WE – Digital Days

HF - filters for data and signal interfaces, design and effectiveness under real conditions

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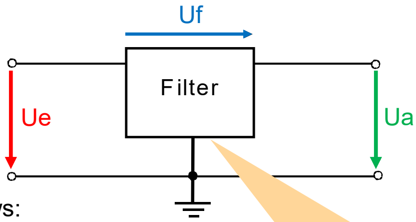
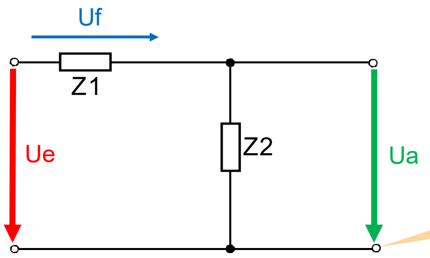
more than you expect

Filtering basics

- Filter principle, two port representation



- The effect of the filtering can be imagined as follows:



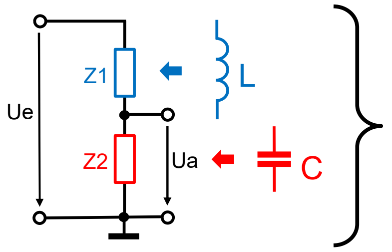
From the two port representation the functionality is not obvious!

The reference ground must be clean, without disturbances.

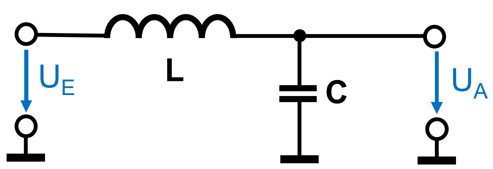
- The effect of filtering is based on frequency-selective voltage division of the input signal Ue.
- At least **one** of the impedances Z1 or Z2 must be frequency selective.

Filtering basics

- From voltage devider to a low path filter



- Low pass 2nd order, 12 dB/Oct. resp. 40 dB/Dec.



$$\frac{U_a}{U_e} = \frac{1}{1 - \omega^2 L_1 C_1}$$

- **For practice:** Large influence via L (ferrite, air coil, choke...) possible, as the interference energy is not drained into the reference ground where it causes noise offset!

Ideal components are assumed here!

Filter components, capacitors

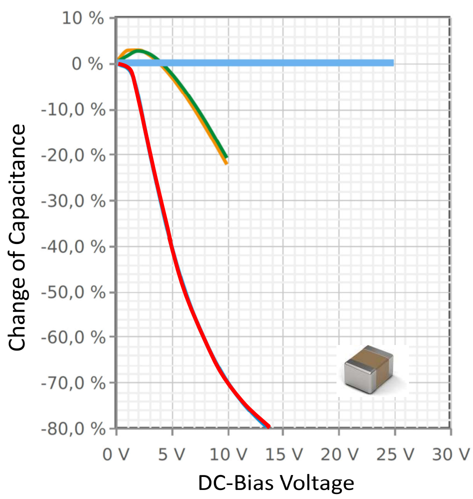
- Selection of capacitors for HF-applications
  - Online Tool: RedExpert (https://redexpert.we-online.com/redexpert/#/)

- Possibility to display electrical parameters of capacitors. It can be used to show
  - Impedance $Z_{(f)}$
  - Equivalent series resistance $ESR_{(f)}$
  - Temperature dependence of the capacitance $C_{(J)}$
  - Capacitance change as a function of the DC bias voltage $C_{(U)}$

Different capacitors can be compared with each other.

Example: Dependence of different capacitors on the DC bias voltage.

X5R – 1206 - 22µF/16V - 885012108018
X7R – 1210 - 22µF/10V - 885012209006
X7R – 1206 - 2,2µF/10V - 885012208015
NP0 – 1812 - 33nF/25V - 885012010004



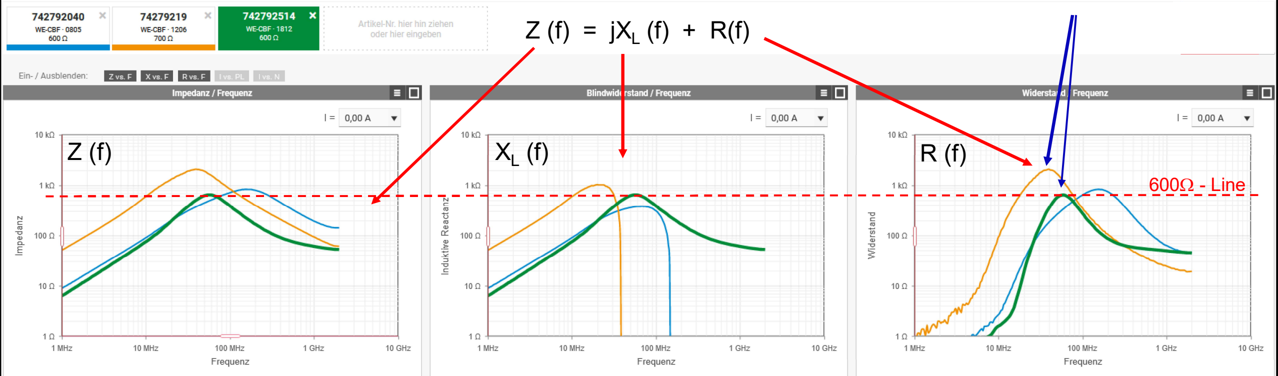
Filter components, inductors

- Selection of inductors for HF-applications

- Online Tool: RedExpert (https://redexpert.we-online.com/redexpert/#/)
  - Can we just use any „600 Ω“ – SMD-ferrite?

Both ferrites: 600Ω at 100 MHz
At 40 MHz: 1400Ω difference!

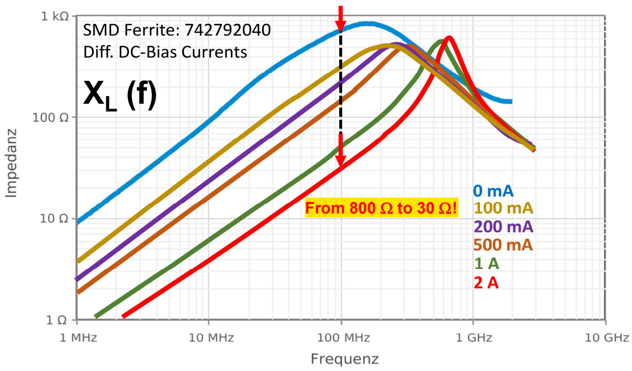
$$Z(f) = jX_L(f) + R(f)$$

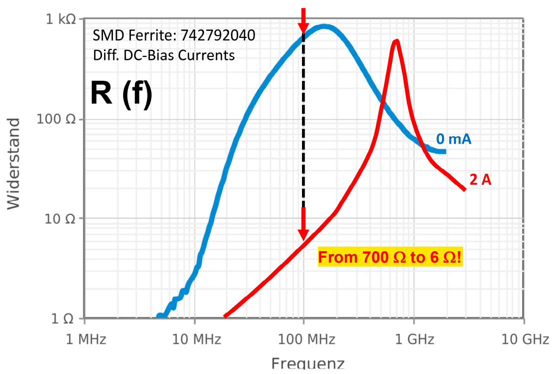


- An impedance Z(f) similar at 100 MHz will not have the same attenuation of the filter over the entire frequency range
- Reactance and loss resistance must be selected individually, according to the application

Filter components, inductors

- Selection of inductors for HF-applications
- Online Tool: RedExpert (https://redexpert.we-online.com/redexpert/#/)
  - What about the rated current? Comparison „600Ω“ – ferrite driven with different DC-Bias current

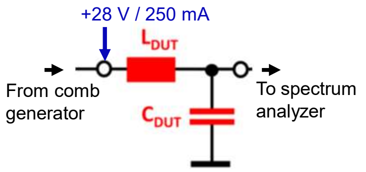




- The rated current I_R, of the SMD ferrite should be at least 2 x I_{DC} (current through the ferrite)
- The impedance drops sharply in the range below the ferrite resonance with increasing I_{DC}, the resistance $R_{(f)}$ drops to < 1%!

Filter components

- Filter degradation under the DC-Bias effect with a capacitor and a SMD ferrite



L_{DUT}: SMD ferrite, 74279272 (300 Ω at 100 MHz)

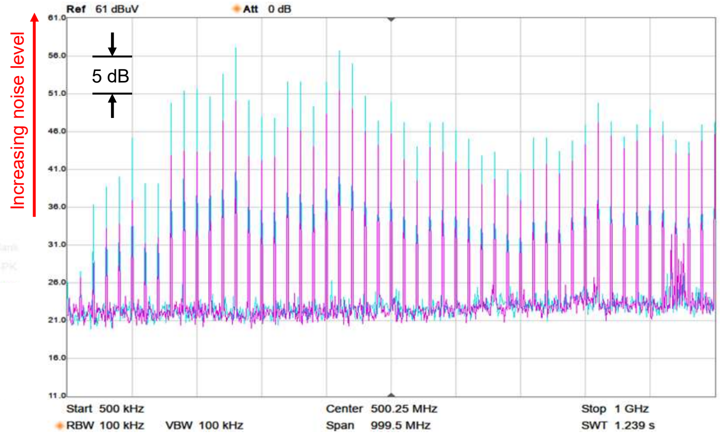
C_{DUT}: MLCC capacitor, 885012107015 (1 µF / 25V)

- DC-Bias voltage: 28 V_{DC} across the capacitor
- DC-Bias current: 250 mA through the SMD ferrite

Loss in filter attenuation: 10 dB!

