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Unconventional Tiled Array Antennas for Long-Range Wireless Power Transmission

Samantha Lusa[1], Aarón Angel Salas Sanchez[1], and Paolo Rocca[1,2]

[1] ELEDIA Research Center (ELEDIA@UniTN - University of Trento), DICAM, Trento, Italy
[2] ELEDIA Research Center (ELEDIA@XIDIAN - Xidian University), Xi'an, China

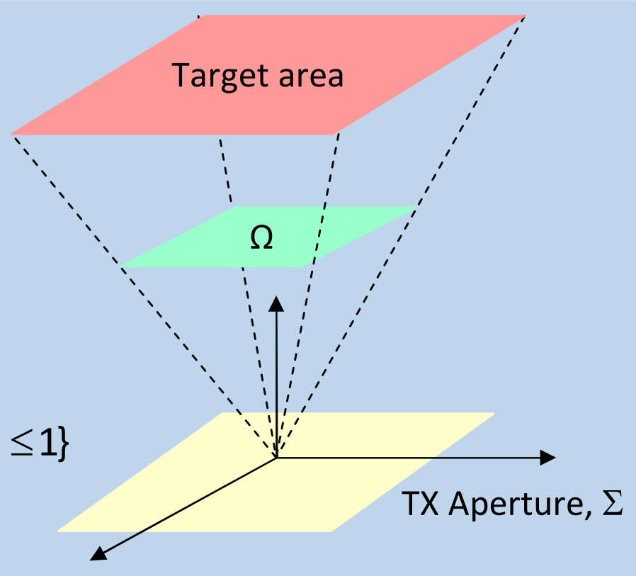
E-mail: samantha.lusa@eledia.org
Web-site : www.eledia.org/eledia-unitn

Abstract

***Abstract* — Long-range wireless power transmission (*WPT*) systems comprise a transmitting (*TX*) device capable of focusing the beam towards a desired region, usually consisting of a phased array (*PA*) antenna, and a receiving (*RX*) device, namely a rectenna, converting the electromagnetic power of the impinging microwave radiation into direct current. To maximize the end-to-end transmission efficiency, the transmitter must be able to focus the power on a limited spatial region, possibly just as large as the rectenna aperture. This imposes non-negligible challenges in the design of the transmitting antenna system, further highlighted when the *TX* and *RX* antennas are located far away. Additionally, conventional *PAs* allow for highly flexible beam-forming but they are extremely expensive and difficult to realize if large antennas are needed. In this context, the proposed research activity focuses on the study of innovative unconventional *PA* solutions based on modular architectures able to offer optimal trade-offs between antenna complexity and transmission efficiency.**

Beam Collection Efficiency (*BCE*) Maximization

Beam Collection Efficiency



$$BCE=\left[\frac{\int_{\Omega}\left|AF(u,v)\right|^{2}dudv}{\int_{\Gamma}\left|AF(u,v)\right|^{2}dudv}\right]$$

Visible range: $\Gamma=\{(u,v):u^{2}+v^{2}\le 1\}$

For **fully-populated array**:

$$AF(u,v)=\sum_{m=1}^{M}\sum_{n=1}^{N}w_{m,n}e^{jk(x_n u+y_m v)}\quad with:\begin{cases}w_{m,n}=\alpha_{m,n}e^{j\beta_{m,n}}\\ u=\sin\theta\cos\phi\\ v=\sin\theta\sin\phi\end{cases}$$

Steering vector:

$$\underline{v}(u,v)=\left[e^{-jk(x_0u+y_0v)},\dots,e^{-jk(x_{N-1}u+y_{M-1}v)}\right]$$

$$AF(u,v)=\underline{w}^{H}\,\underline{v}(u,v)\;\Rightarrow\;BCE=\frac{\underline{w}^{H}A\,\underline{w}}{\underline{w}^{H}B\,\underline{w}}$$

$$\underline{w}^{H}=\left[w_0,\dots,w_{N-1}\right]^{H}$$

$$A=\left[\int_{\Omega}\underline{v}(u,v)\underline{v}^{H}(u,v)dudv\right]\qquad B=\left[\int_{\Gamma}\underline{v}(u,v)\underline{v}^{H}(u,v)dudv\right]$$

$$\underline{w}^{(opt)}=\arg\left\{\max_{\underline{w}}\left[BCE\right]\right\}$$

BCE measures the capability of the TX array of focusing the power in the angular region where it is the aperture of the RX rectenna

Fully-populated array architectures are very expensive!

