Planning of EM Skins for Improved Quality-of-Service in Urban Areas

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Abstract—The optimal planning of electromagnetic skins (EMs) installed on the building facades to enhance the received signal strength, thus the wireless coverage and/or the quality-of-service (QoS) in large-scale urban areas, is addressed. More specifically, a novel instance of the System-by-Design (SbD) paradigm is proposed towards the implementation of a smart electromagnetic environment (SHEME) where low-cost passive static reflective skins are deployed to enhance the level of the power received within selected regions-of-interest (RoIs). Thanks to the ad-hoc customization of the SbD functional blocks, which includes the exploitation of a digital twin (DT) for the accurate yet fast assessment of the wireless coverage condition, effective solutions are yielded. Numerical results, dealing with real-world test-beds, are shown to assess the capabilities, the potentialities, and the current limitations of the proposed EMs planning strategy.

Index Terms—Smart EM Environment (SHEME), EM Skins (EMs), System-by-Design (SbD), Genetic Algorithms (GAs), Global Optimization, Wireless Network Planning.

I. INTRODUCTION

The smart electromagnetic environment (SHEME) is without any doubt a promising and revolutionizing concept for the design of future wireless communications systems [1]-[4]. It is based on the idea that the environment should be no more regarded as an uncontrollable impairment to the overall quality-of-service (QoS). Conversely, it should be exploited as a powerful “tool” to enable unprecedented manipulations of the complex electromagnetic (EM) phenomena for enhancing the overall coverage, the data throughput, and the QoS [3][4].

As a matter of fact, fitting ever-growing needs for ubiquitous connectivity and low latency/resiliency of forthcoming communication standards, also beyond the fifth-generation (5G) [5]-[9], will be possible only if the propagation scenario will play a fundamental role in counteracting the distortions, the delays, the losses, and the fading of the EM waves radiated by the base-stations (BTSs).

A first step towards this path is to address the synthesis of the BTS in an unconventional way by fitting user-defined requirements on the QoS, while bypassing the optimization of standard free-space line-of-sight (LOS) key performance indicators (KPIs) (e.g., gain, sidelobe level, and half-power beamwidth). Indeed, these latter do not take into account the presence of the environment as a stakeholder of the overall system performance [3][10]. Within this framework, the approach in [3] optimizes the BTS excitations by opportunistically exploiting the EM interactions with the surrounding obstacles to fulfill user-defined radiation masks.

Otherwise, many studies have been recently carried out on the possibility to improve the performance of a wireless communication system by using reconfigurable intelligent surfaces (RISs) [11]-[22]. Such a technology consists of engineered tunable reflecting/refracting metasurfaces [23]-[29] that adaptively generate anomalous reflection/transmission of the impinging EM waves coming from the BTSs. Therefore, RISs are exploited to redirect the scattered EM wave towards arbitrary directions, not compliant with the classical Snell’s laws, where the received power would be otherwise weak/insufficient to support a desired throughput and QoS.

The development of effective RIS-based solutions has benefited from the many similarities with the well-established theory of both reflectarrays (RAs) [30][31] and transmittarrays (TAs) [32]. As a matter of fact, the design of advanced metasurfaces with tunable magnitude/phase modulation has been performed by properly extending the RAs/TAs synthesis concepts in order to take into account the presence of finite-size arrangements of sub-wavelengths metallic elements mounted on wall surfaces [12]. However, some unsolved challenges need to be still faced to make RISs an attractive technology for large-scale urban deployments [13][17]. Indeed, new techno-
logical advancements are expected to enable the installation of RISs in wide regions as well as conformal to irregular surfaces with cost-efficient manufacturing, installation, and maintenance, while consuming a low power. Moreover, new switching topologies and materials (e.g., graphene and liquid crystals) are under investigation to improve the sub-optimal performance of PIN diodes and varactors, which are currently employed to implement the RIS reconfigurability in sub-6GHz and millimeter wave/terahertz systems [13][29][32]. Static passive EM skins (EMSs) [4] are a promising simpler, lighter, and cheaper alternative to RISs for increasing the wireless coverage and/or reducing the occurrence of “blind spots” in urban scenarios. EMSs leverage on the capabilities of passive modulated metasurfaces to control the EM interactions through a proper synthesis of their micro-scale physical structure [4]. The absence of diodes, varactors, phase shifters, amplifiers, and other components makes them particularly attractive for a low-cost deployment/maintenance in large-scale environments.

