Modelling of Ground-Noise for Circuits with Short-Channel Transistors

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Overview

- Motivation
- Definition of Ground-Noise
- Modelling of Ground-Noise
  - Ground-Noise model
  - Parameter determination
- Numerical example
- Summary

Motivation: Problems and their solutions

- Expensive measurements on finished product
- Time-consuming simulations of full circuit
- Overlap of different effects

- Partitioning of circuit into functional blocks
- Description of single effect
- Error-free circuit function in consideration of one effect
- High-Level Simulations for complete circuit

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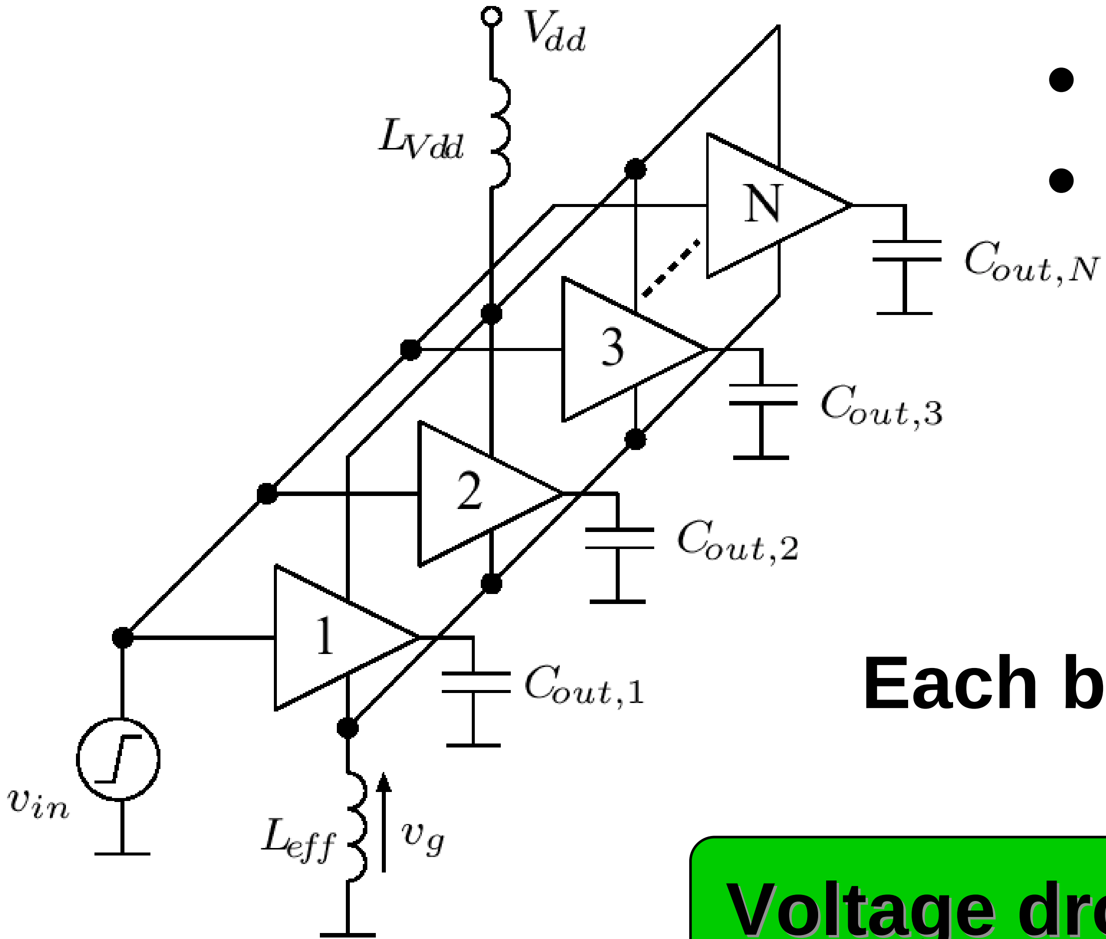
Definition of Ground-Noise

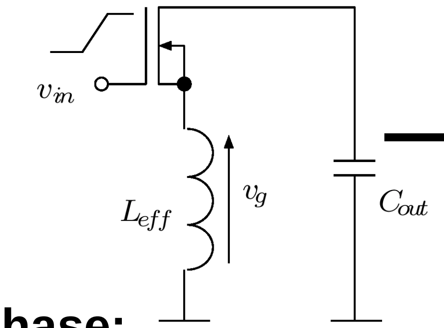


- The ***effective inductance***
- ***N*** **buffers switch simultaneously (High → Low)**

