Electromagnetic Compatibility Essentials

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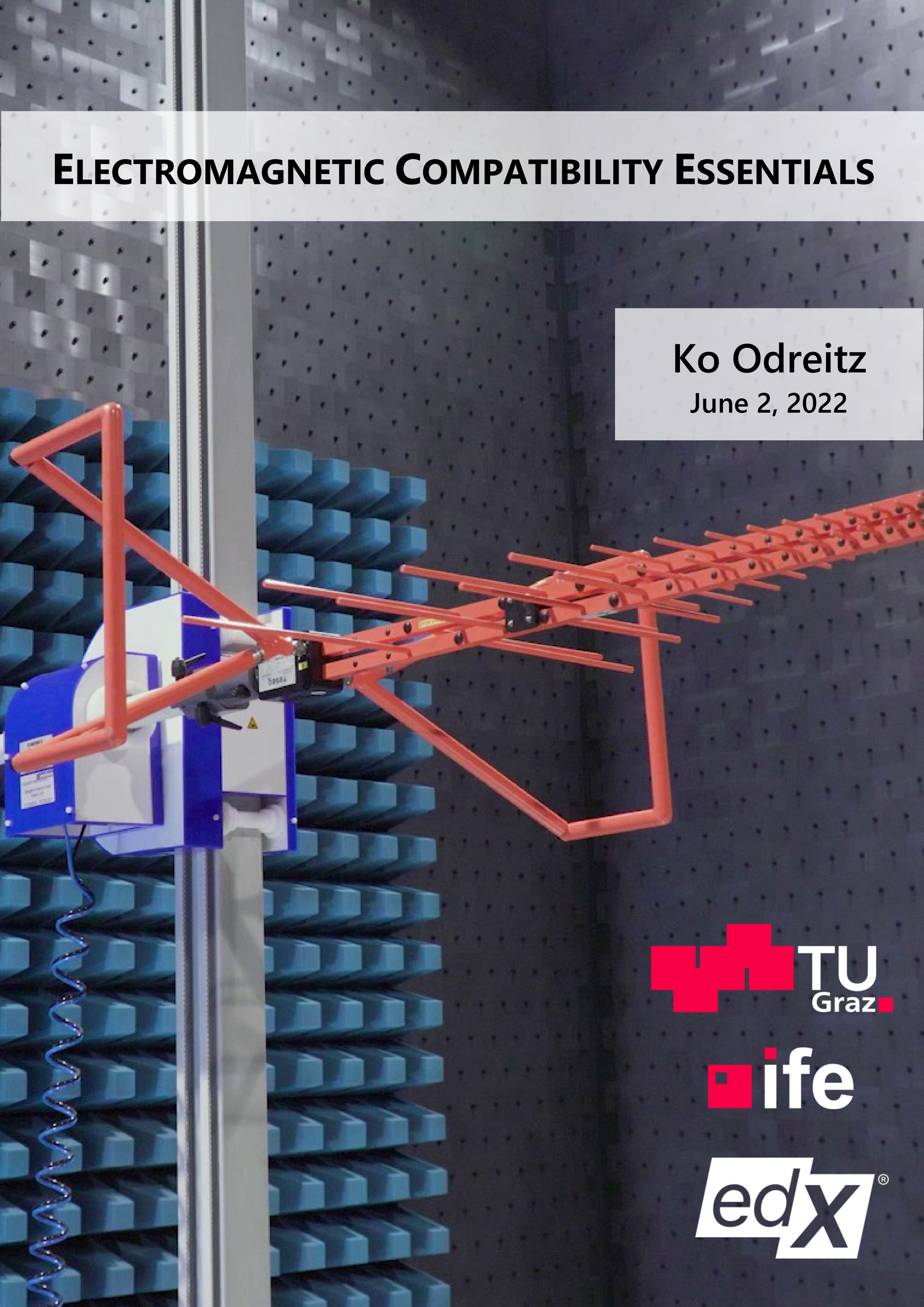

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Welcome to the edX EMC Essentials course!

https://www.edx.org/course/electromagnetic-compatibility-essentials

Complete YouTube playlist:

https://www.youtube.com/playlist?list=PLLpZ1DoEuR9stTVaz-kPTfcBsznYhJP3H

This document contains the complete edX course without exam questions. The content is optimized for the online version; however, we want to provide you with an offline version with this PDF. We decided to offer the complete course for FREE, because it's our main goal to create more awareness about EMC. In case you have chosen the verified track, we thank you very much for your donation! This helps us a lot to further improve the quality of our courses!

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INTRODUCTION

Welcome to our MOOC on the fascinating world of EMC. In this first chapter, you will learn all the basics you need to know about the world of high frequencies. Unfortunately, getting started is never easy and there are a couple of mathematical basics here as well. But stay tuned; it will really pay off in the end. Let's start simple. On the next page, we will explore what EMC is and why this topic is so important.

1.1 WHAT IS EMC?

In this subsection (learning sequence) we clarify the question: what is EMC, and why should we be concerned with it? Among the general public, radio frequency (RF) effects are often not known. **A single system that is not EMC compliant could mean the failure of your project.** For instance, an airplane must be protected from interference from the telecommunications network. Thereafter, we will look at the definition of EMC and break it down to "Emission" and "Immunity". There is a further subdivision of which medium is used to transmit the interference: conducted (wired) and radiated (emitted). Ultimately, it's the high frequencies that cause us problems.

What is a system?

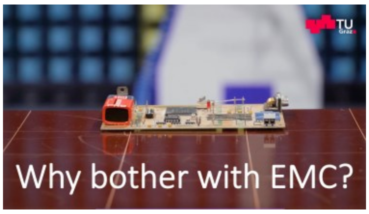
"System" is the term for a complete device. Such a system can be e.g. an assembled PCB including power supply, or a complete mobile phone. This term is important because EMC test measurements are usually performed on a finished system, so-called "system level" tests. Another level would be, for example, "IC level" tests, where only the chip is getting analyzed.

1.1.1 WHY BOTHER WITH EMC

We don't research EMC just for fun. Nor is it a matter of increasing efficiency by a few percentage points. **Without EMC-compliant design of products, crazy situations could arise.** Speakers would buzz again just before the cell phone rings. We could turn on and off a TV with the remote control of the Christmas tree lights. A slot machine could pay out the jackpot after it shocked me. Snoopers could easily eavesdrop on military traffic. In certain places, the car's brakes might suddenly stop working.

All such situations seem mysterious to the non-expert. In reality, however, it is our technological progress that is causing us unexpected problems. In some sense, we have developed products without being aware of its side effects. We built transmitting sites in order to make phone calls and watch TV, but we did not take into account that **other devices might be disturbed** by them.

To prevent these potential dangers, **many regulations have been defined**. Thus, today it is almost impossible to develop an electronic product that is also allowed to be sold, unless you know the laws. The following clip is perhaps presented a bit funny; but without EMC-compliant design, a lot of "black magic" would still happen today.



What is EMC - Electromagnetic Compatibility
https://youtu.be/0lwjjeq570E

1.1.2 DEFINITION

The term "EMC" is defined by the European Parliament (in article 3.1.4) as follows:

> ***EU definition***
>
> *'Electromagnetic compatibility' means the ability of equipment to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to other equipment in that environment.*

This legal text indicates that an electronic system must satisfy specific characteristics to be considered electromagnetically compatible: it must not disturb other devices (**emission** condition), nor be affected by other devices (**immunity** condition).

If a system disturbs other devices, it is considered a source of **electromagnetic interference**. If a system is disturbed by other devices, the system is called **electromagnetically susceptible**; susceptibility is the opposite of immunity.

General definition

So, an electronic system is classified as electromagnetically compatible if it complies with the following conditions:

1. the system does not interfere with other systems (**emission**),
2. the system is not susceptible to emissions from other systems (**immunity**),
3. and obviously, the system does not interfere with itself (signal integrity).

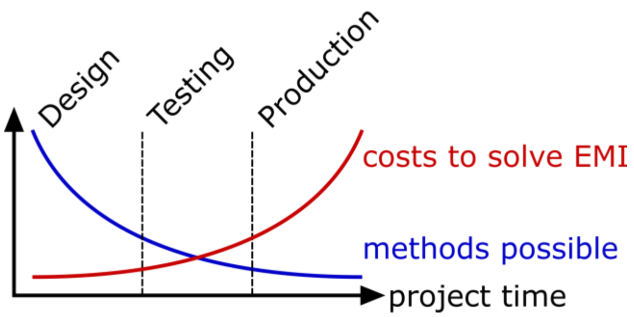
The second condition is often difficult to put into numbers, and an error criterion must be defined here. At the same time, a manufacturer has an interest in ensuring that this condition is met. Otherwise, this product will no longer be purchased by customers. However, selling a product in Germany as an example, the product must comply with both conditions: emission and immunity.

EMC as a figure of merit

In the last century, EMC often played only a minor role. However, this has changed with the increasing complexity of electronic circuits. In electronic based systems (EBS), circuits are being crowded into more limited spaces, while **switching frequencies have increased tremendously**. The same applies to CPUs where billions of transistors with channel lengths of smaller than 10 nm are operating at clock rates above 4 GHz. Thus, there are clear tendencies that worsen the electromagnetic compatibility. Yet, it must be acknowledged that new modern technologies are also improving EMC, for example, shorter transmission lines, more GND layers in PCBs, automatic error correction.

In the real world, a signal always carries unwanted noise components. It is impossible to get rid out of those noisy signals, since this would require ideal filter components. However, as we will learn later on, ideal filters do not exist. The problem with noise is that it can cause unwanted effects. **Thus, if a noise signal triggers an undesired function of a circuit, it is called interference.** This is also referred to as **electromagnetic interference**, abbreviated by **EMI**. The main task of an EMC engineer is to reduce the noise components to such an extent that interference no longer occurs.

By mistake, EMC is regularly used as a single noun - as a synonym for a figure of merit. **Nevertheless, EMC should be part of every electronic product and not be an annoying extra task.** Thinking in this way, **EMC considerations should be involved in every step of the product design phase** which brings a lot of benefits. In early project phases, changes can be made quickly and cost-effectively. After the IC and PCB have already been manufactured, the degrees of freedom for error correction are reduced. In later project phases, EMI problems can often only be resolved with the help of additional components combined with high testing costs.

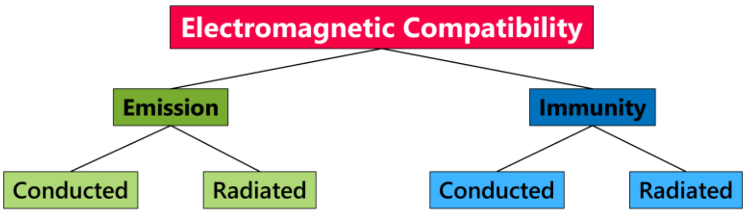


> ***Figure of merit***
>
> *A figure of merit is a quantity to characterize a system. Examples would be: CPU clock rate, camera resolution, calories per serving, or profit of a company. A German translation would be "Kennzahl".*

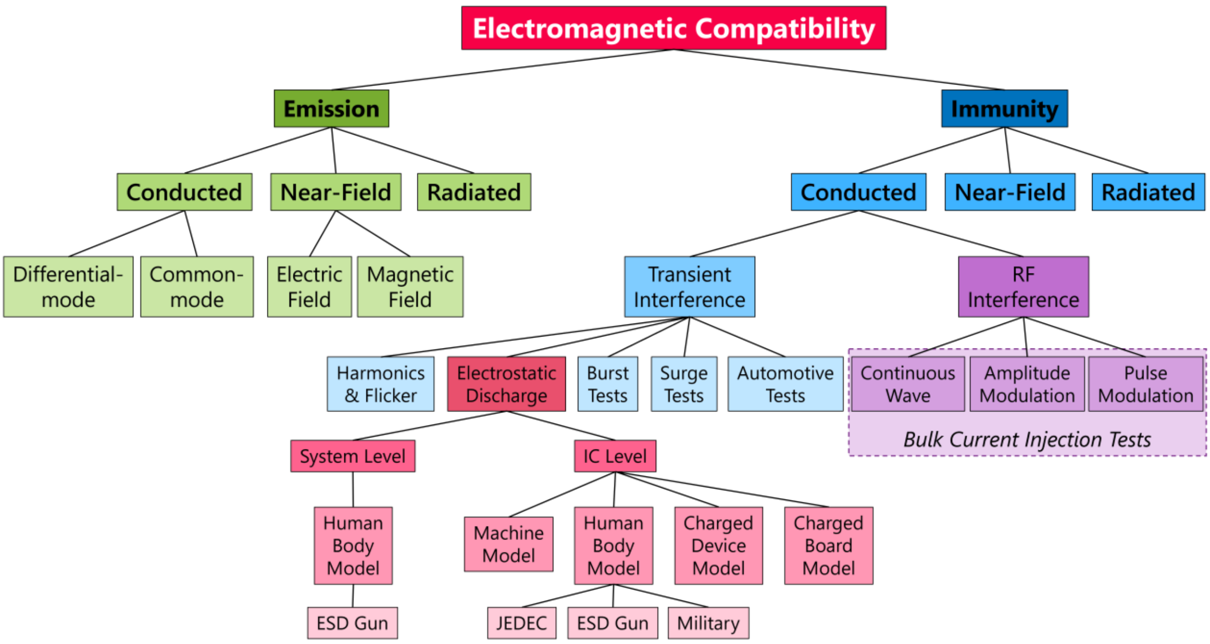
1.1.3 Aspects of an EMC problem

The definition of EMC describes the two properties *emission* and *immunity*. Unfortunately, EMC is not that simple and many more terms exist. First of all, we must distinguish between *conducted* and *radiated* interference. Further, we need to define the *source* and *victim* of EMI.

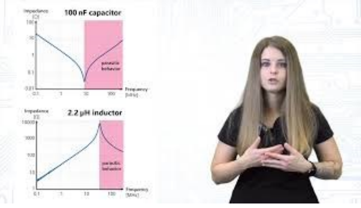
- **Source of EMI**: A typical source is an integrated circuit (IC; or "chip") which often operates at high clock frequencies (e.g. CPU) or with steep switching edges (e.g. power electronics). Everything that has to do with high frequencies can be a potential source of interference, i.e. all digital or logical circuits.
- **Conducted**: Typically, noise components are distributed over conductive wires from source to victim. These interferences are usually considered "only" up to 30 MHz.
- **Radiated**: Interferences above 30 MHz is usually considered radiated. The higher the frequency, the more likely wave propagation and near-field coupling will occur.
- **EMI victim**: Typical victims are analog circuits like operational amplifiers (opamps). Unlike digital circuits, these have to work very precisely and are therefore more susceptible to EMI.



The picture above is a very simplified categorization of EMC. In reality, a much broader distinction must be made. We have tried to show such a breakdown in the following picture. Don't worry, it will take more learning sessions in order to understand the picture below.



Watch the video below in order to get more familiar with these important terms.



Terms of EMC
https://youtu.be/01NycTPPmUU

1.1.4 Knowledge check

EMC is a nice-to-have feat to increase efficiency.

- O True
- O False

Which of the following terms is not one of the four aspects of EMC?

- O Radiated Emissions
- O Conducted Emissions
- O Radiated Immunity
- O Conducted Immunity
- O Project Costs

Which of the following statements are true?

- ☐ An EMC-compliant device must not be disturbed by electromagnetic waves.
- ☐ An EMC-compliant device must not exceed the legal limits for the emission of electromagnetic waves.
- ☐ Susceptibility is a synonym for Immunity.
- ☐ EMI is an undesired disruption.

1.2 Electromagnetic Wave

In high school we learn to calculate with voltages V and currents I. Voltage expresses the ability to push electric charges so that a current flows through the connected load. In many everyday situations, this integral approach is adequate. But not in EMC. Here we have to think in terms of electric and magnetic fields, which can propagate together as an electromagnetic wave. In this subsection, you will learn a little more about the electromagnetic spectrum. Then we will characterize a wave by its wavelength and amplitude. Finally, we discuss the electromagnetic wave itself. Unfortunately, this also requires some knowledge about Maxwell's equations.

> ***Everything is somehow connected...***
>
> *Integrating the electric field strength $\vec{E}$ gives the voltage; integrating the current density*

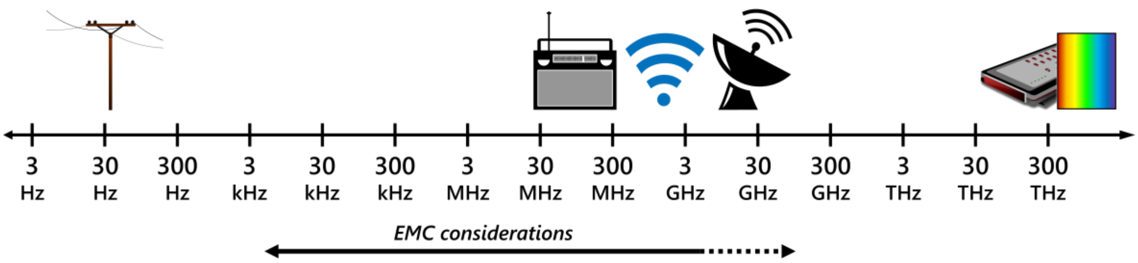
> *$\vec{J}$ gives the current. But a current-carrying conductor also generates a magnetic field. And a varying magnetic field in turn generates an electric field. So, these quantities are all linked together in a complex way somehow. A circuit can generate fields, but fields can also induce voltage and current.*

1.2.1 ELECTROMAGNETIC SPECTRUM

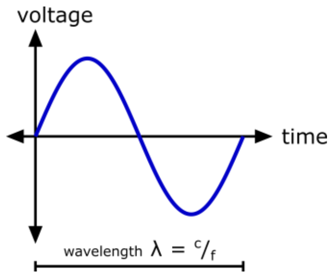
The first step to solving an EMC problem is to figure out where the noise is coming from. Basically, we distinguish between two types of noise sources: natural and man-made.

1) **Natural:** The most important source of natural interference is lightning in thunderstorms. The thunderbolt itself is a very fast transient event and contains many spectral components. But the interference does not come from a single lightning strike. **On Earth, about 40 lightning strikes occur every second.** This leads to a so-called **atmospheric noise below 30 MHz**. This makes low-frequency broadcasting more prone to interferences. Natural noise sources also exist up into the GHz range. This is **cosmic noise** and comes mainly from our Sun or from the center of the Milky Way. It's very hard to measure, but there is also the cosmic microwave background radiation which is a relic of the Big Bang. Natural noise sources ultimately play a minor role.

2) **Man-made** noise starts at 50 Hz and goes up to really high frequencies. Noise above 6 GHz was ignored, but this is changing right now. The very common sources of interference are…
   - **broadcast transmitters** (e.g. AM radio at 1 MHz, FM radio at 100 MHz, DVB-T2 TV at 500 MHz; the picture on the right shows the transmitter in Graz which broadcasts FM radio and DVB-T2 television),
   - **mobile telephony** (e.g. GSM at 900 MHz, UMTS at 2100 MHz, LTE and 5G from 700 MHZ to 3800 MHz; frequency bands in Austria),
   - **Wi-Fi networks** (2.4 and 5 GHz) and **Bluetooth** communication (2.4 GHz; interferes therefore with Wi-Fi),
   - but all our **consumer electronics** as well, especially when **high-speed digital circuits with short rise and fall times** are integrated (e.g. computer, game console, automotive industry, …),
   - but also analog circuits like a **switched-mode power supply** (charging brick).



1.2.2 WAVELENGTH



In EMC, electrical dimensions are measured in wavelengths. A wavelength λ is the distance a sine wave needs to change its phase by 360°. The following formula is very important:

$$v_p = \lambda \cdot f$$

$$\left[\frac{m}{s}\right] = [m] \cdot \left[\frac{1}{s}\right]$$

- Where v_p is the phase velocity, e.g. in free space (**speed of light**),
- where λ is the wavelength of the wave, and
- where f is the frequency of the wave.

Phase velocity

The phase velocity is determined by the permittivity ε and permeability μ of the medium:

$$v_p = \frac{1}{\sqrt{\varepsilon \cdot \mu}}, \qquad with\ \varepsilon = \varepsilon_0 \cdot \varepsilon_r, \qquad \mu = \mu_0 \cdot \mu_r, \qquad \varepsilon_r \geq 1$$

For free space, these values are given by:

$$\varepsilon_0 \approx \frac{1}{36\pi} \cdot 10^{-9} \frac{F}{m}, \qquad \mu_0 \approx 400\pi \cdot 10^{-9} \frac{H}{m}$$

- A high ε leads to a better concentration of the electric field in the material, i.e. a higher capacitance.
- A high μ leads to a better concentration of the magnetic field in the material, i.e. a higher inductance (coil with iron core).

A single sine does not transmit any information. Therefore, we usually modulate the signal in amplitude (AM) or frequency (FM). This modulation represents signal content, and the waveform propagates with group velocity.

λ/10 rule

In RF engineering, dimensions are often measured in electrical lengths. In our course, we consider all dimensions smaller than $\frac{\lambda}{10}$ as electrically short, i.e. such dimensions serve as poor antennas, and we have to deal mainly with the near field only. For conductors larger than $\frac{\lambda}{10}$, we have to worry about its EM radiation, e.g. a 6 cm long trace is already a good antenna for 500 MHz.

Frequency [MHz]	Wavelength (in air)	Wavelength / 10 (in air)
100	3 m	30 cm
300	1 m	10 cm
500	0.6 m	6 cm

1.2.3 DECIBEL

On this page, we would like to clarify what a dBµV is - a unit very often used in the field of EMC. But first of all, let us break down the term **deci-Bel (dB)**:

- **Deci** is an SI unit prefix, similar to Milli, Micro or Nano, but Deci specifies the **factor 0.1**.
- **Bel** is not a conventional unit, but rather a pseudo unit. It indicates the **ratio of two values in a 10-logarithmic scale**. Bel is not a unit for loudness!

In the field of EMC, **a high dynamic range is usually used**, i.e. values might range over many orders of magnitude. Therefore, a logarithmic scale has become popular when expressing values. The following examples compare the two power values $P_1 = 1W$ and $P_2 = 10W$:

$$\log_{10} \frac{P_2}{P_1} = 1B$$

Because the **prefix Deci stands for 0.1**, the equation can also be written like this:

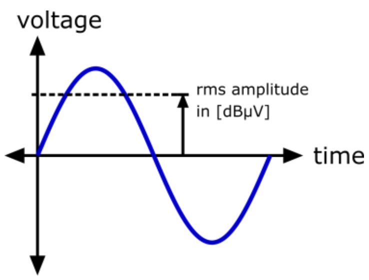
$$10 \cdot \log_{10} \frac{P_2}{P_1} = 10dB$$

It is **common to calculate with voltages** instead of powers:

$$10 \cdot \log_{10} \frac{\frac{V_2{}^2}{R}}{\frac{V_1{}^2}{R}} = 20 \cdot \log_{10} \frac{V_2}{V_1}$$

dBµV

It is important to understand that all formulas above showed the ratio of two numbers. Thus, an expression in dB is always relative. **However, we can also make an absolute expression by defining a common reference. We do so by appending this reference as an additional pseudo unit:**



$$20 \cdot \log_{10} \frac{V_{[V]}}{1\mu V} = V_{[dB\mu V]}$$

Let us assume that we measure $V_{[V]} = 1V$ with an **EMI receiver**. This would result in the following value:

$$20 \cdot \log_{10} \frac{1V}{1\mu V} = 120\ dB\mu V$$

In the field of EMC, this is already a **very high value**. We want to measure the level of interference voltages with an EMI receiver. Imagine that we measure 1V noise voltage - that will cause many errors during a data transfer. In practice, the EMI receiver already displays the value in dBµV, but we can **convert this value back** by rearranging the formula above:

$$1\mu V \cdot 10^{\frac{120\ dB\mu V}{20}} = 1V$$

[dBµV]	-20	0	20	40	60	80	100	120
[V]	0.1µ	1µ	10µ	100µ	1m	10m	100m	1

Value vs. detector

When a value is given in dBµV, it's always the RMS value and not the peak value. *So, the peak of the sine is divided by* $\sqrt{2}$. *For the conversion, it makes no difference whether we convert a peak value or an RMS value.* ***It's only about 3dB difference.***

However, be careful when working with measuring instruments. These devices use so-called ***detectors*** *which are also called "peak", "quasi-peak", "RMS" and "average". You must not mix up these terms! You will learn more about detectors in learning sequence 3.2 - Test Equipment.*

dBm

If you are working with a **spectrum analyzer**, then you will probably be working with powers. Here, you can usually find the pseudo unit **dBm, which is a shorter form for dBmW**:

$$10 \cdot \log_{10} \frac{P_{[W]}}{1mW} = P_{[dBm]}$$

Some further facts

- ***dB always expresses a ratio****. If the ratio is positive, you have an* ***amplification****; if it is negative, then you have a* ***reduction*** *(attenuation) compared to the reference. 0 dB means that you are exactly on the reference.*
- *At the* ***-3dB cutoff frequency****, the power is halved (i.e. voltage divided by* $\sqrt{2}$*).*
- ***A difference is always given in dB****, e.g.*

$$A = 100 \ {}^{dB\mu V}/_{m}$$
$$B = 80 \ {}^{dB\mu V}/_{m}$$
$$A - B = 20 \ dB$$

When someone specify the loudness of a music in dB, the person mostly means the sound pressure level related to the reference level of 20 µPa (based on the absolute threshold of hearing). Thus, this pseudo unit could also be called dB20µPa.

1.2.4 EM WAVE & MAXWELL

Any time-varying electric current (i.e. accelerating electrons) emits electromagnetic waves. These waves can then be radiated via antennas which could be any trace on our PCB. Unless used in radio communications, this conversion of energy is often seen as a loss. Thus, a flow of current causes not only heat losses, but radiation losses as well.

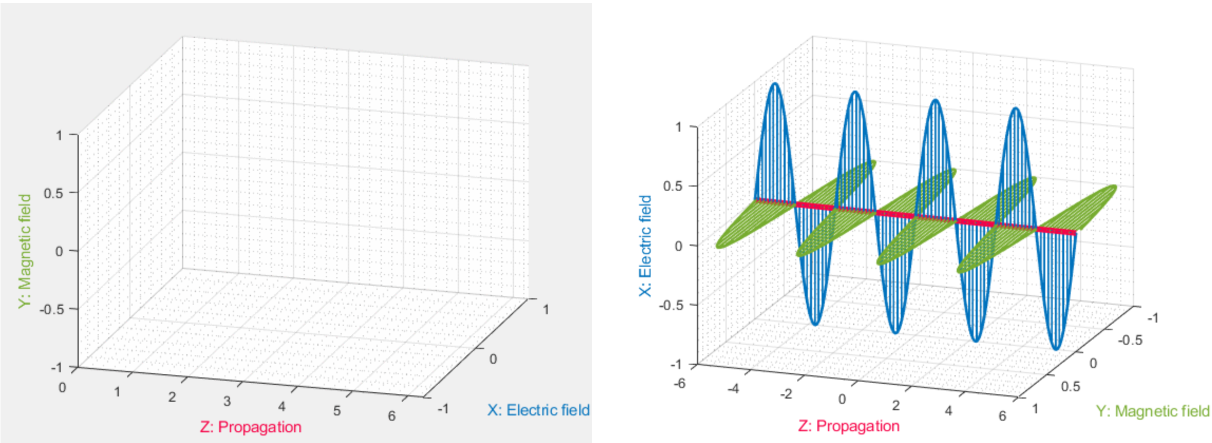
Explanation

James Clerk Maxwell identified the wave-like nature of electric and magnetic fields. You may not recognize it immediately in those equations, but there exists a symmetry between electric and magnetic field:

- Equation 3 shows that a **spatially varying electric field** relates to a **time varying magnetic field**.
- Equation 4 shows that a **spatially varying magnetic field** relates to a **time varying electric field**.

Thus, in an EM wave, a change in the electric field is always followed by a magnetic field and vice versa. One cannot exist without the other in the far field. Together they form a propagating EM wave. The direction of propagation is given by the **Poynting vector**:

$$\vec{S} = \vec{E} \times \vec{H}$$



Animations don't work in the PDF version.

With $\vec{D} = \varepsilon \cdot \vec{E}$ (electric field) and $\vec{B} = \mu \cdot \vec{H}$ (magnetic field):

Maxwell **I**	$div(\vec{D}) = \rho$
Maxwell **II**	$div(\vec{B}) = 0$
Maxwell **III**	$rot(\vec{E}) = -\frac{\partial \vec{B}}{\partial t}$
Maxwell **IV**	$rot(\vec{H}) = \vec{J} + \frac{\partial \vec{D}}{\partial t}$

To analyze a system accurately, it is necessary to solve Maxwell's equations. However, it is very impractical and calculation intensive to solve them. Therefore, **we often simplify electromagnetic problems to an electrical circuit**. The resulting error remains negligible as long as the dimensions are small compared to the wavelength.

> ***Lumped element representation***
>
> *If the dimensions are **smaller than 1/10 of the interfering wavelength** (i.e. near field), we can perform the following approximation:*
>
> - *We use a parasitic **capacitor** to represent an **electric coupling** of two circuits.*
> - *We use two parasitic **inductors** to represent **a magnetic coupling** of two circuits.*

Near and far field

Depending on the distance, a distinction is made between near and far field. The explanations above are valid for the **EM radiation** and thus for the **far field**. Electric and magnetic fields exist due to local changes in each other's fields.

In the **near field**, however, we speak about a **local EM field** where the energy is stored as reactive power. A magnetic field is caused by current flow, and an electric field is caused by charge separation.

The far field is thus that part of the EM field which is already too far away from the source and is therefore independent of it. Whether and how much energy "disappears" into the far field mainly depends on the frequency of the signal and the length of the antenna.

Near field	Far field
$\vec{E}$ and $\vec{H}$ depend on the geometry of the antenna.	$\vec{E}$ and $\vec{H}$ are perpendicular to each other (planar wave).
Reactive power oscillates between antenna and near field. The source reacts if that power is measured or consumed.	Measuring the EM field does not influence the source since the EM wave travels independently.
Energy can be coupled capacitively or inductively but disappears if the power is turned off.	Energy propagates through the EM field independently from the source.

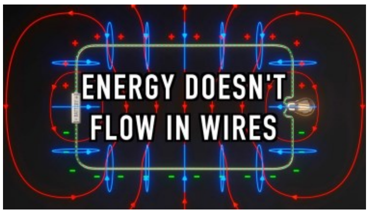
What is an antenna?

An antenna transforms a conducted EM wave into a free-running EM wave and vice versa. Unfortunately, not only the known structures like those of Yagi-Uda are effective antennas. Basically, every conductive trace on a PCB acts like an antenna. Even though it may be a bad antenna, it call still radiate. Ultimately, any antenna can be seen as a superposition of numerous infinitesimal electric and/or magnetic dipoles.

The longer the trace and the higher the frequency, the easier it is for the EM field to pinch off. Even a 50 Hz signal can be seen as high frequency with the appropriate cable length (e.g. electric power transmission lines). Radio frequency effects already occur at any frequency above 0 Hz, but we only notice them at higher frequencies.

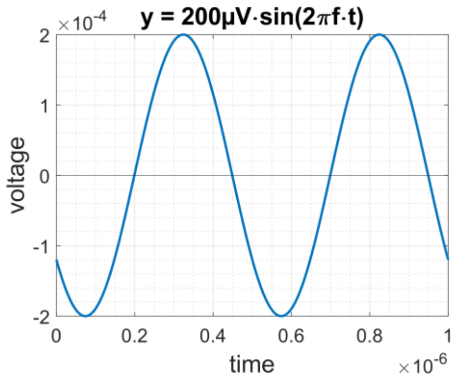
External YouTube video

Watch the following YouTube video to better understand how electrical energy is transported from A to B using the electric and magnetic field. This video went viral in our community and inspired numerous discussions. In a nutshell: energy is always transported by electromagnetic waves and not by the electrons. However, the acceleration of electrons causes electromagnetic waves, and we need conductors in order to guide these waves.



The Big Misconception About Electricity
https://youtu.be/bHIhgxav9LY?t=202
03:22 to 11:40

1.2.5 KNOWLEDGE CHECK



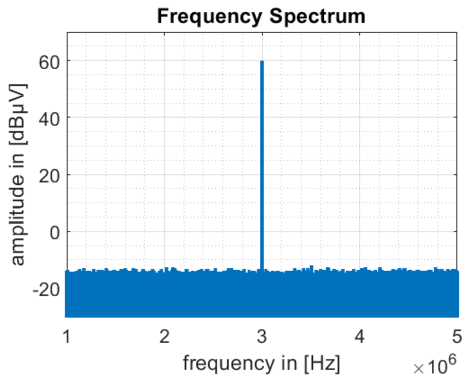
What is the frequency of the signal shown above?

Assuming this wave propagates in the air, what would be its wavelength?

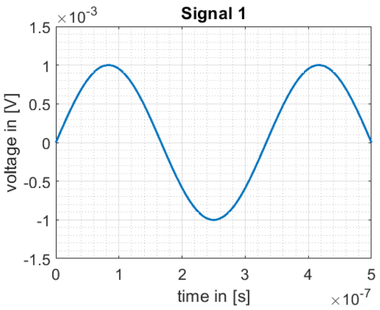
Transform 200 µV into dBµV.

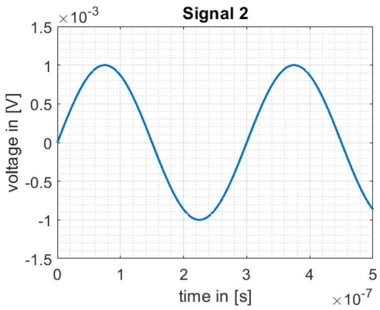
How many dBµV has the signal above? You must take the RMS value!

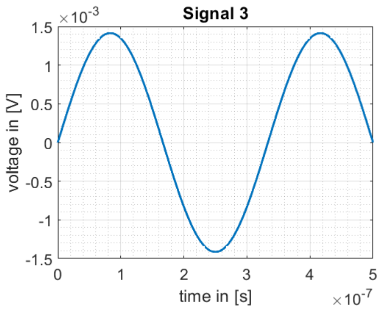
Look at the spectrum. Here you see an amplitude of 60dBµV. How many volts is that?



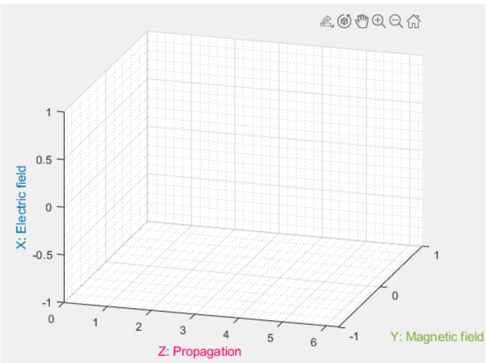
Which signal matches the spectrum above?







Look at the animation. Which of the following statements is correct?



- ○ A correctly propagating electromagnetic wave is shown.
- ○ The Cartesian coordinate system is wrong.
- ○ The direction of propagation is wrong.

What is an electron?

- ☐ It's a subatomic particle with negative charge which doesn't crash into the atomic nucleus *for some reason*.
- ☐ It's the ancient Greek word for amber.

☐ Quantum theory: An electron is a lepton, i.e. an elementary particle of the Standard Model. This quantum mechanical object is both particle and wave at the same time, proven in the double-slit experiment. According to the Copenhagen interpretation, the wave function collapses when we *determine* its location, i.e. it no longer follows the deterministic laws of the Schrödinger equation. In a nutshell: an electron is a quantum mechanical object which takes all possible paths (superposition) but *becomes* a particle at one non-deterministic point when we try to *measure* it.

1.3 50 OHM SYSTEM

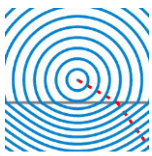
Two different types of impedances exist: electrical impedance and characteristic impedance. It is crucial to distinguish these two from each other.

- **Electrical impedance**: We are familiar with these, especially with the ohmic resistance $R = \frac{V}{I}$.
- **Characteristic impedance**: It's a property of geometry and its field-carrying media in which an electromagnetic wave propagates. The terms **50 ohm** and **matching** often come up.

In this learning sequence, you will learn that characteristic impedance is determined by geometry and material. We will have a closer look at this using a microstrip line. After that, you will see that proper termination is necessary in order to prevent a signal to reflect back unintentionally. Finally, we will look at the Smith chart representation.

> ***50Ω was the best tradeoff***
>
> *The choice of 50Ω as the default value seems arbitrary first. Why not 22Ω or 47Ω, for example; resistance values that can be found in any electronics kit? Historically, the choice of 50Ω was a good compromise* ***between low attenuation*** *(at 77Ω) and* ***maximum power capacity*** *(at 30Ω) for air-filled coaxial cables ($\varepsilon_r = 1$). For this reason, the* ***75Ω standard for cable TV lines*** *became established since minimum loss is important here. Today, the coaxial cables are mostly filled with* ***polyethylene (PE,*** *$\varepsilon_r \approx 2.3$) or* ***Teflon*** *(**PTFE**, $\varepsilon_r \approx 2$). PE has the lowest ohmic losses at 51Ω (source, ch. 11.4). Thus, the 50Ω system remained in place. This leaves us with no choice but to* ***solder two 100Ω resistors in parallel*** *(or 4x 200Ω, …) in order to terminate a coaxial cable.*

1.3.1 CHARACTERISTIC IMPEDANCE



You may have seen the animation on the right from your physics classes (chapter on optics). At the interface of two media with different refractive indices, light is refracted and reflected.

Since **light is electromagnetic radiation**, the rules of optics also apply to electrical engineering. The **wave impedance** is a property of a medium in which a wave propagates, and **transmission and reflection occur at the interface** of two different impedances.

Electrical impedance vs. Characteristic impedance vs. Wave impedance

- ***Electrical impedance*** *Z: gives the ratio between voltage and current. Values can range from 0Ω to $\infty\Omega$. In very rare cases, materials exist that behave mathematically inverse (negative resistance).*
- ***Characteristic impedance*** *Z_0: property of a geometry and its field-carrying media (e.g. coaxial cable) which guides current and voltage waves. Most RF cables are specified with 50Ω. It's not a component but a key figure.*
- ***Wave impedance*** *Z_w: property of free space. Unless otherwise specified, 377Ω may be assumed.*
- *Reminder: an **antenna** transforms a conducted EM wave into a free-running EM wave and vice versa.*

Ω is the unit of impedance

This confuses everyone in the beginning! All impedances have the same unit Ω. The wave impedance in free space is calculated by:

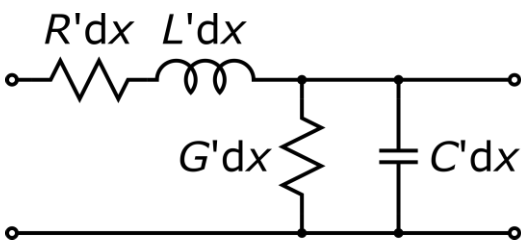
$$Z_w = \frac{|\vec{E}|}{|\vec{H}|} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377\Omega$$

On the other hand, the characteristic impedance for a transmission line in TEM mode (e.g. coaxial cable) is calculated as follows:

$$Z_0 = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}$$

The dashes on the formula symbols indicate that the units are per length. Below, you see an infinitesimally small transmission line element with the length dx. It is basically the equivalent circuit of each trace, but each trace is a connection of an infinite number of these elements.

- R' is the **resistance** per unit length.
- G' is the **conductance** per unit length.
- L' is the **inductance** per unit length.
- C' is the **capacitance** per unit length.
- ω is the **angular frequency**.
- j is the **imaginary unit**.



Thus, it can be seen that the characteristic impedance is independent of the line length. Instead, the other geometric dimensions and the materials are relevant.

Special case 1: DC current

If $\omega = 0Hz$, the characteristic impedance is calculated by:

$$Z_0 = \sqrt{\frac{R'}{G'}}$$

In the ideal case, the characteristic impedance would be ∞, and no RF effects occur. In reality, however, we have about $Z_0 \geq 10M\Omega$ at DC.

Special case 2: low frequency

At low frequencies, you can neglect G' and L'. The equation can thus be simplified to:

$$Z_0 = \sqrt{\frac{R'}{j\omega C'}}$$

This case is not interesting in our course.

Special case 3: high frequency or lossless lines

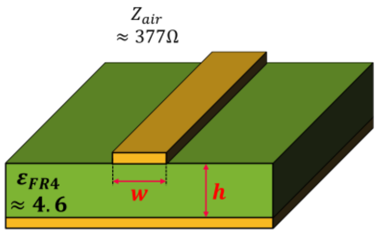
The higher the frequency, the more likely R' and G' are negligible. If both the trace resistance R' and parallel conductance G' is 0, then the characteristic impedance is calculated with:

$$Z_0 = \sqrt{\frac{L'}{C'}}$$

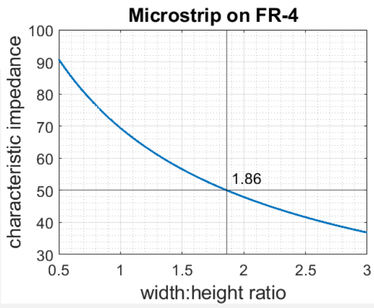
A wave is not damped and can (theoretically) be reflected back and forth an infinite number of times. The characteristic impedance is determined only by L' and C' and thus **by the geometry and the media**. On the next page you will see an example that Z_0 is not so easy to calculate.

1.3.2 MICROSTRIP

The simplest geometry is the microstrip. These can be found on every PCB. Its characteristic impedance can be determined by the following formula (Hammerstad's equation):



$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_{eff}}} \cdot \ln\left(8\dfrac{h}{w} + 0.25\dfrac{w}{h}\right) & if\ w \leq h \\ \dfrac{120\pi}{\sqrt{\varepsilon_{eff}}} \cdot \dfrac{1}{\dfrac{w}{h} + 1.393 + 0.667\ln\left(\dfrac{w}{h} + 1.444\right)} & if\ w \geq h \end{cases}$$



MATLAB code

```
clear
clc

%% Change the Width
W = 2900;

%% Insert Height and Dielectric from manufacturer
H = 1550;
Er = 4.6;

%% Calculation by Hammerstad
if W < H
    F = 1/sqrt(1+12*H/W) + 0.04*(1-W/H)^2;
    Eeff = (Er+1)/2 + (Er-1)/2*F;
```

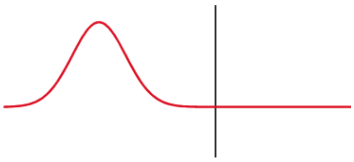
```
    Z0 = 60/sqrt(Eeff) * log(8*H/W + W/4/H)
else
    F = 1/sqrt(1+12*H/W);
    Eeff = (Er+1)/2 + (Er-1)/2*F;
    Z0 = 120*pi/sqrt(Eeff)/(W/H+1.393+0.667*log(W/H+1.444))
end
```

Of course, you don't have to remember this formula. But this example shows you that the **characteristic impedance is determined by geometry** (width w and distance h) **and material** ε_r. For PCBs, FR-4 is the default dielectric material with about $\varepsilon_{FR4} \approx 4.6$. This value fluctuates widely and in addition ages. Nevertheless, the characteristic impedance is **independent of the length** of the trace.

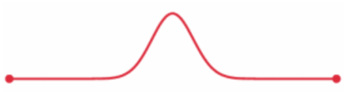
As a PCB designer, you can usually **only determine the width** of the trace, since the rest of the parameters are specified by the manufacturer. If high signal frequencies or steep switching edges are expected on the trace, then the width is usually selected so that a **50 Ohm trace** is obtained. Learn on the next page why this is so important.

> ***Coplanar waveguide***
>
> *The formulas shown on this page are valid for the simple stripline without any corners only. Another very common type for conductive traces on a PCB is the so-called coplanar waveguide. It's basically a microstrip, but the signal line is surrounded with GND lines to the left and right. This arrangement looks more like a coaxial cable. On the Internet you can find calculators to estimate the characteristic impedance of your trace arrangement.*

1.3.3 Reflection coefficient



When a wave propagates from one medium to the next medium, transmission and reflection occur. In the animation on the right, half of the wave is reflected back, because the characteristic impedances are very different. This is also called a **mismatch**. For efficient transmission, as little reflection as possible should be achieved; the systems should be matched.



An additional problem is that the reflected wave can be reflected again if the impedance at the beginning is unmatched as well. A wave would then be constantly reflected back and forth (next animation) until the signal dies because of the cable loss. A so-called **standing wave** is created in the line. This can also result in electromagnetic emission, something we want to avoid.