However, while the facades of the buildings are strategic (e.g., no other costs for realizing customized supporting infrastructures) for the installation of EMSs, a suitable selection of the minimum number of buildings where the EMSs should be installed is mandatory to yield reliable as well as feasible solutions for recovering/yielding the desired QoS within specific regions-of-interest (RoIs).

Within this context, this paper addresses, for the first time to the best of the authors’ knowledge, the planning of EMSs in real-world urban scenarios. The proposed strategy is not customized to a specific technological implementation of the EMSs and it gives the wireless operator a full control of which “candidate” facades/buildings can be used to mount the EMSs. More specifically, the problem at hand is formulated as a global optimization one, which is efficiently solved within the System-by-Design (SbD) framework [33][34] to yield an optimal (i.e., max-coverage-improvement and lowest-cost) EMSs configuration that provides the desired level of received power within the RoIs. Towards this end, a proper selection, customization, and interconnection of the functional blocks of the SbD scheme is carried out starting from the definition of a suitable binary representation of the solution space, which is then effectively explored with a customized implementation of the binary genetic algorithm (BGA) [35]-[38]. Moreover, a fast surrogate of the accurate, but time-consuming, ray-tracing (RT)-based EM coverage simulator is built according to the learning-by-examples (LBE) paradigm [39].

The paper is organized as follows. Section II describes the mathematical formulation of the problem at hand, while the SbD-based planning strategy is detailed in Sect. III. Numerical results are then shown (Sect. IV) to assess the effectiveness and the potentialities as well as the current limitations of the proposed approach for the deployment of EMSs in real-world urban scenarios. Finally, some conclusions and final remarks are drawn (Sect. V).

II. MATHEMATICAL FORMULATION

Let us consider a large-scale urban propagation scenario Ξ served by a BTS antenna located at the position rΨ and working at the operating frequency f. Due to obstructions (caused by buildings/vegetation and other shadowing obstacles), reflections (due to reflective surfaces), refractions (owing to the presence of media characterized by different propagation velocities), and diffractions (generated by edges), the EM waves radiated by the BTS towards the mobile terminals propagate in non-line-of-sight (NLOS) conditions and multi-path phenomena arise. As a consequence, there is a set of S RoIs, Ω = {Ω(s); s = 1,...,S}, within the urban scenario Ξ (Fig. 1) where the nominal received power [40][41], P0(r), turns out to be lower than the minimum coverage threshold, Pth, which guarantees a target throughput and a suitable QoS to the end-users

\[ P_0(r) < P_{th} \quad r \in \Omega(s) \quad (s = 1, ..., S). \]  

In order to restore the wireless coverage condition (P(r) ≥ Pth, P(r) being the optimized received power) within the area Ξ served by the BTS, a set of EMSs is deployed to reflect an adequate level of power towards each s-th (s = 1,...,S) RoI Ω(s). It is worth pointing out that the introduction of such field manipulation devices to implement a SEME cannot be arbitrary since EMSs can be mounted only on the facades of the buildings by also taking into account the architectural constraints. Moreover, the number of EMSs must be kept as low as possible to reduce the overall cost as well as to minimize the environmental impact.

Owing to the “feasibility” constraint, a set of W(s) “candidate” building walls, \( z^{(s)} = \{ w^{(s)}; w = 1,...,W^{(s)} \} \), in the neighborhood of each s-th (s = 1,...,S) RoI Ω(s), \( \Pi^{(s)} \) (Fig. 2), is selected for the installation of EMSs by the network operator. Thus, there are K = \( \sum_{s=1}^{S} W^{(s)} \) admissible locations for deploying the EMSs in the urban scenario at hand. Accordingly, the EMSs planning problem can be stated as follows

**Optimal EMSs Planning Problem (OPP)** - Given K admissible sites, determine the locations and the layouts of the minimum number Q (Q ≪ K) of EMSs so that the power \( P(r) \) received within the s-th (s = 1,...,S) RoI (r ∈ Ω(s)) fulfills the coverage/QoS condition \( P(r) \geq P_{th} \).

