Time and Space Signal Integrity in Pulse-train Excited Array Antennas

A Full TD Analysis

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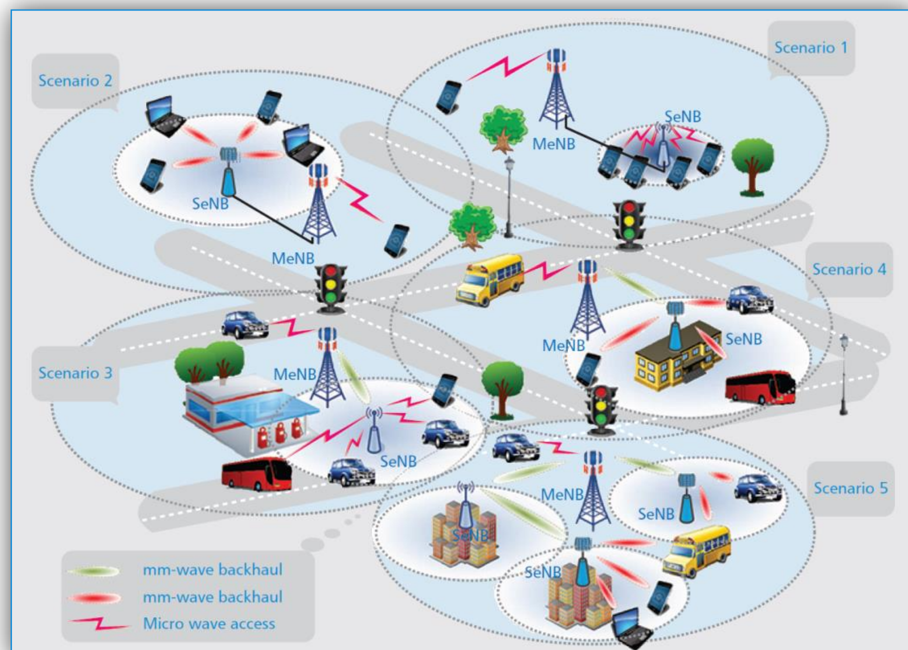
Pulsed-field & ultra-high bit rate, wireless digital signal transfer

10 Gb/s HetSNets with Millimeter-Wave Communications: Access and Networking – Challenges and Protocols

Kan Zheng, Long Zhao, Jie Mei, Mischa Dohler, Wei Xiang, and Yuexing Peng



IEEE Communication Magazine, vol. 53, no. 1, pp. 222–231, Jan. 2015

Modulated carrier wireless transfer

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SATELLITE COMMUNICATIONS AND NETWORKING

Waveform Design Solutions for EHF Broadband Satellite Communications

Mauro De Sanctis, Ernestina Cianca, Tommaso Rossi, Claudio Sa

IMPULSE-BASED UWB WAVEFORMS

In impulse-based UWB waveforms, the information bits are encoded in various characteristics of the transmitted pulse, such as the pulse presence, position and shape.

IEEE Communication Magazine, vol. 53, no. 3, pp. 18–23, Mar. 2015

Pulsed-field & ultra-high bit rate, wireless digital signal transfer

Pulsed-field array antennas

- Overall quality metrics:

  Directional distribution of radiated energy

  Signal fidelity in space and time

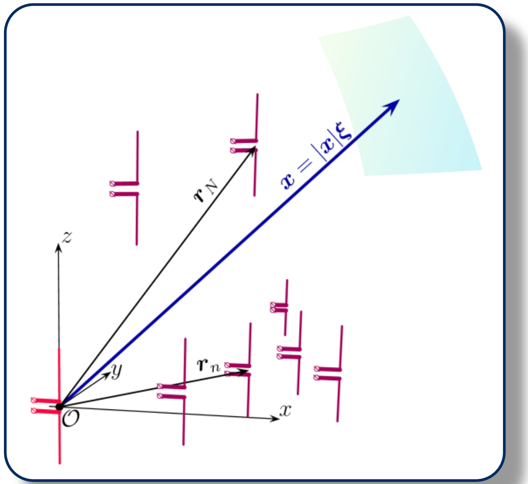
- Time-domain behaviour

  ↔ Time-domain analysis

Synopsis

- Prerequisites
- TD far-field radiation
- Antenna quality metrics
- Illustrative numerical examples
- Conclusions

