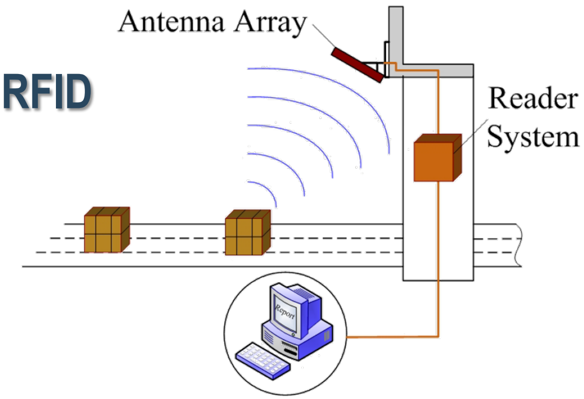
A NOVEL METHOD TO FIELD INTENSITY SHAPING INTO (PARTIALLY) UNKNOWN SCENARIOS

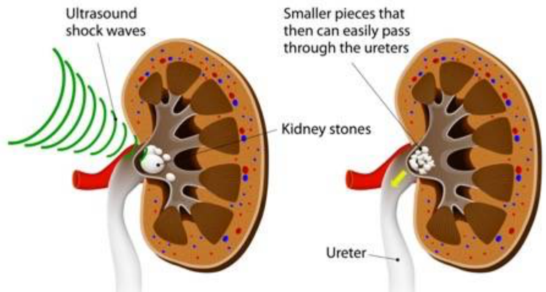
Martina T. Bevacqua[1] and Gennaro G. Bellizzi[2]

[1]DIIES, Università Mediterranea di Reggio Calabria, Italy
[2]Dept. of Radiation Oncology, Erasmus University Medical Center, Rotterdam, The Netherlands