To solve such an OPP, an innovative instance of the SbD strategy is applied (Sect. III).
III. ShbD Solution Approach

Within the ShbD framework [3], the EMSs planning is carried out by implementing the following ShbD blocks (Fig. 3):

1) EMSs Design (EMSD - Sect. III-A) - The purpose of this block is the synthesis of the complete set \( \Gamma_w \) of \( K \) “admissible” EMSs, \( \Gamma_w = \{ \Gamma_w^{(s)}; w = 1, ..., W(w); s = 1, ..., S \} \), starting from the knowledge of the locations of the BTS, \( \Psi_w \), of the selected RoIs, \( \Psi_w = \{ \Psi_w^{(s)}; s = 1, ..., S \} \), and of the EMSs barycenters, \( \{ \Psi_w^{(s)}; w = 1, ..., W(w); s = 1, ..., S \} \), on the “candidate” building walls \( \{ \Psi_w^{(s)}; w = 1, ..., W(w); s = 1, ..., S \} \); and of the \( \Psi \)-coordinate vector \( \psi = \{ \psi_w^{(s)}; w = 1, ..., W(w); s = 1, ..., S \} \), from which the \( \psi \)-coordinate vector \( \psi = \{ \psi_w^{(s)}; w = 1, ..., W(w); s = 1, ..., S \} \) coordination vector is obtained.

2) Problem Formulation (PF - Sect. III-B) - This block implements two different tasks. On the one hand, it defines the set of \( U \) degrees-of-freedom (DoF) to yield the most suitable encoding of the OPP unknowns, \( \chi = \{ \chi_u; u = 1, ..., U \} \). On the other hand, it mathematically formulates the OPP as a global optimization problem by defining a fitness function, \( \varphi(\chi) \), that measures the mismatch between the OPP objectives and the EMSs configuration coded by the DoF vector \( \chi \).

3) Fitness Function Evaluation (FFE - Sect. III-C) - This block is aimed at efficiently evaluating the fitness associated to each trial solution, \( \chi \), of the OPP. To reduce the heavy computational load of a RT-based EM prediction of the wireless coverage within the S RoIs for any trial deployment of the EMSs, a fast yet reliable digital twin (DT) is exploited to assess the coverage condition in quasi real-time;

4) Solution Space Exploration (SSE - III-D) - This block performs an effective sampling of the \( U \)-dimensional solution space to find the global optimum solution, \( \chi_{\text{opt}} \), that fulfills the project requirements by maximizing the fitness function \( \varphi(\chi) \) (i.e., \( \chi_{\text{opt}} = \arg \left( \max_{\chi} \varphi(\chi) \right) \)). On the one hand, the implementation of the SSE block is based on the identification of the most effective optimization “engine” to deal with the OPP-DoFs defined by the PF block. On the other hand, it leverages on the fast predictions of the received power level generated by the FFE block to determine \( \chi_{\text{opt}} \) with a non-negligible time saving with respect to a standard integration of a RT-based EM solver within an optimization tool.

In the following, a detailed description of each ShbD functional block is provided.

A. EMSD Block

Let us consider the design of the \( (w, s) \)-th \( (w = 1, ..., W(w); s = 1, ..., S) \) EMS, \( \Gamma_w^{(s)} \), to be mounted on the building facade \( \tau_w^{(s)} \) at the position \( \tau_w^{(s)} = \{ x_w^{(s)}, y_w^{(s)}, z_w^{(s)} \} \) - Fig. 4] for enhancing the strength of the signal received at the \( s \)-th RoI, \( \Omega_w^{(s)} \), centered at \( \tau_w^{(s)} = \{ x_w^{(s)}, y_w^{(s)}, z_w^{(s)} \} \) - Fig. 4].

Once the directions of incidence, \( \Psi_w^{(s)} \), and of reflection, \( \Psi_w^{(s)} \), of the impinging wave from the BTS are defined as detailed in Appendix I, the \( \Gamma_w^{(s)} \) is designed according to the two-step synthesis procedure described in [4]. Shortly, the “reference” electric/magnetic current distributions on the surface of \( \Gamma_w^{(s)} \), which radiate in far-field a pencil beam pointed towards the RoI, \( \Psi_w^{(s)} \), are computed. Then, the pattern of the metalizations [4] that compose the \( (w, s) \)-th \( (w = 1, ..., W(w); s = 1, ..., S) \) EMS, \( \Gamma_w^{(s)} \), which is realized in low-cost PCB technology, is derived by optimizing the \( \Omega \)-geometric descriptors of the \( L \) unit cells of the EMS, \( d_{w,s,o}^{(o)} = \{ d_{w,s,o}^{(o)}; o = 1, ..., O; l = 1, ..., L \} \), so that the electric/magnetic current distributions induced on the surface \( \tau_w^{(s)} \) by the impinging wave from the BTS match the “reference” ones.

