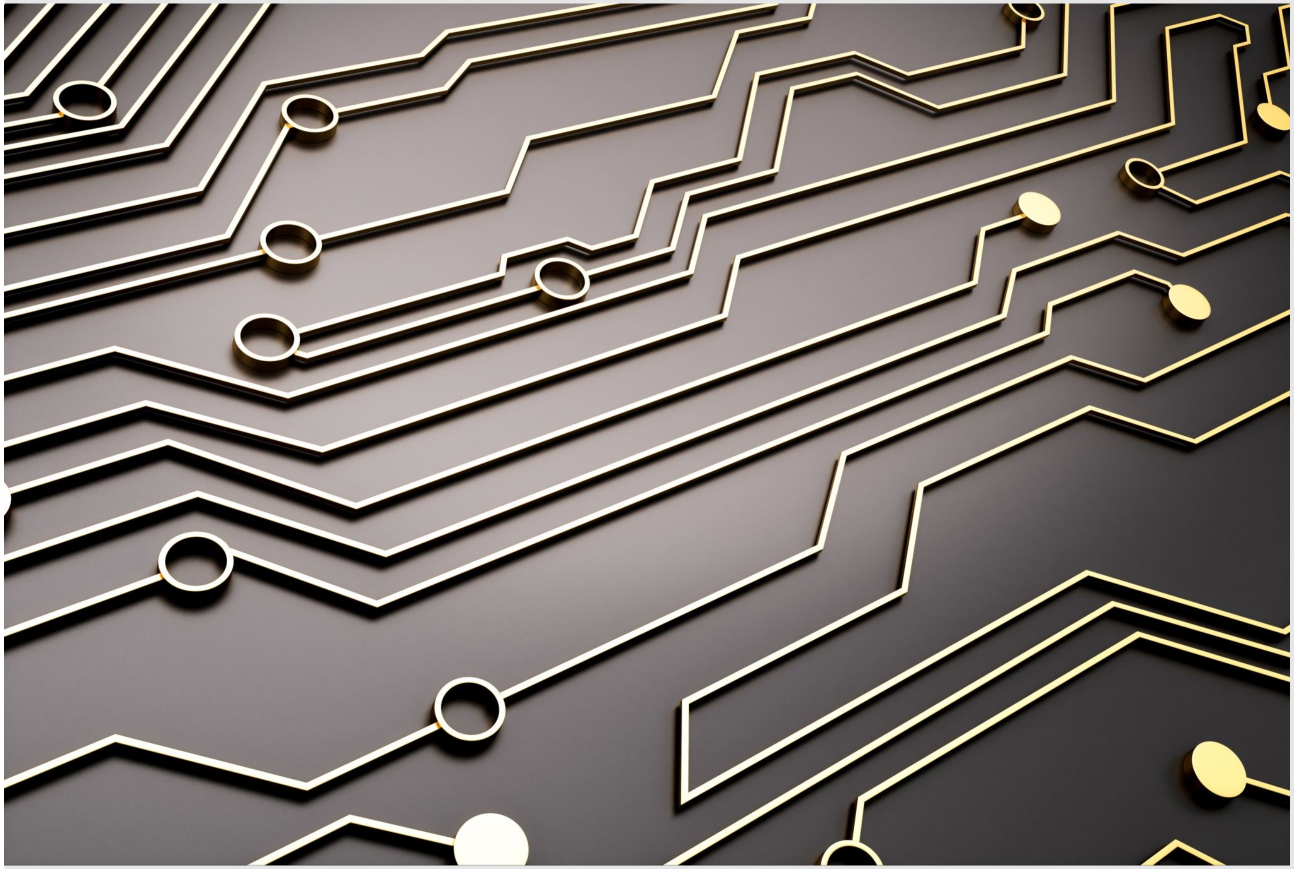
ILLINOIS
Electrical & Computer Engineering
GRAINGER COLLEGE OF ENGINEERING



ECE 477 Engineering Electromagnetic Compatibility

Prof. Victoria Shao
Teaching Associate Professor

Introduction of Prof. Shao

- BS Electrical Engineering 2003
- PhD Electrical Engineering 2008
- Post doctoral training 2009-2013
- Research Assistant Professor 2013-2019
- Teaching Assistant Professor 2019-2024
- Teaching Associate Professor 2024-now

Research Interests

- Electromagnetic compatibility/interference (EMC/EMI)
  - ECE 498 Engineering EMC – Prof. Victoria Shao
- Signal and power integrity analysis (SI/PI)
  - ECE 546 Advanced Signal Integrity – Prof. Jose Schutt-Aine
- Computational electromagnetics (CEM)
  - ECE 540 Computational Electromagnetics – Prof. Jianming Jin
- High-power microwave (HPM)

Outside Classroom

- Two kids (12th grade and 3st grade)
- Playing Volleyball
- Watch Sci Fi movies and criminal TV series
- Have a dog named Molly

EMC498 - Engineering EMC

Lectures: MWF 11:00-11:50 am

Prerequisites: ECE 329 or permission of the instructor

Reference:
1. C. R. Paul, "Introduction to Electromagnetic Compatibility, 3rd Ed.," John Wiley and Sons, New York, 2022.
2. Lecture slides and notes

Grading Policy

Undergraduate students

- Two midterms (25% each x 2 = 50%)
- Final exam (30%)
- Homework (15%)
- Participation (5%)

Graduate students

- Two midterms (20% each x 2 = 40%)
- Final exam (25%)
- Final project (15%)
- Homework (15%)
- Participation (5%)

Course Outline

1. Introduction to EMC
2. EMC Requirements for Electronic Systems
3. Transmission Lines and Signal Integrity
4. Non-ideal Behavior of Components
5. Conducted Emissions and Susceptibility
6. Radiated Emissions and Susceptibility
7. Crosstalk
8. Grounding, Filtering and Shielding
9. System Design for EMC

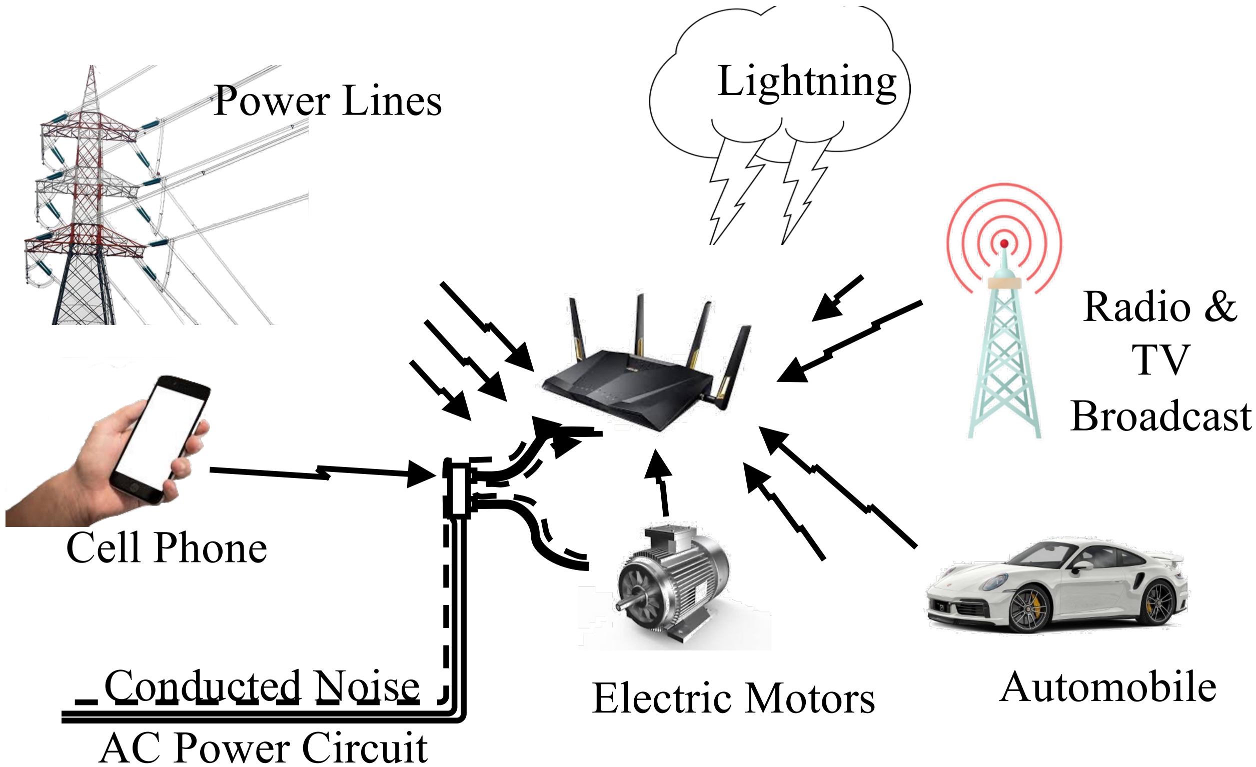
Outline – Week 1

- Definition of EMI & EMC
- Why EMC
- How EMC – Coupling mechanisms
- Electrical dimensions and waves
- EMC Requirements/Regulations
- Decibels and Common EMC units

Electromagnetic Energy Is Everywhere

Electromagnetic Environment

- ***Electromagnetic environment*** is the totality of the electromagnetic phenomena existing a given location.



1.1 What is EMC ?

➢**Electromagnetic interference** (EMI) is electromagnetic energy that adversely affects the performance of electrical/electronic equipment by creating undesirable responses or complete operational failure.

➢**Electromagnetic compatibility** (EMC) is the ability of electrical or electronic equipment/systems to function in the intended operating environment without causing or experiencing performance degradation due to EMI.

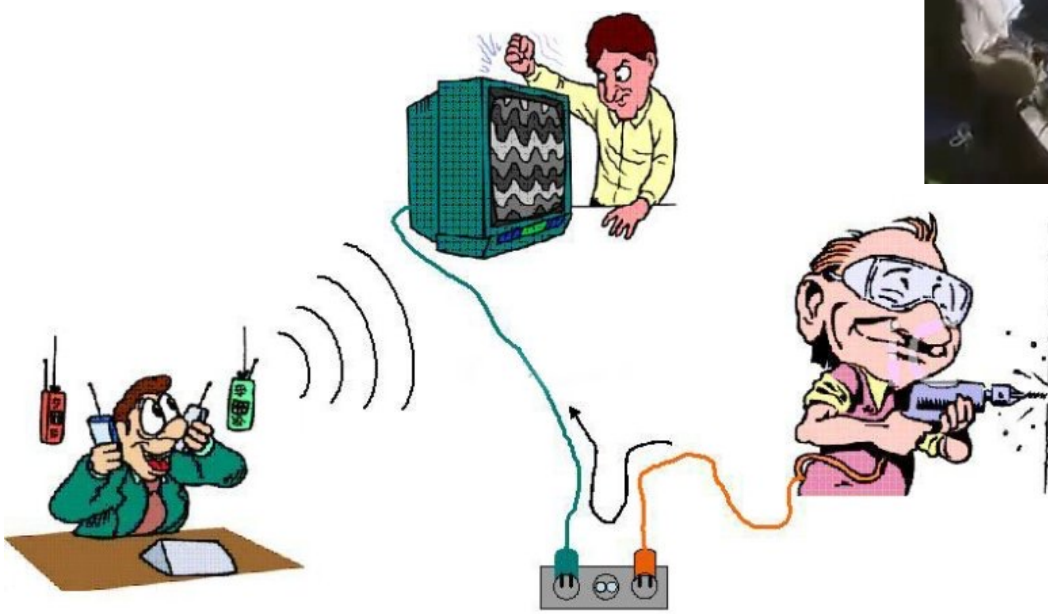
1.1 What is EMI and EMC ?

- EMI
  - Interference: the effect (what we "see")
    - E.g. radio noise, lights flicker, no mobile phone reception.
  - Disturbance: the cause of the problem
    - E.g. mobile phones, lightning, solar flare, jammers, currents, transient signals, fields etc.
- EMC
  - EMI results in not achieving EMC
  - EMI causes EMC issues

A system is ***electromagnetically compatible*** if

- It does not cause interference with other systems.
- It is not susceptible to emissions from other systems.
- It does not cause interference with itself.

Problem of EMI and EMC



Problem of EMI and EMC

20 years ago, cases of cellphones disrupting pacemaker have been reported.

Problem of EMI and EMC

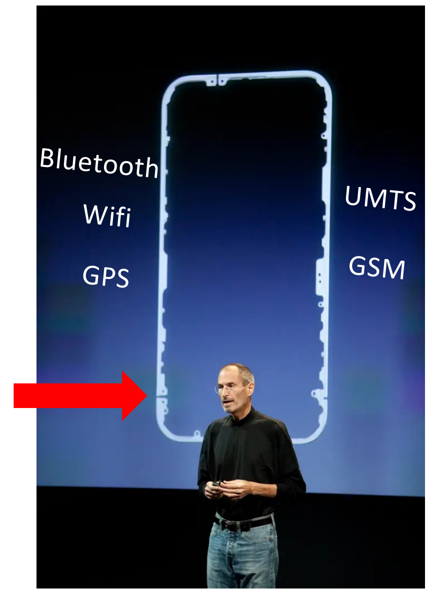
- The early development of EMC owes a great deal to the need to protect aircrafts from lightning strike.