Motivations

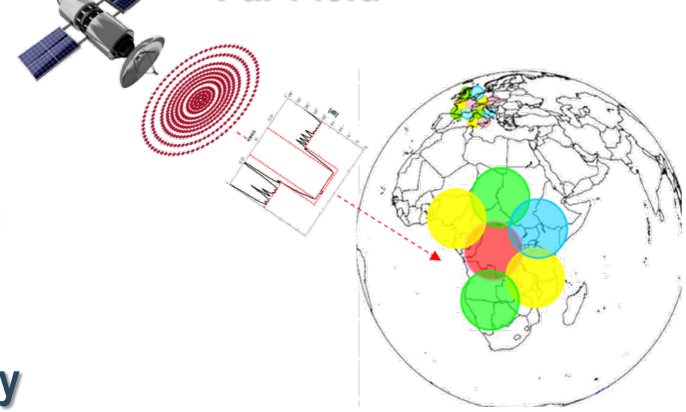
RFID

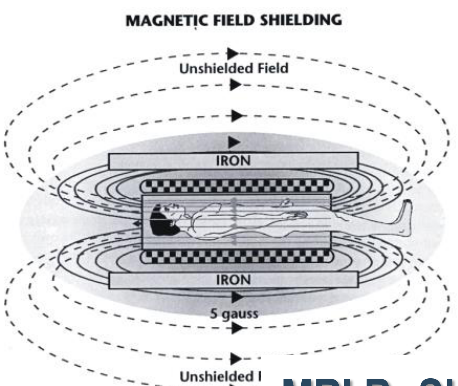




Litothripsy

Far Field

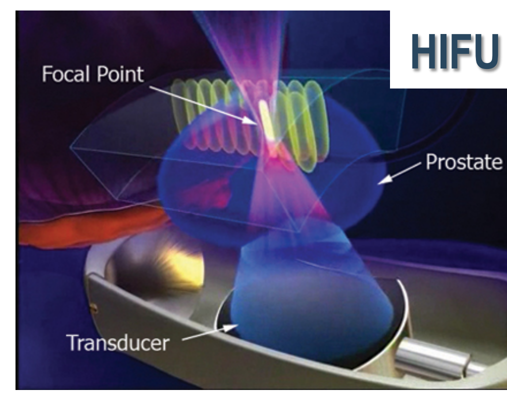




MRI B_0 Shaping

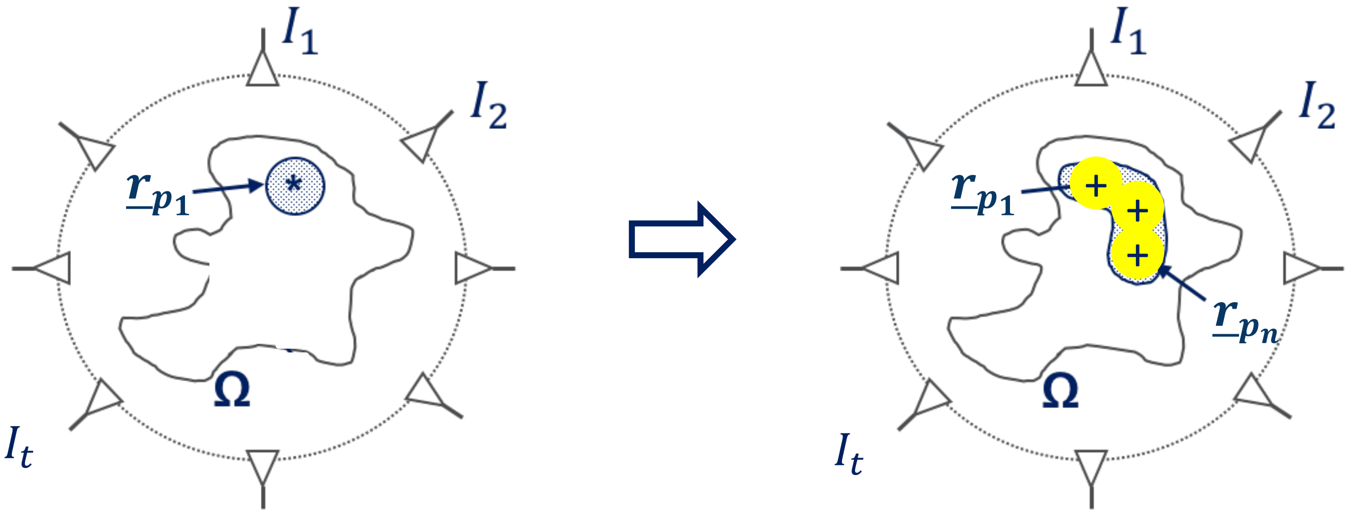
Hyperthermia

HIFU



From Focusing to Shaping in known scenario

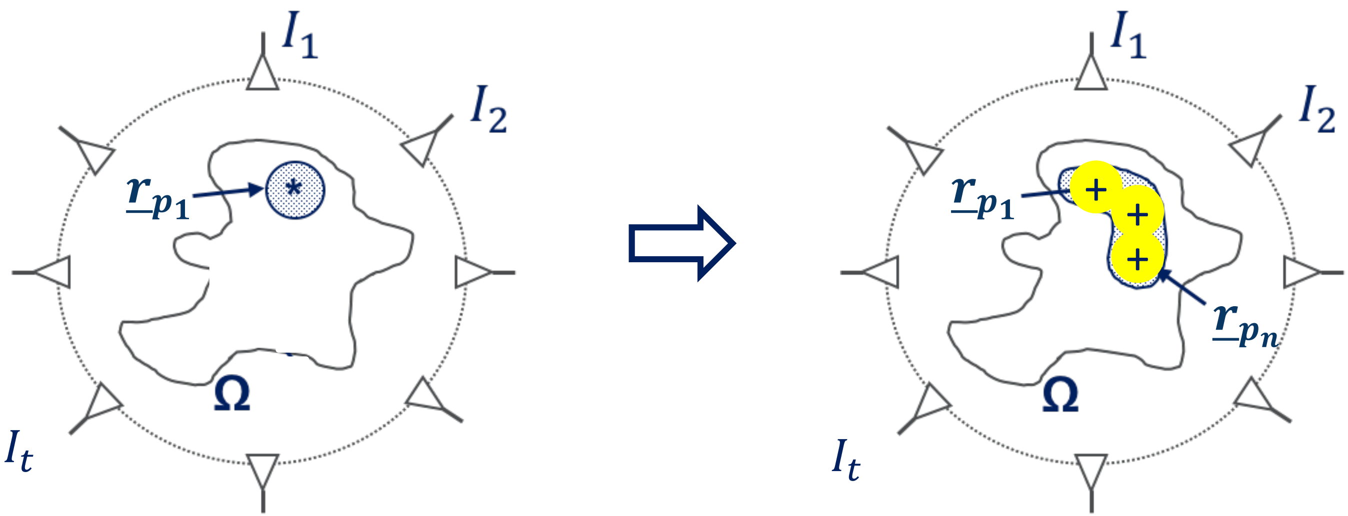
Solving the **focusing** problem at the different "*control points*" **does not** exploit all the **degrees of freedom of the problem…**



… i.e. the phase shifts of the field between the control points!

From Focusing to Shaping in known scenario

Solving the **focusing** problem at the different "*control points*" **does not** exploit all the **degrees of freedom of the problem…**



… i.e. the phase shifts of the field between the control points! Hence, two different techniques have developed and tested:

Multi-Target FOcusing via Constrained Optimization[*]

Optimized Multi-Target Time Reversal[**]

[*] G.G. Bellizzi et al., "3-D field intensity shaping: The scalar case," IEEE Antennas and Wireless Propagation Letters, vol. 17, Is. 3, pp. 360-363, March 2018;
[**] G.G. Bellizzi et al., "3-D Field Intensity Shaping via Optimized Multi-Target Time Reversal", IEEE Trans. on Ant. and Prop., May 2018;

From Focusing to Shaping in unknow scenario

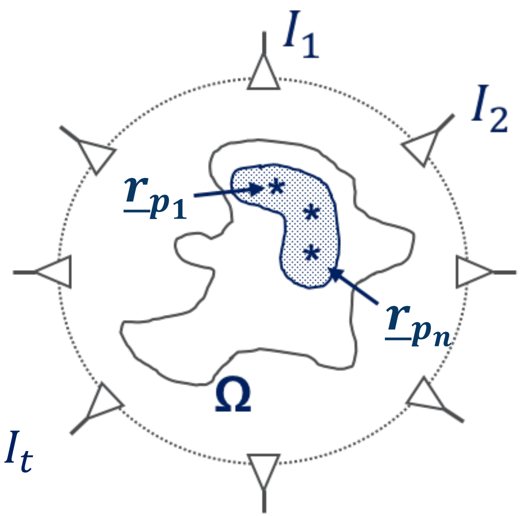
However, both mt-FOCO and O-mt-TR requires the knowledge of the investigated targets and scenario.