B. PF Block

According to the ShbD paradigm [3], the PF block is aimed at formulating the OPP into a proper mathematical framework...
to enable its reliable and cost-effective solution. Towards this end and owing to the problem at hand, a binary encoding is adopted to define the set of $U$ DoFs. More in detail, a deployment of EMSs in the urban scenario is coded with the $K$-size (i.e., $U = K$) binary chromosome $\chi = \{\chi_w; w = 1, \ldots, W(\cdot); s = 1, \ldots, S\}$ whose $(w, s)$-th $(w = 1, \ldots, W(s); s = 1, \ldots, S)$ entry is equal to $0$ if $1 = 1$, and $0 = 0$ when the $(w, s)$-th EMS, $\Gamma^{(s)}_w$, designed in the EMSD block (Sect. III-A), is installed/not-installed on the corresponding building facade $\tau^{(s)}_w$.

The arising binary-coded planning problem is then formulated by the PF block as a global optimization task by properly defining the fitness function $\varphi$. Such a performance index mathematically models the underlying physics by quantifying the fulfillment of the QoS requirement by a trial solution $\chi$ (i.e., a trial EMSs deployment). More specifically, the fitness of a guess $\chi, \varphi \{\chi\}$, is given by the inverse of a two-term single-objective cost function $\Phi \{\chi\}$ as follows (Fig. 3)

$$\Phi \{\chi\} = \Phi_{cov} \{\chi\} + \Phi_{cost} \{\chi\}.$$  

The coverage term $\Phi_{cov} \{\chi\}$ measures the mismatch between the power received within the $S$ RoIs and the threshold value $P_{th}$ through the following expression

$$\Phi_{cov} \{\chi\} \propto \frac{1}{M} \sum_{s=1}^{S} \sum_{m=1}^{M(s)} \left| P_{th} - P \left( r^{(s)}_m \left| \chi \right. \right) \right| \times \left| H \left( r^{(s)}_m \left| \chi \right. \right) \right|$$  

where $M(s)$ is the number of receivers that lay in the positions, $\{r^{(s)}_m; m = 1, \ldots, M(s)\}$, of the $s$-th block as a global optimization task by properly deploying

Figure 4. Pictorial sketch of the local coordinate system for the $(w, s)$-th $(w = 1, \ldots, W(\cdot); s = 1, \ldots, S)$ EMS, $\Gamma^{(s)}_w$.

C. FFE Block

The computation of the fitness of each trial solution $\chi, \varphi \{\chi\}$, could represent the main bottleneck of the overall OPP solution strategy, especially if repeated many times as in the SSE block for the exploration of the $K$-dimensional solution space (Sect. III-D), unless suitable countermeasures are undertaken. As a matter of fact, even though the evaluation of the term (4) is immediate since it only depends on the number of non-null entries of the binary vector $\chi$, on the contrary, the prediction of the level of power within the $S$ RoIs, to assess the fulfillment of the QoS requirements, would be computationally heavy whether using EM simulation tools based on RT techniques due to the large scale of the urban scenario at hand (Fig. 1) 2.

In order to minimize the computational load, the FFE block is responsible for the off-line generation of a DT to estimate the coverage term (3) (i.e., $\Phi_{cov} \{\chi\} \approx \Phi_{cov} \{\chi\}$) so to efficiently predict the cost function value, $\Phi \{\chi\}$, as follows (Fig. 3)

$$\bar{\Phi} \{\chi\} = \bar{\Phi}_{cov} \{\chi\} + \Phi_{cost} \{\chi\}.$$  

Towards this end, a Gaussian Process (GP) [39][42][43] is used to build the DT from the information embedded within an (off-line generated) training set of $T$ input/output (I/O) pairs

$$T = \left\{ \chi^{(t)}; \Phi_{cov} \{\chi^{(t)}\} \right\}; t = 1, \ldots, T \tag{7}$$

randomly-chosen among the full set of $B = 2^K$ EMSs configurations ($T \ll B$). More specifically, the computationally-fast guess of (3) is given by

$$\bar{\Phi}_{cov} \{\chi\} = \nu + \left( \rho \right)^{C-1} \left( \Phi - \nu \right) \tag{8}$$

