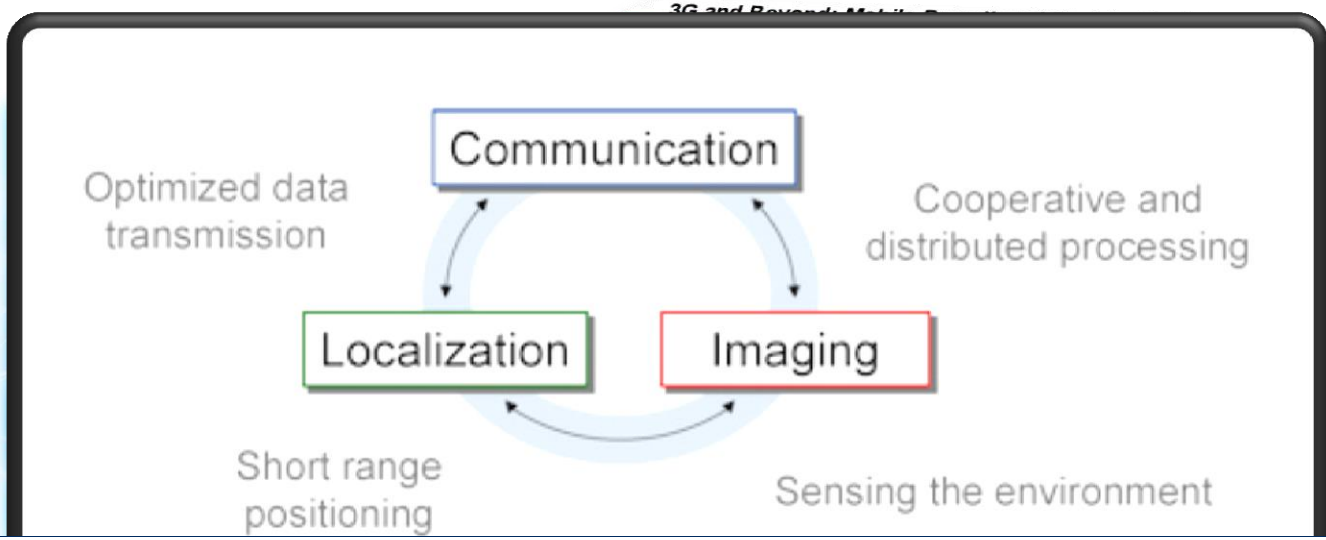
Wireless digital information transfer:
modelling, prediction and assessment

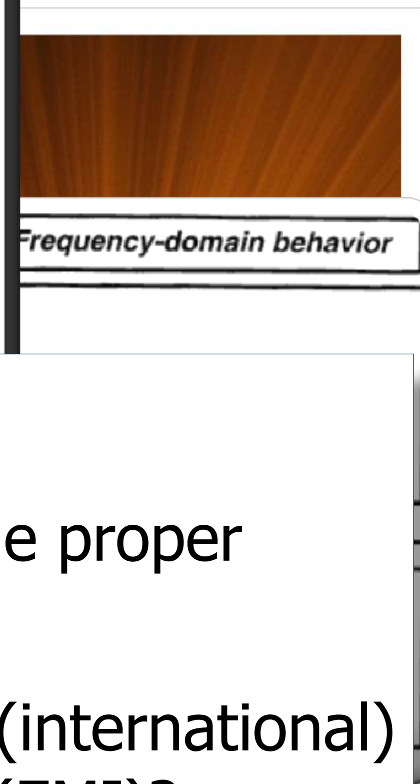
Ioan E. Lager, Adrianus T. de Hoop, Delft University of Technology

Takamaro Kikkawa, Hiroshima University

19 March, 2013

The digital wireless-sphere





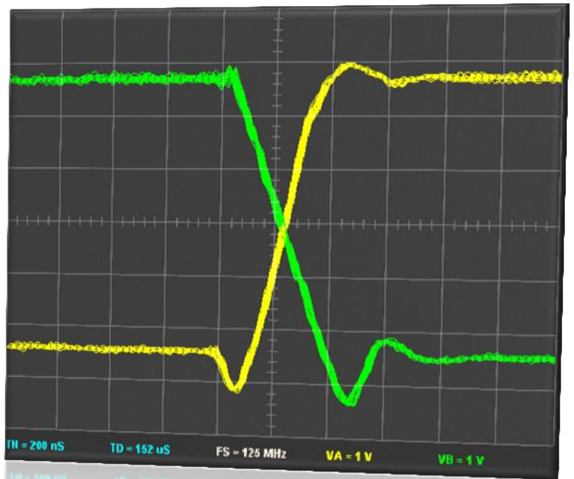
Wireless links' functionality:

- Are the signal levels involved sufficient for the proper system performance?
- Do the field emission levels comply with the (international) regulations on ElectroMagnetic Interference (EMI)?

Synopsis

- Digital signals EMI analysis
- Prerequisites
  - analysed configuration
  - exciting pulses
  - theoretical background
- Loop-to-loop transfer
- Energy spectral density of the emitted field
- Numerical experiments
  - loop-to-loop transfer
  - energy spectral density of the emitted field
- Conclusions

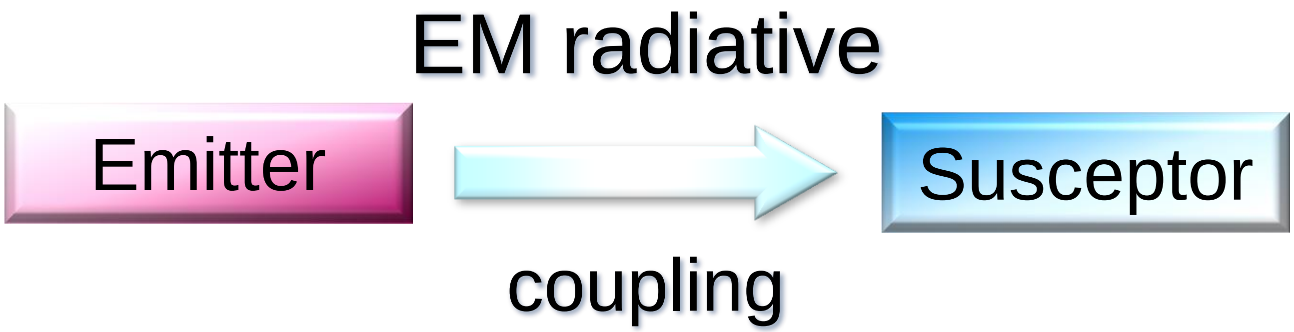
Digital signals EMI analysis



- Digital electronic systems → time-domain
- Their investigation → time-domain

~~frequency-domain~~

Digital signals EMI analysis



The EMI triptych → its simplest representative circuit:

- Transmitting loop ← pulsed electric current feeding
- Receiving loop → generator source of the equivalent Thévenin Kirchhoff circuit
- Coupling path → free space

Digital signals EMI analysis

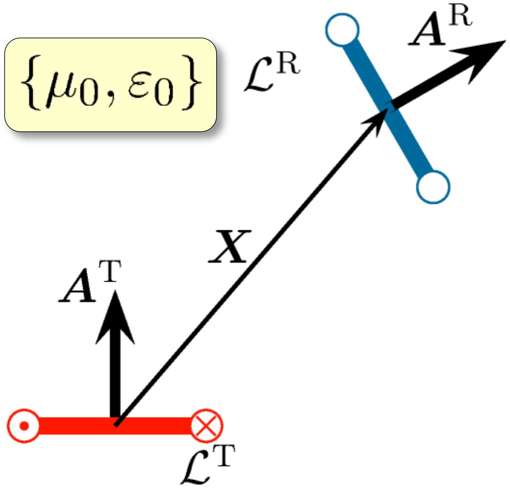
- EM field description: the time-domain magnetic field $\boldsymbol{H}$

compatibility ↕ ?

