WAIM Technology for 5G Applications with Dual-Polarization Waveguide Antennas

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1 Mathematical Formulation

1.1 Cost Function

The cost function used to evaluate the solution quality is defined as follows

$$\Phi\left(\underline{x}\right)=\frac{1}{N_f N_a N_m}\sum_{a=1}^{N_a}\sum_{i=1}^{N_f}\sum_{m=1}^{N_m}\mathcal{H}\left[S_{mm}^{A}\left(\theta_a,\,\phi_a,\,f_i,\,\underline{x}\right)-S_{th}\right] \tag{1}$$

where

- N_a is the number of angular directions of steering considered
- N_m is the number of modes/polarizations considered
- N_f is the number of frequencies considered
- $S_{mm}^{A}\left(\theta_a,\,\phi_a,\,f_i,\,\underline{x}\right)$ is the active S-parameter in $[dB]$ at frequency f_i for the m-th mode/polarization when steering toward $\left(\theta_a,\,\phi_a\right)$ and setting the DoFs of the geometry at $\underline{x}$
- S_{th} is the maximum allowed S-parameter value (threshold) in $[dB]$
- $\mathcal{H}\left[\cdot\right]$ is the Heaviside function defined as:

$$\mathcal{H}\left[\xi\right]=\begin{cases}\xi & \xi>0\\ 0 & \text{otherwise}\end{cases} \tag{2}$$

This definition of the cost function means that the optimization algorithm will search for a configuration that minimizes the average out-of-mask values of the S-parameter with respect to the scan angles, the modes/polarizations, and the frequencies. This means that there is no difference (weight) for a scan angle with respect to another one or between different modes/polarizatoins and frequencies.

2 Numerical Results

2.1 WAIM Optimization [$Q = 1$]

Find a configuration of the WAIM able to minimize the scan loss with only one cross as metallization.

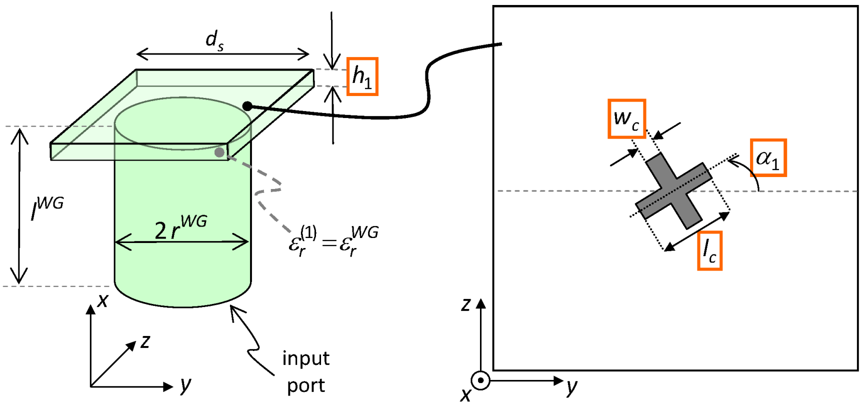
2.1.1 PSO [$Q = 1$, $K = 4$, $P = 8$, $I = 40$]

DoFs

- Number of variables, $K = 4$
- Number of WAIM crosses, $Q = 1$
- Optimization variables and ranges

Physical Meaning	Variable	min	max
Length of the cross arms	l_c	5 [mm]	12 [mm]
Width of the cross arms	w_c	3 [mm]	7 [mm]
Superstrate thickness	h_1	0.127 [mm]	3 [mm]
Tilt of cross	α_1	0 [deg]	90 [deg]

Table I: Variable ranges ($Q = 1$, $K = 4$) - Minimum and maximum allowed values.



(a)

Figure 1: WAIM ($Q = 1$) - Variable physical meaning on the WAIM geometry.