This, instead, is not necessarily possible!

GOAL:

Introduction of a novel adaptive procedure able to shape the field intensity in an unknown (or partially unknown) scenario.

Shaping in unknow scenario



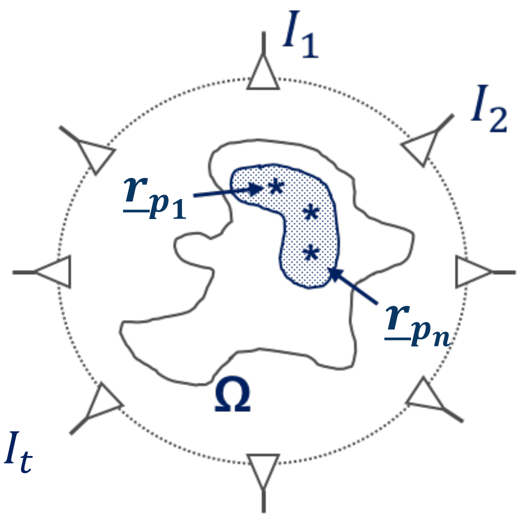
The total field in Ω is given by:

$$E(\underline{r}) = \sum_{t=1}^{T} I_t \, E_{tot}(\underline{r}, \underline{r}_t)$$

I_t :set of the unknown complex excitations

How can one determine I_t when E_{tot} are unknown?

Shaping in unknow scenario: a first possibility



The total field in Ω is given by:

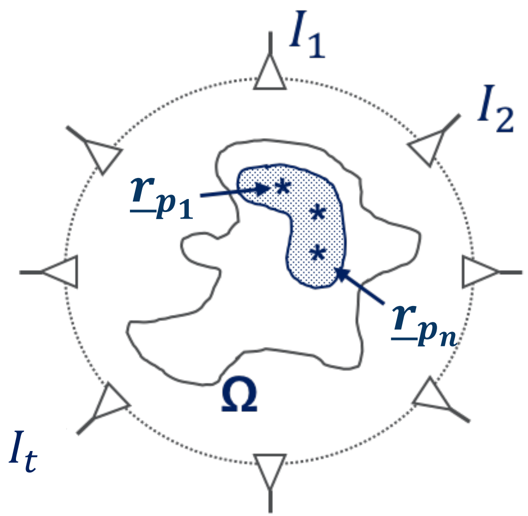
$$E(\underline{r}) = \sum_{t=1}^{T} I_t \, E_{tot}(\underline{r}, \underline{r}_t)$$

I_t :set of the unknown complex excitations

$E_s(\underline{r}_m, \underline{r}_t)$ $E_{tot}(\underline{r}, \underline{r}_t)$ I_t

STEP 1: Preliminary sensing → STEP 2: Quantitative imaging → STEP 3a: Focusing → STEP 3b: Optimal phase shift configuration

Shaping in unknow scenario: the proposed approach



The total field in Ω is given by:

$$E(\underline{r}) = \sum_{t=1}^{T} I_t \, E_{tot}(\underline{r}, \underline{r}_t)$$

I_t :set of the unknown complex excitations

$E_s(\underline{r}_m, \underline{r}_t)$

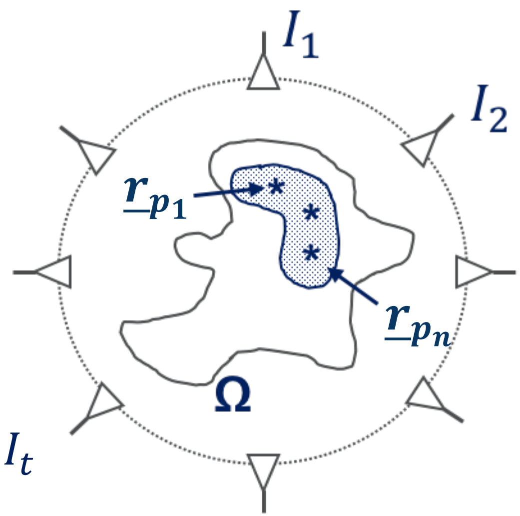
STEP 1: Preliminary sensing

The antennas surrounding Ω are exploited in order to collect information on the unknown scenario.

The scenario is illuminated with known incident fields $E_{inc}(\underline{r}, \underline{r}_t)$ and then the corresponding scattered fields $E_s(\underline{r}_m, \underline{r}_t)$ are measured.

[*] G.G. Bellizzi and M. T. Bevacqua, "The Linear Sampling Method as a Tool for "Blind" Field Intensity Shaping", IEEE Trans. on Ant. and Prop., 2020.