- Lightning flash has several millions of volts and several thousands of amperes, while the microelectronics operate at a few volts and a few milliamperes

One of the biggest scandal of Apple history – ‘Antennagate’

The phone seemed to lose its network connection and drop calls when you held it in your left hand.

"All phones have sensitive areas. Just avoid holding it in this way," – Steve Jobs, CEO



Antennas are designed to surround it, which overlaid with a metal band

Effects of EMI

- Momentary disturbance in TV and radio reception due to operation of mixer-grinder/electric shavers/a passing vehicle, etc.
- Reset of computers and loss of data.
- Change of setting of status of control equipments.
- Failure of pacemaker implemented in a patient due to a ‘walkie talkie’
- Malfunctioning of flight controlling system due to use of laptop by passenger.
- Biological hazards.

Discussion

Is it safe to stay close to microwaves?

Radiation regulations on radiated power density from microwaves

- Federal Communications Commission (FCC) set the regulations.
- In general, for frequencies between 30 MHz and 300 GHz, the maximum permissible exposure (MPE) for the general public is typically set at **1 mW/cm^2** for continuous exposure. – FCC 47 CFR § 1.1310 (Radiofrequency Radiation Exposure Limits)
- For occupational exposure (i.e., people who are regularly exposed to RF radiation as part of their job), the limit is higher, typically **5 mW/cm^2**.
- At higher power densities, particularly those well above **10 mW/cm^2**, immediate thermal effects such as skin burns and tissue damage could occur rapidly.

Distance from microwave oven (cm)	Power density (mW/cm^2) mean ± std dev						
	Front[a]	Left[a]	Left-45°[b]	Right[a]	Right-45°[b]	Up-45°[b]	Down-45°[b]
0	0.27 ± 0.06	0.21 ± 0.02	0.21 ± 0.04	0.26 ± 0.05	0.18 ± 0.04	0.27 ± 0.02	0.33 ± 0.06
30	0.18 ± 0.02	0.06 ± 0.03	0.14 ± 0.03	0.11 ± 0.05	0.08 ± 0.03	0.16 ± 0.02	0.19 ± 0.01
61	0.07 ± 0.04	0.01 ± 0.00	0.07 ± 0.02	0.01 ± 0.01	0.01 ± 0.00	0.05 ± 0.01	0.10 ± 0.00
91	0.02 ± 0.01	0.01 ± 0.00	0.03 ± 0.01	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.05 ± 0.01

A. Xiang, Mapping the electromagnetic field in front of a microwave oven, J of Emerging Investigators, Sept. 2019.

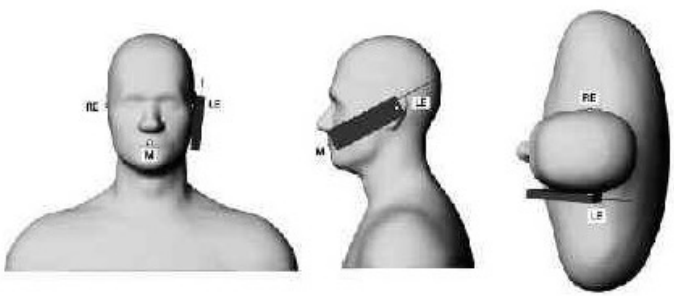
1.2 Why EMC

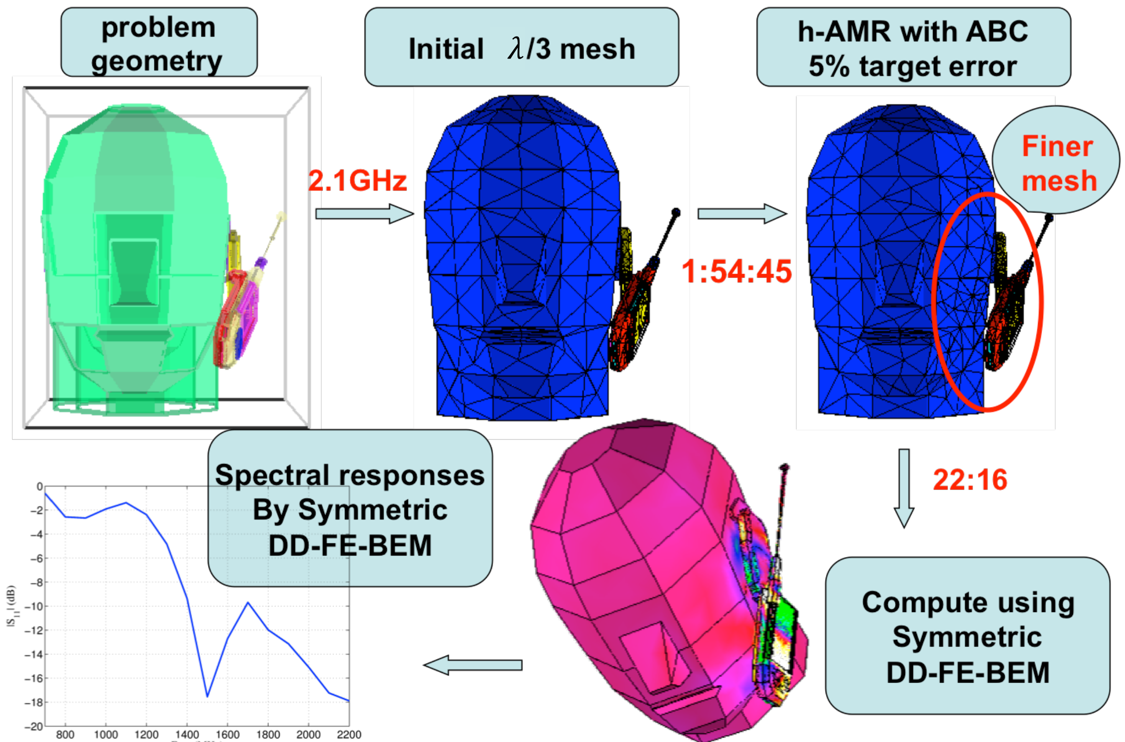
- Healthy reasons:
  - Microwave oven
  - GSM for brain tumor
  - Cancer caused by high power line
- Safety reasons
  - Aircraft navigation
  - Appliance in home

1.2 Why EMC

Wireless communication:

GSM for brain tumor???





Medical Equipment Cases

- Modern medical equipment has experienced EMI problems. From 1979 to 1993, the Food and Drug Administration (FDA) received over 90 reports concerning EMI problems in the field. It was pointed out that users experiencing medical equipment performance degradation might not suspect EMI as a possible cause. Thus, EMI problems are more likely to be under-reported to the FDA.

Medical Devices

Runaway Wheelchairs

Some powered wheelchairs experienced unintentional movements when police, fire, or other transmitters were activated nearby.

(Source: NASA Reference Publication 1374 July 1995)

Ambulance Heart Monitor

A heart attack victim was being taken to the hospital with a monitor/ defibrillator attached to the patient. But, every time the personnel turned on the radio to request medical advice, the machine shut down and the patient died.

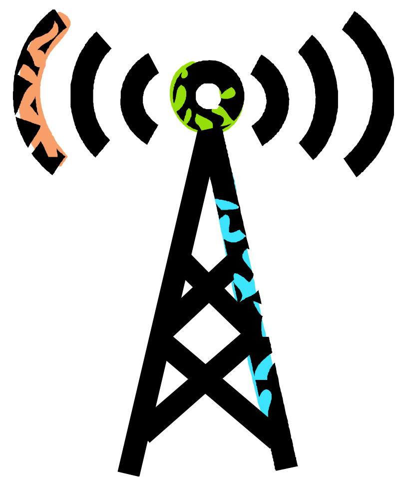
(Source: NASA Reference Publication 1374 July 1995)

ABS Failure

- Early Antilock Braking Systems (ABS) on both aircraft and automobiles were susceptible to electromagnetic interference.
- Accidents occurred when the brakes functioned improperly because EMI disrupted the ABS control system.

Blackhawk Crashes

- Between 1981 and 1987, five *Blackhawk* army helicopters crashed and killed or injured all on board when flew too near radio broadcast transmitters.
- Cause: insufficient immunity of flight (on-board) control electronic sub-system against high intensity radiated fields (HIRF) that produced uncommanded movements while flying past radio broadcast towers.



Sinking of Sheffield

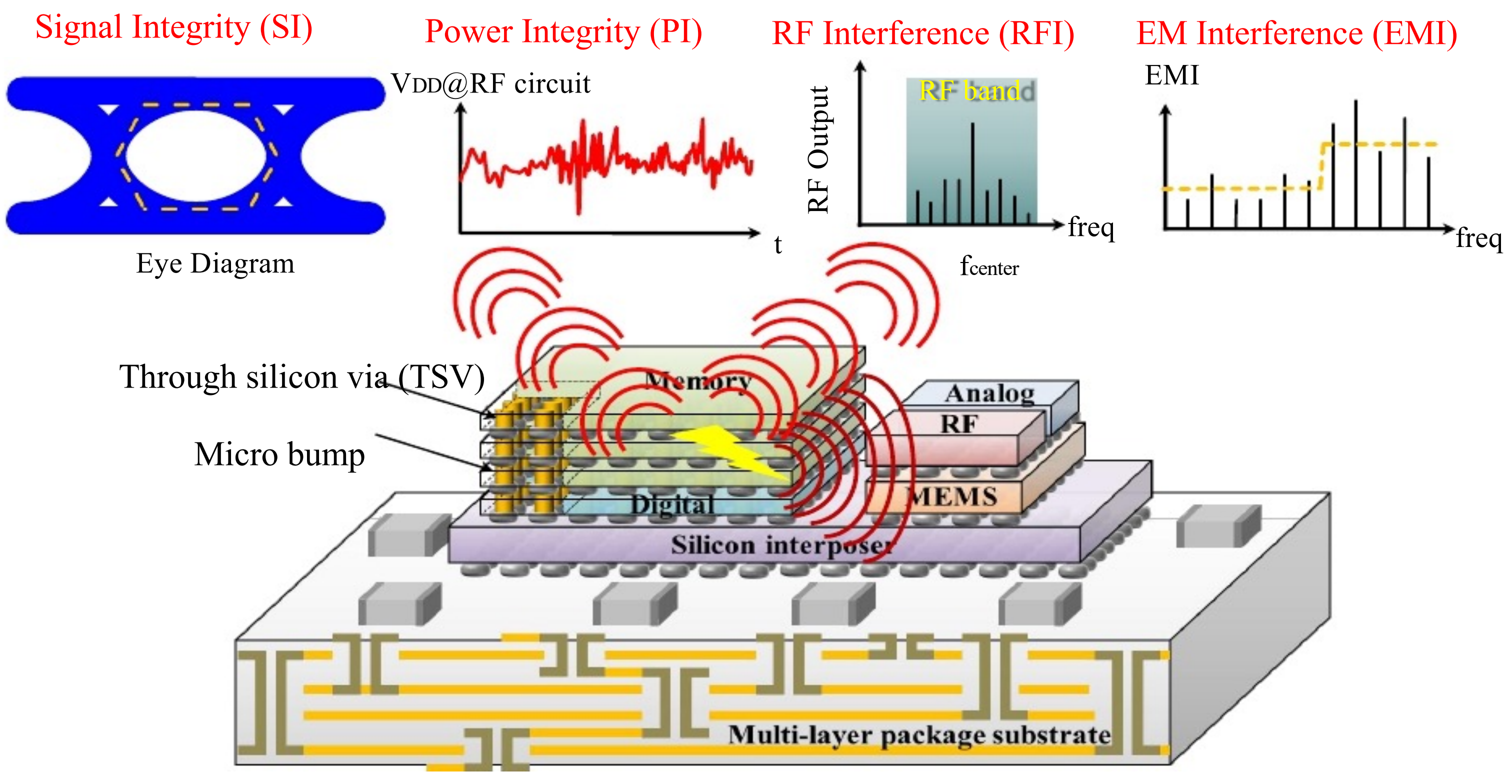
In 1982, Britain and Argentina fought a war over the Falkland Islands. British HMS Sheffield was destroyed by an Exoret missile as it switched off its missile defense system that was causing interference to its satellite communications.

Power lines → cancer?

- WHO: “There is little experimental or theoretical evidence that mutations could be directly caused by ELF [extremely low frequency] magnetic fields…. There is little evidence that ELF electric or magnetic fields can cause malignant transformation of cells in culture.”
- However, EMF emitted from high power lines is much stronger than those surrounding household appliances.