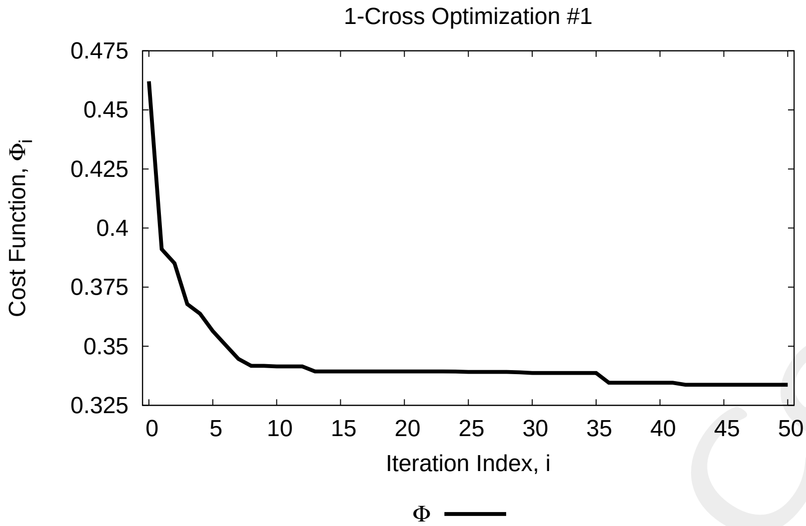
Optimization Parameters

- Optimization algorithm, *PSO*
- Number of particles, $P = 8$
- Number of iterations, $I = 50$
- Swarm initialization, *Random*
- Inertial weight, $w = 0.8$
- Acceleration coefficients, $C_1 = C_2 = 2.0$
- Random seed value, $s = 1$

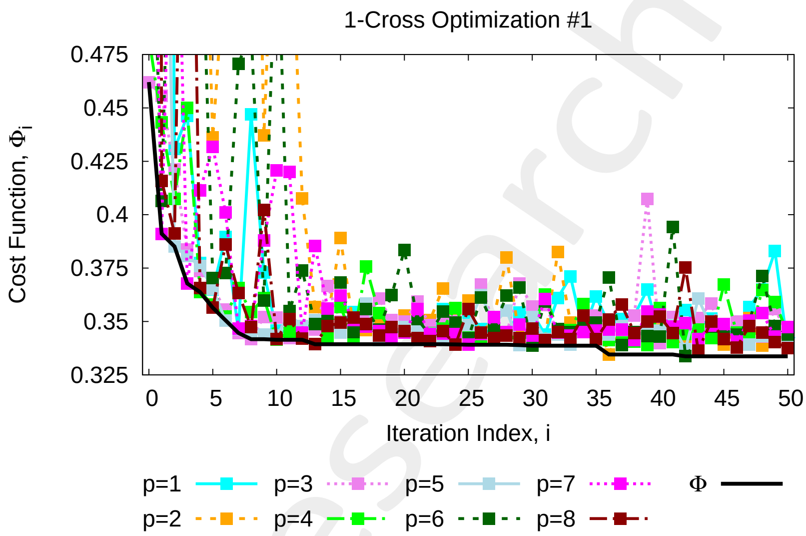
Cost Function

- Angles considered, $N_a = 9$
  - $\phi \in \{-60, 0, 60\}$ [deg] $\times$ $\theta \in \{75, 90, 105\}$ [deg]
- Frequencies considered, $N_f = 3$
  - $f = \{3.30, 3.55, 3.80\}$ [GHz]
- Modes considered, $N_m = 2$ (± 45 [deg])
- S-parameter threshold, $S_{th} = -10$ [dB]

Results



(a)



(b)

Figure 2: *Periodic model* ($Q = 1$, $P = 8$, $I = 50$) - *PSO* Optimization. Cost vs iteration for (a) the global best solution of the *PSO* and (b) showing also the cost of all the *PSO* particles ($p = 1, \ldots, 8$).