Each buffer can be simplified to a CMOS inverter

Voltage drop at the *effective inductance*

Modelling of Ground-Noise: Split of the Ground-Noise signal

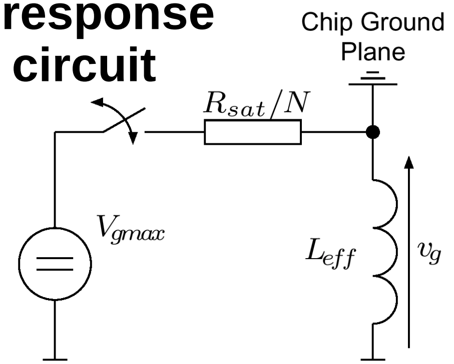


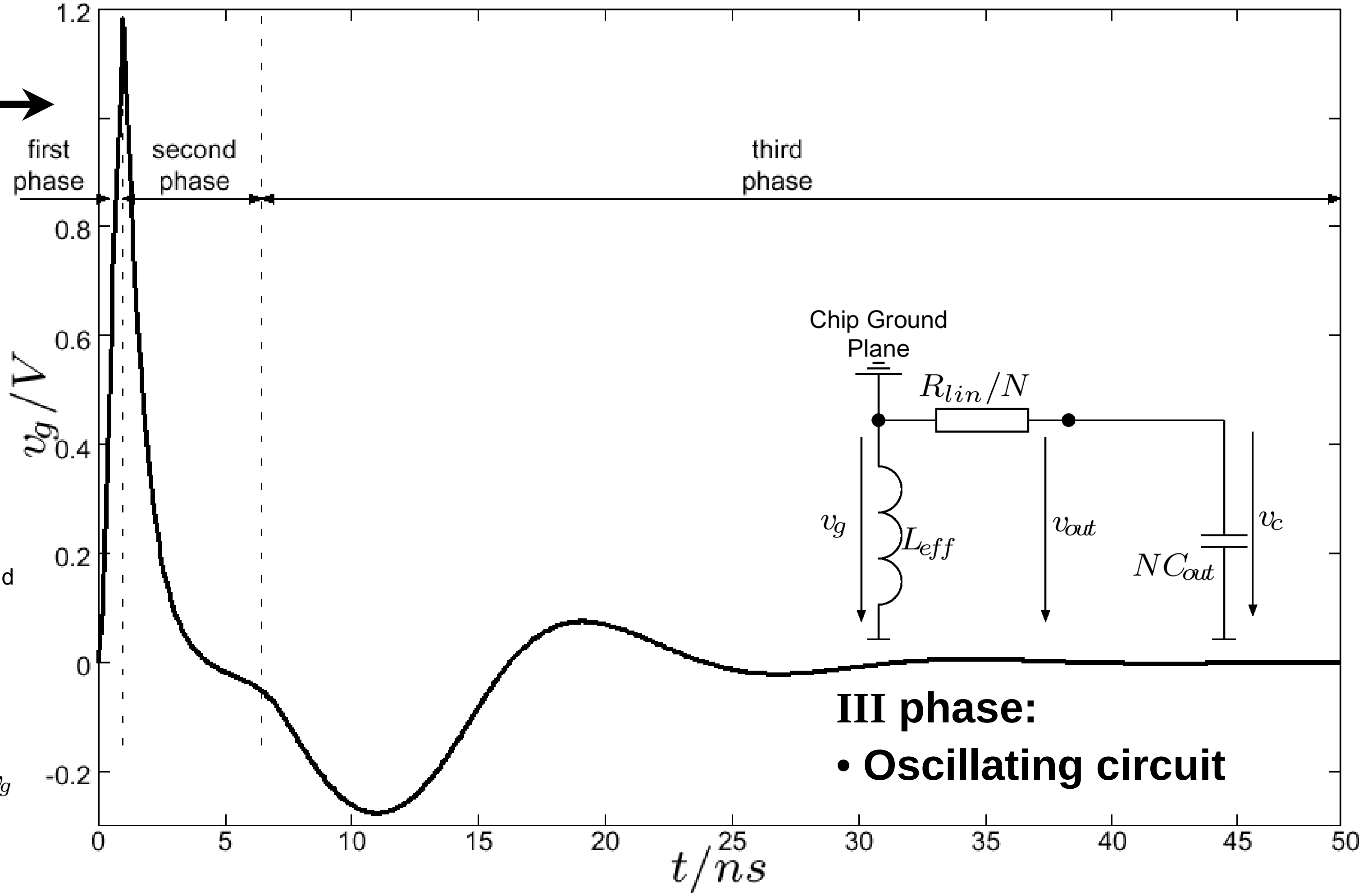
I phase:

- **Linear increase**
- **Charging curve**

II phase:

- **Time response of RL circuit**

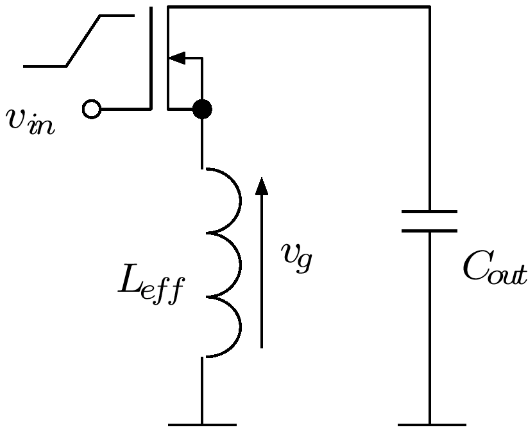




III phase:

- **Oscillating circuit**

Modelling of Ground-Noise: Analysis of the first phase



For signals with short rise/fall time:

- **the load capacitance is relatively large**
- **during the transient process the n-channel transistor operates in the saturation area**
- **current through load capacitance is negligible in comparison with the transistor current**
- **maximal value of noise originates, when the input voltage originates its plateau**
- **noise voltage increases linear**

Starting point:

$$v_g(t) = NL_{eff} \frac{di_d(t)}{dt}$$

BSIM3v3 mobility model for saturation current:

$$i_d = WC_{ox}v_{sat} \frac{(v_{gs} - V_{th})^2}{E_{sat}L + v_{gs} - V_{th}}$$

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Modelling of Ground-Noise: Analysis of the first phase

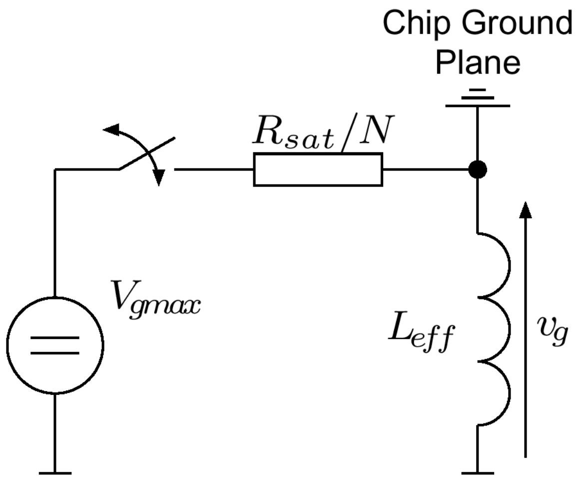
$$V_{gmax} = W C_{ox} v_{sat} N L_{eff} \left(\left(\frac{2(a - V_{gmax})}{b - V_{gmax}} - \frac{(a - V_{gmax})^2}{(b - V_{gmax})^2} \right) \left(\frac{V_{dd}}{t_r} - \frac{V_{gmax}}{t_r - t_d} \right) \right)$$

$$a = V_{dd} - V_{th}$$

$$b = E_{sat} L + V_{dd} - V_{th}$$

V_{gmax}	- noise voltage	W	- channel width
C_{ox}	- oxide capacitance	v_{sat}	- saturation velocity of carrier
N	- number of buffers	L_{eff}	- effective inductance
V_{dd}	- power supply voltage	V_{th}	- threshold voltage
E_{sat}	- electrical field in channel	L	- channel length
t_r	- rise time of input voltage	t_d	- delay time

Modelling of Ground-Noise: Analysis of the second phase



Mathematical description of the circuit

$$v_g(t) = \frac{R_{sat}}{N} i(t) + L_{eff} \frac{di(t)}{dt} = R_s i(t) + L_{eff} \frac{di(t)}{dt}$$

$$i(t) = \frac{V_{gmax}}{R_s}\left(1 - \exp^{-\frac{t}{\tau_L}}\right) \qquad \tau_L = \frac{L_{eff}}{R_s}$$

Mathematical description of the voltage at the inductance:

$$v_g(t) = V_{gmax} - R_s i(t) = V_{gmax} \exp^{-\frac{t}{\tau_L}}$$

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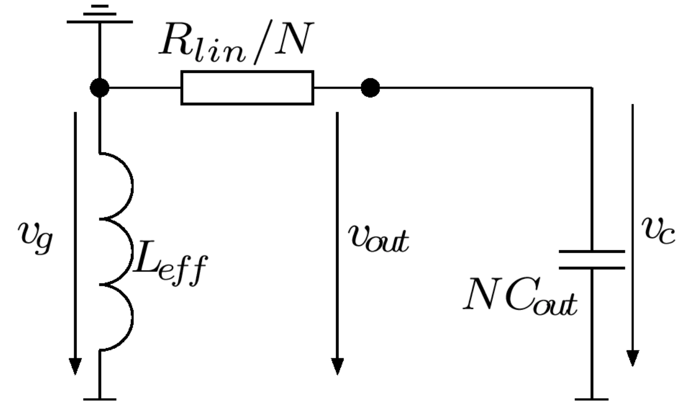
Modelling of Ground-Noise: Analysis of the third phase