Examined configuration

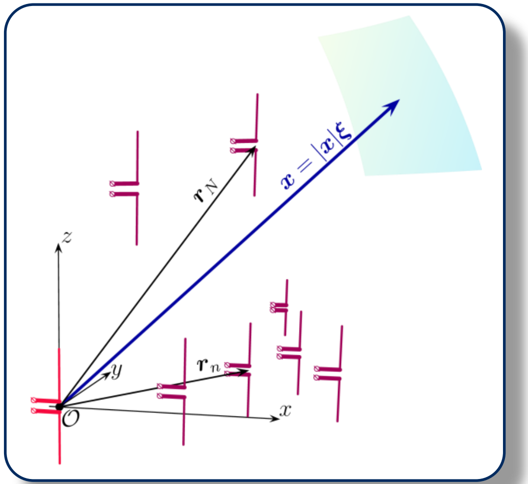


- $N+1(N=0,1,2\ldots,)$ identical, mutually translationally shifted, pulsed electric-current excited elements

- Reference element:
  - spatial support: $\mathcal{D}_0$ (with boundary $\partial\mathcal{D}_0$)
  - characteristic function: $\chi_0(\boldsymbol{x}) = \{1, 1/2, 0\}$ / $\boldsymbol{x} \in \{\mathcal{D}_0, \partial\mathcal{D}_0, \mathcal{D}_0^\infty\}$

- By $\boldsymbol{r}_n$ translationally shifted elements:
  - support: $\mathcal{D}_n$
  - characteristic function: $\chi_n(\boldsymbol{x}) = \chi_0(\boldsymbol{x} + \boldsymbol{r}_n)$

Examined configuration



- **Excitation:**

$$\boldsymbol{J}_n(\boldsymbol{x},t) = I_n^{\mathrm{G}}(t) \overset{(t)}{*} \boldsymbol{J}_n^{\delta}(\boldsymbol{x},t)$$

  - $\boldsymbol{J}_n(\boldsymbol{x},t)$ = volume density of electric current
  - $I_n^{\mathrm{G}}(t)$ = electric current at the Kirchhoff circuit port
  - $\boldsymbol{J}_n^{\delta}(\boldsymbol{x},t)$ = unit Dirac pulse $\delta(t)$ volume density ➡ upon neglecting the mutual coupling:

$$\boldsymbol{J}_n^{\delta}(\boldsymbol{x},t) = \boldsymbol{J}_0^{\delta}(\boldsymbol{x}+\boldsymbol{r}_n,t), \text{ for } n = 1,\ldots,N$$

  - $\overset{(t)}{*}$ = time convolution

- **Embedding medium:** vacuum $\varepsilon_0,\ \mu_0,\ c_0 = (\varepsilon_0\mu_0)^{-1/2}$

TD radiated field (far-field region)

$$\boldsymbol{E} = -\mu_0 \partial_t \boldsymbol{A} + \varepsilon_0^{-1} \partial_t^{-1} [\boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \boldsymbol{A})]$$
$$\boldsymbol{H} = \boldsymbol{\nabla} \times \boldsymbol{A},$$

- $\boldsymbol{E}(\boldsymbol{x}, t)$ = electric field strength
- $\boldsymbol{H}(\boldsymbol{x}, t)$ = magnetic field strength
- $\partial_t^{-1} f(\boldsymbol{x}, t) = \int_{\tau=-\infty}^{t} f(\boldsymbol{x}, \tau) \mathrm{d}\tau$
- $\boldsymbol{A}(\boldsymbol{x}, t) = \sum_{n=0}^{N} \boldsymbol{A}_n(\boldsymbol{x}, t)$ = electric-current potential

with $\boldsymbol{A}_n(\boldsymbol{x}, t) = G(\boldsymbol{x}, t) \overset{(\boldsymbol{x})}{*} \overset{(t)}{*} \boldsymbol{J}_n(\boldsymbol{x}, t)$ for $\boldsymbol{x} \in \mathbb{R}^3$