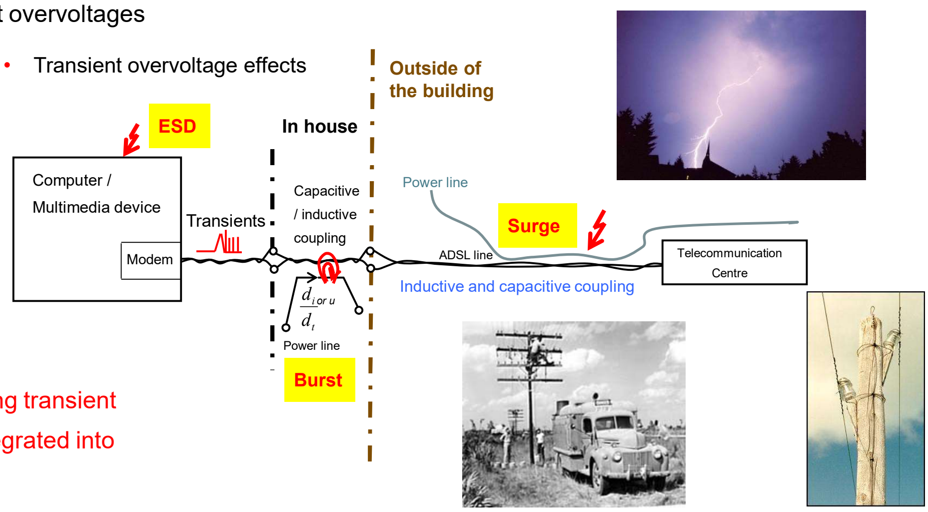
Comparison of the amplitude spectrum at the output of the filter

Pink trace without DC bias / light blue trace with 28 V/250 mA DC bias



Filter components

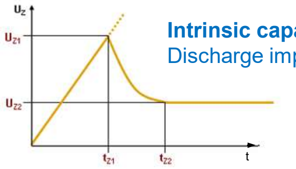
- Additional requirement to the filter effect
- Limitation of transient overvoltages



Components for limiting transient overvoltage, to be integrated into the filter design.

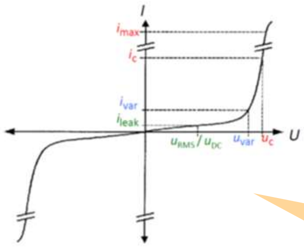
Filter components

- Components for limiting overvoltage
- Parasitic capacitances of the transient voltage limiting devices
- Gas arrester



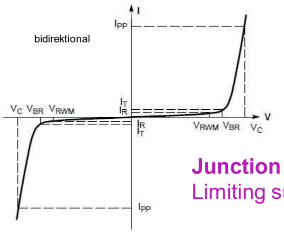
Intrinsic capacitance: typ.< 1 pF
Discharge impulse current: typ. > 5…50 kA

- SMD-varistors



Intrinsic capacitance: typ. 5 … 500 pF
Limiting surge current: typ. 10…200 A

- TVS diodes



Junction capacity: typ. 0,2 … 5 pF
Limiting surge current: typ. 10…200 A

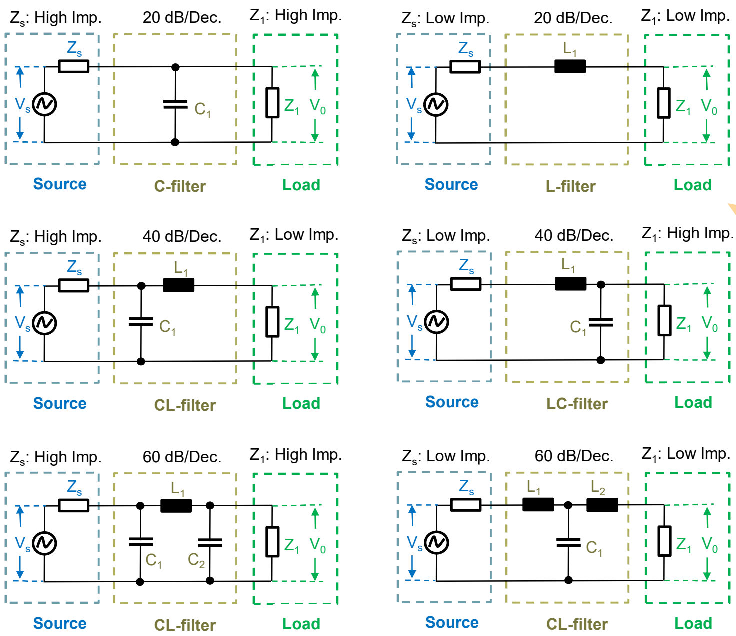
Parasitic capacitance of the voltage-limiting components can be used as "filter capacitance"!

Filtering basics

- Filter, applications

- Topologies for high insertion loss taking into account source and load impedances

- Target: Maximum mismatch in the interference frequency range

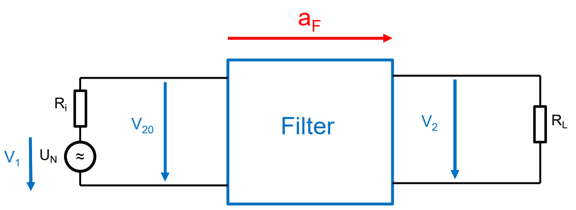


No “real” filter as the undefined source and load impedances are included into the voltage divider!

Filtering basics

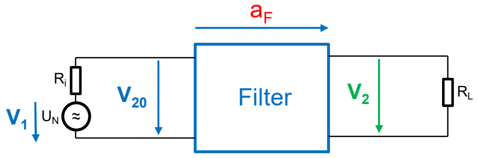
- How much attenuation is needed?
- Without knowing the required attenuation, it is hardly possible to design an EMC filter!
- The required insertion loss is obtained by **subtracting levels**.

$$a_F = 10 \cdot \lg\left(\frac{P_{20}}{P_2}\right) = 20 \cdot \lg\left(\frac{V_{20}}{V_2}\right) = 20 \cdot \lg(V_{20}) - 20 \cdot \lg(V_2)$$



Filtering basics

- How much damping is needed?
- Keeping the interference voltage below a certain limit with an EMC filter means:
  - V_2 must not exceed this limit (e.g. CISPR32).



  - Replacing V_2 with the **limit** value gives the required attenuation, but
    - CM and DM must be distinguished
    - Filters usually have a high non-linearity over the frequency range
    - Source and load impedances are often unknown and non-linear

    ⬇

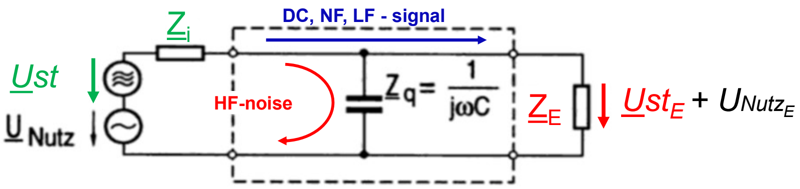
    - However, an assessment should always be made!

But how?

CM: Common Mode
DM: Differential Mode

Filtering basics, effectiveness of filter topologies

- Capacitor, blocking capacitor



Filters are voltage dividers with a frequency-dependent divider ratio!
→ Here: Zi ist part of the voltage devider!

$$a_f = 20\lg\frac{|Ust(\omega)|}{|Ust_E(\omega)|} = 20\lg\frac{\left|\underline{Z}_i + \dfrac{\underline{Z}_E\underline{Z}_q}{\underline{Z}_E+\underline{Z}_q}\right|}{\left|\dfrac{\underline{Z}_E\underline{Z}_q}{\underline{Z}_E+\underline{Z}_q}\right|}$$

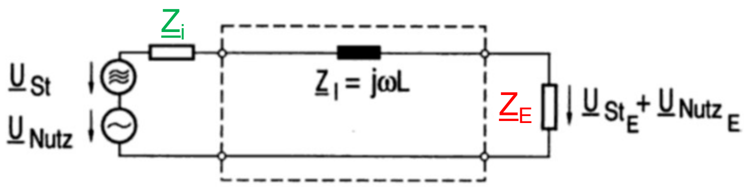
a_f: Filter attenuation

- The capacitor
  - Helps with large source resistance Z_i
  - Doesn´t help if load impedance Z_E is small
  - Filter attenuation in the range of the useful signal (if any) must be small
  - Separation of useful and interfering signal hardly possible

Quelle: Elektromagnetische Verträglichkeit 5. Auflage, Schwab/Kürner, S. 158f

Filtering basics, effectiveness of filter topologies

- Inductance, series choke



Filters are voltage dividers with a frequency-dependent divider ratio!