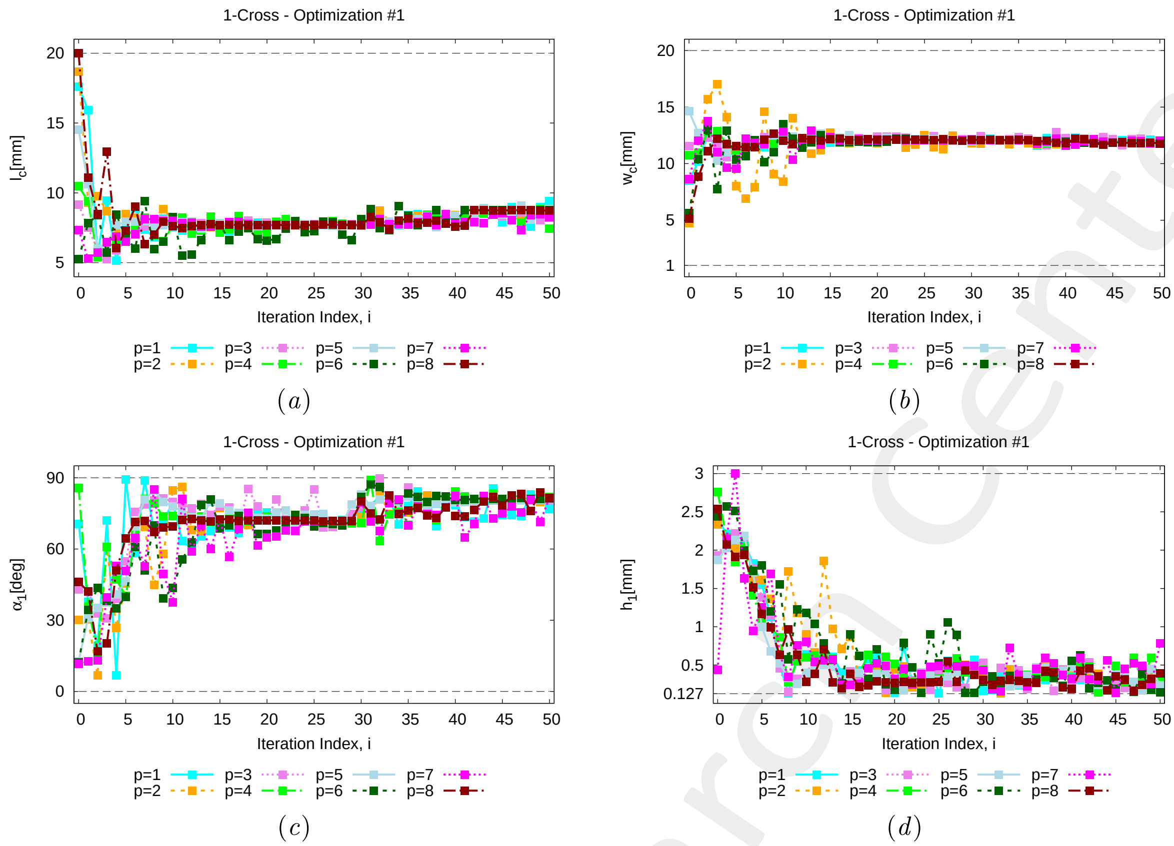


Figure 3: *Periodic model* ($Q = 1$, $P = 8$, $I = 50$) - *PSO* Optimization. Variable vs iteration for all the *PSO* particles ($p = 1, \ldots, 8$).