- International EMI regulations: frequency-domain masks

Prerequisites: configuration

- Transmitting loop $\mathcal{L}^{\mathrm{T}}$
  - reference centre: $\boldsymbol{x} = \boldsymbol{x}^{\mathrm{T}}$
  - area: $\boldsymbol{A}^{\mathrm{T}} = \boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}} A^{\mathrm{T}}$



- Receiving loop $\mathcal{L}^{\mathrm{R}}$
  - reference centre: $\boldsymbol{x} = \boldsymbol{x}^{\mathrm{R}}$
  - area: $\boldsymbol{A}^{\mathrm{R}} = \boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}} A^{\mathrm{R}}$

- Coupling path
  - position: $\boldsymbol{X} = \boldsymbol{x}^{\mathrm{R}} - \boldsymbol{x}^{\mathrm{T}}$ ➡ $\boldsymbol{X}/|\boldsymbol{X}| = \boldsymbol{\Xi}$
  - medium: free space $\{\epsilon_0, \mu_0\}$ ➡ $c_0 = (\epsilon_0 \mu_0)^{-1/2}$

Prerequisites: exciting pulses

Main requirement:

CAUSALITY

Prerequisites: exciting pulses

Time differentiated power exponential pulse (∂_tPE)

$$I(t) = I_{\text{peak}} N(\nu) \left(1 - \frac{t}{t_{0\text{x}}}\right) \left(\frac{t}{t_{0\text{x}}}\right)^{\nu-1} \exp\left[-\nu\left(\frac{t}{t_{0\text{x}}} - 1\right)\right] H(t) \text{ for } \nu > 1$$

where:

- I_{peak} = magnitude of the first peak in $I(t)$
- $t_{0\text{x}}$ = pulse zero-crossing time (= t_{r} of the original PE)
- ν = initial rise power of the original PE
- $H(t)$ = Heaviside unit step function
- $N(\nu)$ = normalisation constant

$$N(\nu) = \nu^{1/2} \left(\frac{\nu^{1/2}}{\nu^{1/2} - 1}\right)^{\nu-1} \exp(-\nu^{1/2})$$

Prerequisites: exciting pulses

Time differentiated power exponential pulse (∂_tPE)

$$I(t) \xrightarrow{\text{LT}} \hat{I}(s)$$

$$\hat{I}(s) = I_{\text{peak}}\, t_{0\text{x}}\, N(\nu)\, \frac{s\, t_{0\text{x}} \Gamma(\nu) \exp(\nu)}{(s\, t_{0\text{x}} + \nu)^{\nu+1}} \text{ for } \mathrm{Re}(s) > -\nu/t_{0\text{x}}$$

where:

- Γ = Euler gamma function

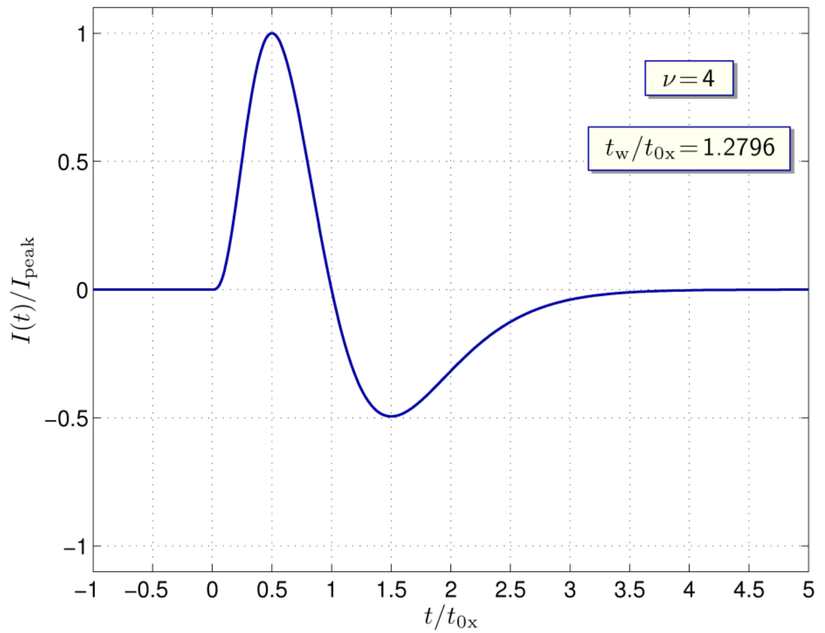
Fourier

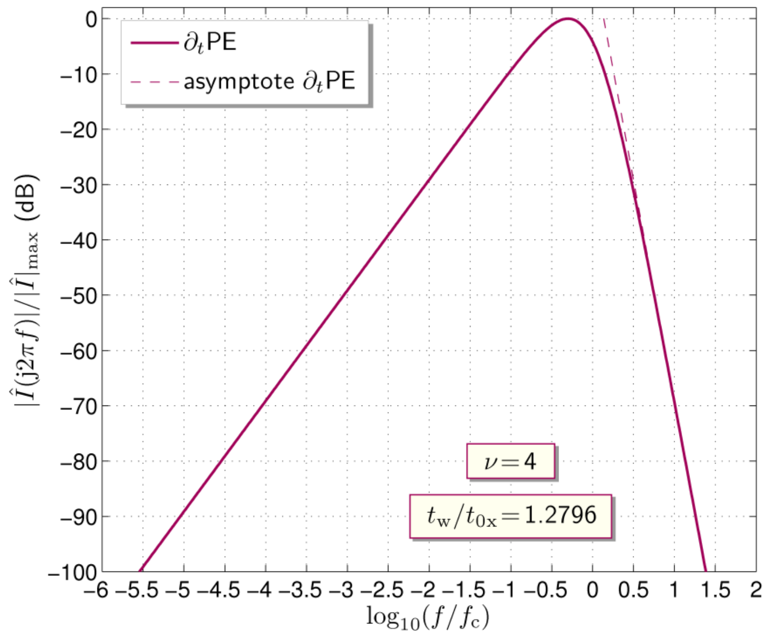
$$I(t) \xrightarrow{\text{FT}} \hat{I}(\mathrm{j}\omega) \Leftrightarrow s = \mathrm{j}\omega = \mathrm{j}2\pi f, \text{ with } \omega \in \mathbb{R},\ f \in \mathbb{R}$$

Prerequisites: exciting pulses

Time differentiated power exponential pulse (∂_tPE)