$\overset{(\boldsymbol{x})}{*}$ = spatial convolution

$$G(\boldsymbol{x}, t) = \frac{\delta(t - |\boldsymbol{x}|/c_0)}{4\pi|\boldsymbol{x}|} \quad \text{for } \boldsymbol{x} \neq \boldsymbol{0}$$

Green's function

TD radiated field (far-field region)

$$\{\boldsymbol{A},\boldsymbol{E},\boldsymbol{H}\}(\boldsymbol{x},t) = \frac{\{\boldsymbol{A}^\infty,\boldsymbol{E}^\infty,\boldsymbol{H}^\infty\}(\boldsymbol{\xi},t-|\boldsymbol{x}|c_0^{-1})}{4\pi|\boldsymbol{x}|}\left[1+O(|\boldsymbol{x}|^{-1})\right], \text{ as } |\boldsymbol{x}|\to\infty$$

$\boldsymbol{\xi} = \boldsymbol{x}/|\boldsymbol{x}|$

- $\{\boldsymbol{A}^\infty,\boldsymbol{E}^\infty,\boldsymbol{H}^\infty\}(\boldsymbol{\xi},t)$ = far-field radiation characteristics
- $\boldsymbol{E}^\infty = -\mu_0[\partial_t\boldsymbol{A}^\infty - \boldsymbol{\xi}(\boldsymbol{\xi}\cdot\partial_t\boldsymbol{A}^\infty)]$
- $\boldsymbol{H}^\infty = -c_0^{-1}\boldsymbol{\xi}\times\partial_t\boldsymbol{A}^\infty$
- $\boldsymbol{A}^\infty = \sum_{n=0}^{N}\boldsymbol{A}_n^\infty$

TD radiated field (far-field region)

- Beam steering (pulse-train excitation):
  - select a reference pulse $I_0^{\mathrm{G}}(t)$
  - take $I_n^{\mathrm{G}}(t) = I_0^{\mathrm{G}}(t - T_n)$ for $n = 1, 2, 3, \ldots, N$, with T_n the relevant time delays

$$\boldsymbol{A}_n^{\infty} = I_0^{\mathrm{G}}(t - T_n) \overset{(t)}{*} \int_{\mathcal{D}_n} \boldsymbol{J}_0^{\delta}[\boldsymbol{x}', t + c_0^{-1}\boldsymbol{\xi}\boldsymbol{\cdot}(\boldsymbol{x}' + \boldsymbol{r}_n)]\mathrm{d}V(\boldsymbol{x}')$$

- Constructive interference: $T_n = c_0^{-1}\boldsymbol{\xi}_{\mathrm{st}}\boldsymbol{\cdot}\boldsymbol{r}_n$

  $\boldsymbol{\xi}_{\mathrm{st}}$ = the ‘direction of steering’

Metrics: directional distribution of radiated energy

$$W^{\mathrm{rad}} = \int_{\boldsymbol{\xi}\cdot\boldsymbol{\xi}=1} \boldsymbol{\Phi}^{\mathrm{rad}}(\boldsymbol{\xi})\cdot\boldsymbol{\xi}\,\mathrm{d}\Omega$$

- W^{rad} = radiated energy
- $\boldsymbol{\Phi}^{\mathrm{rad}}(\boldsymbol{\xi})$ = area density of radiated energy

For free space

$$\boldsymbol{\Phi}^{\mathrm{rad}}(\boldsymbol{\xi}) = \frac{Z_0}{16\pi^2\, c_0^2}\,\boldsymbol{\xi}\int_{t\in\mathbb{R}}[\partial_t\,(\boldsymbol{\xi}\times\boldsymbol{A}^{\infty})\cdot\partial_t\,(\boldsymbol{\xi}\times\boldsymbol{A}^{\infty})]\mathrm{d}t$$

$Z_0 = (\mu_{/}\varepsilon_0)^{1/2}$ the free space electromagnetic wave impedance