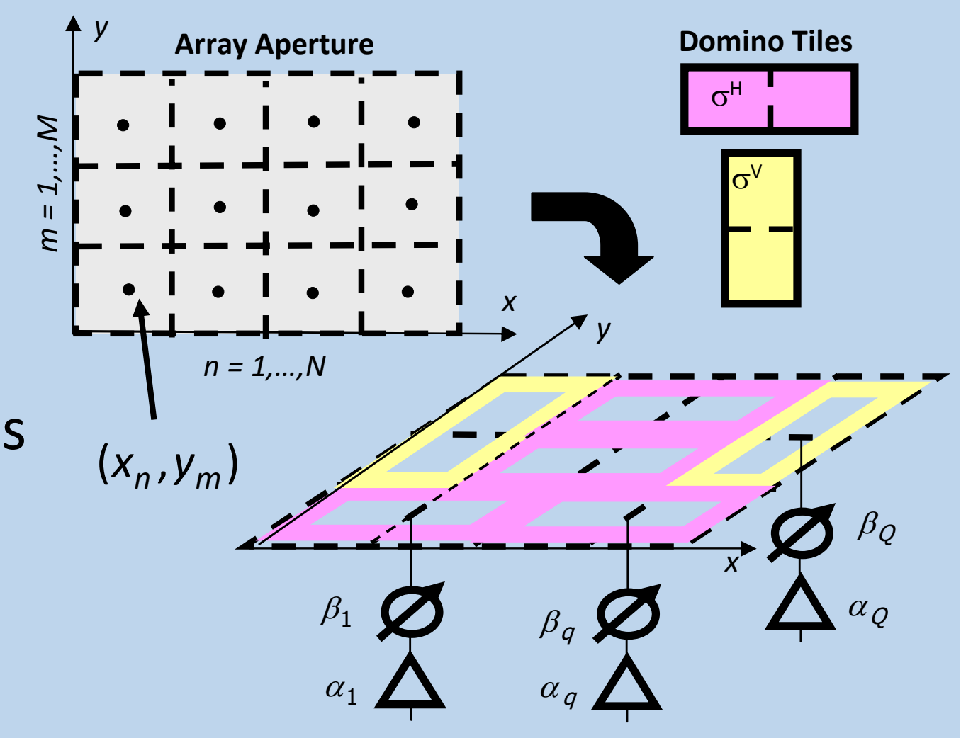
How to deal?

Unconventional *PA* Solution

Problem Statement

Find the optimal tiling/clustering configuration $\underline{C}^{opt}$ and the corresponding sub-array weights, $\underline{\alpha}^{opt}$ and $\underline{\beta}^{opt}$, such that the radiated pattern fits user-requirements, and maximizes the *BCE*

Domino-Tiled Array



$$\left(\underline{C}^{opt};\underline{\alpha}^{opt},\underline{\beta}^{opt}\right)=\arg\left[\min_{\underline{C},\underline{\alpha},\underline{\beta}}\left\{\Psi\left(\underline{C};\underline{\alpha},\underline{\beta}\right)\right\}\right]$$

Questions:

ⓐ How to tile the antenna aperture

ⓑ How to define the weights $\underline{\alpha}$ and $\underline{\beta}$ for each tile to fit radiated pattern requirements