What does this mean from a practical point of view?

We must combine characteristic impedance and electrical resistance well together. Since we want to have as little mismatch as possible, both must have the same value. For example, **most coaxial cables have a characteristic impedance of 50 ohm**; So, we must **terminate it with a 50 ohm resistor in order to prevent reflections**. For this reason, many oscilloscopes have the option to measure with 50 ohm input impedance. This option is used when you want to capture fast signals. Spectrum analyzers and other RF measurement devices all have a 50 ohm input impedance. Signal generators have a 50 ohm output impedance as well in order to drive the signal well into the coaxial cable.

Be careful!

*If you work with measuring devices with 50 ohm input impedance, you must **not overload** them under any circumstances! In general, there is a label printed next to the cable connector like "**MAX 27dBm / 30V DC**". Thus, the following limits apply:*

1) *Do not apply any DC voltage above 30V to the device. Otherwise, it will get damaged due to heat development.*
2) *Do not measure any AC signal with more than **27dBm** which is equal to **0.5W or 5V**. Otherwise, your device will get kaput (irreversibly damaged).*

Can the reflection also be expressed with a number?

Sure! We use the formula symbol Gamma for describing the **reflection coefficient** Γ and calculate it as follows:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}, \qquad |\Gamma| \leq 1$$

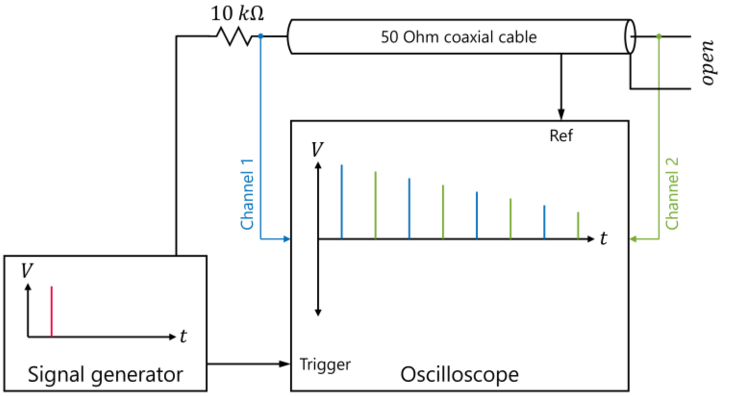
- where Z_L is the load impedance, and
- where Z_0 is the characteristic impedance of the transmission line, i.e. usually 50Ω.

The reflection coefficient Γ can then be used to describe the **voltage standing wave ratio**:

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}, \qquad VSWR \geq 1$$

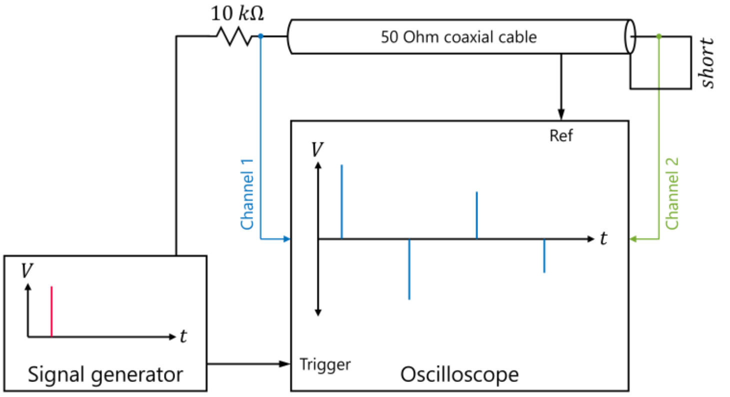
So, you have the following three special cases for a $Z_0 = 50\Omega$ cable:

Load impedance Z_L	Reflection coefficient Γ	VSWR	Description
0	-1	∞	Total inverted reflection at the **shorted** end of the line.
50 Ω	0	1	No reflection thanks to **matching**.
∞	1	∞	Total reflection at the **open** end of the line.



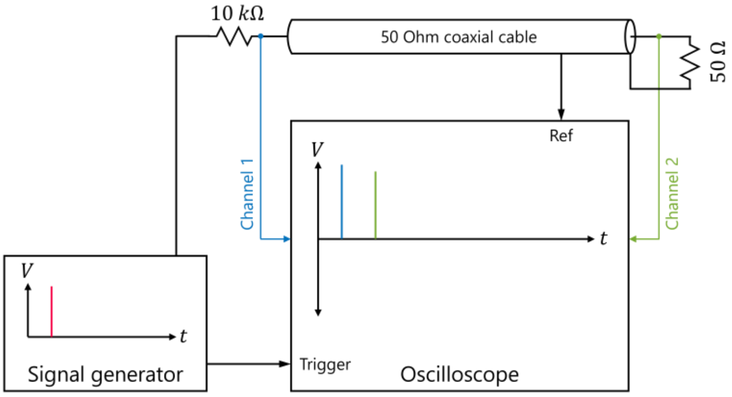
Open

Pulses with an open cable end. The pulses are reflected in phase but become weaker and weaker due to cable losses.



Short

Pulses with a shorted cable end. The pulses are reflected in antiphase but become weaker and weaker due to cable losses.

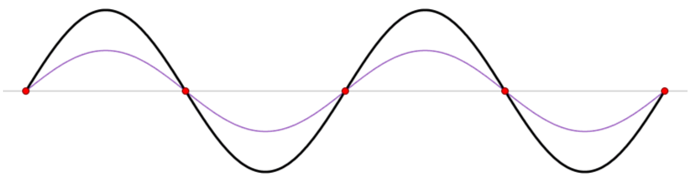


Match

Pulses with a matched load. The pulse energy is converted into heat in the termination resistor.

Standing wave of a shorted cable

Below you can see an animation of a standing wave. Since the boundary conditions are fixed, the wave oscillates in time but its amplitude profile does not change in space. The incident wave (blue) is fully reflected (red), and the black wave shows the resulting standing wave.

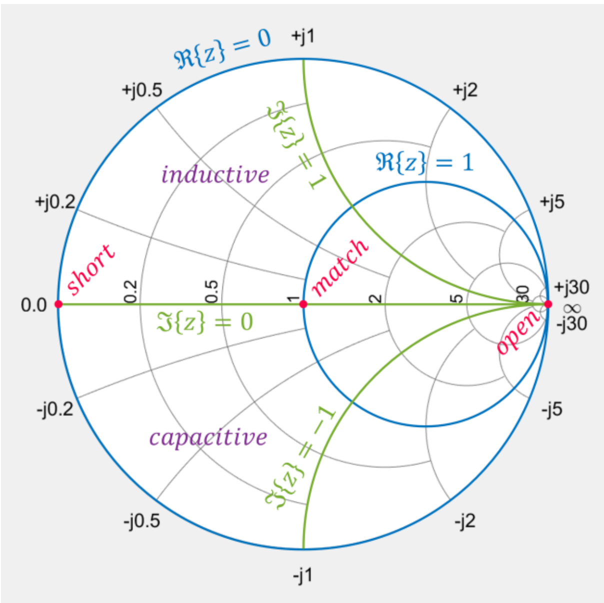


1.3.4 SMITH CHART

The Smith chart is an **alternative visualization** to the usual 2D XY line plot. When you see it for the first time, this appears very confusing. Historically, the Smith chart has been used as a **graphical calculation tool** in order to solve matching problems with additional transmission lines (stubs). However, today's PCs are powerful enough for RF calculations, and thus a Smith chart isn't used for complex calculations anymore. Nevertheless, this representation has lasted in many datasheets until today. Therefore, we want to focus on *how to read a Smith chart* instead of *how to calculate with a Smith chart*.

Below you will find a Smith chart in its **impedance representation**. As you can see, it is a round graph. **All complex numbers with a positive real part are transformed inside the circle.** Since the numbers with negative real part are transformed outside the circle, it is mostly a calibration error if a measuring point is outside.

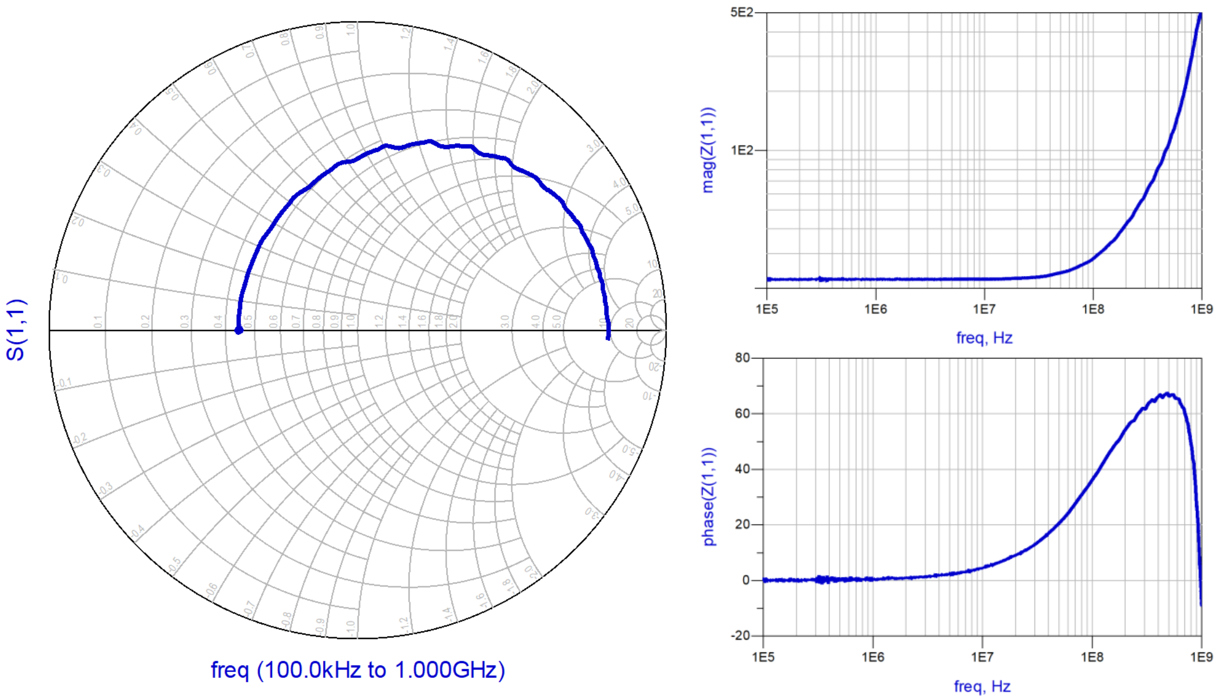
- There are three significant points in this chart:
    1) Short: here you measure 0 ohm or $\Gamma = -1$.
    2) Open: here you measure ∞ ohm or $\Gamma = 1$.
    3) Match: here your system is matched or $\Gamma = 0$, i.e. no reflections.
- Along a blue circle you always have the same real resistance value. But the values are all normalized with the characteristic impedance Z_0, i.e. along the $real\{z\} = 1$ circle you have 50Ω most of the times.
- Along a green line you have the same imaginary part. Therefore, your devive behaves inductive in the upper semicircle and capacitive in the lower semicircle.
- A $\frac{\lambda}{2}$ long coaxial cable causes a 360° clockwise rotation, i.e. a 1:1 transformation if cable losses are neglected (360° = 180° forward + 180° reflected wave).
- The distance between the center of the circle and the measuring point indicates the reflection coefficient $|\Gamma| \leq 1$.



Example 1: datasheet of a resistor

Later in the course we will learn that components are not ideal. In the following image, a **22Ω resistor** was measured using a network analyzer. The result can be displayed either as a magnitude and phase plot, or as a single Smith chart. The following can be read from this:

- **Up to 30 MHz**, our DUT behaves like the **desired 22Ω resistance**. Therefore, our Smith chart starts at the value **0.44** $\left(\frac{Z_L}{Z_0} = \frac{22\Omega}{50\Omega}\right)$ on the horizontal axis.
- From **30 MHz to 900 MHz**, our DUT acts **inductively**. We are in the upper semicircle of the Smith chart.
- From 900 MHz **upwards**, our DUT acts **capacitively**. The horizontal axis is crossed and we are in the lower semicircle of the Smith chart.
- This scheme - inductive, capacitive, inductive, capacitive - continues the higher the measuring frequency is.
- One disadvantage of the printed Smith chart is that you do not know at which frequency the measuring points are located. But you have magnitude and phase concentrated in only one graph.

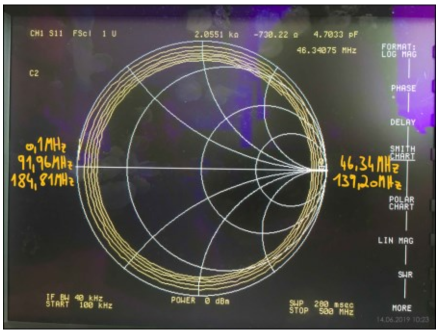


Example 2: locating the error of a cable

Our global Internet traffic runs over miles of [deep-sea cables](). Imagine that somewhere in the sea the cable is broken and it's our task to locate this fault in order to repair (splice) the cable. Okay, these cables transmit light and not electric current, but for our example, we ignore this fact. With the help of the Smith chart, we can now perform the following analysis:

- At first, we see a lot of circles on the display. But with the help of a marker, we see that **low frequencies** are located at the **short** point. This means that the cable is probably broken as a short circuit.

- The higher the measuring frequency, the further the circle **rotates clockwise**. **Cable loss** causes the circles to run closer and closer together.
- At 185MHz, the Smith chart was circled the second time, and there is a whole wavelength λ "inside the cable".
- We can now simply calculate $\lambda = \frac{v}{f} = \frac{3 \cdot 10^8 \frac{m}{s}}{185 \cdot 10^6 \frac{1}{s}} = 1.62m$ (assuming air as dielectric). Thus, the cable must be damaged after 1.62m.

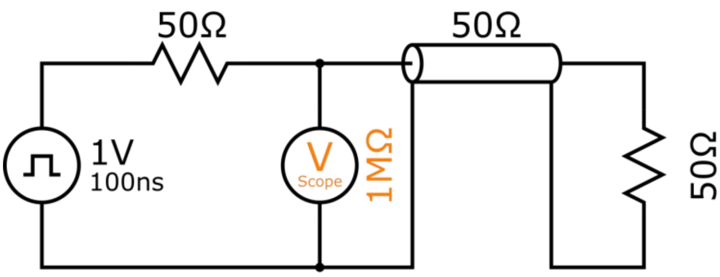


TDR: time-domain reflectometer

In practice, the location of the cable break is determined **with the help of reflections** (the page before). You send a signal into the cable and wait until the signal is reflected back. Based on the elapsed time and the signal shape, the location and type of fault can be determined. You can reproduce the following experiment with signal generator and oscilloscope in your lab. A so-called **TDR (time-domain reflectometer)** is an electronic instrument which has this function implemented.

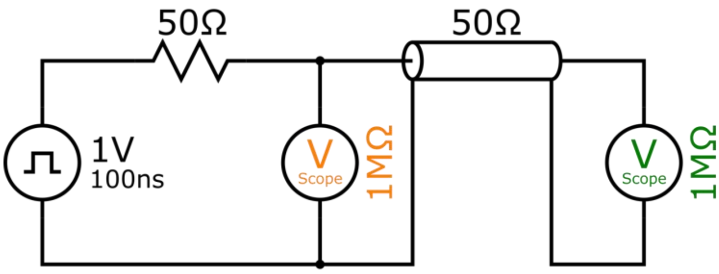
Match

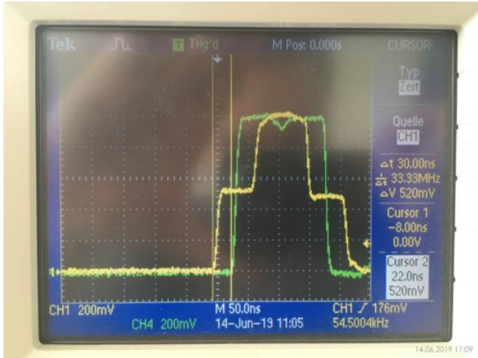
Signal generator, coaxial cable and load resistor all have 50Ω impedance. Thus, the system is **matched** and no reflections occur. **0.5V is measured** since the voltage is divided equally between the internal resistor of the generator and the load resistor.



Open

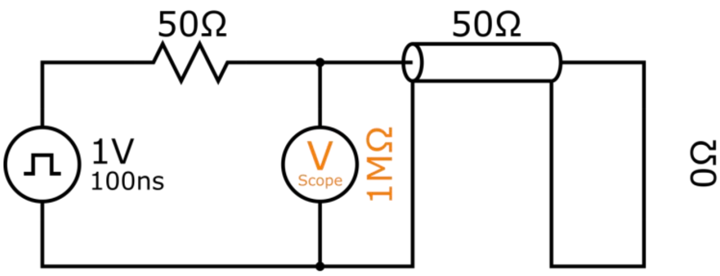
The load resistance is 1MΩ. Thus, there is a reflection factor of about $\Gamma = 1$ and **total reflection** occurs. The green signal rises 30ns later, because the wave has to propagate through the cable first. After another 30ns, the value of the yellow signal doubles, because the input signal and the reflected signal are **superposed positively** (constructive interference).





Short

The load resistance is 0Ω. Thus, there is a reflection factor of about $\Gamma = -1$ and **total inverted reflection** occurs. After 60ns, the value of the yellow signal decreases to 0, because the input signal and the reflected signal are **superposed with different signs** (destructive interference). After another few ns, -0.5V are measured, because only the reflected wave is captured.



If we additionally know the phase velocity, e.g. $v_p = 2 \cdot 10^8 \frac{m}{s}$, we can easily calculate the cable length:

$$30 \cdot 10^{-9} s \cdot 2 \cdot 10^8 \frac{m}{s} = 6m$$

1.3.5 Knowledge check

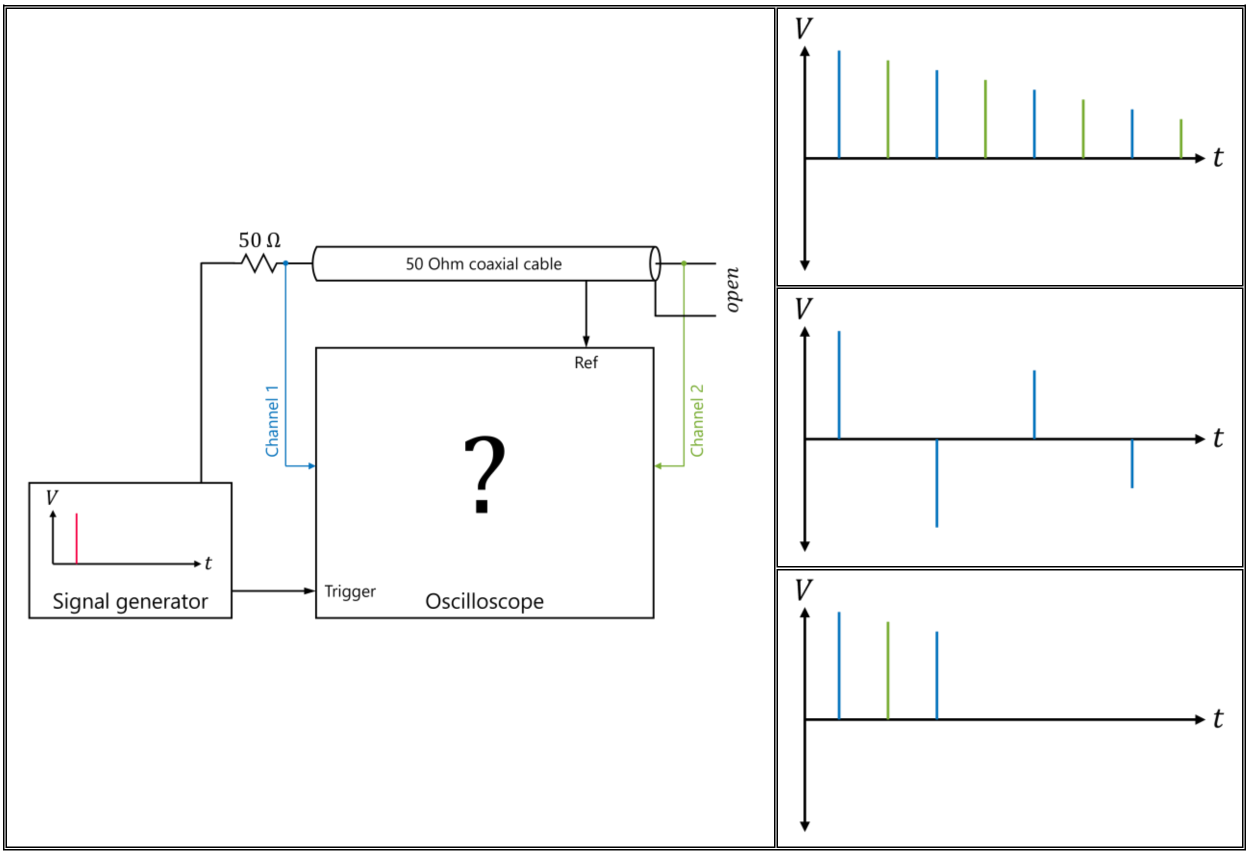
Here are a few statements about this learning sequence. Check all the true ones.

- ☐ Light is an electromagnetic wave just like sound.
- ☐ By changing the width of a microstrip line, we can influence the characteristic impedance.
- ☐ High frequency effects, such as reflections, only appear above 30 MHz.
- ☐ By changing the length of a microstrip line, we can influence the characteristic impedance.
- ☐ Wave impedance and characteristic impedance are synonyms.

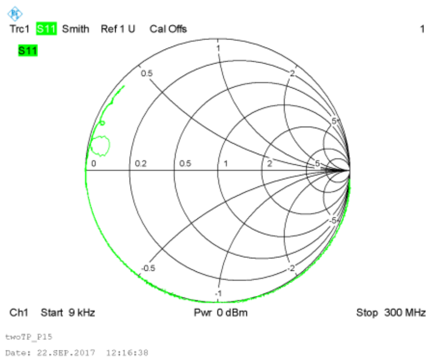
How can the reflection coefficient be calculated? Use Z_L for the load impedance and Z_0 for the characteristic impedance of the transmission line.

A 150Ω resistor is operated on a standard coaxial cable. Calculate the reflection coefficient.

We apply a voltage pulse to a coaxial cable. How does the captured oscilloscope screen look like?



Look at the Smith chart. Which component is it?



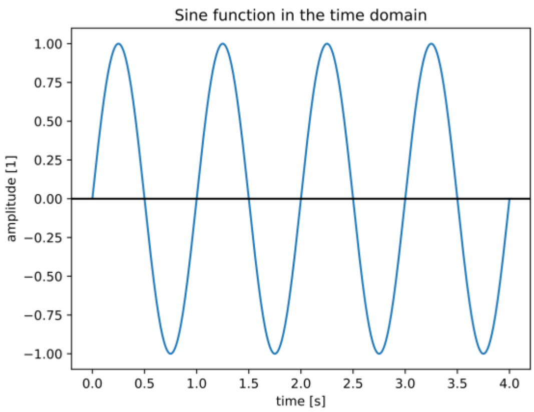
- ○ Resistor
- ○ Capacitor
- ○ Inductor
- ○ Transmission line

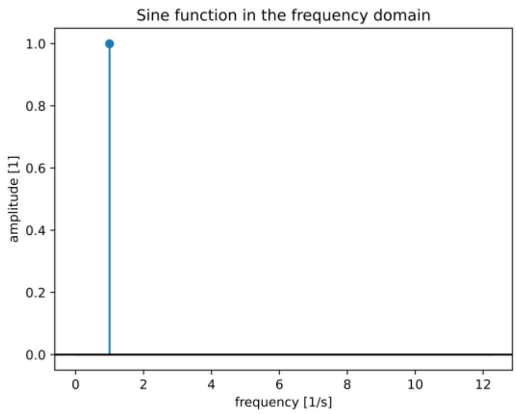
1.4 Time and Frequency Domain

We are familiar with thinking and calculating in the time domain. But in EMC we need to think within the frequency domain. To switch between these two domains, we need to understand the **Fourier theory: any arbitrary signal can be expressed as a superposition of individual sinusoidal signals of different frequencies.** Some of us probably learned this in high school; in EMC, that knowledge is applied. But don't worry. In this learning sequence we summarize Fourier series and transform again. **Thanks to today's PCs, we will rarely perform paper calculations by hand.** Nevertheless, it's important to understand how the spectrum of some common signals looks like - we analyze the frequency spectrum of a square wave signal; a very important lesson.

1.4.1 Time vs. Frequency

Take a look at the following sinusoidal signal. **Left** in the usual ***time domain*** representation; on the **right** in ***frequency domain***:





This is a sine wave with an *amplitude* of **1** and a *frequency* of **1 Hz**. Since there is only one specified frequency, the so-called ***frequency domain*** of a single sine wave is just the single amplitude.

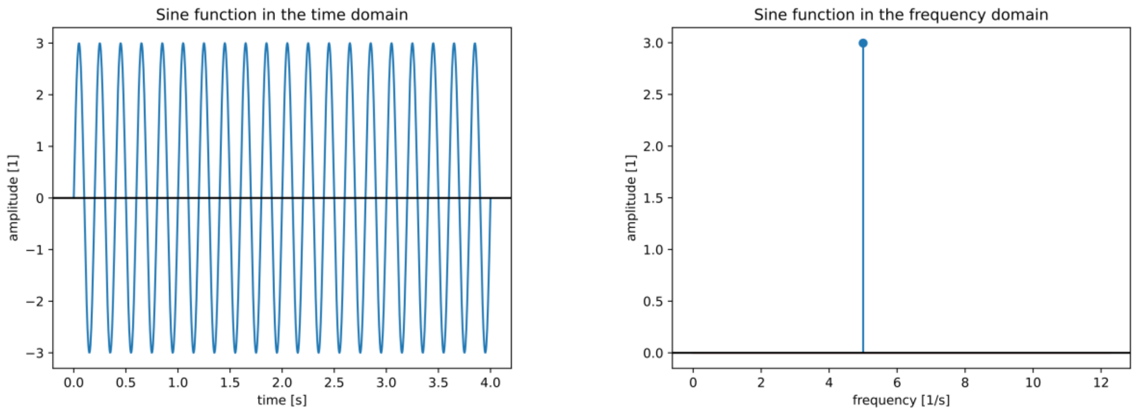
> ***Reminder: frequency vs. angular frequency***
>
> *The equation for a simple sine function is:*
>
> $$A \cdot \sin(\omega \cdot t)\,, \qquad \omega = 2\pi \cdot f$$

Where A is the amplitude and ω is the angular frequency. So, the parameters for the sine wave above are:

$$A = 1, \qquad f = 1Hz$$

Another example

Again, we have a simple sine wave but with other parameters. The *amplitude* is **3** and the *frequency* is **5 Hz**. Take a look at the time domain and the corresponding frequency domain of the following function.



If the signal is composed of more than a single frequency, for example, a superposition of two sine waves, the frequency domain is called ***spectrum*** or the ***frequency content*** of the signal.

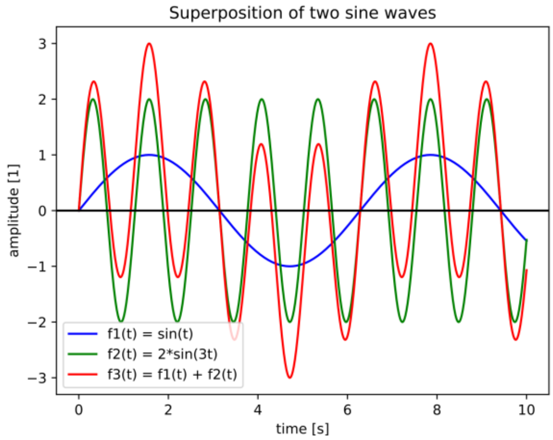
Why are we interested in the frequency domain?

Inspecting the spectrum is one of the key elements of circuit analysis. We usually investigate electromagnetic disturbances in the frequency domain, as the measures against EMI are frequency dependent. Besides: it is impossible to extract the frequency components from a typical time domain signal, just by looking at it.

1.4.2 FOURIER SERIES

Periodic functions are very important in science as they occur in form of vibrations and waves in nature. Thinking in terms of electromagnetic compatibility, we must consider periodic functions since we are dealing with electromagnetic waves.

Consider the following: if we have **two sine waves of the same frequency** and add them up, we get a **new sine wave with the same frequency**. But if we add two sine waves with **different frequencies**, we get a **superposition** which is also a periodic function. For visualization, take a look at the following example:



You can see two sine functions described as ***f1(t)*** and ***f2(t)***. f2 has three times the frequency and twice the amplitude as f1. The function ***f3*** added these two functions together. So, this superposed function consists of two individual sine waves. But the question now is: is this possible with every **arbitrary periodic function**? *Jean Baptiste Joseph Fourier* (1768 - 1830) said: Yes!

We can represent any **arbitrary periodic function** as **summation** of sines (or cosines); the individual frequency components are called **harmonics**. *Fourier* figured out how to calculate the amplitudes and frequencies of these harmonics in order to ***approximate*** any periodic function.

> ***What is a 'harmonic'?***
>
> *If we sum up a 10 Hz signal and a 20 Hz signal, we call the first signal* ***the first harmonic*** *and the second signal* ***the second harmonic****, as the later contains twice the frequency. Following this scheme, an additional 100 Hz signal would be called* ***the tenth harmonic****.*
>
> *Sometimes, the second harmonic is also called* ***the first overtone****. Consequently, the third harmonic is called* ***the second overtone****, and so on.*

Fourier series calculation

The following blue box summarizes the mathematical Fourier series of a periodic function. **You can skip this box**, but you have everything well summarized on this page in case you need it someday.

> ***The Fourier series***
>
> *A periodic function can be decomposed into a Fourier series:*
>
> $$\begin{aligned} f(x) &= \frac{a_0}{2} + a_1\cos(x) + a_2\cos(2x) + \cdots + b_1\sin(x) + b_2\sin(2x) + \cdots \\ &= \frac{a_0}{2} + \sum_{n=1}^{\infty}[a_n\cos(nx) + b_n\sin(nx)] \end{aligned}$$
>
> *This is called the* ***sine-cosine form****.*

The coefficients $a_0, a_1, \dots, b_1, b_2, \dots$ are the Fourier coefficients. Theses coefficients are calculated as follows:

If $f(x)$ is 2π-periodic:

$$a_0 = \frac{1}{\pi}\int_0^{2\pi} f(x)\,\mathrm{d}x\,, \qquad a_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos(nx)\,\mathrm{d}x\,, \qquad b_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\sin(nx)\,\mathrm{d}x$$

If $f(t)$ is T-periodic:

$$a_0 = \frac{2}{T}\int_0^{T} f(t)\,\mathrm{d}t\,, \qquad a_n = \frac{2}{T}\int_0^{T} f(t)\cos(n\omega_0 t)\,\mathrm{d}t\,, \qquad b_n = \frac{2}{T}\int_0^{T} f(t)\sin(n\omega_0 t)\,\mathrm{d}t$$

For the second case, we must change the series slightly:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left[a_n\cos(n\omega_0 t) + b_n\sin(n\omega_0 t)\right], \qquad \text{with } \omega_0 = \frac{2\pi}{T}$$

*In order to draw the amplitude spectrum, we need to represent the Fourier series in its **ampliltude-phase form**:*

$$f(t) = A_0 + \sum_{n=1}^{\infty} A_n \cdot \sin(n\omega_0 t + \varphi_n)$$

with:

$$A_0 = \frac{a_0}{2}, \qquad A_n = \sqrt{a_n{}^2 + b_n{}^2}, \qquad \tan(\varphi) = \frac{a_n}{b_n}, \qquad n = 1, 2, 3, \dots$$

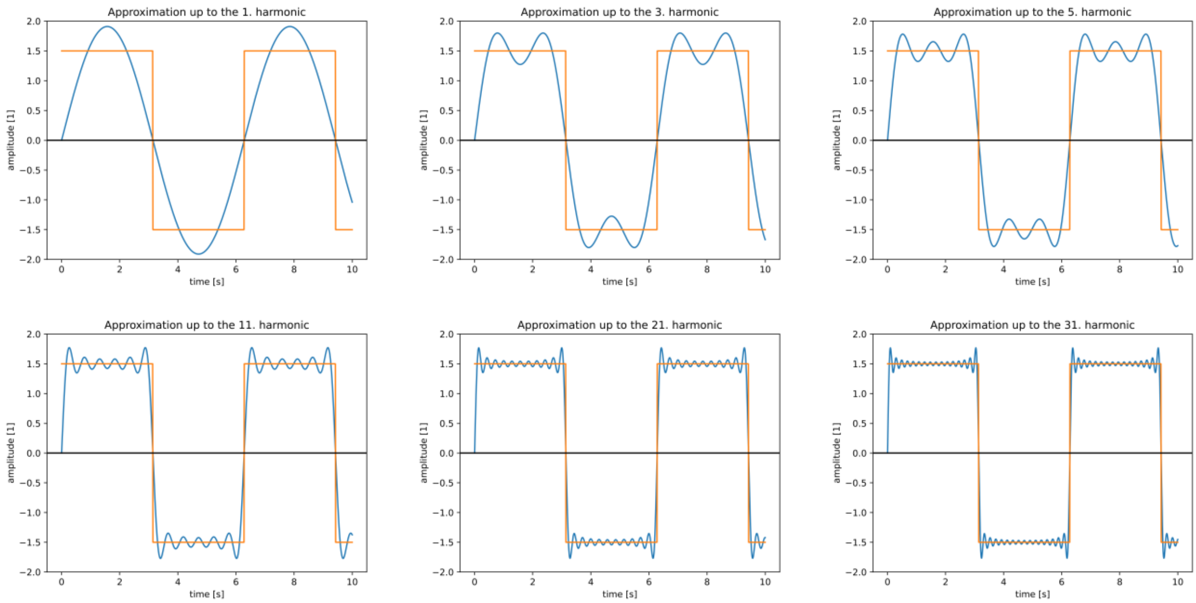
- The term $\frac{a_0}{2}$ represents the **DC component** of the periodic function. An infinite series of sinusoidal functions (or harmonics) follows.
- The 1st harmonic, *or fundamental*, in the Fourier series has the fundamental frequency f_0. The higher harmonics, *or overtones*, have frequencies which are integer multiples of the fundamental frequency f_0.
- The representation as the sum of infinite many sinusoidal functions can be used to show the function in the so-called ***amplitude spectrum***.

The Fourier series shows a discrete spectrum

*The values calculated by the Fourier series are graphically drawn as lines over the **discrete** running index (e.g. 1, 2, 3, …) or the associated angular frequencies (e.g. 10Hz, 20Hz, 30Hz, …).*

Example: continuous square wave

First, let's take a look at a square wave and how this function can be represented using sine waves only. At the time when Fourier lived, most people didn't believe him since this approximation was difficult to imagine.

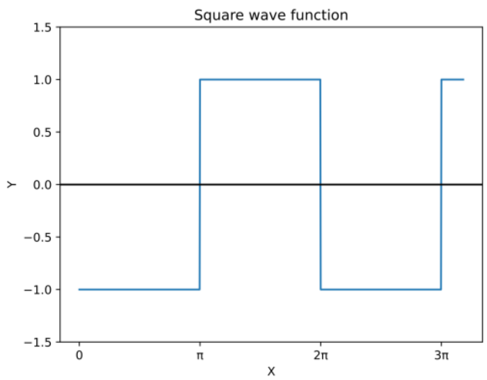


Picture 1 shows the approximation of the square wave as a single sine wave. Picture 2 describes the approximation up to the 2nd harmonic which has twice the frequency of the square wave, and so on... **This proves that a square wave consists of an infinite number of sinusoidal signals with multiples of the fundamental frequency.**

> ***Gibbs phenomenon***
>
> *You can see an overshoot at the edges of the approximated square wave. This is called* [Gibbs phenomenon]() *and occurs everytime when you have points of discontinuity.*

Calculation

Now, we will calculate the Fourier series of the square wave in order to draw the amplitude spectrum. **You can skip this calculation.** Today, nobody calculates the Fourier series by hand except of some poor students at Graz University of Technology 😉



The square wave has a perdiod of 2π and an amplitude of 1. The first step is to calculate the coefficients a_0, a_n and b_n:

1) The DC component a_0 is zero, because the integral over the period becomes zero.

2) For a_n we get:

$$a_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos(nx)\ dx = \frac{1}{\pi}\int_0^{\pi} -1\cdot\cos(nx)\ dx + \frac{1}{\pi}\int_{\pi}^{2\pi} +1\cdot\cos(nx)\ dx$$
$$= -\frac{1}{n\pi}[\sin(n\pi) - \sin(0)] + \frac{1}{n\pi}[\sin(n2\pi) - \sin(n\pi)] = 0$$

3) For b_n we get:

$$b_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\sin(nx)\ dx = \frac{1}{\pi}\int_0^{\pi} -1\cdot\sin(nx)\ dx + \frac{1}{\pi}\int_{\pi}^{2\pi} +1\cdot\sin(nx)\ dx$$
$$= \frac{1}{n\pi}[\cos(n\pi) - \cos(0)] - \frac{1}{n\pi}[\cos(n2\pi) - \cos(n\pi)]$$

Because $\cos(n2\pi)$ is always 1 for $n = 1, 2, 3, \ldots$, we get: $b_n = \frac{2}{n\pi}[\cos(n\pi) - 1]$
i.e. $b_n = -\frac{2}{n\pi}$ if n is uneven and $b_n = 0$ if n is even.

Now, we have everything in order to write down the Fourier series of the square wave function:

Sine-cosine form:

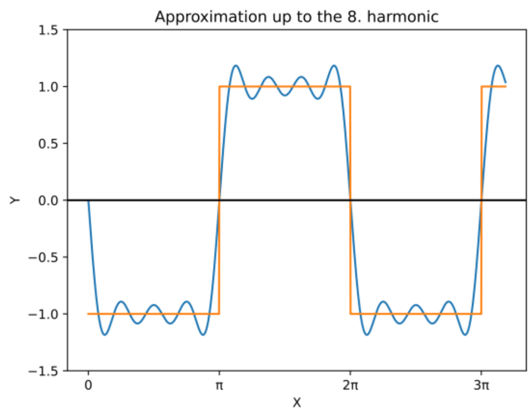
$$\sum_{n=1}^{\infty} b_n \cdot \sin(nx) = -\frac{4}{\pi}\sin(x) - \frac{4}{3\pi}\sin(3x) - \frac{4}{5\pi}\sin(5x) - \cdots$$

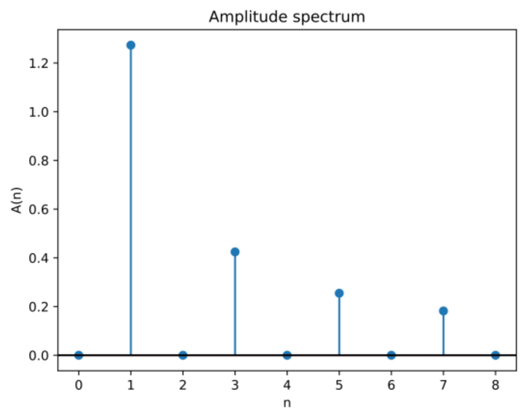
Amplitude-phase form:

$$A_0 = 0, \qquad A_n = \sqrt{{b_n}^2} = |b_n|$$

$$f(x) = \sum_{n=1}^{\infty} |b_n| \cdot \sin(nx)$$

Finally, we can choose an upper limit for the running index n and draw both the approximated function and the corresponding amplitude spectrum. Let's choose an upper limit of $n = 8$:





Remember…

*Only when the **square wave** has a **duty cycle of 50%**, then all even index numbers become 0, i.e. **only odd harmonics exist**. In addition, you should recognize that a square wave at e.g. 10 MHz could **cause EMC problems at multiple frequencies** although the amplitude gets smaller the higher the harmonic order is. The higher the frequency, the easier a noise signal can couple capacitively for instance.*

1.4.3 FOURIER TRANSFORM

We have seen that the **Fourier series** is used to describe a ***periodic*** function by the summation of infinitely many sine waves. This can then be used to describe the function in the frequency domain by drawing the amplitude spectrum.

The **Fourier transform** does completely the same but with ***non-periodic*** functions. Another very important difference is that the amplitude spectrum for the Fourier transform is **continuous and not discrete**.

In a nutshell

*A periodic function has a discrete spectrum, a non-periodic function has a continuous spectrum. **Periodic functions are way more likely to cause EMC problems** because its spectrum shows higher amplitudes. In contrast, non-periodic functions cause disturbances over all frequencies but with lower amplitude. In addition, it might be challenging to capture the spectrum of a non-periodic function with a measuring instrument.*

Fourier transform calculation

To understand the Fourier transform, we need to know about the complex form of the Fourier series. **You can skip this blue box again.** This shows us how to convert from a Fourier series into the Fourier transform.

Complex form of the Fourier series

*In general, the **sine-cosine form** of the Fourier series can be transformed into the **complex form** of the Fourier series.*

If $f(t)$ is a (real) periodic function with period T (or fundamental angular frequency ω_0):

$$f(t) = \sum_{n=-\infty}^{\infty} c_n \cdot e^{jn\omega_0 t}, \qquad \text{with } c_n = \frac{1}{T}\int_{-\frac{T}{2}}^{+\frac{T}{2}} f(t) \cdot e^{-jn\omega_0 t}\,\mathrm{d}t$$

With the following relations between the sine-cosine form *and the* complex form*:*

$$c_0 = \frac{a_0}{2}, \qquad c_n = \frac{1}{2}(a_n - j \cdot b_n), \qquad c_{-n} = \frac{1}{2}(a_n + j \cdot b_n), \qquad n = 1, 2, 3, \dots$$

The absolute values of the coefficients c_n represent the amplitude spectrum of the complex form of the Fourier series. c_0 is again the DC component of $f(t)$. The values of $|c_n|$ are plotted over $\omega = n \cdot \omega_0$.

$$|c_n| = |c_{-n}|$$

$$|c_n| = \frac{1}{2}\sqrt{{a_n}^2 + {b_n}^2} = \frac{1}{2}A_n$$

Since the summation of the Fourier series is from minus infinity *to* plus infinity, *we get* ***negative frequencies*** *as well. This may seem odd first, but these are just computational numbers (which we don't need to bother with in real life).*

Leonhard Euler

The derivation of the complex series is done by using [Euler's](#) formula:

$$e^{j\varphi} = \cos\varphi + j\sin\varphi\,, \qquad with\; j = \sqrt{-1}$$

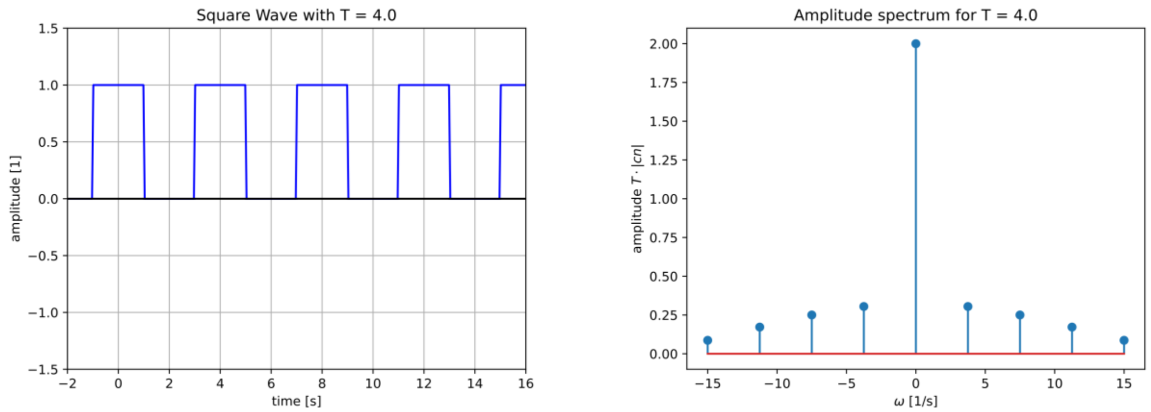
Therefore, we can write sine and cosine the following way:

$$\sin\varphi = \frac{1}{2j}\left(e^{j\varphi} - e^{-j\varphi}\right), \qquad \cos\varphi = \frac{1}{2}\left(e^{j\varphi} + e^{-j\varphi}\right)$$

This allows us to write the Fourier series in its complex form.