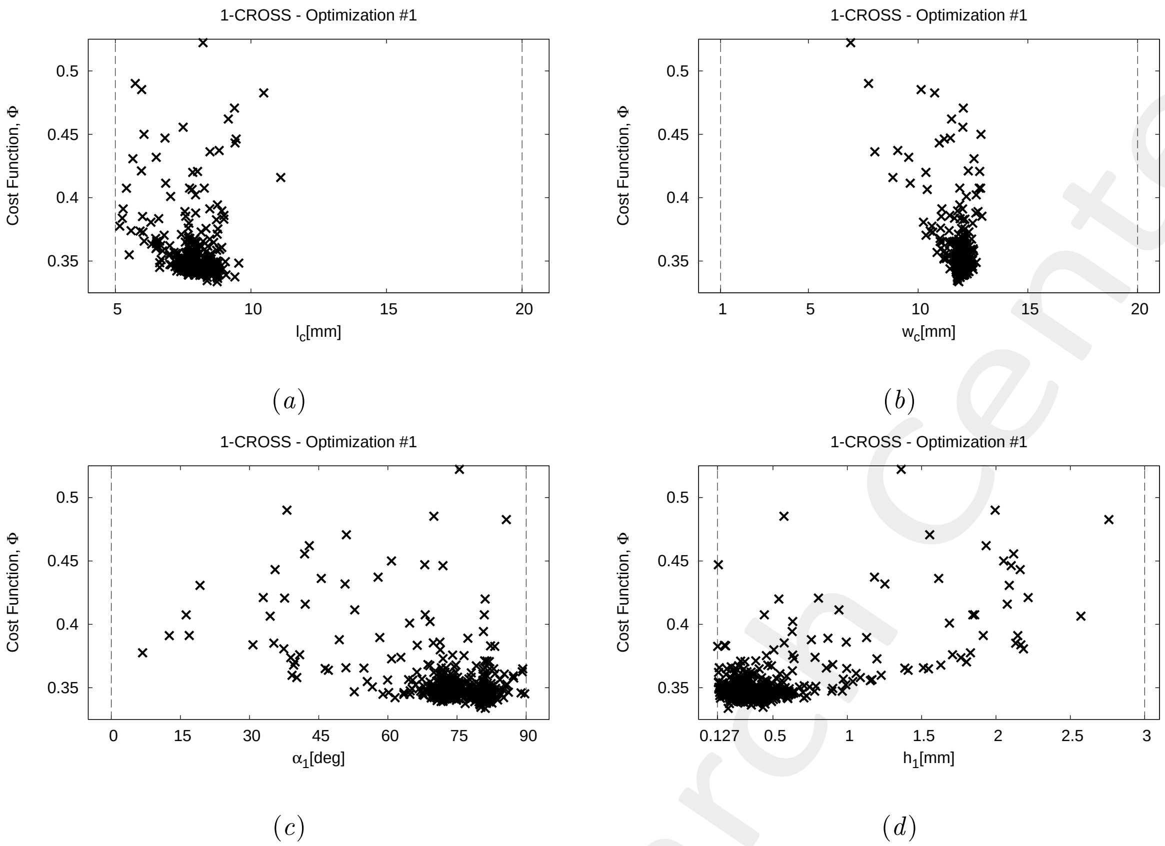
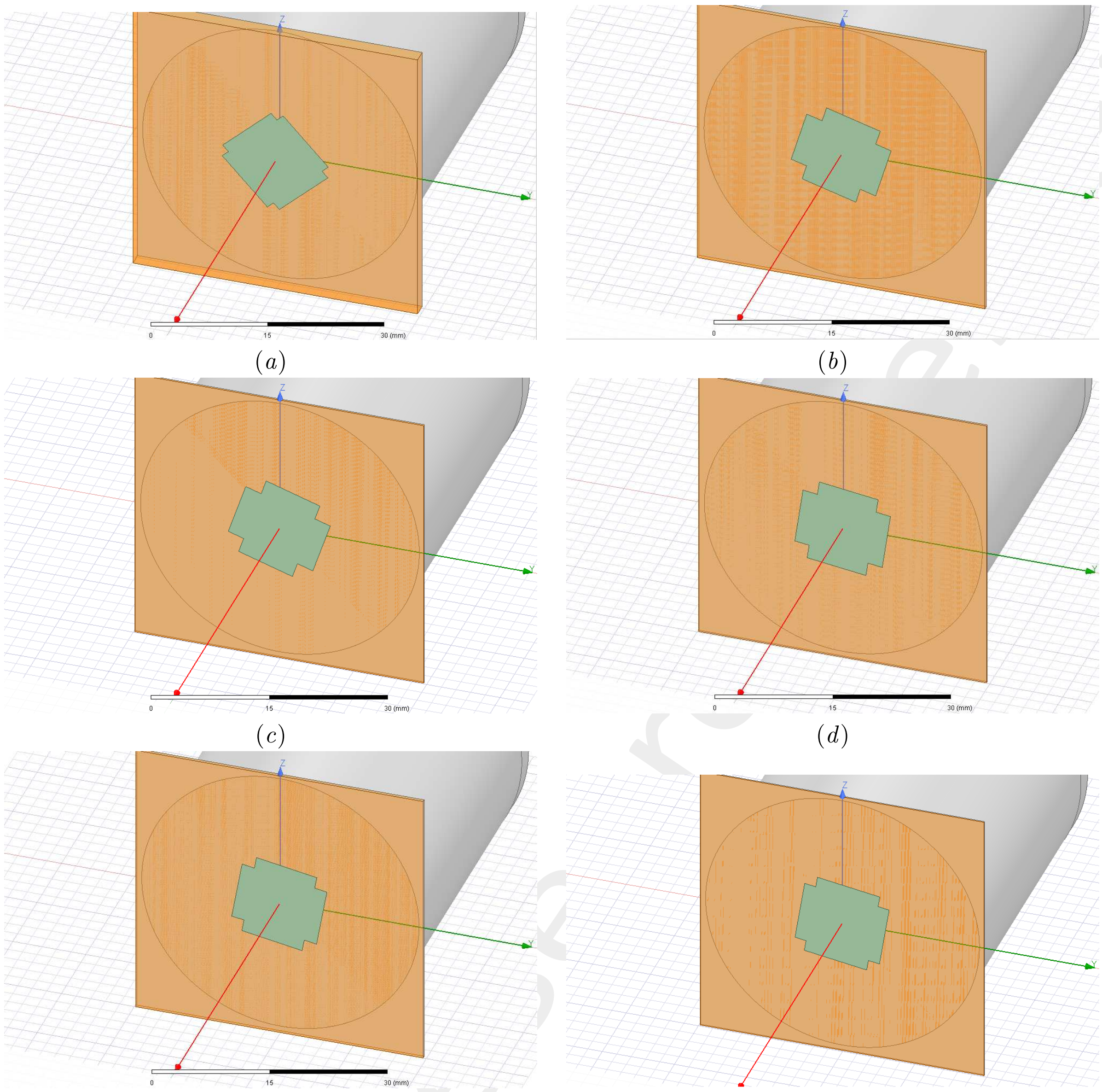