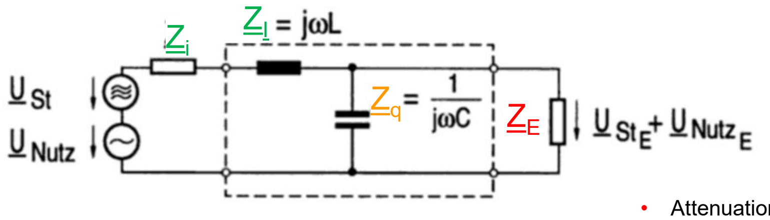
$$a_f = 20\lg\frac{|\underline{U}_{st}(\omega)|}{|\underline{U}_{st_E}(\omega)|} = 20\lg\frac{|\underline{Z}_i + \underline{Z}_l + \underline{Z}_E|}{|\underline{Z}_E|}$$

- Helps with low source impedance Z_i
- Doesn´t help if load impedance Z_E is large
- Separation of useful and interfering signal hardly possible

Quelle: Elektromagnetische Verträglichkeit 5. Auflage, Schwab/Kürner, S. 158f

Filtering basics, effectiveness of filter topologies

- LC-Kombination



$$a_f = 20\lg\frac{|U_{st}(\omega)|}{|U_{st_E}(\omega)|} = 20\lg\frac{\left|Z_i + Z_l + \frac{Z_E Z_q}{Z_E + Z_q}\right|}{\left|\frac{Z_E Z_q}{Z_E + Z_q}\right|}$$

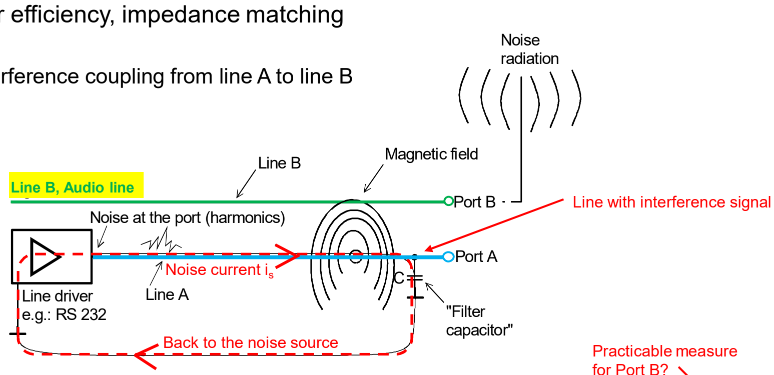
Simulation with RedExpert can support here!

- Attenuation range of the filter must be defined
- $f_0 = \frac{1}{2\pi\sqrt{LC}}$ Does not apply for filters with inductors with lossy, non linear ferrite
- Z_l should be a ferrite-choke with defined curves of u` and u`` over the necessary frequency range.
- High effectiveness if
  - Z_l high, u`` high in the range of the noise
  - Z_q small, but must not influence the useful signal
  - Z_i small and Z_E high

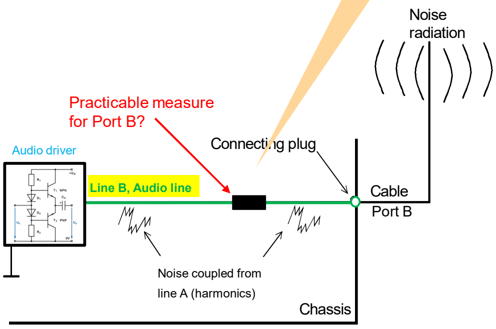
Quelle: Elektromagnetische Verträglichkeit 5. Auflage, Schwab/Kürner, S. 158f

Filtering, case study

- Filter efficiency, impedance matching
  - Interference coupling from line A to line B



Does that help?

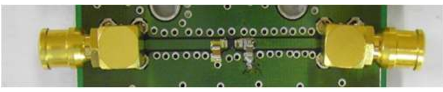


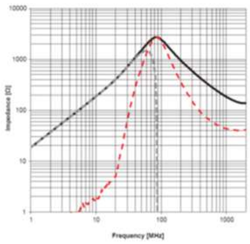
- A filter is a frequency-dependent voltage divider!
- Interference currents must be absorbed and converted into "heat" and not drained into the ground of the device!

Filter, application in 50 Ω system

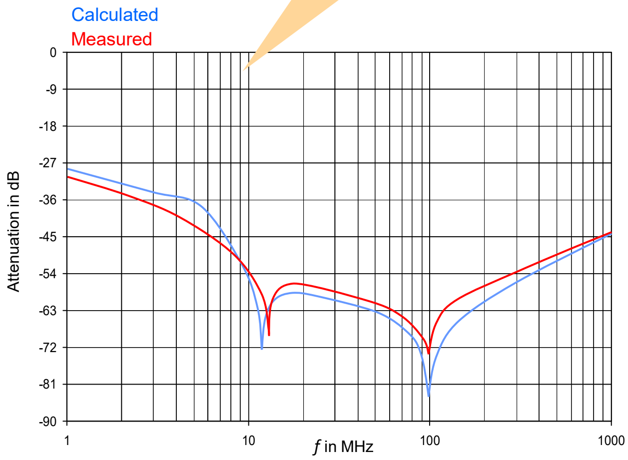
- Usual parameters refer to a 50 Ω system
- π-Filter

- Measurement and simulation in the 50 Ω system



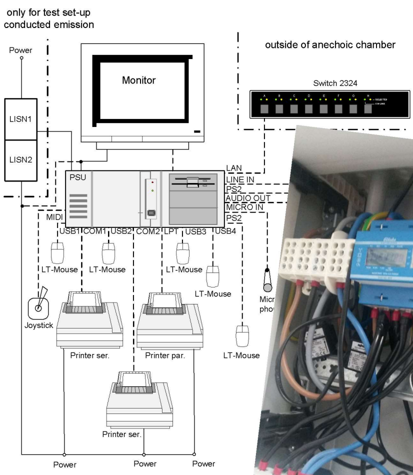


But what does the practice look like?

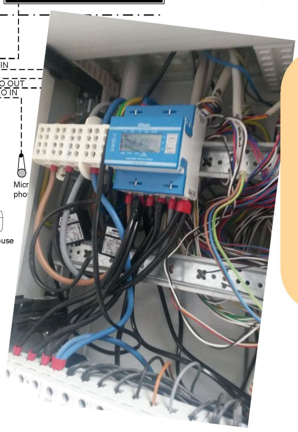


Filter, application at cable interfaces

- Realistic approach



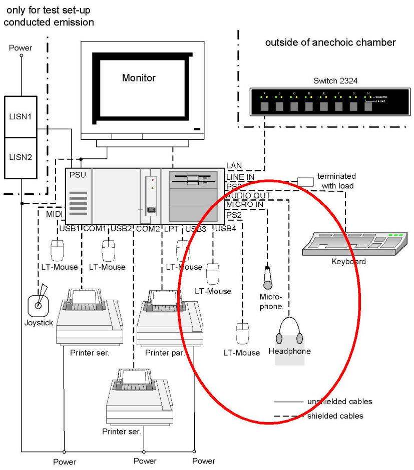
Where is the 50 Ω system?

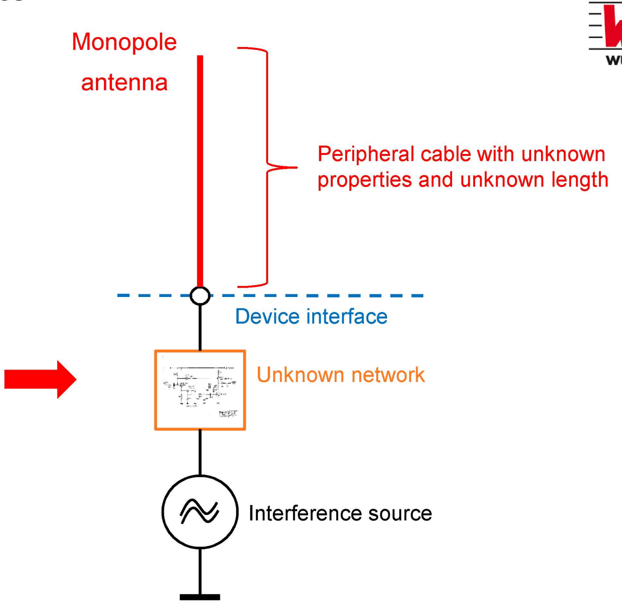


We are dealing with interference sources and antennas whose impedances are rarely known!