Noise interference issues in 3-D IC:

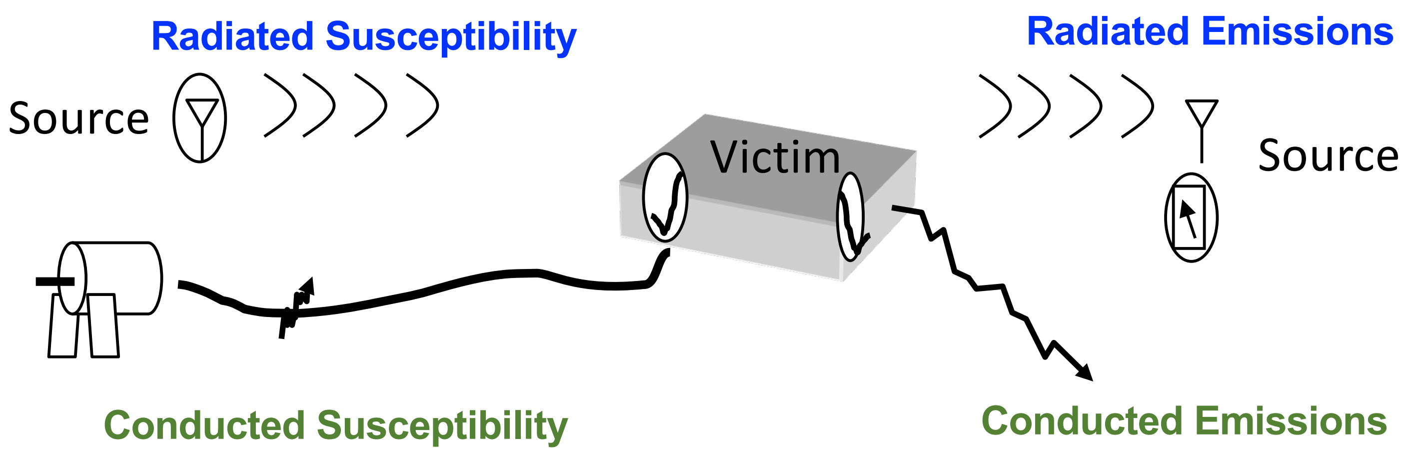
In the high integration and high performance 3D IC, reducing the noise interference either in Intra(inter)-system plays an important role in maintaining performance and stability.



1.3 How Does EMI Affect Electronics?

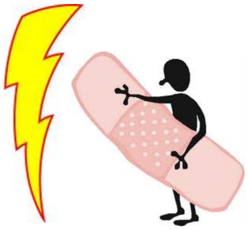
Radiated and conducted interference

- Radiated Interference Enters and Exits Equipment through air or enclosure penetration
- Conducted Interference Enters and Exits Equipment through wires and cables



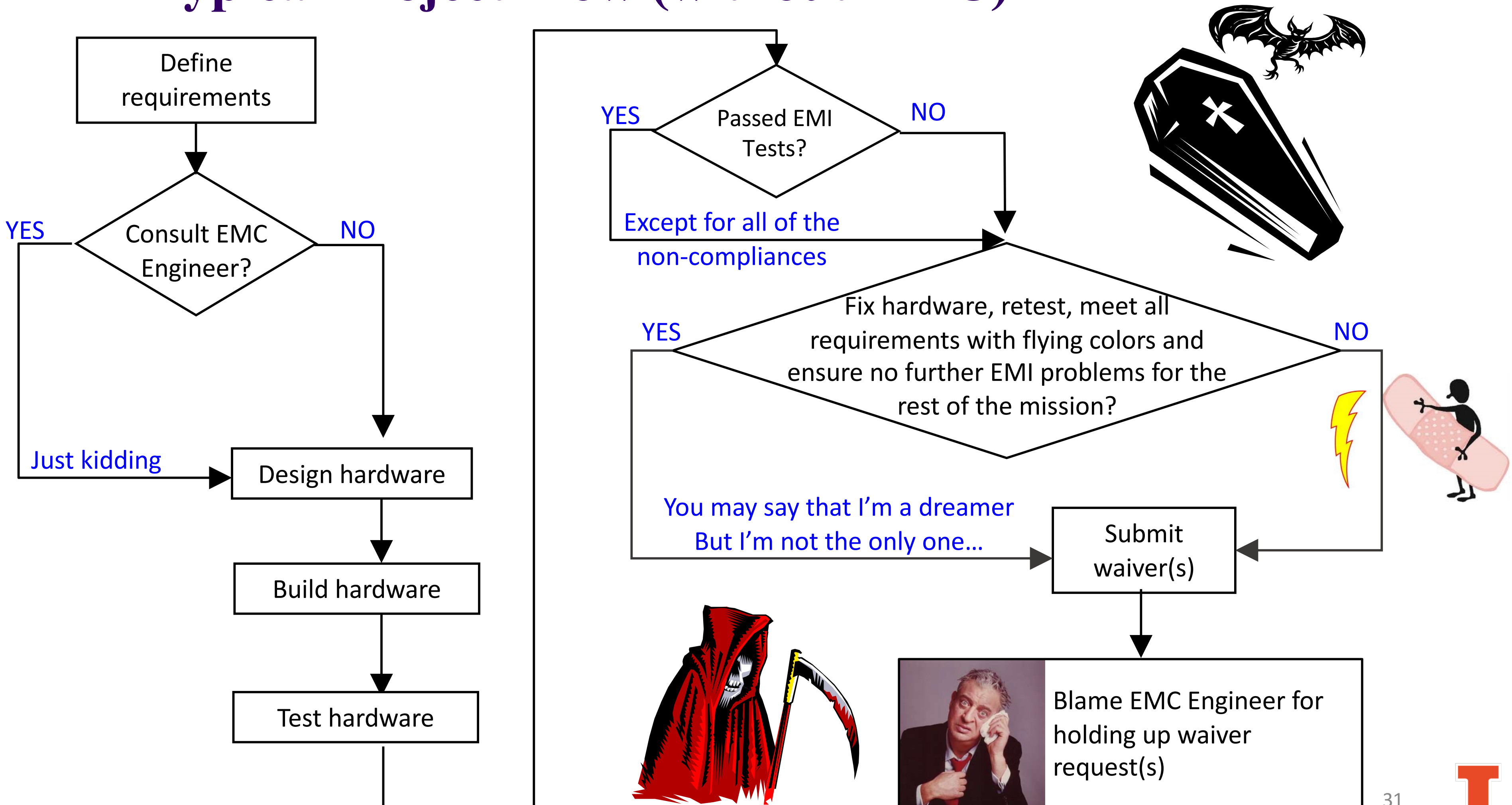
Impacts of EMC Problems

- Technical impacts of EMC problems range from:
  - Occasional "glitches" (annoyance)
  - Compromised mission performance
  - Mission failure
- All EMC problems:
  - Cost projects valuable time and **$$$$** to diagnose
  - Force undesirable decision:
    - Spend additional time and **$$$$** to fix the problem properly, or
    - Spend minimal additional time and **$** to apply "band aid" fix, or
    - Submit waiver and live with compromised performance and risk of continued problems over mission life



"An ounce (28.35 grams) of prevention is worth a pound (0.4536 kilogram) of cure"

Typical Project Flow (without EMC)



1.3.1 EMC Source-Path-Receptor Model

Noise Source → Propagation Path → Receptor (Victim)

Noise Source	Propagation Path	Receptor (Victim)
<u>Natural</u> Terrestrial Atmospheric Sun . . .	<u>Radiation</u> Far-Field Plane Wave Near-Field Capacitate cross-talk Inductive cross-talk	<u>Biological</u> Human Animal Plants
<u>Man-Made</u> Broadcast Radar Fluorescent lights Computing devices Microwave Ovens	<u>Conduction</u> Power distribution Signal distribution Ground loops	<u>Man-Made</u> Broadcast receivers Navigation receivers Radar receivers Computing devices Biomedical sensors

How to Control EMC?

Noise Source → Propagation Path → Receptor (Victim)

Cost:	Low	middle	high

Three ways to prevent the interference

- Suppress the emission at its source
- Make the coupling path as inefficient as possible
- Make the receptor less susceptible to the emission

Noise reduction methods: proper equipment circuit design, shielding , grounding, filtering, isolation, separation, orientation and noise cancellation techniques.

EMC technique include three levels

First: (Basic)

--- After the development of product is completed, we can do all standard EMC tests following the regulations

--- When they can not pass, you can fix the problems by adding components. (Such as cap, choke …)

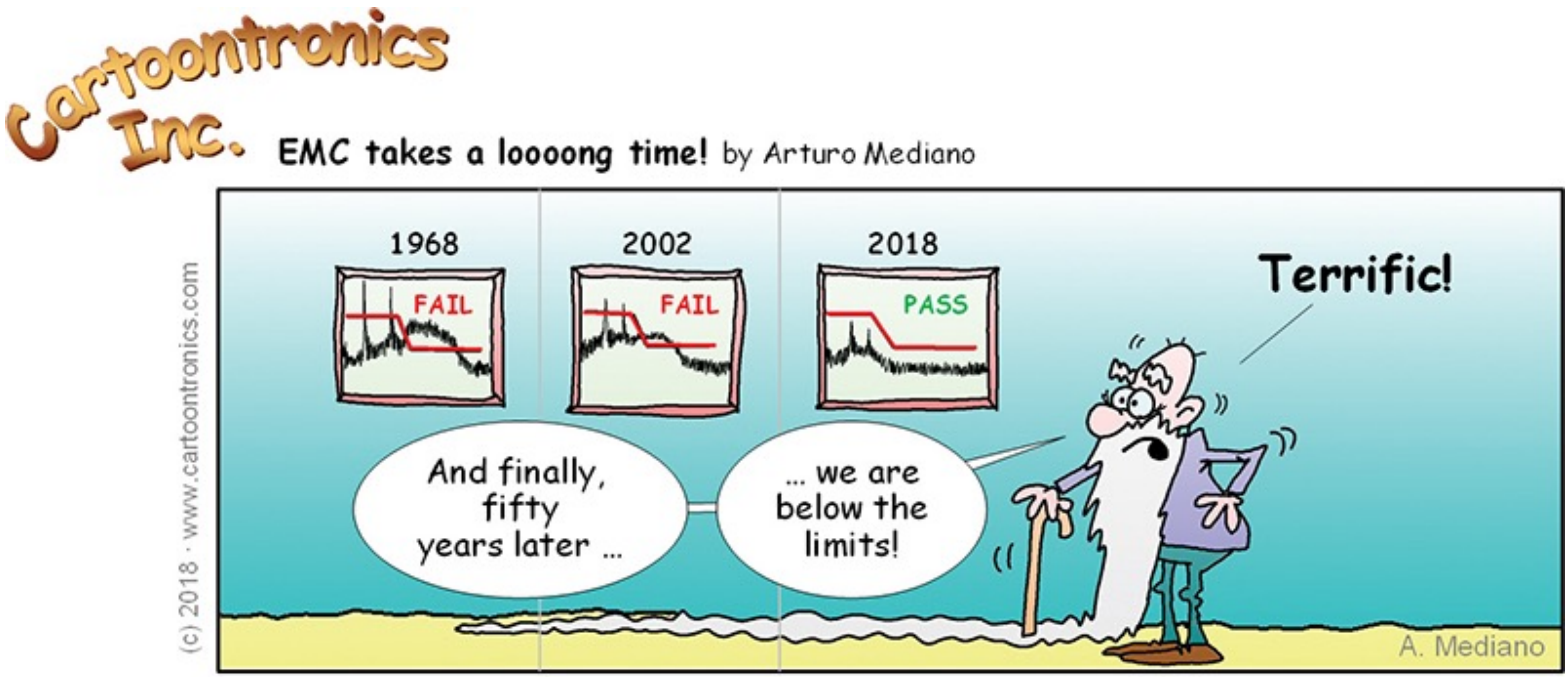
Second: (Middle)

--- In the testing phase, by the knowledge of EMC, the EMC problem can be found and the design can be changed before mass production.

--- at this level, only the subparts can be changed, but the architecture of the system can not be changed.

this course → Third: (Advanced)

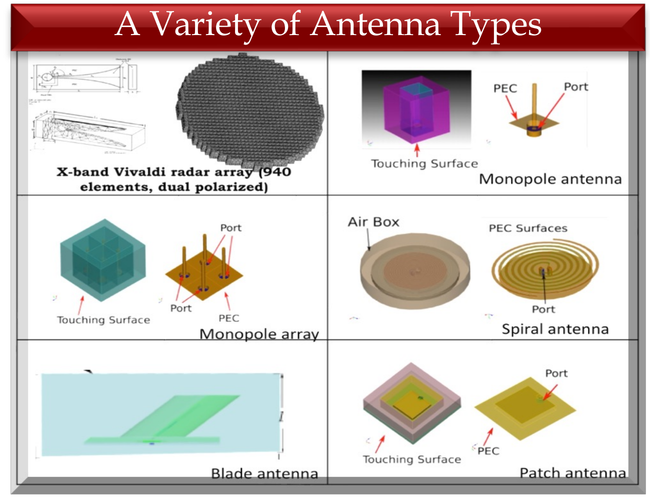
--- In the design stage, the EMC experience, knowledge, and the simulation tool are well employed to design the architecture of the system, you know all what if conditions.