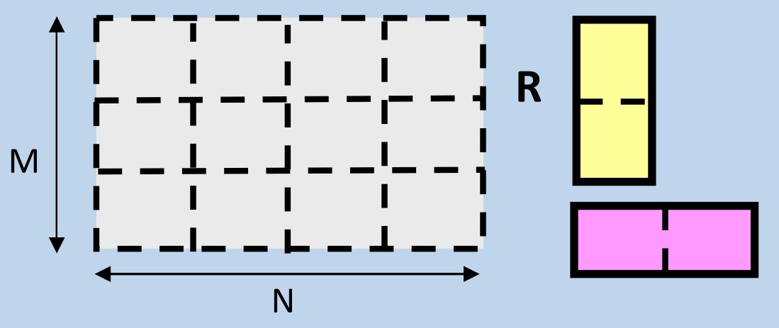
Domino-Tiled Array Synthesis with *BCE* Maximization

① Array Aperture Coverage

Objective Given a rectangular aperture *R* of size $M\times N$, **fully cover** it with **domino tiles**

Covering Theorem [*1*]

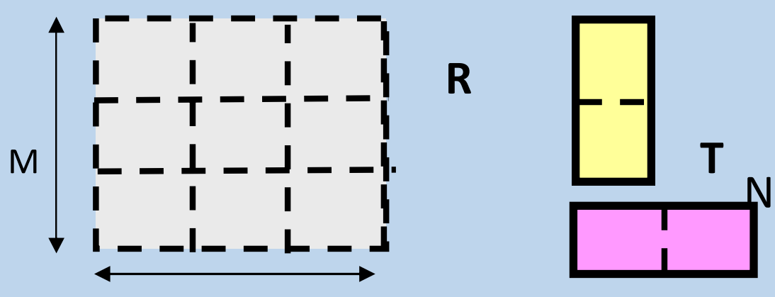
1. A rectangular aperture R of size M × N is **fully covered by domino tiles**, if and only if **M or N are even**.



Example: M=3, N=4

N = 4 mod 2 =0 → **Aperture Fully-Tileable**

2. **Otherwise**, the **empty area** extends to **a square pixel**



Example: M=3, N=3

N,M = 3 mod 2 = 1 → **Aperture NO Fully-Tileable**

② Complete Tiling Configuration

Cardinality Theorem [2]

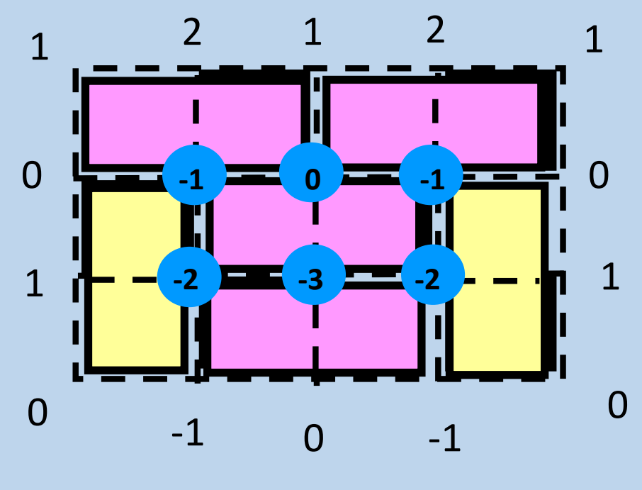
The **number T of domino-tile configurations** that **fully cover** an array aperture R of dimension M × N is:

$$T=2^{\frac{MN}{2}}\prod_{m=1}^{M}\prod_{n=1}^{N}\left[\cos^{2}\left(\frac{\pi m}{M+1}\right)+\cos^{2}\left(\frac{\pi n}{N+1}\right)\right]^{1/4}$$

③ Tiling Coding

Height Function [3]

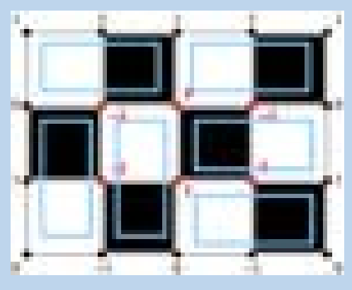
Definition



$\underline{h}$ = (-1, 0, -1, -2, -3, -2)