Figure 4: *Periodic model* ($Q = 1$, $P = 8$, $I = 50$) - *PSO* Optimization. Cost vs variable for all the configurations simulated during the optimization.



(a) (b) (c) (d) (e) (f)

Figure 5: *Periodic model* ($Q = 1$, $P = 8$, $I = 50$) - *PSO* Optimization. Best solution geometry at iterations (a) $i = 0$, (b) $i = 10$, (c) $i = 20$, (d) $i = 30$, (e) $i = 40$, (f) $i = 50$.

Iteration, i	Φ
0	4.621×10^{-1}
10	3.415×10^{-1}
20	3.393×10^{-1}
30	3.387×10^{-1}
40	3.346×10^{-1}
50	3.337×10^{-1}

Table II: *Periodic model* ($Q = 1$, $P = 8$, $I = 50$) - *PSO* Optimization. Cost function at the first iteration compared with the latest iteration. The first iterations represents a random sampling with $P = 8$ samples.

Physical Meaning	Variable	Value	$Q = 4\ s = 1$
Length of the cross arms	l_c	8.451 [mm]	9.836 [mm]
Width of the cross arms	w_c	11.812 [mm]	4.953 [mm]
Distance of the cross centers from the FWG center	d_c	/	7.706 [mm]
Superstrate thickness	h_1	0.384 [mm]	0.245 [mm]
Tilt of upper left cross	α_1	80.20 [deg]	12.70 [deg]
Tilt of upper right cross	α_2	/	28.00 [deg]
Tilt of lower left cross	α_3	/	27.65 [deg]
Tilt of lower right cross	α_4	/	19.50 [deg]

Table III: *Periodic model* ($Q = 1$, $P = 8$, $I = 50$) - *PSO* Optimization. Parameter values of the best solution.