Mathematical description of the circuit

$$L_{eff} C_{outtot} \frac{d^2 v_c(t)}{dt^2} + R_l C_{outtot} \frac{dv_c(t)}{dt} + v_c(t) = 0$$

$$C_{outtot} = NC_{out} \qquad R_l = \frac{R_{lin}}{N}$$

Three cases for solution of differential equation depending on: $\vartheta = \frac{R_l \sqrt{L_{eff} C_{outtot}}}{2L_{eff}}$

- **ϑ > 1: over-damped case - only for some configurations**
- **ϑ = 1: critically damped case - the most uncommonly case**
- **ϑ < 1: under-damped case - the most frequently case**

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Modelling of Ground-Noise: Analysis of the third phase

Under-damped case

$$v_g(t) = V_{dsat} \exp^{-\delta t} \cos(\varpi_d t - \Theta)$$

Damping constant:

$$\delta = \frac{R_l}{2L_{eff}}$$

Damping angle:

$$\Theta = \arctan\left(\frac{\delta}{\varpi_d}\right)$$

Eigen angular frequency:

$$\varpi_d = \frac{1}{\sqrt{L_{eff} C_{outtot}}} \sqrt{1 - \vartheta^2}$$

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Ground-Noise model

$$v_g(t) = \begin{cases} 0 & for \quad t < t_d \\ \frac{V_{gmax}}{t_r - t_d} t - \frac{V_{gmax}}{t_r - t_d} t_d & for \quad t_d \le t \le t_r \\ V_{gmax} e^{-\frac{t - t_r - t_x}{\tau_L}} - K & for \quad t_r < t < t_{23} \\ v_l(t - t_{s3}) & for \quad t_{23} < t \end{cases}$$

- ***K*** - voltage shift for the second phase
- ***t_x*** - time shift for the second phase
- ***$v_l(t)$*** - voltage on the inductance during the third phase
- ***t_{s3}*** - time shift for the third phase

Parameter determination: Split of all parameters

- physical constants,
- transistor parameters, found in the parameter file of a given transistor model,
- circuit parameters, to be read in the schematic,
- parameters, which have to be determined using simulations,

Needed to calculate the maximal value of Ground-Noise due to $\frac{di}{dt}$

Can be taken from IBIS model

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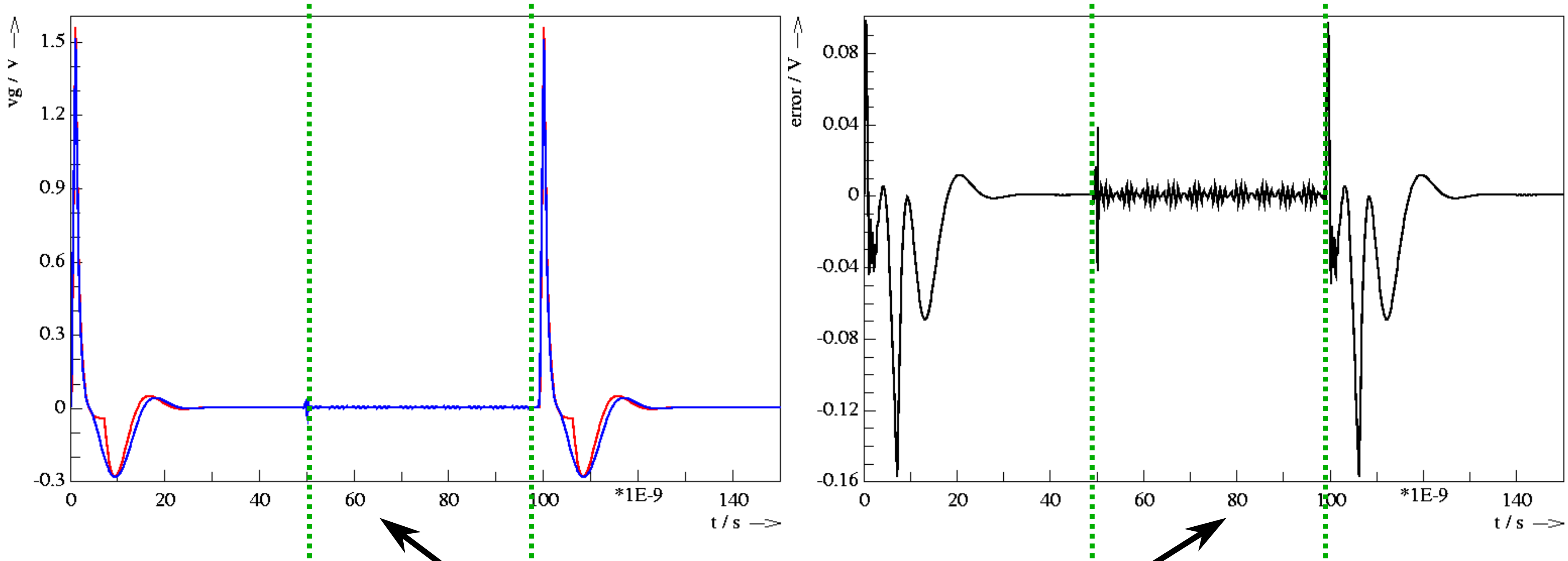
Numerical example I: Circuit and signal parameters