Filter, application at cable interfaces

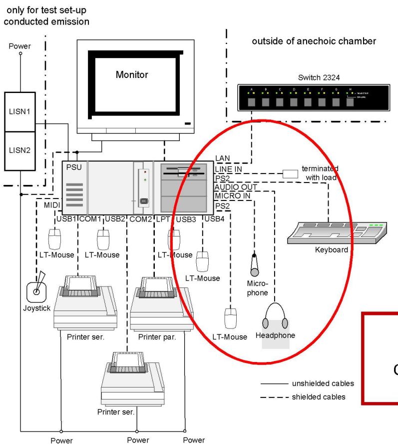
- Realistic approach

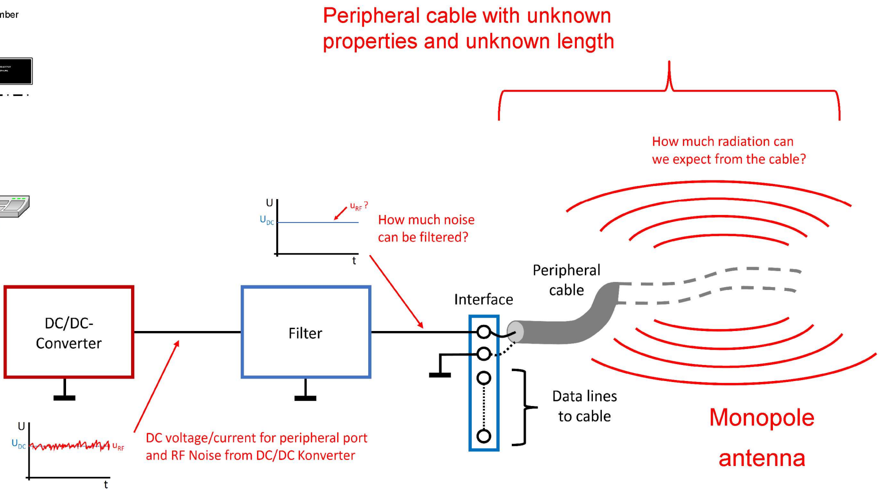




Filter, application at cable interfaces

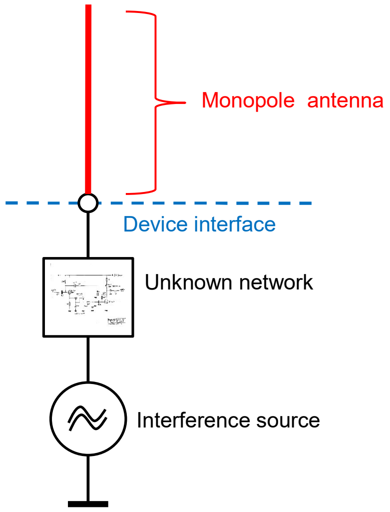
- Realistic approach



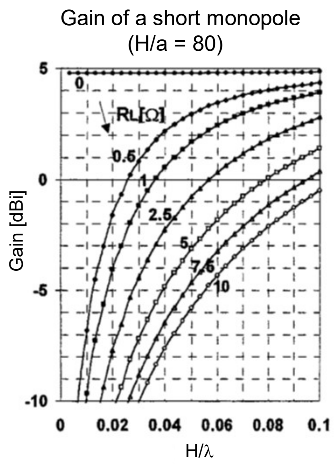


Filter, application at cable interfaces

- Peripheral cable - The monopole antenna



- Radiation characteristics of monopole antennas



- Constant directivity as a function of vertical antenna height, seen above as the first horizontal line
- Gain depends on antenna "height"
  - H: Antenna height
  - a: Antenna diameter
  - R_L: Impedance of the monopole in the matched state

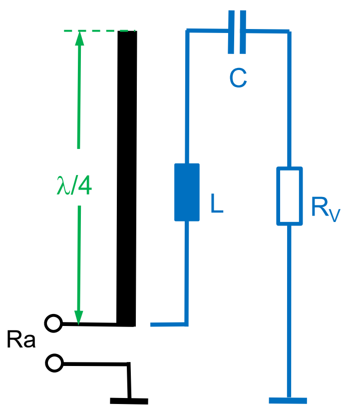
➡ $\Delta Gain_{\_rel.}$ > 15 dB possible!

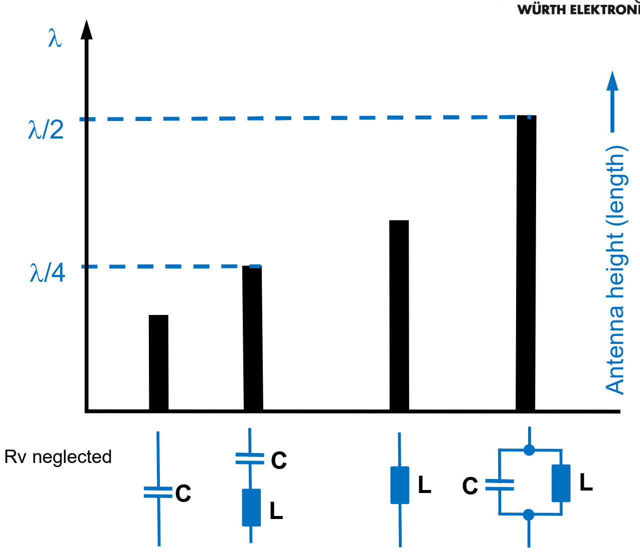
more than you expect

Filter, application at cable interfaces

- Peripheral cable - The monopole antenna
- Equivalent circuit diagram as a function of wavelength

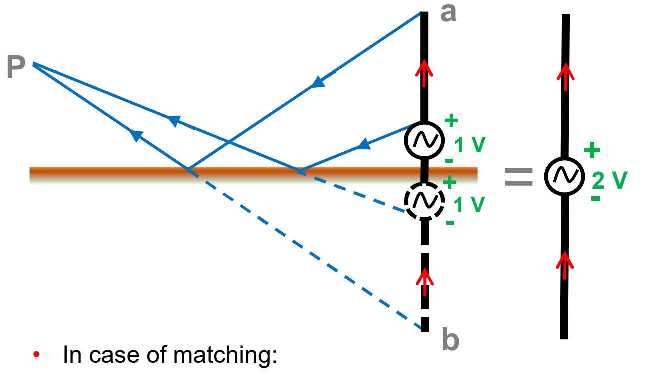
Equiv. Circuit diagram for λ/4

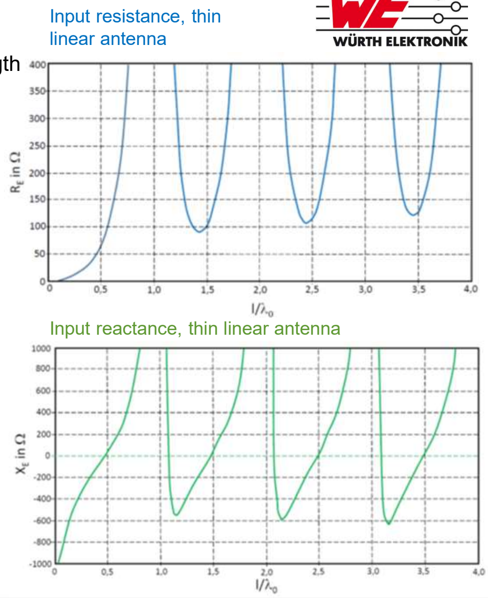




Filter, application at cable interfaces

- Peripheral cable - The monopole antenna
- The impedance of an antenna depends, among other things, on its length in relation to the wavelength of the feeding signal (interference signal).



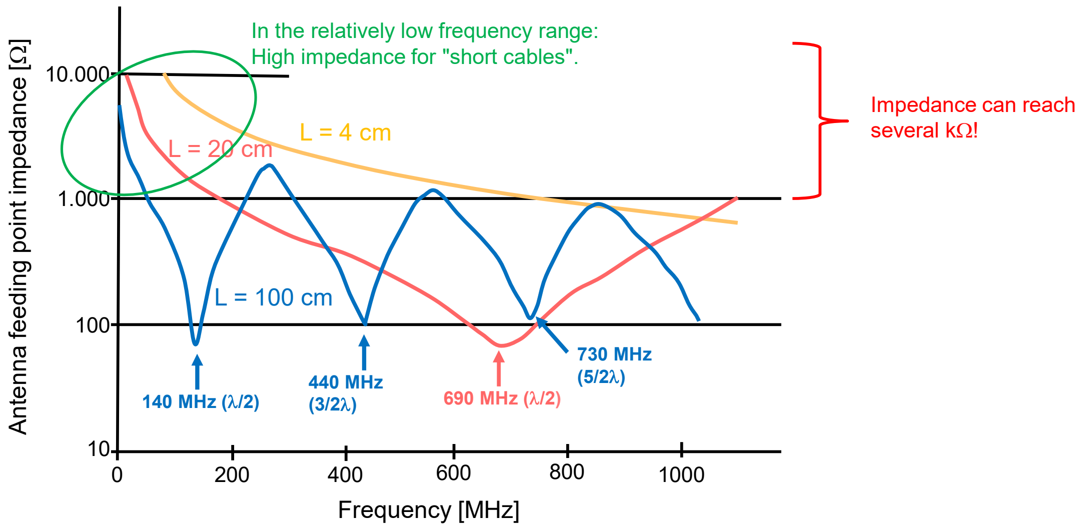


- In case of matching:

$$Z_{E\_Monopole\ \lambda/4} = \tfrac{1}{2} Z_{E\_Dipole} = 36{,}5\ \Omega$$

Filter, application at cable interfaces

- Peripheral cable - The monopole antenna
- Impedance of an antenna on an untuned system, L = 4 cm, 20 cm, 100 cm



Filter, application at cable interfaces

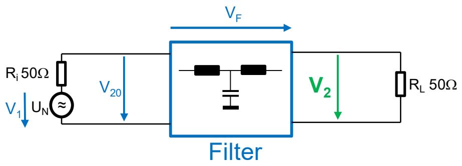
- Peripheral cable - The monopole antenna
- Essential parameters that influence the radiation properties of the antenna or the peripheral cable
  - Input impedance $Z_E = R_E + jX_E$
  - Wire- or effective antenna length, depending on the signal frequency or wavelength
  - Wire diameter (antenna shortening factor)
  - Conductivity of the wire material
  - Condition of the cable (shielding, ground connection, type of plug, ...)
  - Position or orientation of the wire to the receiver resp. the noise sink
  - Capacitive coupling to the reference ground ("GND plane" condition)

Calculation, simulation of the system radiation including the cables doesn`t make much sense!