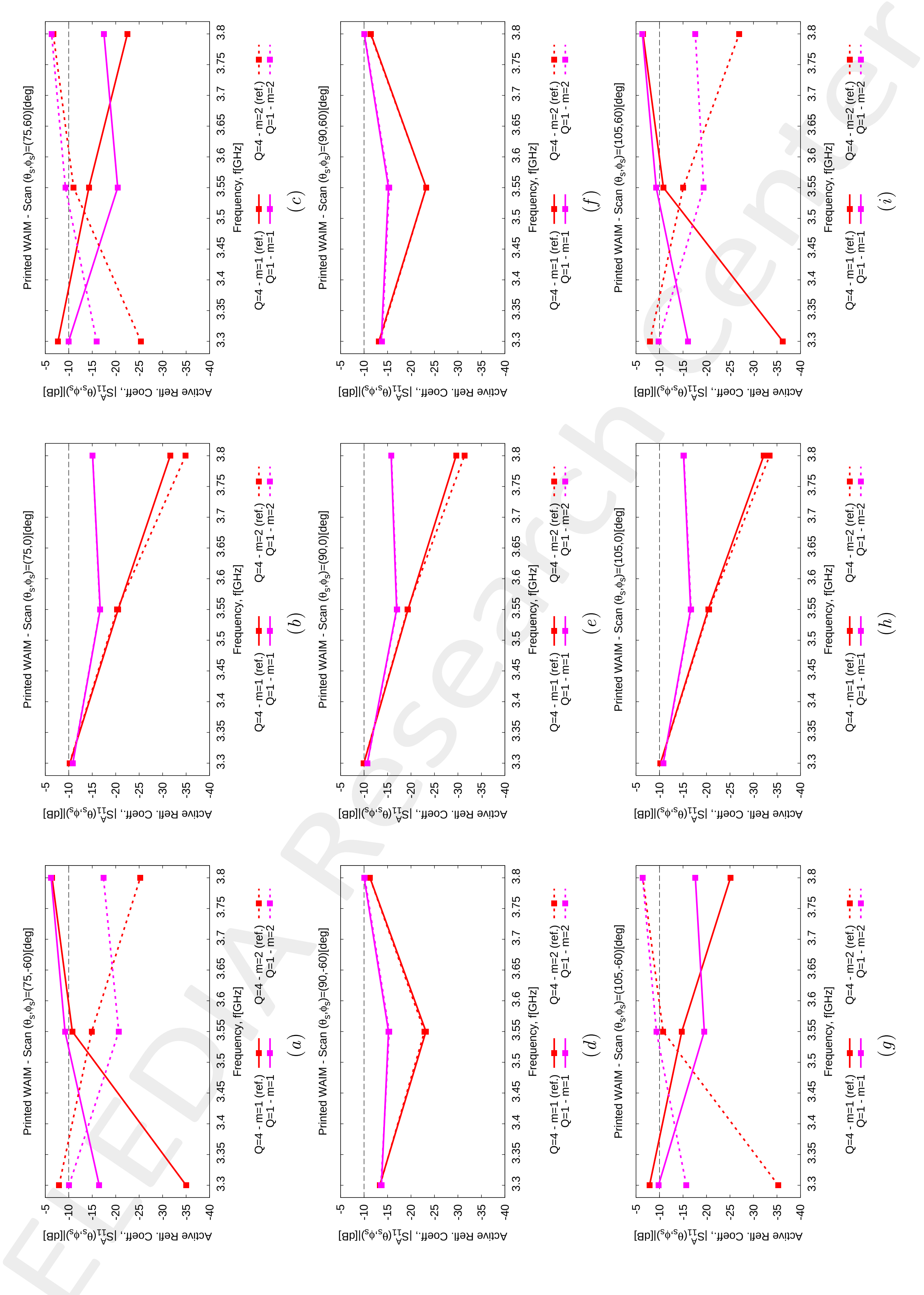


Figure 6: *Periodic model* ($Q = 1$, $P = 8$, $I = 40$) - S-parameter performance of best solution obtained reported in the frequency range for the two polarizations ($m = 1, 2$) and in all the considered array scan points. The "*Reference*" solution, in red, comes from a previous optimization $Q = 4$ where the frequency range was $f \in [3.4, 3.8]$ [GHz].

