Inter-chip and Intra-chip Pulsed Signal Transfer Between Transmitting and Receiving Loops in Wireless Interconnect Configurations

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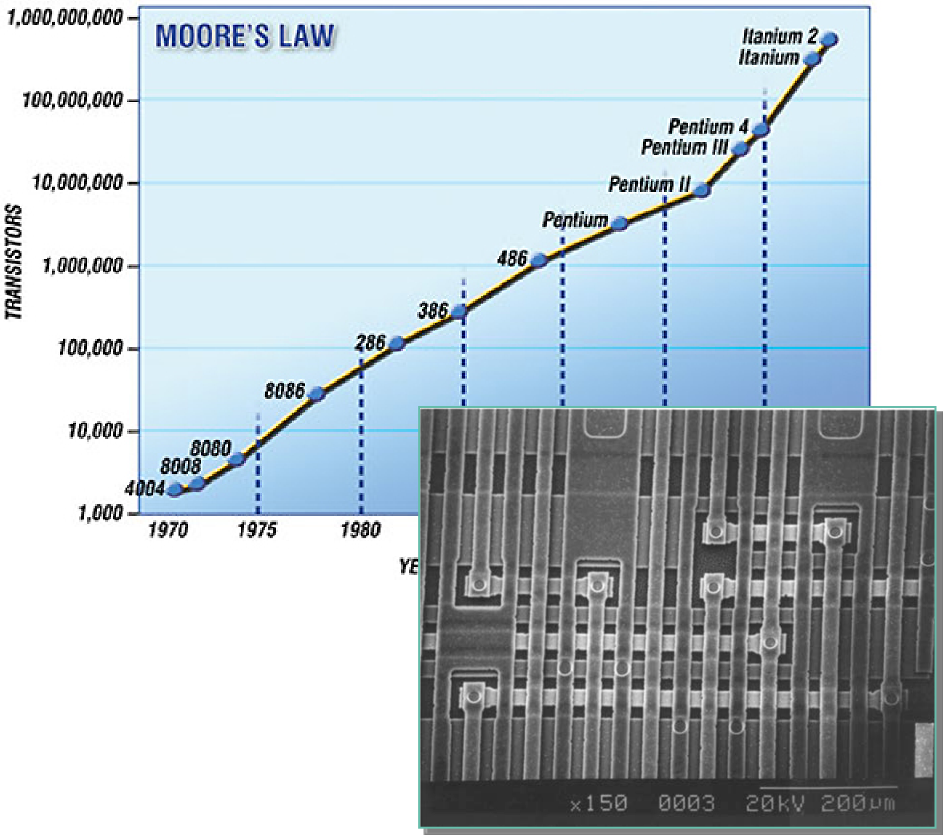
Effective and feasible interconnect a prime concern for IC technology



Persisting trend of downsizing integrated electronic circuit components

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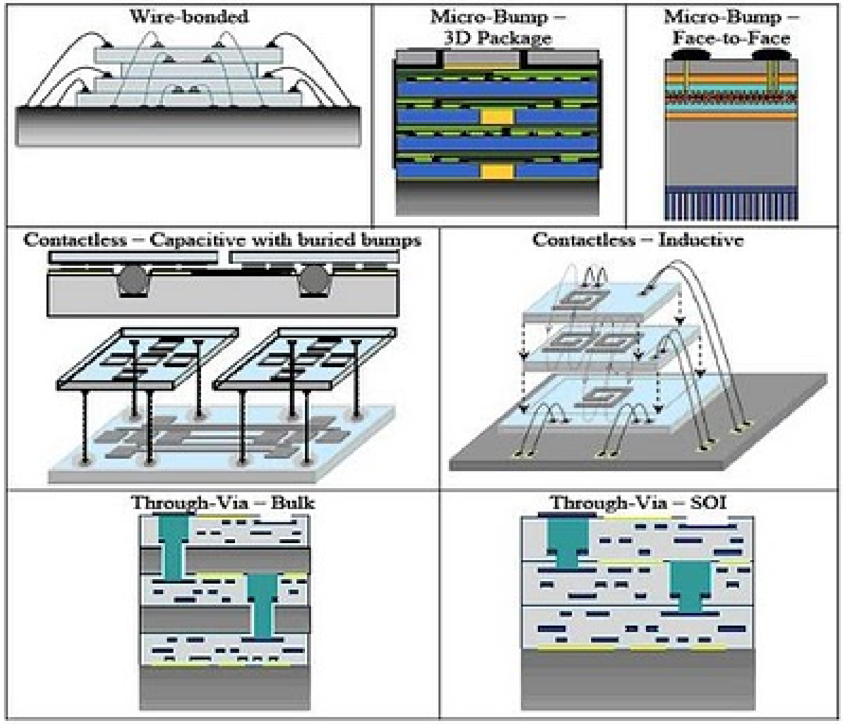
Insufficient space for the input and output ports that are to perform the necessary intra- and inter-chip signal communication