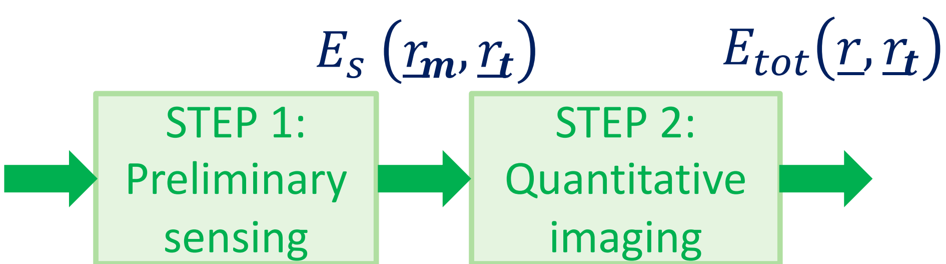
Shaping in unknow scenario: a first possibility



The total field in Ω is given by:

$$E(\underline{r}) = \sum_{t=1}^{T} I_t \, E_{tot}(\underline{r}, \underline{r}_t)$$

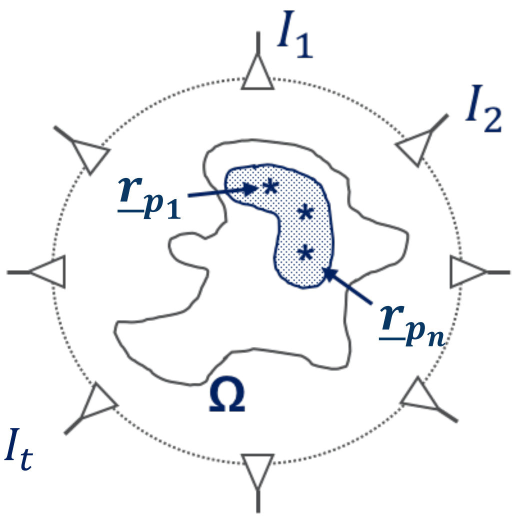
I_t :set of the unknown complex excitations



The geometry and electromagnetic properties of the unknown scenario are retrieved through an **inverse scattering problem**.

This step also yields the evaluation of the total field within the domain of interest.

Shaping in unknow scenario: a first possibility



The total field in Ω is given by:

$$E(\underline{r}) = \sum_{t=1}^{T} I_t \, E_{tot}(\underline{r}, \underline{r}_t)$$

I_t :set of the unknown complex excitations

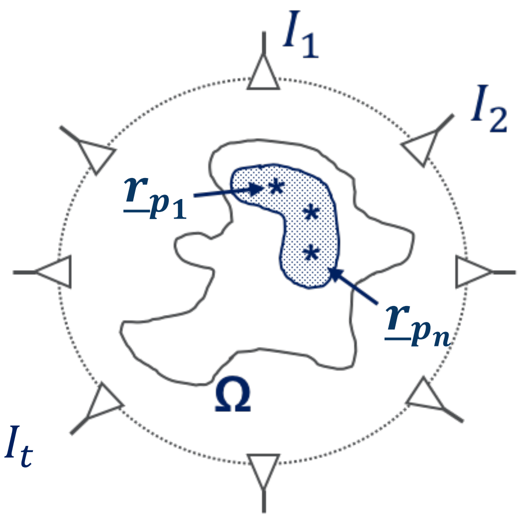
$E_s(\underline{r}_m, \underline{r}_t)$ $E_{tot}(\underline{r}, \underline{r}_t)$

STEP 1: Preliminary sensing → STEP 2: Quantitative imaging →

The geometry and electromagnetic properties of the unknown scenario are retrieved through an **inverse scattering problem**.

non-linear and ill-posed inverse problem!

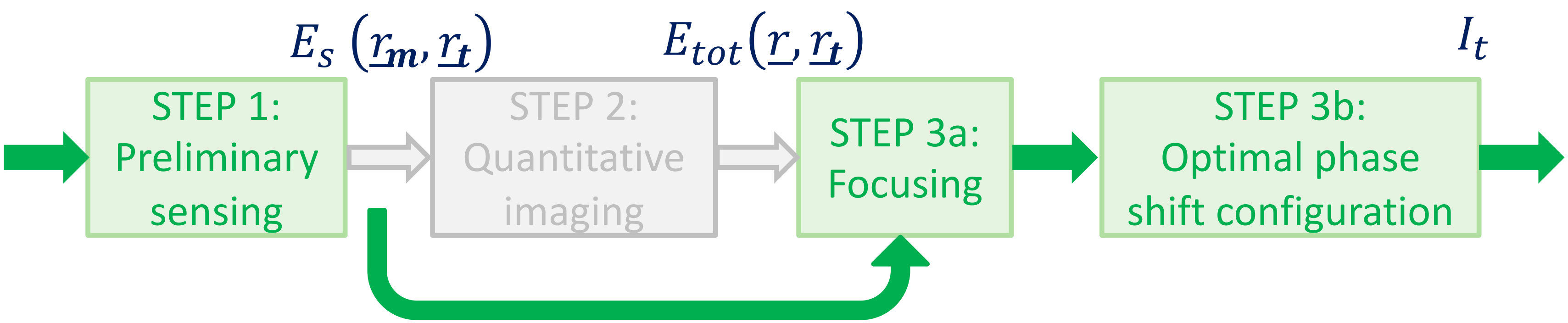
Shaping in unknow scenario: the proposed approach



The total field in Ω is given by:

$$E(\underline{r}) = \sum_{t=1}^{T} I_t \, E_{tot}(\underline{r}, \underline{r}_t)$$

I_t :set of the unknown complex excitations



By means of Linear Sampling Method (LSM)!