Filter, application at cable interfaces

- Filtering, facts – reference impedance

- All filters work on the principle of creating a large discontinuity in the system characteristic impedance (mismatch).
- Most of the energy of the signal is reflected back.
- Filters generally have their parameters specified to 50 Ω source and load impedances.



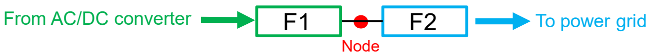
- Filter specifications therefore refer to 50 Ω source and load impedances, as almost all RF measurement equipment and associated cables have 50 Ω impedance.
- Filter specifications are always hopelessly optimistic compared to their performance in practice.

Why?

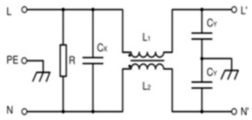
Filter, application at cable interfaces

- Filtering, facts – impedance stabilization, Example
  - Use of a mains filter, between the AC mains and the AC-DC converter
    - Impedance of the AC network varies from 2 Ω to 2 kΩ during the day, depending on the connected loads and on the frequency between 150 kHz and 30 MHz.
    - Characteristic impedance of the network topology (2-wire line) is approx. 150 Ω. Impedance of the AC-DC converter resembles a short circuit (rectifier with electrolytic capacitors).

➡ A combination of several stages is required to create an impedance-stable node between the filters of the source side and the load side.

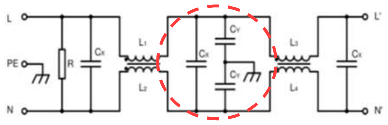


WE-CLFS Line Filter Single-Stage, 810911006



E-CLFS Line Filter Two-Stage, 810913006

Decoupled impedance node

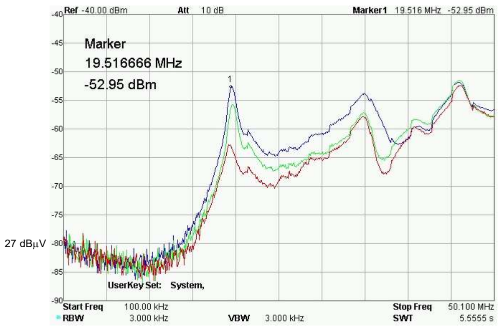


Filter, application at cable interfaces

- Filtering, facts – impedance stabilization, Example

WE-CLFS Line Filter Single-Stage, 810911006

E-CLFS Line Filter Two-Stage, 810913006



Purple curves: 0 Ω termination
Green curves: 500 Ω termination
Red curves: ∞ Ω (open)

- Single-stage filter, especially up to approx. 10 MHz: Strong dependence on line impedance
  - Difference is up to 20 dB
- Two-stage filter shows hardly any impedance dependence.
  - Filters with two or more stages have a decoupled impedance node

Filter design

- Filtering, facts – parasitic effects

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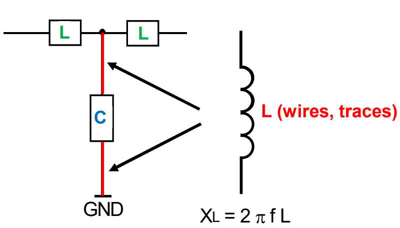
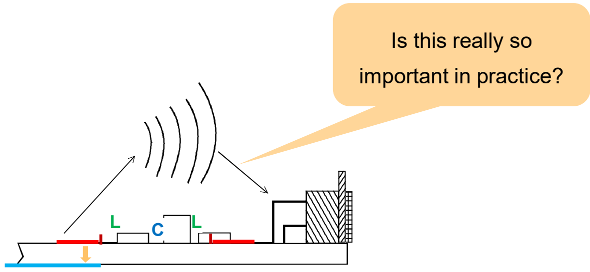
- Parasitic inductance in the capacitive path to GND



- The frequency-selective voltage divider no longer works properly!

- Parasitic coupling capacitance between input and output



- Coupling is ~ f !
  The filter is bypassed

Filter design

- Filtering, facts – parasitic effects
- Example

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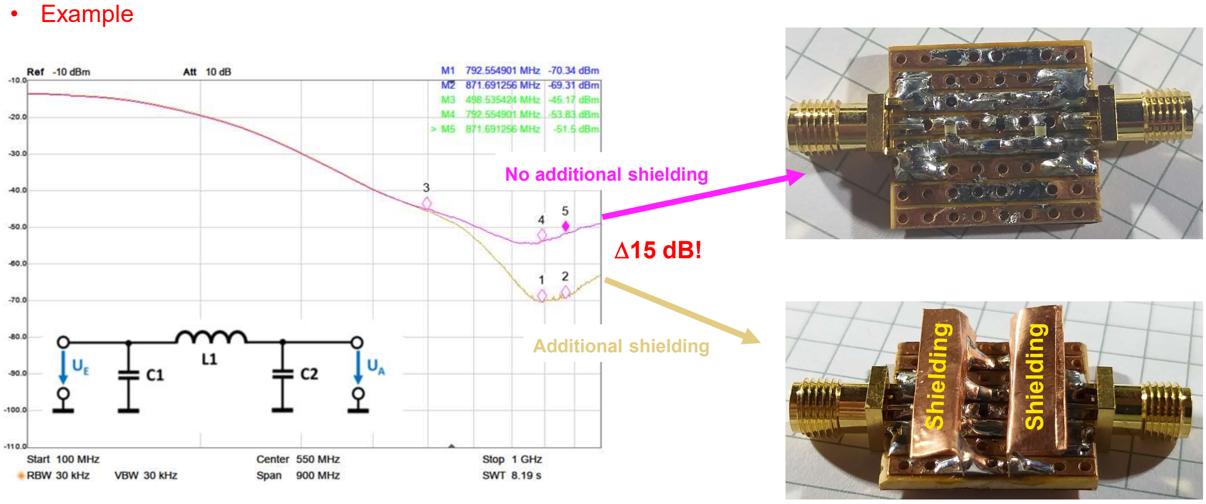
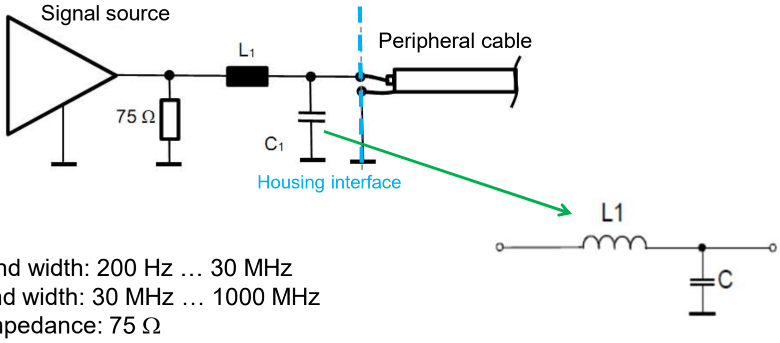


Filter design

- Filtering, facts – parasitic effects
- Example



Singal band width: 200 Hz … 30 MHz
Noise band width: 30 MHz … 1000 MHz
Source Impedance: 75 Ω
Load Impedance: > 1 kΩ (for noise signal!)

Second-order low-pass filter with an attenuation of 12 dB/octave or 40 dB/decade.

Filter design

- Filtering, facts – parasitic effects, example
- Parameters to be taken into account
  - Source impedance: 75 Ω with following second-order low-pass filter
  - The peripheral cable is connected to the output of the filter
  - Cables form a monopole antenna from an RF point of view
  - Impedance of the monopole antenna depends on cable properties and the wavelength of the signal, > 2 kΩ possible (E-field antenna!)
- Conditions for a high attenuation of the filter
  - The interference source must be highly impedance **mismatched in the stopband of the filter**
  - The high impedance base of the cable must be **terminated with a low impedance**

⬇

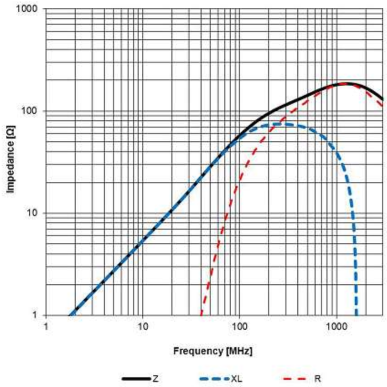
The data sheets are required for dimensioning the two filter components.