Effective and feasible interconnect a prime concern for IC technology



- IC capacity increase by complex, 3D architectures

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- Physical limitations for the realisation of through layers interconnects

Effective and feasible interconnect a prime concern for IC technology

- **Problem:** Classical electrical conductive-wire reach their physical limits[1]

- **Solution:** Wireless interconnects, that perform the signal transfer through electromagnetic (EM) radiation

[1]M.-C.F. Chang, V.P. Roychowdhury, L. Zhang, H. Shin, and Y. Qian, "RF/wireless interconnect for inter- and intra-chip communications," *Proceedings of IEEE*, vol. 89, no. 4, pp. 456–466, April 2001

Effective and feasible interconnect
a prime concern for IC technology

- Challenge: the need of accommodating ever higher bit rates in the pulsed signals handled by the circuits

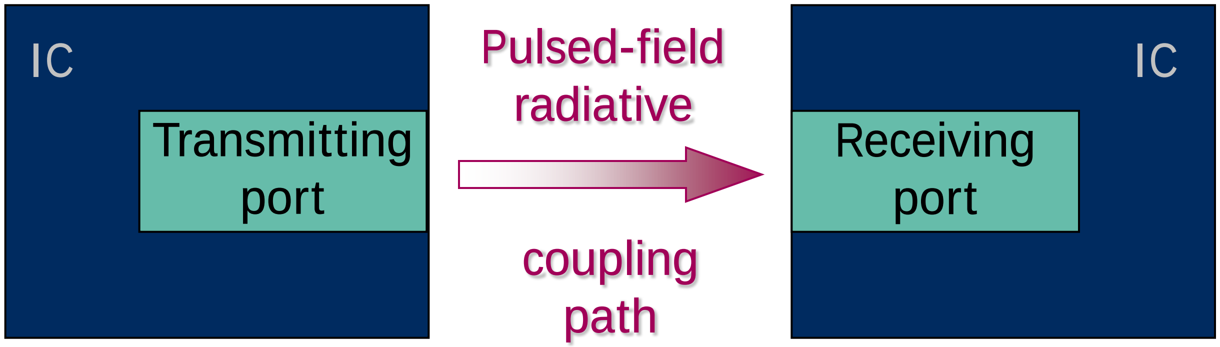
- From a wireless perspective:
  - fast, reliable, error-free communication channels
  - ElectroMagnetic Interference (EMI)
  - the **pulsed** nature of the signals in present-day information technology ⇒ the real technical-physical problem to be solved is one in **space-time**

- We need: an adequate theory and analysis, with accompanying optimisation procedures

Synopsis

- System description
- Prerequisites
- Illustrative numerical results
- Conclusions