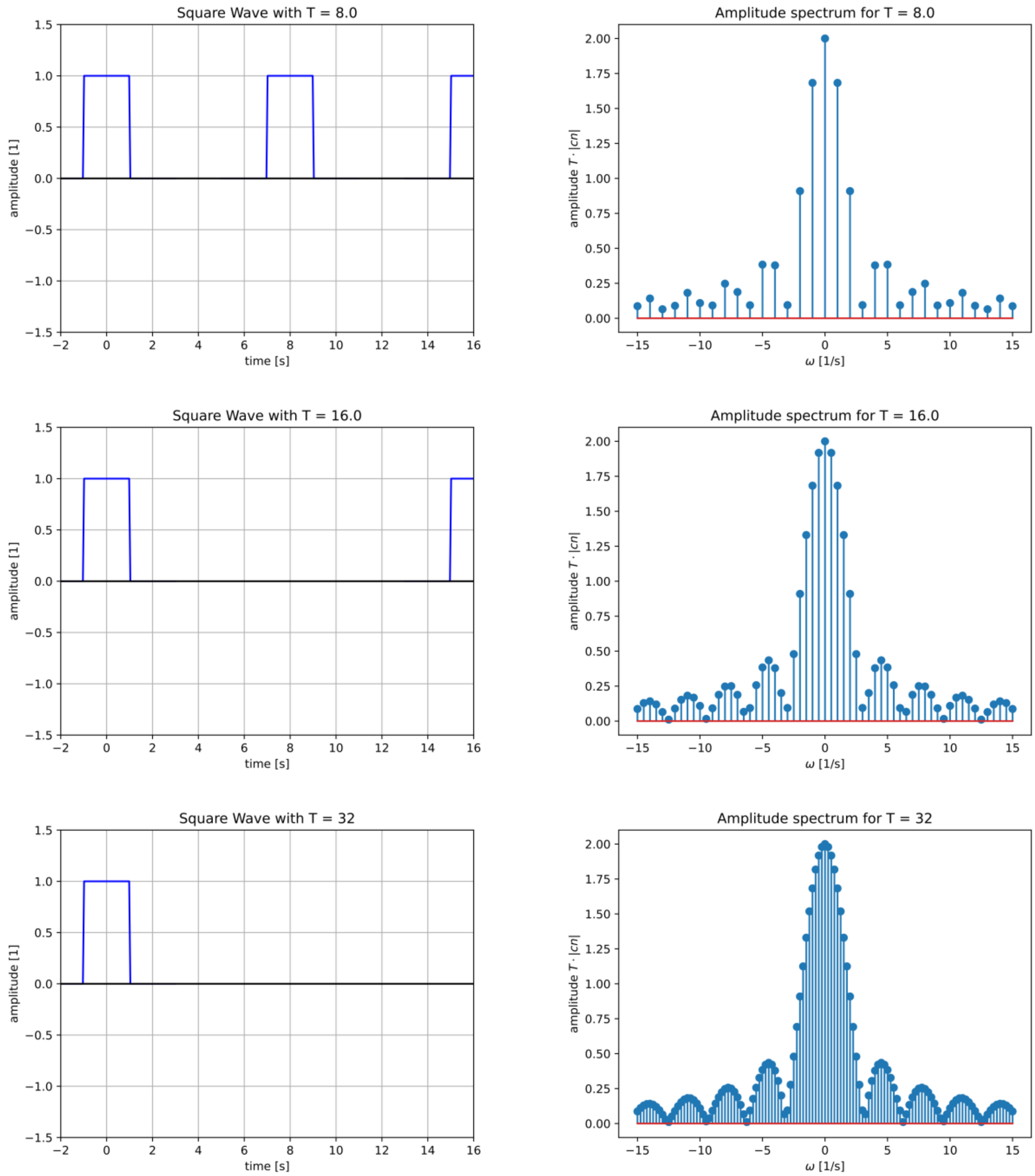
Example: single square pulse

Let's try to derive the Fourier transform of a single square pulse. First of all, we consider the periodic square wave (like in the previous page).



The blue lines of the complex spectrum show $T \cdot |c_n|$. For a better y-scaling, these spectral lines are multiplied with T; otherwise, $|c_n|$ would decrease the higher T gets because of $c_n = \frac{1}{T} \cdot [\dots]$.

Now, let's consider what happens when we just skip every second square pulse, i.e. the period T is a multiple of $4s$?



If we now assume $T \rightarrow \infty$, **the descrete spectrum becomes a continuous spectrum**, and the time domain signal becomes a **non-periodic** function: a rectangular shaped pulse. This spectrum might be familiar to you; it's the so-called $|sinc|$ function.

The Fourier transform

$$T \cdot c_n = \int_{-\frac{T}{2}}^{+\frac{T}{2}} f(t)\, e^{-jn\omega_0 t}\, dt \quad \Rightarrow \quad F(\omega) = \int_{-\infty}^{+\infty} f(t)\, e^{-j\omega t}\, dt$$

*$F(\omega)$ is called the **Fourier-transformed**. We can recover the function in its time domain $f(t)$ again:*

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega)\, e^{j\omega t}\, \mathrm{d}\omega$$

- $F(\omega)$ *contains the same information as the time domain function* $f(t)$.
- *Similar to the* complex form *of the Fourier* series, *the Fourier*-transformed *contains negative frequencies. These are just mathematical values and have no physical meaning.*
- *The Fourier-transformed is a complex quantity which can be represented as*

$$F(\omega) = |F(\omega)| \cdot e^{j\varphi(\omega)} = real\big(F(\omega)\big) + j \cdot imag\big(F(\omega)\big).$$

- $|F(\omega)|$ *is called the* ***amplitude density*** *and* φ *the* ***phase density***.

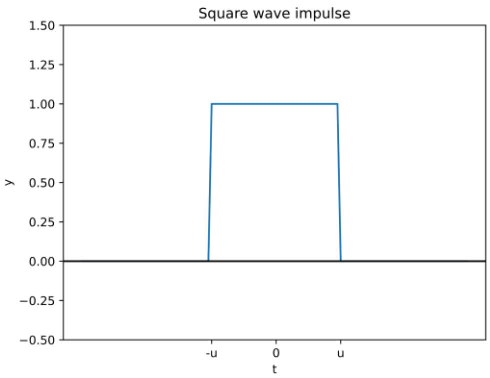
Prism analogy

A prism is able to decompose light into the colors of which it is composed. The Fourier-transform is a mathematical tool which decomposes a time-domain function into the frequencies it contains.

You may have recognized that the Fourier transform looks quite similar to the Laplace transform. This is not a coincidence, but the **Laplace transform is the generalized form of the Fourier transform**. Therefore, Laplace is generally used in system theory.

Calculation

Now, we will calculate the Fourier transform of a single pulse. **Of corse, you can skip this calculation again.** In daily practice, we just look for the result in a formula book or on the Internet.



We can describe this function with the following formula:

$$f(t) = \begin{cases} 1 & -u \le t \le u \\ 0 & otherwise \end{cases}$$

Applying the Fourier-transform yields:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\, e^{-j\omega t}\, \mathrm{d}t = \int_{-u}^{+u} 1 \cdot e^{-j\omega t}\, \mathrm{d}t$$

$$= \frac{1}{-j\omega} e^{-j\omega t} \Big|_{-u}^{+u} = \frac{1}{-j\omega} \left(e^{-j\omega u} - e^{-j\omega(-u)} \right)$$

For the next step, we will use Euler's formula:

$$\sin(a \cdot \omega) = \frac{1}{2j} \left(e^{j\omega \cdot a} - e^{-j\omega \cdot a} \right)$$

Which means that we need to rearrange the equation a little bit:

$$F(\omega) = \frac{1}{j\omega} \left(e^{j\omega \cdot u} - e^{-j\omega \cdot u} \right) = \frac{2}{\omega} \cdot \frac{1}{2j} \left(e^{j\omega \cdot u} - e^{-j\omega \cdot u} \right) = \frac{2\sin(u\omega)}{\omega}$$

This is the final result. However, the equation is not defined for , i.e. we have to calculate it by hand. For this, we could apply the rule of de L'Hôpital.

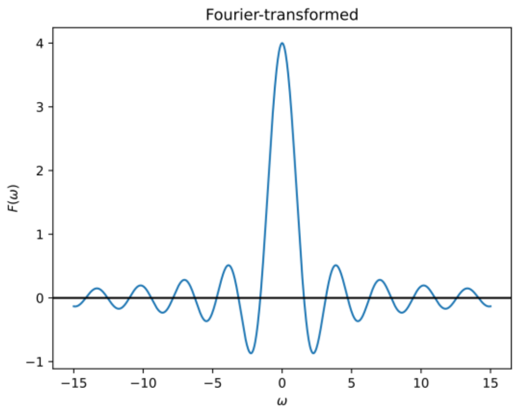
$$\lim_{\omega \to 0} \frac{2\sin(u\omega)}{\omega} = \lim_{\omega \to 0} \frac{2\cos(u\omega) \cdot u}{1} = 2u$$

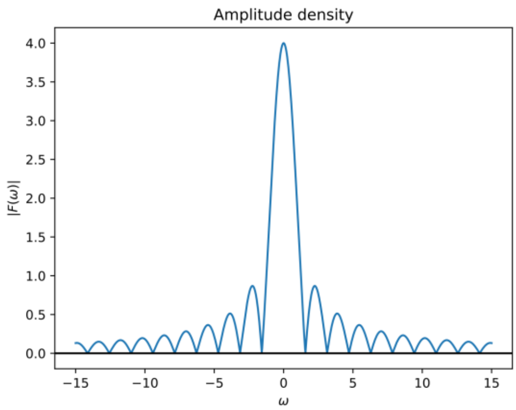
Thus, we can summarize our final result to:

$$f(\omega) = \begin{cases} 2\sin(u\omega)/\omega & \omega \neq 0 \\ 2u & \omega = 0 \end{cases}$$

Because this is a very common result, mathematicians have created a new function for it; the so-called $sinc$ function. It is defined as $sinc(x) = \frac{\sin(x)}{x}$.

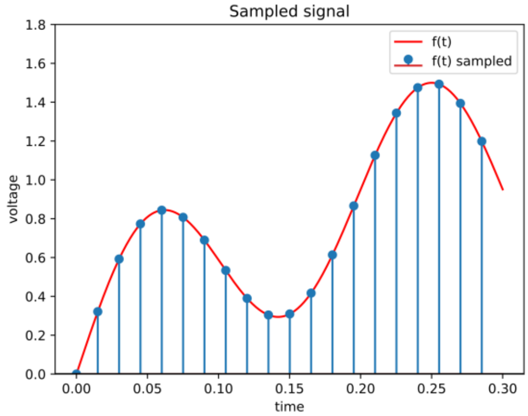
The Fourier-transformed for $u = 2s$ is shown below. The left figure shows $F(\omega)$. The right figure shows $|F(\omega)|$. In EMC, we typically analyze the absolute spectrum which is called the **amplitude density**.





1.4.4 DISCRETE-TIME FOURIER TRANSFORM

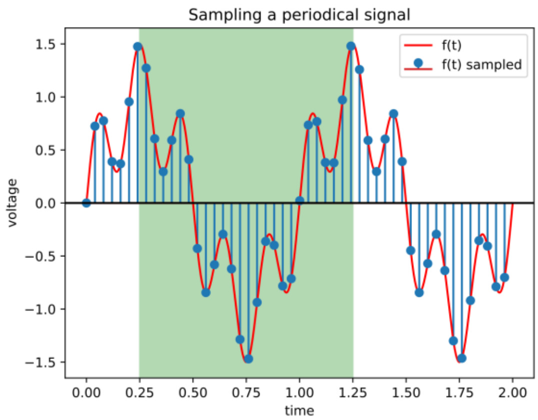
Imagine you want to measure some value like temperature, moisture or voltage with an electronic sensor. In this case, the measurement is done in a discrete way: namely **sampling**. So, you end up with a **discrete function** of time, which could look like this:



If you are now interested in the frequency behavior of this function, you will get stuck with the methods we already described in this learning sequence. The reason is, that **we can't integrate any discrete function**. Therefore, we just want to give a quick overview of the numerical methods that are usually used. Nowadays, these methods are widely implemented in software, e.g. in a scope, or in a modern EMI receiver.

DFT: discrete Fourier transform

The name *Discrete Fourier Transform* is a bit misleading. The DFT calculates the Fourier **series** of a discrete function like the function above. This method works for a finite number of samples, the so-called **sampling window**, which must be **exactly one period or a multiple of this period**.



The green area in the picture above is the samping window. It is important to know that the sampling rate must be high enough in order to reconstruct the orignal function from the sampled function, i.e. we must comply with the *Nyquist–Shannon sampling theorem*.

> ***Nyquist–Shannon sampling theorem***
>
> *A signal can be reconstructed from its samples if*
>
> $f_s > 2 \cdot f_{max}$*ere* f_s *is the sampling frequency and* f_{max} *the highest occurring frequency in the signal. Violation of this theorem results in aliasing.*

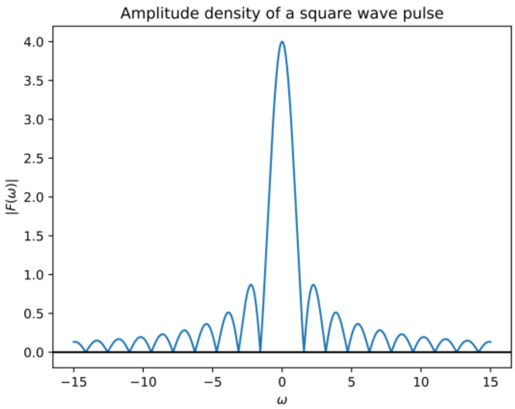
In case you are more interested in this topic, you will find tons of materials in the internet.

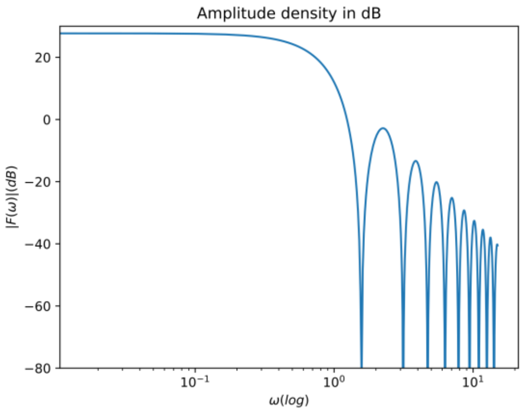
FFT: fast Fourier transform

The *Fast Fourier Transform* does exactly the same as the DFT, but it implements the mathematical calculation in a very efficient way. So, it's not another "standalone" method but an **optimized algorithm**.

1.4.5 Trapezoidal signal

Nowadays, nobody calculates the spectrum by hand anymore except the local students at Graz University of Technology. Today's PCs manage such calculations way better. In EMC, the spectrum is usually given in decibels, i.e. the left plot is just manipulated by $20 \cdot \log_{10}(\ldots)$ in order to achieve the right plot. Both plots show the spectrum of the same **rectangular pulse**.



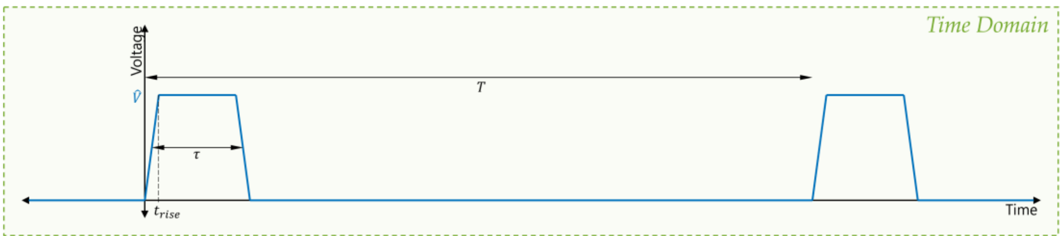


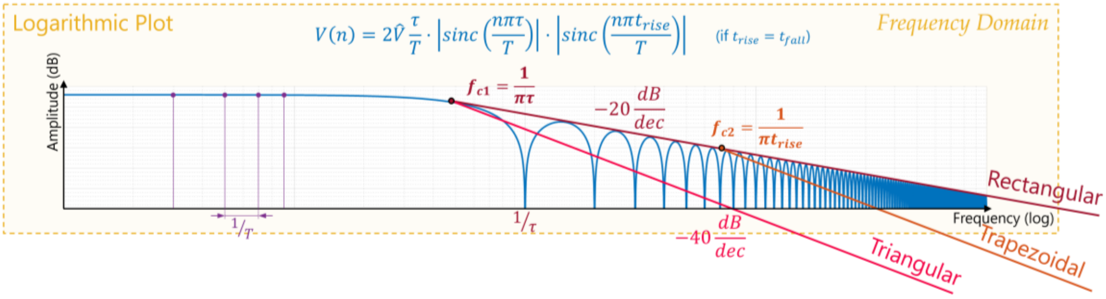
It is important to understand how the spectrum of a **trapezoidal signal** is constructed. It is **a mix of a rectangular and a triangular signal**. The formula of the spectrum is:

$$V(n) = \frac{2\hat{V}\tau}{T} \cdot \left|sinc\left(\frac{n\pi\tau}{T}\right)\right| \cdot \left|sinc\left(\frac{n\pi t_{rise}}{T}\right)\right|, \qquad if\ t_{rise} = t_{fall}$$

Thus, we get **two cutoff frequencies**.

1) The **first** is determined by τ: $\quad f_{c1} = \frac{1}{\pi\tau}$
2) The **second** is determined by $t_{rise} = t_{fall}$: $\quad f_{c2} = \frac{1}{\pi t_{rise}}$
3) In case rise and fall times differ, this single cutoff frequency would split into two separate ones.





Watch the video below to see again the spectrum of a trapezoidal signal. Remember: an EMC problem does not necessarily arise at the fundamental frequency of a signal. A 1MHz clock signal might provoke problems at 15MHz. If you have lab equipment available, you can simply use a **frequency generator** to output any arbitrary signal and analyze it with an **oscilloscope** (*time domain*) and **spectrum analyzer** (*frequency domain*). In the video below, we demonstrate this measurement setup. However, you may want to complete this MOOC first before conducting your own experiments. You must be careful not to set a signal amplitude that is too high; otherwise, your measuring equipment will be damaged.

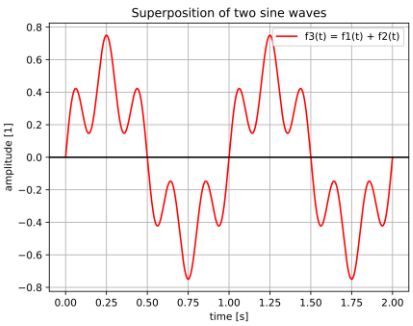
Frequency Spectrum of the Rectangular, Triangular and Trapezoidal Signal
https://youtu.be/_Mbfv-Aek3Y

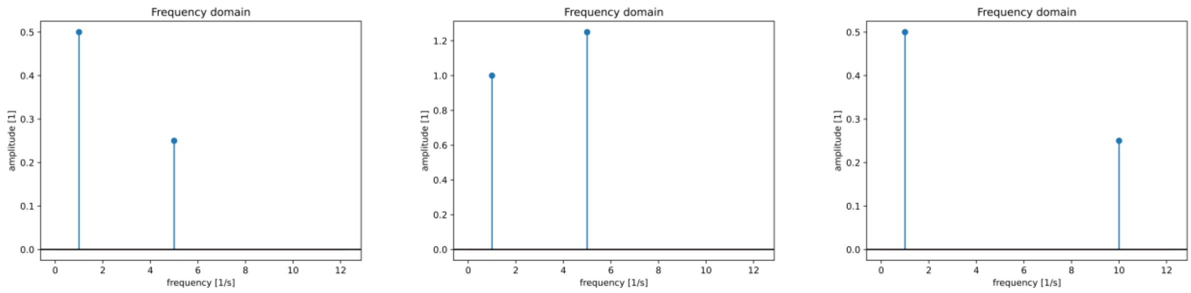
1.4.6 KNOWLEDGE CHECK

A few statements about Fourier. Which statements are true?

☐ The Fourier series is used for non-periodic signals.
☐ The Fourier transform is used for non-periodic signals.
☐ We can calculate the frequency-domain from the time-domain signal with Fourier's tools.
☐ It is not possible to calculate the time-domain signal out of the frequency-domain.
☐ The Laplace transform shows a lot of similarities to the Fourier transform.
☐ The spectrum of the Fourier series is discrete.
☐ The spectrum of the Fourier transform is continuous.

Select the correct frequency domain of the time domain signal.

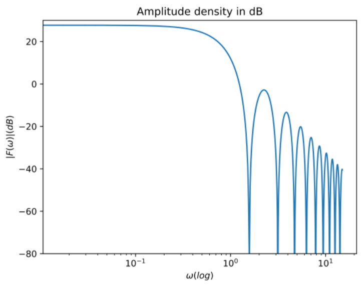




What is the *sinc* function?

- ☐ The Fourier-transformed of a single rectangular pulse.
- ☐ $\frac{\mathrm{d}\sin(t)\cdot t}{\mathrm{d}t}$
- ☐ $\frac{\sin(a)}{a}$
- ☐ An Austrian pasta dish, similar to mac and cheese.

Take a look on the spectrum. Which time-domain signal is plotted here?



- ○ A sine wave
- ○ A square wave
- ○ A triangular wave
- ○ None of them

A periodic signal is sampled every 10ms with an oscilloscope. How can we easily transform this signal into the frequency domain?

- ☐ Fourier series
- ☐ Fourier transform
- ☐ DFT
- ☐ FFT
- ☐ It's not possible with the tools learned.

Periodic signals tend to cause more often EMC problems.

- ○ True, because of the higher amplitudes of periodic signals!
- ○ False, because non-periodic signals have a spectrum over all frequencies!

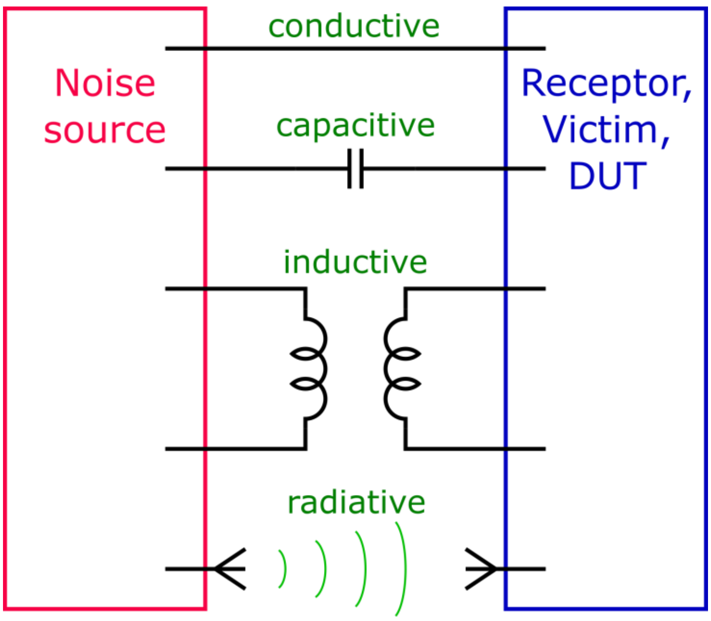
1.5 COUPLING MECHANISMS

In this learning sequence, we look at how disturbances can couple into our system. The picture below shows us that an interfering signal always couples in via a path.

- **Noise source**: There are numerous sources of electromagnetic interference. These can be natural or man-made. Regardless of the origin, EMC test engineers try to recreate these noise sources in the lab.
  - *Natural*: lightning strike, solar flare, cosmic noise, ...
  - *Man-made*: broadcast stations, cell phone, the clock trace of your electronic system, ...

- **Coupling path**: The interfering signal must enter our system through some path.
  - **Galvanic coupling** (conductive through a common impedance)
  - **Capacitive coupling** (near-field)
  - **Inductive coupling** (near-field)
  - **Radiated coupling** (far-field)

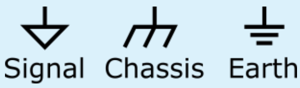
- **Receptor**: This is our system. An EMC test technician would call this system a DUT (device under test).
  - Especially analog parts of your electronic system, e.g. operational amplifiers or analog/digital converters, are susceptible to EMI.



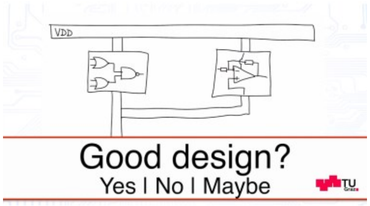
coupling channel

1.5.1 GALVANIC COUPLING

Galvanic coupling is when two circuits share the same path. This means that disturbances in one circuit have a direct effect on the other circuits. Unfortunately, it is often not so easy to provide a **"clean" GND potential** for all circuits.

> ***<u>What does GND mean?</u>***
>
> *GND, or ground, can mean many things. For some, GND means the physical connection into the earth. For others, GND means the green-yellow protective earth wire. These are examples of **safety grounds**.*
>
> *In our course, GND means the big plane on a PCB that is connected to the blue or black test jack. This is not a safety ground but a **signal ground**. A better term would probably be **current return path**.*
>
> *We engineers designate just everything with GND because they are mostly connected to the same potential. However, this does not mean that they really have the same potential since the GND plane has an impedance as well.*
>
> 
>

Watch the video below to learn more about galvanic coupling.



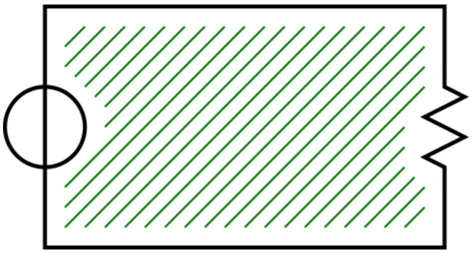
Galvanic coupling - Common ground impedance
https://youtu.be/zgaoLKTW0Q4

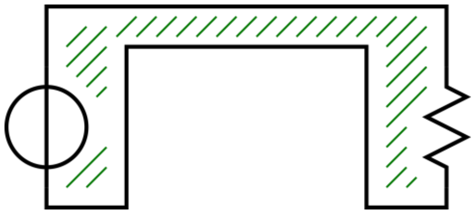
<u>How to reduce parasitic inductance</u>

To reduce the effects of galvanic coupling, it is important to draw the PCB layout EMC-aware in order to avoid common impedance paths. For instance, it is necessary to minimize the parasitic inductances. This is achieved by keeping the loop sizes in the circuit as small as possible.

Compare the two sketches below. **A small loop area reduces the parasitic inductance.** Thus, the right sketch is better related to EMC. This is not only to reduce the effects of galvanic coupling but **also to reduce parasitic inductive coupling**.

> ***<u>What is a parasitic element?</u>***
>
> *Unfortunately, ideal components do not exist. For instance, if we buy a resistor, there are parasitic inductances (due to the loop) and capacitances (between the connections). Since we only want to have a pure ohmic resistance, we call all other elements 'parasitic'. In the example below, parasitic inductance shows up because of the connecting cables.*





1.5.2 CAPACITIVE COUPLING

In general, energy is stored in the electric and magnetic field. When the distance between two electrodes (conductors) is electrically small, we can express the capacitive energy storage as a capacitor. The material that separates these two objects (e.g. air) is called dielectric. When the potential (or electric field) between the electrodes changes, a **displacement current** occurs, which can lead to EMC problems. This phenomenon falls under the category: **near-field coupling**.

$$Z_C = \frac{1}{j\omega C}, \qquad i_C = C \cdot \frac{\mathrm{d}u}{\mathrm{d}t}$$

> ***We represent parasitic behavior with electrical symbols***
>
> *We often learn electrical components in their ideal behavior. We have learned symbols for resistance, capacitance and inductance. These symbols describe the ideal physical behavior, but we use the same symbols to represent parasitic elements. For instance, we draw a parasitic capacitor in a schematic even if we don't solder in a real capacitor.*

We can use the formula of a **plate capacitor** for the simplest approximation

$$C = \varepsilon \cdot \frac{A}{d}$$

where A is the **area** of the plates and d the **distance** between them. ε is called **permittivity** which indicates how polarizable the dielectric material inside is. Thus, it can be said that a dielectric material with high ε stores electric fields very well. $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$ is valid, where ε_0 is a constant and ε_r depends on the dielectric material.

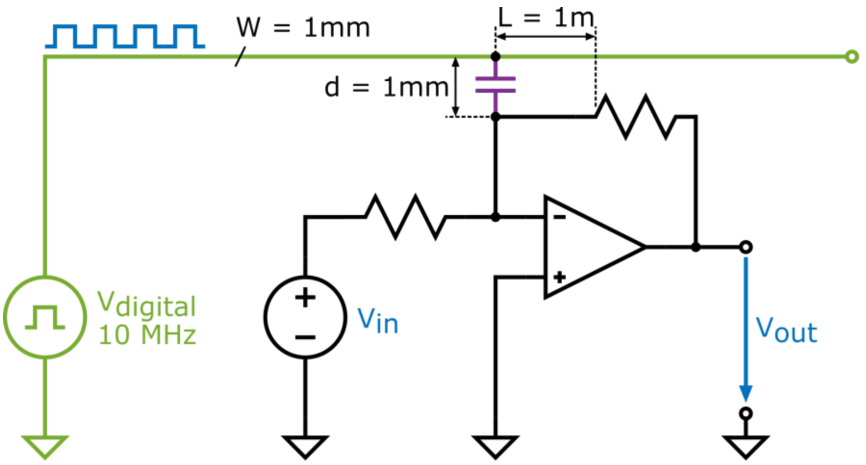
$$\varepsilon_0 = 8.854 \cdot 10^{-12} \frac{As}{Vm}$$

Two materials are relevant to our course: Air and FR4.

- **Air**: We can assume $\varepsilon_r \approx 1$.
- **FR-4**: This material is used in standard PCBs. The relative permittivity (or dielectric constant) varies depending on frequency, temperature and aging. We therefore assume $\varepsilon_r \approx 4.6$ for FR-4 if nothing else is stated.

An example

Suppose we have a PCB. A signal line runs on the top plane, and an opamp is designed on the bottom plane. Its feedback line runs exactly below the signal line. This leads to a parasitic capacitance as shown in the following picture (you could also imagine 2 cables lying next to each other inside a 1m cable tray but filled with FR-4 instead of air).



1.5.3 INDUCTIVE COUPLING

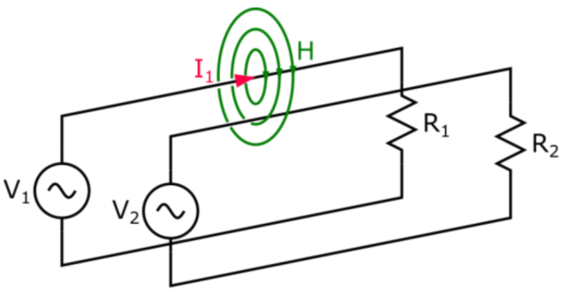
In addition to the electric field, we must take the **magnetic field** into account. Such near-field coupling can be intentional (transformer), but also unintentional (EMI). However, the principle is the same.

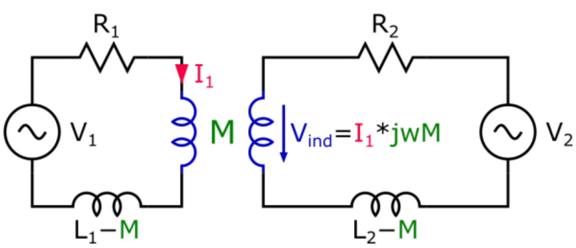
Every current-carrying conductor leads to a magnetic field (Ampère's circuital law). Now, when the current in circuit 1 alternates, a voltage is induced in circuit 2 (**Faraday's law of induction**). Both circuits are coupled via the **mutual inductance** M (not to be confused with the **self-inductance** L).

$$Z_M = j\omega M, \qquad v_2 = M \cdot \frac{\mathrm{d}i_1}{\mathrm{d}t}$$

In a **transformer**, this coupling is strengthened by intention with the help of a ferromagnetic core and a certain arrangement. Thus, an attempt is made to achieve a very high M.

Unfortunately, **two adjacent conductor loops are also magnetically coupled** to each other, i.e. $M > 0$. This is a parasitic behavior and leads to crosstalk.



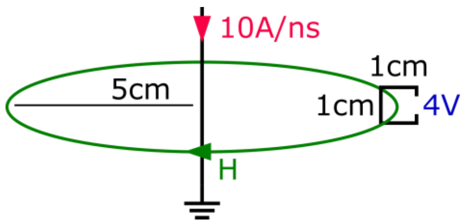


What can we do against near-field coupling?

- The simplest way to reduce near-field coupling is to **increase the distance** between transmitter and receiver. The electric and magnetic field decreases with $\frac{1}{r^2}$ or $\frac{1}{r^3}$, depending on which is the dominating field.
- Further measures against inductive coupling (which is usually more difficult to protect against):
  - **Change the orientation of one loop by 90 degrees** in the correct axis. This reduces the mutual inductance significantly.
  - **Reduce the loop area.** As a result, the magnetic field can no longer couple as well.
  - Twist the forward and return conductors together to obtain loop areas which *cancel each other out*.
- **Correct shielding** (increases costs)
  - If possible, the shield should cover the entire conductor.
  - The shield must be properly terminated. Usually, this means a good GND connection at both ends (for electrically small H-field shielding).
- As a more general rule: do not place interfering and susceptible circuits next to each other.

A demonstration calculation

Everyone knows it: those annoying sparks especially when wearing plastic clothing. These are called **electrostatic discharges**, abbreviated by **ESD**. ESD is a subfield of EMC and can cause serious damage. Look at the following calculation.



An ESD discharge occurs. A small 1x1cm conductor loop is located 5cm further away. The induced voltage can be calculated as follows, assuming a current change of $\frac{\mathrm{d}i}{\mathrm{d}t} = 10\frac{A}{ns}$ (yes, this is a realistic value) and a homogeneous magnetic field throughout the loop:

$$V = N \cdot \frac{\mathrm{d}\phi}{\mathrm{d}t} = N \cdot A \cdot \mu_0 \cdot \frac{\mathrm{d}H}{\mathrm{d}t}$$

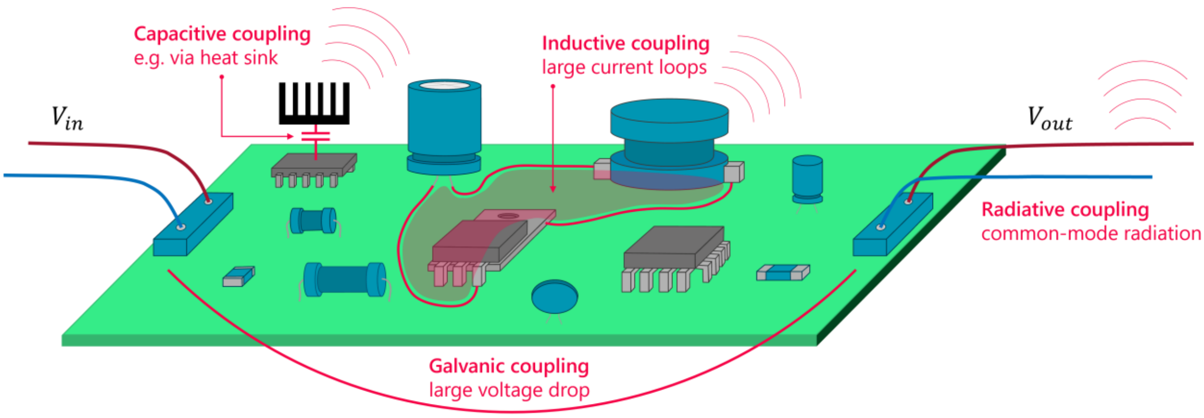
μ is called **permeability** which indicates how magnetizable a material is. Thus, it can be said that a core material with high μ stores magnetic fields very well. $\mu = \mu_0 \cdot \mu_r$ is true. For a straight conductor, the magnetic field at distance is calculated by $H = \frac{i}{2\pi r}$.

$$V = \frac{N \cdot A \cdot \mu_0}{2\pi r} \cdot \frac{\mathrm{d}i}{\mathrm{d}t} = \frac{1 \cdot 0.01m \cdot 0.01m \cdot 1.257 \cdot 10^{-6}\frac{Vs}{Am}}{2\pi \cdot 0.05m} \cdot \frac{10A}{1 \cdot 10^{-9}s} = 4V$$

This calculation is to show that an **ESD discharge can induce a significant voltage** (here: $4V$) on a small conductor loop. We must therefore protect our circuits against direct (galvanic coupled) and indirect (inductive coupled) discharges.

1.5.4 Radiated coupling

Integrated circuits (ICs) are often the source of spurious emissions due to fast switching but not the reason for emission problems as it is **too small to radiate** effectively below 1 GHz. But the **connection lines** are often **unintended antennas** which emit these emissions. Every conductor can be represented as a superposition of electric and magnetic dipoles. This means that **every non-TEM cable is an antenna**. The longer the cable, the better the emissions can be emitted and received.



International test measurements include far-field measurements where an antenna measures the emitted noise signals from a DUT. This test antenna is usually located about 3m to 10m away from the test object in order to achieve far-field coupling. As EMC engineers, we must **keep conductive traces as short as possible and take care of the return plane** to reduce radiation into the far-field. At the same time, the immunity of our product increases.

Our main interest is usually the far field. So, we have to ask ourselves when the far field begins. Literature often uses a fixed value like $\frac{\lambda}{20}$, $\frac{\lambda}{10}$ or $\frac{\lambda}{2\pi}$. In reality, however, we cannot draw a straight boundary between the near and far-field. It also depends on the geometry of the antenna.

1.5.5 Knowledge check

What does the abbreviation "DUT" stand for?

An electromagnetic interference always couples into the DUT via <u>one of the four</u> coupling mechanisms.

- O True
- O False

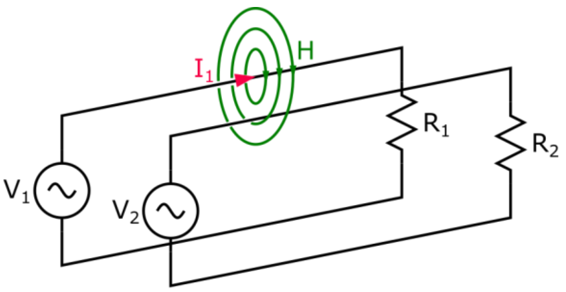
Everything below 30 MHz is about galvanic coupling; beyond that, is about field coupling.

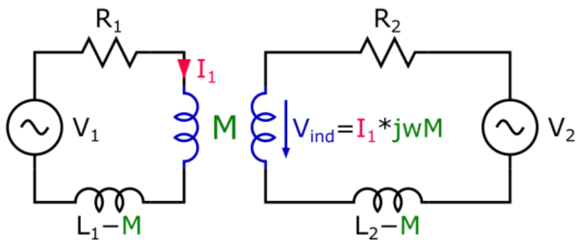
- O True
- O False

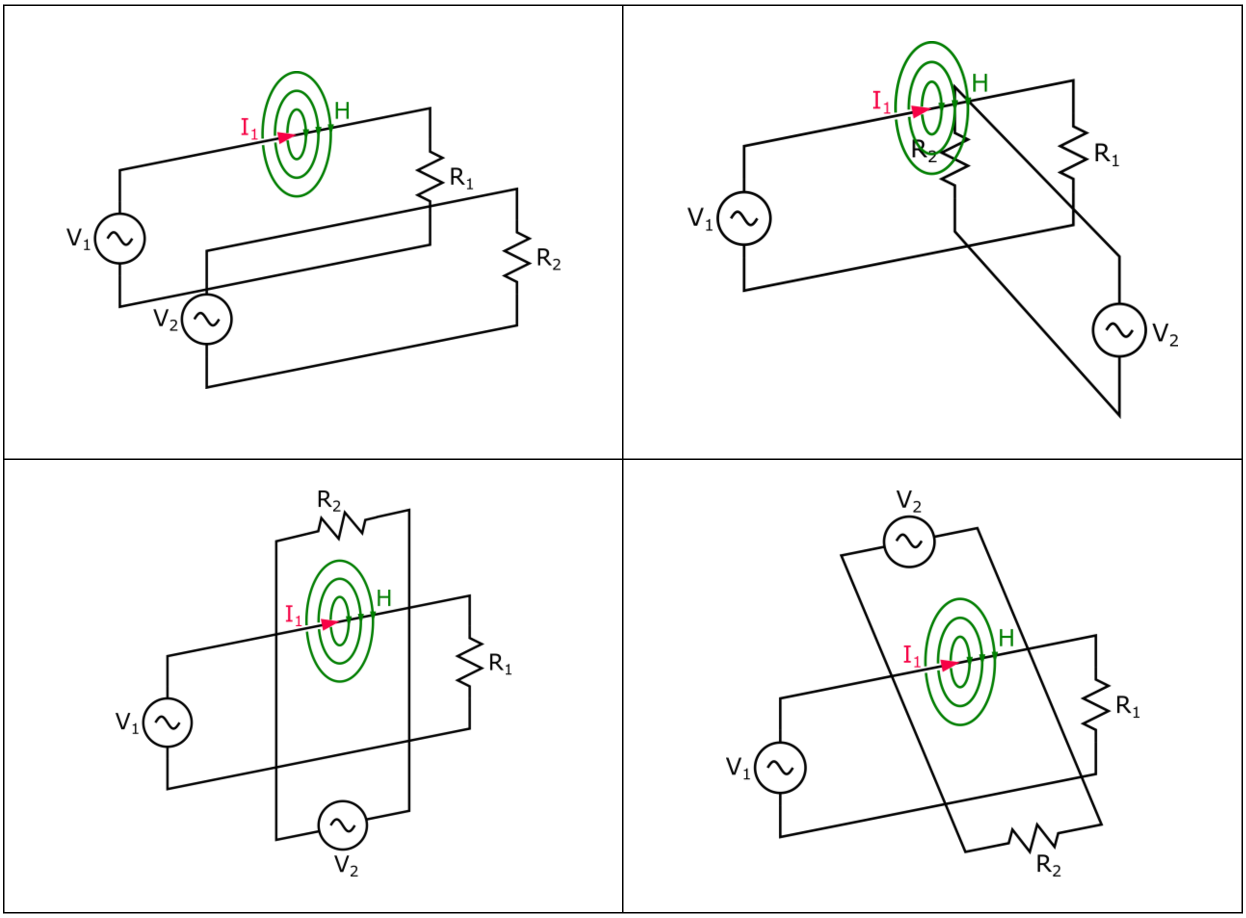
When transmitting signals between two circuits with a simple wire, the signal could be radiated to the surroundings since every wire can act like an antenna.

- O True
- O False

In the picture below, inductive coupling between two conductor loops may occur. How could we reduce the mutual inductance M_{12}? Select all circuits with less inductive coupling.







1.6 RECAP 1

EMC must be considered **in all aspects** of system design.

An EMC-compliant system emits few **conducted and radiated emissions** and isn't **susceptible** against them.

Whenever **electrons are accelerated**, electromagnetic waves are propagated.

An antenna transforms a conducted EM wave into a free-running EM wave and vice versa. **A trace on a PCB is also an antenna.**

We distinguish between galvanic, capacitive, inductive and radiative **coupling**.

Performing an **FFT** means that we perform a frequency-domain analysis.

A 10 MHz clock signal may provoke **EMC problems at higher frequencies**.

The **wave impedance** in free space is 377Ω.

The **characteristic impedance** is determined by geometry and its field-carrying media (usually 50Ω). It's not a component.

Any load other than 50Ω will usually create a **mismatch**.

If the input of a measurement device is labeled with 27 dBm, only a **maximum of 5V AC** is allowed to be applied.

$$v_p = \lambda \cdot f$$

$$10 \cdot \log_{10} \frac{P_{[W]}}{1mW} = P_{[dBm]}$$

$$20 \cdot \log_{10} \frac{V_{[V]}}{1\mu V} = V_{[dB\mu V]}$$

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}, \qquad |\Gamma| \leq 1$$

Tick all **learning objectives** that you have understood.

I know how ...

1.1 - What is EMC?

☐ to name everyday situations where EMC is relevant.
☐ to formulate the definition of EMC.
☐ to list the most important aspects of EMC.

1.2 - Electromagnetic Wave

☐ to summarize the electromagnetic spectrum from 3 kHz up to 3 GHz.
☐ to calculate the amplitude of a wave in dBµV.
☐ to explain how electromagnetic waves propagate.

1.3 - 50 Ohm System

☐ to implement a proper microstrip line for efficient transmission.
☐ to calculate the reflection coefficient of a load resistance.
☐ to interpret the behavior of a component based on its Smith chart.

