A System-by-Design Approach for Optimal Planning of *EM* Skins in Smart Urban Areas

Marco Salucci[1], Arianna Benoni[1], Sotirios K. Goudos[2], and Andrea Massa[3,1,4]
[1] ELEDIA Research Center (ELEDIA@UniTN - University of Trento), DICAM, Trento, Italy (andrea.massa@unitn.it)
[2] ELEDIA Research Center (ELEDIA@AUTH - Aristotle University of Thessaloniki), Thessaloniki, Greece (sotirios.goudos@eledia.org)
[3] ELEDIA Research Center (ELEDIA@UESTC – UESTC), Chengdu, China (andrea.massa@uestc.edu.cn)
[4] ELEDIA Research Center (ELEDIA@TSINGHUA – Tsinghua University), Beijing, China (andrea.massa@tsinghua.edu.cn)

***Abstract*—This work deals with the optimal planning of low-cost/low-profile passive and static electromagnetic skins (*EMS*s) allowing to implement Smart Electromagnetic Environments (*SEME*s) in large urban areas. Owing to the high complexity/scale of the *EM* problem at hand, the planning problem is formulated as a global optimization one efficiently solved thanks to a suitably-customized System-by-Design (*SbD*) methodology relying on Machine Learning (*ML*) and Evolutionary Algorithms (*EA*s). An illustrative example is shown to assess the effectiveness of the proposed *SEME* planning method in a realistic scenario.**

Keywords—Smart EM Environment (SEME), Electromagnetic Skins (EMSs), System-by-Design (SbD), Machine Learning (ML), Wireless Network Planning.

I. Introduction

Recently, the Smart Electromagnetic Environment (*SEME*) has been emerging as an unconventional and very powerful paradigm for designing future wireless communications systems [1]-[3]. The main driving idea of the *SEME* is the exploitation of the propagation scenario as a fundamental key-actor to improve the overall coverage and perceived Quality-of-Service (*QoS*) by the mobile end-users. Therefore, it will be a fundamental asset for building the next generation (i.e., *6G* and beyond) networks in order to meet the ever-growing necessity of ubiquitous and high-throughput connectivity [4]. Several pioneer attempts towards the dream of *SEME*s in everyday life have demonstrated the high potential of such a vision. For instance, capacity-driven approaches [5]-[7] have successfully verified that a base-station (*BTS*) antenna for mobile communications can be more reliably and robustly designed if standard free-space and line-of-sight (*LOS*) assumptions (and associated performance indicators) are substituted/integrated with other system performance indicators (e.g., capacity) that allow taking into account the presence of non-*LOS* (*NLOS*) propagation environments and multi-path phenomena. A step forward in this direction is to consider the surrounding obstacles as key-actors that do not only perturb/modify the propagation of *EM* waves emitted by the *BTS*, but also enhance their transmission towards the mobile terminals. This can be done for instance by synthesizing "smart" *BTS*s capable of recognizing and opportunistically exploiting the surrounding buildings to improve the coverage within the served cell [2].
Otherwise, a promising yet widely unexplored and challenging *SEME* implementation is represented by the introduction of suitable field manipulating devices (*FMD*s) into the propagation environment. In this framework, reconfigurable intelligent surfaces (*RIS*s) [8]-[11] have been recognized as a promising technology for realizing controllable "skins" on the building facades, allowing to redirect the *BTS* signals towards the locations of the end-users via anomalous (i.e., non-Snell) reflections and/or transmissions. However, significant efforts are still required to address paramount challenges including, among the others, the study of new manufacturing technologies for enabling a more effective and inexpensive mass production and deployment. Otherwise, *PCB*-based passive and static *EM* skins (*EMS*s), although providing lower flexibility because of the lack of reconfigurability, have recently raised attention from the scientific and industry communities because of their easier and cheaper realization [12]-[14]. *EMS*s can be designed exploiting several effective synthesis methodologies to afford pencil or shaped beams [14] towards unconventional reflection/transmission directions, being therefore a perfect candidate for focusing the *EM* waves emitted by the *BTS* and enhance the coverage/*QoS* within selected regions of interest (*RoI*s) [12]. In such a context, one important task to be carefully addressed is the selection/positioning of the minimum number of *EMS*s that allow fitting the user/operator-defined requirements in terms of received power level. Therefore, this work introduces an innovative methodology for the optimal planning of *EMS*s in urban areas. Owing to the large scale of the *EM* problem at hand, the high-complexity of the resulting optimization problem is effectively and efficiently tackled by means of an innovative methodology formulated within the System-by-Design (*SbD*) framework [15] and relying on Machine Learning (*ML*) and Evolutionary Algorithms (*EA*s).