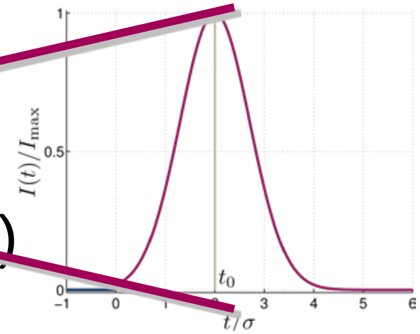
System description



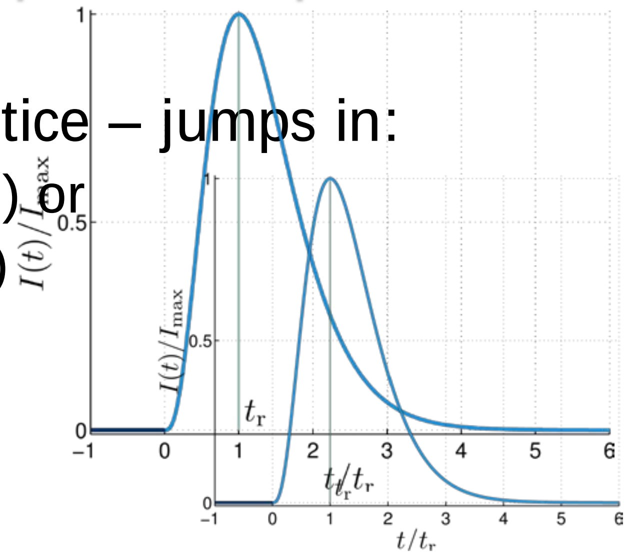
- Elements:
  - the emitter (a transmitting loop)
  - the coupling path (free-space electromagnetic wave propagation)
  - the susceptor (a receiving loop)

System description

- Habitual excitation: the Gaussian pulse
  - non-causal
  - infinitely smooth (infinitely differentiable)



- The proper excitation: the power exponential pulse
  - causality is preserved
  - accounts for the signals met in practice – jumps in:
    - their amplitudes (rectangular pulses) or
    - their derivatives (trapezoidal pulses)
  - pulse amplitude
  - pulse rise time
  - pulse time width
  - pulse fall time



International Electrotechnical Vocabulary

System description

- Analysis tool: the electromagnetic field/source reciprocity theorem of the time-convolution type[2]

The response of the receiving loop follows from an equivalent Thévenin Kirchhoff circuit

Generator voltage strength

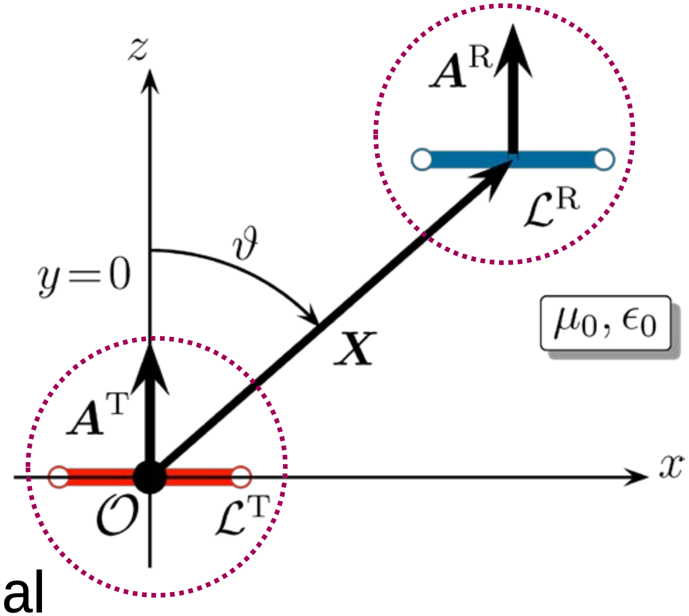
$$= f \left(\begin{array}{l} \text{the exciting current in the transmitting loop} \\ \text{the geometry of the loop/loop configuration} \end{array} \right)$$

[2]A.T. de Hoop, I.E. Lager, V. Tomassetti, "The pulsed-field multiport antenna system reciprocity relation – a time-domain approach," IEEE Trans.~Antennas Propag., vol. 57, no. 3, pp. 594–605, March 2009

Prerequisites

Analysed configuration:

- the emitter
- the susceptor
- the coupling path:
  - electric permittivity ϵ_0
  - magnetic permeability μ_0
  - wave speed $c_0 = (\epsilon_0 \mu_0)^{-1/2}$
- loops:
  - maximum diameters $\ll$ the spatial extent of the exciting pulse
  - arbitrary shapes