- Array antenna directivity:

$$D_{\mathrm{dB}}(\boldsymbol{\xi}) = 10\log_{10}\left[\boldsymbol{\Phi}^{\mathrm{rad}}(\boldsymbol{\xi})\cdot\boldsymbol{\xi}/4\pi W^{\mathrm{rad}}\right]$$

Metrics: signal fidelity

- System fidelity [Lamensdorf & Susman, 1994]:

$$F(S_{\mathrm{sys}}, S_{\mathrm{ref}}) = \max_{\tau\in\mathbb{R}} \int_{t=-\infty}^{\infty} \frac{S_{\mathrm{sys}}(t)}{\|S_{\mathrm{sys}}(t)\|}\frac{S_{\mathrm{ref}}(t-\tau)}{\|S_{\mathrm{ref}}(t)\|}\mathrm{d}t$$

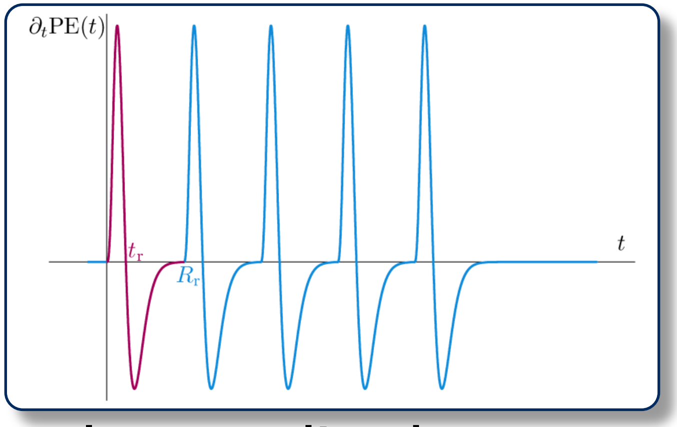
  - S_{sys} and S_{ref} = scalar signals
  - normalised cross-correlation evaluated empirically

- Array antenna = subsystem ➡ directional fidelity factor:

$$F_{\mathrm{f}}(\boldsymbol{\xi}) = \max_{\tau\in\mathbb{R}} \int_{t=-\infty}^{\infty} \frac{\boldsymbol{A}^{\infty}(\boldsymbol{\xi},t)\cdot\boldsymbol{A}_0^{\infty}(\boldsymbol{\xi},t-\tau)}{\|\boldsymbol{A}^{\infty}(\boldsymbol{\xi},t)\|\,\|\boldsymbol{A}_0^{\infty}(\boldsymbol{\xi},t)\|}\mathrm{d}t$$

  - $\boldsymbol{A}_0^{\infty}(\boldsymbol{\xi},t)$= electric-current potential corresponding to the reference element

Numerical experiments: excitation



- **Trains of causal monocycle pulses:** pulse amplitude, pulse time rise $t_\mathrm{r} > 0$ and pulse rising power $\nu > 1$

$$\mathrm{d}_t\mathrm{PE}(t) = N(\nu)\left(t'^{\nu-1} - t'^{\nu}\right)\exp\left[-\nu\left(t'-1\right)\right]H(t)$$

  - $t' = t/t_\mathrm{r}$ = normalised time
  - $N(\nu)$ ⇒ unit amplitude of $\mathrm{d}_t\mathrm{PE}$

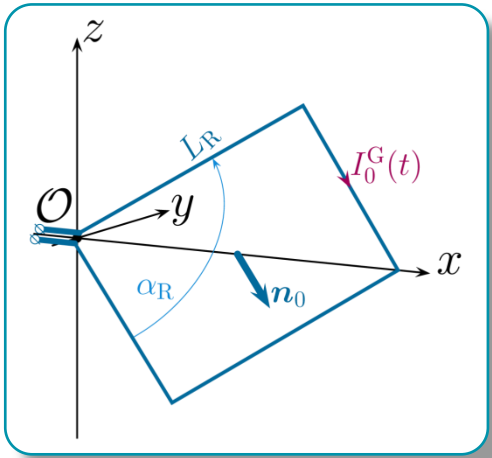
$$t_\mathrm{w} = \int_0^{t_\mathrm{r}} \mathrm{d}_t\mathrm{PE}(t)\,\mathrm{d}t = N(\nu)$$

pulse width

$$I^\mathrm{G}_\mathrm{ref}(t) = \sum_{m=0}^{M} I_0\,\mathrm{d}_t\mathrm{PE}(t + mR_\mathrm{r})$$