II. Mathematical Formulation

Let us consider a *BTS* antenna ξ located at position $\underline{r}_\xi = (x_\xi, y_\xi, z_\xi)$ and serving the end-users within a large-scale urban area A. Because of the surrounding environment comprising several obstacles such as buildings and vegetation, let us assume that *NLOS* propagation conditions occur and that the received power is below a desired threshold P_{th} (needed for guaranteeing a certain throughput

This work benefited from the networking activities carried out within the Project "MITIGO Mitigazione dei rischi naturali per la sicurezza e la mobilita' nelle aree montane del Mezzogiorno" (Grant no. ARS01_00964) funded by the Italian Ministry of Education, University, and Research within the Program "Progetti di Ricerca Industriale e Sviluppo Sperimentale nelle 12 aree di specializzazione individuate dal PNR 2015-2020", Specialization Area "Smart Secure & Inclusive Communities", the Project "SPEED" (Grant No. 6721001) funded by the National Natural Science Foundation of China, and the Project "CYBER-PHYSICAL ELECTROMAGNETIC VISION: Context-Aware Electromagnetic Sensing and Smart Reaction (EMvisioning)" (Grant no. 2017HZJXSZ) funded by the Italian Ministry of Education, University, and Research within the PRIN2017 Program (CUP: E64I19002530001).

and overall *QoS*) inside a set of Q *RoI*s $\underline{\sigma}=\{\sigma_q \subset A; q=1,...,Q\}$. In other words, assuming to know/measure the received power $P_{ref}(x,y)=P_{ref}(\underline{r})|_{z=h}$ at a given height h from the ground level, it turns out that

$$P_{ref}(x,y)<P_{th}\,,\;\; (x,y)\in\sigma_q; q=1,...,Q\,. \tag{1}$$

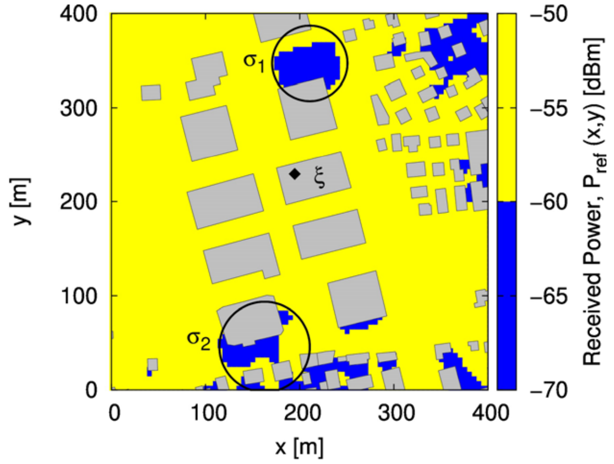


Fig. 1. *Illustrative Example* (f = 3.5 [GHz], Q=2, P_{th} = -60 [dBm]) - Thresholded received power generated by the *BTS* (ξ) and location of the Q=2 *RoI*s.