Prerequisites

Excitation: the power exponential pulse (PEP)

$$I^{\mathrm{T}}(t) = I^{\mathrm{T}}_{\mathrm{max}}(t/t_{\mathrm{r}})^{\nu} \exp[-\nu(t/t_{\mathrm{r}}) + \nu]H(t)$$

- pulse amplitude $I^{\mathrm{T}}_{\mathrm{max}}$
- rising exponent ν
- pulse rise time t_{r}
- pulse time width t_{w}

$$t_{\mathrm{w}} = \Gamma(\nu + 1)\frac{\exp(\nu)}{\nu^{\nu+1}}t_{\mathrm{r}}$$

Prerequisites

PEP – normalized Bode spectrum

$$\left|\hat{I}^{\mathrm{T}}(\mathrm{j}\omega)/\hat{I}^{\mathrm{T}}(0)\right|_{\mathrm{dB}} = -10(\nu+1)\log_{10}\left[\omega^2(t_{\mathrm{r}}/\nu)^2+1\right]$$

– spectral bounds

$$\left|\hat{I}^{\mathrm{T}}(\mathrm{j}\omega)/\hat{I}^{\mathrm{T}}(0)\right|_{\mathrm{dB}} \leqslant 0$$

$$\left|\hat{I}^{\mathrm{T}}(\mathrm{j}\omega)/\hat{I}^{\mathrm{T}}(0)\right|_{\mathrm{dB}} < -20(\nu+1)\log_{10}(\omega t_{\mathrm{r}}/\nu)$$