Comparison between simulation results and calculation results

number of buffers	(N)	= 8
frequency of input signal	(f)	= 10 MHz
rise time of input voltage	(t_{r_in})	= 1 ns
power supply voltage	(V_{dd})	= 3.3 V
effective inductance	(L_{eff})	= 10 nH
load capacitance	(C_{out})	= 50 pF
fall time of output voltage	(t_f)	= 6.85 ns

Numerical example I: In the time domain



outside of the validity area

full circuit simulation (blue)

model (red)

$$error = v_{simul} - v_{model}$$

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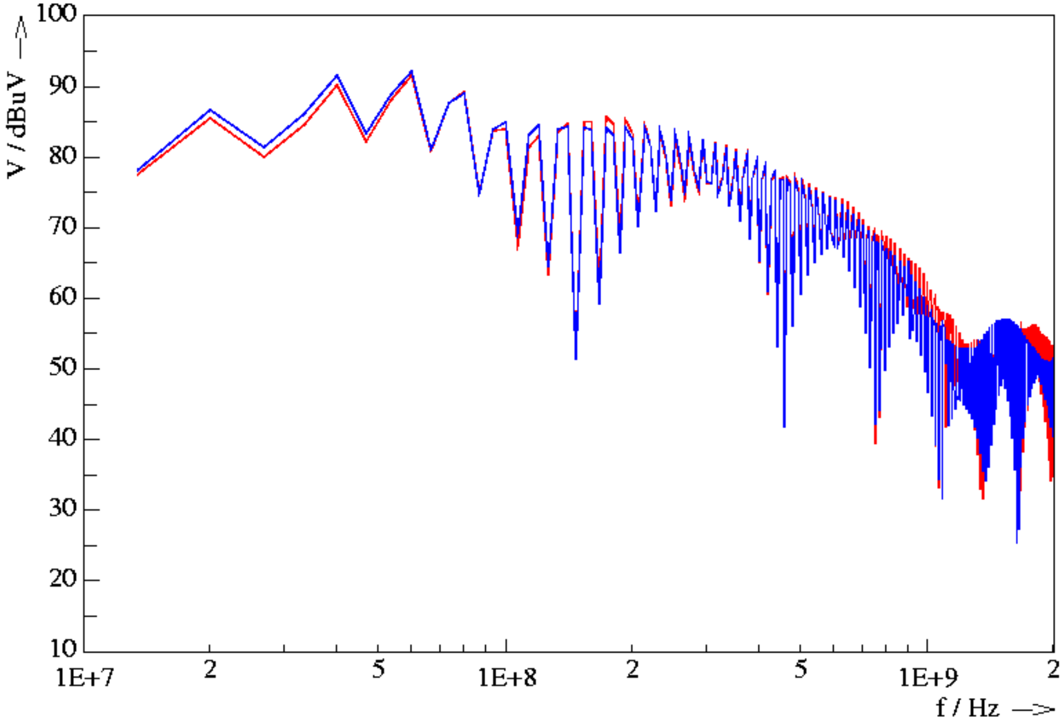
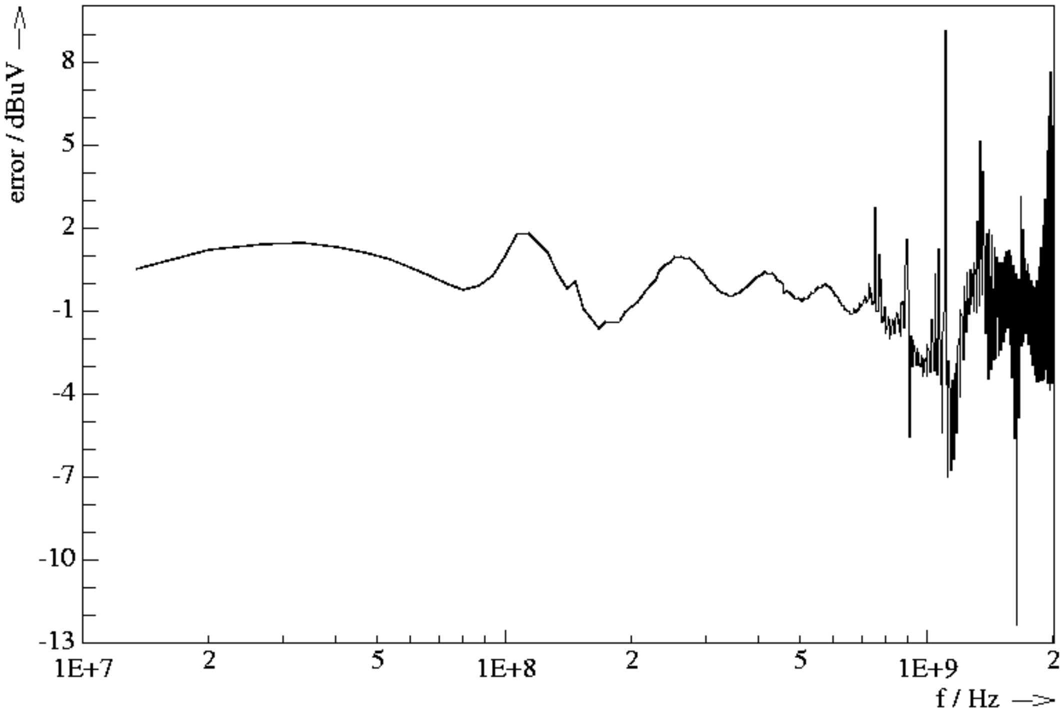
Numerical example I: In the frequency domain