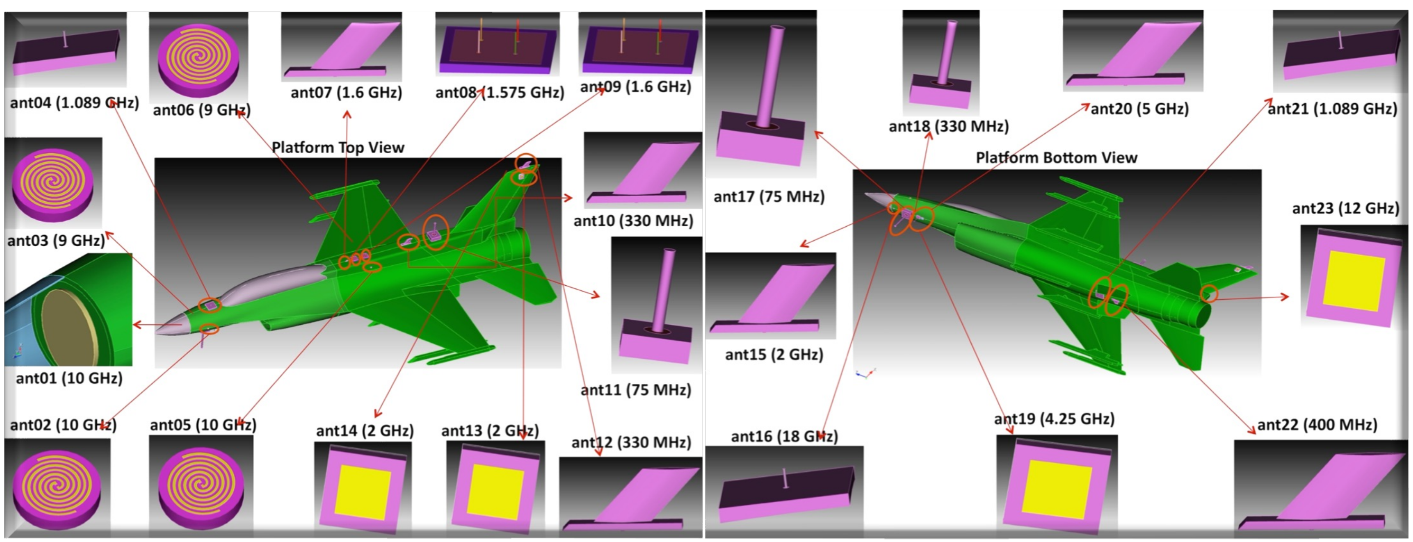

Cartoontronics Inc.
EMC takes a loooong time! by Arturo Mediano
(c) 2018 · www.cartoontronics.com
1968
FAIL
2002
FAIL
2018
PASS
And finally, fifty years later ...
... we are below the limits!
Terrific!
A. Mediano

Summary of Lecture 1

- Electromagnetic environment
- What is EMC and EMI
- Why EMC is important
- How does EMI couple to systems?
  - EMC model: source, coupling path, victim

EMC Analysis Complex Airborne Antenna Systems



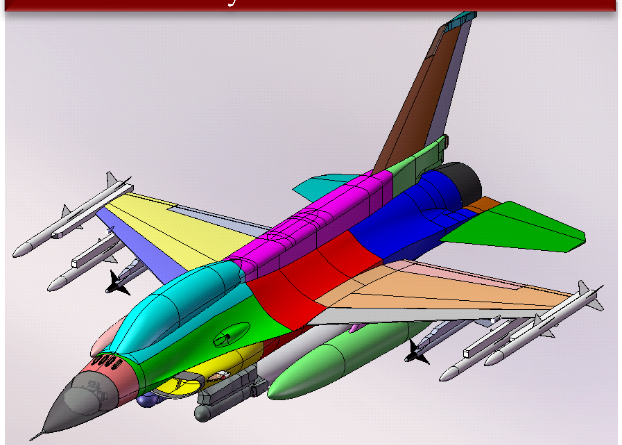


Complex Airborne Systems---Hierarchical partitions

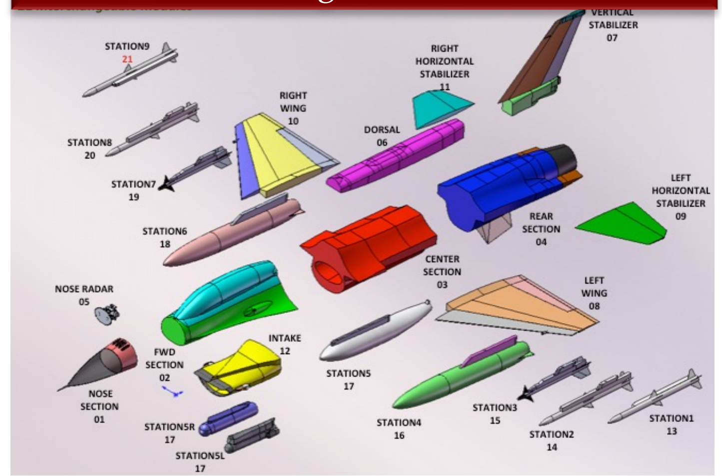
Multiple Airborne Systems

Same airframe, different load configuration

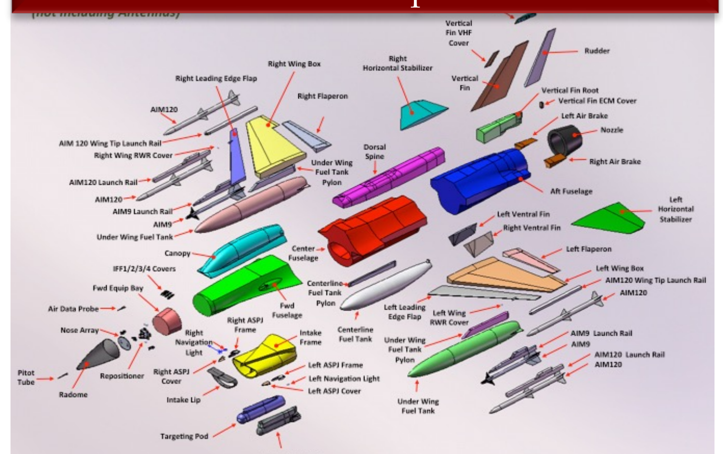
System Level



Interchangeable Modules

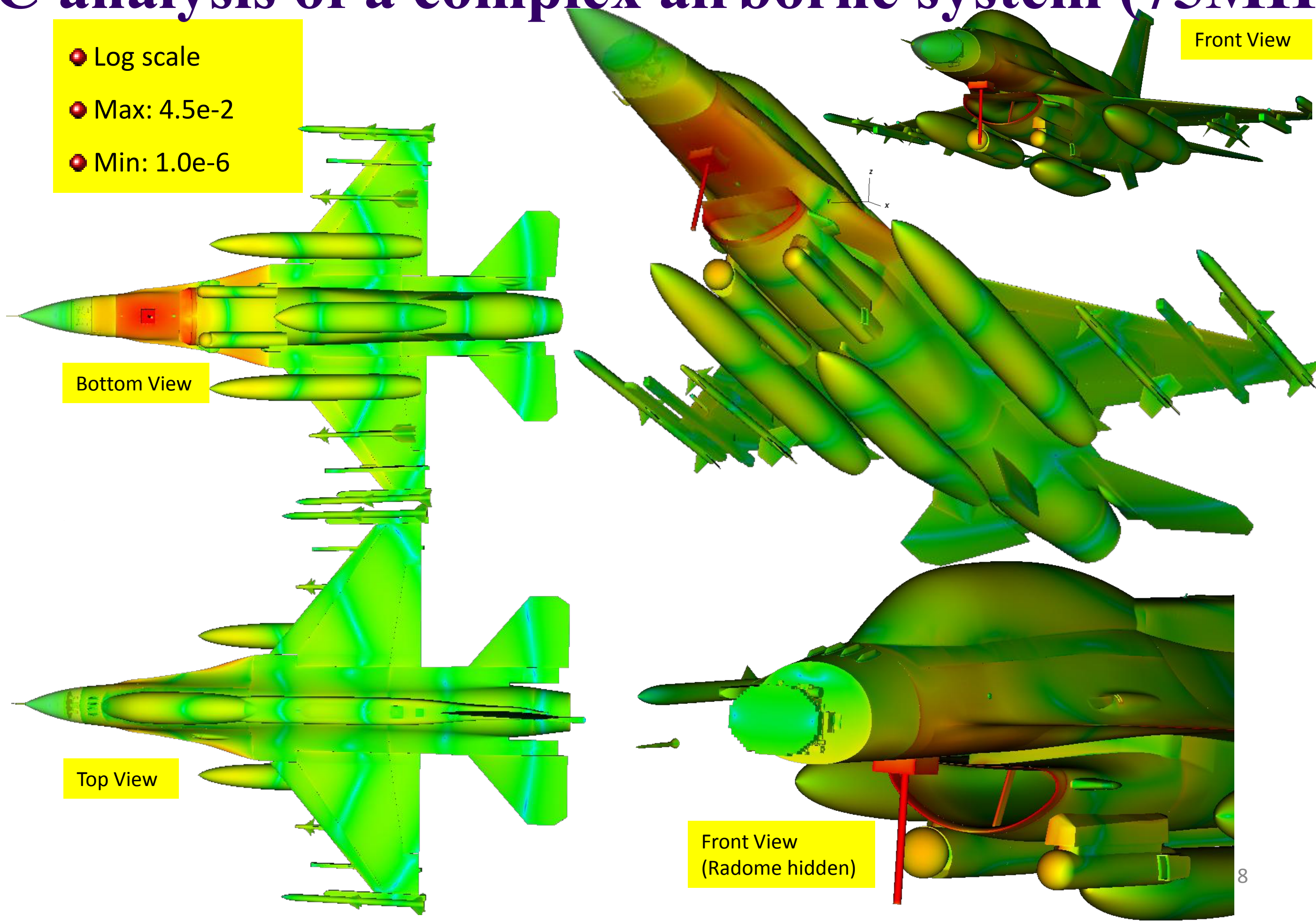


Detailed Components

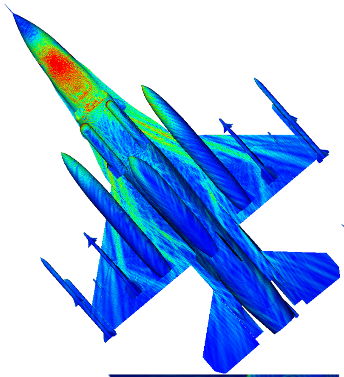


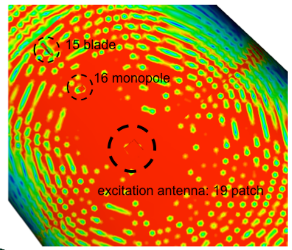
EMC analysis of a complex airborne system (75MHz)

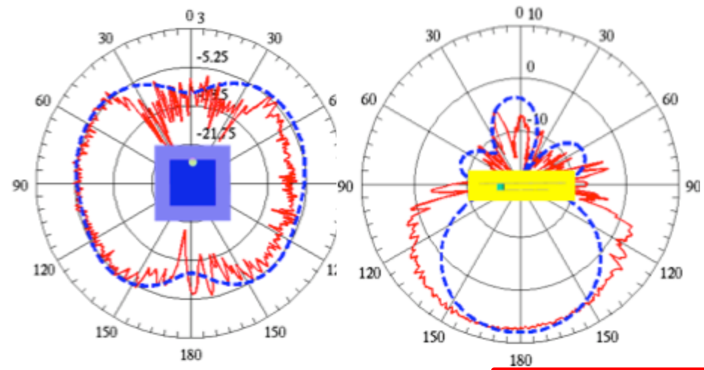
- Log scale
- Max: 4.5e-2
- Min: 1.0e-6

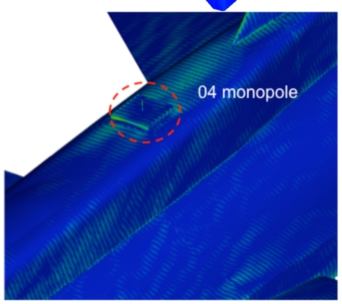


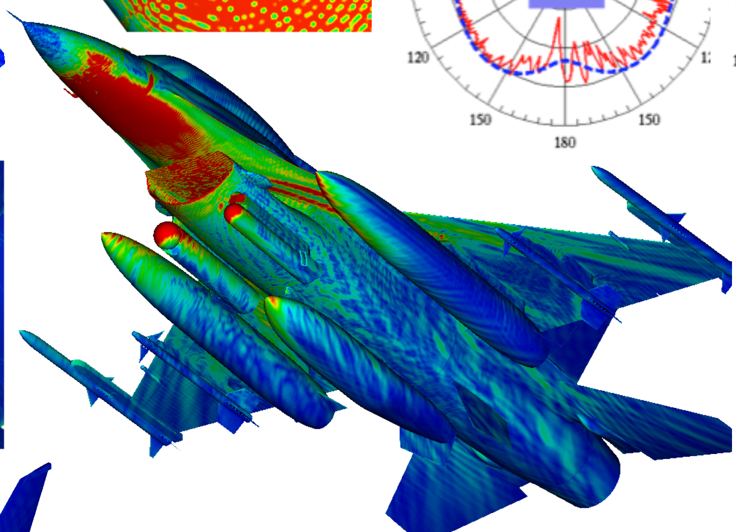
EMC analysis of a complex airborne system (4GHz)