[*] G.G. Bellizzi and M. T. Bevacqua, “The Linear Sampling Method as a Tool for “Blind” Field Intensity Shaping”, IEEE Trans. on Ant. and Prop., 2020.

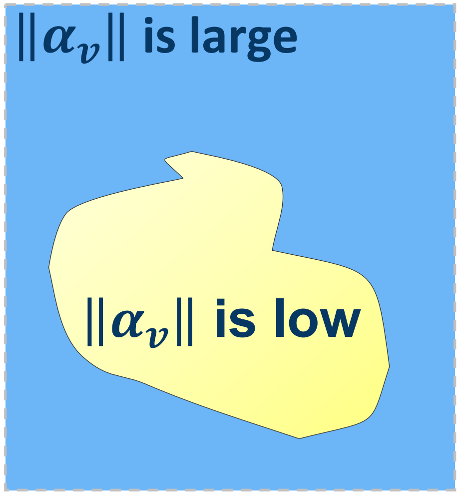
Linear Sampling method

The LSM consists in sampling the region under test into an arbitrary grid of points and solving for each point, say $\underline{r}_{\boldsymbol{p_n}}$, the LSM equation as given in:

$$\alpha_t : \sum_{t=1}^{N} \alpha_t\left(\underline{r}_{\boldsymbol{t}}, \underline{r}_{\boldsymbol{p_n}}\right) E_s\left(\underline{r}_{\boldsymbol{t}}, \underline{r}_{\boldsymbol{m}}\right) = G\left(\underline{r}_{\boldsymbol{t}}, \underline{r}_{\boldsymbol{p_n}}\right)$$

"Far Field Equation"

THE ENERGY OF α_t ALLOWS TO GUESS THE SHAPE OF THE UNKNOWN SCATTERER.

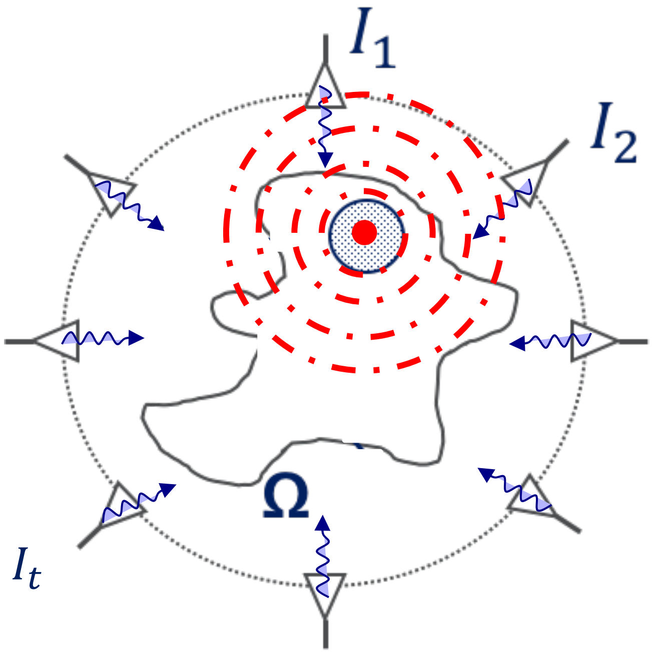


[*] L. Crocco, L. Di Donato, D. A. M. Iero, and T. Isernia, "An Adaptive Method to Focusing in an Unknown Scenario," Progress In Electromagnetics Research, 2012.

Linear Sampling method

LSM allows to focus the total field $\mathcal{E}(\underline{r}, \underline{r}_{\boldsymbol{p_n}})$ in a given control point $\underline{r}_{\boldsymbol{p_n}}$ as follows:

$$\mathcal{E}(\underline{r}, \underline{r}_{\boldsymbol{p_n}}) = \sum_{t=1}^{N} \alpha_t\, (\underline{r}_{\boldsymbol{t}}, \underline{r}_{\boldsymbol{p_n}}) E_{tot}(\underline{r}, \underline{r}_{\boldsymbol{t}})$$



[*] L. Crocco et al., "The linear sampling method as a way to quantitative inverse scattering", IEEE Trans. on Ant. and Prop., 2012.

Linear Sampling method

LSM allows to focus the total field $\mathcal{E}(\underline{r}, \underline{r}_{\boldsymbol{p_n}})$ in a given control point $\underline{r}_{\boldsymbol{p_n}}$ as follows:

$$\mathcal{E}(\underline{r}, \underline{r}_{\boldsymbol{p_n}}) = \sum_{t=1}^{N} \alpha_t \left(\underline{r}_{\boldsymbol{t}}, \underline{r}_{\boldsymbol{p_n}}\right) E_{tot}\left(\underline{r}, \underline{r}_{\boldsymbol{t}}\right)$$