- ***Univocally*** define a tiling configuration
  $\underline{C}\rightarrow\{h_{mn}=h(v_{mn})\mid v_{mn}\notin\partial\Sigma\}$
- ***Analytically-defined*** on the **lattice vertexes**
  $h_{mn}=h(v_{mn})$ m = 0,…,M; n = 0,…,N
- ***Integer*** **values** function
  $h_{mn}\in Z$
- ***Efficient tiling coding*** (h-values internal nodes)
  dim($\underline{h}$) = (M – 1) × (N – 1) vs. dim($\underline{C}$) = M × N

Tiling Wording [4]



Height Function

$$\mathbf{h}^{(t)}=\left\{h_{mn}^{(t)};\forall v_{mn}\notin\partial A\right\}\;\longrightarrow\;\tau_{l}^{(t)}=\frac{h_{mn}^{(t)}-h_{mn}^{(1)}}{4}\;\longrightarrow\;\boldsymbol{\tau}^{(t)}=\left\{\tau_{l}^{(t)};l=1,\dots,L\right\}$$

$l=m+(n-1)\times(M-1)$

Tiling Word

$L=(M-1)\times(N-1)$

④ Optimization Tiling Method

Binary Genetic Algorithm (*GA*) [6,7]

Objective Choose the best possible complete tiled configuration to fit the requirements

Tiling Word

$\boldsymbol{\tau}^{(t)}=\{1\;1\;1\;2\;2\;1\;1\}$

$L=(M-1)\times(N-1)$

$\xrightarrow{\textit{Binary Coding}}$

GA Chromosome

0101011010 0101

$B_{\mathrm{w}}=L\times\log_2\left(w^{\max}\right)$

$\tau^{\max}=\max_{l=1,\dots,L}\left\{\tau_{l}^{(t)}\right\}$

⑤ Excitation Definition

***BCE* Maximization**

Apply **BCE maximization** to retrieve the best set of reference weights.

$$\underline{w}^{(ref)}=\arg\left\{\max_{\underline{w}}\left[BCE\right]\right\}$$

Compute the **sub-array** optimal set of weights applying:

$$\underline{w}^{(opt)}=\frac{1}{2}\sum_{m=1}^{M}\sum_{n=1}^{N}\delta_{C_{nm},q}\,\underline{w}_{mn}^{(ref)}$$

The best arrangement is selected by evaluating all the *T'* tiling configurations (*T'* ⊂ *T* subset of sol. explored by the *GA*):

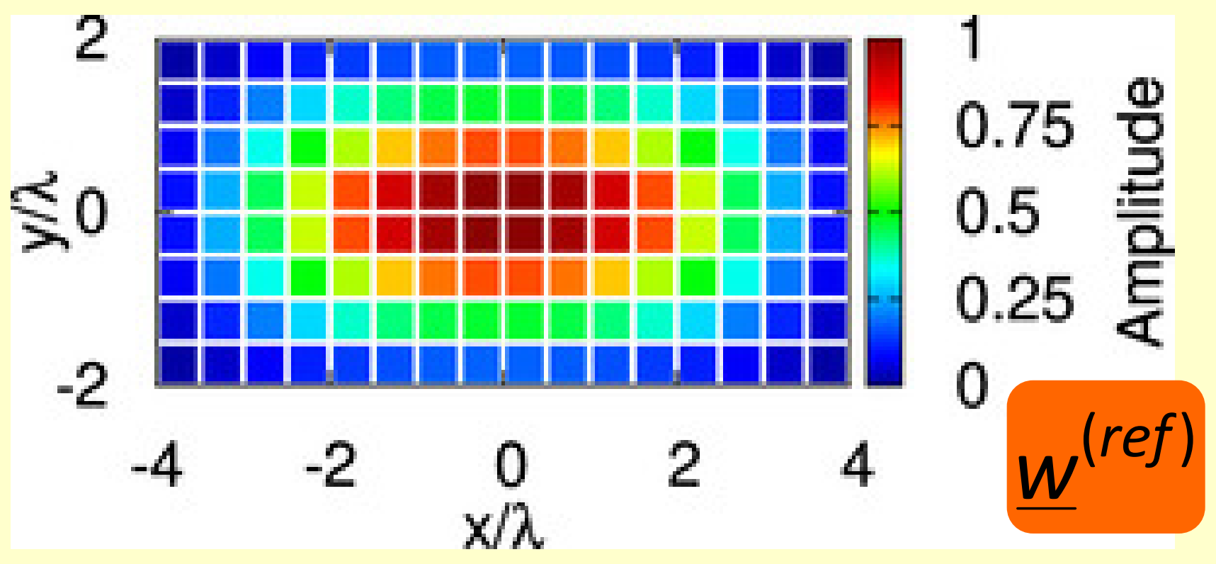
$$\underline{C}^{(opt)}=\min_{t=1,\dots,T}\left[\Psi\left(\underline{C}^{(t)},\underline{w}^{(opt)}\right)\right]$$