Observations

- The *PSO* solution is a slightly tilted (80.20 [deg]) quasi-square since $l_c = 8.451$ [mm] is not much different than $w_c = 11.812$ [mm].
- The cost function dynamic from the first iteration (random sampling) to the final $I = 50$ improves less than an order of magnitude (28%), probably there are not enough DoFs to gain more.
- Comparing with the *reference* solution which was optimized in the narrower frequency range $f \in [3.4, 3.8]$ [GHz] one can notice that overall the performance decreased in the central frequency f_0 but has improved in the lowest one $f_{\min} = 3.3$ [GHz]. This was expected since the *reference* solution was not optimized with that objective and the current problem is more difficult, since the band is wider, than the previous.
- The S-parameter shows to be poor for the high diagonal steerings (Fig. $6(a)(c)(g)(i)$) and the highest frequency $f_{\max} = 3.8$ [GHz] gets the poorest performance.
- The performance of the two modes/polarizations is very similar even if the cross is tilted and not perfecly simmetrical.

More information on the topics of this document can be found in the following list of references.

References

[1] M. Salucci, G. Oliveri, M. A. Hannan, and A. Massa, “System-by-design paradigm-based synthesis of complex systems: The case of spline-contoured 3D radomes,” *IEEE Antennas and Propagation Magazine - Special Issue on 'Artificial Intelligence in Electromagnetics,'*, vol. 64, no. 1, pp. 72-83, Feb. 2022.

[2] G. Oliveri, P. Rocca, M. Salucci, and A. Massa, “Holographic smart EM skins for advanced beam power shaping in next generation wireless environments," *IEEE J. Multiscale Multiphysics Comput. Tech.*, vol. 6, pp. 171-182, Oct. 2021.

[3] G. Oliveri, A. Gelmini, A. Polo, N. Anselmi, and A. Massa, “System-by-design multi-scale synthesis of task-oriented reflectarrays," *IEEE Trans. Antennas Propag.*, vol. 68, no. 4, pp. 2867-2882, Apr. 2020.

[4] M. Salucci, L. Tenuti, G. Gottardi, A. Hannan, and A. Massa, “System-by-design method for efficient linear array miniaturisation through low-complexity isotropic lenses" *Electronic Letters*, vol. 55, no. 8, pp. 433-434, May 2019.

[5] M. Salucci, N. Anselmi, S. Goudos, and A. Massa, “Fast design of multiband fractal antennas through a system-by-design approach for NB-IoT applications" *EURASIP J. Wirel. Commun. Netw.*, vol. 2019, no. 1, pp. 68-83, Mar. 2019.

[6] M. Salucci, G. Oliveri, N. Anselmi, and A. Massa, “Material-by-design synthesis of conformal miniaturized linear phased arrays," *IEEE Access*, vol. 6, pp. 26367-26382, 2018.

[7] M. Salucci, G. Oliveri, N. Anselmi, G. Gottardi, and A. Massa, “Performance enhancement of linear active electronically-scanned arrays by means of MbD-synthesized metalenses," *Journal of Electromagnetic Waves and Applications*, vol. 32, no. 8, pp. 927-955, 2018.

[8] G. Oliveri, M. Salucci, N. Anselmi and A. Massa, “Multiscale System-by-Design synthesis of printed WAIMs for waveguide array enhancement," *IEEE J. Multiscale Multiphysics Computat. Techn.*, vol. 2, pp. 84-96, 2017.

[9] A. Massa and G. Oliveri, “Metamaterial-by-Design: Theory, methods, and applications to communications and sensing - Editorial," *EPJ Applied Metamaterials*, vol. 3, no. E1, pp. 1-3, 2016.

[10] G. Oliveri, F. Viani, N. Anselmi, and A. Massa, “Synthesis of multi-layer WAIM coatings for planar phased arrays within the system-by-design framework," *IEEE Trans. Antennas Propag.*, vol. 63, no. 6, pp. 2482-2496, June 2015.

[11] G. Oliveri, L. Tenuti, E. Bekele, M. Carlin, and A. Massa, “An SbD-QCTO approach to the synthesis of isotropic metamaterial lenses" *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 1783-1786, 2014.

[12] A. Massa, G. Oliveri, P. Rocca, and F. Viani, "System-by-Design: a new paradigm for handling design complexity," *8th European Conference on Antennas Propag. (EuCAP 2014)*, The Hague, The Netherlands, pp. 1180-1183, Apr. 6-11, 2014.