1It should be pointed out that, although less accurate than full-wave methods, RT-based simulators represent nowadays a proper compromise between precision and computational efficiency for the optimization problem at hand.
where \( \Phi = \{ \Phi_{cpx}, \{ \chi(t) \}; t = 1, ..., T \} \) and \( \nu = \left( \frac{1}{2} \right)^{\frac{d}{2}} \) being the transpose operator and \( \frac{1}{2} \) is a \((T \times 1)\)-size vector of unitary entries. Moreover, \( C = \{ \Lambda (\chi^{(p)}, \chi^{(q)}); p, q = 1, ..., T \} \) and \( \rho = \{ \Lambda (\chi^{(a)}, \chi^{(b)}); t = 1, ..., T \} \) are the training correlation matrix and the correlation vector of \( \chi \), respectively, the correlation between two input samples \( \chi^{(a)} \) and \( \chi^{(b)} \) being computed as
\[
\Lambda (\chi^{(a)}, \chi^{(b)}) = \exp \left( -\sum_{k=1}^{K} \beta_k \left| \chi^{(a)}_k - \chi^{(b)}_k \right|^{\gamma_k} \right) \tag{9}
\]
where \( \beta = \{ \beta_k > 0; k = 1, ..., K \} \) and \( \gamma = \{ 1 \leq \gamma_k \leq 2; k = 1, ..., K \} \) are \( GP \) hyper-parameters determined during the off-line training phase by maximizing the likelihood function of \( T \) \cite{39}\cite{42}\cite{43}.

D. SSE Block

By following the ShBD guidelines \cite{3} and according to the no-free-lunch theorem for optimization \cite{44}, the implementation of the SSE block is driven by the nature of the fitness function and of the solution space defined by the PF block (Sect. III-B). As a matter of fact, it is profitable to select the most suitable optimization engine that assures a proper balance between exploration and local sampling of the solution space, while hill-climbing local minima of the cost function, to converge towards the global optimum of (2), \( \chi^{(opt)} \). Moreover, the optimization tool is required to properly handle (i.e., without considering time-expensive coding/decoding operations) the binary nature of the DoFs of the OPP.

Owing to these considerations, a binary genetic algorithm (BGA)-based strategy is adopted to find \( \chi^{(opt)} \) by evolving a population of \( P \) binary individuals, \( P_i = \{ \chi^{(p)}; p = 1, ..., P \} \) \((i = 1, ..., I; \ i \) being the iteration index) \((I \) iterations according to the concepts of natural selection and genetic pressure \cite{35}\cite{37}). Moreover, the BGA is here customized to take full advantage of the ShBD framework for obtaining a considerable time saving by avoiding the time-costly assessment of each \((i, p)\)-th \((i = 1, ..., I; \ p = 1, ..., P \) trial solution, \( \chi^{(p)} \)), with a full-wave EM simulation. Towards this end, the iterative minimization of (2) leverages on the profitable interconnection of the SSE block with the DT derived in the FFE block (Sect. III-C). Furthermore, the proposed implementation of the BGA benefits from the knowledge of the training set \( T \) to enhance the convergence rate of the optimization process according to the “schemata theorem” of GAs \cite{38}, which states that “above average schemata receive exponentially increasing trials in subsequent generations”. Accordingly, since the probability to yield “good” schemata \cite{38} by randomly-selecting \( P \) binary chromosomes from the whole set of \( B \) \((B \geq 2^K)\) admissible binary sequences \((P \ll B)\) is generally low, the individuals of the initial population \( P_0 \) are chosen among the fittest ones of the \( T \) solutions of the training set, \( \{ \chi^{(t)}; t = 1, ..., T \} \).

The sequence of procedural steps carried out in the “schemata theorem” of GAs \cite{38}, which states that “above average schemata receive exponentially increasing trials in subsequent generations”. Accordingly, since the probability to yield “good” schemata \cite{38} by randomly-selecting \( P \) binary chromosomes from the whole set of \( B \) \((B \geq 2^K)\) admissible binary sequences \((P \ll B)\) is generally low, the individuals of the initial population \( P_0 \) are chosen among the fittest ones of the \( T \) solutions of the training set, \( \{ \chi^{(t)}; t = 1, ..., T \} \).