1.4 - Time and Frequency Domain

☐ to discuss the advantages of the frequency domain.
☐ to calculate the spectrum of periodic and non-periodic functions.
☐ to forecast the spectrum of a rectangular, triangular and trapezoidal signal.

1.5 - Coupling Mechanisms

☐ to identify how an interference signal could couple into a victim.
☐ to recognize some advantages of a small loop area.
☐ to compare simple measures in order to mitigate coupling.

2
EMC DESIGN

We are very happy that you have decided to continue learning. You made it through the introduction; hopefully it wasn't too mathematical for you. EMC focuses on two main topics: "Design" and "Testing". In this chapter, we address the question how to design products EMC-aware. This topic is very extensive, but we will try to cover the most important points in this MOOC. We will start again with some theory, but after this section, you will know the essential EMI measures.

2.1 DIFFERENTIAL- VS. COMMON-MODE

Before we take action against EMI, we need to be able to better classify the interfering signal. In the introduction we have already learned that frequency plays a crucial role in EMC. In this learning sequence, we will see that we need to make a further distinction between differential- and common-mode noise.

- Differential-mode: The current flows through a conductor and returns, taking the intended path.
- Common-mode: Many local students are confused by this concept. Here, the current exploits the wiring as antennas. The circuit is thus closed via parasitic paths such as the air. Very often, the feed line is causing common-mode radiation due to the standing wave inside.

2.1.1 CURRENT RETURN PATH

We often tend to think in terms of sources and sinks. As engineers, it is our task to bring the current flow from source to load somehow. But that is only half the story - we rarely think about how the electricity flows from the load back to the source. Often, we just draw some GND symbol in our schematic, and that's it.

You probably noticed during the last learning sequence that the layout of a circuit has a big influence on the EMC behavior. **We can influence how the current flows with the layout.** And this current flow is again relevant for the effect of parasitic elements and later EMC problems. Therefore, we must always consider the whole current flow, since **current always flows in loops**.

Resistance vs. impedance

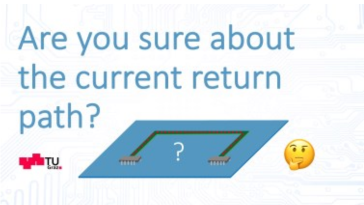
»Electricity takes the path of least resistance!«

Most engineers learn this quote at the beginning of their career. However, **this statement is wrong**. You could correct it by replacing "resistance" with "**impedance**". In addition, it must be realized that electricity never chooses only "the one path". The current always splits, with one path usually predominating.

The main issue with the word "resistance" is that this only works for DC. In case of alternating currents, parasitic effects play a very important role. **Every current-carrying conductor shows an inductance.** If it's not a TEM transmission line (like a coaxial cable), this inductance *chokes* high frequencies. In this case, we need to keep the parasitic inductance as small as possible by **keeping the conductor loops small**.

The problem, however, is identifying conductor loops. We tend to place all signal paths hand by hand but handle the return path via a large GND plane. So, the signal current path is often well known, but **the return path is uncertain**. Watch the video below in order to see an example.

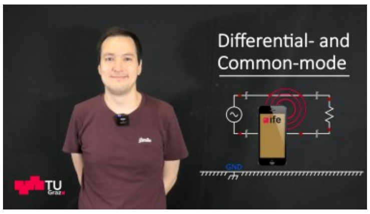
> ***In a nutshell...***
>
> *Current always takes the path of lowest impedance. For high frequencies, this is usually the path with the smallest conductor loop.*



Current return path
https://youtu.be/7OoODwOy4Mg

2.1.2 Differential-mode signal

Any unwanted disturbance in an electrical signal is called noise. Such noise can have various origins, but we differentiate between *differential-mode* and *common-mode* noise. The video below explains the differences between differential- and common-mode. The text below then explains differential-mode in more detail.



Differential- and Common-mode
https://youtu.be/7OoODwOy4Mg

Differential-mode in more detail

Differential-mode radiation arises from the normal operation of a circuit. The current flows in loops from the power supply to the system and back again. A pure differential-mode signal is equal in both lines but with different signs.

$$I_{dm} = \frac{I_1 - I_2}{2}, \qquad V_{dm} = V_1 - V_2$$

We usually prefer the definition via current. The problem with the definition via voltage is that voltage itself is not defined at radio frequencies. We cannot measure high frequency voltages to GND because voltage depends on the integration path.

We generally want to operate signals in differential-mode, but the signal may include some noise components as well. An amplifier for example is not amplifying a signal 100% linearly, but distorting it slightly, i.e. the generation of harmonics. Other signals like a clock signal already include harmonics implicitly. These interferences then might couple into other systems.

Simple and cheap measures

The video showed the use of **LC filters against differential-mode** interference. This is a very efficient method, but often not desired, due to the additional space required and the costs (power supply filtering). In addition, filtering could influence our desired signal as well (e.g. USB signaling). By designing the system with EMC in mind, there would be many further **inexpensive ways** to minimize differential-mode noise:

Minimize the loop area of critical traces (e.g. clock signal)!!!

- Optimize the PCB layout! Those traces that conduct periodic signals with high frequency should be kept as short as possible.

Place connectors and components as close as possible to each other.

- This avoids unnecessary loops.

Reduce the magnitude, frequency and rise/fall times of periodic signals.

- Decrease these parameters as far as possible.

Cancel out loops.

- Do not use a single return line, but one or more ground planes. A radiation of two loops can cancel each other (one clockwise, one counterclockwise).

More complex and costly measures

In addition, other methods exist, which, however, mean **additional costs** in production:

Use shielded components.

- A shielded coil for example costs more but can significantly eliminate unwanted coupling.

Control the signal with an advanced IC.

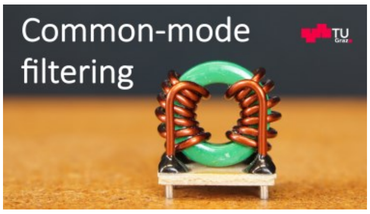
- Control the slew rate and smooth the edges. Reduce the ringing with the help of an adjustable resistor. Eliminate crowbar and dynamic switching currents.
- More on this topic in the EMC4 course: EMC of Integrated Circuits.

Take advantage of spread-spectrum techniques.

- You do not have to use the same switching frequency all the time time but always a slightly different one. This splits the interference in the frequency spectrum.
- More on this topic in the EMC2 course: EMC-aware Design of Electronic Systems.

2.1.3 COMMON-MODE NOISE

Watch the video below in order to better understand common-mode problems.



Common-mode filtering
https://youtu.be/QAZo9xbiflQ

Common-mode in more detail

Common-mode signals are always unwanted and lead to electromagnetic interference. Think of an operational amplifier where a very high common-mode rejection ratio (CMRR) is desired. We often receive these common-mode noise signals via radiated coupling to our connection cables; the current flow is closed via parasitic stray capacitances. Therefore, these interferences are often at a frequency above 30 MHz.

$$I_{cm} = \frac{I_1 + I_2}{2}, \qquad V_{cm} = \frac{V_1 + V_2}{2}$$

Measures against common-mode noise

Again, we can take steps to mitigate common-mode currents. The video showed how to use filters on a power supply, namely with a **common-mode choke** and **Y-capacitors**. Filtering is a very efficient method and is almost always necessary at the input/output cables. But we can take further measures here as well:

- **Use correct filter elements.**
  - We need Y-capacitors and common-mode chokes, because a few microamperes can lead to non-compliance with international standards.
- **Shield the connection cables.**
- **Reduce the magnitude, frequency and rise/fall times of periodic signals (e.g. clock).**
- Try to achieve a GND with as little noise as possible.
- Keep traces as short as necessary.
- Place digital and analog circuit elements far away from each other.

> ***At which frequency?***
>
> *As a rule,* ***common-mode problems usually occur below 300 MHz****. Above 300 MHz, problems are more often of differential-mode nature.*

2.1.4 KNOWLEDGE CHECK

Which of the following statements are correct?

☐ Electricity takes the path of least resistance!
☐ Every current must return to its source somehow.
☐ The signal current always returns back through the ground plane.
☐ A poorly placed current return path is often the cause of emission and susceptibility problems.

Below are three different symbols for GND. Often these are used synonymously. But do you know the original meaning of these symbols?

Two different areas of the ground plane have different potential. The interference signal exploits the connection lines as an antenna in order to close the loop via ground again. Which type of disturbance is it?

○ Differential-mode
○ Common-mode

A power MOSFET permanently switches between ON and OFF all the time. The resulting current spikes interfere with a neighboring analog-to-digital converter. Since both ICs are connected to GND, the loop is closed. What type of disturbance is it likely to be?

○ Differential-mode
○ Common-mode

Which of the following methods suppress EMI?

☐ Minimize loop areas.
☐ Reduce the frequency of critical signals.
☐ Avoid steep edges of critical signals.
☐ Reduce the amplitude of critical signals.
☐ Use proper filter components.
☐ Use proper shielding.

2.2 FILTERING

Filters are used in many applications around the world. For instance, a coffee filter is used in order to separate coffee from the powder; or image filters are applied in order to let a photo look better on the smartphone. In electronics, **we use filters in order to separate undesired frequencies from the useful signal**.

Filters is a very broad topic and everyone has prior knowledge with some type of filter. Therefore, in this learning sequence, we will first discuss how to classify filters. Afterwards, we will recap the basic principle of simple analog filter circuits and extend this knowledge with the aspect of **characteristic impedance**. Finally, a best practice EMI filter is presented.

EMI filters are commonly used in order to **comply with international regulations**. It is the simplest method to remove interfering signals efficiently. To master EMC, however, it is important to understand different coupling mechanisms in order to prevent interference signals from coupling in the first place.

2.2.1 FILTER SPECIFICATION

Various filter types exist. In our course we will cover the most basic **analog, passive EMI filter** circuit. But let's start with a brief overview of the different filter implementations because everyone means something different by a filter.

Analog vs. digital filter

1) Analog filters are those we know from classical electronics. We use R, L, C, but maybe also an opamp, in order to realize our filter.
2) A digital filter first samples the signal and then mathematically processes the stored values using a microprocessor. They are more complex and expensive to implement but can achieve very high filter orders.

Famous filters such as *Butterworth*, *Bessel* or *Chebyshev* can be realized as analog or digital filter.

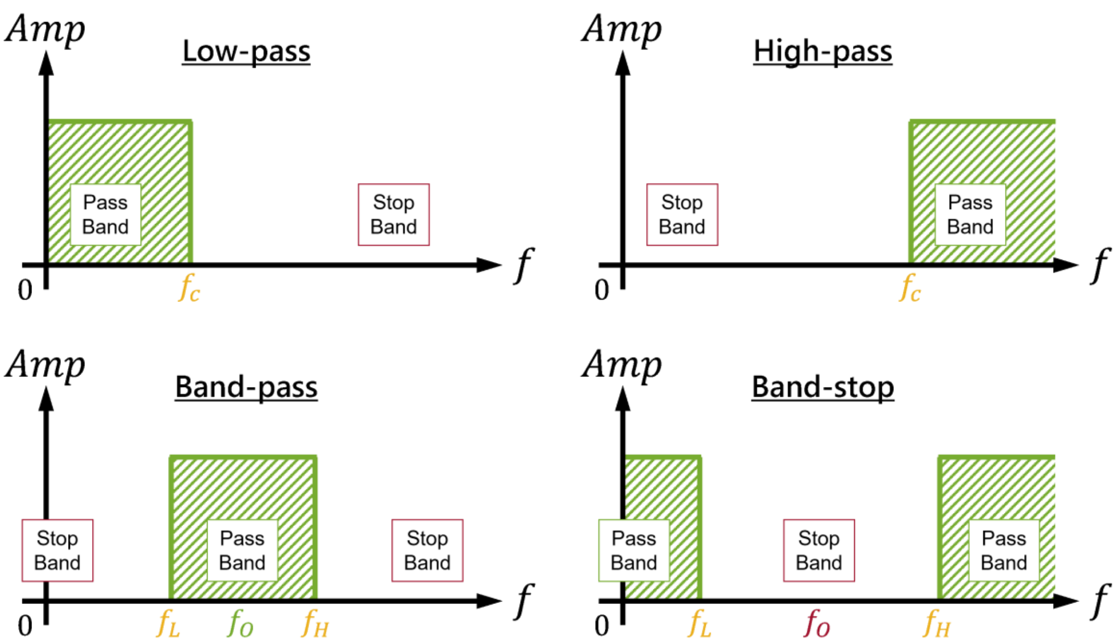
Passive vs. active filter

This distinction is about analog filters.

1) A passive filter consists of the components R, L and C.
2) An active filter has at least one active component which is usually an opamp. This allows much more complex filters to be designed compared to purely passive filters. The most famous topology is called Sallen–Key. With this topology a *Butterworth* filter can be realized for example.

Low-pass, high-pass, band-pass, band-stop

Regardless of whether analog or digital or passive or active, all filters must be further specified somehow. In the animation below the different filter types are shown, as ideal and non-ideal filter.

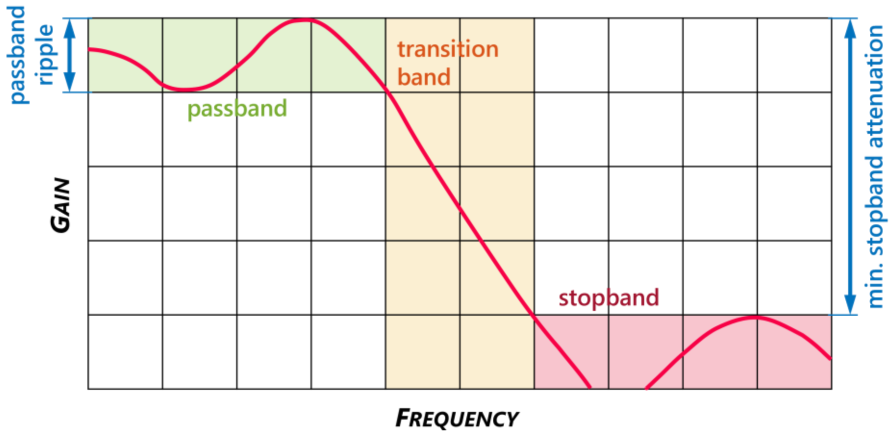


IDEAL FILTER SHAPES

As you can see, the difference between ideal and real filters is the additional **transition band**. Depending on the application, a very narrow transition band may be required. To keep this band as small as possible, we need a high **filter order**. For each filter order, the transition band becomes narrower by **20dB per decade**. But this in turn also means a higher effort in the realization of the analog filter. As an example: a simple **RC filter has the filter order 1**; an **LC filter the filter order 2**. By cascading, we can achieve even higher filter orders.

- Another important factor is the **phase shift** caused by the filter which is mostly undesirable. The higher the filter order the stronger the phase shift.
- An active filter could also have a **gain**, i.e. the y-axis can start at higher values than 0dB.

- Shortly before the transition band starts, an additional **passband ripple** may occur (for example at the *Chebyshev* filter).
- The picture below shows an example of how a filter is usually specified. The allowed passband ripple, the width of the transition band and the stopband attenuation must be defined in order to determine the filter order.



2.2.2 LOW-PASS FILTER

Every system can be described by a **transfer function** $H(j\omega)$ (with $s = j\omega$ in case the Laplace notation is applied). Thus, any filter circuit can be described with a transfer function as well. The very general form of a transfer function looks like this:

$$H(j\omega) = \frac{b_0 + b_1(j\omega) + b_2(j\omega)^2 + \cdots + b_m(j\omega)^m}{a_0 + a_1(j\omega) + a_2(j\omega)^2 + \cdots + a_n(j\omega)^n} = A \cdot \frac{\left(\frac{j\omega}{\Omega_0}\right)^{m_1}\left(1+\frac{j\omega}{\Omega_1}\right)\left(1+\frac{j\omega}{\Omega_2}\right)\cdot \ldots}{\left(\frac{j\omega}{\omega_0}\right)^{n_1}\left(1+\frac{j\omega}{\omega_1}\right)\left(1+\frac{j\omega}{\omega_2}\right)\cdot \ldots}$$

The 4 elementary components of a Transfer Function

A transfer function is built up out of the following 4 elementary components with $\Omega_0, \Omega_1, \Omega_2, \ldots, \omega_0, \omega_1, \omega_2, \ldots$ as zeros and poles respectivly, i.e. corner frequencies.

Amplification factor A $\in \mathbb{R}$

- *Passive circuits can never have $A > 1$.*

***Terms** of the form* $\left(\frac{j\omega}{\omega_0}\right)^{\lambda}$ *with* $\lambda \in \mathbb{Z}$

- *constant +20dB per decade crossing the 0dB line at Ω_0; including constant +90° phase shift @$\lambda = 1$*
- *constant -20dB per decade crossing the 0dB line at ω_0; including constant -90° phase shift @$\lambda = 1$*

***Linear factors** of the form* $\left(1 + \frac{j\omega}{\omega_1}\right)$

- *+20dB per decade starting at Ω_1 including +90° phase shift during two decades*
- *-20dB per decade starting at ω_1 including -90° phase shift during two decades*

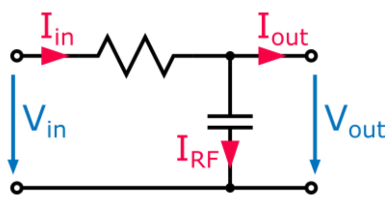
- *e.g.* ***RC filter*** *with* $\omega_1 = \frac{1}{RC}$

Quadratic factors *of the form* $\left(1 + 2d\frac{j\omega}{\omega_3} - \frac{\omega^2}{{\omega_3}^2}\right)$ *with* $0 \le d < 1$

- *similar to two linear factors but with a pass-band ripple depending on the damping factor d (resistance)*
- *e.g.* ***LC filter*** *with* $\omega_3 = \frac{1}{\sqrt{LC}}$ *and* $d = 0$

We have to admit: the whole thing sounds very academic. But with the help of these rules, it's possible to draw the Bode plot of a filter circuit by hand. Therefore, let's look at the simple low-pass filter as an example:

1st order low-pass filter calculation



This is the simplest filter of all: the RC circuit. The capacitor shows low impedance at high frequencies. Therefore, high frequencies cannot pass from left to right.

The first step is to set up the transfer function, i.e. we must write down a formula like this: **output voltage divided by input voltage**. This can be done easily by using the voltage divider rule:

$$H(j\omega) = \frac{V_{out}(j\omega)}{V_{in}(j\omega)} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = \frac{\frac{1}{j\omega C}}{\frac{1 + j\omega RC}{j\omega C}} = \frac{1}{1 + j\omega RC}$$

We can identify the following elementary components in our transfer function:

Linear factor of the form $\left(1 + \frac{j\omega}{\omega_1}\right)$ with $\omega_1 = \frac{1}{RC}$.

Bode plot

A Bode plot consists of two separate plots: a **magnitude plot** (in decibels) and a **phase plot**. It visualizes the ratio of the output voltage to the input voltage depending on the frequency. The following Bode plot describes the transfer function of the 1st order RC low-pass filter with the following values:

- $R = 7.23\,\Omega$
- $C = 220\,nF$

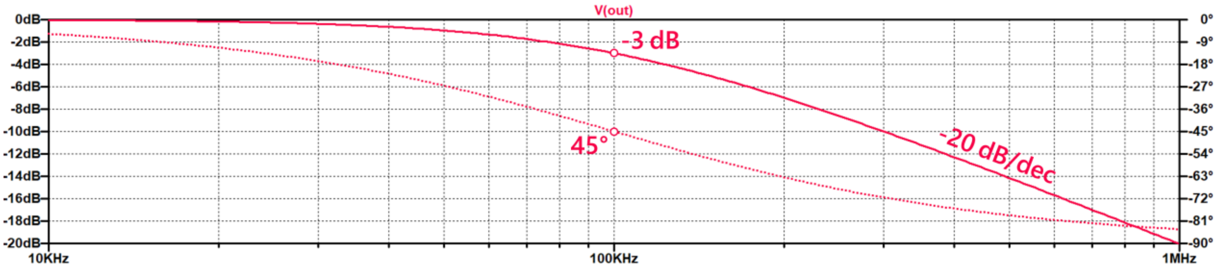
Thus, the pole can be calculated:

$$\omega_1 = \frac{1}{7.23\frac{V}{A} \cdot 220 \cdot 10^{-9}\frac{As}{V}} = 629\frac{1}{s} \quad \Rightarrow \quad f_1 = \frac{\omega_1}{2\pi} = 100\,kHz$$

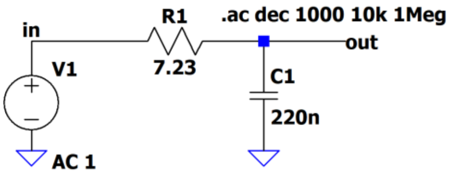
This frequency f_1 is also called **cutoff frequency** or **corner frequency**. This is the point where the passband meets the transition band. A signal of this frequency is attenuated by

3dB (half power) and a phase shift of 45° occurs. Following the rules above, the Bode plot can now be easily drawn:

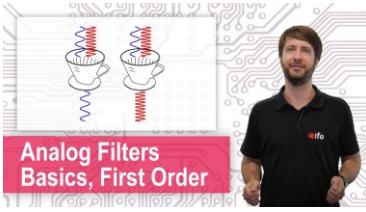
»-20dB per decade starting at ω_1 including -90° phase shift during two decades«



As you may have noticed, we created this plot using [LTspice](). Nowadays, **filter dimensioning is always computer-aided**; nobody, except the local TU Graz students, calculates the filters by hand anymore.



Nevertheless, it is essential to know how Bode plots are created. In the video below you will learn these basics again. On the next page we would like to explain filter design from an EMC point of view.



Analog Filters - Basics, First Order, Ideal Filters, RC Low Pass, Phasor Diagram, Bode Plot
https://youtu.be/5ijn9RPFA9I

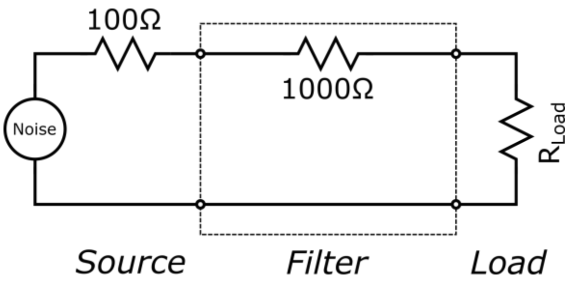
2.2.3 GENERATING MISMATCH

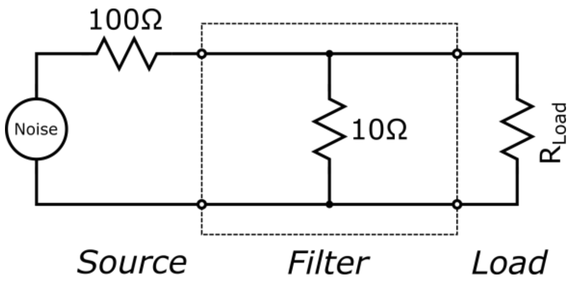
How does a filter actually work? In classical electronics, the Bode plot is considered. For example, a capacitor connected in parallel ensures that high-frequency components are attenuated. A capacitor connected in series, on the other hand, prevents the signal propagation of low frequency components. The equation for the capacitor $X_C = \frac{1}{j\omega C}$ or the inductor $X_L = j\omega L$ is considered in filter design. However, if an EMC filter is designed, **the characteristic impedance must be taken into account as well**.

> ***<u>How does a filter work?</u>***
>
> *In order to design an EMI filter, we must create a discontinuity in the characteristic impedance seen by the noise signal that is propagating from the source to the load. Thus, most of the noise energy is reflected back.*

<u>Example: a single resistor as a filter</u>

The simplest filter consists only of a single resistor. We can install this resistor in our circuit in the following two variants: in series, or in parallel.

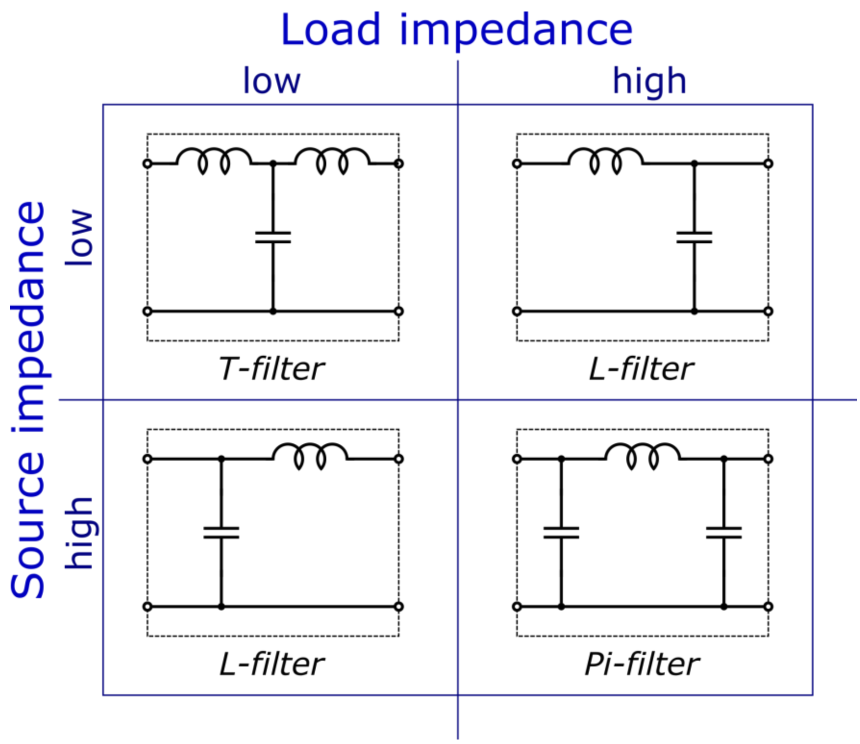




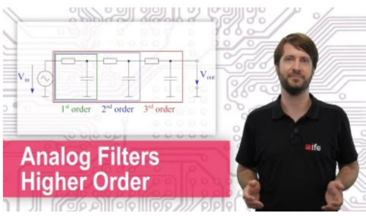
You may have noticed that the filter components are designed in a **1:10** (in series) or **10:1** (in parallel) **ratio**. This creates a mismatch between the source and the filter on purpose. As a result, only **10% of the noise signal reaches the load** which is an attenuation of 20dB. The problem of a filter which consists of only one resistor is that the **desired signal is affected in the same way**. Therefore, capacitors and inductors are usually used.

Selection guideline for an EMI low-pass filter

To optimize the filter effect, we create a discontinuity not only between the noise source and the filter, but also between the filter and the load. The following table gives you an overview of which passive filter is best used for which boundary conditions.



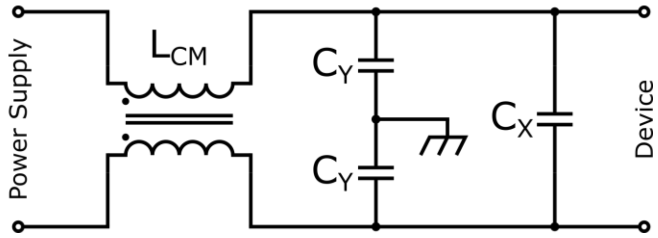
To save money and space, the use of coils is often avoided. Therefore, an RC filter is often implemented instead of an LC filter, although a higher filter order is sacrificed. The video below explains the general filter design in more detail.



Analog Filters - Higher Order Filters, Cascading Passive Filters, Filters with Inductances, AM Radio
https://youtu.be/RkWtU_AGxtM

2.2.4 EMI FILTER

In order to fix EMI problems, we can use simple filter circuits. The following picture shows a **best practice EMI filter circuit for the power supply line** which can suppress differential-mode and common-mode noise.



Common-mode filtering

- L_{CM}: Common-mode choke
- C_Y: two identical **Class-Y** "line to ground" capacitors

Differential-mode filtering

- Stray inductance of the common-mode choke
- C_X: single **Class-X** "across the line" capacitor

> ***In which order do you place the filters?***
>
> *The filter shown above is just an example. In practice, the placement of components may vary. Particularly the common-mode choke is placed where less current flows. In this way, you can save component size and money.*

Class-X and -Y capacitors are generally known as EMI filter components for the power supply lines. These designations are safety classes, with Y-capacitors meeting the higher requirements. The use of Y-capacitors is also the only exception to use the protective line (PE).

The IEC 60384-14 standard specifies the criteria in detail (for the European market) and further divides the classes into X1 to X3 and Y1 to Y4. The lower the number, the higher the safety standards required, i.e. higher rated voltage and peak impulse voltage that can be withstood. Other requirements are, for example, that Y-capacitors are designed to fail open.

> ***What are the tasks of a capacitor?***
>
> *A capacitor can be used for many different tasks. Basically, these can be divided into the following three:*
>
> ***Bulk capacitor***
>
> - *These are used to maintain constant DC voltage and current. They also prevent power dropout due to high current surges.*
> - *e.g. 10 µF electrolytic capacitor*

Filter capacitor

- *EMI/RFI suppression capacitor; AC line filter safety capacitor*
- *These create an AC short in order to conduct away high frequency interference.*
- *RF signal is filtered because of* $Z = \frac{1}{j\omega C}$ *and mismatch of the characteristic impedance.*
- *e.g. 100 nF ceramic or film capacitor*

Decouple capacitor

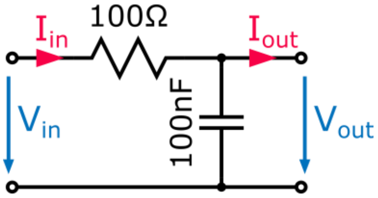
- *These operate as small charge reservoirs for the supply voltage. They are soldered as close as possible to an IC to minimize the amount of line inductance and series resistance. Thus, voltage spikes and ground bounce are mitigated.*
- *e.g. 220 nF MLCC*

The following video shows our best practice EMI filter in a real-life example. At the same time, it is a preview of *Chapter 3: EMC Testing*.

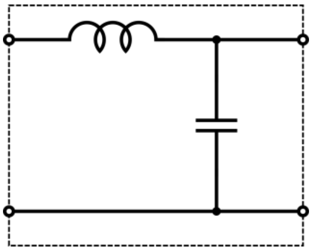
Conducted emissions, EMI filter
https://youtu.be/a-CXbrxW210

2.2.5 KNOWLEDGE CHECK

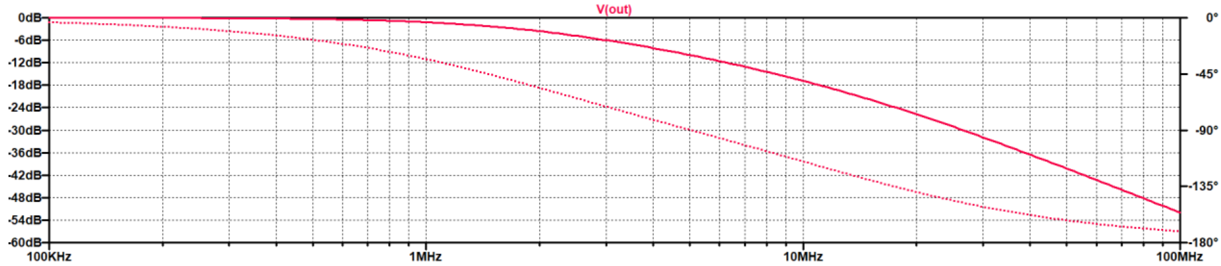
Look at the RC filter. Calculate the -3dB cutoff frequency f_1.



Below you can see an LC filter. On the left side the input voltage is applied, and on the right side the output voltage is taken. Determine the transfer function $H = f(\omega, L, C)$.

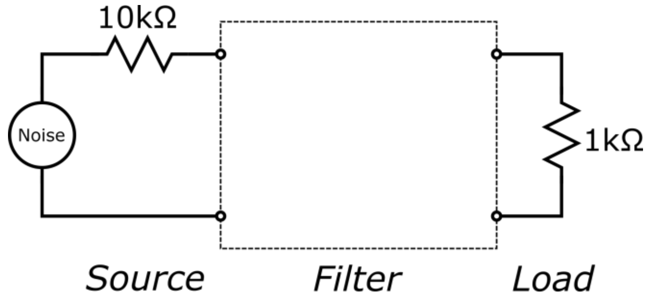


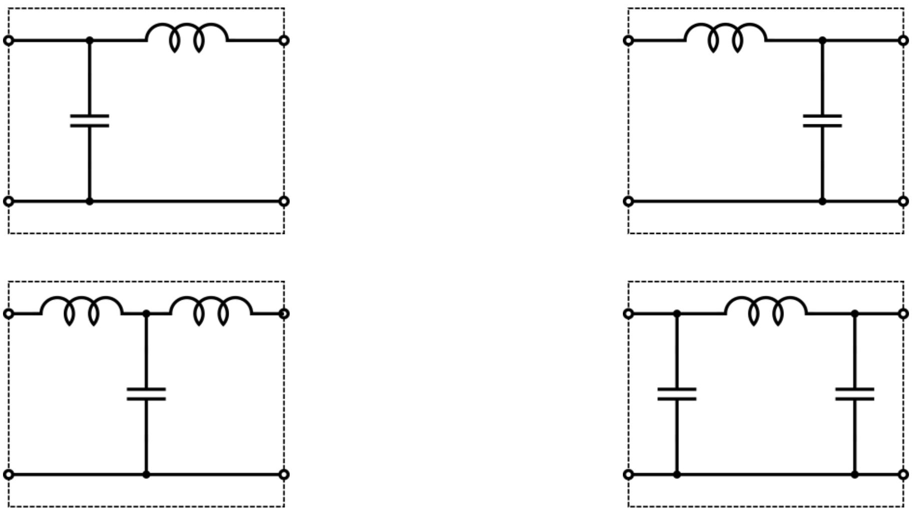
Look at the Bode plot below. Which of the following low-pass filter topologies could lead to such a Bode diagram?



- ☐ RC filter
- ☐ LR filter
- ☐ LC filter
- ☐ π filter (L-C-L)
- ☐ T filter (C-L-C)

Look at circuit below. Which filter would you use in order to filter the noise signal?





2.3 SHIELDING

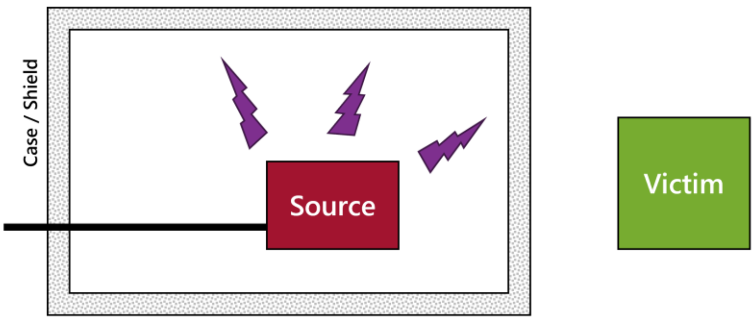
Shielding is the second key measure against EMI, besides filtering. In a nutshell, **we simply build an aluminum box around our product**. But this is often not possible, due to weight, cost, or the fact that the DUT must remain accessible. Therefore, it is important to understand the concept of shielding in order to proper shield a cable, for example.

While a filter circuit is used to remove conducted interference, shielding ensures that this interference does not couple in the first place. At the same time, a shield also works the other way around: our DUT itself emits fewer emissions to the outside. Additionally, in this learning sequence, we will become more familiar with both E-field and H-field.

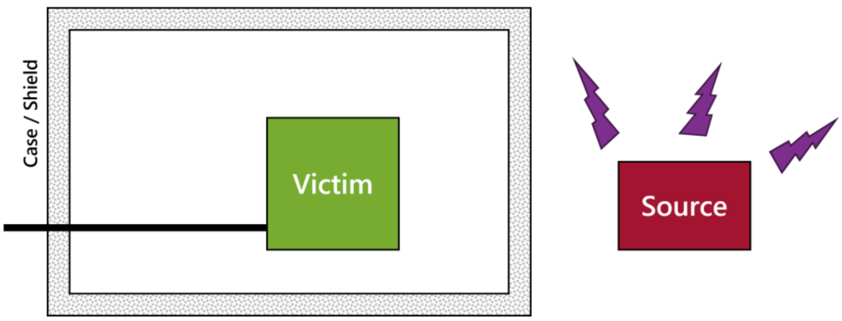
2.3.1 SHIELDING BASICS

In a nutshell, shielding is the protection of our system against electromagnetic waves from the outside. This prevents electric and magnetic waves to couple into our system. Those shields are usually metal enclosers. But it also works vice versa: shielding can be the protection of other systems by enclosing our own system. Thus, a shield is a barrier which reduces the transmission of electromagnetic fields. The following picture illustrates both shielding concepts.

Version 1: we restrict the fields to our system



Version 2: we prevent fields from entering the system



Examples why we shield

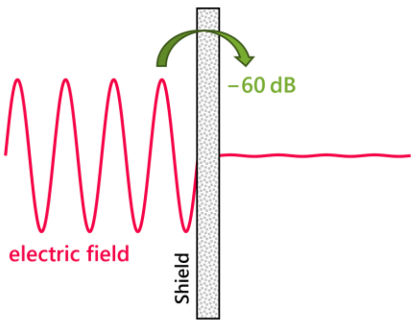
- In order to meet EMC regulations.
- Reduce the vulnerability of our system to external signals, e.g. television transmitters, radios or radars.
- Protect external systems from our system.
- Protect a magnetic sensor from the earth's magnetic field.
- Protect a high impedance circuit, like a scope probe, from 50/60Hz coupling.
- Shield against EM-waves of a broadcast station during an antenna test measurement (see anechoic chamber).

> ***Shielding vs. Filtering***
>
> *Shielding is very similar to filtering but with the difference that **shielding prevents the coupling of interference in advance**. Similar to filtering, we will never achieve to block all frequencies, but only a certain bandwidth. A key difference is that in filtering we think in terms of voltages and currents. With **shielding**, on the other hand, we have to think in terms of **E- and H-fields**.*

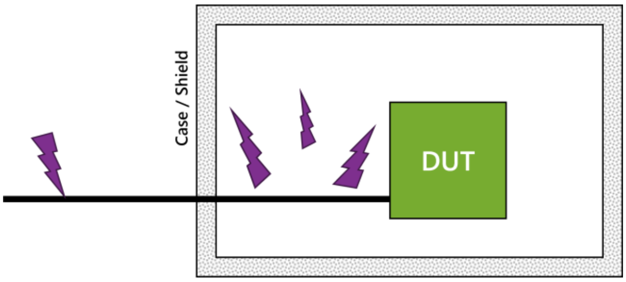
	Shielding	Filtering
Main objective	Reduce electric and magnetic fields	Reduce voltages and currents
Related questions	▪ Which field to shield? (H- and/or E-field?) ▪ Source type? (electric, magnetic or plane wave?) ▪ Material properties? (ε, μ, σ) ▪ Geometry? (size, shield thickness, distance to source)	▪ Filtering by spectral content; e.g. low-pass ▪ Filtering by modal structure; common-mode vs. differential-mode ▪ Filtering by magnitude; e.g. surge suppressor

Shield effectiveness

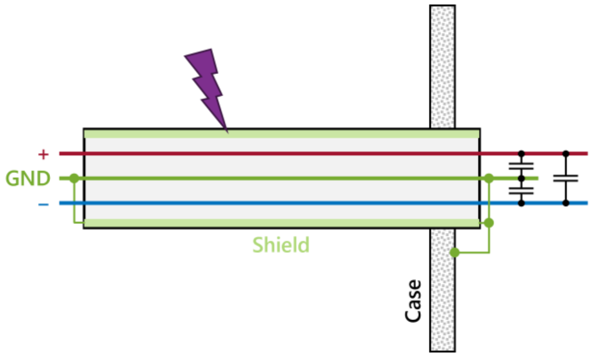
Shielding can never be perfect. To give an example: if a shield promotes an effectiveness of, e.g. 60dB, this shield attanuates the incident wave by a factor of 1,000. In order to achieve highly effective shields, we should follow some best practices.



- A shield should **completely enclose our system**. However, a cable into our system could significantly decrease the effectiveness of that shield. Interference can couple into this cable which then causes problems within the case.



- If your product has a mains connection, you cannot leave out this cable. In this case, we usually build a **filter circuit at the entry point**. In case of a USB cable which transmitts RF signals, we should **shield this cable** and attach the cable shield to an *ideal* **ground on one or both ends** (it depends). This ideal ground is a zero-potential point which **does not fluctuate**. If this potentual flactuates, the shielded cable acts as a transmitting antenna.



- **Holes and slots in our shield may decrease the shield effectiveness**, because fields might radiate through them. An aperture in the ground plane also might act as an antenna. A usual antenna is just a piece of metal surrounded by air; but you also get an antenna when a slot (piece of air) is surrounded by metal. This kind of antenna is called slot antenna. We should seal such slots with conductive gasketing material.

The bottom line

- *Completely enclose your system with a shield.*
- *Cables should be shielded as well. This shield must be connected to an ideal ground. An additional filter circuit at the entry point is recommended.*
- *If you have slots, gaps, or apertures: short-circuit them with conductive material.*

2.3.2 ELECTRIC AND MAGNETIC DIPOLE

We have discussed the basics of EM waves in the learning sequence *1.2 - Electromagnetic Wave*. Here, we will continue to explore how electric and magnetic waves are generated, since we need to think about E and H fields when discussing shielding. In a nutshell:

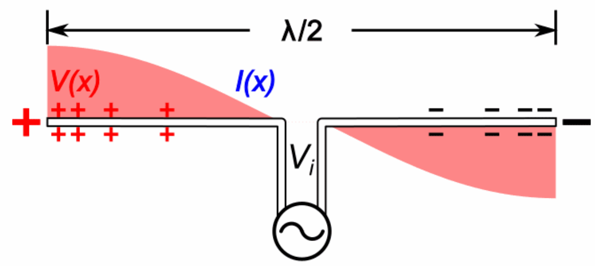
- Any time-varying electric current emits EM waves, i.e. this circuit radiates.
- An antenna transforms a conducted EM wave into a free-running EM wave and vice versa. If we build an antenna, we optimize its geometrics in order to control the emitted or received waves.
- Unfortunately, we always build unintentional **antenna-like structures** in our system, i.e. we emit and receive **undesired EM waves**.

Usual unintended antenna-like structures

- *System level:* ***cables, interfaces, apertures, ...***
- *PCB level:* ***microstrips, loop structures, vias, slots, a poorly designed ground plane, ...***

The electric dipole

Any antenna can be seen as a superposition of numerous infinitesimal electric and/or magnetic dipoles. These dipoles are therefore the smallest unit to describe an antenna; it's an ideal construct which doesn't exist. **An electric dipole generates primarily time-varying electric fields.** A real antenna, however, always consists of both electric and magnetic dipoles. If you build an antenna as shown below, the electric field dominates in the near field. The magnetic field follows the electric field phase-shifted. In the far field, it's not possible anymore to determine whether the source was electric or magnetic.

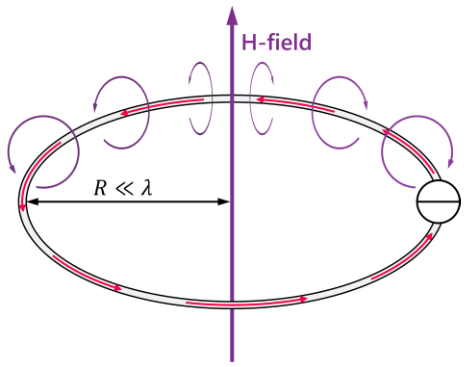


The source is a sinusoidal oscillating voltage which pushes the electrons from one side to the other side of the wire. If the electrons are pushed towards one end of the conductor, a maximum of the time-varying electric field is generated with its corresponding voltage ***V(x)***. Now, during the electrons are pushed towards the opposite side, the current ***I(x)*** generates a time-varying magnetic field. Both fields are 90° out of phase with each other. So, the change of electric field generates a magnetic field and vice versa; EM waves can propagate throughout space.

To be precise, this explanation with voltage ***V(x)*** is wrong. The problem is that this voltage cannot be measured. For a more correct explanation, we need to think about charge carriers and how they flow. Their separation results in a voltage; when they flow, it's a current.

The magnetic dipole

The magnetic dipole is a very, very small current loop (magnetic field lines are always closed). The key difference is that **a magnetic dipole generates primarily a time-varying magnetic field with a current source**.



