Metasurface Cloaks for Large Cylindrical Cluster Configurations

These slides will be casted into a poster form – here is just an overview of results that I would like to show. There are probably too many results/figures – I would rather go for fewer, thus making the poster clear. Let me know of you opinion.

1 S. Arslanagić and 2 A. B. Yakovlev

1 Department of Electrical Engineering
   Electromagnetic Systems
   Technical University of Denmark

2 Center for Applied Electromagnetic Systems Research (CAESR)
   Department of Electrical Engineering,
   University of Mississippi

DTU Elektro
Institut for Elektroteknologi
Outline

• Background & motivation

• Configuration(s) & numerical model - HFSS

• Reference configuration – analytical/numerical treatment – verification of models

• Column configurations

• Slab-like configurations

• Ultimate goal – cloaking of electrically large slabs with meta-surface cloak impregnation

• Summary and conclusions
Background & motivation

Electromagnetic invisibility by metamaterials:

- the coordinate transformation method
- the scattering cancellation method with a plasmonic coating,
- anomalous localized resonance method,
- transmission line/waveguide technique
- the scattering cancellation method by a metasurface (mantle) cloak

Alex – in the motivation I will mention the work of Alu with plasmonic cloaking of a single column of cylinders, and another reference of Bilotti that was introduced in our paper upon its revision.

Then I will say that we want to do not only column of cylinders, but even larger configurations with the aim of investigating meta-surface potentials for large structure cloaking/scattering suppression.

If you have anything to add, please do so 😊
Alex, this figure will change – the new one will have the figure to the right, the mesh-grid surface, and a sketch of a full HFSS model (which will explain that the source is of a finite radius, and that symmetry planes are used on the top & bottom, as well as that PMLs are used to model infinite space).
Reference configuration

\[ E_i^j = -\frac{I_e \omega \mu_0}{4} H_0^{(2)}(k_s | \bar{\rho} - \bar{\rho}_s^j |) \]

\[ E_{1s} = -\frac{I_e \omega \mu_1 n}{4} \sum_{n=0}^{\infty} \tau_n C_{1n} J_n(k_1 \rho) \cos(n\phi) \]

\[ E_{2s} = \frac{I_e \omega \mu_0}{4} \sum_{n=0}^{\infty} \tau_n C_{2n} H_n^{(2)}(k_0 \rho) \cos(n\phi) \]

\[ H = -\frac{1}{j \omega \mu_i} \nabla \times \vec{E} \]

BCs & orthogonality relations

\[ E_z^{s1} \big|_{\rho=\rho_1} = (E_z^{s2} + E_z^i) \big|_{\rho=\rho_1} \]

\[ E_z^{s1} \big|_{\rho=\rho_1} = Z_s \left[ (H_\phi^{s2} + H_\phi^i) \big|_{\rho=\rho_1} - H_\phi^{s1} \big|_{\rho=\rho_1} \right] \]

\[ \vec{C}_n = \overline{M}_n^{-1} \Lambda_n \]

\[ \Lambda_n = \begin{bmatrix} \Lambda_{1n} \\ \Lambda_{2n} \end{bmatrix} = \begin{bmatrix} \mu_0 J_n(k_0 \rho_1) H_n^{(2)}(k_0 \rho_s) \\ jk_0 Z_s J_n(k_0 \rho_1) H_n^{(2)}(k_0 \rho_s) \end{bmatrix} \]

\[ \overline{M}_n = \begin{bmatrix} -\mu_0 H_n^{(2)}(k_0 \rho_1) \\ -\mu_0 H_n^{(2)}(k_0 \rho_1) - jk_0 Z_s H_n^{(2)}(k_0 \rho_1) \end{bmatrix} \]

Reference configuration was also treated in HFSS!
Reference configuration

$$\varepsilon_c = \varepsilon_0 10$$

$$\mu_c = \mu_0$$

$$\varepsilon_0, \mu_0, k_0, \eta_0$$

Initial (analytical) results [cf. [1]]:

$$f_0 = 300 \text{ MHz} \quad \lambda_0 = 1 \text{ MHz}$$

$$\rho_1 = \lambda_0 / 10 \quad (= 0.1 \text{ m})$$

$$D = \lambda_0 / 16 \quad (= 0.0625 \text{ m})$$

$$w = \lambda_0 / 200 \quad (= 0.005 \text{ m})$$

$$Z_s = j48.9 \Omega$$

HFSS model:

$$D = 0.0625 \text{ m} \quad \rho_1 = 10D / (2\pi) = 0.99471839 \text{ m} \quad f_0 = 304 \text{ MHz} \quad Z_s = j49.6 \Omega$$

$$w = 0.005 \text{ m}$$

$$\rho_s = 0.2 \text{ m}$$

Cloaking observed!