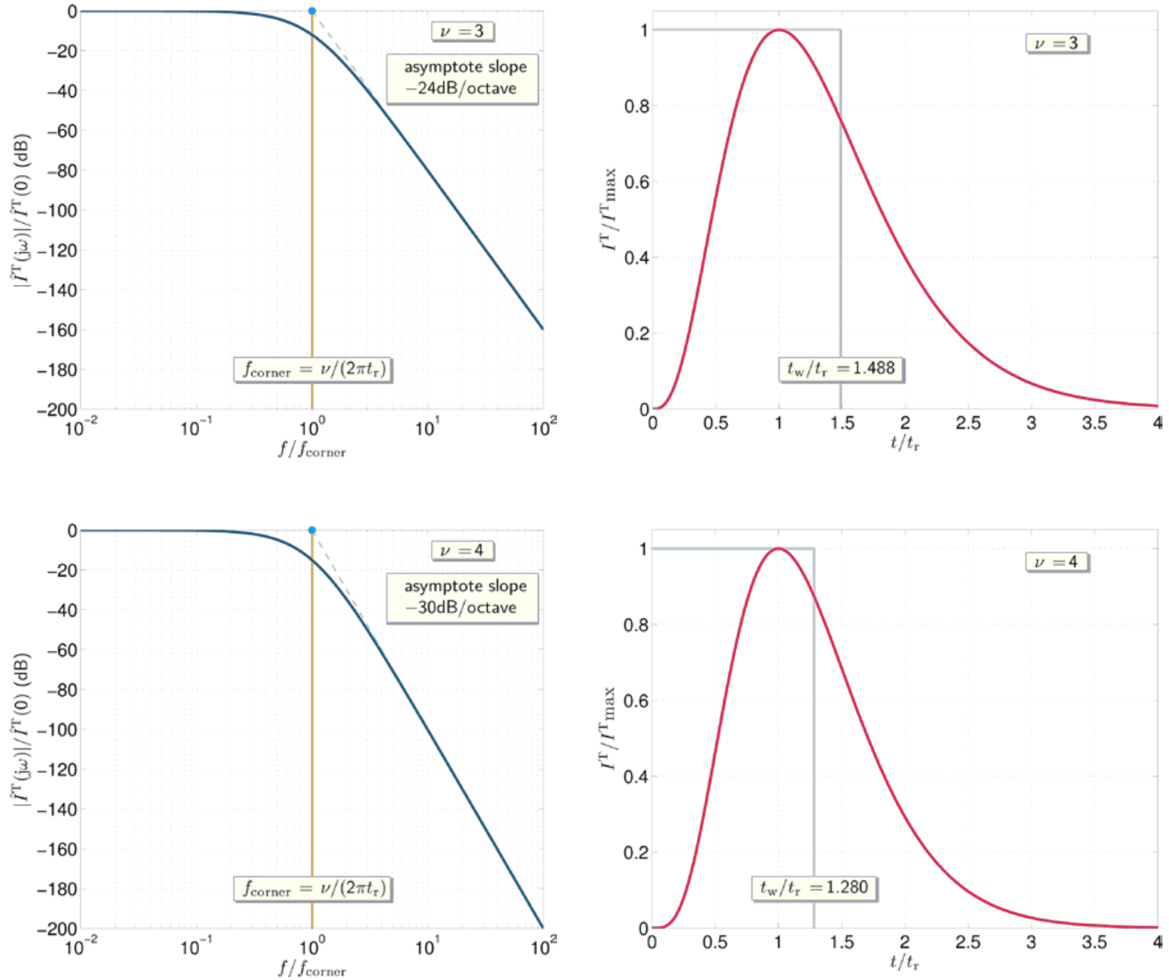
– corner frequency

$f_{\mathrm{corner}} = 2\pi(\nu/t_{\mathrm{r}})$ ⇨ $6(\nu+1)$ dB/octave

Prerequisites

Utilised pulses:

	$\nu = 3$	$\nu = 4$
t_{w}	100 ps	100 ps
t_{r}	67 ps	78 ps
f_{c}	7.1 GHz	8.15 GHz
spatial extent $c_0 t_{\mathrm{w}}$	30 mm	30 mm



Prerequisites

The equivalent Thévenin circuit generator voltage:

$$V^{\mathrm{G}}(t) \simeq -\mu_0 \partial_t \boldsymbol{H}^{\mathrm{T}}(\boldsymbol{X}, t) \cdot \boldsymbol{A}^{\mathrm{R}}$$

$$\boldsymbol{H}^{\mathrm{T}} = \boldsymbol{H}^{\mathrm{NF}} + \boldsymbol{H}^{\mathrm{IF}} + \boldsymbol{H}^{\mathrm{FF}}$$

- near-field constituent

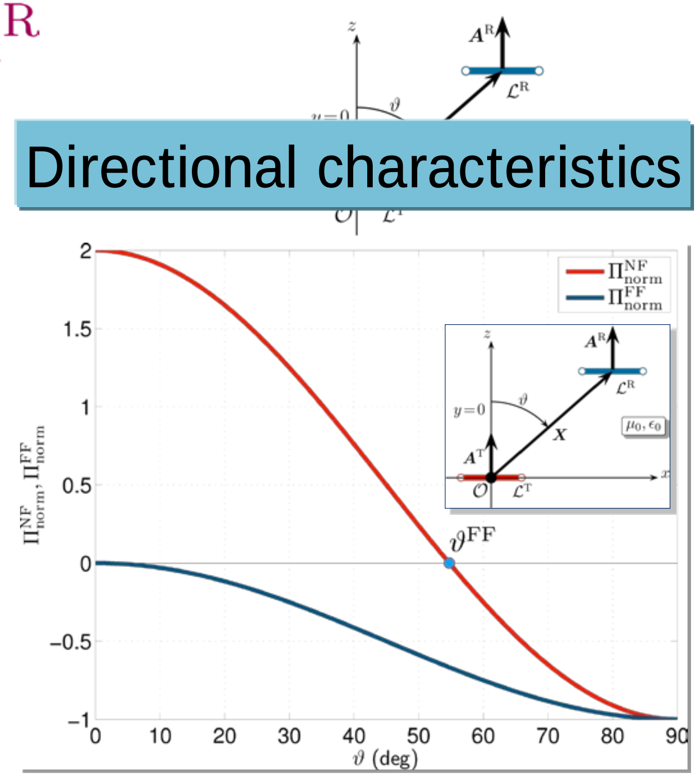
$$\boldsymbol{H}^{\mathrm{NF}} = \left[3\left(\boldsymbol{\Xi} \cdot \boldsymbol{A}^{\mathrm{T}}\right)\boldsymbol{\Xi} - \boldsymbol{A}^{\mathrm{T}}\right] \frac{I^{\mathrm{T}}(t - |\boldsymbol{X}|/c_0)}{4\pi|\boldsymbol{X}|^3}$$