$\nu = 4$

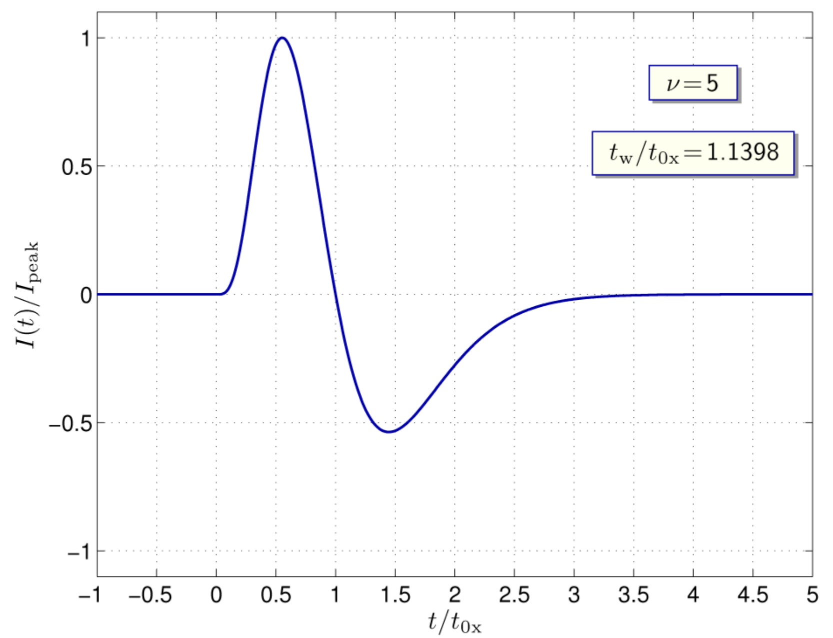


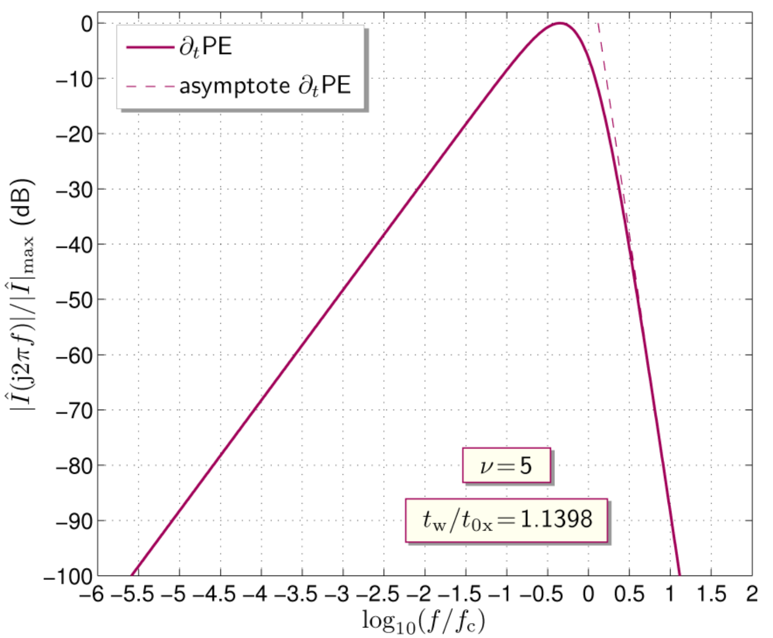


Prerequisites: exciting pulses

Time differentiated power exponential pulse (∂_tPE)

$\nu = 5$





Prerequisites: exciting pulses

Power exponential modulated – sinc-cosine pulse

- Normalised, unipolar, power exponential

$$I_{\mathrm{PE}}(t) = I_0\,(t/t_{\mathrm{r}})^{\nu} \exp\left[-\nu\,(t/t_{\mathrm{r}} - 1)\right] H(t)$$

  where:
  - I_0 = pulse amplitude
  - $t_{\mathrm{r}} > 0$ = pulse rise time

- Sinc-cosine function

$$G(t) = \mathrm{sinc}[B(t - t_0)] \cos\left[2\pi f_{\mathrm{c}}(t - t_0)\right]$$

  where:
  - t_0 = arbitrary delay
  - B = (prescribed) bandwidth $B = f_{\mathrm{h}} - f_{\mathrm{l}}$, with $0 < f_{\mathrm{l}} < f_{\mathrm{h}}$
  - f_{c} = centre frequency $f_{\mathrm{c}} = (f_{\mathrm{l}} + f_{\mathrm{h}})/2$

Prerequisites: exciting pulses

Power exponential modulated – sinc-cosine pulse

- Normalised, unipolar, power exponential

$$I_{\mathrm{PE}}(t) = I_0\,(t/t_{\mathrm{r}})^{\nu} \exp\left[-\nu\,(t/t_{\mathrm{r}} - 1)\right] H(t)$$

  where:
  - I_0 = pulse amplitude
  - $t_{\mathrm{r}} > 0$ = pulse rise time

- Sinc-cosine function

$$G(t) = \mathrm{sinc}[B(t - t_0)] \cos\left[2\pi f_{\mathrm{c}}(t - t_0)\right]$$

  where:
  - t_0 = arbitrary delay
  - B = (prescribed) bandwidth $B = f_{\mathrm{h}} - f_{\mathrm{l}}$, with $0 < f_{\mathrm{l}} < f_{\mathrm{h}}$
  - f_{c} = centre frequency $f_{\mathrm{c}} = (f_{\mathrm{l}} + f_{\mathrm{h}})/2$

non-causal

Prerequisites: exciting pulses

Power exponential modulated – sinc-cosine pulse

- Normalised, unipolar, power exponential

$$I_{\mathrm{PE}}(t) = I_0 \left(t/t_{\mathrm{r}}\right)^{\nu} \exp\left[-\nu \left(t/t_{\mathrm{r}} - 1\right)\right] H(t)$$

causal

where:

- I_0 = pulse amplitude
- $t_{\mathrm{r}} > 0$ = pulse rise time

- Sinc-cosine function

$$G(t) = \mathrm{sinc}[B(t - t_0)] \cos\left[2\pi f_{\mathrm{c}}(t - t_0)\right]$$

non-causal

where:

- t_0 = arbitrary delay
- B = (prescribed) bandwidth $B = f_{\mathrm{h}} - f_{\mathrm{l}}$, with $0 < f_{\mathrm{l}} < f_{\mathrm{h}}$
- f_{c} = centre frequency $f_{\mathrm{c}} = (f_{\mathrm{l}} + f_{\mathrm{h}})/2$