The sequence of procedural steps carried out in the SSE block is summarized in the following.

1) Initialization \((i = 0)\) - Sort the training solutions of \( \{ \chi^{(t)}; t = 1, ..., T \} \), according to their fitness values, \( \phi \{ \chi^{(t)} \} \) \((t = 1, ..., T) \), and build the

\[
\Psi = \{ \chi^{(t)}; t = 1, ..., T \}
\]

where \( \Psi = \{ \chi^{(p)}; p = 1, ..., P \} \) being the transpose operator and \( 1 \) is a \((T \times 1)\)-size vector of unitary entries. Moreover, \( C = \{ \Lambda (\chi^{(p)}, \chi^{(q)}); p, q = 1, ..., T \} \) and \( \rho = \{ \Lambda (\chi^{(a)}, \chi^{(b)}); t = 1, ..., T \} \) are the training correlation matrix and the correlation vector of \( \chi \), respectively, the correlation between two input samples \( \chi^{(a)} \) and \( \chi^{(b)} \) being computed as
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b) Exploit the FFE block (Sect. III-C) to predict, according to (8) and (6), the fitness function of each individual of \( P_i \), \( \phi \{ \chi^{(p)} \} \) \((p = 1, ..., P) \). Select through elitism \cite{35} the fittest individual

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Figure 5. Numerical Assessment - Picture of (a) the Google Map of the test-bed region (Gardolo district - Trento, Italy), (b) the corresponding cartography from the OSM database, and (c) the WinProp simulation scenario.
generated until the current $i$-th iteration, $\chi^{(i)} = \arg\left[\min_{p=1,...,P} \min_{j=1,...,J} \Phi \left( \chi^{(p)} \right) \right]$. 

3) Output Phase - Output the OPP solution given by

$$\chi^{(opt)} = \arg\left[\min_{p=1,...,P} \Phi \left( \chi^{(p)} \right) \right]. \quad (11)$$

IV. NUMERICAL VALIDATION

The goal of this section is to assess the capabilities and the potentialities of the approach to enhance the wireless coverage and the overall QoS in large urban scenarios thanks to the optimal deployment of EMs on the building facades.

Such an assessment has been carried out in a real-world scenario by considering the Gardolo district of the city of Trento (Italy) as the benchmark test-bed (Fig. 5). As it can be inferred from the satellite image [Fig. 5(a)] taken from the Google Maps website [46], the selected area $\Xi$ is a square region 1 [Km]-sided that comprises several streets, a railway, and a quite dense distribution of civil, commercial, and industrial buildings.

The actual position of the BTS, which serves the users in $\Xi$, is $r_{\Psi} = (3.95 \times 10^2, 5.79 \times 10^2, 30)$ [m] and it has been extracted from the official BTS cartography publicly accessible on the website of the city of Trento [45] [Fig. 5(b)]. The site consists of $V = 3$ sectors having an angular extension equal to $\Delta \phi = 120$ [deg] in azimuth, pointed towards the directions $\phi_{\Psi} = (v-1) \times 120$ [deg] ($v = 1,...,V$), with a mechanical down-tilt of $\Delta \theta = 2$ [deg] in elevation [51][52][53]. Each $v$-th ($v = 1,...,V$) sector has been assumed to be illuminated by a panel of the BTS, which is composed by a planar array (Fig. 6) of $N = (13 \times 2) \frac{\lambda}{2}$ spaced slot-coupled dual-polarized (slant-45) square patch radiators working at $f = 3.5$ [GHz] with a ground plane of size $(L_y \times L_z) = (1.75 \times 7) \lambda$ [52][53] (see the inset in Fig. 6). Such an antenna array has been accurately modeled in the Ansys HFSS simulation suite [47] to take into account all mutual coupling effects. The co-polar gain pattern for the +45-polarization operation, $G_{+45} (\theta, \phi)$ [48], is shown in Fig. 6, the maximum gain being $G_{+45}^{\max} = \max_{\theta, \phi} G_{+45} (\theta, \phi) = 16.3$ [dBi] 3.