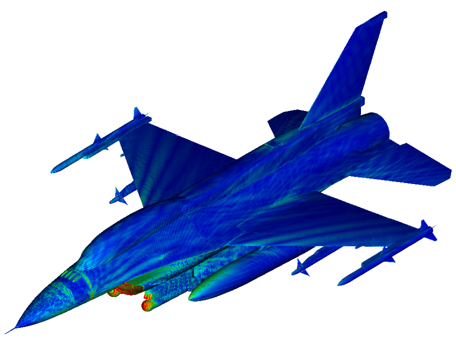












High frequency (X, Ku …) applications

↑

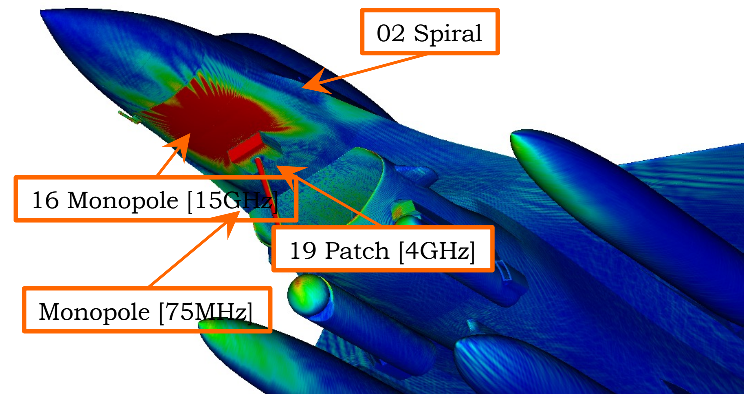
Discretization Based on Accuracy of Geometry

↓

Low frequency (L, VHF, HF…) applications

	S para(magnitude)	Phase (degree)
19patch(Excite)	-28.7 dB	-174.2
04monopole	-75.9 dB	57.8
15blade	-48.1 dB	136.4
16monopole	-66.2 dB	-178.8

EMC analysis of a complex airborne system (15GHz)

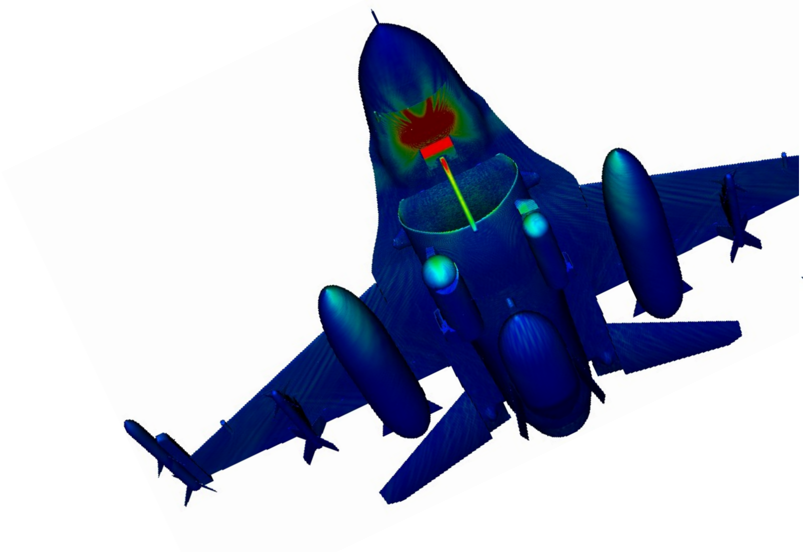


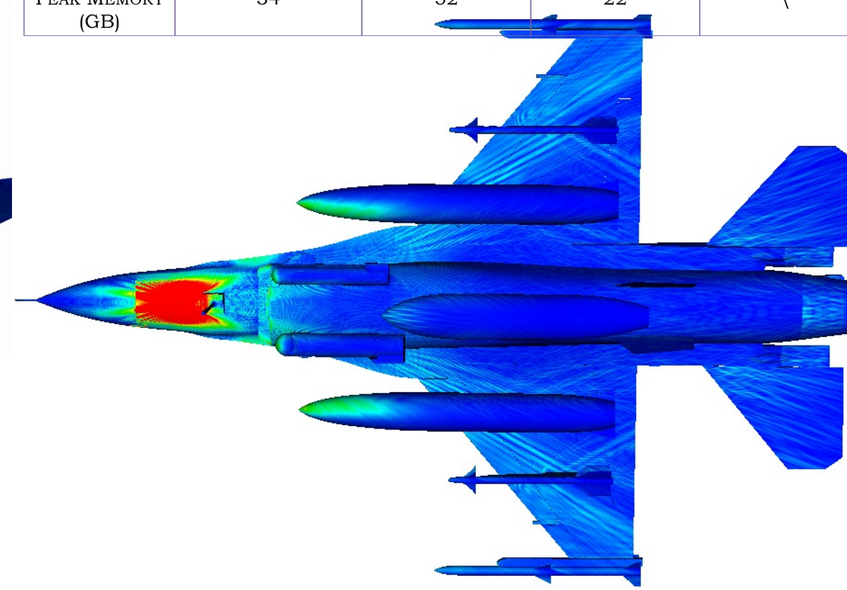
COMPUTATIONAL STATISTICS: INSTALLED ANTENNAS AT A AIRBORN PLATFORM AT KU BAND

- Operating Frequency: 15GHz
- Electrical Size: 720λ×480λ
- Number of DOFs: 693 millions
- Num. of Partitions: 37

- Num. of Cores: two quad-core
- Num. of Threads: 8
- CPU Time: 8 days
- Peak Memory: 85GB

	SUB-REGIONS(37) (PRECONDITIONER)	COUPLING (MV OPERATION)	KRYLOV VECTORS	NON-MV (DISK IO)
CPU TIME (HOURS)	68	93	\	23
PEAK MEMORY (GB)	34	52	22	\

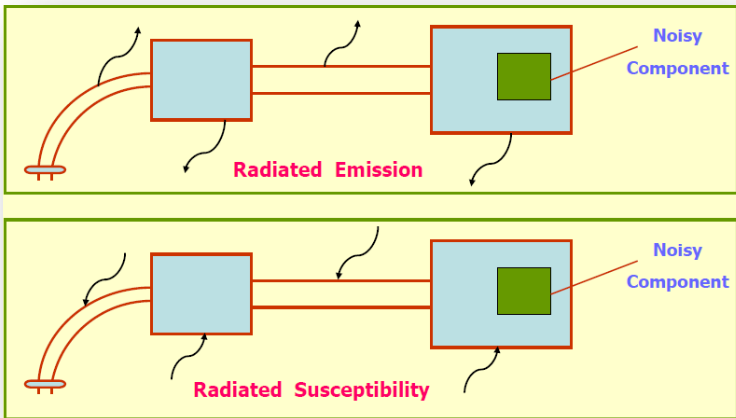




Outline

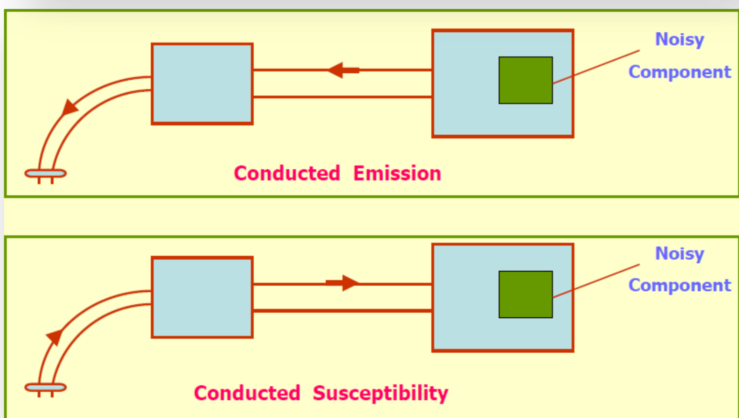
- How EMC – Coupling mechanisms (Continued)
- Electrical dimensions and waves
- EMC Requirements
- Decibels and Common EMC units

Radiated and Conducted Interference



Radiated Interference

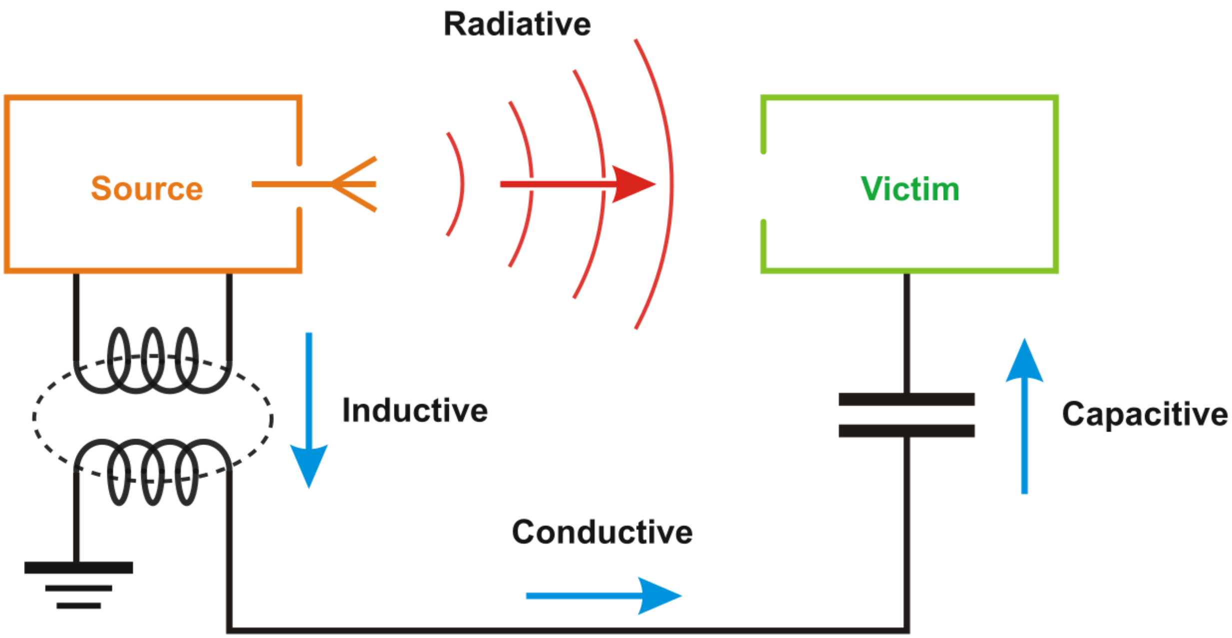
- (a) Radiated emission
- (b) Radiated susceptibility



Conducted Interference

- (c) Conducted emission
- (d) Conducted susceptibility

Coupling Mechanisms



Basic arrangement of noise source, coupling path and victim/receptor.

Source and victim are usually electronic hardware devices, though the source may be a natural phenomenon such as a lightning strike, electrostatic discharge(ESD).

Four basic coupling mechanism

1. Conductive
2. Capacitive (Electric)
3. Inductive (Magnetic)
4. Radiative

<u>Conductive coupling:</u>

<u>Conductive coupling</u> occurs when the coupling path between the source and the receptor is formed by *direct contact* with a conducting body, for example a transmission line, wire, cable, PCB trace or metal enclosure.

<u>Conduction modes:</u>

Conducted noise is also characterized by the way it appears on different conductors:

- **Common mode or common impedance coupling**:

  Noise appears in phase(in the same direction) on two conductors.

- **Differential mode coupling:**

  Noise appears out of phase(in the opposite direction)on two conductors.

Capacitive coupling:

- **Capacitive coupling** occurs when a varying electrical field exists between two adjacent conductors typically less than a wavelength apart, inducing a change in voltage across the gap.

Inductive coupling:

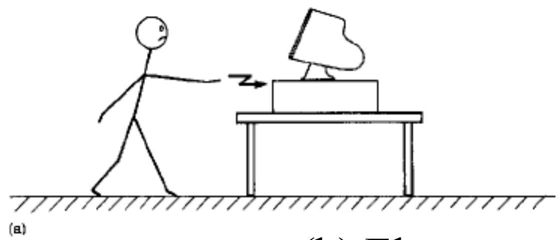
- **Inductive coupling** occurs where the source and receiver are separated by a short distance (typically less than a wavelength).
- Inductive, or magnetic coupling is similar to radiative coupling but is associated with near-fields, in a region where the magnetic field is dominant. Due to the relatively small separation, the presence of the receptor can affect the behavior of the source. This two-way phenomenon is referred to as *mutual coupling*.

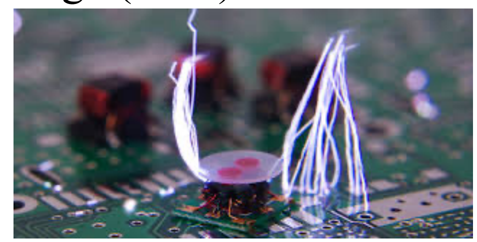
Radiative coupling:

- **Radiative coupling** or **electromagnetic coupling** occurs when source and victim are separated by a large distance, typically more than a wavelength.
- Source and victim act as radio antennas: the source emits or radiates an electromagnetic wave which propagates across the open space in between and is picked up or received by the victim.