- full circuit simulation (blue)
- model (red)

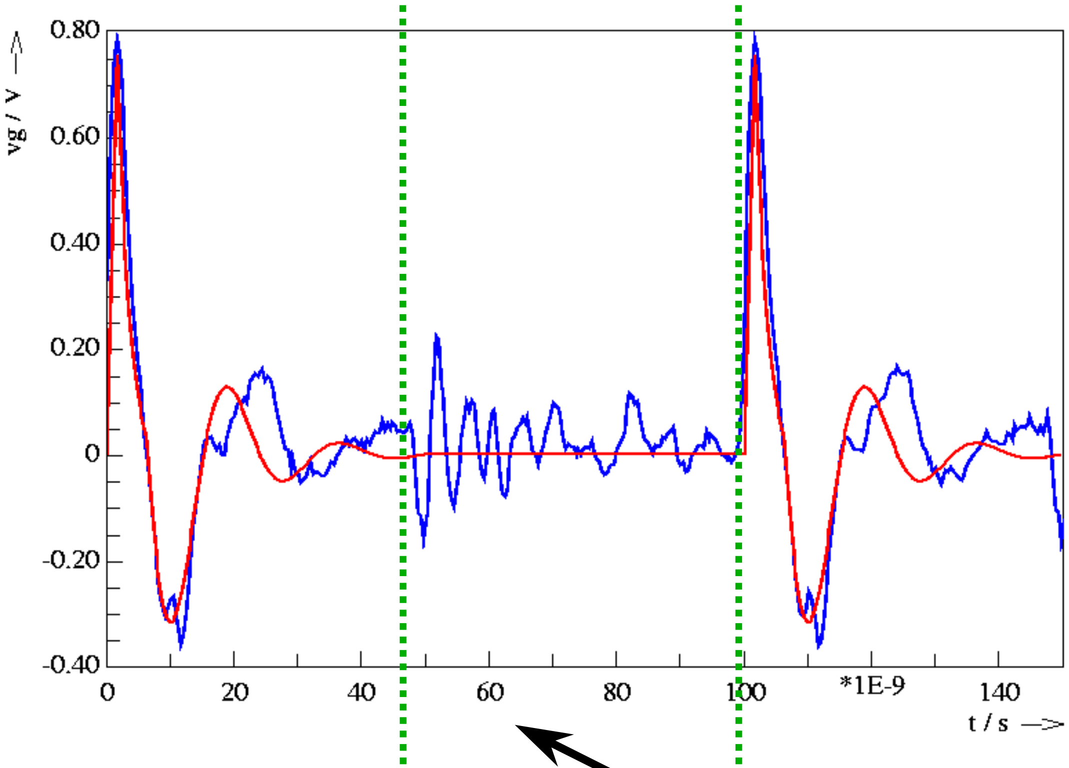
$$error = v_{simul} - v_{model}$$

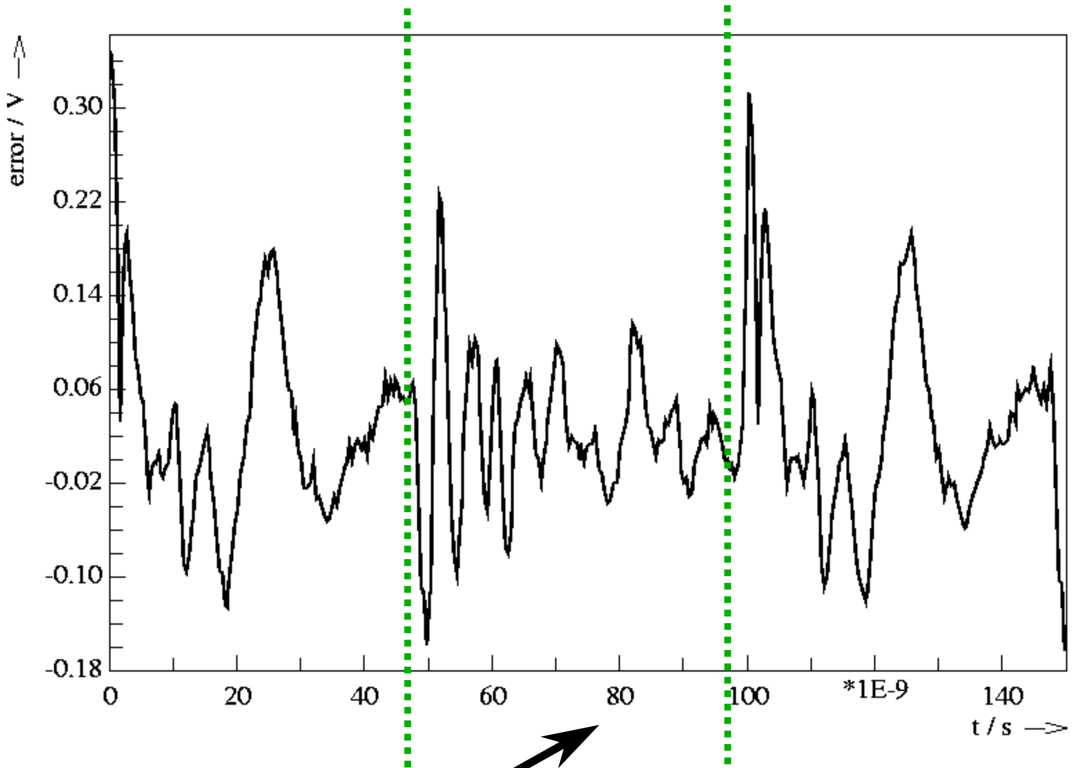
Numerical example II: Circuit and signal parameters

Comparison between measurements and calculation results

number of buffers	(N)	= 8
frequency of input signal	(f)	= 10 MHz
rise time of input voltage	(t_{r_in})	= 2 ns
power supply voltage	(V_{dd})	= 3.0 V
effective inductance	(L_{eff})	= 18 nH (recalculated)
load capacitance	(C_{out})	= 47 pF
fall time of output voltage	(t_f)	= 5.00 ns