Moreover, it allows to approximate the total internal field $\mathcal{E}(\underline{r}, \underline{r}_{\boldsymbol{p_n}})$ by the sum of a cylindrical wave centered on the corresponding 'pivot' point $\underline{r}_{\boldsymbol{p_n}}$ and the recombined incident field:

$$\boxed{\mathcal{E}(\underline{r}, \underline{r}_{\boldsymbol{p_n}}) \cong \mathcal{E}_{LSM}(\underline{r}, \underline{r}_{\boldsymbol{p_n}}) = \sum_{t=1}^{N} \alpha_t \left(\underline{r}_{\boldsymbol{t}}, \underline{r}_{\boldsymbol{p_n}}\right) E_{inc}\left(\underline{r}, \underline{r}_{\boldsymbol{t}}\right) + LP\left\{H_{\boldsymbol{0}}^{2}\left(k_b \left|\underline{r} - \underline{r}_{\boldsymbol{p_n}}\right|\right)\right\}}$$

[*] L. Crocco et al., "The linear sampling method as a way to quantitative inverse scattering", IEEE Trans. on Ant. and Prop., 2012.

Shaping in unknow scenario: the proposed approach

$E_s\left(\underline{r}_{\boldsymbol{m}}, \underline{r}_{\boldsymbol{t}}\right)$ $\alpha_t\left(\underline{r}_{\boldsymbol{t}}, \underline{r}_{\boldsymbol{p_n}}\right)$

STEP 1: Preliminary sensing → STEP 2a: LSM-based Focusing →

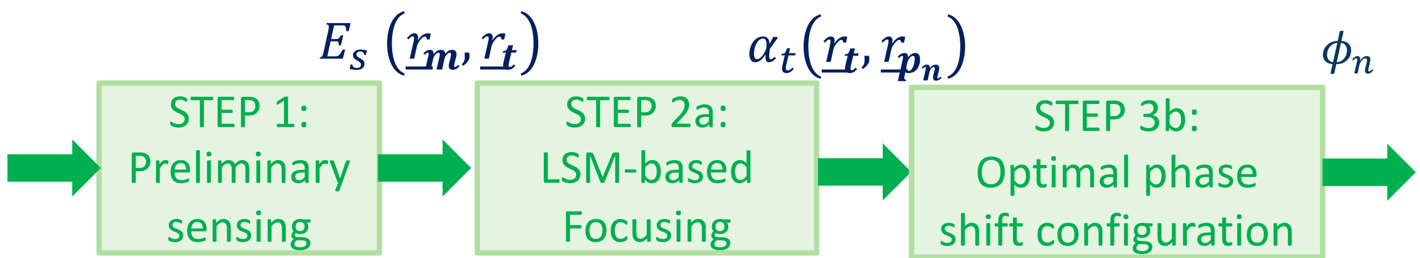
$$I_t = \sum_{n=1}^{L} \alpha_t\left(\underline{r}_{\boldsymbol{t}}, \underline{r}_{\boldsymbol{p_n}}\right) e^{j\phi_n}$$

- ϕ_n is the phase shift between the fields in the control point $\underline{r}_{\boldsymbol{p_1}}$ and $\underline{r}_{\boldsymbol{p_n}}$, to be optimally determined within the range [0, 2π].

- L is the number of control points $\underline{r}_{\boldsymbol{p_n}}$(n = 1, .., L).

[*] G.G. Bellizzi and M. T. Bevacqua, “The Linear Sampling Method as a Tool for “Blind” Field Intensity Shaping”, IEEE Trans. on Ant. and Prop., 2020.

Shaping in unknow scenario: the proposed approach



The optimization problem for the selection of the optimal phase shifts ϕ_n can be cast as:

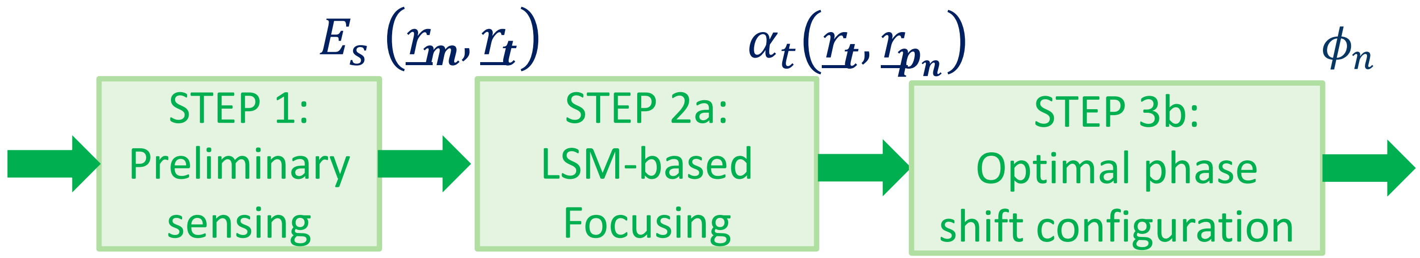
$$\phi_{opt} = \max_{\phi_n} \int_{\Pi(\underline{r})} \left| \sum_{n=1}^{L} \mathcal{E}_{LSM}\left(\underline{r},\underline{r}_{\boldsymbol{p_n}}\right) e^{j\phi_n} \right|^2$$

Then the optimal array excitations are given by:

$$I_t = \sum_{n=1}^{L} \alpha_t\left(\underline{r}_{\boldsymbol{t}},\underline{r}_{\boldsymbol{p_n}}\right) e^{j\phi_{opt}}$$

[*] G.G. Bellizzi and M. T. Bevacqua, “The Linear Sampling Method as a Tool for “Blind” Field Intensity Shaping”, IEEE Trans. on Ant. and Prop., 2020.