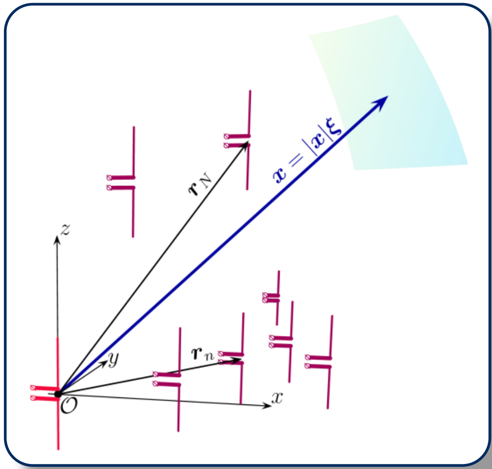
  - I_0 = electric current amplitude
  - R_r = pulse repetition rate

Numerical experiments: array antenna



Elementary antennas ➡ rhombic antennas:

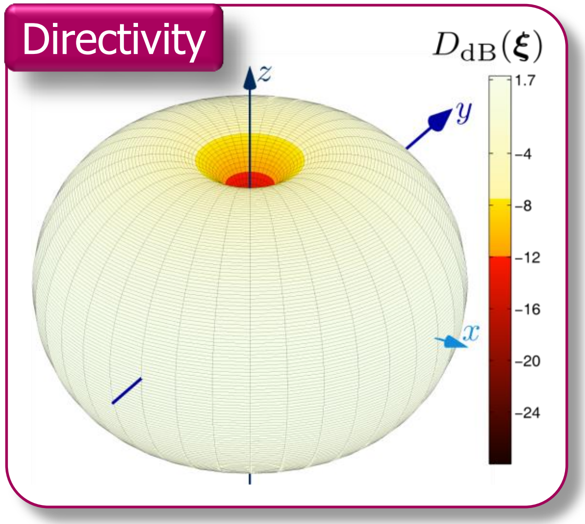
- Opening angle: $\alpha_{\mathrm{R}} = 90°$
- Side length: $L_{\mathrm{R}} = c_0 t_{\mathrm{w}}/20$
- Orientations: $\boldsymbol{n}_0 \cdot \boldsymbol{i}_z = 0$ or $\boldsymbol{n}_0 \cdot \boldsymbol{i}_z = 1$

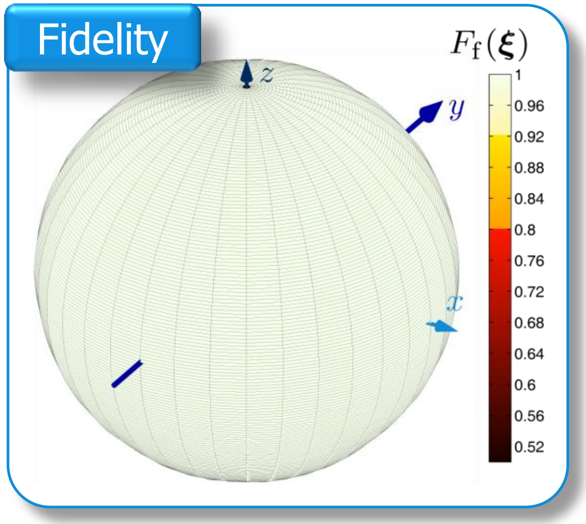


Examined cases:

- Single elements
- Linear array antennas with $\boldsymbol{r}_n \parallel \boldsymbol{i}_z$:
  - number of elements: 8
  - location: $\boldsymbol{r}_n = z_n \boldsymbol{i}_z$, with $z_n = n\,(c_0 R_{\mathrm{r}}/2)$, $n = 0, 1, 2, \ldots, 7$