Prerequisites: exciting pulses

Power exponential modulated – sinc-cosine pulse

- Normalised, unipolar, power exponential (envelope)

$$I_{\mathrm{PE}}(t) = I_0 \left(t/t_{\mathrm{r}}\right)^{\nu} \exp\left[-\nu \left(t/t_{\mathrm{r}} - 1\right)\right] H(t)$$

causal

where:
  - I_0 = pulse amplitude
  - $t_{\mathrm{r}} > 0$ = pulse rise time
- Sinc-cosine function (carrier)

$$G(t) = \mathrm{sinc}[B(t - t_0)] \cos\left[2\pi f_{\mathrm{c}}(t - t_0)\right]$$

non-causal

where:
  - t_0 = arbitrary delay
  - B = (prescribed) bandwidth $B = f_{\mathrm{h}} - f_{\mathrm{l}}$, with $0 < f_{\mathrm{l}} < f_{\mathrm{h}}$
  - f_{c} = centre frequency $f_{\mathrm{c}} = (f_{\mathrm{l}} + f_{\mathrm{h}})/2$

Prerequisites: exciting pulses

Power exponential modulated – sinc-cosine pulse

- By taking $t_0 = t_\mathrm{r}$

$$I(t) = I_0\,(t/t_\mathrm{r})^\nu\,\mathrm{sinc}\,[B(t - t_\mathrm{r})]\cos\,[2\pi f_\mathrm{c}(t - t_\mathrm{r})]\exp\,[-\nu\,(t/t_\mathrm{r} - 1)]\,H(t)$$

- Choices:
  - $\nu = 1, 2, 3, \ldots$
  - $B \leftrightarrow t_\mathrm{r}$ as

$$t_\mathrm{r} = K_\mathrm{sc}/B, \text{ with } K_\mathrm{sc} = 1, 2, 3, \ldots$$

Prerequisites: exciting pulses

Power exponential modulated – sinc-cosine pulse

$$I(t) \overset{\text{FT}}{\longmapsto} \hat{I}(\mathrm{j}\omega)$$

$$\hat{I}(\mathrm{j}\omega) = \frac{1}{2\pi}\left[\hat{I}_{\mathrm{PE}}(\mathrm{j}\omega) \overset{(\mathrm{j}\omega)}{*} \hat{G}(\mathrm{j}\omega)\right]$$

$$= I_0 \frac{\exp(-\mathrm{j}\omega t_{\mathrm{r}})}{4\pi B}\left[\mathcal{I}\left(\omega-\omega_{\mathrm{h}}, \omega-\omega_{\mathrm{l}}\right) + \mathcal{I}\left(\omega+\omega_{\mathrm{l}}, \omega+\omega_{\mathrm{h}}\right)\right]$$

where:

– $\overset{(\mathrm{j}\omega)}{*}$ = frequency convolution

Prerequisites: exciting pulses

Power exponential modulated – sinc-cosine pulse

$$I(t) \xrightarrow{\text{FT}} \hat{I}(\mathrm{j}\omega)$$

$$\mathcal{I}\left(\omega_{\mathrm{i}}, \omega_{\mathrm{f}}\right) = \int_{\omega_{\mathrm{i}}}^{\omega_{\mathrm{f}}} \left[\exp(\mathrm{j}\omega' t_{\mathrm{r}}) \hat{P}(\mathrm{j}\omega')\right] \mathrm{d}\omega'$$

$$= I_0\, t_{\mathrm{r}}\, \Gamma(\nu + 1)\, \exp(\nu) \int_{\omega_{\mathrm{i}}}^{\omega_{\mathrm{f}}} \frac{\exp(\mathrm{j}\omega' t_{\mathrm{r}})}{(\mathrm{j}\, t_{\mathrm{r}}\, \omega' + \nu)^{\nu+1}} \mathrm{d}\omega'$$

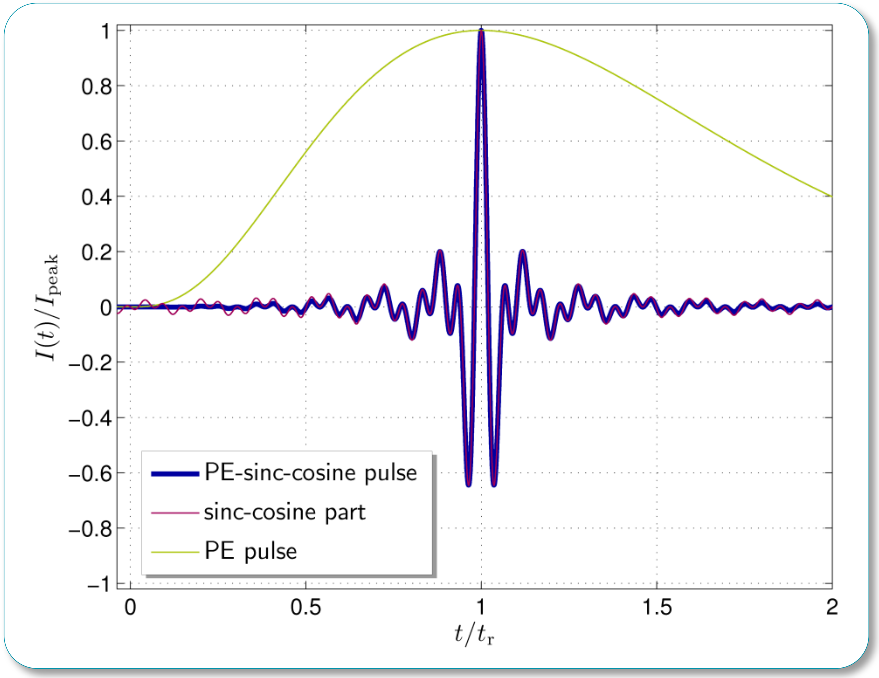
$$= I_0 \left(\exp(\nu) \boxed{\int_{t_{\mathrm{r}}\omega_{\mathrm{i}}}^{t_{\mathrm{r}}\omega_{\mathrm{f}}} \frac{\exp(\mathrm{j}\,\xi)}{\mathrm{j}\,\xi + \nu} \mathrm{d}\xi} + \mathrm{j} \sum_{m=1}^{\nu} \left\{ \Gamma(m) \left[\exp(\alpha)\, \alpha^{-\nu+m-1}\right] \Big|_{\alpha_{\mathrm{i}}}^{\alpha_{\mathrm{f}}} \right\} \right)$$

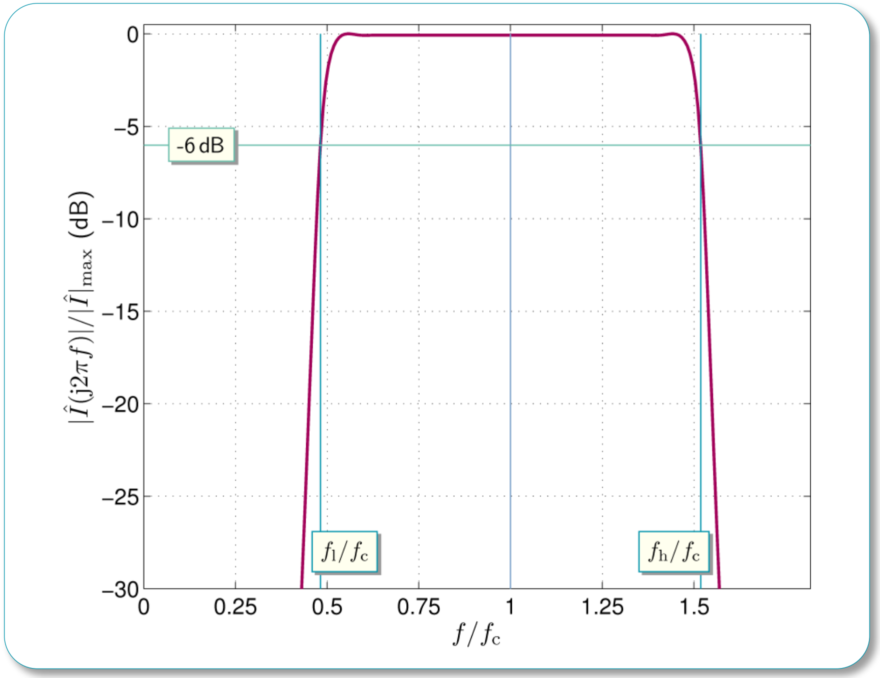
with $\alpha_{\mathrm{i}} = \mathrm{j}\, t_{\mathrm{r}}\, \omega_{\mathrm{i}} + \nu$ and $\alpha_{\mathrm{f}} = \mathrm{j}\, t_{\mathrm{r}}\, \omega_{\mathrm{f}} + \nu$