A time-varying current source pushes the current ***I*** through a closed loop. Thus, a magnetic field around that wire is generated; the ***purple arrows*** indicate its direction. We can validate the direction of the field by using the **right-hand rule**: the thumb points in the direction of the current flow whereas the fingers curl around the wire, indicating the direction of the magnetic field. Since the current is driven by an AC source, both magnetic and electric field changes (see Maxwell). So, similar to the electric dipole, the magnetic dipole also radiates an EM wave that propagates through space.

In a nutshell

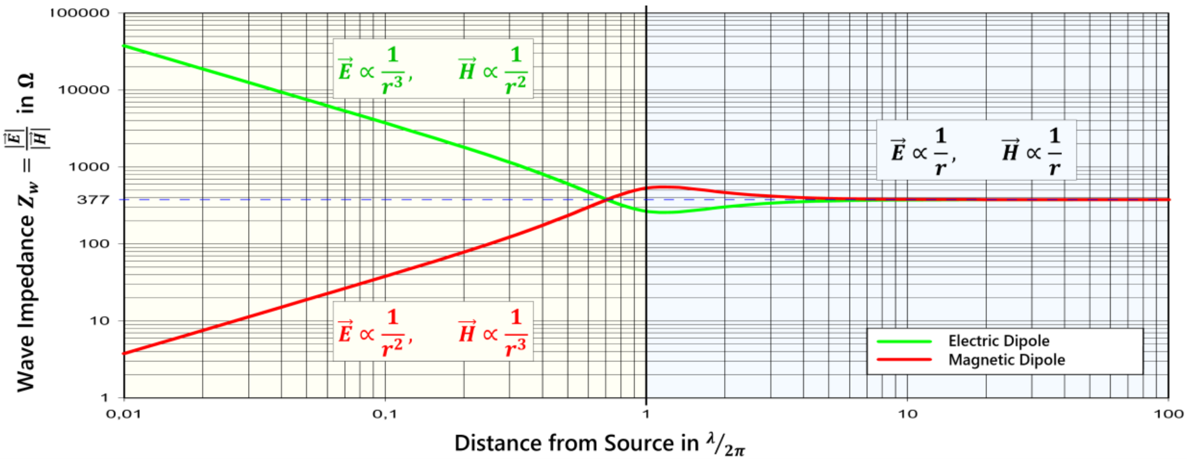
The quality of an antenna depends on the dimensions and the frequency. For example, the length of a good electric dipole is equal to half a wavelength or longer. We must be aware that we may have many unintentional antenna structures in our designs. One best practice is to ***avoid conductor loops*** *in order to get rid of some antenna structures.*

Wave impedance

For far field, the wave impedance is the impedance Z_w of an EM field in free space and can be calculated by:

$$Z_w = \frac{|\vec{E}|}{|\vec{H}|} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377\,\Omega$$

The graph below shows the magnitude of the characteristic impedance depending on the distance. Be careful: this graph is misunderstood very often. It's only valid if our field-generating structure (DUT) is significantly smaller than the distance to a measuring antenna. In other words: our DUT must be small. This is especially important when we try to analyze the near field. Here, the range of validity of the equations is regularly missing. These equations are wrong if we try to measure the field strengths very close to the DUT. The distance between DUT and measuring antenna should be at least five times longer than the length of the DUT. Otherwise, both electric and magnetic field decreases with e.g. $\frac{1}{r}$ (for a thin conductive wire) very close to the DUT.

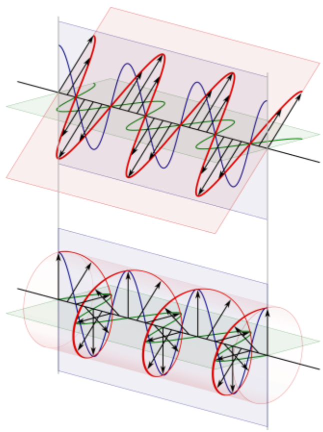


An **electric dipole shows high impedance** in the near field, whereas a **magnetic dipole shows low impedance**. The characteristic wave impedance is a key figure when we want to suppress electric or magnetic field. This knowledge helps us to choose the type of solution in order to attenuate EM fields.

Polarization

You probably already know this effect from optics: the light from the sun is unpolarized. If the sun's rays are reflected on the ground, then the light is polarized; polarized sunglasses, filter out these reflections. Polarization occurs because light is an electromagnetic wave consisting of E- and H-fields. When an E-field hits a surface, the **electrons start to oscillate like in a dipole antenna**. This movement of the electrons leads to the emission of new electromagnetic waves, which we then simply call reflection.

It is important to understand that our electronic devices also emit polarized electromagnetic waves. The type of polarization again depends on the antenna structure, e.g.

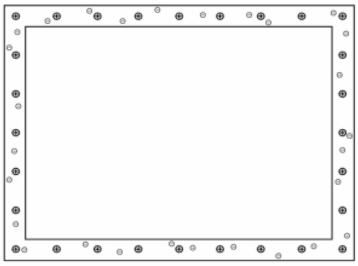


- the basic dipole antenna transmits **linearly polarized** EM waves,
- a turnstile antenna transmits **circularly polarized** EM waves, but
- both linear and circular polarization are considered to be special cases of the **elliptical polarization**.

This consideration is very relevant in EMC testing. For emission measurements, a linear-polarized antenna (e.g. log-periodic antenna) is usually used. Thus, we measure a different level of emissions, depending on the orientation of the antenna. But this consideration is also relevant in EMC design, because we could build a shield that only shields EM waves of a certain polarization.

2.3.3 Shielding of E-fields

In case we want to shield from E-fields, we should place our DUT inside a **Faraday cage**.



This cage is made out of conductive material which surrounds the vulnerable electronics inside. The external E-field in the animation above forces the electrons within the cage to move to the left. This leaves positive charged ions on the right side of the cage. Therefore, the new placement of the electrons will create another E-field opposing the external field in order to make the **space inside the cage field-free**. If this box is made out of metallic materials, we usually assume that there are enough electrons to compensate the external E-field. Thus, the resulting internal field $\vec{E}_{int}$ will be equal to the external field $\vec{E}_{ext}$.

$$\vec{E}_{total} = \vec{E}_{ext} + \vec{E}_{int} = 0$$

Remember

The E-field inside a Faraday cage will decrease to zero.

Time-varying E-field

Above, a static E-field was assumed, but if the E-field changes over time, we must consider the so-called **relaxation time** τ. This variable describes the time the electrons need in order to reach the other side of the cage. After about 3τ, 95% of the electrons reached their new equilibrium point. So, if the E-field changes faster than the electrons can follow, the shielding efficiency drops drastically.

Relaxation time and permittivity

The relaxation time τ is given by

$$\tau = \frac{\varepsilon}{\sigma}$$

- *where ε is the permittivity; i.e. the resistivity of a material against an external E-field, and*
- *where σ is the conductivity; i.e. if a material is a good conductor ($\sigma = \infty$) or not ($\sigma = 0$).*

2.3.4 SHIELDING OF H-FIELDS

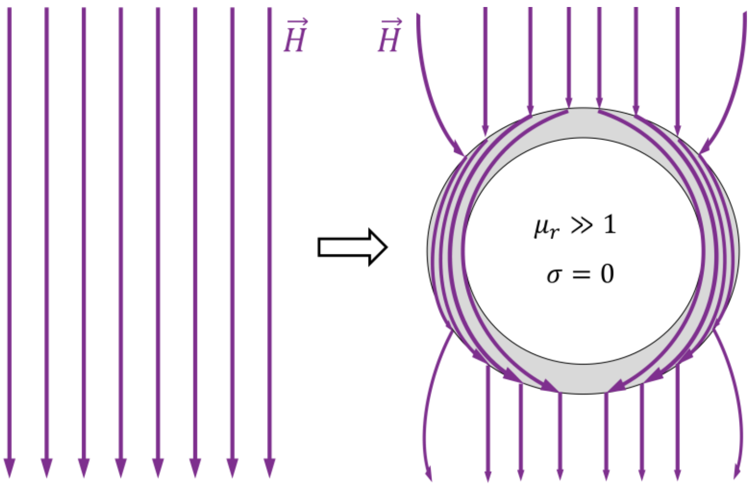
When shielding magnetic fields, we need to consider different frequency ranges.

Against low frequencies we use electrical non-conductors $\sigma \approx 0$ with high permeability $\mu \gg 1$ like a ferrite. The idea is to **concentrate the magnetic field inside the shielding material** so that no field lines can penetrate. But, we shield low frequencies in special application only like in a magnetic sensor. Then we also often use some special material like mu-metal.

Against high frequencies we use good electrical conductors $\sigma \gg 0$ with low permeability $\mu \approx 1$ like aluminum. The idea is to **induce eddy currents** inside the shielding material. The generated magnetic field then counteracts the external field, similar to Faraday's cage. When talking about shielding, people usually mean this method.

Low-frequency H-fields by permeability

The image below demonstrates shielding by permeability. The shield material has very high μ but is an electrical non-conductor. When this shield enters an external magnetic field, then the material magnetizes. Thus, the magnetic field lines are guided within the shield material. In case $\sigma > 0$, the magnetic field would induce a current within that shield.

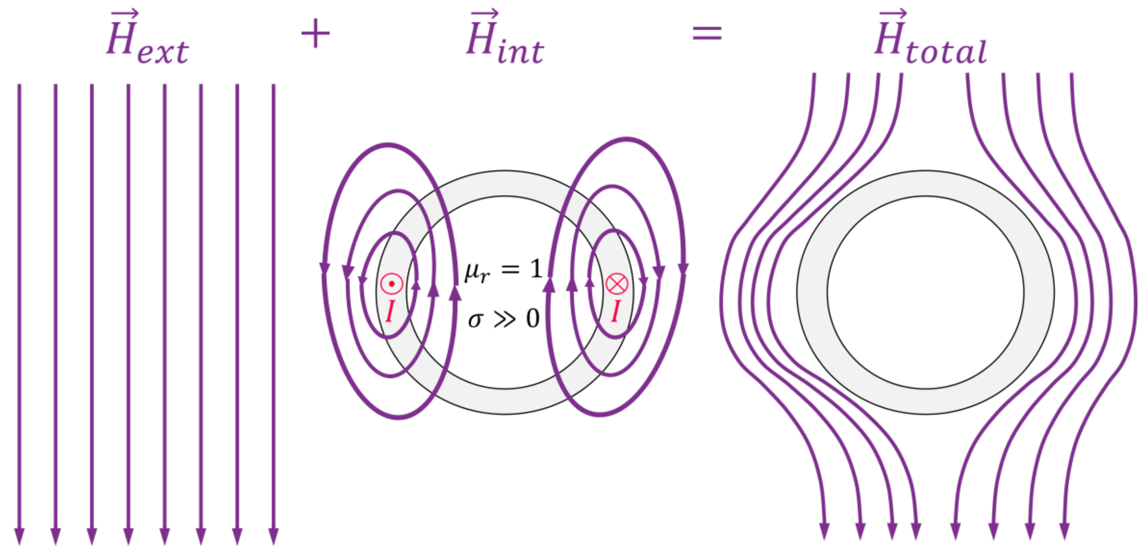


There is a **frequency limit** with this type of shielding. Similar to the relaxation time of a Faraday cage, the magnetic domains in a ferromagnetic material cannot align infinitely fast, i.e. $\boldsymbol{\mu}$ **decreases with** $\boldsymbol{f}$. This limit can already be at a few MHz. Thus, this type of shielding only works for low-frequency magnetic fields, but it's very effective.

> ***Permeability μ***
>
> *Permeability, or **magnetic conductivity**, determines the magnetization of a material in an external magnetic field. For instance, a piece of iron, nickel or cobalt is attracted by a permanent magnet because these materials have a very high μ. Like permittivity ε, permeability μ also decreases with increasing frequency.*
>
> $$\mu = \mu_0 \cdot \mu_r$$

High-frequency H-fields by induced currents

This is the usual shielding approach and works similar to Faraday's cage. A highly conductive shielding material with low permeability μ is required here, i.e. you can use copper or aluminum. The changing magnetic field H_{ext} induces eddy currents inside the shield material. This current then creates a magnetic field H_{int} itself. Thus, the two fields cancel each other out; the magnetic field lines are *pushed out*.



This is the go-to method in order to shield against high-frequency magnetic fields. The upper frequency limit usually originates because of the openings in the housing.

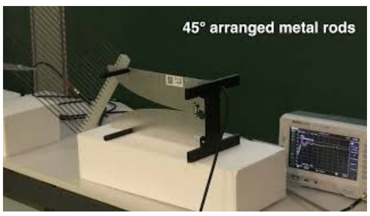
The bottom line

- *Shielding by high permeability traps the magnetic field lines inside the shielding material.*
- *Shielding by induced currents squeezes the magnetic field lines out of the protected area.*

2.3.5 MATERIAL DEPENDENCY

We have learned that the shield effect depends on both which kind of field we want to shield and the frequency. In practice, we usually **simply build a metal housing (e.g. aluminum) around our product**; this is the default solution. The limitation at high frequencies is often caused by the openings in that housing.

In the following video you can see the summary of an on-campus lecture. Dr. Pommerenke demonstrates the shielding effect depending on frequency and material.



Shielding experiments, Dr. David Pommerenke
https://youtu.be/GlCplGKLia0

2.3.6 KNOWLEDGE CHECK

Our shielded system has an opening for a cable. What should we pay attention to?

☐ We should keep the opening for that cable as small as possible.
☐ If it's a power supply cable, a filter may be needed.
☐ If it's a data cable, we should shield it and connect the shield to GND.
☐ The potential of a poorly designed shield could fluctuate.

A Teflon (PTFE) tape lies in front of you. It's permittivity $\varepsilon_r = 2$, and it's conductivity $\sigma = 0.1 \cdot 10^{-15}$. Is it a good material for shielding against electric fields?

O Yes
O No

We measure a wave impedance lower than 377Ω next to an electronic system. Which kind of field is primarily active?

O Electric field
O Magnetic field

The electronic system from before is emitting RF emissions. What strategy should we follow in order to achieve effective shielding?

O Faraday cage
O Shielding by permeability
O Shielding by induced currents

We want to shield from the earth's magnetic field. What strategy should we follow in order to achieve effective shielding?

O Faraday cage
O Shielding by permeability
O Shielding by induced currents

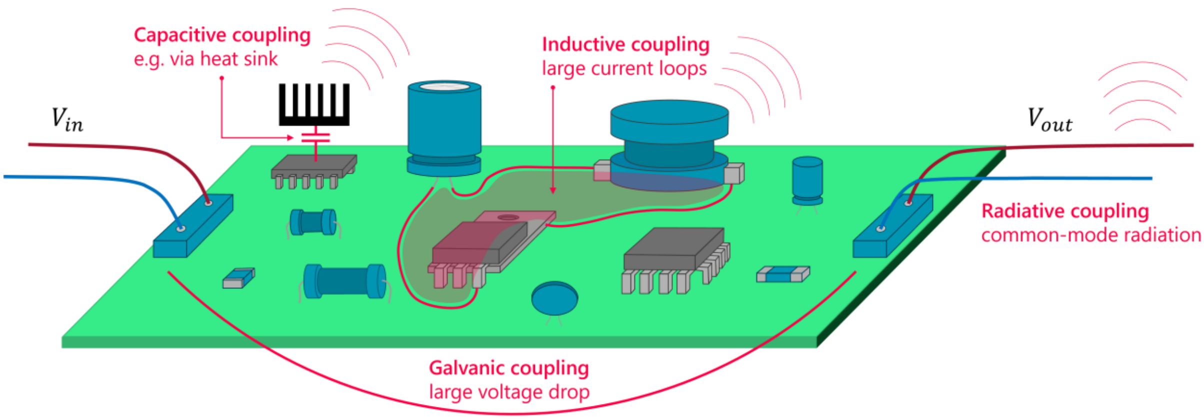
There are tiny vias and slits on our circuit board. These are so tiny that hardly any light shines through them. Should we be worried about that?

☐ If these vias are located everywhere on the board, they are probably used for a stable GND potential.
☐ If there are slots on a shielding plane, we should seal them with conductive material.
☐ Every slot on our board might act as an undesired antenna.
☐ Only if the depth of the via is exactly $\lambda/2$, then we might run into trouble.
☐ As a rule, if a via is too small to see any light through, then we don't care about it.

2.4 PCB DESIGN

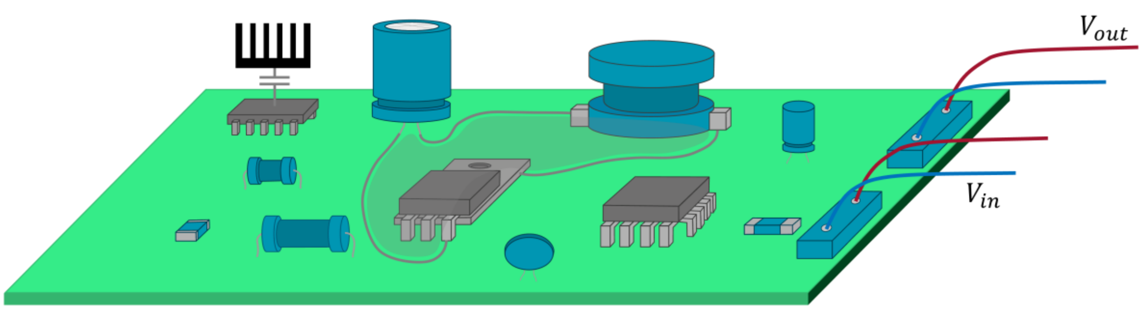
In this learning sequence, we'll look at a few best practices on how to design a PCB to be EMC-aware. You may have asked yourself during PCB design how to best place the components. Although there is no ultimate answer, taking into account a few design recommendations, the EMC of your product can be improved significantly. Even if you have never designed a PCB before, this learning sequence will teach you how a board is organized. At the end, we also look how to include decoupling capacitors which is essential for a proper operation of an IC.

Below you can see a PCB and the coupling mechanisms that are present everywhere. A key objective in printed circuit board design is to eliminate these coupling mechanisms. This includes to keep unwanted conductor loops to a minimum. But you'll learn more best practices on the next pages.



2.4.1 CONNECTOR PLACEMENT

In your future designs, you should always follow this rule: **place your connectors as close to each other as possible** no matter if I/O or power supply. The picture above shows you how not to do it. You may not believe it right away, but a connector placement as shown in the following image significantly improves the EMC of your product.

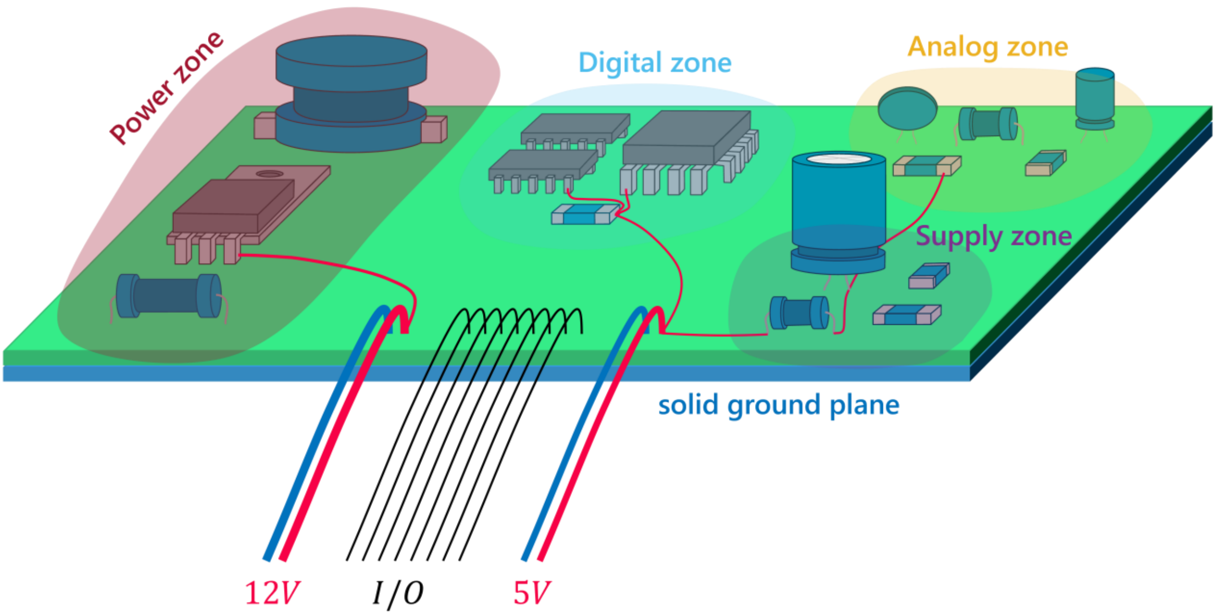


This simple change gives us a **smaller loop size** and a more **stable GND potential**. This design concept is not only true at the PCB level. Nowadays, most ICs have bonded power supply and GND pin right next to each other; if possible, in a **90° angle** to each other. This does not really reduce the radiated emissions, but since the antenna is polarized in one direction during an EMC test measurement, less emissions are measured.

2.4.2 PCB floor planning

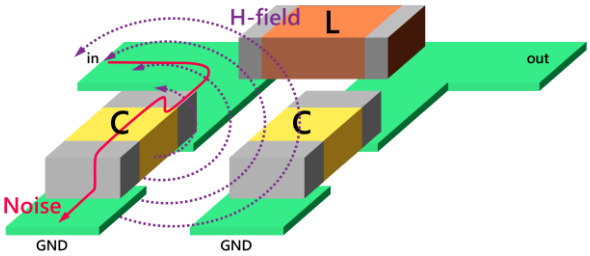
In PCB design, you should pay attention to **place all components of one group together**. This gives us a design like the illustration below.

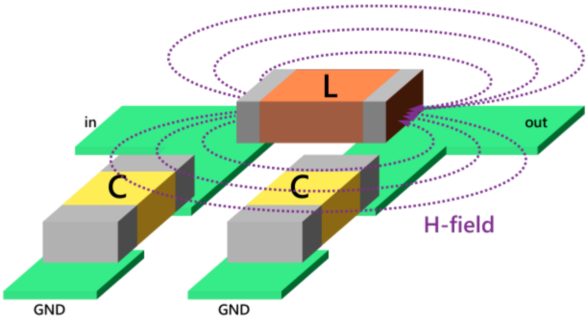
- Use both layers. The bottom layer should be a **solid ground plane**. Any free area of the top layer should also carry ground potential (polygon pour). The cost savings of using only one layer is not worth it.
- Start with the connectors by placing them side by side. Group the other components.
- **Place noisy zones (power and digital) close to the connectors. Susceptible zones (analog) should be placed far away from them.**
- In case no solid ground plane is available: Keep the loop areas formed by Power- and GND-lines as small as possible.
- Supply your circuit via a **central star point** and in a **tree structure**, i.e. don't make a loop in your supply line.
- Don't mix the supply of different zones, i.e. avoid galvanic coupling between digital and analog zone.



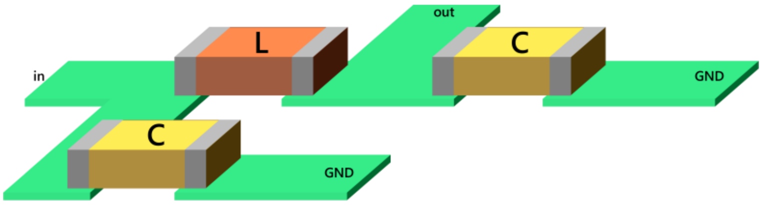
Example: Pi-filter design

This simple separation of "digital" (source of emissions) and "analog" (susceptible parts) **improves the EMC significantly**. An experienced designer also places the components themselves EMC-aware. Let's take a **low-pass filter in π-arrangement** as an example. The two pictures below show the usual arrangement. Out of habit, we usually place the components exactly as we draw them in our schematic.





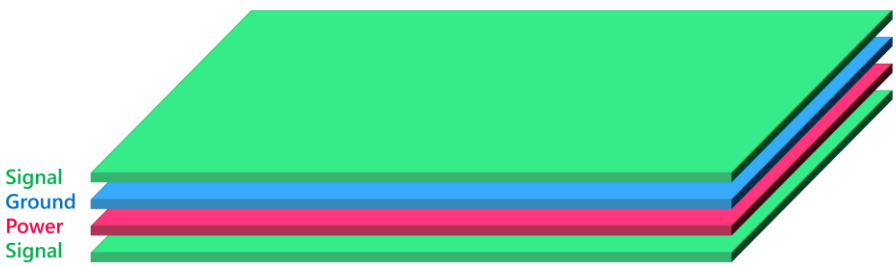
The problem with this design is that the resulting magnetic fields (in reality, these are not beautiful circles because of neighboring structures) can couple into the neighboring elements and thus induce an interfering voltage there. In the case of the inductor, the internal structure of the windings determines how the magnetic field lines propagates. Nevertheless, an arrangement as shown below can improve the filter performance. Ultimately, we have to consider each time individually which arrangement of the components is the best.



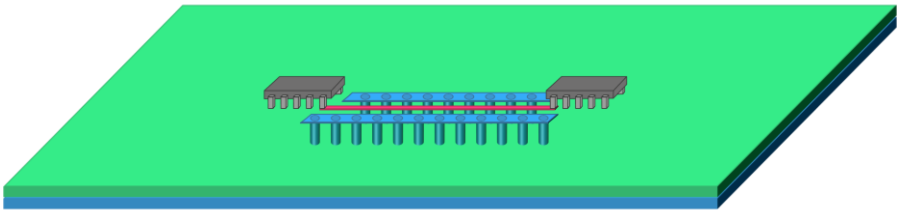
2.4.3 PCB layer stackup

There is no general recommendation on how we should use the layers in a **larger stackup**. Here are a few considerations:

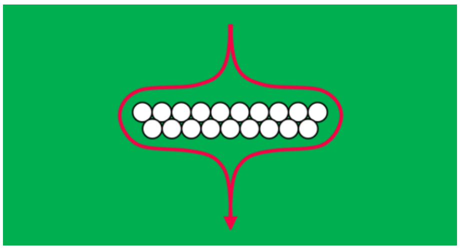
- Place ground and power supply layers next to each other. This gives us a good decoupling capacitor for free.
- In case we use the <u>two inner layers for the supply</u>, we get large values for this **decoupling capacitor**.
- In case we use the <u>two outer layers for ground</u>, we achieve a good **shielding** effect.
- In general, we should **avoid slots** in ground and power supply planes. Otherwise, we get an undesired antenna.
- If more planes are available, we could establish an inner signal layer which is surrounded by ground in order to protect critical high-frequency signals like in a coaxial cable. This gives us a good waveguide for TEM wave propagation.



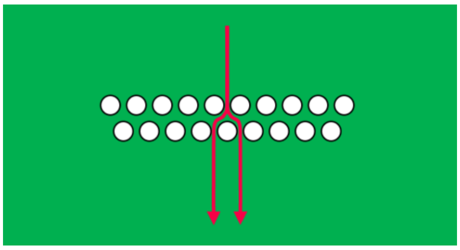
It happens frequently that we want to **protect critical high-frequency signals in a 2-layer stackup** as well. Here, the ground plane should definitely be placed underneath but also next to the signal line. This structure is called coplanar waveguide. Two layers will not support a true TEM wave but a quasi-TEM wave. Ground vias are often placed next to this critical signal line in order to provide a better waveguide by keeping a good ground potential. In general, you should **route critical traces as short and direct as possible**. For your design, it's best to start with these lines.



By the way, be careful when placing vias. You could unintentionally redirect the reverse current flow as shown in the picture below.



no GND between vias

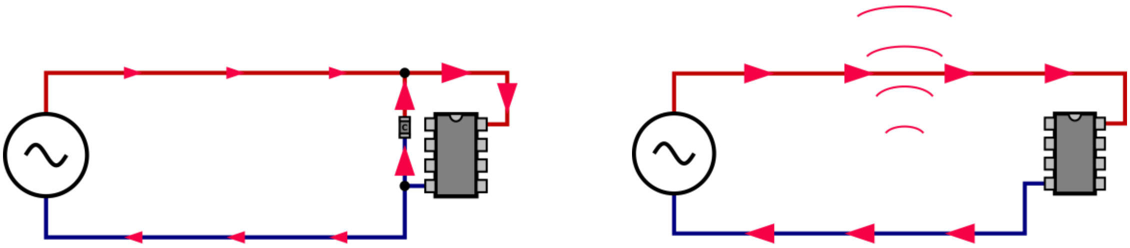


GND plane remains between vias

2.4.4 DECOUPLING CAPACITORS

We have looked at capacitors as filter components in learning sequence *2.2 - Filtering*. This time we look at the capacitor as a **decoupling** element.

There are many decoupling capacitors in an electronic system: electrolytic bulk capacitors inside the power supply, SMD capacitors close to an IC, capacitance between supply and GND plane and on-chip capacitors. These capacitances are **all connected in parallel between supply and GND** and are part of the power distribution network. They serve as a reservoir of charge carriers in order to stabilize the supply voltage. Thus, the charge carriers take shorter paths, resulting in **smaller loop sizes and less inductive coupling** (smaller coil).



<u>Best practice</u>

Always place decoupling capacitors as close as possible to the IC.

- The smallest capacitor value should be placed closest to the IC supply pins.

As a rule, a large SMD capacitor in a small package is the right choice.

- This was often a 100nF X7R-MLCC capacitor in a 0805 case size in older designs.

Often, an additional (tantalum) electrolytic capacitor (e.g. 10µF) is soldered in parallel.

- In general, you must always be careful when using 2 capacitors in parallel, because they show an unwanted parallel resonance. Electrolytic capacitors have a high dissipation factor (i.e. a low Q factor) which dampens that parallel resonance.

In case you are not sure, solder a 220nF X7R capacitor in parallel to a 10µF tantalum.

Classification of MLCC

Ceramic capacitors are categorized into:

- Class 1: high stability and low losses for resonant circuit applications.
- Class 2: high volumetric efficiency for smoothing, by-pass, coupling and **decoupling** applications.
- Class 3: special applications / obsolete.

Class 1 capacitors (e.g. **NP0** or C0G) show excellent characteristics, including a stable temperature behavior. Unfortunately, however, they have a low ε_r (i.e. low capacitance) which makes them not suitable for decoupling. For this reason, class 2 capacitors are always used for decoupling such as **X7R** or Y5V. This labeling indicates the change in capacitance over the temperature.

Low-end operating temperature	High-end operating temperature	Capacitance change over that temperature range
X = -55°C or -67°F	2 = 45°C or 113°F	A = ±1.0%
Y = -30°C or -22°F	4 = 65°C or 149°F	B = ±1.5%
Z = +10°C or +50°F	5 = 85°C or 185°F	C = ±2.2%
	6 = 105°C or 221°F	D = ±3.3%
	7 = 125°C or 257°F	E = ±4.7%
	8 = 150°C or 302°F	F = ±7.5%
	9 = 200°C or 392°F	P = ±10%
		R = ±15%
		S = ±22%
		T = +22/-33%
		U = +22/-56%
		V = +22/-82%

What are the tasks of a capacitor?

A capacitor can be used for many different tasks. Basically, these can be divided into the following three:

Bulk capacitor

- *These are used to maintain constant DC voltage and current. They also prevent power dropout due to high current surges.*
- *e.g. 10 µF electrolytic capacitor*

Filter capacitor

- *EMI/RFI suppression capacitor; AC line filter safety capacitor*
- *These create an AC short in order to conduct away high frequency interference.*
- *RF signal is filtered because of* $Z = \frac{1}{j\omega C}$ *and mismatch of the characteristic impedance.*
- *e.g. 100 nF ceramic or film capacitor*

Decouple capacitor

- *These operate as small charge reservoirs for the supply voltage. They are soldered as close as possible to an IC to minimize the amount of line inductance and series resistance. Thus, voltage spikes and ground bounce are mitigated.*
- *e.g. 220 nF MLCC*

2.4.5 KNOWLEDGE CHECK

A few PCB design statements. Which ones are true?

☐ We keep conductor loops as short as necessary to minimize inductive coupling.
☐ It is a good idea to connect our heat sinks to a nearby GND potential.
☐ It is best that we never use a heat sink.
☐ It is best to place our connectors as close to each other as possible.
☐ We separate digital circuits from analog circuits.
☐ It is a best practice to create a supply loop around the entire PCB.

A few statements about decoupling capacitors. Which ones are correct?

☐ We use decoupling capacitors in order to filter undesired EMI.
☐ We often solder two capacitors for decoupling. The capacitor with the lower capacitance is placed closer to the IC.
☐ The IC would not work without a decoupling capacitor.
☐ The more the better: Using two decoupling capacitors is always better than just using one.
☐ If the supply plane and the GND plane are designed directly below each other, a decoupling capacitor is obtained for free.
☐ NP0 capacitors show better characteristics than X7R capacitors. If they were not so expensive, we would always use NP0.

2.5 PASSIVE COMPONENTS

In the last learning sequence of this chapter, we would like to emphasize again that **all components show a parasitic behavior** at higher frequencies. This parasitic behavior becomes dominant above a certain frequency which can lead to unexpected problems in circuit design. Imagine you want to filter high frequencies with a capacitor, but the actual filtering effect is much lower than expected.

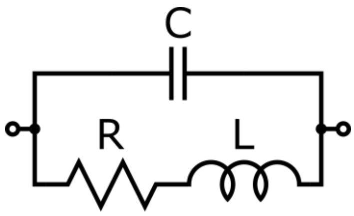
We are used to design circuits with ideal components. But for considerations above 10 MHz, we have to think about the parasitic behavior. This comes **primarily from the connections**. There is always a capacitive coupling between the two connections; if current flows through the component, there is always an inductive effect.

A simple example: we roughly estimate **1nH/mm for a usual trace** on a PCB. At the same time, this trace also has a resistance ≠0Ω and a capacitance to GND, e.g. 0.1pF/mm. This LC structure would have its resonant frequency at 16 GHz which is usually no problem. Also don't forget that the characteristic impedance is determined by both L and C:

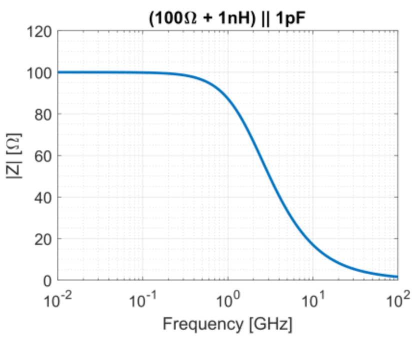
$$Z_0 \approx \sqrt{\frac{L}{C}} = 100\,\Omega$$

You will notice in this learning sequence that the higher L or C is, the sooner we will see resonance effects. We will look at passive components only. For active components, you must do similar considerations.

2.5.1 RESISTOR



Let's start with the simplest component: the resistor. No matter in which package you buy it, the resistor always shows a parasitic behavior. First, there is a stray capacitance between the connections. Second, the resulting loop gives us an inductivity; **Inductance results from the loop - it's not a fixed parameter!** We now try to represent these effects as so-called *lumped-elements* in an equivalent circuit.



Consequently, different variants of such an equivalent circuit exists. A typical one is shown here; we have an **RLC resonant circuit**. It is important to estimate the orders of magnitude here. Roughly, the following applies to an SMD 0603 package (1.55 x 0.85 mm):

- $L \approx 1\,nH$
- $C \approx 1\,pF$

To better understand the impact of these parasitic elements, it is best to run a simulation. On the right you can see the frequency response of a 100Ω resistor using the assumptions from above.

We realize: **up to about 100MHz we have a good 100Ω resistor**. At higher frequencies, the parasitic elements dominate. This is because we have an LC parallel resonant circuit, i.e. first the impedance should increase, then it will decrease. We simply cannot see the increase, because this RLC circuit is damped by 100Ω. When the impedance drops, it behaves *capacitively*. In short, we can use this resistor up to 100MHz. Attention: **the lower the resistance, the more problematic the parallel resonance might be!**

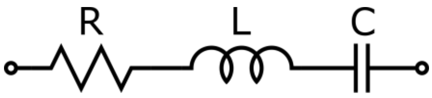
MATLAB code

```
close all
clear
clc
tic

freq = linspace(10,100000,100000)*10^6;
w = 2*pi*freq;
R = 100;
L = 1*10^(-9);
C = 1*10^(-12);
RLC = (R+i.*w.*L).*(1./(i.*w.*C)) ./ (R+i.*w.*L + 1./(i.*w.*C));

figure
semilogx(freq/10^9,abs(RLC),'LineWidth',2.5)
grid on
grid minor
ylim([0 120])
title('(100\Omega + 1nH) || 1pF')
xlabel('Frequency [GHz]')
ylabel('|Z| [\Omega]')
set(gca,'FontSize',15)
toc
```

The right choice of resistor depends on many factors, especially on your application. Here is some food for thought:

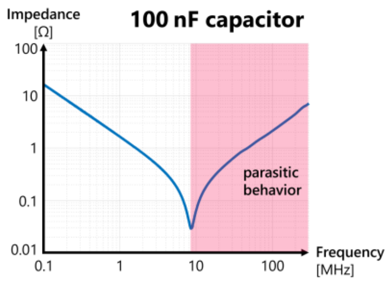
- Any component soldered on our PCB will cause a **mismatch**.
- How much **power** must my resistor withstand? A 0603 resistor is usually labled with "1/10 W". This means that the resistor heats up by 50°C, starting from 25°C, i.e. 75°C in total, when it is stressed with 100mW. At high power, you may not be able to use an SMD component, i.e. the parasitic elements become more annoying.
- Resistors are **temperature dependent**. Usually, the hotter the component, the higher the resistance.
- Larger components should not be exposed to temperature gradients. Otherwise, temperature voltages could be generated.
- Do I use the resistor in an RL, or RC network? Then I have to consider the cutoff frequency $f_c = \frac{1}{2\pi\tau}$ with $\tau = \frac{L}{R}$ and $\tau = RC$ respectively.
- Resistors noise! The noise voltage density is calculated by $v_n = \sqrt{4k_B TBR}$ with the Boltzmann constant k_B.

2.5.2 CAPACITOR



Different types of capacitors exist. The most important are:

- Ceramic capacitor; typical values from 1 pF to 10 µF, usually sold as tiny MLCCs
- Film capacitor; typical values from 100 pF to 10 µF, X- and Y-capacitors
- Electrolytic capacitor; very high capacity possible in a little space (high), poor properties in return



When you buy a capacitor, you will get an inductor for free! We always get an **RLC series resonant circuit**. Of course, different versions of the equivalent circuit exist here as well. It is important to understand that a capacitor acts capacitively only up to its resonant frequency $f_0 = \frac{1}{2\pi\sqrt{LC}}$.

How can I calculate the resonant frequency?

It's straightforward:

1) Determine the impedance of your circuit.

$$Z = R + j\omega L + \frac{1}{j\omega C}$$

2) Rearrange the equation, and separate out the imaginary numbers. There should be no more imaginary numbers in the denominator.

$$Z = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

3) At the resonance frequency f_0, the imaginary parts cancel each other out.

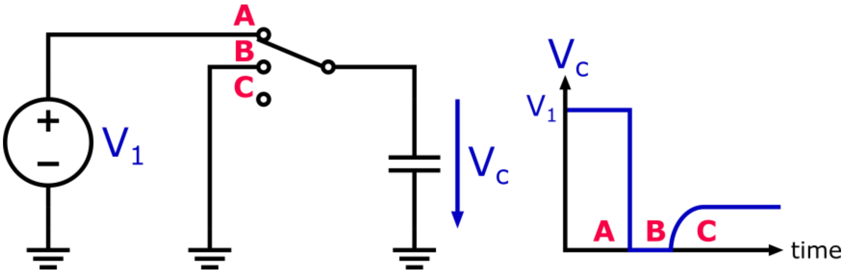
$$\omega_0 L \stackrel{!}{=} \frac{1}{\omega_0 C}$$

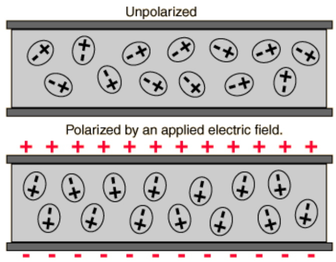
$$\omega_0{}^2 = \frac{1}{LC}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

But this also means that we get an undesired parallel resonant circuit if we connect two capacitors in parallel; we regularly solder two decoupling capacitors in parallel. As a consequence, the impedance increases rapidly with parallel resonance unless the system is damped with high ESR (parasitic resistance).

Another important effect is dielectric absorption. Look at the circuit below. If a charged capacitor (A) is short-circuited (B) and this short-circuit is released again after a short time (C), then the capacitor is still slightly charged. The reason for this is that the orientation of the electric dipoles does not change infinitely fast but after a relaxation time. This effect occurs especially with electrolytic capacitors. Depending on the short circuit time, about **10% of the voltage can be recovered**. This effect can be represented in an equivalent circuit as RC elements connected in parallel to the main capacitor.

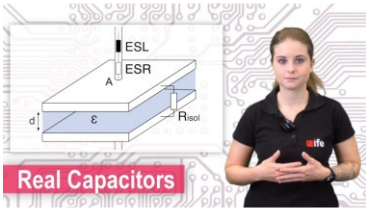




Another very important property is the voltage dependence $C = f(V)$. **Class 2 MLCCs can lose up to 90% of their capacity** at their nominal voltage. Here, we must definitely check the data sheets and, if necessary, switch to capacitors with higher nominal voltage.

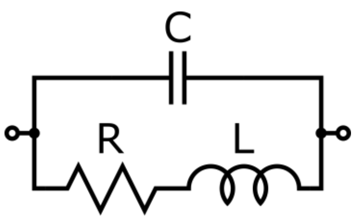
Depending on the application, many other properties are also relevant, such as breakdown voltage, leakage current, temperature dependency, wide tolerance range, aging, piezoelectricity, ...

Watch the video below in order to learn more about the frequency dependence of a capacitor.

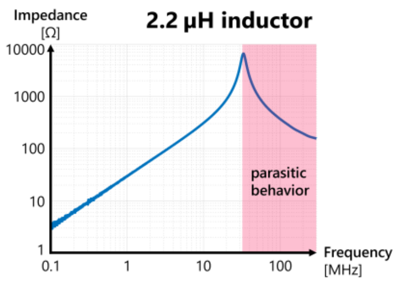


Real Capacitors
https://youtu.be/hlmPFbHTHTw

2.5.3 INDUCTOR



Unlike resistors and capacitors, inductors are not as commonly used in circuit design because they are more complex to manufacture and therefore larger and more expensive. A coil exists either as simple **air windings**, or is **wound around a magnetic core** (e.g. iron or ferrite) in order to increase inductance drastically. A typical application is a switched-mode power supply.



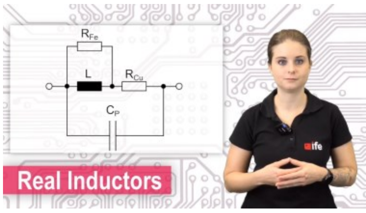
The equivalent circuit of a real coil might look the same as that of the real resistor. After the parallel resonance, the coil acts capacitively. This parasitic capacitance originates from the stray capacitance between the leads, but also between the windings themselves. Although it is not a true **RLC parallel resonant circuit**, to a first approximation we can estimate the resonant frequency equal to the series resonant circuit $f_0 = \frac{1}{2\pi\sqrt{LC}}$.

Strictly speaking, the parasitic ohmic resistance itself is also frequency dependent due to the following effects:

- Skin effect: High frequency currents push the electrons to the outer regions of the conductor. The current flows inside a round conductor only to the maximum depth of $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$. Thus, the higher the frequency, the permeability and the conductivity, the less cross-section is used by the current.
- Proximity effect: Two adjacent current-carrying conductors influence each other. Thus, the current distribution is constrained to smaller regions.
- Magnetic domains in a ferromagnetic material cannot align infinitely fast, i.e. μ decreases with f. The core material heats up during remagnetization which is equivalent to an ohmic loss.

Also very important: the **core material of a coil can saturate**, i.e. $L = f(I)$. Above a critical material-dependent flux density $\vec{B}$, the core saturates, causing the magnetic conductivity μ and thus the inductance L to drop sharply.

Watch the video below in order to learn more about the frequency dependence of an inductor.