Shaping in unknow scenario: the proposed approach



When just a few control points are of interest, one possibility to solve problem is that of determining the optimal phase configuration by enumerative optimization.

Notably, such an optimization approach, while automatic, becomes less effective as the number of control points grows.

The very general mathematical connotation allows a straightforward implementation of different optimization strategies, such as parallel computing and machine learning procedure.

[*] G.G. Bellizzi and M. T. Bevacqua, "The Linear Sampling Method as a Tool for "Blind" Field Intensity Shaping", IEEE Trans. on Ant. and Prop., 2020.

Numerical examples

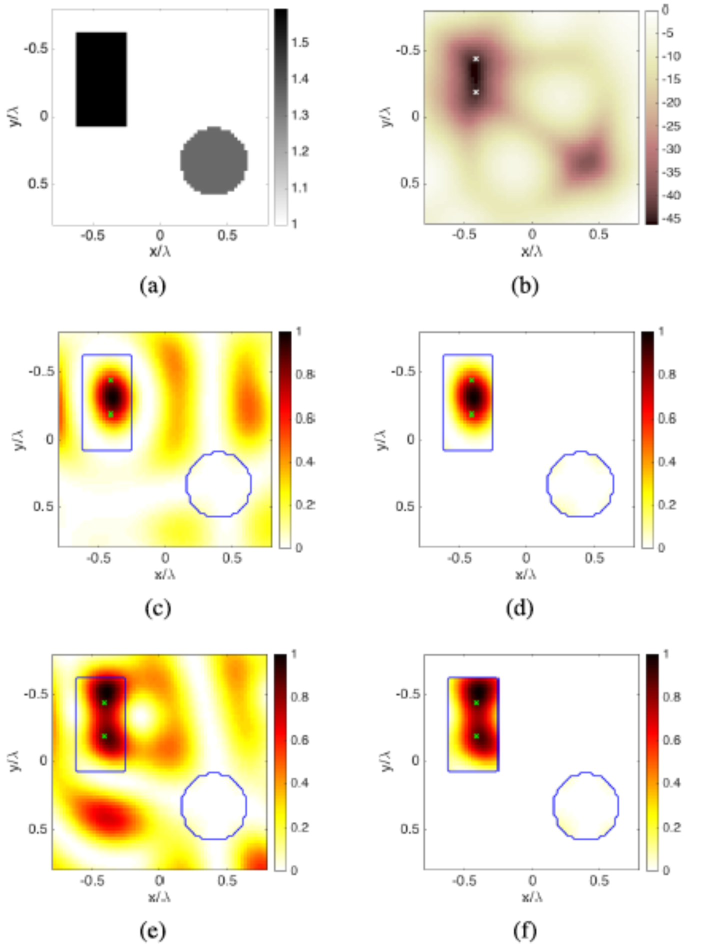


Fig. 2. (a) Relative permittivity profile and (b) normalized LSM indicator map in logarithmic scale for configuration I. The normalized squared field amplitudes achieved by means of mt-LSM and O-mt-LSM are depicted within the whole domain of investigation in (c) and (e) and within the actual support of the unknown objects in (d) and (f), respectively. Control points are marked as "*x.*"

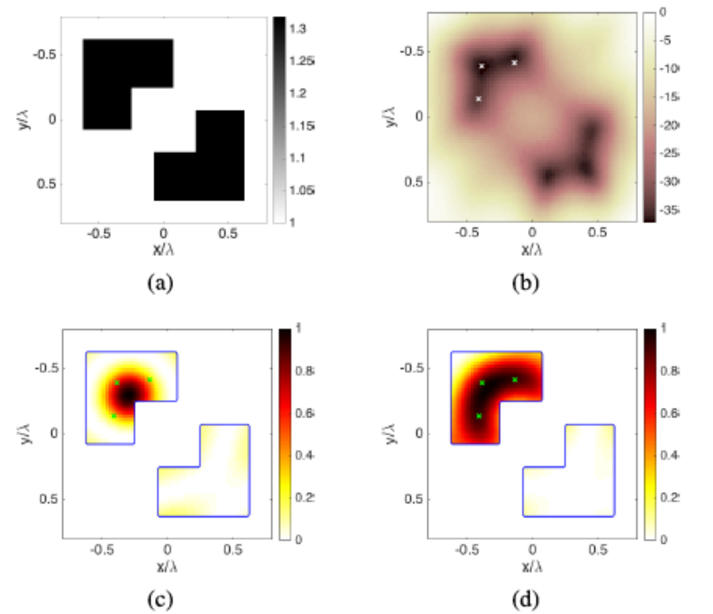


Fig. 3. (a) Relative permittity profile and (b) normalized LSM indicator map in logarithmic scale for configuration II. The normalized squared field amplitudes achieved within the actual support by means of (c) mt-LSM (d) and O-mt-LSM, respectively. Control points are marked as "*x.*"

[*] G.G. Bellizzi and M. T. Bevacqua, "The Linear Sampling Method as a Tool for "Blind" Field Intensity Shaping", IEEE Trans. on Ant. and Prop., 2020.