$$\Psi(\underline{C},\underline{w})=BCE^{(ref)}-BCE(\underline{C},\underline{w})$$

Numerical Results

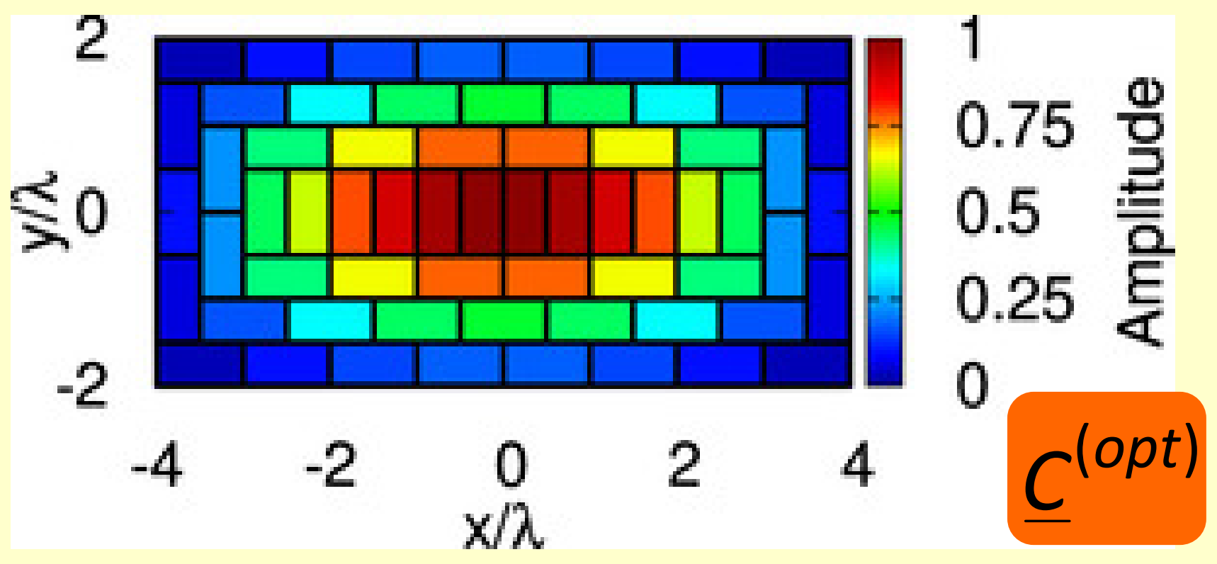
Configuration

Benchmark Configuration
- N = 16
- M = 8
- Q = 64
- θ_s = [0 °,45°]
- ϕ_s = [0 °,360°]
- Ω = {u_0 = 0.4 ; v_0 = 0.4}