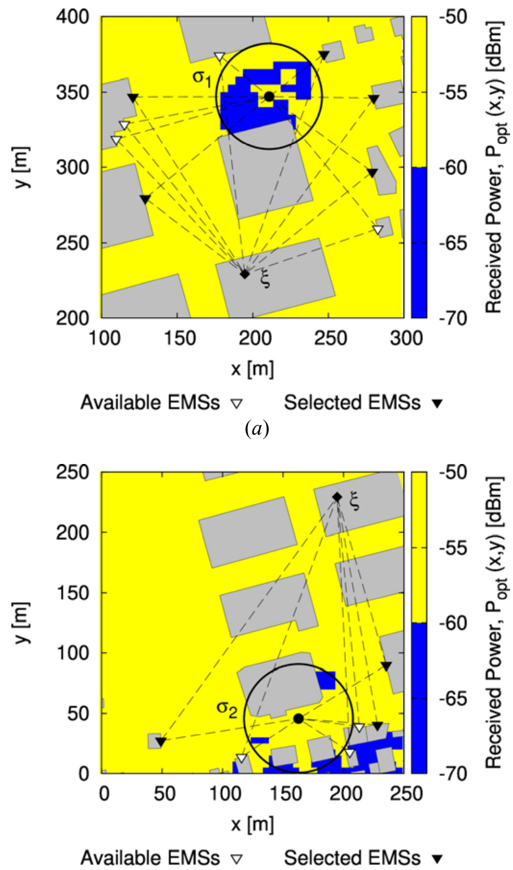
According to the *SEME* paradigm [12][14], in order to increase the received power to a level larger or equal than P_{th} inside such regions, a set of low-cost static and passive *EMS*s is deployed at "strategic" positions within the urban scenario. Such low-profile skins are implemented in *PCB* technology and are designed in order to yield the required field manipulation, by reflecting the impinging *EM* radiation emitted by the *BTS* towards unconventional directions not complying with the traditional Snell's theory to reach the *RoI*s barycenter [14].
It should be pointed out that such devices can be in principle installed on any fixed surface present in the environment, such as, for instance, the facades of properly-chosen buildings. However, although relatively inexpensive from the manufacturing point of view, the overall number of installed devices should be kept as low as possible to limit the cost and the environmental/architectural impact. Therefore, a suitable planning strategy is needed to select, among the possible configurations, the minimum number of installed *FMD*s in the environment to achieve the desired coverage improvement within the identified *RoI*s. Accordingly, indicating with K the total amount of building facades suitable for the installation of *EMS*s, the problem at hand is to select the minimum cardinality sub-set of skins able to restore the desired *QoS*. Owing to the high complexity imposed by the numerical assessment of large-scale *EM* scenarios, the problem is addressed by means of a suitably-customized *SbD* methodology [15]. More specifically, the optimum *EMS* planning within A is found by solving a global optimization problem aimed at minimizing the following fitness function

$$\Phi(\underline{\chi})=\Phi_1(\underline{\chi})+\Phi_2(\underline{\chi}) \tag{2}$$

where the first cost term is defined as

$$\Phi_1(\underline{\chi})=\frac{1}{M\times|P_{th}|}\sum_{q=1}^{Q}\sum_{m=1}^{M^{(q)}}H\left\{P_{th}-P\left(\underline{r}_m^{(q)}\middle|\underline{\chi}\right)\right\} \tag{3}$$

and quantifies the mismatch between the received power and the desired threshold within each q-th ($q=1,...,Q$) *RoI*, $M^{(q)}$ being the number of probing locations inside it, being $M=\sum_{q=1}^{Q}M^{(q)}$ and $H(a)=a$ if $a>0$, $H(a)=0$ otherwise.



(*b*)

Fig. 2. *Illustrative Example* (f = 3.5 [GHz], Q = 2, P_{th} = -60 [dBm]) - Thresholded received power yielded by the optimal *EMS* planning within the *RoI*s (*a*) σ_1 and (*b*) σ_2.

Moreover, in (2)(3) $\underline{\chi}=\{\chi_k\in(0,1); k=1,...,K\}$ is a binary vector encoding the planning solution, its k-th ($k=1,...,K$) entry being equal to $\chi_k=1$ if the k-th *EMS* is installed on the k-th wall, $\chi_k=0$ otherwise. Finally, the second cost term in (2) is computed as

$$\Phi_2(\underline{\chi})=\frac{\|\underline{\chi}\|_0}{K} \tag{4}$$

$\|.\|_0$ being the ℓ_0-norm and provides an index of the overall "cost" of the planning configuration encoded by $\underline{\chi}$, which is directly related to the number of its unitary entries (i.e., installed *EMS*s).