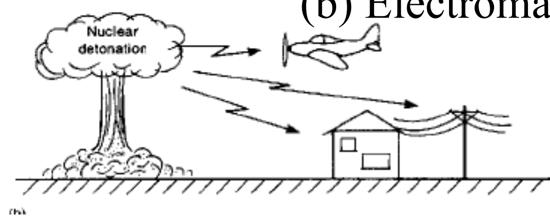
Other aspects of EMC

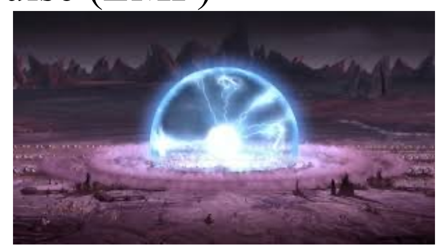
(a) Electrostatic discharge (ESD)



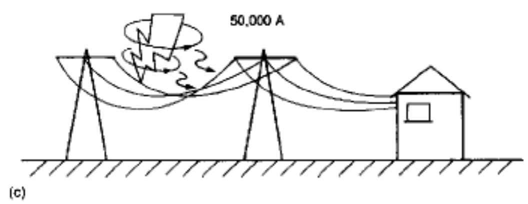


(b) Electromagnetic pulse (EMP)

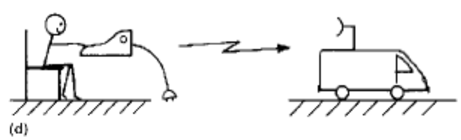




(c) Lightning

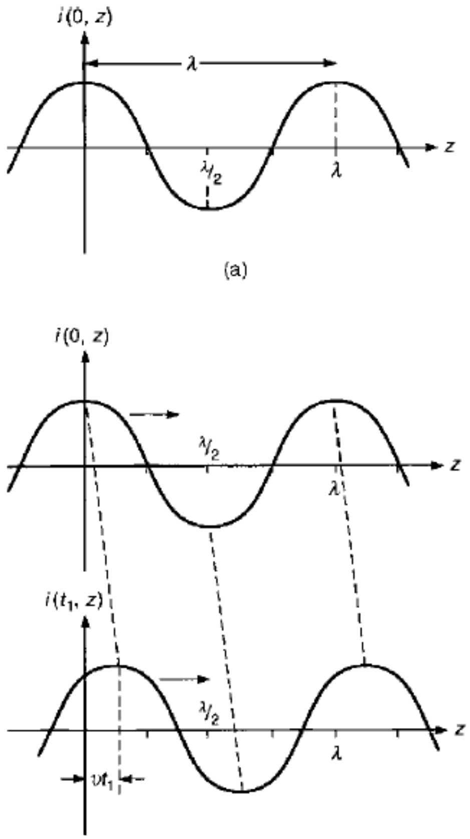


(d) TEMPEST (secure communication and data processing)



1.4 Electrical dimensions and waves

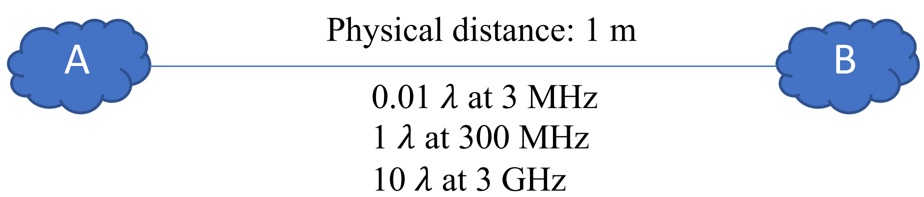
- Physical dimensions of a radiating structure such as an antenna are not important, per se, in determining the ability of that structure to radiate electromagnetic energy.
- Electrical dimensions of the structure in wavelengths are more significant in determining this.



Wave propagation: (a) wave propagation in space and wavelength; (b) wave propagation as time progresses.

1.4 Electrical dimensions and waves

It is very important to correctly calculate the electrical dimensions of a structure at a particular frequency. The key to doing this is to realize that a dimension of one meter in free space (air) is one wavelength at a frequency of 300 MHz.



$$\lambda\Big|_{3GHz} = \frac{3\times10^{8}}{3\times10^{9}} = 0.1\ m$$

The velocity of propagation of a wave in a nonconductive medium other than free space is determined by the permittivity ϵ and permeability μ of the medium. For free space these are denoted as ϵ_o and μ_o are given by

$$\epsilon_o \approx \frac{1}{36\pi}\times10^{-9}\ \text{F/m} \qquad \text{(approximate)}$$

$$\mu_o = 4\pi\times10^{-7}\ \text{H/m} \qquad \text{(exact)}$$

Frequencies and Corresponding Wavelengths of Electronic Systems

Frequency Band[a]	Wavelength	Uses
EHF (30–300 GHz)	1 cm–1 mm	Radar, remote sensing, radio astronomy
SHF (3–30 GHz)	10 cm–1 cm	Radar, satellite communication, remote sensing, microwave electronic circuits, aircraft navigation, **digital systems**
UHF (300–3000 MHz)	1 m–10 cm	Radar, TV, microwave ovens, air navigation, cell phones, military air traffic control communication and navigation, **digital systems**
VHF (30–300 MHz)	10 m–1 m	TV, FM broadcasting, police radio, mobile radio, commercial air traffic control (ATC) communication and navigation, **digital systems**
HF (3–30 MHz)	100 m–10 m	Shortwave radio (ham), citizens band
MF (300–3000 kHz)	1 km–100 m	AM broadcasting, maritime radio, ADF direction finding
LF (30–300 kHz)	10 km–1 km	Loran long-range navigation, ADF radio beacons, weather broadcasting
VLF (3–30 kHz)	100 km–10 km	Long-range navigation, sonar
ULF (300–3 kHz)	1 Mm–100 km	Telephone audio range
SLF (30–300 Hz)	6214 mi–621 mi	Communication with submarines, commercial power (60 Hz)
ELF (3–30 Hz)	62,137 mi–6214 mi	Detection of buried metal objects

[a]E = extra, S = super, U = ultra, V = very, H = high, M = medium, L = low, F = frequency.

Relative Permittivities of Various Dielectrics

Material	ϵ_r
Air	1.0005
Styrofoam	1.03
Polyethylene foam	1.6
Cellular polyethylene	1.8
Teflon	2.1
Polyethylene	2.3
Polystyrene	2.5
Nylon	3.5
Silicon rubber	3.1
Polyvinyl chloride (PVC)	3.5
Epoxy resin	3.6
Quartz (fused)	3.8
Epoxy glass (printed circuit substrate)	4.7
Bakelite	4.9
Glass (pyrex)	5.0
Mylar	4.0
Porcelain	6.0
Neoprene	6.7
Polyurethane	7.0
Silicon	12.0

Relative Permeabilities and Conductivities (Relative to Copper) of Various Metals

Conductor	σ_r	μ_r
Silver	1.05	1
Copper-annealed	1.00	1
Gold	0.70	1
Aluminum	0.61	1
Brass	0.26	1
Nickel	0.20	600
Bronze	0.18	1
Tin	0.15	1
Steel (SAE 1045)	0.10	1000
Lead	0.08	1
Monel	0.04	1
Stainless Steel (430)	0.02	500
Zinc	0.32	1
Iron	0.17	1000
Beryllium	0.10	1
Mumetal (at 1 kHz)	0.03	30,000
Permalloy (at 1 kHz)	0.03	80,000

Electrical dimensions in dielectric media

In dielectric media,

$$v = \frac{1}{\sqrt{\mu\epsilon}} = \frac{1}{\sqrt{\mu_o\epsilon_o}} \cdot \frac{1}{\sqrt{\mu_r\epsilon_r}} = \frac{c}{\sqrt{\mu_r\epsilon_r}}$$

$$\lambda = \frac{v}{f} = \frac{c}{f\sqrt{\mu_r\epsilon_r}} = \frac{\lambda_o}{\sqrt{\mu_r\epsilon_r}}$$

Example: a circuit or radiating structure whose maximum dimension is 0.36m and is operated at a frequency of 860 MHz.

a) What's the electric size in wavelength of the structure in free space?

b) If this structure were immersed in a polyvinyl chloride (PVC) dielectric ($\epsilon_r = 3.5, \mu_r = 1$), its maximum dimension of 0.36m would be __________ wavelengths?

Poll: Wave propagation speed in Teflon ($\epsilon_r = 2.1, \mu_r = 1$)

(No calculator needed)

A. c
B. 0.5c
C. 0.69c
D. 1.5c

1.5 EMC Requirements/Regulations

There are two classes of EMC requirements:

- Those mandated by governmental agencies
- Those imposed by the product manufacturer

1.5.1 Federal Communications commission(FCC)

Part 15 (radio frequency devices) 9kHz~3000GHz

Part 18 (industrial, scientific and medical equipment)

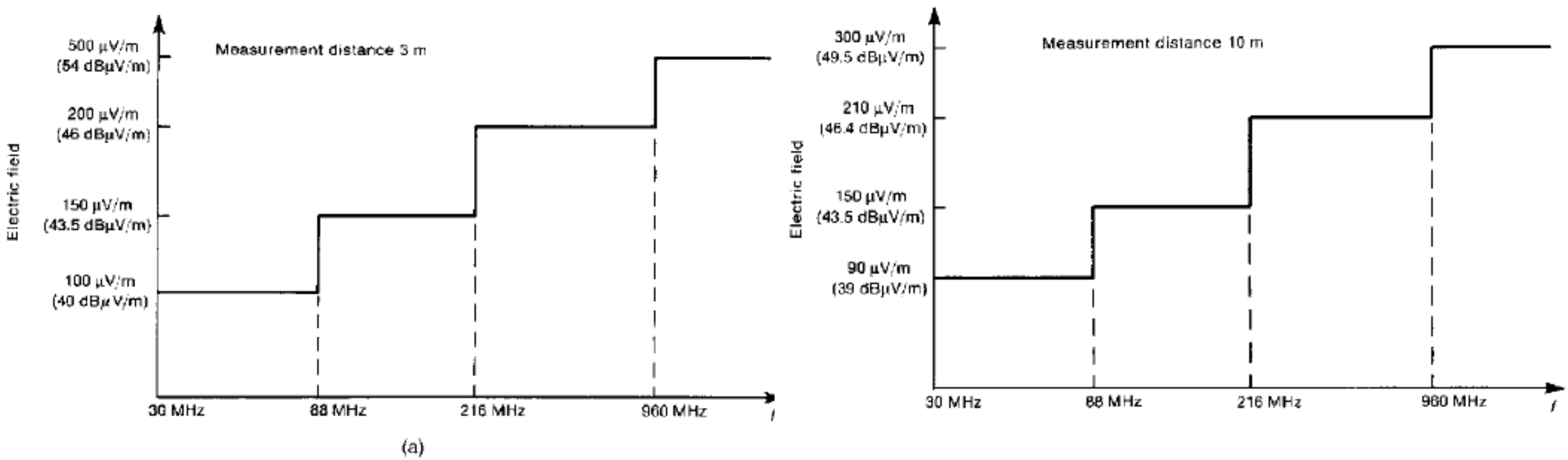
digital device class of products:

- Class A: commercial, industrial or business environment
- Class B: residential environment

Guess which class is more stringent?

Federal Communications commission(FCC)

- The radiated emissions for Class B devices are to be measured at a distance of 3m from the product
- The radiated emissions for Class A products are to be measured at a distance of 10m.



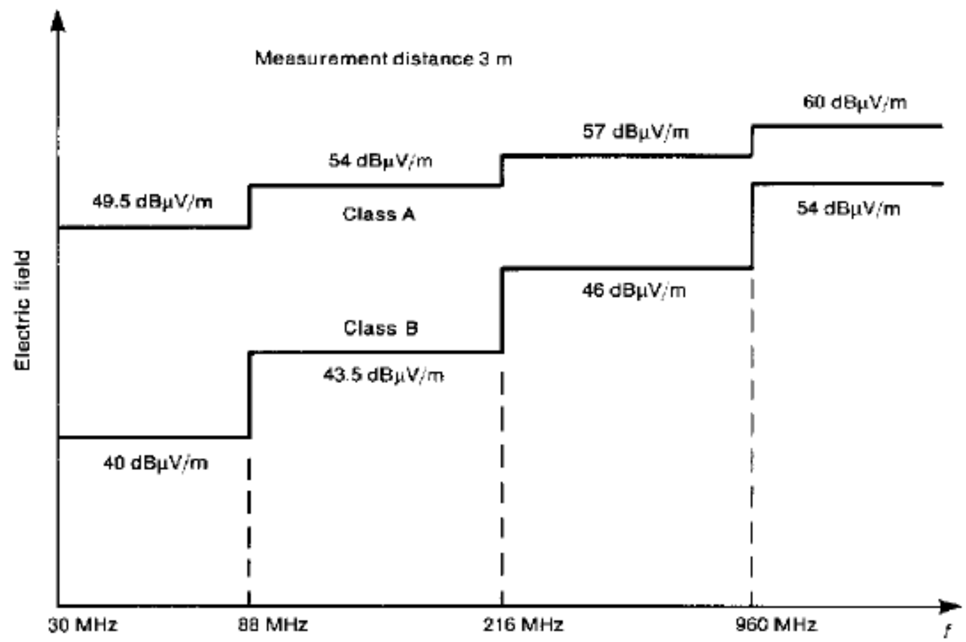
FCC radiated emission limits: (a) Class B; (b) Class A.

How to scale measurement levels to different distances

A common way of scaling these measurement levels for different measurement distances is the inverse distance method, in which the emissions are assumed to fall off linearly with increasing distance to the measurement antenna.

3m→10m: E field reduced to $\frac{3}{10}$

10m→3m: E field increased to $\frac{10}{3}$



A comparison of the FCC Class A and FCC Class B radiated emission limits for a measurement distance of 3 m.

10m->3m: $$20\log_{10}\left(\frac{10}{3}\right) \approx 10.46\text{dB}$$

1.5.2 International Special Committee on Radio Interference (CISPR)

~1GHz

CISPR 22 similarly have both Class A and Class B limits like FCC.