Filter design

- Filtering, facts – parasitic effects, example

- Filter components, inductor
  - WE-CBF SMD , No. 742792716
    - I_R: 300 mA (no issue here)
    - R_{DC}: 0,25 Ω, small in relation to 75 Ω
    - Reactance increases to only 18 Ω at 30 MHz, resistive part is very small at 30 MHz (~ 0 Ω)

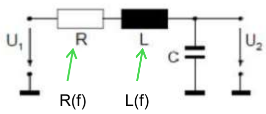
- Filter components, capacitor
  - WCAP-CSMH, No. 885342006002, NP0
    - C: 33 pF
    - U_R: 250V
    - f_{res}: > 1 GHz



Filter design

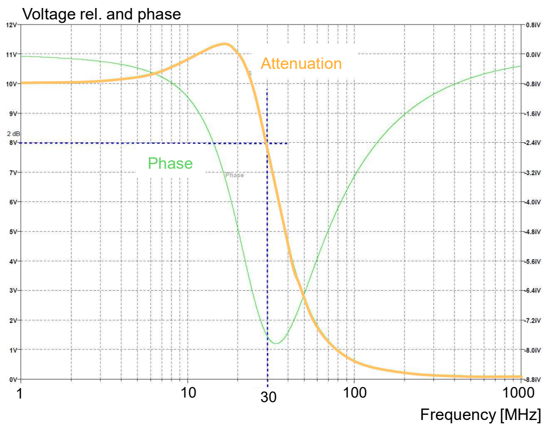
- Filtering, facts – parasitic effects, example
- Attenuation curve of the filter

Division into resistive and inductive part of the choke impedance results in the following circuit diagram with corresponding transfer function of the filter:



$$\frac{\underline{U}_2}{\underline{U}_1} = \frac{1}{1 + j\omega RC + (j\omega)^2 LC} = \frac{1}{1 + j\frac{\omega}{\omega_0} R\sqrt{\frac{C}{L}} + \left(j\frac{\omega}{\omega_0}\right)^2}$$

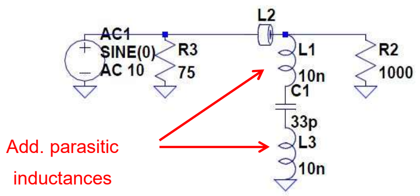
- Att. at 30 MHz: approx. 2 dB, from 50 MHz approx. 10 dB
- For small capacitance values of C: Consider parasitic capacitance of tracks and connectors.

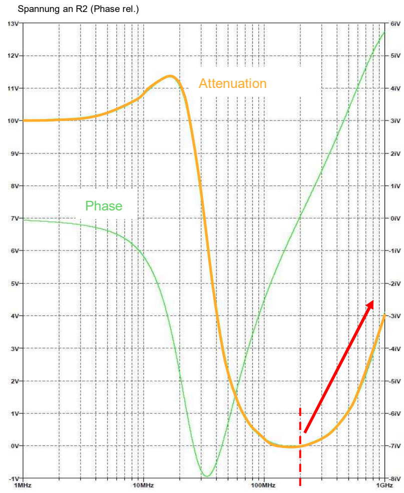


Filter design

- Filtering, facts – parasitic effects, example
- Additional parasitic impedance in the connections to the capacitor
  - 10nH (traces, vias, pads of the capacitor)

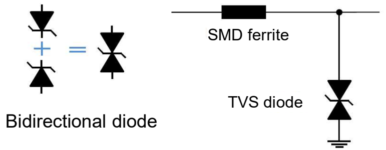
The attenuation of the filter drops significantly above 200 MHz

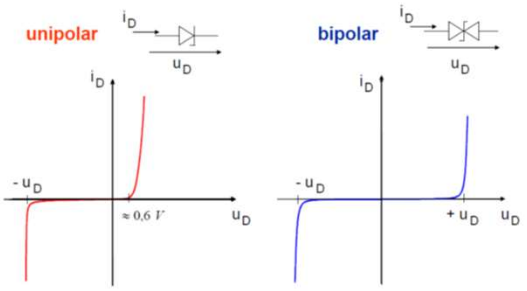


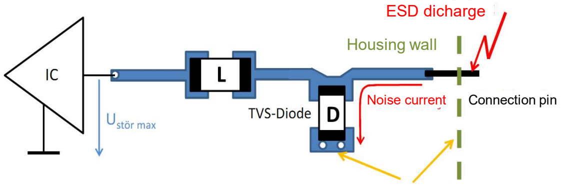


Filter design, additional protection against transient overvoltage

- Design of an HF filter with additional transient protection by TVS diode





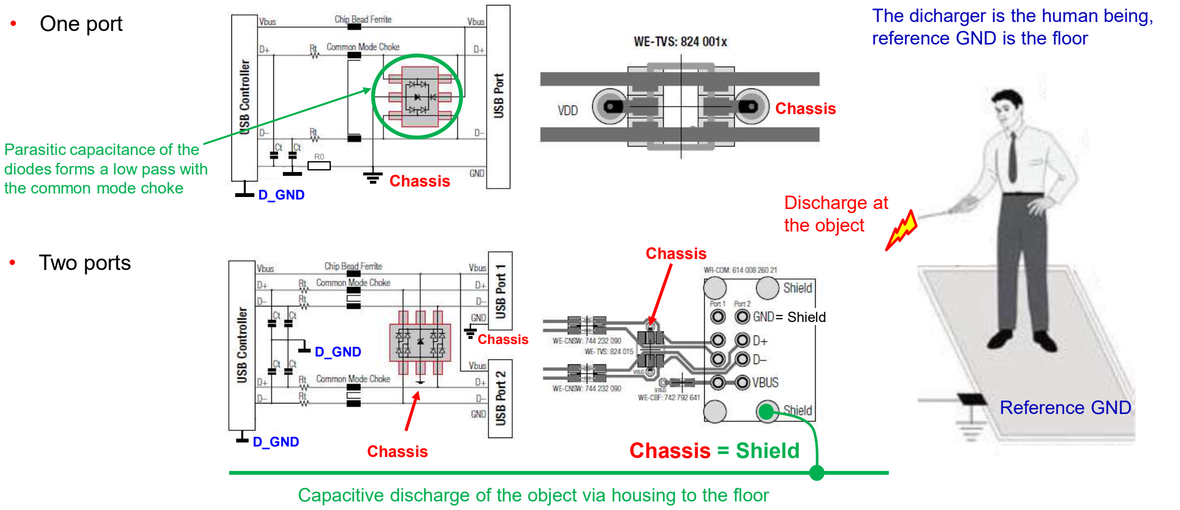


Interference current must be discharged directly via the TVS diode to the ground reference of the interference source.

Filter design, additional protection against transient overvoltage

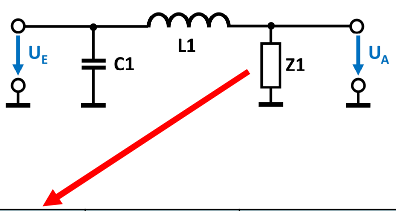
- Design of an HF filter with additional transient protection by TVS diode

- One port
- Two ports

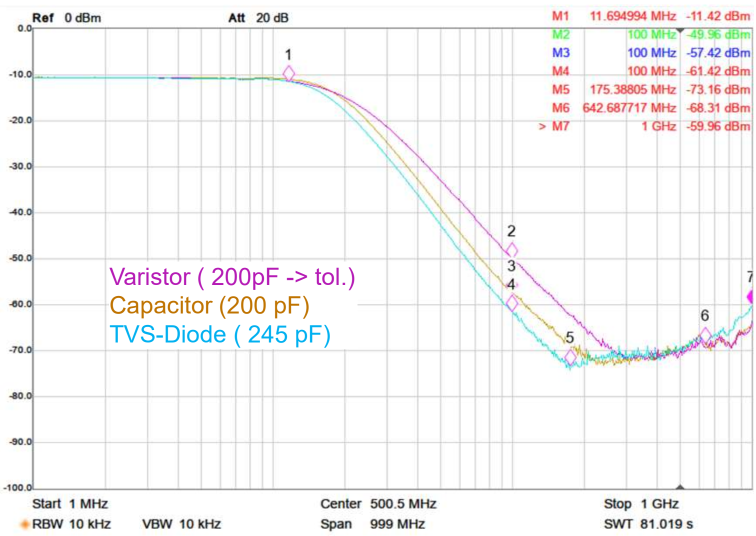


Filter design, additional protection against transient overvoltages

- Example of an HF filter with additional transient protection

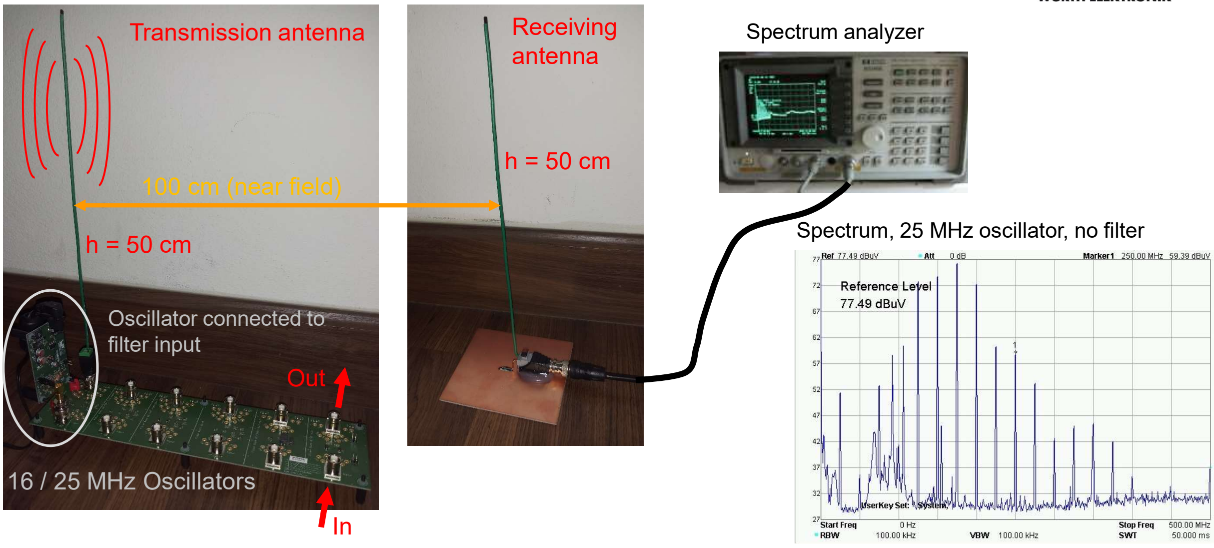


Z1	Value	Number
Varistor	26V, 200 pF	WE-VS, 82556200
Capacitor	2 x 100 pF, NP0	WCAP-CSGP, 885012006079
TVS-Diode	24V, 245 pF	WE-TVSP, 824501241