Numerical experiments: single element

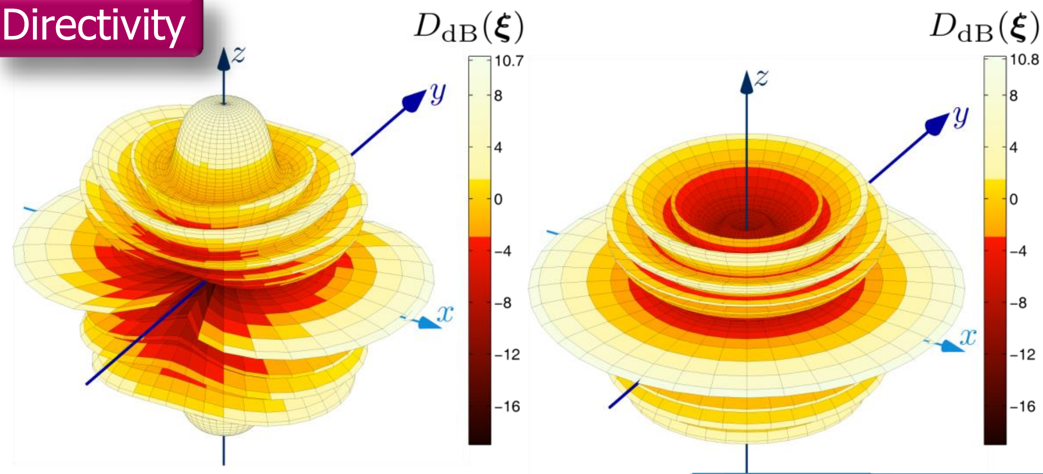




- **Directivity:** the 'doughnut' shape ⟺ dipoles
- **Fidelity:** 1

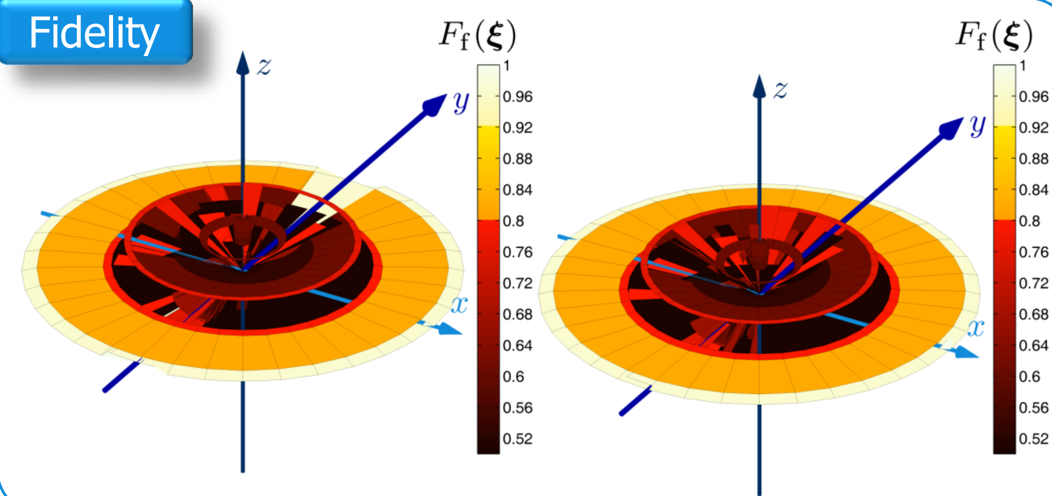
Numerical experiments: uniform linear array, broadside

Directivity



- Directivity:
  - clear main beam
  - sidelobes (SL) ➡ some generated by partial interference
- Fidelity: at least 3dB higher spatial selectivity