[13] P. Rocca, M. Benedetti, M. Donelli, D. Franceschini, and A. Massa, "Evolutionary optimization as applied to inverse problems," *Inverse Problems - 25 th Year Special Issue of Inverse Problems, Invited Topical Review*, vol. 25, pp. 1-41, Dec. 2009.

[14] P. Rocca, G. Oliveri, and A. Massa, "Differential Evolution as applied to electromagnetics," *IEEE Antennas Propag. Mag.*, vol. 53, no. 1, pp. 38-49, Feb. 2011.

[15] P. Rocca, N. Anselmi, A. Polo, and A. Massa, "Pareto-optimal domino-tiling of orthogonal polygon phased arrays," *IEEE Trans. Antennas Propag.*, vol. 70, no. 5, pp. 3329-3342, May 2022.

[16] P. Rocca, N. Anselmi, A. Polo, and A. Massa, "An irregular two-sizes square tiling method for the design of isophoric phased arrays," *IEEE Trans. Antennas Propag.*, vol. 68, no. 6, pp. 4437-4449, Jun. 2020.

[17] P. Rocca, N. Anselmi, A. Polo, and A. Massa, "Modular design of hexagonal phased arrays through diamond tiles," *IEEE Trans. Antennas Propag.*, vol.68, no. 5, pp. 3598-3612, May 2020.

[18] N. Anselmi, L. Poli, P. Rocca, and A. Massa, "Design of simplified array layouts for preliminary experimental testing and validation of large AESAs," *IEEE Trans. Antennas Propag.*, vol. 66, no. 12, pp. 6906-6920, Dec. 2018.

[19] N. Anselmi, P. Rocca, M. Salucci, and A. Massa, "Contiguous phase-clustering in multibeam-on-receive scanning arrays" *IEEE Trans. Antennas Propag.*, vol. 66, no. 11, pp. 5879-5891, Nov. 2018.

[20] G. Oliveri, G. Gottardi, F. Robol, A. Polo, L. Poli, M. Salucci, M. Chuan, C. Massagrande, P. Vinetti, M. Mattivi, R. Lombardi, and A. Massa, "Co-design of unconventional array architectures and antenna elements for 5G base station," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6752-6767, Dec. 2017.

[21] N. Anselmi, P. Rocca, M. Salucci, and A. Massa, "Irregular phased array tiling by means of analytic schemata-driven optimization," *IEEE Trans. Antennas Propag.*, vol. 65, no. 9, pp. 4495-4510, September 2017.

[22] N. Anselmi, P. Rocca, M. Salucci, and A. Massa, "Optimization of excitation tolerances for robust beam-forming in linear arrays" *IET Microwaves, Antennas & Propagation*, vol. 10, no. 2, pp. 208-214, 2016.

[23] P. Rocca, R. J. Mailloux, and G. Toso, "GA-Based optimization of irregular sub-array layouts for wideband phased arrays desig," *IEEE Antennas and Wireless Propag. Lett.*, vol. 14, pp. 131-134, 2015.

[24] P. Rocca, M. Donelli, G. Oliveri, F. Viani, and A. Massa, "Reconfigurable sum-difference pattern by means of parasitic elements for forward-looking monopulse radar," *IET Radar, Sonar & Navigation*, vol 7, no. 7, pp. 747-754, 2013.

[25] M. Salucci, L. Poli, A. F. Morabito, and P. Rocca, “Adaptive nulling through subarray switching in planar antenna arrays," *Journal of Electromagnetic Waves and Applications*, vol. 30, no. 3, pp. 404-414, February 2016

[26] T. Moriyama, L. Poli, and P. Rocca, “Adaptive nulling in thinned planar arrays through genetic algorithms" *IEICE Electronics Express*, vol. 11, no. 21, pp. 1-9, Sep. 2014.

[27] L. Poli, P. Rocca, M. Salucci, and A. Massa, “Reconfigurable thinning for the adaptive control of linear arrays," *IEEE Trans. Antennas Propag.*, vol. 61, no. 10, pp. 5068-5077, Oct. 2013.

[28] P. Rocca, L. Poli, G. Oliveri, and A. Massa, “Adaptive nulling in time-varying scenarios through time-modulated linear arrays," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 101-104, 2012.