Real Inductors
https://youtu.be/753kj6wM958

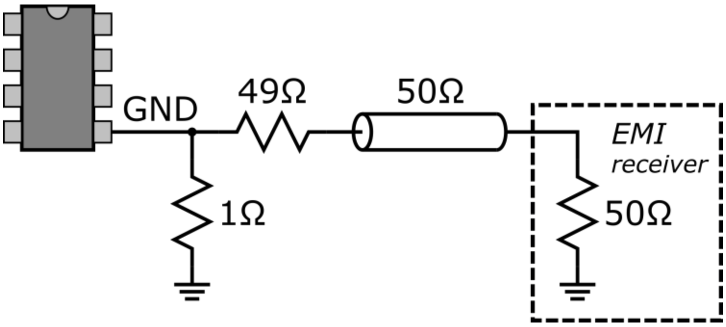
2.5.4 IC LEVEL 1Ω

Considering the parasitic elements is very important for circuit design, and we haven't even discussed the parasitics of active elements yet. Here is a small example of why this topic is so important.

The IEC 61967 standard is usually used in order to characterize the emissions of an IC. Part 4 of that standard shows two different methods to measure the conducted emissions:

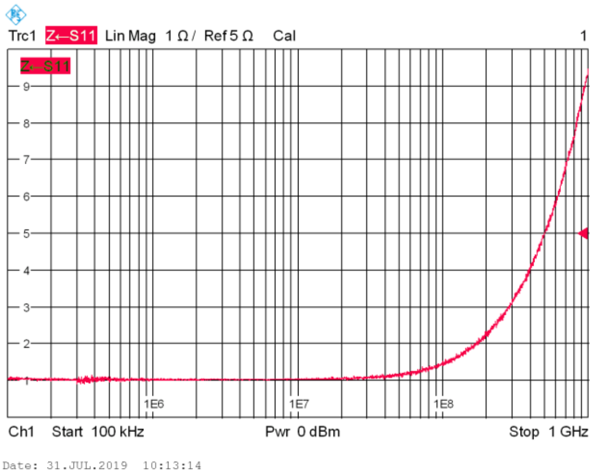
- 150Ω method
- 1Ω method

The first method is much more popular, because with the help of a simple modification, a DPI (direct power injection) immunity measurement according to IEC 62132-4 can be carried out easily. However, we will turn our attention to the lesser known 1Ω method. It's not important here to understand how this measurement setup works; we are planning an entire MOOC on chip design. The essential thing is that we want to measure the **voltage drop across a 1Ω resistor**. According to the 61967-4 standard, we have to build the following circuit for this purpose.

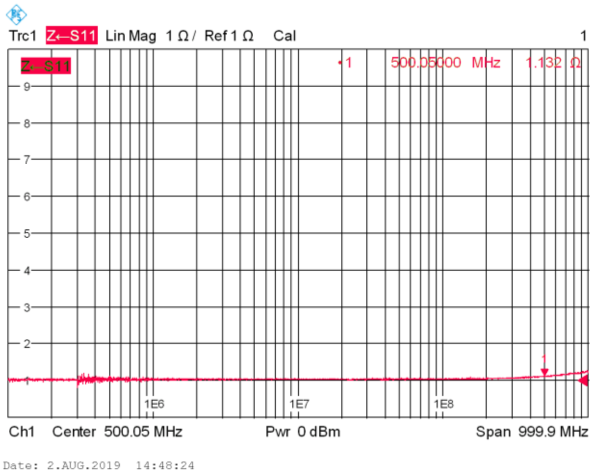


So, we *only* need to solder two resistors. Unfortunately, there is no 49Ω resistor available according to the E series. Alternatively, we could connect two resistors in parallel, e.g. 100Ω || 95.3Ω. It's best to solder the two SMD resistors on top of each other. The real troublemaker, however, is the **realization of the 1Ω resistor**. According to the standard, both 49Ω and 1Ω are only **allowed to deviate by 1%**; and that **up to 1GHz**. The difficulty is that the **parasitic inductance of a resistor** is too large, and thus increases the impedance enormously.

Two measurements are shown below. On the left, a 1Ω resistor in MICRO-MELF package was measured; these are known for predictable characteristics. We can see that a measurement **above 30 MHz can no longer be carried out** in accordance with the standard (violates the ±1% tolerance range). Instead, the right picture shows the impedance curve when the following six resistors are connected in parallel: 4.7Ω || 4.7Ω || 4.7Ω || 5.6Ω || 5.6Ω || 5.6Ω.



single 1Ω MICRO-MELF resistor



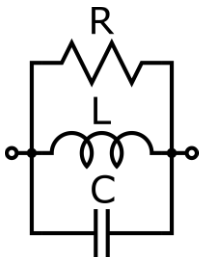
six resistors in parallel

So, if you ever want to realize a small resistor as accurately as possible (e.g. shunt resistor for high-frequency current sensing), you should consider the following design suggestions.

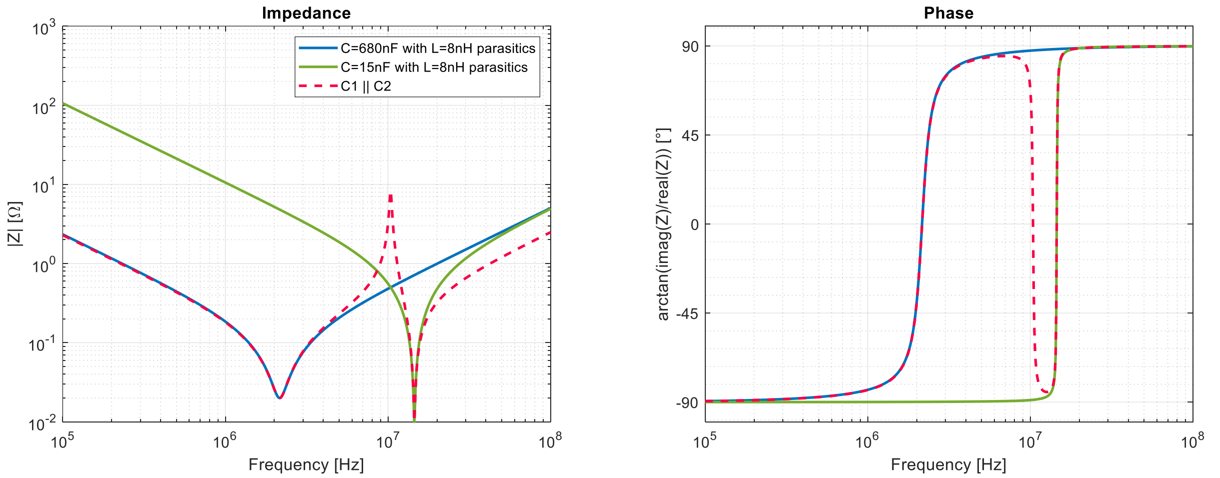
- Keep the conductor loop as small as possible.
- Smaller components tend to have fewer parasitic elements.
- The parasitic inductance can be reduced by connecting several components in parallel. If possible, place the resistors concentrically around the test port.

2.5.5 KNOWLEDGE CHECK

Below you can see an RLC circuit. Determine the formula for the resonant frequency $f_0 = f(L, C)$.



Look at the picture below. Which statements are true?



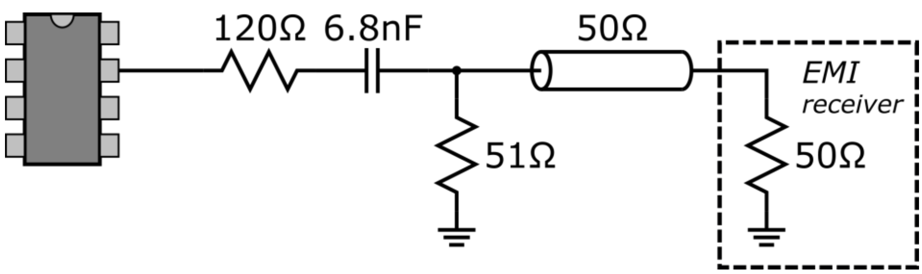
- ☐ The blue and the green line show two separate capacitors. The red line shows both impedance and phase when the two capacitors are connected in parallel.
- ☐ The red line shows a reduced impedance over the entire frequency range.
- ☐ Parallel resonance might cause problems at 10MHz.
- ☐ If the blue capacitor would be replaced by an electrolytic capacitor with high ESR, the parallel resonance would be significantly damped.

MATLAB code

```
%% Reset
close all
clear
clc
tic

%% Frequency
freq = (100:1:100000)*10^3;
w = 2*pi*freq;

%% RLC1
R1 = 0.02;
L1 = 8*10^(-9);
C1 = 680*10^(-9);
RLC1 = R1 + i.*w.*L1 + 1./(i.*w.*C1);
```

```
%% RLC2
R2 = 0.01;
L2 = 8*10^(-9);
C2 = 15*10^(-9);
RLC2 = R2 + i.*w.*L2 + 1./(i.*w.*C2);

%% RLC1 || RLC2
RLC3 = RLC1.*RLC2./(RLC1+RLC2);

%% Plot
figure('position',[0,50,1500,500])
subplot(1,2,1)
loglog(freq,abs(RLC1),'LineWidth',2,'DisplayName','C=680nF with
L=8nH')
hold on
loglog(freq,abs(RLC2),'LineWidth',2,'DisplayName','C=15nF with
L=8nH', 'color','#77AC30')
loglog(freq,abs(RLC3),'--','LineWidth',2,'DisplayName','C1 || C2',
'color','#F70146')
grid on
grid minor
legend('Location','northeast')
title('Impedance')
xlabel('Frequency [Hz]')
ylabel('|Z| [\Omega]')
set(gca,'FontSize',12)

subplot(1,2,2)
semilogx(freq,atan(imag(RLC1)./real(RLC1)).*360/2/pi,'LineWidth',2)
hold on
semilogx(freq,atan(imag(RLC2)./real(RLC2)).*360/2/pi,'LineWidth',2,
'color','#77AC30')
semilogx(freq,atan(imag(RLC3)./real(RLC3)).*360/2/pi,'--',
'LineWidth',2,'color','#F70146')
grid on
grid minor
title('Phase')
xlabel('Frequency [Hz]')
ylabel('arctan(imag(Z)/real(Z)) [°]')
set(gca,'YTick',[-90, -45, 0, 45, 90])
set(gca,'FontSize',12)

toc
```

We haven't shown this circuit yet, but you may still know what it is.



Answer: 150Ω method

2.6 RECAP 2

Differential-mode filtering: X-capacitors and series inductivity.

Common-mode filtering: Y-capacitors and common-mode choke.

Common-mode currents exploit the **wiring as antennas**.

A good filter is created with the help of a **mismatch**.

A distinction is made between class 1 (NP0) and class 2 (**X7R**) MLCCs.

Best practice for **decoupling**: a 220nF X7R in parallel to a 10µF tantalum. The X7R is soldered closer to the IC.

Separate digital and analog circuits on your PCB.

Solder your PCB connectors side by side; **avoid large loops**!

An **aluminum housing** provides good shielding.

A capacitor is **voltage dependent**; a coil is current dependent.

The **transfer function** $H(j\omega)$ describes the ratio of output voltage to input voltage. From this, the -3dB cutoff frequency f_1 can be determined.

All components have **parasitic elements**. After the resonant frequency f_0, the component acts contrary.

$f_0 = \frac{1}{2\pi\sqrt{LC}}$ for series and parallel **RLC resonant circuit**.

At the resonant frequency f_0, the imaginary parts cancel each other out.

Two capacitors connected in parallel can cause an **undesirable parallel resonance**.

Tick all **learning objectives** that you have understood.

I know how ...

2.1 - Differential- vs. Common-mode

☐ to recognize that the current path plays a crucial role in EMC issues.
☐ to distinguish between differential and common-mode.
☐ to explain how a common-mode choke works.

2.2 - Filtering

☐ to derive the classical filter design including transfer function and Bode plot.
☐ to choose a suitable filter for a given noise and load impedance.
☐ to apply a best practice EMI filter for the supply lines.

2.3 - Shielding

☐ to draft a basic shielding concept.
☐ to decide which shielding material to use.
☐ to illustrate the origin of electromagnetic radiation at dipole level.

2.4 - PCB Design

☐ to design a PCB EMC-aware.
☐ to implement traces for guiding RF signals.
☐ to select the right decoupling capacitors.

2.5 - Passive Components

☐ to estimate the values of parasitic elements.
☐ to calculate the resonant frequency of real passive components.
☐ to sketch a resistor with low parasitic inductance.

3 EMC TESTING

Now that you know the main EMC design methods, let's turn our attention to how to measure *EMC. It is a task of characterizing the emission and immunity behavior of our product with some numbers. While emissions can be measured with a simple antenna, immunity is a question of the stress level at which a fault situation occurs (e.g. the emission level when the remote control stop working). But often it is not easy to define this error condition. But let's start again with some theory.*

3.1 S-PARAMETERS

The name *S-parameter* is an analogy to optics where electromagnetic waves (e.g. light) hit a plane and are thus reflected and trasmitted. These parameters are used in order to **characterize the behavior of linear electrical networks**. Since the small-signal behavior is analyzed by means of wave quantities (e.g. reflection coefficient Γ), these parameters are primarily used in RF engineering.

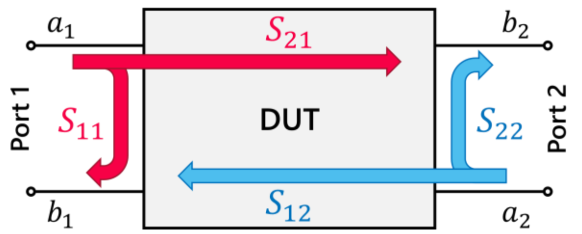
If an RF circuit is designed, its S-parameters are usually simulated. After production, the S-parameters are then measured using a vector network analyzer (**VNA**) in order to **verify** the simulation results and to generate a **simulation model**. Classical I–V parameters are often difficult to measure because perfect short circuits and openings are difficult to realize. Another reason why S-parameters became popular is that the wave impedance is always measurable; also when the circuit is in its normal operation. For instance, an amplifier must never be operated in short circuit or open circuit where it could be destroyed.

This learning sequence thus represents a link between design and testing. We need simulation models for EMC-compliant design, but at the same time we must be able to handle test equipment.

3.1.1 S-PARAMETER THEORY

The S-parameter matrix for 2-port networks is the most popular form and gives the relation between the **incident** (or incomming) power waves a_i and the **transmitted** (or reflected) power waves b_i.

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$



$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$ is the input port voltage reflection coefficient by a matched output.

$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$ is the reverse voltage gain by a matched input.

$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$ is the forward voltage gain by a matched output.

$S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$ is the output port voltage reflection coefficient by a matched input.

Calculation by hand

Thanks to powerful PCs, of course, no one calculates these parameters by hand anymore except for the local students at Graz University of Technology. Nevertheless, a simple calculation will be demonstrated briefly.

- The reflection coefficients S_{11} and S_{22} can be calculated like Γ:

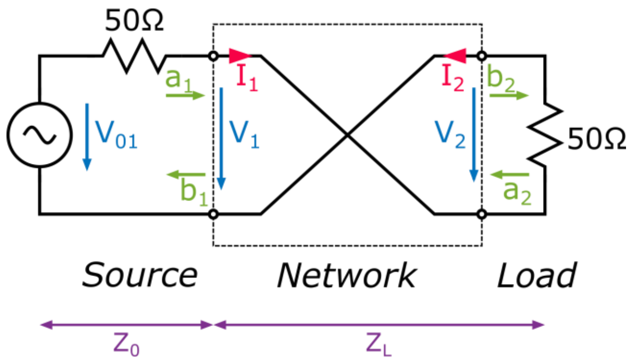
$$S_{ii} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

- The transmission coefficients S_{21} and S_{12} can be calculated as below:

$$S_{ji} = \frac{2V_j}{V_{0i}} \sqrt{\frac{Z_{0i}}{Z_{0j}}}$$

where usually $Z_{0i} = Z_{0j}$ applies.

Look at the following example:



- In order to characterize this network, it is terminated with 50Ω. We can calculate the reflection coefficients as follows:

$$S_{11} = \frac{50\Omega - 50\Omega}{50\Omega + 50\Omega} = 0$$

- The transmission coefficients are a bit trickier to calculate. Here, we must express the voltage with the help of the voltage divider rule:

$$S_{21} = \frac{2V_2}{V_{01}}\sqrt{\frac{50\Omega}{50\Omega}} = \frac{2\frac{-V_{01}}{2}}{V_{01}} = -1$$

The S-parameter matrix is therefore:

$$S = \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix} = \begin{bmatrix} -\infty\, dB & 0\, dB \\ 0\, dB & -\infty\, dB \end{bmatrix}$$

- The reflection coefficients are 0. This means that nothing is reflected since the system is **matched** by 50Ω. However, a VNA would not display -∞dB in its magnitude plot but its noise level of about -100dB.
- The transmission coefficients are -1. This means that the whole signal is transmitted but with negative sign. With the usual representation in dB, this sign can no longer be distinguished.
- **Symmetry**: $S_{11} = S_{22}$ i.e. this network is symmetrical. A symmetrical network is always reciprocal.
- **Reciprocity**: since $S_{21} = S_{12}$, i.e. $S = S^T$, this matrix is called reciprocal. All passive circuits (R, L, C only) are reciprocal.
- The S-parameters are **frequency dependent** as soon as an inductor or a capacitor is included in the network.

3.1.2 Z- AND Y-PARAMETERS

We have to consider the S-parameters as an additional way to describe a network. We are used to think in terms of **Z-parameters**, the so-called **impedance parameters**. Sometimes we also use its reciprocal, the Y-parameters, or the admittance parameters. You may have already noticed that all matrices look quite similar:

S-parameters

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

Z-parameters

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

Y-parameters

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

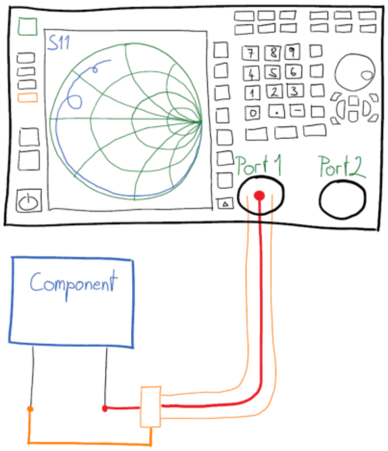
It is important to know that we can **mathematically transform between these parameters at any time.** Of course, many simulation programs and the VNA itself have already implemented the conversion natively. Nevertheless, the S-parameters are often converted by hand into the Z-parameters in case you do a short series of measurements.

1-port networks

For 1-port networks, the reflection coefficient Γ can be easily converted into the corresponding load impedance Z_L. Imagine you want to characterize the frequency behavior of a capacitor. You can connect the capacitor directly to a VNA and then convert the measured S-parameters into an impedance.

$$\Gamma = S_{11} = \frac{Z_L - Z_0}{Z_L + Z_0} \quad \Leftrightarrow \quad Z_L = Z_0 \frac{1 + S_{11}}{1 - S_{11}}$$

REFLECTION COEFFICIENT

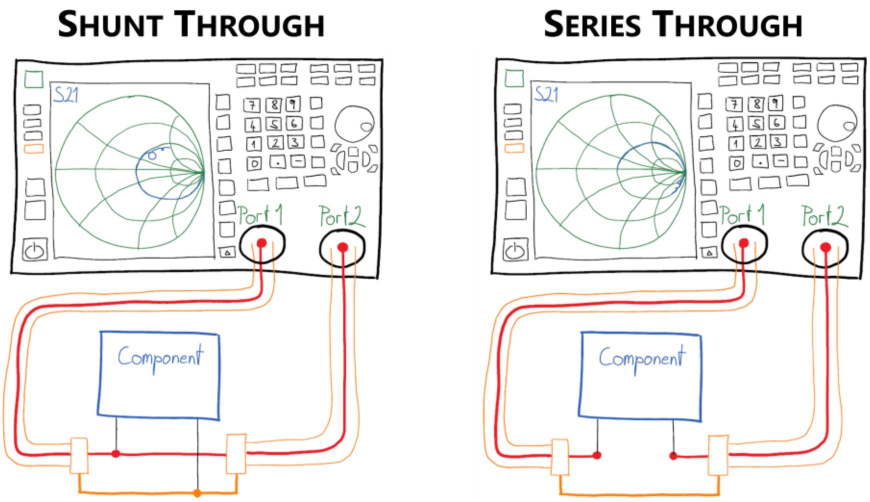


$$Z_{DUT} = 50\Omega \cdot \frac{1 + S_{11}}{1 - S_{11}}$$

2-port networks

But you can also characterize the same capacitor with a 2-port measurement. Two different options are available to you for this:

- <u>Shunt through</u>: this measuring method is preferred for **low impedances**, as they are to be expected e.g. with a **capacitor**.
- <u>Series through</u>: this measuring method is preferred for **high impedances**, as they are to be expected e.g. with an **inductor**.



$$Z_{DUT} = 25\Omega \cdot \frac{S_{21}}{1 - S_{21}} \qquad Z_{DUT} = 100\Omega \cdot \frac{1 + S_{21}}{S_{21}}$$

The formulas above takes S_{21} in order to transform it into the impedance of the DUT. But of course, you can transform any S-parameter into the corresponding Z- or Y-parameter. Therefore, we have created a table where you can directly read out the formula in case you ever need it:

	S	Z	Y
S_{11}	S_{11}	$\frac{(Z_{11}-Z_0)(Z_{22}+Z_0)-Z_{12}Z_{21}}{\det(Z)}$	$\frac{(Y_0-Y_{11})(Y_0+Y_{22})+Y_{12}Y_{21}}{\det(Y)}$
S_{12}	S_{12}	$\frac{2 \cdot Z_{12}Z_0}{\det(Z)}$	$\frac{-2 \cdot Y_{12}Y_0}{\det(Z)}$
S_{21}	S_{21}	$\frac{2 \cdot Z_{21}Z_0}{\det(Z)}$	$\frac{-2 \cdot Y_{21}Y_0}{\det(Y)}$
S_{22}	S_{22}	$\frac{(Z_{11}+Z_0)(Z_{22}-Z_0)-Z_{12}Z_{21}}{\det(Z)}$	$\frac{(Y_0+Y_{11})(Y_0-Y_{22})+Y_{12}Y_{21}}{\det(Y)}$
Z_{11}	$Z_0\frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$	Z_{11}	$\frac{Y_{22}}{\lvert Y\rvert}$
Z_{12}	$Z_0\frac{2 \cdot S_{12}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$	Z_{12}	$\frac{-Y_{12}}{\lvert Y\rvert}$
Z_{21}	$Z_0\frac{2 \cdot S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$	Z_{21}	$\frac{-Y_{21}}{\lvert Y\rvert}$
Z_{22}	$Z_0\frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{(1-S_{11})(1-S_{22})-S_{12}S_{21}}$	Z_{22}	$\frac{Y_{11}}{\lvert Y\rvert}$
Y_{11}	$Y_0\frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}}$	$\frac{Z_{22}}{\lvert Z\rvert}$	Y_{11}
Y_{12}	$Y_0\frac{-2 \cdot S_{12}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}}$	$\frac{-Z_{12}}{\lvert Z\rvert}$	Y_{12}
Y_{21}	$Y_0\frac{-2 \cdot S_{21}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}}$	$\frac{-Z_{21}}{\lvert Z\rvert}$	Y_{21}
Y_{22}	$Y_0\frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{(1+S_{11})(1+S_{22})-S_{12}S_{21}}$	$\frac{Z_{11}}{\lvert Z\rvert}$	Y_{22}

N-port networks

The general formula for converting is:

$$Z = Z_0 \cdot (I - S)^{-1} \cdot (I + S)$$

$$Y = \frac{1}{Z_0} \cdot (I + S)^{-1} \cdot (I - S)$$

In order to calculate back:

$$S = \left(\frac{1}{Z_0} \cdot Z - I\right) \cdot \left(\frac{1}{Z_0} \cdot Z + E\right)^{-1}$$

$$S = (I - Z_0 \cdot Y) \cdot (I + Z_0 \cdot Y)^{-1}$$

where I is the identity matrix.

3.1.3 LIBREVNA

This is the instrument in order to measure the S-parameters of a DUT. It is a very important device with a lot of settings. Like most measuring instruments, its handling is best learned in a lab exercise. On this page we try to summarize a few important facts.

- A **network analyzer** is an expensive instrument (about 20,000$) which has 2 ports in its basic configuration.
- A **test signal**, which changes in frequency, is applied to one of the ports.
- **Reflection and transmission** coefficients of a 2-port network (DUT; e.g. filter or amplifier) are measured in order to characterize it.
- The typical plug connection of the ports is called **type-N connector**. Low-budget VNAs (like the one in the video below) usually have the standard **SMA connector**.

In order to better understand the video below, you need to understand the following terms:

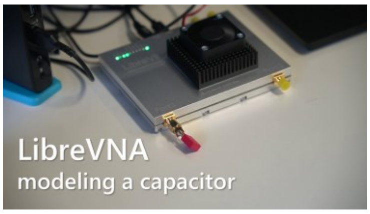
- **Frequency range**, e.g. 100 MHz to 1 GHz. We usually set "start" and "stop" frequency. Alternatively, we can also set the frequency "span" and the "center" frequency.
- **Frequency type**: Most VNAs use a "linear" sweep per default (i.e. 100, 200, 300, ...). Often, a "logarithmic" sweep is preferred (i.e. 100, 1000, 10000, ...).
- **Number of points**, e.g. 4001 measuring points are placed over the *frequency range*. The more measuring points, the longer the *sweep time* takes.
- **Sweep time**: This is not a real setting that we can adjust but results from other settings. It takes one *sweep time* in order to measure all measuring points.
- **IF filter bandwidth**: By narrowing it, we can decrease the measured noise level. Thus, the dynamic range is improved for the cost of longer *sweep times*.
- **Source power**, e.g. -10 dBm. The *test signal* is output with this power. Most of the time -10 dBm or 0 dBm is a good choice.

- **Calibration**. After making the settings above, you need to calibrate the VNA. Only by a correct calibration the measuring lines are considered correctly. Without calibration you can throw away your measurement data.

LibreVNA Unboxing and Setup
https://youtu.be/V4XWHbEjofo

3.1.4 Modeling a capacitor

In the previous chapter we learned that a capacitor also contains parasitic elements in form of resistance and inductance. Characterizing a capacitor including its parasitic elements is a very basic application using a VNA. We can create a simulation model consisting of so-called *lumped-elements* out of the measured S-parameters. We can then include the generated model in our next SPICE simulation. Watch the video below to see such a workflow.



LibreVNA, modeling a capacitor
https://youtu.be/ilg4NGcQk5k

MATLAB code

```
%% Setup
close all  % close all Figures
clear      % clear the Workspace
clc        % clear the Command Window
tic        % start recording the elapsed time

%% Import
Import = ...
readmatrix('test.s1p','FileType','text','ExpectedNumVariables',3);
% "readmatrix" requires R2019a upwards. Use "csvread" for older vers.
freq = Import(:,1)*10^9;                  % Column 1 of the *.s1p file
Sparam = Import(:,2) + i*Import(:,3);     % Column 2 and 3 of the *.s1p
Zparam = 50*(1+Sparam)./(1-Sparam);      % Convert S-param into Z-param

%% Model
w = 2*pi*freq;     % angular frequency
R = 0.02;          % resistance at resonance
L = 10*10^(-9);    % approx. 1nH per mm
C = 680*10^(-9);   % according to the data sheet
RLC = R + i.*w.*L + 1./(i.*w.*C);  % Series RLC resonant circuit

%% Plot Magnitude
figure
loglog(freq, abs(Zparam), 'LineWidth',2)  % Measurement data
hold on
loglog(freq, abs(RLC), 'LineWidth',2)     % Simulation data
grid on
grid minor
```

```
xlabel('Frequency [Hz]')
ylabel('|Z| [\Omega]')

%% Plot Phase
figure
semilogx(freq,atan(imag(Zparam)./real(Zparam)).*360/2/pi,'LineWidth',2)
hold on
semilogx(freq,atan(imag(RLC)./real(RLC)).*360/2/pi,'LineWidth',2)
grid on
grid minor
xlabel('Frequency [Hz]')
ylabel('phase(Z) [°]')

toc  % stop recording the elapsed time
```

3.1.5 Knowledge Check

Combine left and right cells.

The input port voltage reflection coefficient by a matched output.	S11
The output port voltage reflection coefficient by a matched input.	S12
The forward voltage gain by a matched output.	S21
The reverse voltage gain by a matched input.	S22

Combine left and right cells.

$S_{ii} = 0$	Symmetry
$S = S^T$	Reciprocity
$S_{11} = S_{22} = S_{33} = [\dots]$	Matched

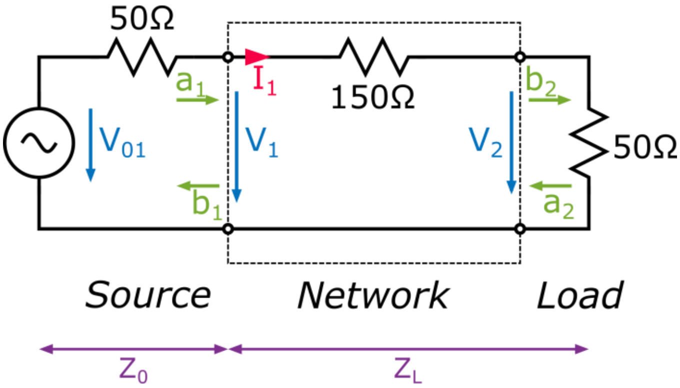
If a circuit consists of R, L, C only, usually $S_{21} = S_{12}$ applies.

- O True
- O False

If a circuit consists of R, L, C only, usually $S_{11} = S_{22}$ applies.

- O True
- O False

Look at the symmetrical circuit below, i.e. $S_{11} = S_{22}$ and $S_{21} = S_{12}$. Calculate both the reflection coefficient and the transmission coefficient.



$S_{11} =$
$S_{21} =$

You're configuring a VNA. Select all options that definitely <u>increase the sweep time</u>.

- ☐ Increase the frequency range
- ☐ Increase the number of measuring points
- ☐ Increase the signal power
- ☐ Decrease the IF bandwidth
- ☐ Use of averaging

You're configuring a VNA. Your measured parameter almost disappears in the noise. What options could help you in order to <u>increase the dynamic range</u>?

- ☐ Increase the frequency range
- ☐ Increase the number of measuring points
- ☐ Increase the signal power
- ☐ Decrease the IF bandwidth
- ☐ Use of averaging

3.2 Test Equipment

Until now, EMC was a rather theoretical subject. But this is not the truth: an EMC engineer spends a lot of time in the lab. Theoretical knowledge (Chapter 1) is necessary in order to design a system EMC-aware (Chapter 2). But we also have to verify this system in the laboratory (this chapter). Here, we need standard equipment such as multimeter, oscilloscope, power supply and waveform generator. Furthermore, every laboratory needs a spectrum analyzer and a VNA.

Depending on the company, your lab workplace will be better or worse equipped, but you can basically tinker many test setups yourself. It's ultimately a decision from the management department: if your company carry out in-house EMC tests more *standard-compliant*, it can better predict the results of the final EMC test measurements. At the same time, the purchase of standard-compliant equipment is very expensive. Therefore, start-up companies often cooperate with technical offices like our institute which offer equipment and know-how.

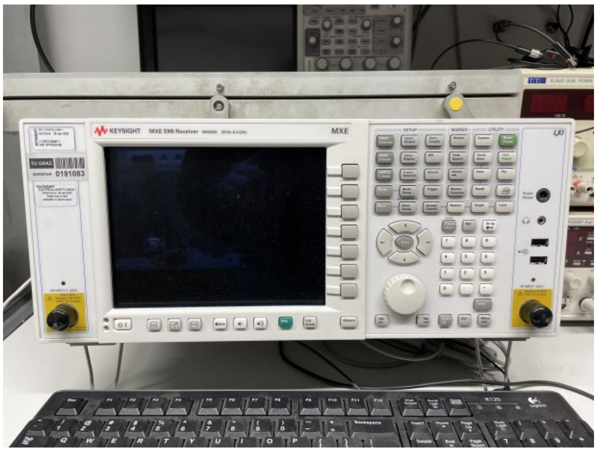
Remember: EMC should be considered in every aspect of the product design. The later you start looking at EMC, the fewer options are available. Failing the final EMC tests at the end of the project can result in a financial disaster.

3.2.1 EMI receiver

This is the measuring device with which we perform our emission measurements. Basically, we only need to connect our DUT (*conducted*) or an antenna (*radiated*) to it and press the start button. Unfortunately, it's not that simple. The difficulty is to set up the measurement according to the standards and to make the correct settings on the EMI receiver.

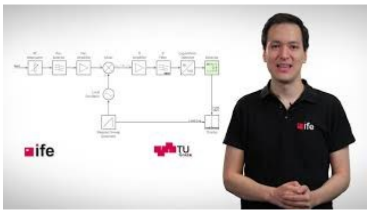
Basically, two different types of receivers are available: superheterodyne and FFT-based. The latter measure a time signal similar to an oscilloscope and calculate the frequency spectrum from it. They are more modern, faster and more expensive.

Superheterodyne EMI receiver



Modern FFT-based EMI receiver

In the video below, you will learn how a superheterodyne receiver works. Don't get frustrated if you don't understand everything right away. As EMC test engineer, it's your task to configure the EMI receiver correctly. Therefore, it's more important to understand the terms like attenuator, preamplifier, resolution bandwidth, measurement time and quasi-peak detector.



How does an EMI Receiver work?
https://youtu.be/6ZyE-UywnFs

Important settings

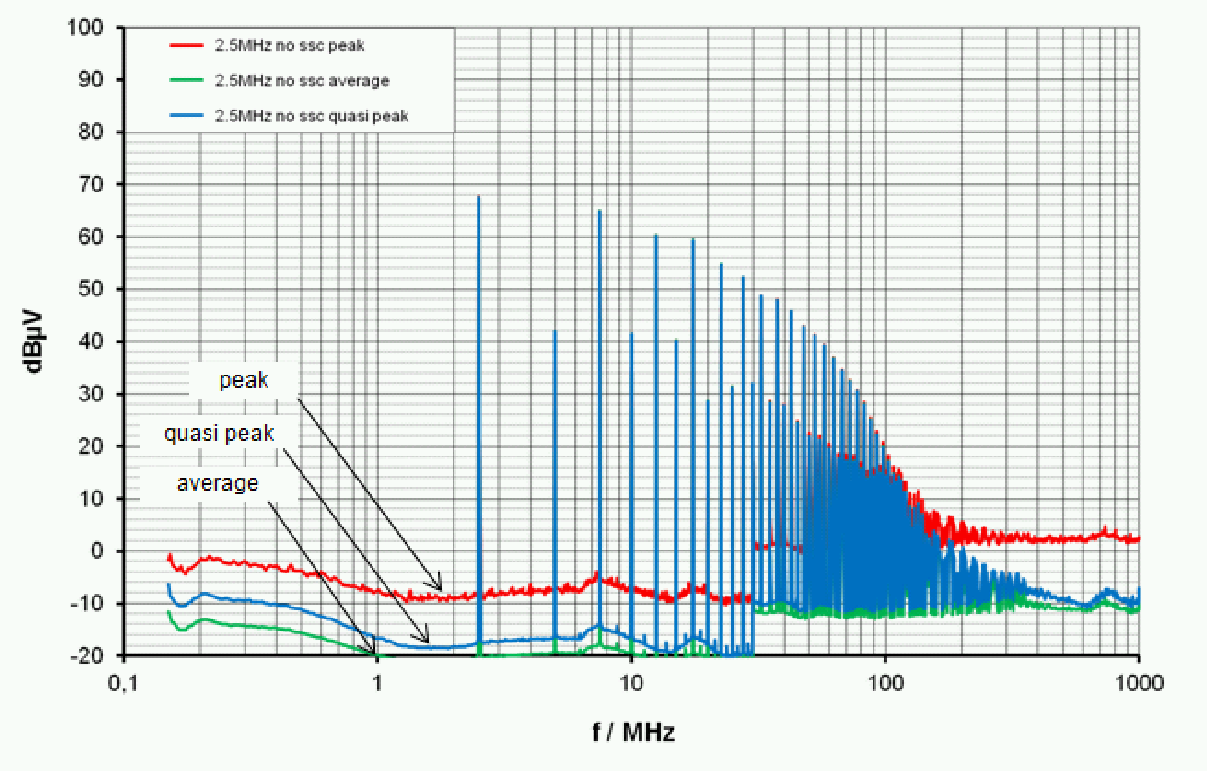
A typical plot is shown below where conducted emissions of an IC were measured which **operates with 2.5MHz**. We performed this measurement three times with three different detectors. The measurement results of the detectors overlap, this is always true. So, it's not so easy to see that the peak detector always gives the highest value. **We thus always use the peak detector for our worst-case analyses**, even if the final standard-compliant measurement is often performed with a quasi-peak detector by historical reasons.

Another important setting is the **resolution bandwidth (RBW)**. Many standards require a RBW of 9kHz from 150kHz to 30MHz. From 30MHz to 1GHz, a RBW of 120kHz is then required. Therefore, **exactly at 30MHz you see a jump to higher emissions of the noise floor**. The real-world noise level doesn't make a jump at 30MHz, of course, but we simply measure differently.

The **measurement time setting** often causes confusion as well. This should be set **at least 3 times of one full operation cycle**. For instance, our IC operates with 2.5 MHz. This is equal to 400 ns. Thus, we should set the measurement time to 1.2 µs or above. But maybe there is an additional 100 kHz resonant circuit oscillating in the IC. In this case, we would have to choose the measurement time to 30 µs or longer. These switching frequencies must be told to you by the circuit designers. If you are unsure, **you are on the safe side with a longer measurement time**. The only disadvantage is that a measurement then takes longer, of course.

Don't get too confused by the **attenuator and preamplifier settings** when you first start working with this instrument. These are important settings as well; but if you set the attenuator to 10dB, the final result will add 10dB again in order to get comparable results. So, we use these settings when we expect a very high or very low input signal.

The spectrum below and the MATLAB code are two different experiments.



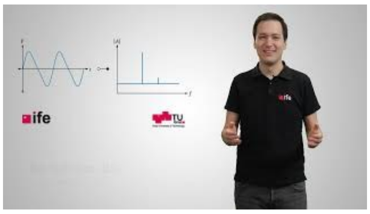
MATLAB code

```
%% Comments
% Rigol DG1022 is used
% 4096 values must be defined from 0 to 16383
% The *.rdf file must be written in 16-bit little-endian HEX

%% Reset
close all  % close all Figures
clear      % clear the Workspace
clc        % clear the Command Window
disp('MATLAB R2019a Skript is running ...')

%% Rectangular Signal
x = 1 : 1 : 4096;
y(1) = 0;
y(2:3) = 16383;
y(4:length(x)) = 0;

%% Plot
figure
plot(x*20e-3/4096, y/16383, 'LineWidth',2)
grid on
grid minor
title('Arbitrary Waveform')
xlabel('Time in [s]')
ylabel('Amplitude in [V]')
xlim([0 5*20e-3/4096])

%% Write *.rdf file
export = uint16(y);                             % Create a 16-bit integer
filename = 'KoOdreitz.rdf';                     % Store in this file
file = fopen(filename, 'w');                    % Open file for writing
fwrite(file, export, 'uint16', 'ieee-le');      % 16-bit, little endian
fclose(file);                                   % Close file
```

3.2.2 SPECTRUM ANALYZER

The **EMI receiver** has one significant drawback: its cost of about **$200,000**. For small and medium-sized enterprises this is a high financial cost, especially if the measuring device is not used frequently. In addition, there is a risk that an unexperienced user will destroy this instrument with a single measurement, e.g. if the power supply is directly applied to its port. But worst-case estimations can also be performed with a **spectrum analyzer** which costs around **$10,000**. If the budget of your company doesn't allow even that, then you should at least purchase a cheap LibreVNA ($500) or NanoVNA ($200).

In case you already have more experience in electrical engineering, then you know the spectrum analyzer for sure. One could say that an EMI receiver is a special spectrum analyzer which complies with international regulations thanks to some fancy options. In fact, both devices are very similar, even if the usage differs. In the video below you will see the differences between EMI receiver and spectrum analyzer.



Basics of a Spectrum Analyzer - Differences to an EMI Receiver
https://youtu.be/eVuM44tz72Q

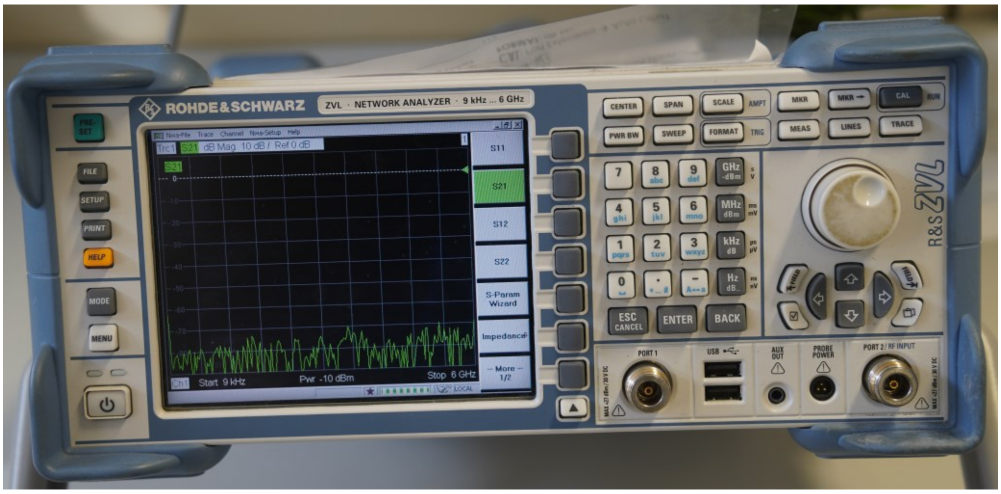
MATLAB code

```
%% Comments
% Rigol DG1022 is used
% 4096 values must be defined from 0 to 16383
% The *.rdf file must be written in 16-bit little-endian HEX

%% Reset
close all  % close all Figures
clear      % clear the Workspace
clc        % clear the Command Window
disp('MATLAB R2019a Skript is running ...')

%% Arbitrary signal
x = 1 : 1 : 4096;
y = 7500*sin((x-1)/4095*2*pi) + 1500*sin(2*(x-1)/4095*2*pi) + 8191;

%% Plot
figure
plot(x, y, 'LineWidth',2)
grid on
grid minor
title('Arbitrary Waveform')
xlabel('Time in [s]')
ylabel('Amplitude in [V]')
xlim([1 4096])
ylim([0 16383])

%% Write *.rdf file
export = uint16(y);                            % Create a 16-bit integer
filename = 'KoOdreitz.rdf';                    % Store in this file
file = fopen(filename, 'w');                   % Open file for writing
fwrite(file, export, 'uint16', 'ieee-le');     % 16-bit, little endian
fclose(file);                                  % Close file
```

3.2.3 VECTOR NETWORK ANALYZER (VNA)

We have discussed the LibreVNA in learning sequence *3.1 - S-parameters*. A VNA is basically an upgrade to a spectrum analyzer. In addition to measuring a signal, we can now also send out a signal. And that's exactly what a VNA does: a signal is sent out on one port while measurements are performed on both ports. This gives us the S-parameters S11, S21, S12 and S22. This allows us to characterize and better understand our systems.

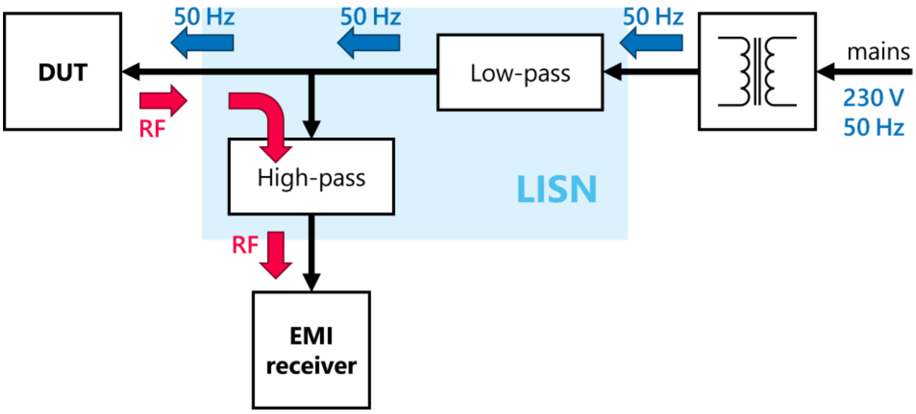
A VNA should be part of the basic equipment in every laboratory. Click on the interactive image below in order to learn the basic functions of a commercially available VNA which costs about $20,000 (*only possible on edX.org*). It's the same device as shown in the previous video, but we use it as a VNA now. If your company's budget is limited, cheap alternatives like the LibreVNA ($500) are available. These may not be as accurate, but you should definitely use them for your worst-case estimates.