Numerical examples

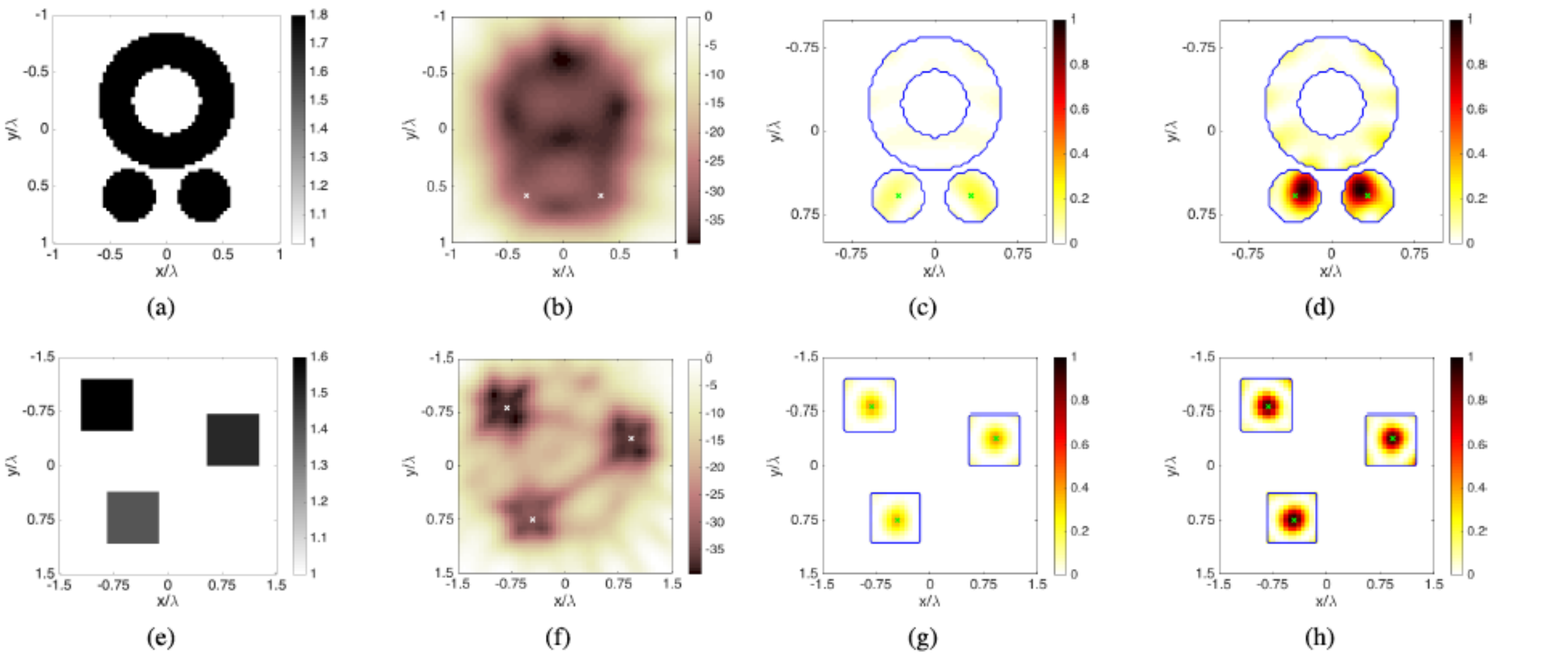


Fig. 4. (a) and (e) Relative permittity profiles and (b) and (f) normalized LSM indicator map in logarithmic scale for configurations **III** and **IV**, respectively. The normalized squared field amplitudes achieved by means of mt-LSM and O-mt-LSM: (c) and (d) for configuration **III** and (g) and (h) for configuration **IV**. Control points are marked as "*x.*"

[*] G.G. Bellizzi and M. T. Bevacqua, "The Linear Sampling Method as a Tool for "Blind" Field Intensity Shaping", IEEE Trans. on Ant. and Prop., 2020.

Conclusions

- An approach for blind shaping able to arbitrary shape the field intensity distribution into a (partially) unknown scenario without the need of quantitative retrieving the electromagnetic properties of the targets.

- Use of **LSM physical interpretation** as a tool to focus the electromagnetic field intensity in the presence of unknown obstacles and the additional degrees of freedom that are the **phase shifts** of the field in the considered control points.

- Limited computational time of the proposed approach as compared to other more cumbersome approaches.

- Future efforts: devising and testing novel selection criterion as well as optimization strategies for the optimal phase shift selection, exploiting the proposed procedure within a real 3-D application scenario.

[*] G.G. Bellizzi and M. T. Bevacqua, “The Linear Sampling Method as a Tool for “Blind” Field Intensity Shaping”, IEEE Trans. on Ant. and Prop., 2020.

A Novel Method to Field Intensity Shaping into (Partially) Unknown Scenarios

Martina T. Bevacqua[1] and Gennaro G. Bellizzi[2]

[1]DIIES, Università Mediterranea di Reggio Calabria, Italy
[2]Dept. of Radiation Oncology, Erasmus University Medical Center, Rotterdam, The Netherlands