It is worth observing that the evaluation of (3) requires to simulate the large-scale *EM* propagation scenario *A* in order to assess the coverage improvement yielded by any trial guess solution of the planning problem. Although efficient solvers have been recently introduced [e.g., based on Ray Tracing (*RT*) methodologies], the iterated evaluation of the fitness function (2) required by multiple-agent evolutionary-inspired optimization algorithms would determine a very high computational cost of the synthesis process. To remarkably alleviate such an issue, a surrogate model (*SM*) is built exploiting the Gaussian Process learning-by-examples theory [16][17] to provide a very fast (yet accurate) alternative to the *RT* solver for assessing the fitness of each trial solution during the optimization. More precisely, before entering the minimization process, a database of *T* training samples

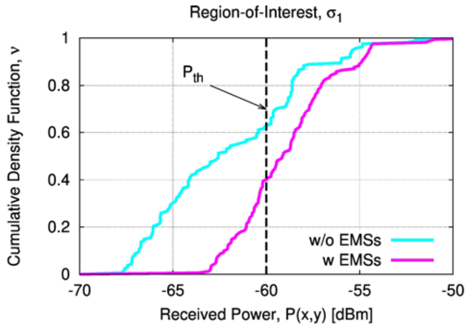
$$\aleph = \left\{\left(\underline{\chi}^{(t)}, \Phi_1\left(\underline{\chi}^{(t)}\right)\right); t = 1,...,T\right\} \quad (5)$$

is generated by randomly selecting *T* planning configurations among the full set of $B = 2^K$ ones and evaluating the corresponding coverage within the *Q RoI*s with the help of a 3D-*RT* solver. Finally, the effective exploration of the *K*-dimensional solution space is performed by means of a customized optimization tool based on the Genetic Algorithm (*GA*) operators [18] integrated with the *SM* to predict the fitness function (2) and significantly accelerate the convergence towards the global optimum.

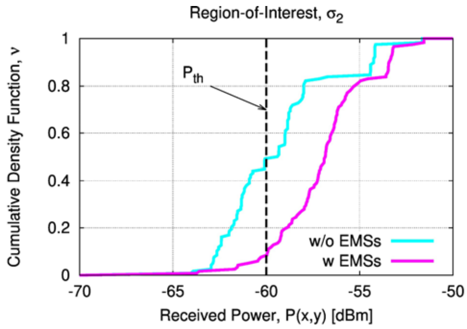
III. Illustrative Example

To provide an illustrative example of the effectiveness and potentialities of the proposed *SbD* approach, let us consider in the following a urban area of side $L_A = 400$ [m] served by a *BTS* located in $\underline{r}_{\xi} = (194.74, 228.8, 30)$ [m] working at central frequency $f = 3.5$ [GHz]. The scenario at hand has been simulated by means of the *RT*-based Altair WinProp suite [19] and the resulting thresholded received power distribution at height $h = 1.5$ [m] is shown in Fig 1 ($P_{th} = -60$ [dBm]), enabling the identification of $Q = 2$ *RoI*s. A set of $K = 15$ building facades has been identified inside the investigated area for the installation of *EMS*s capable of redirecting the *EM* radiation emitted by the *BTS* towards the *RoI*s, yielding a total number of $B = 2^{15}$ possible planning configurations. Each *EMS* has been synthesized following the two-step design approach in [14] starting from the identification of the necessary incidence (i.e., from the *BTS*) and reflection (i.e., towards the corresponding *RoI*) spherical angles.

The outcome of the *SbD* optimization is shown in Fig. 2. It can be observed that the optimized received power level is higher than the desired threshold within large portions of both *RoI*s σ_1 [Fig. 2(*a*)] and σ_2 [Fig. 2(*b*)]. Globally, the coverage has been significantly improved, as also quantitatively verified by the value of the coverage fitness term corresponding to the optimal planning configuration, $\Phi_1\left(\underline{\chi}_{opt}\right) = 1.86 \times 10^{-2}$. Such outcomes have been achieved with the installation of only $\left\|\underline{\chi}_{opt}\right\|_0 = 8$ *EMS*s, resulting in an "implementation cost" of $\Phi_2\left(\underline{\chi}_{opt}\right) = 5.33 \times 10^{-1}$. Moreover, the cumulative density function (*CDF*) of the received power within the two *RoI*s (Fig. 3) is significantly improved with respect to the nominal scenario (i.e., w/o *EMS*s), further verifying the effectiveness of the proposed *SbD* planning strategy.



(*a*)



(*b*)

Fig. 3. *Illustrative Result* ($f = 3.5$ [GHz], $Q = 2$, $P_{th} = -60$ [dBm]) - *CDF* of the received power with and without the *EMS*s within the *RoI*s (*a*) σ_1 and (*b*) σ_2.