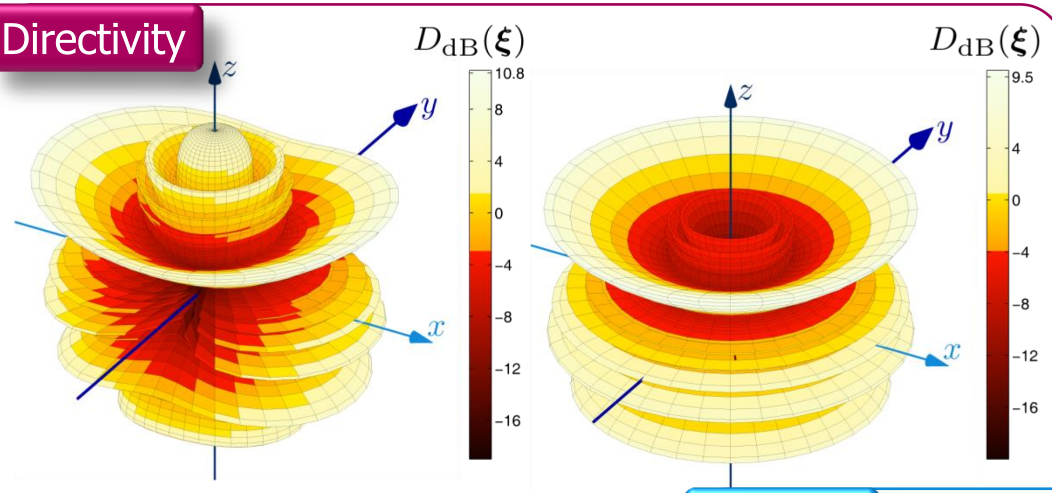
Fidelity



$5\times \mathrm{d}_t\mathrm{PE}(t)$ pulses
R_{r} pulse repetition rate
$c_0 R_{\mathrm{r}}/2$ inter-element spacing
broadside scanning

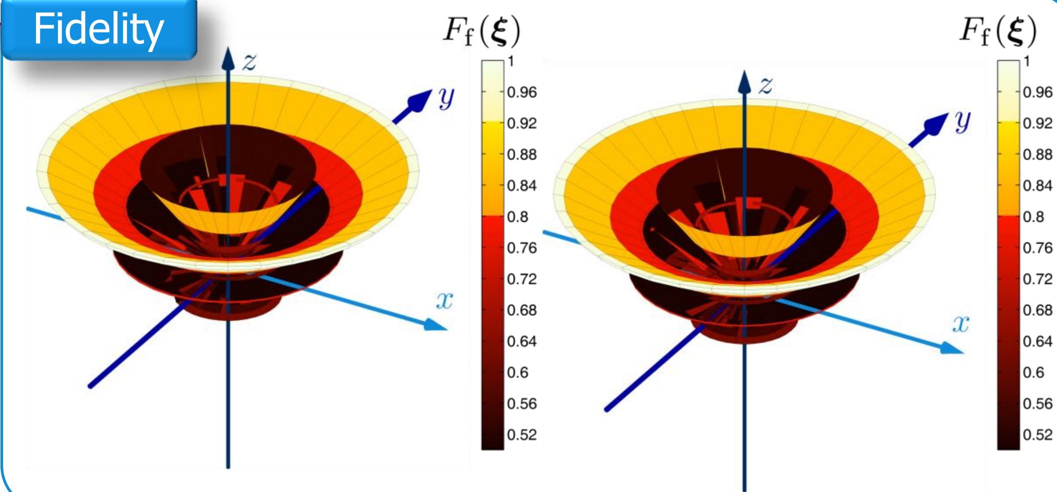
Numerical experiments: uniform linear array, scanning

Directivity



- Directivity:
  - prescribed scanning obtained
  - SL are displaced
- Fidelity:
  - $F_{\mathrm{f}}(\boldsymbol{\xi})$ in the main beam
  - 3dB gain is preserved

Fidelity



5×d_tPE(t) pulses
R_{r} pulse repetition rate
$c_0 R_{\mathrm{r}}/2$ inter-element spacing
$\boldsymbol{\xi}_{\mathrm{st}}, \boldsymbol{i}_z = 30^\circ$ scanning

Conclusions

Pulse-train Excited Array Antennas

- New metric definition: the directional fidelity factor → a purely directional quantity
- Beam shaping & beam steering → demonstrated
- Full TD analysis

Applications:
ultra-high bit rate wireless transfer
ultra-low power, short-range wireless transfer