Reference fully/populated array

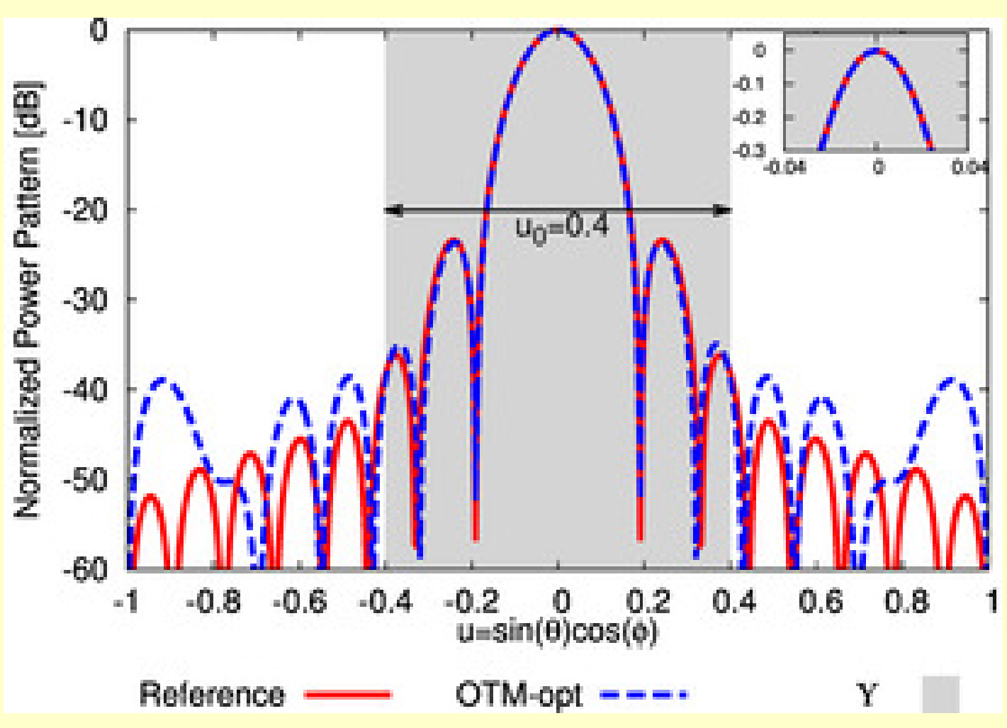
$BCE^{(ref)}=99.93\%$



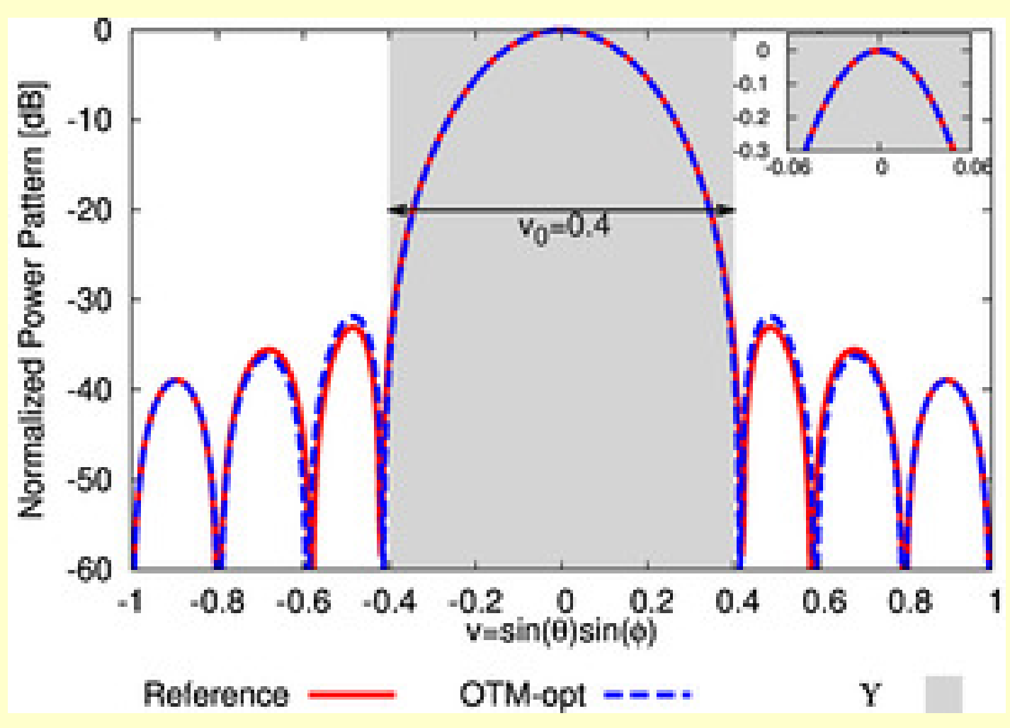
Best tiled array configuration

Control point reduced by 50%!

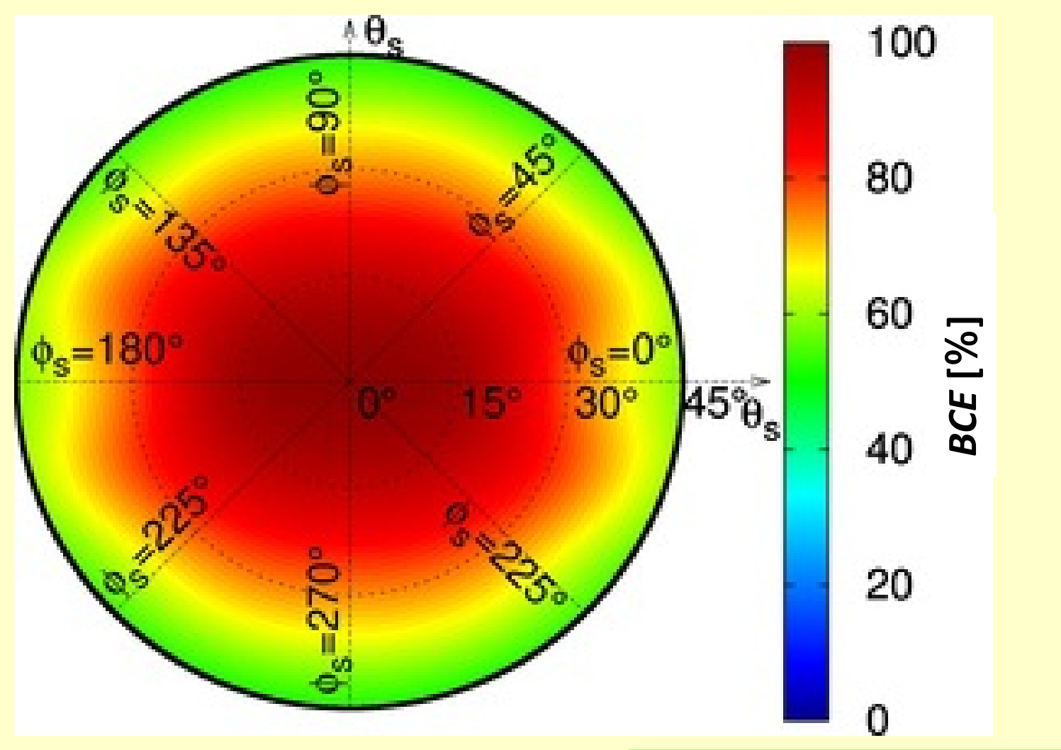
Tiled Array Configuration Results



ϕ=0°



ϕ=90°



$$\beta_q=-\frac{2\pi}{\lambda}\left(x_q\sin\theta_s\cos\phi_s+y_q\sin\theta_s\sin\phi_s\right)$$

$$\begin{pmatrix}x_q\\ y_q\end{pmatrix}=\sum_{m=1}^{M}\sum_{n=1}^{N}\delta_{C_{mn}q}\begin{pmatrix}x_n\\ y_m\end{pmatrix}$$

$BCE^{(opt)}=99.83\%$

$\Psi^{(opt)}=0.1\%$

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