Conclusion

In the *SEME* framework, the optimal planning of passive and static *EMS*s on the building facades to improve the coverage within selected urban regions has been addressed by means of an innovative *SbD* methodology. A numerical illustrative example has been shown to assess the effectiveness and the potentialities of the proposed approach for the design of next-generation communications systems.

References

[1] M. Di Renzo et *al.*, "Smart radio environments empowered by reconfigurable AI meta-surfaces: An idea whose time has come," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 129, pp. 1-20, 2019.

[2] A. Massa et *al.*, "Designing smart electromagnetic environments for next-generation wireless communications," *Telecom*, vol. 2, no. 2, pp. 213-221, 2021.

[3] M. Di Renzo et *al.*, "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2450-2525, Nov. 2020.

[4] W. Jiang, B. Han, M. A. Habibi and H. D. Schotten, "The road towards 6G: A comprehensive survey," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 334-366, 2021.

[5] G. Oliveri, G. Gottardi and A. Massa, "A new meta-paradigm for the synthesis of antenna arrays for future wireless communications," *IEEE Trans. Antennas Propag.*, vol. 67, no. 6, pp. 3774-3788, Jun. 2019.

[6] G. Oliveri, G. Gottardi, N. Anselmi, and A. Massa, "Capacity-driven low-interference fast beam synthesis for next generation base stations," *IEEE Trans. Antennas Propag.*, in press.

[7] N. Anselmi, P. Rocca, S. Feuchtinger, B. Biscontini, A. M. Barrera, and A. Massa, "Optimal capacity-driven design of aperiodic clustered phased arrays for multi-user MIMO communication systems," *IEEE Trans. Antennas Propag.*, in press.

[8] E. Basar et *al.*, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753-116773, 2019.

[9] Q. Wu, S. Zhang, B. Zheng, C. You, and R. Zhang, "Intelligent reflecting surface-aided wireless communications: A tutorial," *IEEE Trans. Commun.*, vol. 69, no. 5, pp. 3313-3351, May 2021.

[10] G. C. Trichopoulos et *al.*, "Design and evaluation of re-configurable intelligent surfaces in real-world environment," 2021. [Online]. Available: arXiv:2109.07763.

[11] F. H. Danufane, M. D. Renzo, J. de Rosny, and S. Tretyakov, "On the path-loss of reconfigurable intelligent surfaces: An approach based on Green's theorem applied to vector fields," *IEEE Trans. Commun.*, vol. 69, no. 8, pp. 5573-5592, Aug. 2021.

[12] P. Rocca, P. Da Rù, N. Anselmi, M. Salucci, G. Oliveri, D. Erricolo, and A. Massa, "On the design of modular reflecting EM skins for enhanced urban wireless coverage," *IEEE Trans. Antennas Propag.*, in press.

[13] C. Huang, S. Hu, G. C. Alexandropoulos, A. Zappone, C. Yuen, R. Zhang, M. Di Renzo, and M. Debbah, "Holographic MIMO surfaces for 6G wireless networks: Opportunities, challenges, and trends," *IEEE Wireless Commun.*, vol. 27, no. 5, pp. 118-125, Oct. 2020.

[14] 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 Multiphys. Comput. Tech*., vol. 6, pp. 171-182, Oct. 2021

[15] A. Massa and M. Salucci, "On the design of complex EM devices and systems through the System-by-Design paradigm - A framework for dealing with the computational complexity," *IEEE Trans. Antennas Propag.*, doi: 10.1109/TAP.2021.3111417.

[16] A. Massa, G. Oliveri, M. Salucci, N. Anselmi, and P. Rocca, "Learning-by-examples techniques as applied to electromagnetics," *J. Electromagn. Waves Appl.*, pp. 1-16, 2017.

[17] A. I. J. Forrester, A. Sobester, and A. J. Keane, *Engineering Design via Surrogate Modelling: A Practical Guide*. Hoboken, N.J.: John Wiley & Sons, 2008.

[18] P. Rocca, M. Benedetti, M. Donelli, D. Franceschini, and A. Massa, "Evolutionary optimization as applied to inverse scattering problems," *Inverse Probl.*, vol. 25, no. 12, pp. 123003, Dec. 2009.

[19] Altair Winprop 2020, Altair Engineering, Inc., www.altairhyperworks.com/feko