3.2.4 LISN (FOR EMISSION)

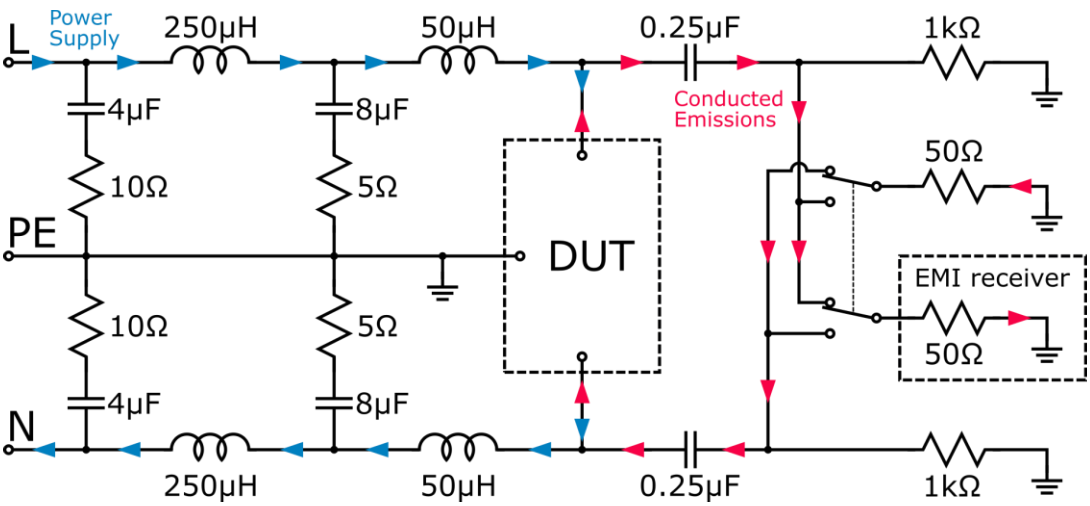
A LISN is usually used for measuring **conducted emissions**. You have already seen this device in learning sequence *2.2 - Filtering*. This device has the following three tasks:

1) Decouples the high-frequency emissions from the DUT in order to send them to a spectrum analyzer or an EMI receiver.
2) Suppresses existing noise from the power supply.
3) Provides a normalized impedance for the DUT.



Below you can see a typical schematic of a LISN. A closer study reveals:

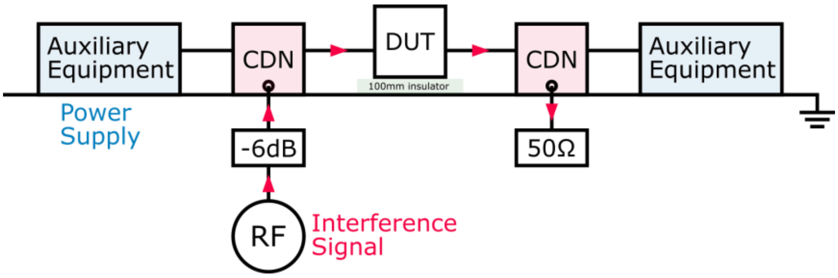
1) The high-frequency interference from the DUT follows the path "to the right" and thus enters the EMI receiver. It's a high-pass filter.
2) The 50Hz supply voltage, on the other hand, can be provided via the inductors. Any noise from the mains is shunted to ground. It's a low-pass filter.
3) The LISN provides a standardized impedance to the power supply of the DUT. In this case it is 50uH + 5Ω. This is important in order to obtain repeatable measurement results.

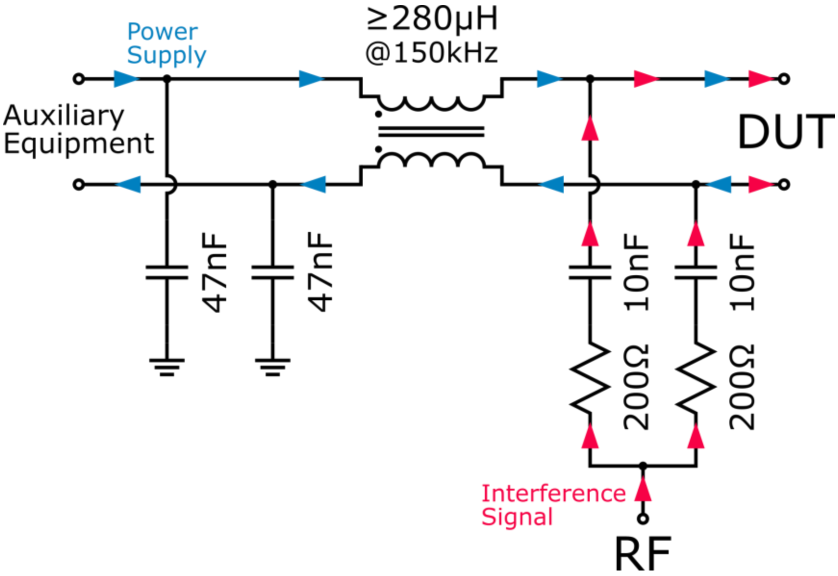


3.2.5 CDN (FOR IMMUNITY)

A CDN is usually used for **conducted immunity testing**. Different measurement setups exist in order to determine the susceptibility of a system. The picture below shows a usual method. Here, an interference signal is coupled into the DUT with a CDN. At the same time, the DUT is decoupled from possible disturbances of the power supply (auxiliary equipment). The interference is terminated at a 2nd CDN with 50 Ohm.

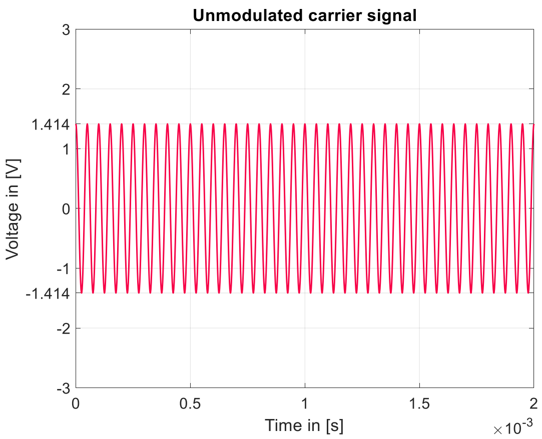
A schematic of a CDN is shown below. The interference signal is fed to the DUT in common mode. There exist also 3-pole CDNs; in this case the resistors have 300Ω each instead of 200Ω. At the same time, the filter elements suppress any interference from the auxiliary equipment.

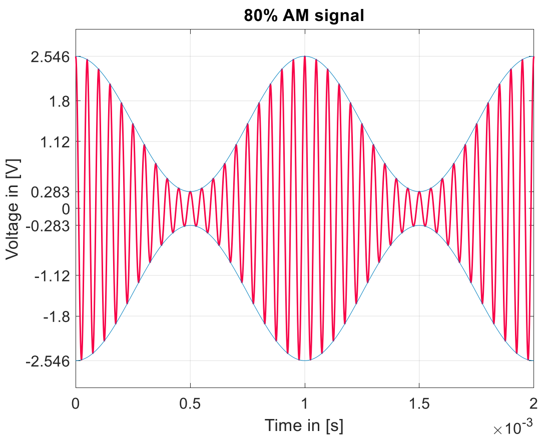




Test signal of immunity tests

Depending on the standard, our DUT must be stressed with a test signal. Usually, it is an 80% amplitude modulated signal (e.g. 1 kHz sine multiplied with a 150 kHz to 80 MHz carrier signal). It is important to study the applied standard carefully. According to **IEC 61000-4-6**, for instance, 80% AM means that an unmodulated signal $V_{rms} = 1V$ is modulated to $V_{rms} = 0.2V$ and $V_{rms} = 1.8V$. Military standards and IC-level standards define this test signal differently. The DUT is now monitored while it is stressed; it must not report an error during the test. Unfortunately, a key difficulty with immunity tests is to define appropriate error criteria.





MATLAB code

```
%% Reset
close all  % close all Figures
clear      % clear the Workspace
clc        % clear the Command Window
tic        % start recording the elapsed time

%% Variables
t = linspace(0, 0.002, 100000);  % 0 to 2 with 100000 steps

f_signal = 1000;     % Usual test signal
f_carrier = 20000;   % 150 kHz to 80 MHz

m = 0.8;             % modulation depth

%% Calculation
V_carrier = 1;
V_signal = V_carrier*m;

y_signal = V_signal*cos(2*pi*f_signal*t);
y_carrier = sqrt(2)*cos(2*pi*f_carrier*t);

y_AM = (V_carrier + y_signal) .* y_carrier;

%% Plot y_carrier
figure('Position',[50 100 800 600])
plot(t,y_carrier, 'LineWidth',1.5, 'Color','#F70146')
grid on
title('Unmodulated carrier signal')
xlabel('Time in [s]')
ylabel('Voltage in [V]')
ylim([-3 3])
set(gca, 'XTick',[0 0.5 1 1.5 2]*10^(-3))
set(gca, 'YTick',[-3, -2, -1.414, -1, 0, 1, 1.414, 2, 3])
set(gca, 'FontSize', 16)

%% Plot y_AM
figure('Position',[10 60 800 600])
plot(t,y_AM, 'LineWidth',1.5, 'Color','#F70146')
hold on
plot(t, sqrt(2)*(y_signal+V_carrier), 'Color','#0080C0')
plot(t,-sqrt(2)*(y_signal+V_carrier), 'Color','#0080C0')
grid on
title('80% AM signal')
xlabel('Time in [s]')
ylabel('Voltage in [V]')
set(gca, 'XTick',[0 0.5 1 1.5 2]*10^(-3))
set(gca, 'YTick',[-2.546,-1.8,-1.12,-0.283,0,0.283,1.12,1.8,2.546])
set(gca, 'FontSize', 16)
toc
```

3.2.6 NEAR-FIELD PROBES

Near-field probes can be used in order to **identify emission sources** on a circuit quickly. We distinguish between

- **E-field probes** and
- **H-field probes**.

Especially H-field probes are extremely helpful, as they display a voltage depending on their orientation. In the following picture you can see some professional near field probes. Only the two on the right are for measuring the E-field. The others all measure primarily the H field. Usually, a preamplifier is used between the spectrum analyzer and the field probe. That's this black brick on the left.

Watch the video below in order to learn more about near-field probes.

H Field Probes
https://youtu.be/LNxcCBJ-q7c

3.2.7 KNOWLEDGE CHECK

Which EMI receiver technology gives the measurement result faster?

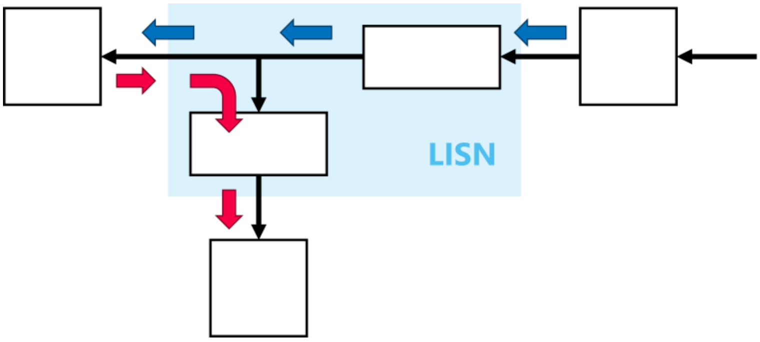
- ○ Superheterodyne EMI receiver
- ○ FFT-based EMI receiver

Which detector gives the highest possible value?

- ○ Quasi-Peak
- ○ Peak
- ○ Average
- ○ RMS

What does the abbreviation LISN stand for?

Complete the picture below with the following words: DUT, EMI receiver, high-pass, low-pass, mains, RF, transformer, 50 or 60 Hz



Which of the following tasks is not a function of a LISN?

- O Suppresses existing noise from the power supply.
- O Decouples the high-frequency emissions from the DUT.
- O Enables the coupling of an 80% AM signal.
- O Provides a normalized impedance for the DUT.

You have the two signals $V_{signal} = \cos(\omega t)$ and $V_{carrier} = \cos(\Omega t)$ with $\Omega \gg \omega$. How can we calculate the amplitude modulation?

- O $V_{signal} + V_{carrier}$
- O $(V_{DC} + V_{signal}) \cdot V_{carrier}$
- O The Fourier transform $F(\omega) = \int_{-\infty}^{+\infty} f(t) \cdot e^{-j\omega t}\,\mathrm{d}t$ must be calculated from both signals. Afterwards, they can be added by means of superposition.
- O We need to multiply both functions by the corresponding Bessel function. Afterwards, they can be added by means of superposition.
- O The Mandelbrot set specifies exactly when a superposition is allowed. Since both signals can be multiplied by the Mandelbrot series without violating convergence criteria, we can add both products.

3.3 INTERNATIONAL REGULATIONS

Some students think this subject is extremely boring, others love it. This is not a MOOC about law, but it is crucial to know about the most important standards and international organizations. EMC has a different meaning for everyone.

- For physicists, EMC is the application of Maxwell's equations to analyze wave propagation. They setup full-wave simulations and share their knowledge with technicians.
- For technicians, EMC involves the tasks: decrease emissions, prevent coupling and enhance immunity. We must design and test the products accordingly in order to ensure EMC compliance.

- Lawyers, on the other hand, are dealing with the question of how to define this "EMC compliance". They also define the penalties if a product is sold that does not comply with EMC.

We therefore try to summarize the most important EMC regulations in this learning sequence. However, we can only provide a brief overview from a European perspective here - We are sorry if this chapter is not relevant for you. **Be careful with all the information you find on the Internet**; our information is not complete either. Furthermore, these **laws are not set in stone but can change at any time**. There is a reason why the profession of lawyer exists.

3.3.1 STANDARDS ORGANIZATIONS

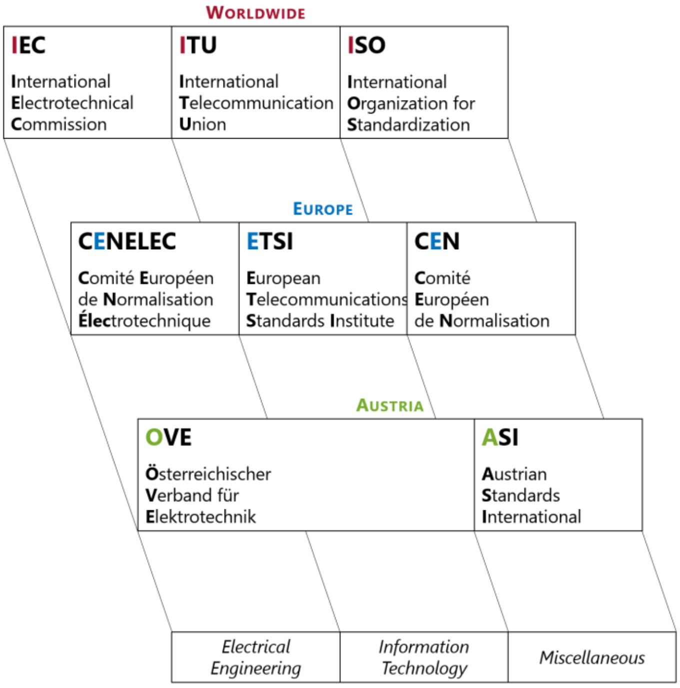
Ignorance does not protect from punishment. Unfortunately, international EMC regulations are not known to the general public. In addition, directives are not easy to find, and standards are often hidden behind paywalls.

National laws are published similarly in most countries: in an **official journal**. As soon as a new regulation is published in this journal, it is assumed that the general public is aware of it. For instance, the Official Journal of the European Union is the government gazette of the EU, and the Federal Register is the official journal of the US.

Project managers must be aware of the regulations that apply in the countries where the product will be sold. In addition, EMC regulations may also change within the project period. If a product does not meet the EMC requirements of the respective country, the product must not be sold there. Otherwise, penalties may be threatened.

Who sets the rules?

There are several international organizations that deal with standardization. Standards are not legislatively compliant by default. However, in case of Europe, if an **EU directive** is drafted, it **dominates over national law**. Thus, **standardization organizations have indirect political influence**. The following picture shows some of the most important standardization organizations in the world. In the field of electrical engineering, two of these possess major significance: **IEC** and **CENELEC**.

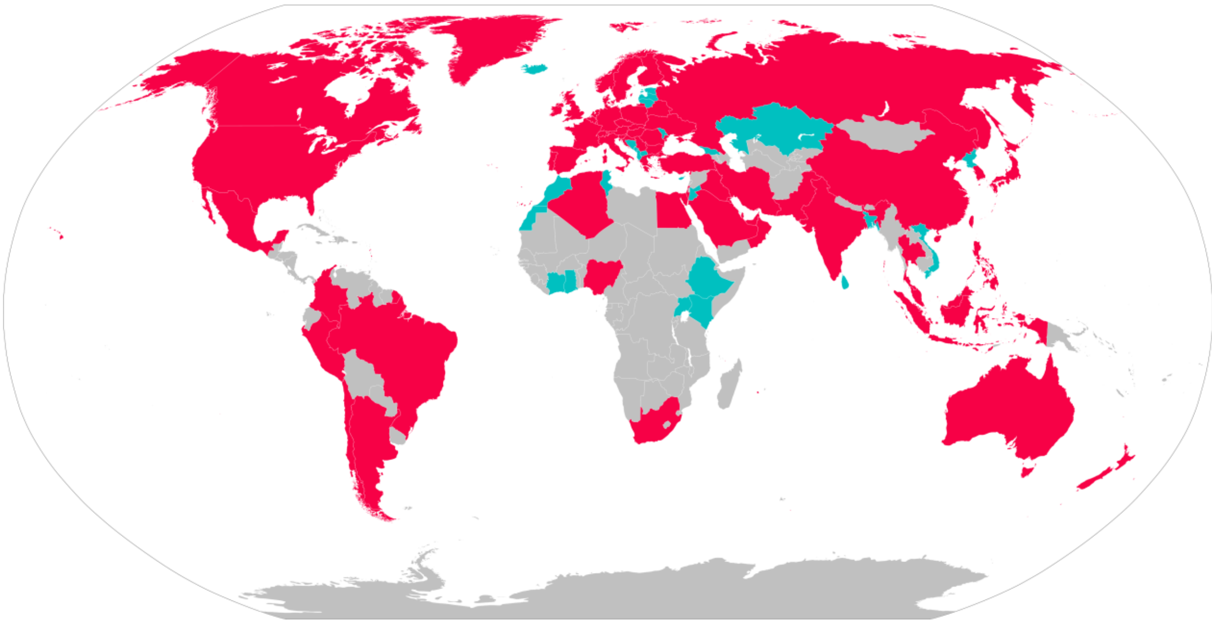


IEC - International Electrotechnical Commission

The world map below shows all countries participating in the IEC and therefore illustrates the global relevance of that organization. The IEC distinguishes its **national committees (NC; a single country)** between full members and associate members. An associate member only needs to pay reduced fees, but has full access to all documents. In return, these countries have only limited voting rights. Within an NC, a further distinction is made between P-members (participating) and O-members (observer).

In a vote, each P-member has a right to vote, but the vote is counted as 1/(number of P-members of the NC). A 2/3 majority of all P-votes is required for a motion to pass. To keep the story brief: **each IEC-NC has one vote. This system favors especially the many European countries.**

The map below shows all IEC members as of Feb. 2022. The up-to-date list can be found on the homepage of the IEC.



CENELEC - European Committee for Electrotechnical Standardization

The IEC standards have been transferred to national standards in over 130 countries. About **78% of all CENELEC standards originate from IEC standards** (as of 2014). Therefore, unfortunately, it is no secret that lobbying is also carried out.

The electoral system within CENELEC is different. CENELEC provides a weighted voting right with 3 to 29 votes per NC (a single country). There are 412 votes in total. **71% of the votes and 50% of the NCs must agree** to accept a proposal.

> ***The bottom line***
>
> *This page is intended to provide a small insight into the political system of international standardization communities. Usually, a standard of the IEC is adopted by CENELEC, which leads to automatic legislation in European countries. Therefore, lobbyists might attempt to influence the IEC.*

3.3.2 US MARKET

Since the administrative regulations of the US are published chronologically in the Federal Register, it is difficult to do research there. For this reason, the **Code of Federal Regulations** (CFR) exists to summarize the regulations in an organized form. This book is reprinted annually, with Titles 42–50 always updated on October 1, but an online version of the Code of Federal Regulations (eCFR) exists as well. This electronic version usually updates within 2 days of publication in the Federal Register, although the eCFR is not a true official version of the CFR.

For EMC, 47 CFR 15 (read as: **CFR - Title 47 - Part 15**) is very important. This is part of the Federal Communications Commission's (**FCC**) rules and regulations. This document defines quite precisely the limits that must not be exceeded.

47 CFR 15.1(a) states that in the US **every radiator must be licensed unless it complies with this regulation** or is subject to other exemptions.

47 CFR 15.3(k) clearly defines that any device or system with a **clock rate of 9kHz or higher** is a **digital device** which falls under the category of "unintentional radiator". Thus, almost **any system that includes a microprocessor** falls under this regulation.

47 CFR 15.3(h) and (i) divide digital devices into two categories:

1) **Class A**: the device is used in a commercial, industrial or business environment.
2) **Class B**: the device is used in a residential environment. The emission limits are **stricter by about 10dB** compared to Class A devices, because it is assumed that Class B devices are located in closer proximity to other radiators. EMC tests are mandatory.

47 CFR 2.803(h) generally states that a radio frequency (RF) device (i.e. 9kHz upwards) must not be *marketed* before the product has been compliance tested.

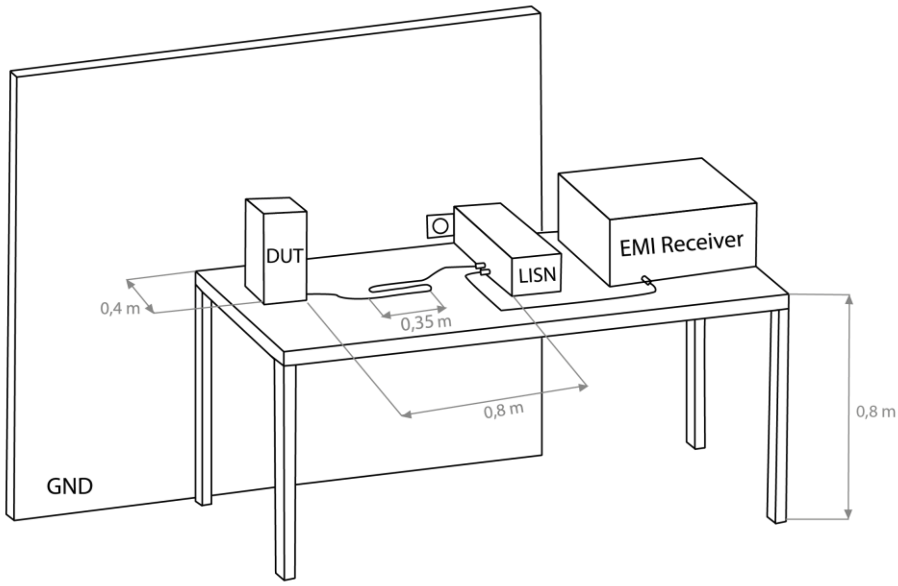
> ***In a nutshell***
>
> *As a rule, the manufacturer must verify compiance by testing the product. Verification is a **self-certification** where nothing needs to be submitted to the FCC unless explicitly requested. Compliance is ensured by random sampling by the FCC.*
>
> *So, before we are allowed to market our product, we have to perform EMC tests on a representative number of samples. If our product fails the final EMC tests, this usually means an enormous financial loss for the company. In order to avoid such unexpected surprises, we should design the product to be EMC-compliant right from the start and perform pre-compliance measurements regularly.*

Testing Emissions

The **FCC Part 15 Subpart B** requires compliance with certain limits regarding conducted and radiated emissions.

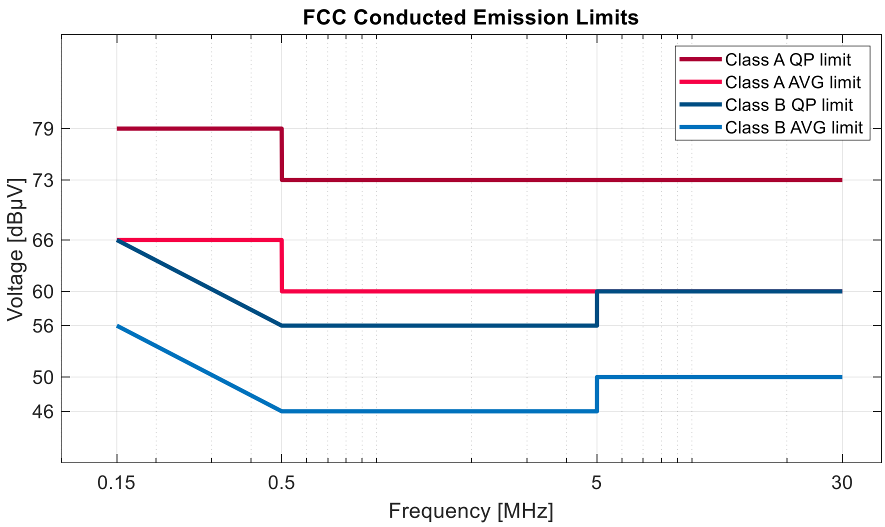
Conducted Emissions

This measurement setup has already been demonstrated in learning sequence *2.2 - Filtering*. The following picture summarizes the setup again.



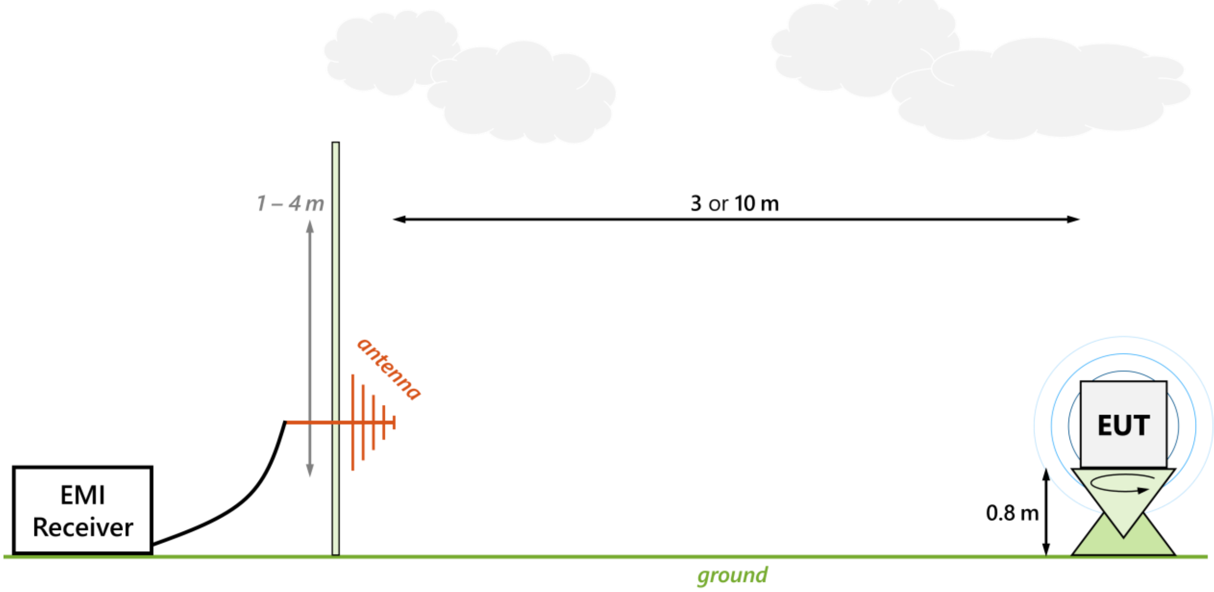
Adapted from: EN 55016-2-1:2014 (picture 11)

47 CFR 15.107(a) and (b) define the limits for conducted emissions. Don't be confused by the terms "LISN, EMI receiver, QP and AVG detector". We will explain these terms in the next learning sequence *3.3 - Test Equipment*.



Radiated Emissions

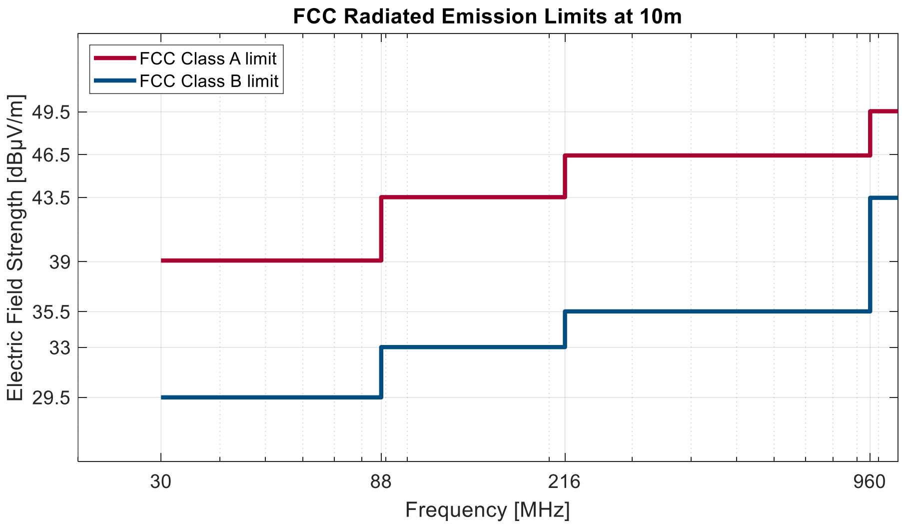
The measurement setup for radiated emissions is straightforward: we measure our DUT with an antenna from a standardized distance. Below is shown the so-called **o**pen **a**rea **t**est **s**ite (**OATS**). We will discuss this in more detail in the learning sequence *3.4 - Radiated Emissions*. Spoiler: an OATS is pretty much not used anymore. Instead, we usually measure inside a (semi-)anechoic chamber.



You may have noticed that the picture is showing an EUT instead of a DUT. This term shows up more frequently in standards and describes the DUT with additional electronics, e.g. a power supply.

- **DUT**: device under test
- **EUT**: equipment under test

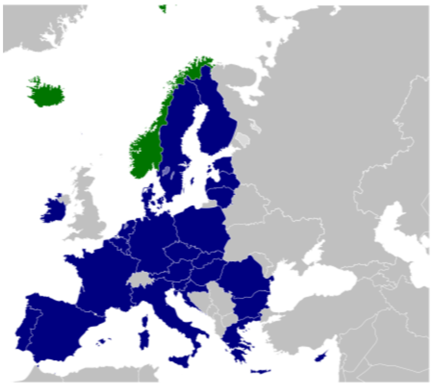
47 CFR 15.109(a) and (b) define the limits for radiated emissions. The graph below shows limit values in dB. Furthermore, the class B limit line is converted from 3m into 10m measurement distance r. A $\frac{1}{r}$ decrease of the electrical field strength is assumed, i.e. -10.5dB difference between 3m and 10m.



Testing Susceptibility

No explicit regulations for immunity testing exist. The U.S. government is relying on self-regulation here. Or would you buy a product that doesn't work because it's regularly disturbed by EMI?

3.3.3 EU MARKET



To sell a product within the **European Economic Area (EEA; map on the right)**, the product must comply with all applicable EU directives. By affixing the **CE marking** (conformité européenne), the manufacturer affirms the conformity that **all legal requirements** are fulfilled.

It is important to note that the **CE marking** is not a seal of quality or origin but **is a compulsory seal** to sell a product within the EEA. Not every product must have a CE mark but only those where there is a standard for it. For instance, a wooden beam does not carry a CE mark.

EMC directive

Whenever a new harmonized standard needs to be developed, the European Commission mandates one of the three European Standardization Organizations (CENELEC, ETSI, CEN). In the field of electrical engineering, the CENELEC is responsible for standardization. In this course, the directive 2014/30/EU (short name: **EMC directive**) is of relevance. Its legal text can be read in the official Journal of the EU. **Interestingly, this directive does not state any particular standard to use.** Instead, within *Annex I*, two very general requirements of a product are stated:

- The electromagnetic disturbance generated does not exceed the level above which radio and telecommunications equipment or other equipment cannot operate as intended.
- It has a level of immunity to the electromagnetic disturbance to be expected in its intended use which allows it to operate without unacceptable degradation of its intended use.

The first rule falls under the category "**Emission**", while the second rule is connected to "**Immunity**". However, it is not stated how these conditions must be fulfilled but refers to *Annex II* and *Annex III*.

And the rest the EMC directive?

The rest of the EMC directive defines some terms and defines obligations of **manufacturers**, **importers** and **distributors**. In addition, the directive states that technical documentation must be kept for at least 10 years and that address of the manufacturer and importer must be included in the operating instructions. The **manufacturer must ensure conformity**, and the **importer must ensure** that the manufacturer has carried out the conformity assessment procedure according to *Article 14*. But also the **distributor must ensure** that the product is attached by all required documentation and must check the CE imprint on the product.

<u>The EU EMC directive in a nutshell</u>

The EMC directive states that a device must neither disturb other devices, nor be interfered by other devices; i.e. unlike the US market, a product must also be robust against EMI. However, the directive doesn't state how both criteria must be met and doesn't set any limits. ***In most cases, we will try to meet a given standard in order to ensure EMC compliance.*** *If no product-specific standard exists, the generic standards must be applied. Nevertheless, it's <u>not mandatory by law</u> to perform EMC tests for most consumer electronics; Signing a declaration of conformity means that the product will pass all EMC tests if we <u>would</u> test it.*

<u>Declaration of conformity</u>

After performing compliance measurements (we don't need to perform any measurements by law) but before being allowed to affix the CE mark, an **EU declaration of conformity** must be drawn up in one of the official languages of the EU. After signing it, **the manufacturer** (or an authorised representative, or an importer, but not the test house) **declares that all relevant EU directives are complied with and that he:she takes full responsibility for its compliance**. This document must be stored for at least 10 years and must be made available to the authorities immediately upon request. If the regulations change after market launch, the product may have to be withdrawn from the market. The declaration of conformity is therefore often (but not always, e.g. for medical devices) a **self-certification process**.

There are basically **two ways in order to comply with the EMC directive**:

1) Meet a given harmonized standard.
2) Define your own EMC tests.

It is best to **use harmonized standards** as this leads to a **presumption of conformity** for your product. However, this is not mandatory (EMC directive, *Annex II*, 3d). You could also define your own EMC tests to comply with **self-determined criteria**. This is mainly used if no harmonized standards exist, i.e. for innovative products. However, this regulation could also motivate a manufacturer not performing any EMC test measurements at all but still issuing a declaration of conformity. If authorities find a failure to comply with the EMC directive, **there are high national fines and prison sentences!**

How does such a declaration look like?

Annex IV of the EMC Directive provides a template for the mandatory information to be included in this declaration. The following picture shows a very simple example how such a declaration could look like. Please note that **the declaration of conformity must contain different contents depending on your product**. Please check this before using a template from the internet!

EU Declaration of Conformity

Issuer:

Graz University of Technology
Institute of Electronics
Inffeldgasse 16/I
8010 Graz, Austria

Product:

Name: Lorem ipsum
Serial number: 1234 5678
Description: dolor sit amet

Product photo:

?

Further details:

- consetetur sadipscing elitr
- sed diam nonumy eirmod

I declare and take full responsibility that the product described above is in conformity with the essential conditions of the following legislation:

- **2014/30/EU** Electromagnetic Compatibility (EMC) Directive
- [...]

via the technical standards and specifications stated below:

- **EN 61000-3-2:2019** – Electromagnetic compatibility (EMC) – Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤16 A per phase)
- **EN 61000-3-3:2013+A1:2019** – Electromagnetic compatibility (EMC) – Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤16 A per phase and not subject to conditional connection
- **EN 61000-6-1:2007** – Electromagnetic compatibility (EMC) – Part 6-1: Generic standards. Immunity for residential, commercial and light-industrial environments
- **EN 61000-6-3:2007+A1:2011** – Electromagnetic compatibility (EMC) – Part 6-3: Generic standards. Emission standard for residential, commercial and light-industrial environments
- [...]

Graz, December 24, 2021
(place, date)

Ko Odreitz, [authorized position, e.g. CEO]

3.3.4 IMPORTANT STANDARDS

This page is relevant for the EU market. Here, a distinction must be made between directives and standards.

- **Directives** are the legal requirements to sell a product within the EEA. The EMC directive is written in a very general way without specifying how to fulfill this directive.
- **Standards** provide the **usual way to meet these legal requirements**. The difficulty here is in identifying the applicable standards. Unfortunately, a standard is only available for purchase. You don't need to buy any standard for this course. In case you are a local student at Graz University of Technology, you can download the most important standards for free.

- Product-specific standard: We must perform a research in order to determine whether a corresponding standard exists for our product. We then have to meet this standard in order to declare our product as EMC compliant.
- Generic standard: **In case no product-specific standard exists, the so-called generic standards must be used.**

Generic standards

The **EN 61000** is the harmonized electromagnetic compatibility standard. It consists of the following parts:

- Part 1: General
- Part 2: Environment
- **Part 3: Limits**
- **Part 4: Testing and measurement techniques**
- Part 5: Installation and mitigation guidelines
- **Part 6: Generic standards**
- Part 9: Miscellaneous

Part 3 specifies two requirements that **every product must meet if mains connections exist**: Harmonics and Flicker (voltage fluctuations).

Limits for...	Harmonics	Flicker
Normal environment	EN 61000-3-2	EN 61000-3-3
Industry environment	EN 61000-3-12	EN 61000-3-11

List of usual EMC tests

***Part** 4 specifies many immunity tests. The most important EMC tests are listed in this box.*

- ***Radiated emissions** (EN 55016-2-3, learning sequence 3.4 - Radiated Emissions)*
- ***Conducted emissions** (EN 55016-2-1, learning sequence 2.2 - Filtering)*
- ***Radiated immunity** (IEC 61000-4-3, the opposite of radiated emissions)*
- ***Conducted immunity** (IEC 61000-4-6, you need two CDNs for this)*
- ***Burst immunity** (IEC 61000-4-4, this is about fast transients)*
- ***Surge immunity** (IEC 61000-4-5, this is about high power)*
- ***Harmonics & Flicker** (IEC 61000-3-2 & -3, this is about voltage fluctuations)*
- ***ESD direct & indirect** (IEC 61000-4-2, learning sequence 3.5 - Electrostatic Discharge)*

Part 6 specifies the **generic standards** where we have to distinguish between "normal" (residential, commercial and light-industrial) and "industrial" environment; similar to Class B and Class A devices in the US.

Generic standard for...	Immunity	Emission
Normal environment	EN 61000-6-1	EN 61000-6-3
Industry environment	EN 61000-6-2	EN 61000-6-4

The generic standards specify which tests must be performed and which limits must be met; however, they refer to other standards in which the test setups are described.

Product-specific standards

The generic standards are only applicable in case no product-specific standard exists; but many product-specific standards exist. Many important standards are listed below:

Product standard for...	Emission	Immunity
Industrial, scientific and medical equipment	EN 55011	-
Sound and television broadcast receivers and associated equipment	EN 55013	EN 55020
Requirements for household appliances, electric tools and similar apparatus	EN 55014-1	EN 55014-2
Lighting	EN 55015	EN 61547
Information technology equipment	EN 55022	EN 55024
Medical electrical equipment	EN 60601-1-2	
Adjustable speed electrical power drive systems	EN 61800-3	

Different product categories may require different measurement methods including different limit lines. So, if we design a new product, we need to do a lot of research first on order to determine which standards we must meet. Such research often begins online.

Syntax of European Norms (EN)

You may have noticed that all standards above start with "**EN**". This abbreviation stands for "European Norm". The numbers from EN 60000 to EN 69999 are reserved for CENELEC standards which have been adopted by IEC standards with possible modifications.

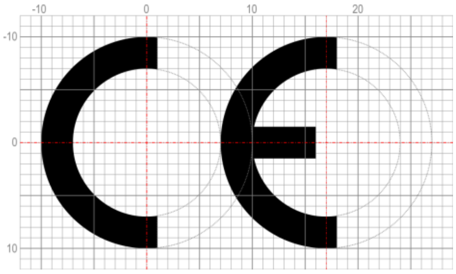
EU governments must transpose European standards into national laws. For this, each European country is allowed to nominate one CENELEC national member. This organization is responsible to implement the "EN" standards as national standards. Therefore, a standard can be found under the following designation in Austria:

OVE EN IEC 61000-6-3

- **OVE** is the name of the CENELEC national member of Austria.
- **EN** indicates that this is a European standard which must be implemented in national standards.
- **IEC** indicates that this standard has been adopted in part or in whole by the IEC organization.
- **61000** is the code number of the standard, here: the "Electromagnetic compatibility (EMC)" standard.
- **-6** specifies the part of the standard, here: the "Generic standards".
- **-3** specifies the subpart of the standard, here: the "Emission standard for residential, commercial and light-industrial environments".

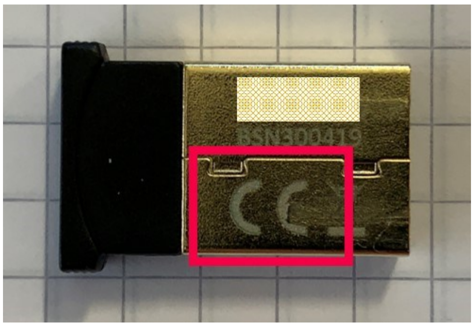
3.3.5 CE, FCC, VCCI

The **CE mark is not a quality mark** but a necessary seal to be allowed to sell the product within the EEA. Both, the 2014/30/EU *EMC directive* and the 2014/35/EU *Low Voltage Directive (LVD)*, state that the **CE mark must be affixed to the product by the manufacturer** (or by his:her EEA authorized representative). The marking must be shown on the packaging, on the warranty certificate, on the operating instructions, and on the product itself if possible. In case the product is not subject to a corresponding standard, then no CE mark is allowed to be affixed in order to avoid confusion. For instance, no CE mark is attached on a tissue or handkerchief.



CE marking proportion requirements; a minimum height of 5mm is necessary

Look at the following photos where the CE mark is attached to the product. Without a CE mark, it's not allowed to sell these products within the EEA. The CE mark is not exclusive for electronic products; an FFP2 mask also has a CE mark attached.




FCC and VCCI marking

A wide variety of marks can be found on all products. While the CE mark is important for import and sale within the EEA, the FCC mark is important for similar purposes within the USA. The VCCI mark is somehow the equivalent in Japan. However, the VCCI or "Voluntary Control Council for Interference by Information Technology Equipment" mark is not a certification mark. As its name suggests, its scheme is voluntary but provides good international comparability.

- **CE mark** ... required for sale in the **EEA** (= EU + Norway + Iceland + Liechtenstein)
- **FCC mark** ... required for sale in the **USA**
- **VCCI mark** ... voluntary; from **Japan**

Presumption of conformity

It's not always mandatory to perform EMC tests. Suppose we want to sell a **custom PC** within the EEA. Numerous combinations exist with different motherboard, CPU, GPU, RAM, HDD, SSD, fans, power supply and casing. But we don't have to perform new EMC test measurements with each individually assembled PC. After all, such measurements in an **accredited test house usually cost more than 1000€**.

All individual components in our custom PC are already CE marked. These were installed in a "standard setup" when they were EMC tested. Therefore, we can do a **presumption of conformity** for our custom PC. This presumption of conformity is very often applied. Meeting the EMC directive by complying with harmonized standards is ultimately a conformity assumption itself. Take a look inside your PC. You will find CE, FCC and VCCI labels on most components.

3.3.6 STEPS TO SELF-CERTIFICATION

On the one hand, complying with the EU EMC directive is straightforward, because it is a self-certification process in most cases. On the other hand, performing the process correctly is anything but simple. Therefore, we would like to recap the most important steps of a usual certification process.

Step 1: Identify the applicable directives

In the EU it is necessary to comply with the 2014/30/EU EMC directive. Please don't forget that there are also other directives to comply with.

Step 2: Identify the requirements of these directives

The EMC directive states at *Annex I* that "*Equipment shall be so designed and manufactured [...] that (a) the electromagnetic disturbance generated does not exceed [...] (b) it has a level of immunity [...]*". This directive doesn't tell us how to prove compliance. However, we can make a conformity assumption by meeting harmonized standards.