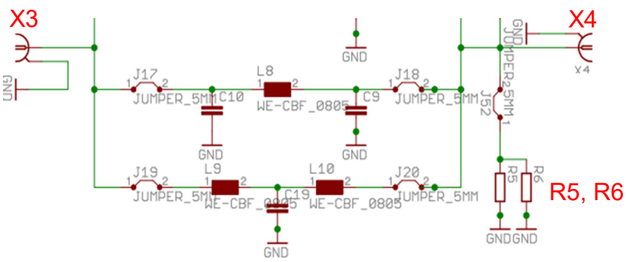
Filter, application at cable interfaces

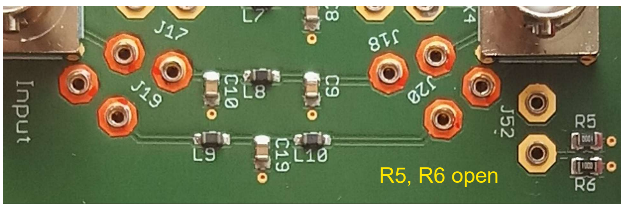
- System set up for filter evaluation via antenna coupling



Filter, application at cable interfaces

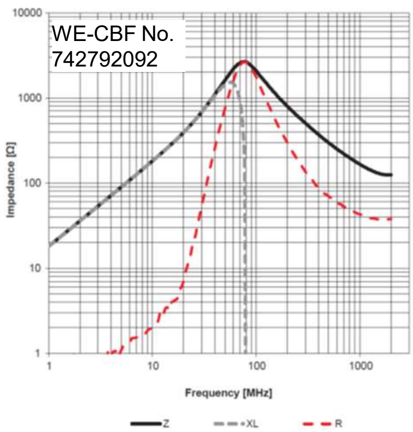
- Comparison between π-filter and T-filter (R5 and R6 open) with a wide-band-SMD-ferrite





C10, C19: 100 nF
C9: 10 nF

➡ High C-values, thus the filter is not suitable for data lines!



Filter, application at cable interfaces

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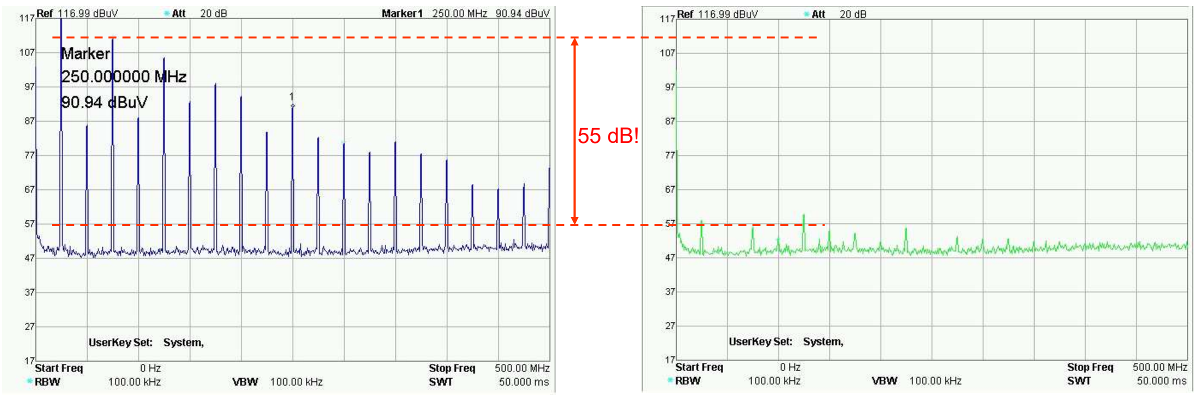
- Comparison between π-filter and T-filter with a wide-band-SMD-ferrite
- **π-filter**, Spectrum with direct connection, i.e. output filter via cable to the analyzer (50Ω)

Without filter, via cable | With filter, via cable

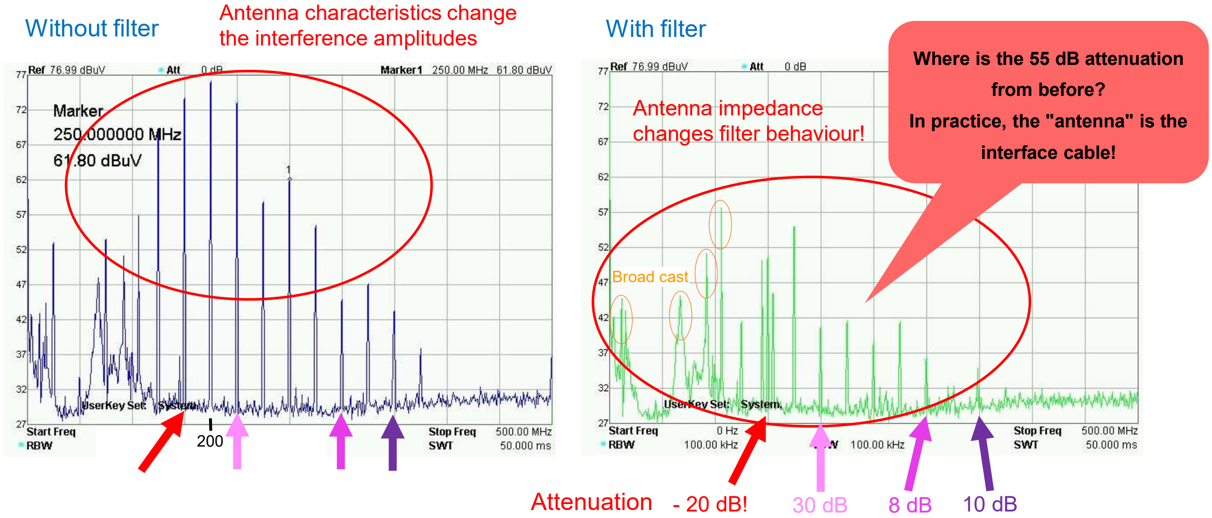


Filter, application at cable interfaces

WÜRTH ELEKTRONIK

- Comparison between π-filter and T-filter with a wide-band-SMD-ferrite
- **π-Filter**, Spectrum measured over 50 cm long monopoles at a distance of 1 m

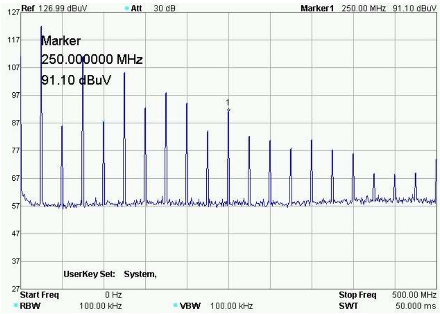
Without filter | Antenna characteristics change the interference amplitudes | With filter



Filter, application at cable interfaces

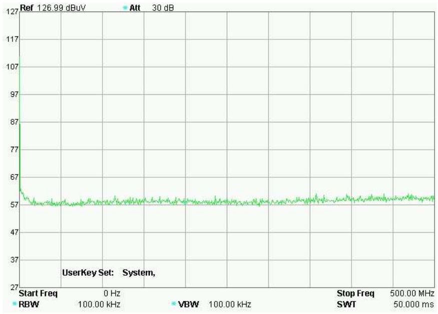
- Comparison between π-filter and T-filter with a wide-band-SMD-ferrite
- **T-Filter**, Spectrum with direct connection, i.e. output filter via cable to the analyzer

Without filter, via cable

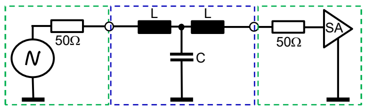


> 65 dB!