- Class A: commercial, industrial or business environment
- Class B: residential environment

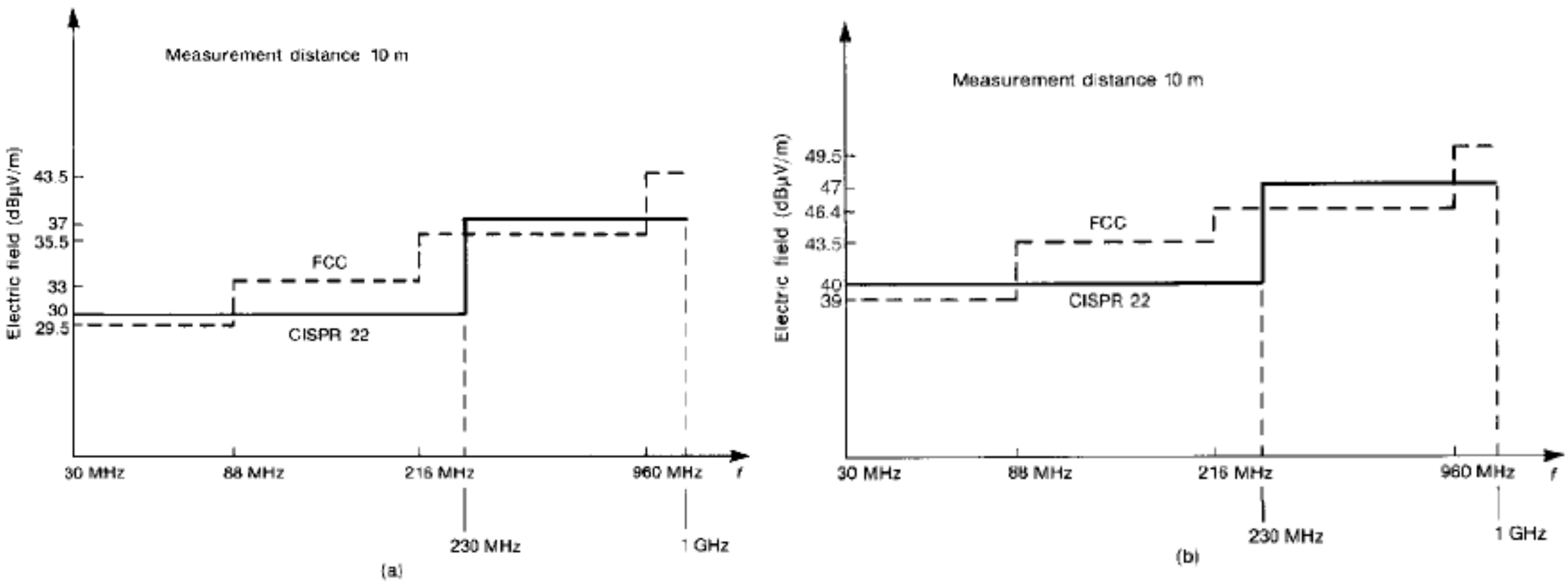
FCC and CISPR 22 limits for Class A equipment are both to be measured at 10m.
In order to scale these to the CISPR 22 Class B measurement distance of 10m using the inverse distance rule, we subtract from the FCC Class B limits at 3m.

$$20\log_{10}\left(\frac{10}{3}\right) \approx 10.46\text{dB}$$

FCC Class $B|_{@3m} - 10.46dB$ → limit @ 10m

Or we could add 10.46 dB to the CISPR 22 Class B limits at 10m to scale to the FCC Class B limits at 3 m.

CISPR Class $B|_{@10m} + 10.46dB$ → limit @ 3m



The CISPR 22 radiated emission limits compared to the FCC radiated emission limits: (a) Class B; (b) Class A.

CISPR 22 has replaced by CISPR 32 on Mar. 5, 2017

Frequency Range	CISPR 22 Class A	CISPR 32 Class A	CISPR 22 Class B	CISPR 32 Class B
30 MHz to 230 MHz	40 dBµV/m at 10m	40 dBµV/m at 10m	30 dBµV/m at 10m	30 dBµV/m at 10m
230 MHz to 1 GHz	47 dBµV/m at 10m	47 dBµV/m at 10m	37 dBµV/m at 10m	37 dBµV/m at 10m
1 GHz to 3 GHz	N/A	56 dBµV/m at 3m	N/A	46 dBµV/m at 3m
3 GHz to 6 GHz	N/A	60 dBµV/m at 3m	N/A	50 dBµV/m at 3m

1.5.3 Military Standards (MIL-STD-461E)

30Hz~

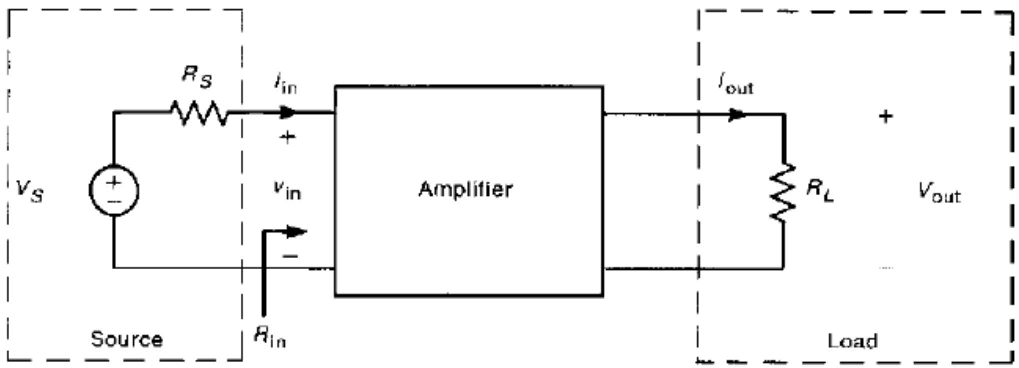
The limits and applicability are much more complicated and span much larger frequency ranges than do those of the FCC or CISPR 22. One key difference between these military requirements and the commercial requirements (FCC and CISPR 22) is that the military requirements can be *waived* and/or *tailored*.

TABLE 2.8 Emission and Susceptibility Requirements of MIL-STD-461E

Requirement	Description
CE101	Conducted emissions, power leads, 30 Hz–10 kHz
CE102	Conducted emissions, power leads, 10 kHz–10 MHz
CE106	Conducted emissions, antenna terminal, 10 kHz–40 GHz
CS101	Conducted susceptibility, power leads, 30 Hz–150 kHz
CS103	Conducted susceptibility, antenna port, intermodulation, 15 kHz–10 GHz
CS104	Conducted susceptibility, antenna port, rejection of undesired signals, 30 Hz–20 GHz
CS105	Conducted susceptibility, antenna port, cross-modulation, 30 Hz–20 GHz
CS109	Conducted susceptibility, structure current, 60 Hz–100 kHz
CS114	Conducted susceptibility, bulk cable injection, 10 kHz–200 MHz
CS115	Conducted susceptibility, bulk cable injection, impulse excitation
CS116	Conducted susceptibility, damped sinusoidal transients, cables and power leads, 10 kHz–100 MHz
RE101	Radiated emissions, magnetic field, 30 Hz–100 kHz
RE102	Radiated emissions, electric field, 10 kHz–18 GHz
RE103	Radiated emissions, antenna spurious and harmonic outputs, 10 kHz–40 GHz
RS101	Radiated susceptibility, magnetic field, 30 Hz–100 kHz
RS103	Radiated susceptibility, electric field, 2 MHz–40 GHz
RS105	Radiated susceptibility, transient electromagnetic field

1.6 Decibels and Common EMC units

- EMC units are expressed in ***decibels***(dB) --- large *dynamic range*
- Decibel is a logarithmic quantity used in sound and radio engineering
- Later this definition was extended to other electrical quantities such as voltage, current, electric field, magnetic field, and power.



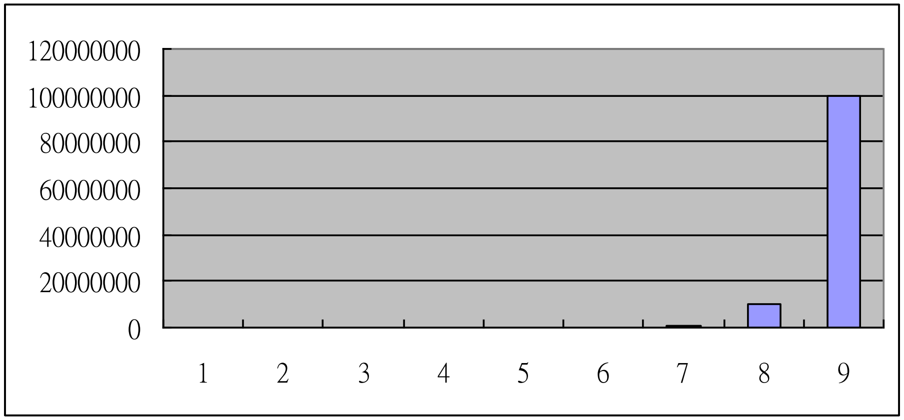
$$P_{in} = \frac{v_{in}^2}{R_{in}} \quad P_{out} = \frac{v_{out}^2}{R_L} \quad \text{Power gain} \equiv \frac{P_{out}}{P_{in}} \quad \text{Voltage gain} \equiv \frac{v_{out}}{v_{in}} \quad \text{Current gain} \equiv \frac{i_{out}}{i_{in}}$$

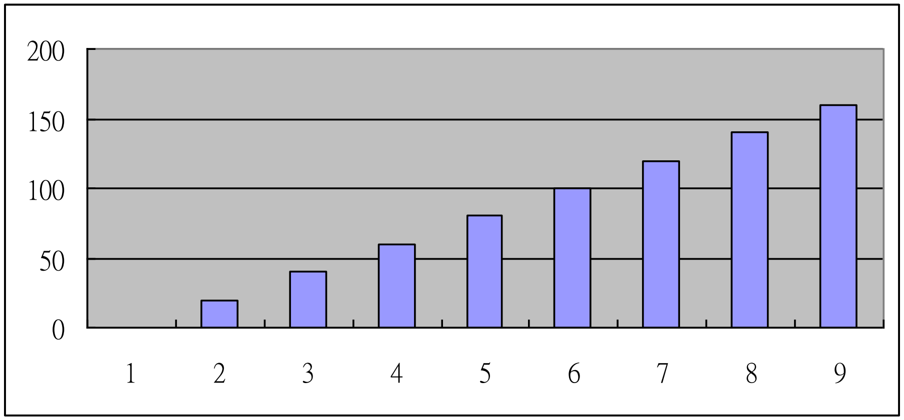
An illustration of the definition and use of the decibel (dB)

Why Decibels?

- Decibels have the property of compressing data.

	dB
1	0
10	20
100	40
1000	60
10000	80
100000	100
1000000	120
10000000	140
100000000	160





1. Power $\text{gain}_{\text{dB}} = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) = 10\log_{10}\left(\frac{P_2}{P_1}\right)$

- dBW: the reference power level P_1 is 1W.
- dB*m*: the reference power level P_1 is 1mW. $dBm = 10\log_{10}(\frac{Watts}{1mW})$

Example 1, P_1=1mW, P_2=20W, calculate power gain

Example 2, P=1W, reference power level is 1mW, calculate P in dB*m*

2. Voltage $\text{gain}_{dB} = 20\log_{10}\left(\frac{V_2}{V_1}\right)$

- dBV: the reference voltage V_1 is 1V
- dBμV: the reference voltage V_1 is 1μV. dBμV=$20\log_{10}\left(\frac{volts}{1\mu V}\right)$
- dBμV/MHz: the reference voltage V_1 is 1μV/MHz

Example 1: V_1=10mV, V_2=20 μV, calculate V_r in dB

Example 2: V=1V, reference to 1 μV in dBμV

3. Current $\text{gain}_{dB} = 20\log_{10}\left(\frac{I_2}{I_1}\right)$

- dBA : the reference current I_1 is $1A$.
- dBμA : the reference current I_1 is 1μA. dBμA$=20\log_{10}\left(\frac{Amperes}{1\mu A}\right)$

Exercise: I_1=2mA, I_2=2A, calculate I_r in dB

Electric field:

- dBμV/m : the reference level is $1\mu V/m$.
- dB$\mu(V/m)/MHz$: the reference level is $1\ (\mu V/m)/MHz$

.

Magnetic field:

- dBmA/m : the reference level is $1mA/m$.
- dB$\mu A/m$: the reference level is $1\mu A/m$.