Step 3: Identify the way (i.e. standards) to achieve conformity

An expert might need 10 minutes for this step; as a beginner, it can take several days. The best way to get started is to read the EN 61000. If product-specific standards exist, they must be applied. Otherwise, the generic standards must be applied. Conducted and radiated emissions and immunity tests must be performed.

Step 4: Clarify if it is a self-certification process

In certain cases, a third party is required for the certification process. You aren't allowed to sell a medical device without third-party review, for instance.

Step 5: Perform the measurements

Usually, it's in your interest as an EMC technician to perform preliminary worst-case measurements in your company. This is the best way in order to estimate the risk of failing the final EMC tests. If there is no measurement equipment available in-house, cheap supporting offices for startup companies exist; e.g. our Institute of Electronics offers supporting EMC activities as well. The final EMC tests are usually performed inside an accredited test house, as its test reports are reliable and are accepted by the authorities. These measurements, however, are usually expensive (1,000$ upwards).

Step 6: Make a declaration, archive all relevant documents (technical file) and affix the CE mark

Your technical documentation should include every aspect relating to conformity. You must provide this documentation to the authorities immediately on request.

3.3.7 KNOWLEDGE CHECK

Which statements are true?

- ☐ EMC laws will never change.
- ☐ The IEC has 89 member countries (full and associate) with additional 81 affiliate countries (Feb. 2022).
- ☐ The main task of CENELEC is the definition of EMC standards.
- ☐ By law, performing EMC tests for the European market is optional.
- ☐ Products for residential use have stricter limits.

Eyeglasses have a CE mark.

- ○ True
- ○ False
- ○ What does this have to do with EMC?

Which statements are true?

- ☐ The limit values specified in the EMC directive must be complied with.
- ☐ In case no product-specific standard exist, the generic standards must be used.
- ☐ EN 61000 explains the measurement setups to be performed.
- ☐ A product must be robust against EMI to be allowed to be sold in the EEA.
- ☐ Iceland is an EEA member.

3.4 RADIATED EMISSIONS

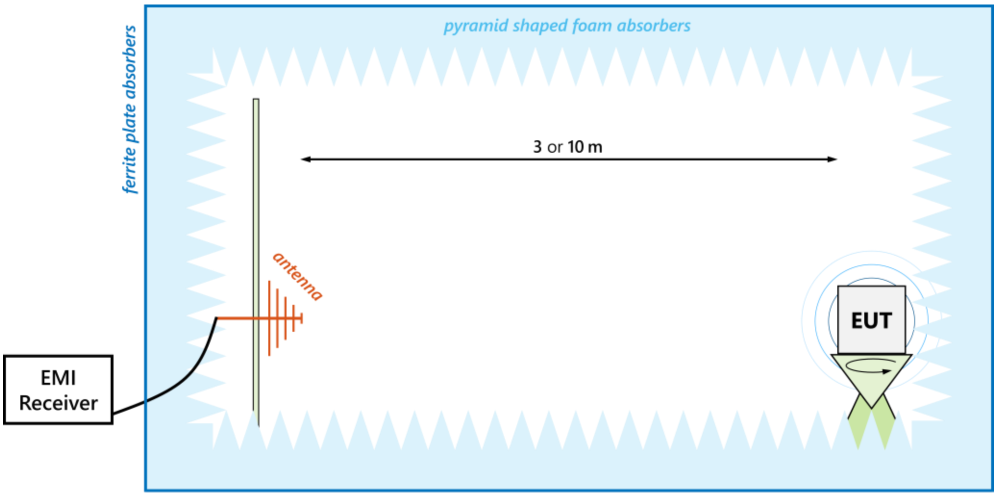
Performing radiated emission measurements is the most basic test. Final measurements usually take place in an accredited test house, since a required measurement chamber including equipment might cost 1,000,000$. Nevertheless, it is also possible to perform pre-compliance measurements for less money. After all, one of the main tasks of us EMC technicians is to ensure that final compliance tests will pass with a high degree of confidence. In addition to an EMC-aware design, this also includes preliminary testing.

In this learning sequence, we first look at why a measurement chamber is so expensive. Afterwards, we will go on a trip to an accredited test house in order to have measurements performed according to EN 61000-6-3. Thereby we also learn how an official test report looks like. Finally, we demonstrate a measurement on IC level in order to demonstrate how different radiated emissions can be measured.

3.4.1 SEMI-ANECHOIC CHAMBER

In learning sequence *3.2 - International Regulations* we have already introduced the OATS. In a nutshell: we place our DUT somewhere and measure from 3 or 10m distance with an antenna. The main disadvantage of this method is that we are surrounded by electromagnetic radiation. Consequently, this ambient noise is unintentionally measured by our antenna and thus falsifies the measurement result.

In order to obtain reproducible results, a building is constructed around this measurement setup: the so-called **anechoic chamber**. This room is designed in such a way that no radiation can penetrate from outside (Faraday cage). An-echoic means non-reflective; i.e. the walls inside do not reflect anything but absorb everything. This simulates the DUT radiating in free space.



How do we achieve 100% absorption?

We will not achieve 100% absorption. To ensure that the walls are as absorbent as possible, they are covered with pyramid-shaped foam which is impregnated with carbon and iron. For a good absorption, the impedances of foam and free-space $Z_0 \approx 377\,\Omega$ must be matched to each other. A good conductor $Z_L = 0$ or insulator $Z_L \rightarrow \infty$ would reflect or transmit respectively.

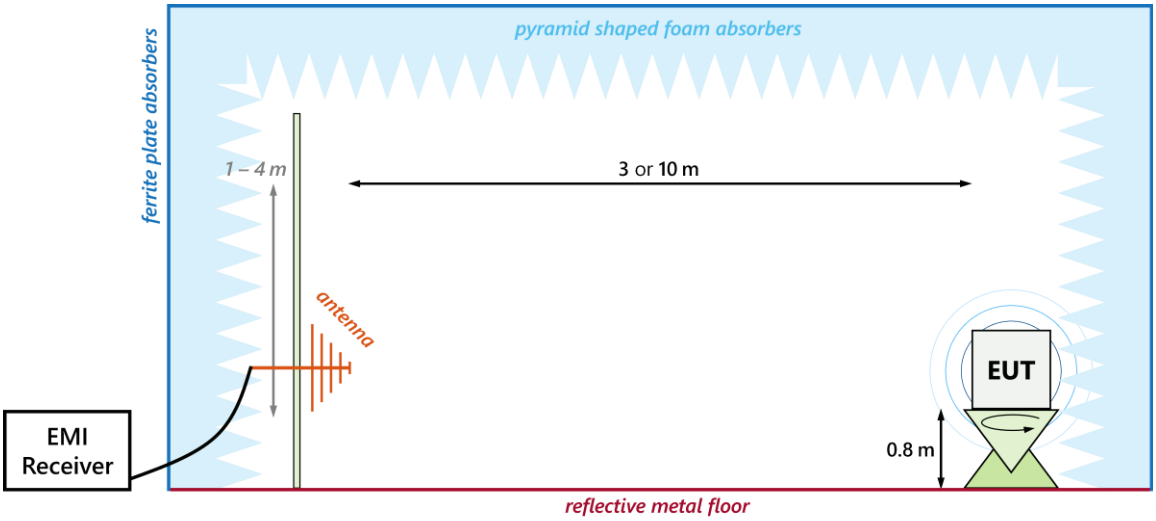
In addition, the shape of the pyramids has a major impact on the attenuation of the reflections. The remaining EM waves scatter incoherently into the pyramid structure for destructive interference as good as possible. The pyramid angle is chosen in order to achieve as many reflections into the structure as possible. With each bounce, another part of the wave energy is converted into heat energy.

One problem with the pyramid shape is that they would have to be very large (>50cm height) in order to attenuate frequencies below 500MHz well. Therefore, a professional anechoic chamber is covered with additional **ferrite plates underneath the foam**. These provide good absorption below 1GHz. Thus, the pyramid-shaped foam can be kept at an acceptable size.

Semi-anechoic chamber and height sweep

A measurement in an anechoic chamber is not the same as a measurement in an OATS. When measuring in an open area test site, the ground tends to be reflective. For this reason, the floor of an usual test chamber is also reflective, i.e. a metal floor instead of pyramids made of foam. We call this room: **semi-anechoic chamber**. Due to the reflections on the ground, there is contructive or destructive interference of the EM wave at the measuring antenna. So, in the extreme cases we can measure about twice the field strength (+5.5 dB), or no emissions at all.

Regulators are usually interested in evaluating the highest possible risk that electromagnetic waves can cause. This highest EMI is determined by adjusting the height of the measuring antenna. The highest measured value is then recorded in the measurement report ("max hold" during the scan). The animation below shows you how the reflected wave interferes with the direct wave.

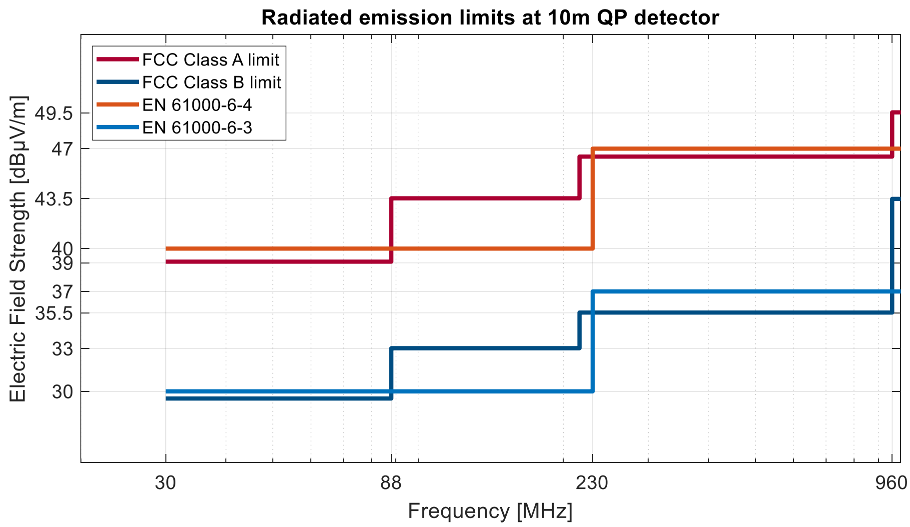


EN 61000-6-3

On the next page we will show you how a final EMC test in an accredited measurement house is performed. In our scenario, we want to sell a consumer alarm clock without mains connection and without radio connection. So, it's the most basic product where no product-specific standards exist, i.e. we have to apply the generic standard **EN 61000 Part 6**. **Subpart 3** and **Subpart 4** define the **maximum emission limit lines** (chapter 11, table 1). Typical measuring distances are 3m and 10m; far field conditions usually still apply for frequencies above 30MHz at 3m antenna distance, but this depends on the size of the DUT.

If the antenna measures the DUT at a distance of 10m inside a semi-anechoic chamber, the following quasi-peak values must not be exceeded. These limits for the European market differ from those of the FCC. In case the highest internal clock frequency is higher than 108MHz, additional measurements with peak and average detector are required. The standard defines the rules quite clearly.

Unfortunately, EN 61000-6-3 does not explain *how to* perform this measurement. The measurement setup is described in EN 55016-2-3 (**CISPR 16-2-3**). The measurement equipment must comply with CISPR 16-1-1 and CISPR 16-1-4; no standard is accessible free of charge, but you can download them in case you are a local student of TU Graz.



3.4.2 SEIBERSDORF LABORATORIES

How do final EMC measurements look like in an accredited test house? On this page we measure radiated emissions according to EN 61000-6-3 in the most important test house in Austria, Seibersdorf Laboratories.

An accredited test house is usually contacted in the final phase of a project. A test house usually offers limited support, i.e. they will not troubleshoot with you in case your product fails. If you need help in EMC questions during the product development, you might seek advice somewhere else, for example at our Institute for Electronics. Usually, a **preliminary discussion via telephone** takes place before you send your product to the test house. This allows the test house to plan its preparations in advance.

Join us on our trip to Seibersdarf Laboratories. In the first part, we will review the basics of a semi-anechoic chamber and make a preliminary phone call with the accredited test house.

EMI Measurements at Seibersdorf Laboratories
https://youtu.be/t_YU7JYr8Yc

<u>**06:21 - 15:15 | Visit at Seibersdorf Labor GmbH**</u>

We are at Seibersdorf Laboratories. Please remember that your product should already be EMC optimized when you perform measurements in an accredited test house. Only for educational purposes, we have added an error on purpose in order to demonstrate how crucial an EMC-aware design is. The measurements are also not carried out by yourselves, but by a trained measurement specialist.

<u>**15:16 - 19:07 | Official EMC test report**</u>

A few days after the measurement, you will receive the **official test report** by mail. This must be included with your technical documentation. This is the official proof of how many emissions our product emits. This allows us to make the assumption of conformity with the EMC directive. Please keep in mind that measuring radiated emissions is only one point to comply with the EMC directive. Depending on your product, many more tests are required (see Summary of this learning sequence).

Accordingly, we can comply with the EU EMC directive. Keep in mind that we have to comply with other directives as well before we are allowed to sell our product within the EEA. For the US market, on the other hand, different rules apply again.

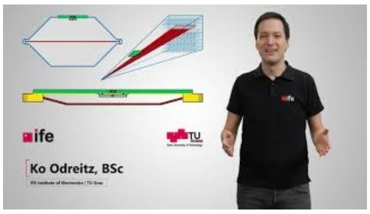
3.4.3 SMALLER CHAMBERS

The measurement of radiated emissions doesn't necessarily require an OATS, a semi-anechoic- or a full anechoic chamber. Smaller chambers for cheap in-house preliminary measurements exist as well. Although a measurement in such a chamber cannot be used for certification, it often provides us EMC engineers a solid **worst-case estimation**. In the picture below, a small chamber (MAC 2) is shown which we use sometimes at the institute.

Since the DUT is placed much closer to the measurement antenna, we must set the limit lines less strictly - We also increase our limit lines by 10dB (EU) or 10.5dB (US) if we measure at 3m distance instead of 10m distance inside a semi-anechoic chamber. The main issue with distances below 3m is that frequencies above 30MHz are **not in far-field anymore**. Manufacturers of those small measurement chambers therefore specify a valid space where far-field conditions are somehow *simulated*. It is important that you place your DUT accordingly.

In addition to the lower cost, a key advantage of smaller chambers is that they can be used for **radiated immunity tests** easily. An immunity test is performed the other way round to the emission test: the antenna transmits a standardized signal while the DUT is monitored in order to see whether it is still working properly. In a small chamber you need significantly less signal power compared to a measurement inside a 10m semi-anechoic chamber.

In the video below, we would like to give you an impression of how emission measurements are carried out at **chip level**. In the video we also show the so-called GTEM cell. This can be used both at chip level and at system level.



Electromagnetic Emission Measurements of ICs - TEM Cell and IC Stripline
https://youtu.be/slIM5zabaH4

3.4.4 KNOWLEDGE CHECK

Due to copyright, a screenshot of the EN 61000-6-3 standard cannot be copied here. Instead, the relevant part of the standard is expressed here in similar wording.

Chapter 11: Measurement requirements for interference emission

Table 1 - Emitted interference - housing

Tab	Connection	Frequency range	Limits	Basic standard	Applicability	Comments
1.1	Housing Measuring equipment: open area test site OR semi-anechoic chamber	30MHz to 230MHz 230MHz to 1000MHz	30dBµV/m QP at 10m 37dBµV/m QP at 10m	Equipment must comply with section 4 of CISPR 16-1-1. Antennas must comply with section 4.4 of CISPR 16-1-4. Measureing site must comply with section 5 of CISPR 16-1-4. Measurement method must comply with section 7.2 of CISPR 16-2-3.	See footnotes (a), (b) and (e)	Measurements may be performed at 3m measurement distance using limits increased by 10dB. The height of the antenna must be varied between 1m and 4m as specified in CISPR 16-2-3. Additional guidance on the measurement procedure can be found in section 7.3 and 8 of CISPR 16-2-3.
1.2	Housing Measuring equipment: full anechoic chamber	30MHz to 230MHz 230MHz to 1000MHz	[...]	[...]	[...]	[...]
1.3	Housing Measuring equipment: TEM waveguide	30MHz to 230MHz 230MHz to 1000MHz	[...]	[...]	[...]	[...]
1.4	Housing Measuring equipment: open area test site OR semi-anechoic chamber OR full anechoic chamber	1GHz to 3GHz 3GHz to 6GHz	[...]	[...]	[...]	[...]

(a) For devices containing components operating at frequencies below 9kHz, measurements need only be made up to 230kHz.

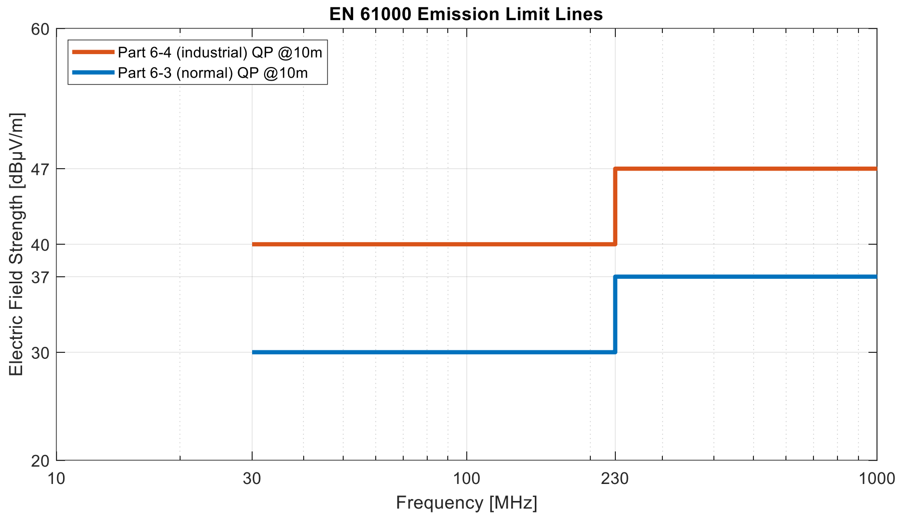
(b) The device is presumed to meet the requirements for radiated emissions if it satisfies the requirements of one or more of table sections 1.1, 1.2, or 1.3.

(c) If the highest internal clock frequency is below 108MHz, the measurement must only be performed up to 1GHz. If it is between 108MHz and 500MHz, it must be measured up to 2GHz. If it is between 500MHz and 1GHz, it must be measured up to 5GHz. If it is higher than 1GHz, measurements up to 6GHz must be performed.

(d) [...]

(e) In the case of double-defined frequencies, the lower limit value applies in each case.

The limit lines in the Seibersdorf video are at 40 and 47 dBµV/m although the table above says 30 and 37 dBµV/m. Why is that?



- ○ Because the limits of the industrial standard are used here. The orange line shows these exactly at 40 and 47 dBµV/m.
- ○ Because the blue line shows the peak values, not the quasi-peak values. Therefore, the limit must also be set 10dB higher.
- ○ Because the antenna in the video was only 3m away from the DUT. Therefore, higher measured values are to be expected and the limit lines must be increased accordingly.
- ○ Seibersdorf Laboratories has clearly made a mistake here.

Suppose we would measure inside a chamber where DUT and antenna are 5m away from each other instead of 10m. By how much dB can we increase the limit lines?

A few statements about the EN 61000-6-3 measurement setup shown in this learning sequence. Which are true?

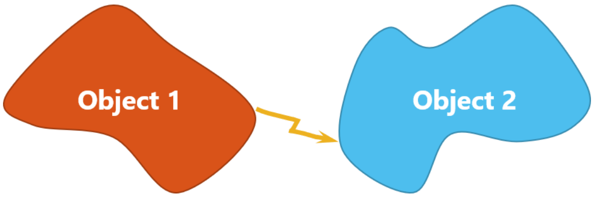
- ☐ The EU's limit lines are stricter than those of the US.
- ☐ The height of the antenna must be varied between 1 and 4m. The peak value is noted in the test protocol.
- ☐ The antenna must be oriented once horizontally and once vertically. Both antenna positions are recorded in the test protocol.
- ☐ Emission tests at chip level are also performed inside a semi-anechoic chamber according to EN 61000.

A few statements about absorption inside an anechoic chamber. Which are true?

- ☐ The pyramid-shaped foam of an anechoic chamber is an excellent insulator.
- ☐ The blue color of the pyramid-shaped foam provides better absorption.
- ☐ The larger the pyramidal structure, the lower frequencies can be absorbed.
- ☐ Sometimes additional ferrite plates are placed between metal wall and foam in order to absorb frequencies below 1GHz.

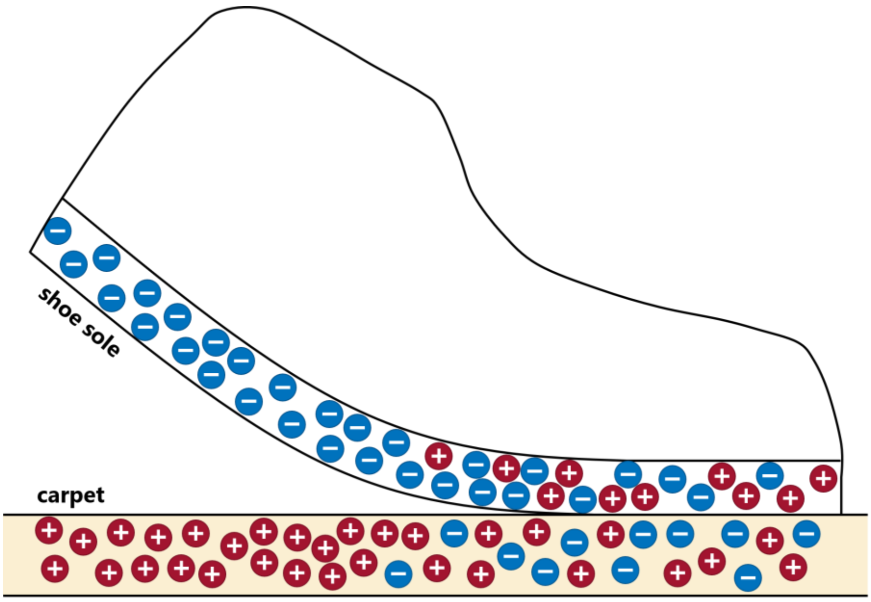
3.5 Electrostatic Discharge (ESD)

Sometimes we hear it, sometimes we see it, sometimes we feel it. It's about those little annoying sparks, often after you've walked on a carpet. In technical jargon, this effect is called **electrostatic discharge**, or ESD. Such a discharge is created very simple. Basically, only two objects with different electrostatic potentials are needed. If the objects are brought together, a spark occurs.



3.5.1 Triboelectric effect

Almost every ESD problem is caused by the triboelectric effect. Tribocharging means the separation of electric charges. This happens when **two different materials are brought together and then separated again**.

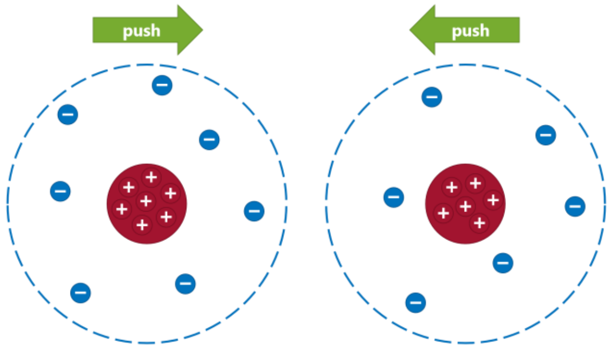


Very simple model

In the picture above, you can see that certain regions of the shoe and the carpet are charged.

Step 1: push both objects together

Thanks to adhesion, electrons can move from one object to another in order to equilize their electrochemical potential.

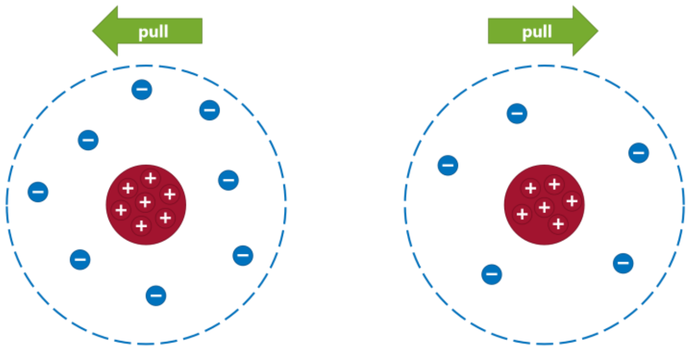


7 protons
7 electrons

6 protons
6 electrons

Step 2: separate both objects

When separated, some electrons tend to stay with the new object. Rubbing leaves significantly more electrons with the other object since the objects touch and separate again very often.



7 protons
8 *electrons*

6 protons
5 *electrons*

Positive or negative?

The voltage level and the polarity strongly depend on the materials of the two objects. The following triboelectric series shows very roughly how much a material charge relative to another material. The farther away two materials are from each other in the list, the stronger the charge exchange. This is the reason why people are more likely to experience ESD when wearing plastic (polyester) clothing than when wearing cotton clothing.

Teflon (PTFE)	most **negatively** charged
Silicon (Si)	
Plastic wrap	
Polyester	
Cu, Ag, Au	
Rubber	
Wood	
Cotton, Wool	no charge
Paper	
Aluminium (Al)	
Cat fur	
Leather	
Glass	
Nylon	most **positively** charged
Skin and hair	

Did you know…

*…that **lightning** is an electrostatic discharge as well? For this, warm air must rise very quickly. The exact explanation is quite complicated and in fact not 100% researched. But basically, there is a lot of friction and charge separation within the thundercloud. At some point, the insulation of the air is no longer sufficient and discharge occurs. It is not always a cloud-to-earth lightning but can be an earth-to-cloud lightning as well.*

3.5.2 Triboelectric effect cont'd

The voltage level depends very much on the environmental conditions. In general, however, we are talking about several kilovolts. Here are a few examples:

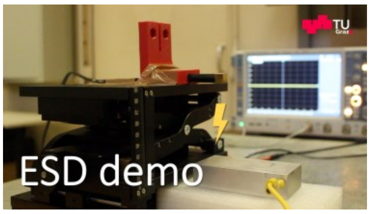
- **2000 V** … Threshold of perception
- **4000 V** … You can hear the discharge. Some people already experience this as uncomfortable.
- **8000 V** … You can see the discharge.

Influence of humidity

Humidity is a critical parameter. We have not measured these values, but this table should show you that high humidity massively reduces the risk of ESD.

Humidity	20 %	80 %
General activities in the office	4000 V	300 V
Put on or off plastic clothes	7000 V	600 V
Intensive office chair race with non ESD-safe chairs	20000 V	1500 V

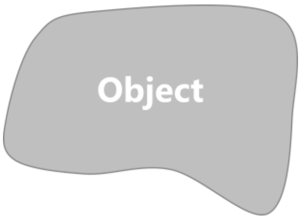
Watch the video below to better understand the triboelectric effect and ESD.



What is ESD - Electrostatic Discharge
https://youtu.be/ImucVxVLI8c

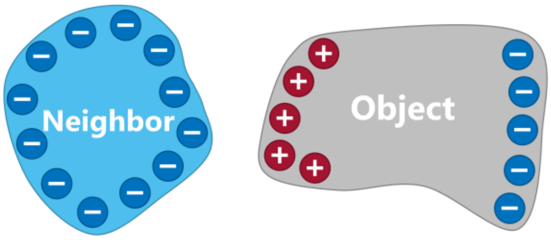
3.5.3 Electrostatic induction

Since almost every ESD problem is due to the triboelectric effect, we will only briefly discuss **electrostatic induction** (also known as electrostatic **influence**). For this purpose, let's consider an arbitrary uncharged conducting object. Its charges are freely distributed.



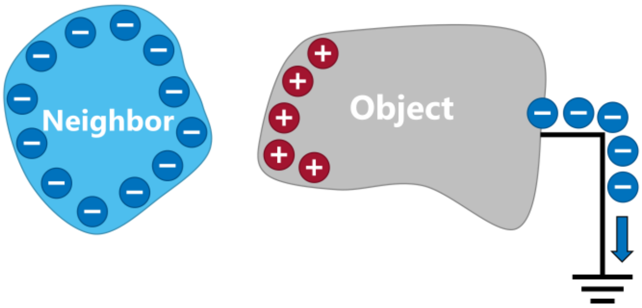
Step 1: Bring a charged neighbor next to our object.

The mobile electrons are now driven away and change their positions towards the right end of our object. This creates a positively charged region and a negatively charged region within our object. However, this does not change the total charge on our object. In case we remove our neighbor, the charge carriers would be randomly distributed in the object again.



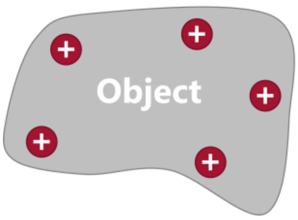
Step 2: Attach a conductor to ground.

However, if we now connect our object to ground, then the electrons flow away. This happens because the ground is a huge reservoir of charge carriers, both positive and negative.



Step 3: Remove the ground connection.

If we remove the conductor again, our object remains loaded. In our case, the object is left with a net positive charge.



However, technical ESD problems due to this phenomenon are rather rare.

3.5.4 Measures

ESD may seem like nothing more than an annoying everyday situation to us. Unfortunately, this does not apply to integrated circuits (ICs). **A single 100V discharge might irreversibly damage the component**, although most components will survive such low voltage levels. Ignoring ESD in product design can lead to poorer yield during fabrication, many returns from the customer, and extensive troubleshooting. Or in other words:

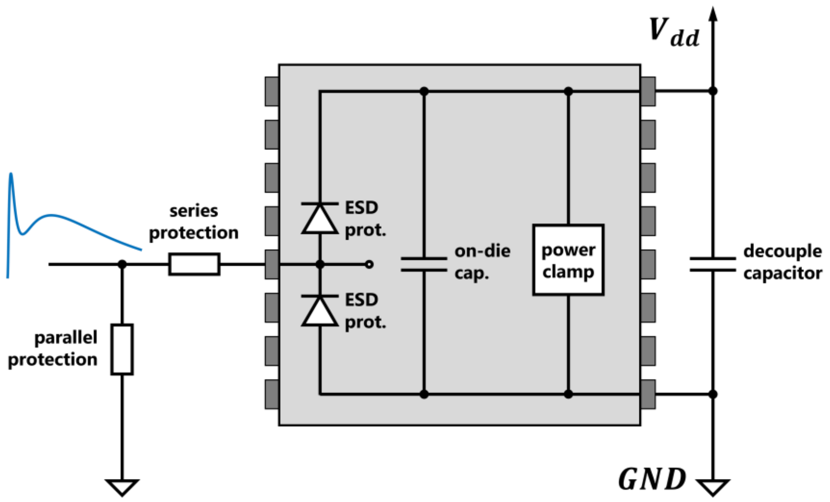
- high costs,
- project delays, and
- unsatisfied customers.

It is very important to prevent ESD damage. So, we have to ensure protection at various levels.

IC level protection

IC level means that we are looking at the silicon chip. Various topologies for the internal protective circuit exist. Mostly, however, this consists of at least two diodes connected in series, as shown in the picture below.

- A positive ESD pulse is discharged via the upper diode.
- A negative ESD pulse is discharged via the bottom diode.



System level protection

On system level, we consider protection components for the whole circuit. Here, a distinction is made between protection elements that are connected in series and elements that are connected in parallel. Components written in gray are not designed for ESD protection.

Over voltage protection (in parallel)	Over current protection (in series)
Transient-voltage-suppression (TVS) diode	Resistor
Varistor (VDR, MOV)	Thermistor (PTC)
Gas discharge tube (GDT)	Fuse

Don't get confused by all these names. The choice of the appropriate parallel protection element (transient suppressor) depends on how fast and how much current must be dissipated. But in general, they all have a similar task: they have to protect our circuit in case of overvoltage.

	TVS diode	Varistor	Gas tube
Turn-on time	ps	ns	µs
Power dissipation	low	medium	high
Leakage current	nA	nA	fA
Intrinsic capacity	0.1 pF to 100 pF (low)	5 pF to 100 nF (medium)	fF (very low)

Control of the surroundings

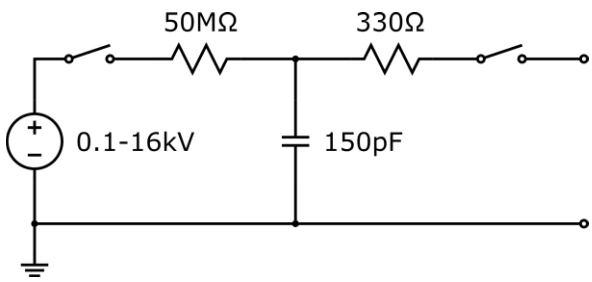
Finally, many laboratory guidelines exist as well to make working with electronics ESD-safe. Check out the list below. Maybe you already know some of the measures from your workplace.

- **ESD shoes** (you can see my shoes on the right)
  - Your employer probably offers a station where you can check your shoes daily.
- **ESD wrist straps**
- **Dissipative floor, tables and chairs**
  - A laboratory floor (the picture with the shoes) usually consists of a lot of conductive material. But if you measure this floor with an ohmmeter, you will measure overload, because the conductor (e.g. copper) is located a few mm below the floor. In this way, you have a relatively low capacitance to ground.
  - ESD-safe rooms are usually marked.
- **Keep the humidity above 40%**
  - High humidity alone does not protect against ESD.
- **Use ESD-safe packaging** (i.e. conductive) while transporting critical electronics.
  - These packages are often marked with C (conductive) or S (shielding).
  - Close these bags and boxes carefully when you transport them outside of an ESD-safe room.
  - An A (antistatic) label is not sufficient.

3.5.5 IEC 61000-4-2

Testing for ESD safety is very important. In terms of system level ESD, the most important standard is the **IEC 61000-4-2**. This standard describes the ESD test generator (schematic below). ESD tests must then be carried out with the aid of this generator. The final voltage level to be set depends on the standard and the test method. For example, the generic standards (**IEC 61000-6-1, table 1**) specify **4kV for contact discharges** and **8kV for air discharges**.

- By closing the left switch, the capacitor will be charged.
- To perform a discharge, we must close the right switch (ESD gun trigger).



How to perform?

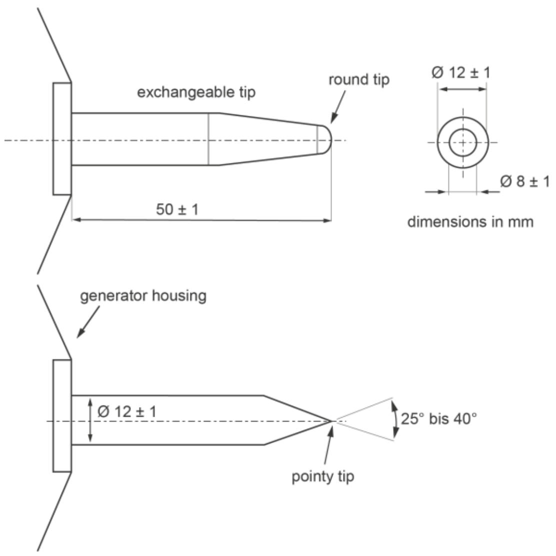
Contact discharge: *Place the ESD gun on the test object and only then pull the trigger. You must use a* ***pointy tip****. Direct and indirect tests must be performed.*

- *Direct: The gun must be in direct contact with the DUT.*
- *Indirect: The gun is positioned on the metal plate below the DUT.*

Air discharge: *Pull the trigger first and then move quickly to the test object. You must use a* ***round tip****.*

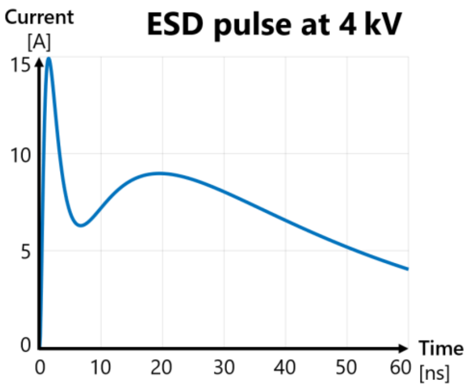
Regardless of the test method: the reference cable must hang freely and be connected to ground with low impedance. Do not let this cable touch the table.

Contact discharge tests require a pointy test tip; air discharge tests a round test tip. You can easily replace these tips.



Standard test signal

The following test signal can be found in the IEC 61000-4-2 standard (picture 2). A 4kV contact discharge on a 2Ω resistor is shown. Parameters for other voltage values can be found in the standard.



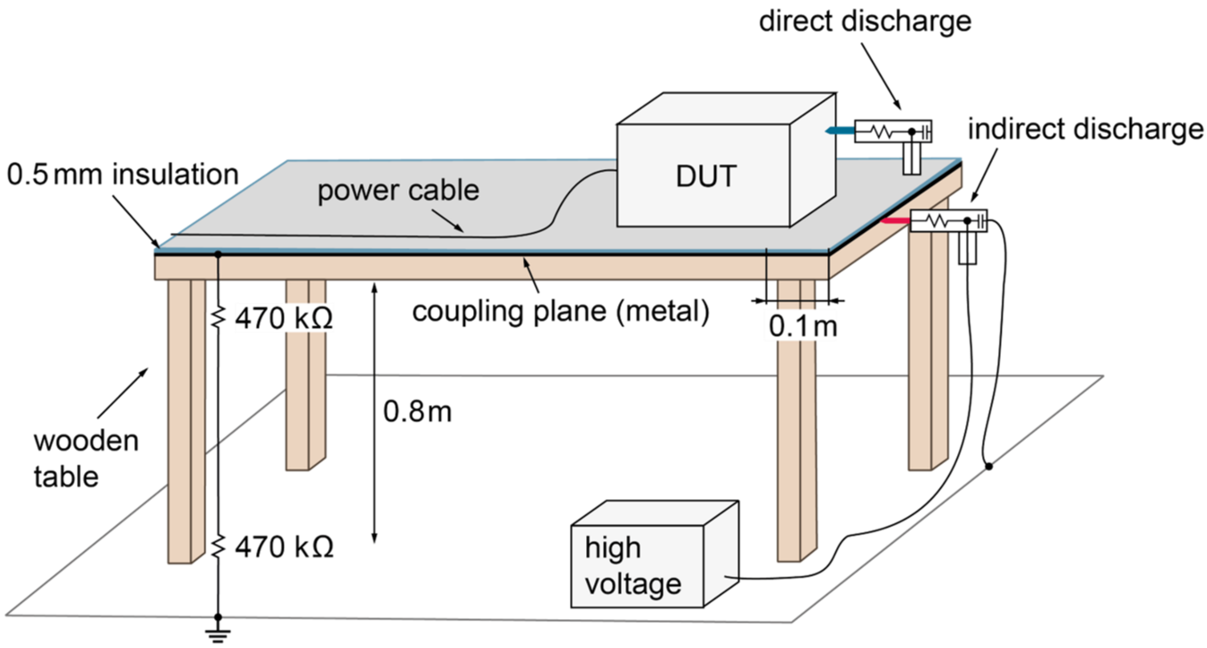
Similar to Figure 2 in IEC 61000-4-2:2008

MATLAB code

```
close all
clear
clc

%% Variables defined in the standard
T1 = 1.1*10^(-9);
T2 = 2*10^(-9);
T3 = 12*10^(-9);
T4 = 37*10^(-9);
I1 = 16.6;
I2 = 9.3;
n = 1.8;
k1 = exp(-T1/T2*(n*T2/T1)^(1/n));
k2 = exp(-T3/T4*(n*T4/T3)^(1/n));

%% Calculation
t = 0:0.1*10^(-9):1000*10^(-9);
I = I1/k1*((t/T1).^n)./(1+((t/T1).^n)).*exp(-t/T2) +
I2/k2*((t/T3).^n)./(1+((t/T3).^n)).*exp(-t/T4);

%% Plot
figure
plot(t,I,'LineWidth',2)
grid on
grid minor
xlim([0 100*10^(-9)])   % change this line for the x-scaling
```

3.5.6 ESD tests

The IEC 61000-4-2 standard shows a wide variety of test setups. The following picture explains the most important setups for conducted ESD discharges. The video afterwards shows how to perform these ESD tests. Please keep in mind that this video is not showing a complete ESD compliance measurement.



ESD tests on iPhone XS
https://youtu.be/SvxQ5fmCc44

3.5.7 Knowledge check

What is the most relevant physical effect regarding ESD?

- O Triboelectric effect
- O Electrostatic induction or influence
- O Seebeck effect
- O Mpemba effect

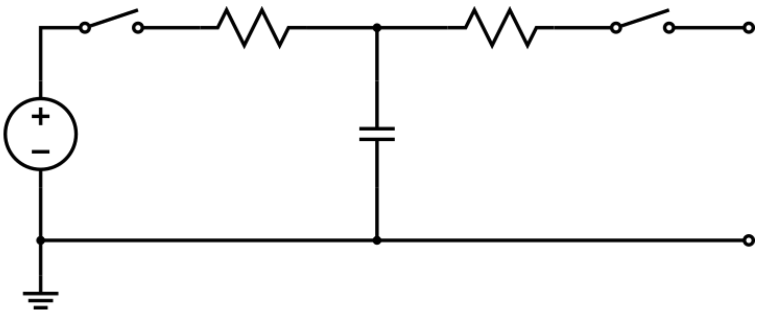
Does the weather affect our electrostatic charge?

- O Yes!
- O No!

Tick all the options that can protect you from ESD.

☐ ESD footwear
☐ Plastic clothing
☐ ESD-safe office equipment
☐ Use ESD-safe packaging with "S" and "C" labling
☐ Keep the humidity at constant 40%

Complete the circuit diagram of a typical ESD gun. What are the typical values?



The round test tip is used for air discharges and the pointy tip for contact discharges.

○ True!
○ False!

3.6 RECAP 3

S_{11} and S_{22} are input and output **reflection coefficients**. and are **forward and reverse voltage gain** respectively.

$S_{21} = \frac{2V_2}{V_{01}}\sqrt{\frac{Z_{01}}{Z_{02}}}$

1-port: $Z_{DUT} = 50\Omega\frac{1+S_{11}}{1-S_{11}}$; 2-port shunt-thru: $Z_{DUT} = 25\Omega\frac{S_{21}}{1-S_{21}}$; series-thru: $Z_{DUT} = 100\Omega\frac{1+S_{21}}{S_{21}}$

A **spectrum analyzer** is used to measure a signal in the frequency domain.

An **EMI receiver** is a very special spectrum analyzer with different detector settings in order to perform standard-compliant measurements.

A **VNA** is an upgraded spectrum analyzer that can emit and measure signals simultaneously on at least 2 ports in order to measure S-parameters.

International regulators specify emissions and immunity testing.

A product may only be marketed after these regulations have been met.

Radiated system-level **emission** measurements usually take place in a semianechoic chamber; IC-level measurements with a TEM cell.

Conducted system-level **emission** measurements are performed with the help of a LISN; IC-level measurements with a 150Ω network.

Radiated immunity tests are performed inversely to emission measurements: the antenna emits an interfering signal.

Conducted immunity tests are performed with the help of two CDNs; IC-level tests with a DPI setup.

An **80% AM signal** is usually used for immunity tests.

The **triboelectric effect** is usually the cause of electrostatic discharges.

Depending on the product, there are **more tests** to be performed that were not covered in this course.

Tick all **learning objectives** that you have understood.

I know how ...

3.1 - S-parameters

- ☐ to calculate the S-parameters of simple resistor networks.
- ☐ to choose correct settings to set up a VNA.
- ☐ to execute measurements for characterizing passive components.

3.2 - Test Equipment

- ☐ to compare spectral analyzer, EMI receiver and VNA.
- ☐ to setup simple lab experiments.
- ☐ to plan what special equipment is needed for basic emissions and immunity testing.

3.3 - International Regulations

- ☐ to express the international relevance of EMC regulations.
- ☐ to illustrate the legally relevant steps until a product may be sold.
- ☐ to identify relevant EMC markings on products.

3.4 - Radiated Emissions

- ☐ to summarize the concept of a semi-anechoic chamber.
- ☐ to interpret a test report from an accredited test house.
- ☐ to describe the measurement of radiated emissions at system and chip level.

3.5 - Electrostatic Discharge (ESD)

- ☐ to explain the root causes of ESD.
- ☐ to implement basic measures in order to protect against ESD.
- ☐ to perform simple ESD tests on your product.