Prerequisites: exciting pulses

Power exponential modulated – sinc-cosine pulse

$K_{sc} = 13, \ \nu = 3, \ B = 7.1\,\text{GHz}, \ f_c = 6.85\,\text{GHz} \ \ f_l = 3.1\,\text{GHz}, \ f_h = 10.4\,\text{GHz}$





Prerequisites: radiated field

$$\boldsymbol{H}^{\mathrm{T}}(\boldsymbol{X},t) = \frac{A^{\mathrm{T}}}{4\pi|\boldsymbol{X}|^3}\left\{\boldsymbol{\Theta}_{\boldsymbol{H}}^{\mathrm{NF}}\left[I^{\mathrm{T}}(t') + \frac{|\boldsymbol{X}|}{c_0}\partial_t I^{\mathrm{T}}(t')\right] + \boldsymbol{\Theta}_{\boldsymbol{H}}^{\mathrm{FF}}\frac{|\boldsymbol{X}|^2}{c_0^2}\partial_t^2 I^{\mathrm{T}}(t')\right\}$$

where:

- $t' = t - |\boldsymbol{X}|/c_0$ = wave travel time retarded, time coordinate
- $\boldsymbol{\Theta}_{\boldsymbol{H}}^{\mathrm{NF}}$ = near-field radiated field directional characteristic

$$\boldsymbol{\Theta}_{\boldsymbol{H}}^{\mathrm{NF}}(\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}, \boldsymbol{\Xi}) = 3\left(\boldsymbol{\Xi}\cdot\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}\right)\boldsymbol{\Xi} - \boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}$$

- $\boldsymbol{\Theta}_{\boldsymbol{H}}^{\mathrm{FF}}$ = far-field radiated field directional characteristic

$$\boldsymbol{\Theta}_{\boldsymbol{H}}^{\mathrm{FF}}(\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}, \boldsymbol{\Xi}) = \left(\boldsymbol{\Xi}\cdot\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}\right)\boldsymbol{\Xi} - \boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}$$

Prerequisites: received signal

EM reciprocity theorem of the time-convolution type

⇒ Thévenin circuit generator voltage in $\mathcal{L}^{\mathrm{R}}$

$$V^{\mathrm{G}}(\boldsymbol{X},t') = -\frac{\mu_0 A^{\mathrm{T}} A^{\mathrm{R}}}{4\pi|\boldsymbol{X}|^3}\left\{\Theta^{\mathrm{NF}}(\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}},\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}},\boldsymbol{\Xi})\left[\partial_t I^{\mathrm{T}}(t') + \frac{|\boldsymbol{X}|}{c_0}\partial_t^2 I^{\mathrm{T}}(t')\right]\right.$$
$$\left. + \Theta^{\mathrm{FF}}(\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}},\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}},\boldsymbol{\Xi})\frac{|\boldsymbol{X}|^2}{c_0^2}\partial_t^3 I^{\mathrm{T}}(t')\right\}$$

where:

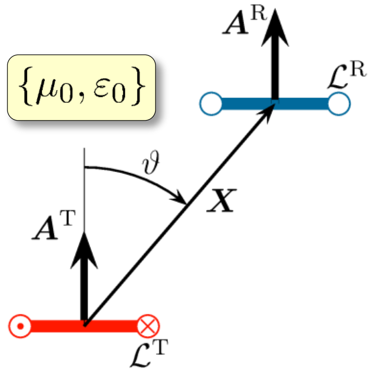
- Θ^{NF} = near-field directional characteristic

$$\Theta^{\mathrm{NF}}(\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}},\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}},\boldsymbol{\Xi}) = 3\left(\boldsymbol{\Xi}\cdot\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}\right)\left(\boldsymbol{\Xi}\cdot\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}}\right) - \boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}\cdot\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}}$$

- Θ^{FF} = far-field directional characteristic

$$\Theta^{\mathrm{FF}}(\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}},\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}},\boldsymbol{\Xi}) = \left(\boldsymbol{\Xi}\cdot\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}\right)\left(\boldsymbol{\Xi}\cdot\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}}\right) - \boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}\cdot\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}}$$

Loop-to-loop transfer



Investigated canonical configurations

- Mutually parallel loops: $\boldsymbol{A}^{\mathrm{T}} \cdot \boldsymbol{A}^{\mathrm{R}} = A^{\mathrm{T}} A^{\mathrm{R}}$

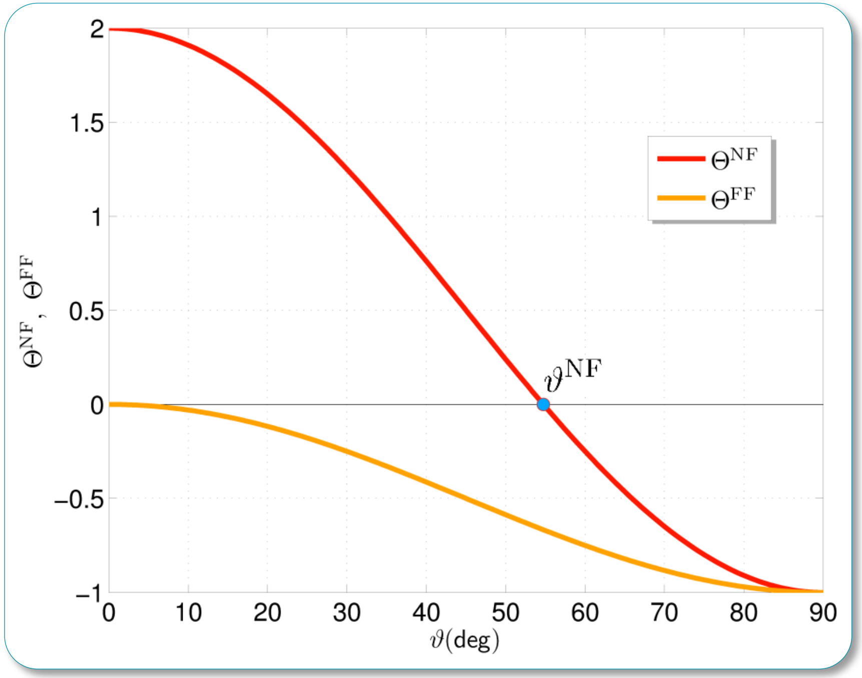
- Directional characteristics:

$$\Theta^{\mathrm{NF}}(\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}, \boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}}, \boldsymbol{\Xi}) = 3\cos^2(\vartheta) - 1$$