Numerical example II: In the time domain





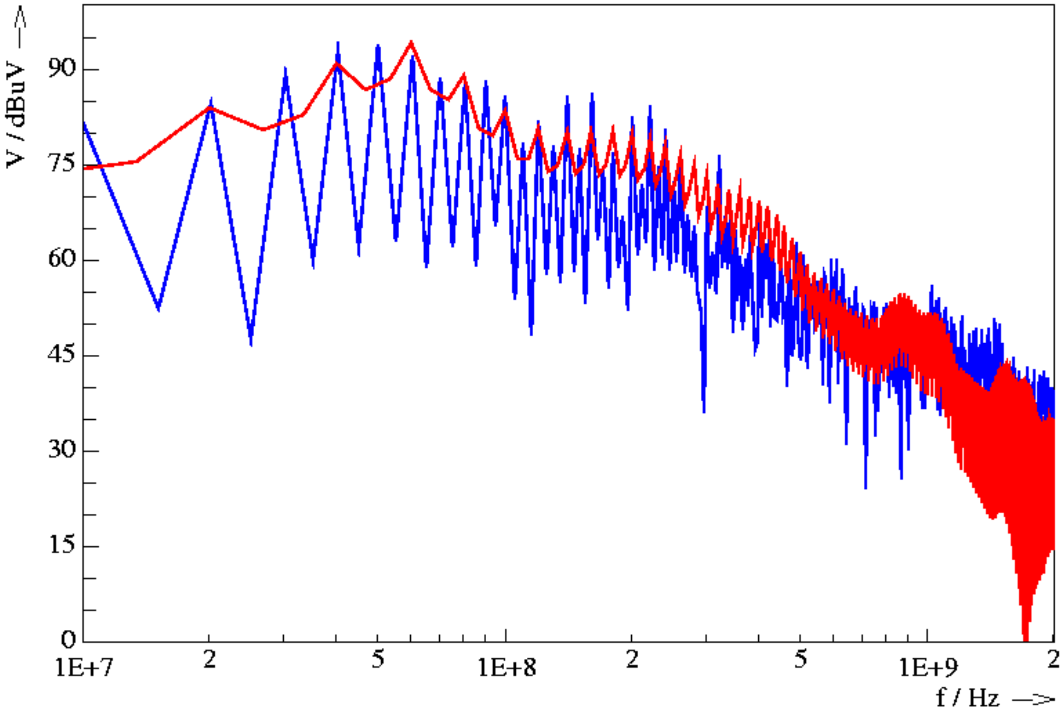
outside of the validity area

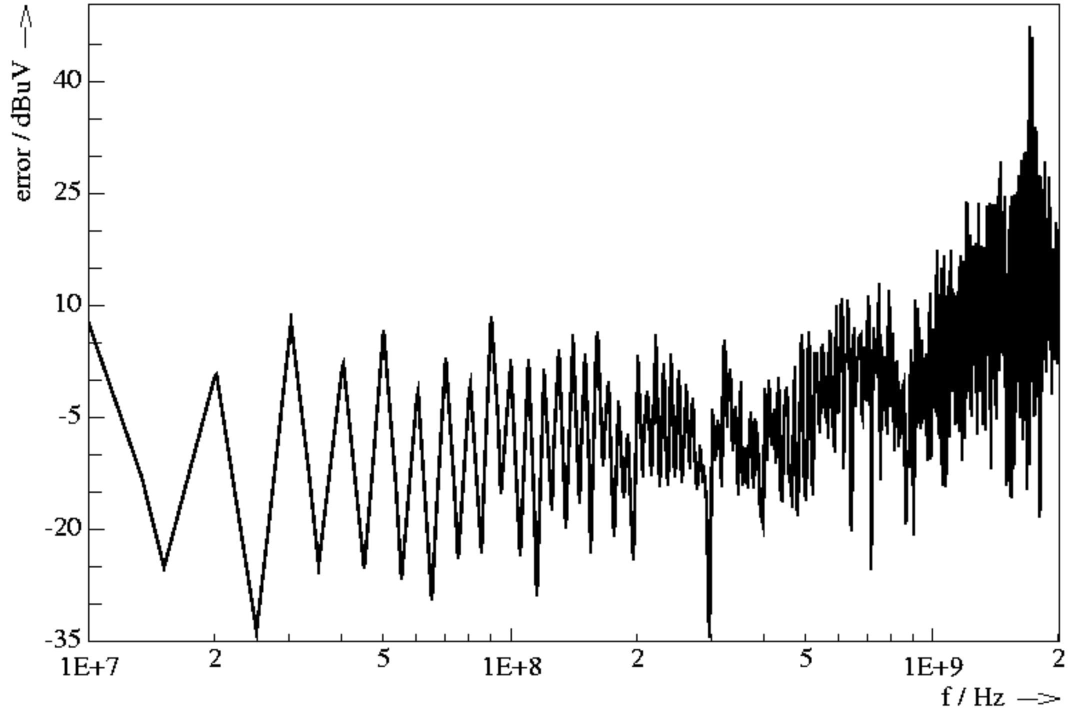
measurements

model

$$error = v_{measurements} - v_{model}$$

Numerical example II: In the frequency domain





measurements (blue)
model (red)

$$error = v_{measurements} - v_{model}$$

Summary

- Motivation
- Definition of Ground-Noise
- Modelling of Ground-Noise
- Determination of parameters
- Accuracy of model
    - model $\leftrightarrow$ simulations
    - model $\leftrightarrow$ measurements