- intermediate-field constituent

$$\boldsymbol{H}^{\mathrm{IF}} = \left[3\left(\boldsymbol{\Xi} \cdot \boldsymbol{A}^{\mathrm{T}}\right)\boldsymbol{\Xi} - \boldsymbol{A}^{\mathrm{T}}\right] \frac{\partial_t I^{\mathrm{T}}(t - |\boldsymbol{X}|/c_0)}{4\pi c_0|\boldsymbol{X}|^2}$$

- far-field constituent

$$\boldsymbol{H}^{\mathrm{FF}} = \left[\left(\boldsymbol{\Xi} \cdot \boldsymbol{A}^{\mathrm{T}}\right)\boldsymbol{\Xi} - \boldsymbol{A}^{\mathrm{T}}\right] \frac{\partial_t^2 I^{\mathrm{T}}(t - |\boldsymbol{X}|/c_0)}{4\pi c_0^2|\boldsymbol{X}|}$$

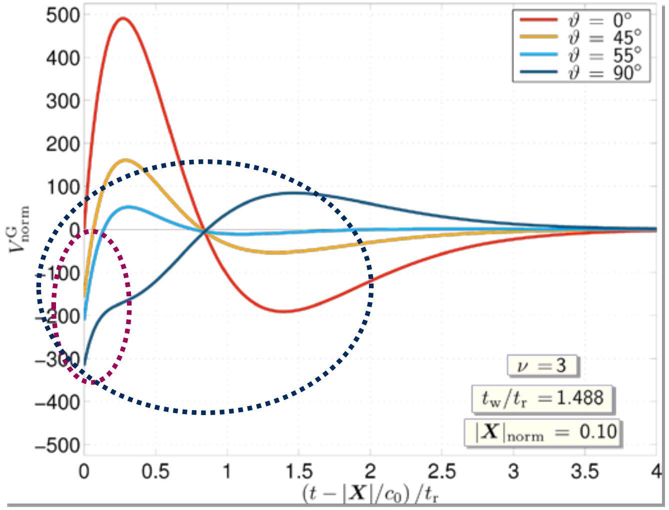


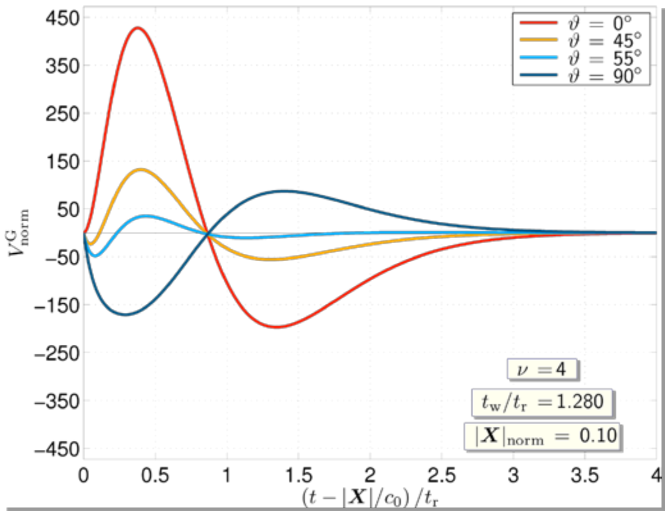
Illustrative numerical results

- Loops: $A^{\mathrm{T}} = A^{\mathrm{R}} =$ 0.314 mm^2 ⇨ 0.2mm diameter
- Normalisation:
  - the inter-loop spacing: $|\boldsymbol{X}|_{\mathrm{norm}} = |\boldsymbol{X}|/c_0 t_{\mathrm{w}}$
  - the wave travel shifted time coordinate: $(t - |\boldsymbol{X}|/c_0)\,/t_{\mathrm{r}}$
  - the generator source voltage:

$$V^{\mathrm{G}}_{\mathrm{norm}}(t) = -\left[\left(\frac{\mu_0}{\epsilon_0}\right)^{1/2} I^{\mathrm{T}}_{\mathrm{max}}\,\frac{A^{\mathrm{R}}A^{\mathrm{T}}}{(c_0 t_{\mathrm{w}})^4}\right]^{-1} V^{\mathrm{G}}(t)$$