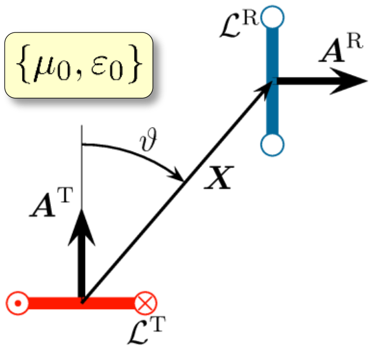
$$\Theta^{\mathrm{FF}}(\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}, \boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}}, \boldsymbol{\Xi}) = \cos^2(\vartheta) - 1$$

zero $V^{\mathrm{G}}(\boldsymbol{X}, t')$ contributions

$$\begin{cases} \cos(\vartheta) = \pm 3^{-1/2} & \text{NF} \\ \cos(\vartheta) = \pm 1 & \text{FF} \end{cases}$$



Loop-to-loop transfer



Investigated canonical configurations

- Mutually perpendicular loops: $\boldsymbol{A}^{\mathrm{T}} \cdot \boldsymbol{A}^{\mathrm{R}} = 0$

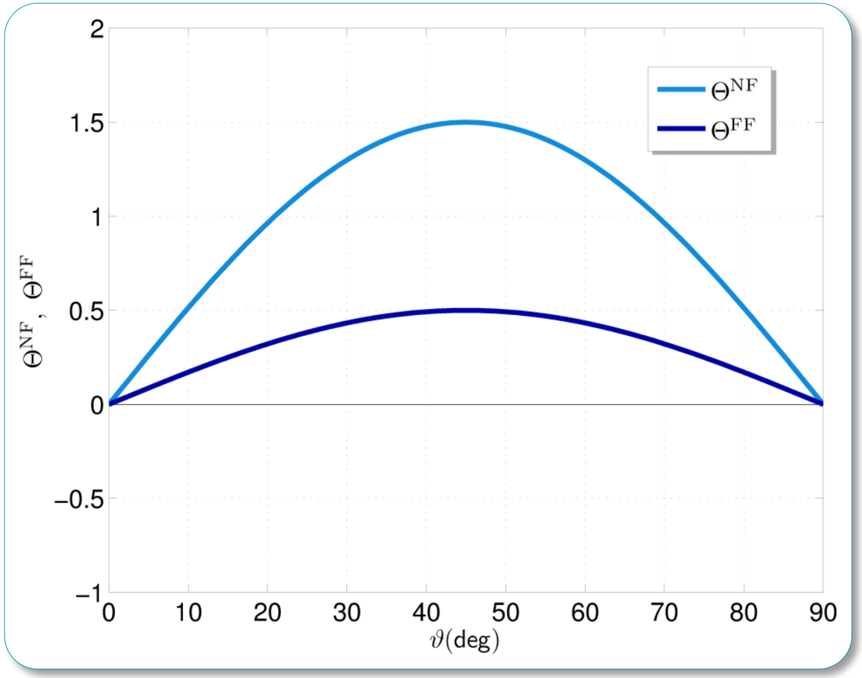
- Directional characteristics:

$$\Theta^{\mathrm{NF}}(\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}, \boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}}, \boldsymbol{\Xi}) = (3/2)\sin(2\vartheta)\sin(\varphi)$$

$$\Theta^{\mathrm{FF}}(\boldsymbol{i}_{\boldsymbol{A}^{\mathrm{T}}}, \boldsymbol{i}_{\boldsymbol{A}^{\mathrm{R}}}, \boldsymbol{\Xi}) = (1/2)\sin(2\vartheta)\sin(\varphi)$$

zero $V^{\mathrm{G}}(\boldsymbol{X}, t')$ contributions

$$\begin{cases} \varphi = \{0, \pi\} & \text{NF} \\ \vartheta = \{0, \pi/2, \pi\} & \text{FF} \end{cases}$$



Energy spectral density of emitted field

- International regulations on EMI:

  a) Federal Communications Commission, "First Report and Order," April 2002.
  b) National Telecommunications and Information Administration, "Manual of regulations and procedures for federal radio frequency management," May 2011 Revision of the 2008 Edition, [Online] Available: http://www.ntia.doc.gov/files/ntia/publications/manual_5_11.pdf.
  c) Industry Canada, "Spectrum management and telecommunications. Radio standards specification. Devices using ultra-wideband (UWB) technology," RSS-220, Issue 1, March 2009.

power spectral density

- Pulsed field → energy spectral density

Energy spectral density of emitted field

- International regulations on EMI: far-field radiation
- For loop-to-loop transfer

$$\{\boldsymbol{E}^{\mathrm{T}},\boldsymbol{H}^{\mathrm{T}}\}(\boldsymbol{X},t) = \frac{\{\boldsymbol{E}^{\mathrm{T};\infty},\boldsymbol{H}^{\mathrm{T};\infty}\}(\boldsymbol{\Xi},t-|\boldsymbol{X}|/c_0)}{4\pi|\boldsymbol{X}|}[1+o(1)] \text{ as } |\boldsymbol{X}|\to\infty$$

where:

- $\boldsymbol{H}^{\mathrm{T};\infty}$ = far-field radiated magnetic field strength

$$\boldsymbol{H}^{\mathrm{T};\infty}(\boldsymbol{\Xi},t) = A^{\mathrm{T}}\boldsymbol{\Theta}_H^{\mathrm{FF}}\frac{1}{c_0^2}\partial_t^2 I^{\mathrm{T}}(t)$$

- $\boldsymbol{E}^{\mathrm{T};\infty}$ = far-field radiated electric field strength

$$\boldsymbol{E}^{\mathrm{T};\infty}(\boldsymbol{\Xi},t) = (\mu_0/\epsilon_0)^{1/2}\boldsymbol{H}^{\mathrm{T};\infty}(\boldsymbol{\Xi},t)\times\boldsymbol{\Xi}$$

Energy spectral density of emitted field

- The total energy radiated by the loop

$$W^{\mathrm{rad}} = \left(\frac{1}{4\pi}\right)^2 \left(\frac{\mu_0}{\epsilon_0}\right)^{1/2} \int_{\Xi\in\Omega} \mathrm{d}\Omega \int_{t=-\infty}^{\infty} |\boldsymbol{H}^{\mathrm{T};\infty}(\Xi, t)|^2 \mathrm{d}t$$

Parseval's theorem

$$W^{\mathrm{rad}} = \int_{f=-\infty}^{\infty} w^{\mathrm{rad}}(f)\mathrm{d}f = 2\int_{f=0}^{\infty} w^{\mathrm{rad}}(f)\mathrm{d}f$$

where:

– w^{rad} = energy spectral density

$$w^{\mathrm{rad}}(f) = \left(\frac{1}{4\pi}\right)^2 \left(\frac{\mu_0}{\epsilon_0}\right)^{1/2} \int_{\Xi\in\Omega} |\hat{\boldsymbol{H}}^{\mathrm{T};\infty}(\Xi, 2\pi \mathrm{j} f)|^2 \mathrm{d}\Omega$$

Energy spectral density of emitted field

- The total energy radiated by the loop

$$W^{\mathrm{rad}}(f) = \frac{8\pi}{3}\left(\frac{A^{\mathrm{T}}}{4\pi}\right)^2\left(\frac{\mu_0}{\epsilon_0}\right)^{1/2}\frac{1}{c_0^4}\int_{t=0}^{\infty}\left[\partial_t^2 I(t)\right]^2 \mathrm{d}t$$

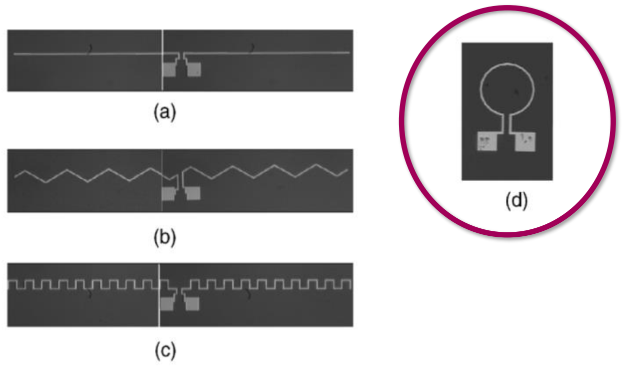
- The energy spectral density

$$w^{\mathrm{rad}}(f) = \frac{8\pi^3}{3}(A^{\mathrm{T}})^2\left(\frac{\mu_0}{\epsilon_0}\right)^{1/2}\frac{1}{c_0^4}f^4|\hat{I}^{\mathrm{T}}(2\pi\mathrm{j}\,f)|^2$$

Numerical experiments

Loop-to-loop transfer

- Loops:
  - $A^{\mathrm{T}} = A^{\mathrm{R}} = 0.0314\ \mathrm{mm}^2$
  - for circular loops d =0.2mm



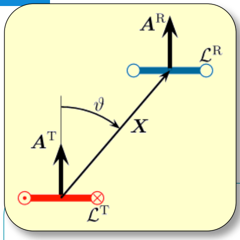
K.K. O, *et al.* "On-chip antennas in Silicon ICs and their application," *IEEE Trans. Electron Devices*, vol. 57, no. 1, pp. 1312–1321, July 2005.

- Feeding pulse:
  - pulse type: monocycle
  - peak current: $I_{\mathrm{peak}} = 1$ mA
  - pulse zero-crossing time: $t_{0\mathrm{x}} = t_{\mathrm{r}} = 0.1$ ns