Summary of base quantity

- $dBW \equiv 10\log_{10}\left(\frac{watts}{1W}\right)$, $dBm \equiv 10\log_{10}\left(\frac{watts}{1mW}\right)$, $dB\mu W \equiv 10\log_{10}\left(\frac{watts}{1\mu W}\right)$
- $dBV \equiv 20\log_{10}\left(\frac{Volts}{1V}\right)$, $dBmV \equiv 20\log_{10}\left(\frac{Volts}{1mV}\right)$, $dB\mu W \equiv 20\log_{10}\left(\frac{Volts}{1\mu V}\right)$
- $dBA \equiv 20\log_{10}\left(\frac{Amperes}{1A}\right)$, $dBmA \equiv 20\log_{10}\left(\frac{Amperes}{1mA}\right)$, $dB\mu A \equiv 20\log_{10}\left(\frac{Amperes}{1\mu A}\right)$

- $Watts = 10^{dBW/10} = 10^{dBm/10}\times 10^{-3} = 10^{dB\mu W/10}\times 10^{-6}$
- $Volts = 10^{dBV/20} = 10^{dBmV/20}\times 10^{-3} = 10^{dB\mu V/20}\times 10^{-6}$
- $Amperes = 10^{dBA/20} = 10^{dBmA/20}\times 10^{-3} = 10^{dB\mu A/20}\times 10^{-6}$

Unit Conversion

$$
\begin{aligned}
15\,\text{mV} &= 15{,}000\ \mu\text{V} \\
&= 83.52\,\text{dB}\mu\text{V} \\
&= 23.52\,\text{dBmV} \\
630\,\text{mA} &= 630{,}000\ \mu\text{A} \\
&= 115.99\,\text{dB}\mu\text{A} \\
&= 55.99\,\text{dBmA} \\
250\,\text{mW} &= 250{,}000\ \mu\text{W} \\
&= 53.98\,\text{dB}\mu\text{W} \\
&= 23.98\,\text{dBm}
\end{aligned}
$$

4. Conversion of dBm to dBμV

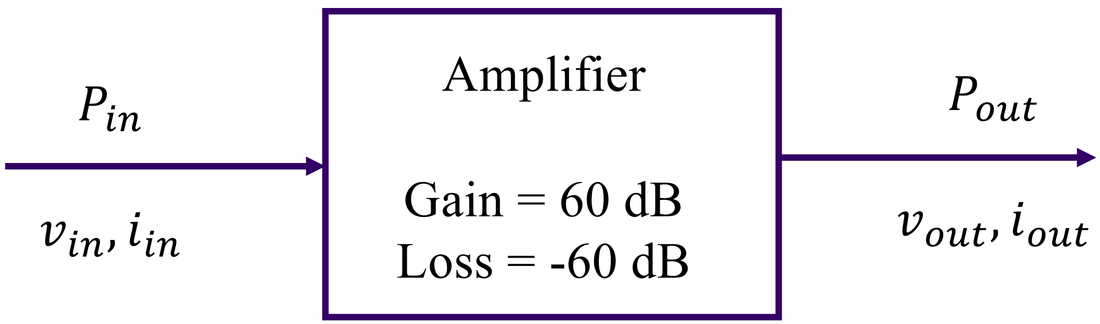
$$P_{dBm} = U_{dB\mu V} - 90dB - 10\log_{10} R$$

or

$$U_{dB\mu V} = P_{dBm} + 107dB$$

Proof:

The use of the decibel in computing amplifier performance



$$P_{\text{out dBm}} = Gain_{\text{dB}} + P_{\text{in dBm}}$$

$$P_{\text{out dB}\mu W} = Gain_{\text{dB}} + P_{\text{in dB}\mu W}$$

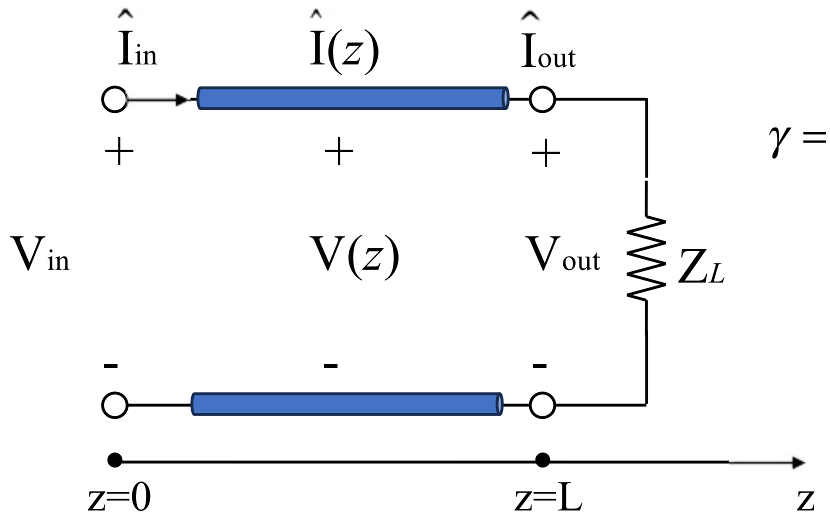
$$v_{\text{out dB}\mu V} = Gain_{\text{dB}} + v_{\text{in dB}\mu V}$$

$$v_{\text{out dB}mV} = Gain_{\text{dB}} + v_{\text{in dB}mV}$$

$$i_{\text{out dB}\mu A} = Gain_{\text{dB}} + i_{\text{in dB}\mu A}$$

$$i_{\text{out dB}mA} = Gain_{\text{dB}} + i_{\text{in dB}mA}$$

1.7. Power loss in Cables (basic transmission line)



Propagation constant

$$\gamma = \alpha + j\beta = \sqrt{\left(R + j\omega L\right)(G + j\omega C)}$$

Characteristic impedance

$$Z_c = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

$$V(z) = V^+ e^{-\alpha z} e^{-j\beta z} + V^- e^{+\alpha z} e^{+j\beta z} = V_f(z) + V_b(z)$$

$$\hat{I}(z) = \frac{V^+}{Z_c} e^{-\alpha z} e^{-j\beta z} - \frac{V^-}{Z_c} e^{+\alpha z} e^{+j\beta z} = \frac{V_f(z)}{Z_c} - \frac{V_b(z)}{Z_c}$$

reflection coef. $\Gamma(z) = \frac{V_b(z)}{V_f(z)} = \frac{V^-}{V^+} e^{2\alpha z} e^{j2\beta z}$

reflection coef. at the load

$\Gamma(z) = \frac{Z_L - Z_C}{Z_L + Z_C}$ ➡ $\Gamma = 0$ if $Z_L = Z_C$ ➡ matched load

➡ $\mathrm{V}_b(z) = 0$

power delivered :

$$\mathrm{P}_{zv}(z) = \frac{1}{2}\mathrm{Re}\left[\mathrm{V}(z)\hat{\mathrm{I}}^*(z)\right]$$

power loss for cables :

$$(\text{cable loss}) = \frac{P_{av}(z=0)}{P_{av}(z=L)} = \frac{P_{in}}{P_{out}} = e^{2\alpha L}$$

cable length

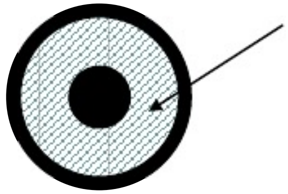
$$(\text{cable loss})_{\text{dB}} = 10 log_{10} e^{2\alpha L} = 20\alpha L log_{10} e = 8.686\alpha L$$

In general, α is due to the loss of conductor $\propto \sqrt{f}$

Example: for cable RG-58U

cable loss=4.5dB/100ft.

ε_r = 2.1(Teflone). coaxial cable

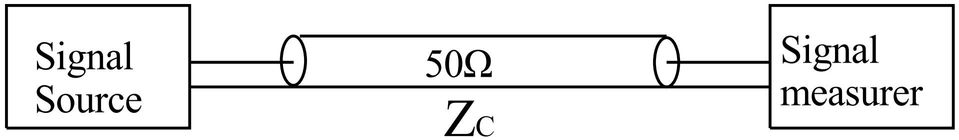


$$\alpha = \frac{\text{power loss in dB/length}}{8.686L}$$

matched load!

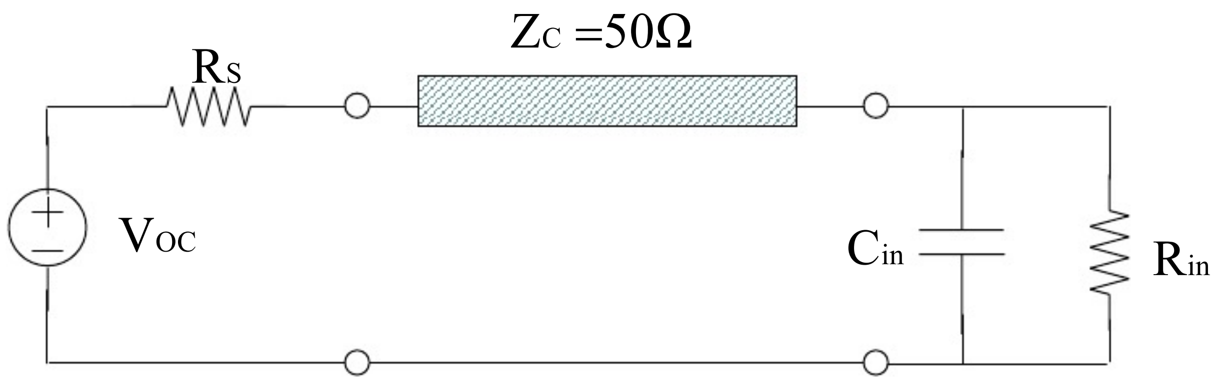
$$= \frac{4.5}{8.686 \times 100} = 5.18 \times 10^{-3}\,\text{Np/ft}$$

Example. Signal Source Specification



ex： Signal Generator   Spectrum Analyzer

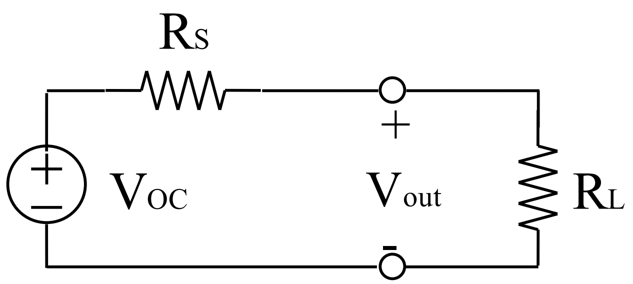
equivalent circuit



Generally in industrial standard, $R_S = Z_C = R_{in} = 50\Omega$ for RF instrument

Calculation of a signal source output

$R_L = R_S = 50\Omega$ Matched load!



$$V_{out} = \frac{R_L}{R_S + R_L} V_{oc} = \frac{1}{2} V_{oc}$$

$$P_{out} = \frac{V_{out}^2}{R_L} = \frac{V_{out}^2}{50}$$

Note : It is industrial standard that voltage and currents are specified in their RMS values and no factor of 1/2 is then required in power expression.

i.e. $V_{out} = \frac{1}{\sqrt{2}} \left(V_{out}\right)_{peak}$

Example (1): a Signal generator shows -37dBm output, Calculate V_{out}

$$-37\ \text{dBm} = 2 \times 10^{-4}\ \text{mW}$$
$$= 2 \times 10^{-7}\ \text{W}$$
$$2 \times 10^{-7}\ \text{W} = V_{out}^2/50$$
$$V_{out} = \sqrt{50 \bullet P_{out}} = 3.162\text{mv(RMS)} = 70\text{dB}\mu\text{V}$$

Many signal measures such as spectrum analyzers also have their response specified assume a 50Ω input impedance to the instrument.

for example: a Spectrum Analyzer. shows the maximum input rating of 30dBm=1W

- Can obtain a relation: $-37 + 107 = 70$.
- For example: $-40dBm + 107 = 67dB\mu V$

$$P_{dBm} + 107dB = U_{dB\mu V}$$

Example (2), matched load

-25 dBm or 0.003162 mW of power is dissipated, calculate the voltage in $dB\mu V$

- 1st method

$$V_L = \sqrt{50 \times 0.003162mW}$$

$$= 12.574mV$$

$$= 82dB\mu V$$

- Another method

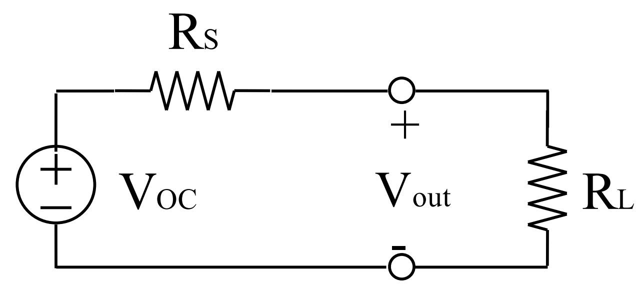
$$dB\mu V(RMS) = 107 + dBm$$

$$= 107 - 25$$

$$= 82dB\mu V$$

Example (3), matched load

The output power P_L = -26 dBm on a 50 Ω matched load $R_{L.}$ Find the open circuit voltage Voc

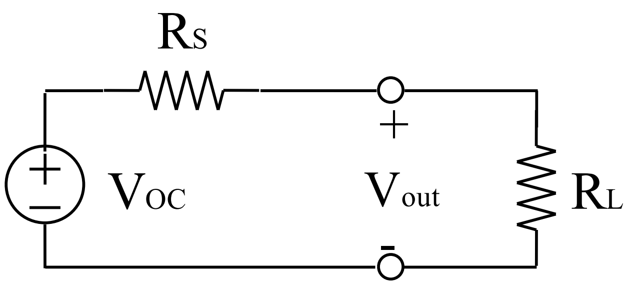


(DC condition)

Example (4), unmatched load

$R_S = 50\Omega, R_L = 150\Omega, V_{OC} = 22.4mV$, find V_{out} in $dB\mu V$

- Method 1



- Method 2