With filter, via cable



Circuit diagram of the impedances:



Ideal mismatch in 50 Ω system!
→ High attenuation

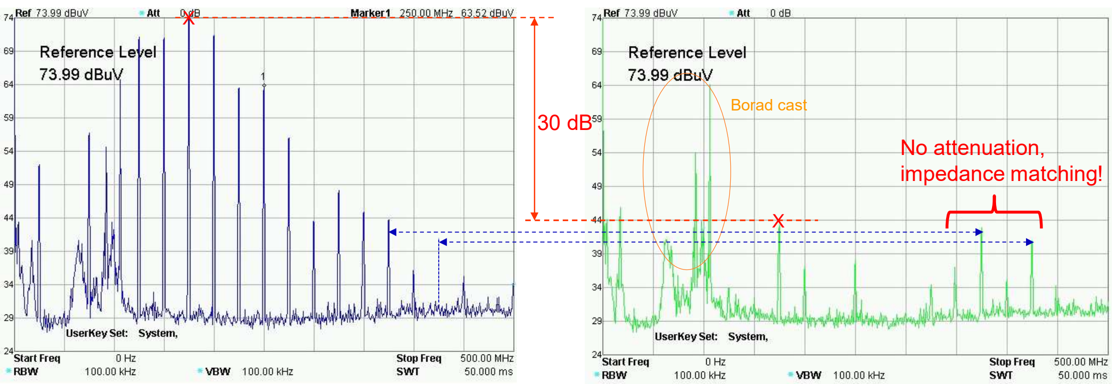
more than you expect

Filter, application at cable interfaces

- Comparison between π-filter and T-filter with a wide-band-SMD-ferrite
- **T-filter**, spectrum via antennas (distance: 100 cm)

Without filter, via antennas

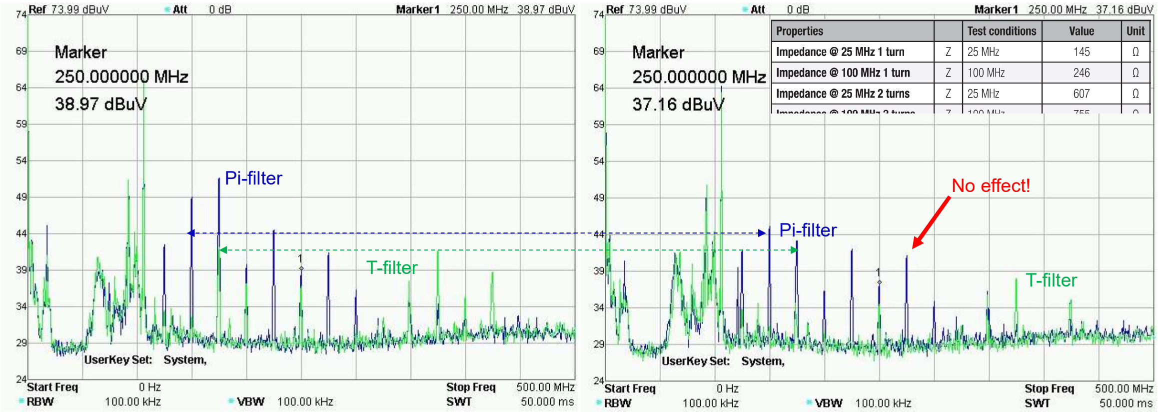
With filter, via antennas



The filter attenuates approx. 2 - 30 dB, depending on the frequency. The attenuation behaviour cannot be determined exactly because the antenna has a non-constant impedance over the wavelength.

Filter, application at cable interfaces

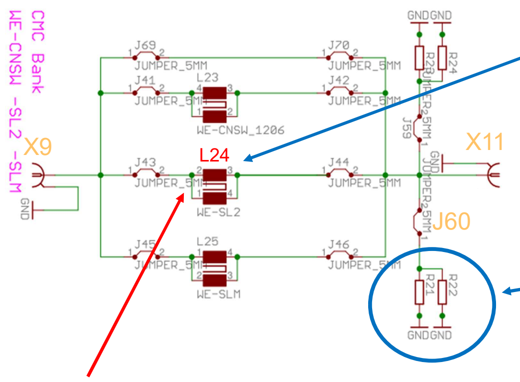
- π-filter and T-filter with a wide-band-SMD-ferrite and an **additional snap ferrite**
- π-filter and T-filter **without** snap ferrite via antenna
- π-filter and T-filter **with** snap ferrite via antenna



- A ferrite (here: 74271131) with ½ turn causes frequency-dependent an attenuation of up to 6 dB for both filters. The attenuation depends on the frequency-related antenna impedance and my go down to 0 dB!

Filter, application at cable interfaces

- Common-mode chokes, CM attenuation and resonance (1/4)
- Filter description



Choke L24: 744221

~~R21, R22~~

Alternatively open, or capacitors assembled:

$C_{21/22}$ = 100 pF

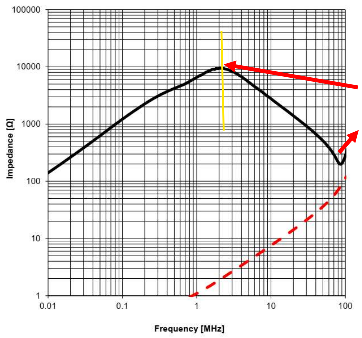
Only common mode attenuation is measured

Filter, application at cable interfaces

- Common-mode chokes, CM attenuation and resonance (2/4)
- Filter measurements with L24: WE-SL2 744221

Properties		Test conditions	Value	Unit	Tol.
Number of windings	N		2		
Inductance	L	100 kHz/ 5 mV	2000	µH	±50%
Maximum Impedance	Z_{max}		9200	Ω	typ.
Rated Current	I_R	ΔT = 40 K	600	mA	max.
DC Resistance	R_{DC}	@ 20 °C	0.42	Ω	max.
Leakage Inductance	L_S	1 MHz/ 1 mA	130	nH	typ.
Insulation Test Voltage	V_T		500	V (AC)	max.
Rated Voltage	V_R		80	V	

!

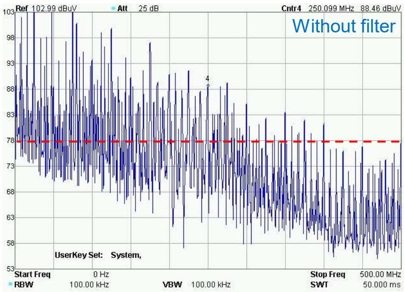


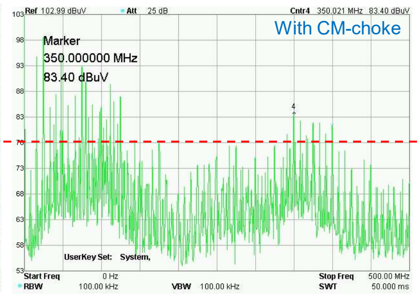
Low resonance frequency in common mode filter operation

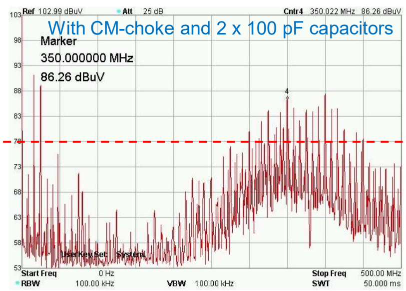
But further resonance exists in the higher frequency range (turn to turn)

Filter, application at cable interfaces

- Common-mode chokes, CM attenuation and resonance (3/4)
- Filter measurements on CM choke L24, **via cable** to the analyzer
  16 MHz **and** 25 MHz oscillators in operation





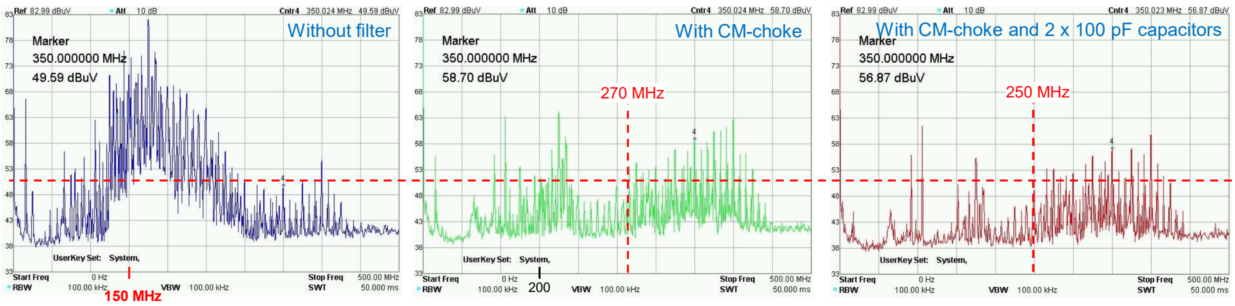


- Resonance clearly visible above 350 MHz, choke attenuates no longer.

- Resonance above 250 MHz, approx. 15 dB higher interference level!
- Capacitor amplifies the resonance and reduces the filter attenuation, improves the matching to the line impedance.

Filter, application at cable interfaces

- Common-mode chokes, CM attenuation and resonance (4/4)
- Filter measurements on CM choke L24 **via antenna** (monopole)
  16 MHz **and** 25 MHz oscillators in operation



- Pronounced resonance due to antenna impedance $Z_{(f)}$
- Parasitic capacitance of the CM choke amplifies the radiation from approx. 270 MHz onwards
- Capacitors cause
  - Add. attenuation < 250 MHz
  - No effect > 250 MHz

- Rough estimation: $\lambda/4$ = 0,5m → f_o = 150 MHz → Antenna base connection impedance ~ 36 Ω

HF - filters for data and signal interfaces

- Summary and conclusions

- For a rough estimation, a filter calculation/simulation in advance is useful and important.
- A high filter attenuation in a 50 Ω system does not guarantee a high filter attenuation in the circuit or in the target system..
- Impedances of the noise source and the noise sink cannot be calculated with realistic effort, but can be estimated.
- Especially with interface filters, variable load impedances over the frequency due to the peripheral cables must be expected.
- Shield attenuation of the peripheral cables must also be taken into account (current clamp measurement!)
- Parasitic impedances of the components can even increase the interference level under "unfavourable conditions" compared to the conditions without filters. Component behavior can be checked with REDEXPERT
  https://redexpert.we-online.com/redexpert/
- An overall consideration of all system impedances (source, filter, sink/cable) is necessary to be able to make a realistic statement about the filter functionality.

Questions, Comments, Complaints ?