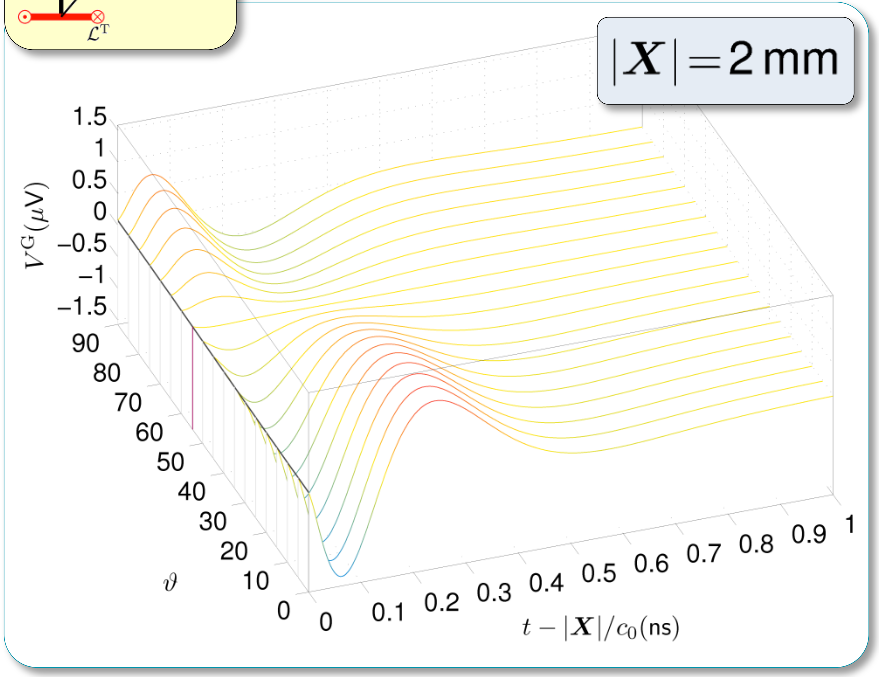
Numerical experiments

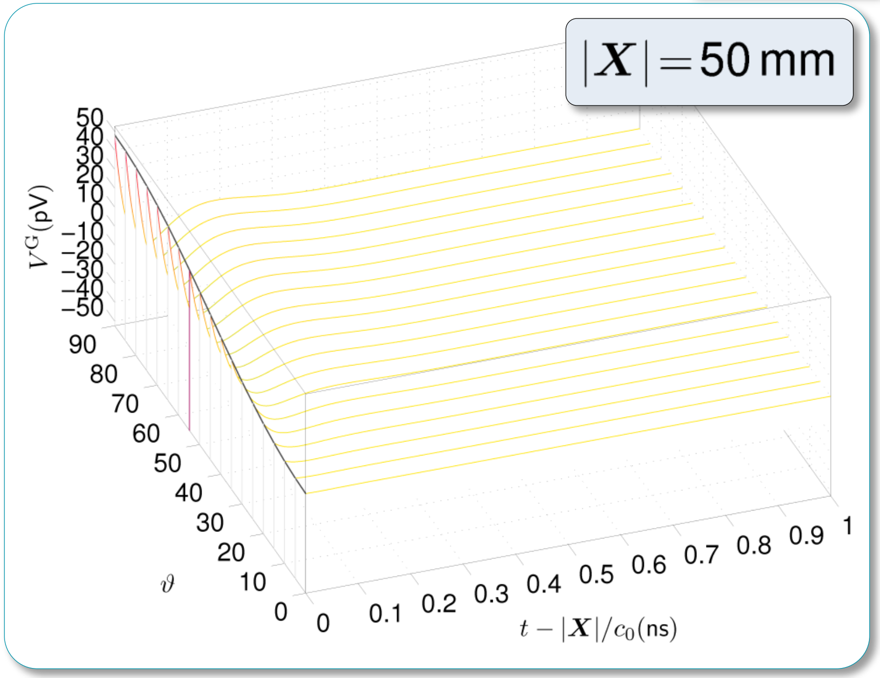
Loop-to-loop transfer

- strong NF signal + low FF signal
- intricate behaviour



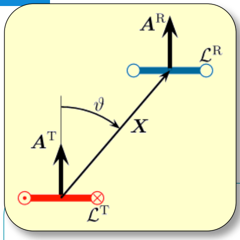
$\nu = 4$





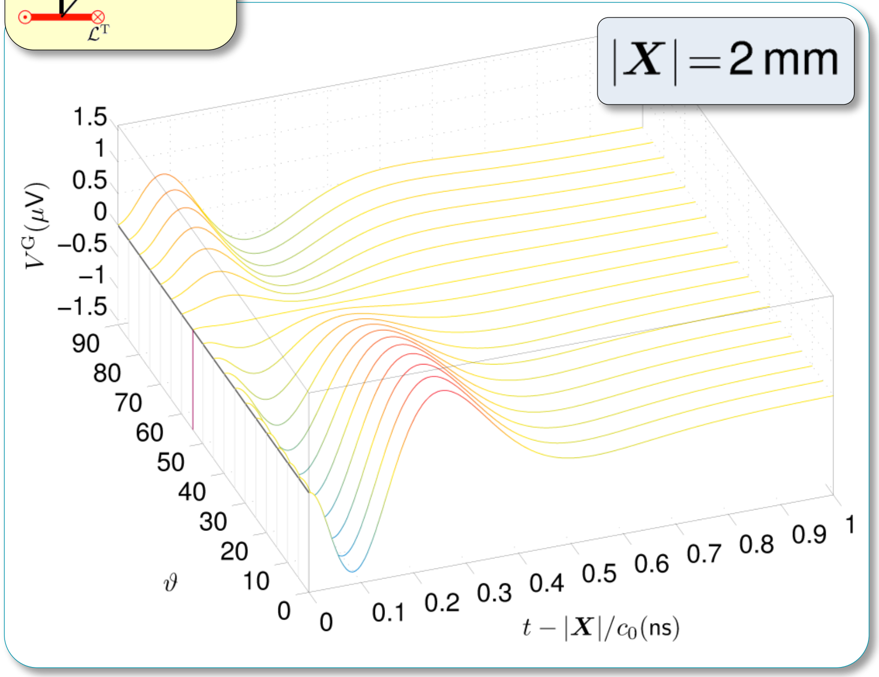
Numerical experiments

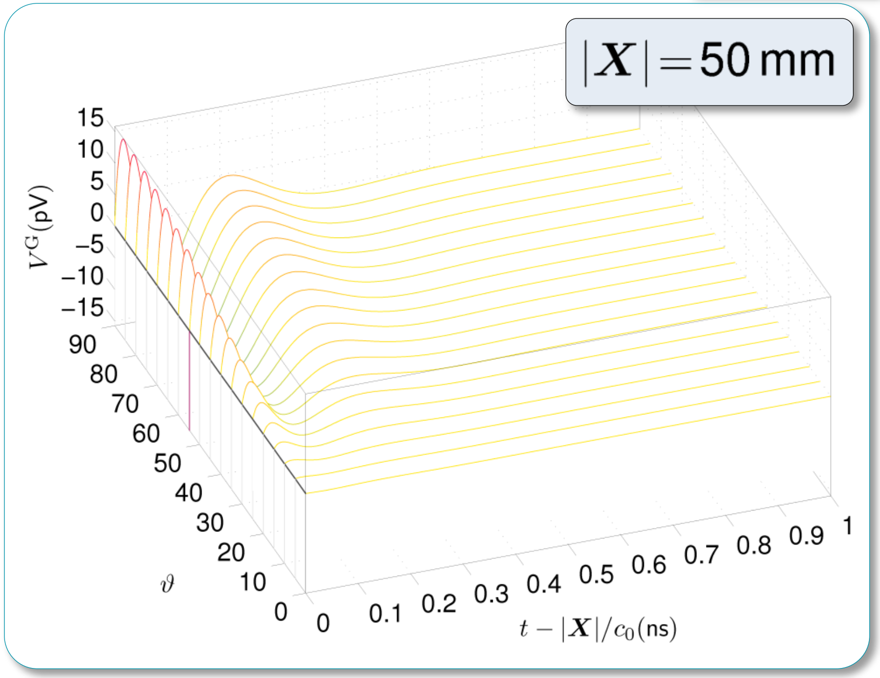
Loop-to-loop transfer



- strong NF signal + low FF signal
- intricate behaviour

$\nu = 5$





Numerical experiments

Loop-to-loop transfer

Practical implications:

- Highly idealised conditions
- Pulsed field loop-to-loop transfer ⇒ large potential to establish a viable intra-chip link
- Large NF/FF ratio ⇒ low EM contamination
- Already hint at the intricacy of the signal transfer ⇒ impact on the complexity of the signal processing

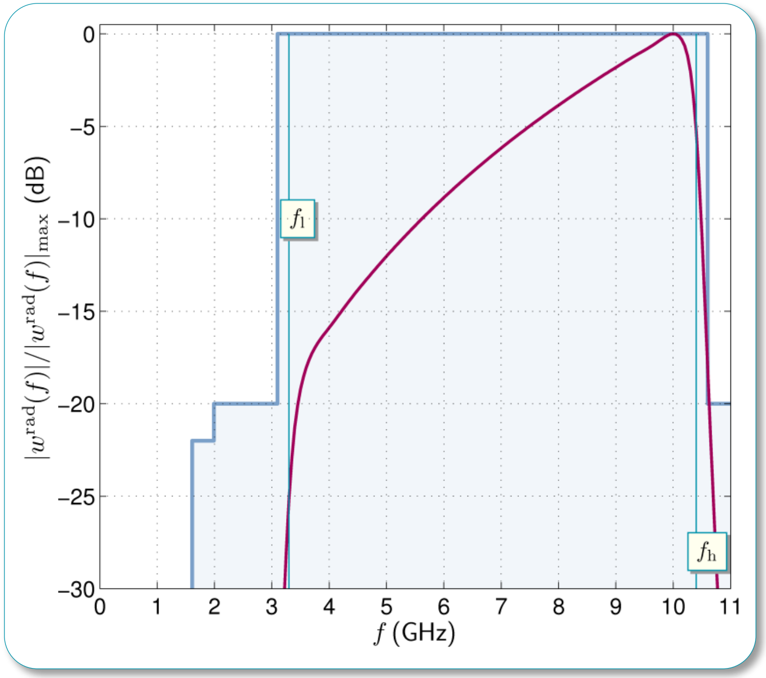
Numerical experiments

Energy spectral density analysis

- Transmitting loop:
  - same
- Feeding pulse:
  - Power exponential modulated – sinc-cosine pulse
  - Parameters: K_{sc} =13, ν =3, f_{l} =3.1 GHz, f_{h} = 10.4 GHz, B =7.1 GHz, f_{c} =6.85 GHz
- Reference behaviour: the FCC mask 3.1–10.6 GHz

Numerical experiments

Energy spectral density analysis



- Practical implications:
  - Full compliance to the FCC mask
  - Design strategy: determine I_0 for this pulse signature
  - Verify the system functionality

Conclusions

- Pulsed transfer:
  - clear theoretical description
  - clear design rules
  - opportune system properties

- Pulsed-field wireless transfer has the potential of becoming the enabler of future digital data transfer technologies

Thank you