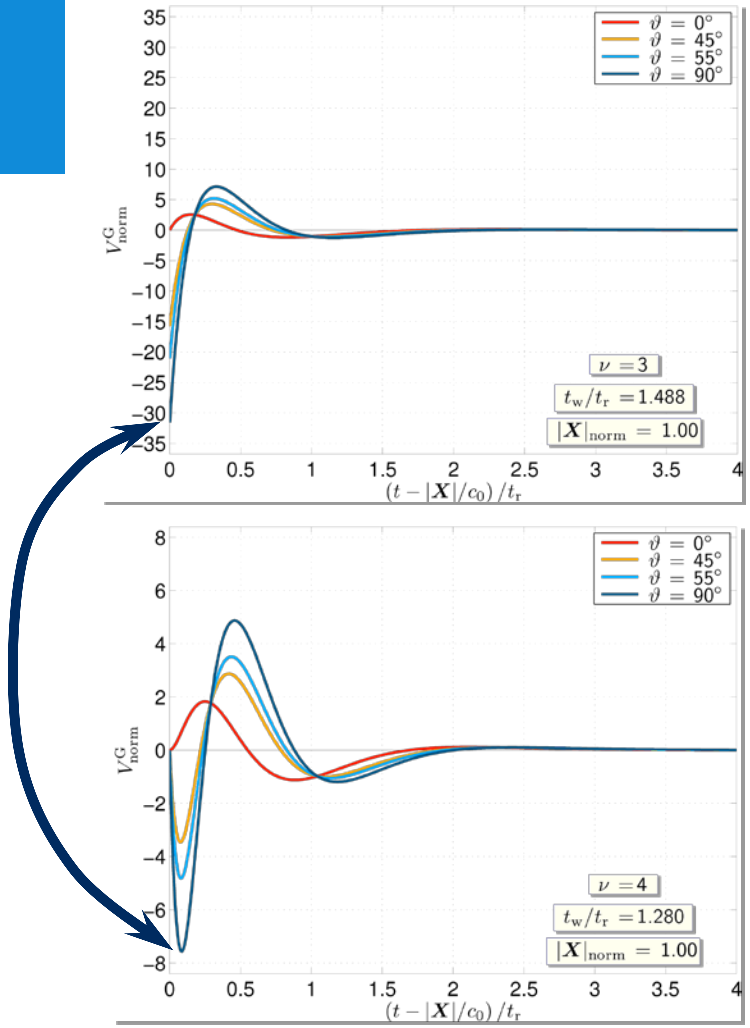
Illustrative numerical results





- Predominantly near-field constituent (containing $\partial_t I^{\mathrm{T}}(t)$)
- The effect of the step discontinuity at the field's onset
- Particular time signature: steep front and a smooth tail ⇨ potential for easier signal processing

Illustrative numerical results



- Predominantly far-field constituent (containing $\partial_t^3 I^{\mathrm{T}}(t)$)
- The effect of the shorter rise time for $\nu = 3$ on the amplitude of the received signal

Such effects must be accounted for when evaluating the inter-channel interference when transmitting sharp pulses!

Conclusions

- The wireless inter-chip and intra-chip pulsed signal transfer entails an intricate behavior consisting of constituents that are related to the structure of the magnetic field in the coupling path as it is radiated by an electric-current excited transmitting loop
- The numerical results evidence the complexity of the transfer
- The model provides a first basis for the study of signal integrity in integrated circuit design with wireless interconnect signal transfer