Cloaking observed!
Reference configuration

Initial (analytical) results [cf., [1]]:

- $f_0 = 300 \text{ MHz}$
- $\lambda_0 = 1 \text{ MHz}$
- $\rho_1 = \lambda_0 / 10$ ($= 0.1 \text{ m}$)
- $D = \lambda_0 / 16$ ($= 0.0625 \text{ m}$)
- $w = \lambda_0 / 200$ ($= 0.005 \text{ m}$)

$Z_s = j48.9 \Omega$

HFSS model:

- $D = 0.0625 \text{ m}$
- $w = 0.005 \text{ m}$
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- $f_0 = 304 \text{ MHz}$
- $Z_s = j49.6 \Omega$

Analytical vs. HFSS; $\text{Re}(E_z) \text{ [V/m]}$; $\rho_s = 0.2 \text{ m}$ $f_0 = 304 \text{ MHz}$

Excellent correspondence between analytical and HFSS results – models are verified!

From now on, only HFSS results are shown!
Reference configuration

\[ \rho_s = 0.2 \text{ m} \quad f_0 = 304 \text{ MHz} \]

HFSS results – field overlay plots:

- **Free space**
- **No cloak**
- **Cloak**

**Poynting vector** [W/m²]

**Origin**

**x**

**y**

4 m

**Re(\(E_z\))** [V/m]

**P_{\text{radiated}}** [W/m] = XXX.XX

Cloaking not just along the x-axis, but **many** observation points outside the cylinder!

Alex, comment to you 😊
Reference configuration

\[ \rho_s = 0.5 \text{ m} \quad f_0 = 304 \text{ MHz} \]

Cloaking not just along the \( y \)-axis, but many observation points outside the cylinder!
Column configurations I

\[ |E_z| \text{ [V/m]} \]

\[ \rho_s = 0.2 \text{ m} \quad f_0 = 304 \text{ MHz} \]

Scattering suppression / cloaking in evidence when observing the absolute value of the field!
Scattering supression / cloaking in evidence when observing the real part of the field!

Near-field cuts will be shown along the "white lines" for 2-, 3-, and 5-cylinder configurations:

Line 1: $x=0$, as a function of $y$.  Line 2: $y=0$, as a function of $x$.  Line 3: Diagonal
Scattering suppression/cloaking in evidence in all cases – but slightly direction dependent!
**Column configurations IV**

Re($E_z$) [V/m]  \[ \rho_s = 0.5 \text{ m} \quad f_0 = 304 \text{ MHz} \]

Scattering suppression / cloaking in evidence!

Direction dependence confined mostly to the parts of the $y<0$ half-space, while $y>0$ works better now!

**PS:** Near-field cuts can be done when I get back! Otherwise, I will keep just what is shown here!
Column configurations V

$|E_z| \text{[V/m]} \quad \rho_s = 0.5 \text{ m} \quad f_0 = 304 \text{ MHz}$

Scattering supression / cloaking in evidence!
**Slab-like configurations I**

\[ \text{Re}(E_z) \, [\text{V/m}] \]

\[ \rho_s = 0.2 \, \text{m} \quad f_0 = 304 \, \text{MHz} \]

Near-field cuts will be shown along the “white lines” for both of these configurations.

**Line 1:** \( x=0 \), as a function of \( y \).  **Line 2:** \( y=0 \), as a function of \( x \).
Slab-like configurations II

\[ \text{Re}(E_z) \text{ [V/m]} \]
\[ \rho_s = 0.2 \text{ m} \quad f_0 = 304 \text{ MHz} \]

2 by 3 cylinders

3 by 3 cylinders

Line 1
\( x = 0 \)

Line 2
\( y = 0 \)

Slightly better results along x-axis than y-axis – but scattering suppression still present!

Note: the field between the cylinders (and not just around them all) in the “cloaked cylinders” case approached the “no cylinders case” – this is quite remarkable!
Electrically large structures – Metasurface cloak impregnation

Illustrating the concept and final purpose – **ongoing and future work**! Results obtained for 28-cylinder case!

Collection of electrically small (ES) dielectric cylinders

Equiavalent electrically large (EL) dielectric slab

Meta-surface

Model an EL slab by collection of tiny ES cylinders. Equivalence must first be established!

If the collection of cylinders can be cloaked by meta-surfaces on each of them, then the EL slab should be cloaked by retaining the meta-surface cloaks as shown in the figure.
Summary and conclusions

• This will come when I get back – I worked too much now to make sound and clear conclusions 😊
Additional results I – Configuration I

\[ \rho_s = 0.2 \text{ m} \quad f_0 = 304 \text{ MHz} \]

Analytical results (HFSS results on p. 8)

• I have them, but they are not needed, I suppose. Note, I did not make any normalization when comparing HFSS results with Matlab, they fitted right on the spot from the very beginning.

• If you look at colour plots they will differ because the colorbars are simply using different span of colors to represent same field values (and I say this even when dynamic ranges in HFSS and Matlab are identical!). This is why I would not show the analytical color figures – the verification done in terms of cuts should be sufficient for the present purposes.
Additional results II – Configuration I

\[ \rho_s = 0.5 \text{ m} \quad f_0 = 304 \text{ MHz} \quad \text{Analytical results (HFSS results on p. 9)} \]

- I have them, but they are not needed, I suppose. Note, I did not make any normalization when comparing HFSS results with Matlab, they fitted right on the spot from the very beginning.

- If you look at colour plots they will differ because the colorbars are simply using different span of colors to represent same field values (and I say this even when dynamic ranges in HFSS and Matlab are identical!). This is why I would not show the analytical color figures – the verification done in terms of cuts should be sufficient for the present purposes.