As for the wireless coverage, the power distribution in $\Xi$ (Fig. 5) has been computed with the RT-based Altair WinProp simulator [49]. Towards this end, the exact position, orientation, and dimensions of each building has been first extracted from the OpenStreetMap (OSM) Geographic Information System (GIS) database [50] [Fig. 5(b)], then it has been imported into WinProp to generate the EM simulation scenario in Fig. 5(c) where the buildings have been assumed to be made of concrete with relative permittivity $\varepsilon_r = 4$ and conductivity $\sigma = 10^{-2}$ [S/m] [54][56]. The time and memory cost of a single RT simulation is equal to $\Delta t_{sim} = 75$ [sec] and $R = 210$ [MB], respectively, on a standard laptop equipped with an Intel(R) Core(TM) i5-8250U CPU @ 1.60GHz and 16 [GB] of RAM. Fig. 7(a) shows the power distribution (i.e., $P_r (r)$, $r \in \Xi$)

3For symmetry reasons, the co-polar pattern for the −45 operation, $G_{-45} (\theta, \phi)$, coincides with $G_{+45} (\theta, \phi)$. Accordingly, all the results reported in the following refer to the +45 operation of the BTS.
computed at a standard user height of \( h = 1.5 \) [m] \([55]\) on a grid of points uniformly-spaced (\( \Delta_x = \Delta_y = 5 \) [m] being the spacing along \( x- \) and \( y- \) axes), when feeding the BTS panels with an input power of \( P^{(v)}_{in} = 20 \) [W], \( v = 1, \ldots, V \) \([52],[53]\). In addition to the standard attenuation due to the path loss, the distribution of the power radiated by the BTS turns out to be strongly affected by the presence of the buildings, which cause shadowing effects as well as wave-guiding phenomena (e.g., canyoning along the main streets).

The RoIs in \( \Xi \) have been identified by thresholding \( P_{th} = -65 \) [dBm]\(^4\) being the value of the coverage threshold) the distribution of \( P_\Omega \). The binary map in Fig. 7(b) shows \( S = 2 \) RoIs. The first one has an area of \( A(\Omega^{(1)}) = 1225 \) [m\(^2\)] \( (M^{(1)} = 49) \) and it is centered at \( r_{\Omega}^{(1)} = (411, 698, 1.5) \) [m] \([Fig. 7(b) \text{ and Figs. 8(a)}]\), while the other is located at \( r_{\Omega}^{(2)} = (123, 280, 1.5) \) [m] and extends on a support of \( A(\Omega^{(2)}) = 1075 \) [m\(^2\)] \( (M^{(2)} = 43) \) \([Fig. 7(b) \text{ and Figs. 8(b)}]\).

\(^4\)The value \( P_{th} = -65 \) [dBm] is often assumed as the reference signal received power (RSRP) to support advanced high-throughput wireless services (e.g., high-definition video streaming \([57]\) ).
Table I
DESCRIPTORS OF THE URBAN SCENARIO AND OF THE OPP.

| $P_{th}$ [dBm] | $S$ | $K$ | $B$ | $\Phi_{cov}$ | $\Phi$ | $\Phi_{cov}$ | $\Phi_{cov}$ | $\Phi_{cov}$ |
|----------------|-----|-----|-----|--------------|--------|--------------|--------------|--------------|
| $-65$          | $2$ | $20$|     | $1.05 \times 10^9$ | $2.10 \times 10^{-2}$ | $7$ | $3.50 \times 10^{-4}$ | $2.50 \times 10^{-4}$ | $3.50 \times 10^{-4}$ |
| $-60$          | $4$ | $38$|     | $2.75 \times 10^{11}$ | $5.41 \times 10^{-2}$ | $24$ | $6.40 \times 10^{-4}$ | $1.40 \times 10^{-4}$ | $6.32 \times 10^{-4}$ |

Figure 12. Numerical Assessment ($f = 3.5$ [GHz], $P_{th} = -65$ [dBm], $S = 2$, $K = 20$) - Picture of the thresholded power map in the neighborhood of the RoI $\Omega^{(1)}$, $\Pi^{(1)}$, when deploying (a) $Q^{(1)} = 1$ and (b) $Q^{(1)} = 2$ EMSs according to the SHD-based planning method.

Figure 13. Numerical Assessment ($f = 3.5$ [GHz], $P_{th} = -65$ [dBm], $S = 2$, $K = 20$) - Picture of the thresholded power map in the neighboring of the RoI $\Omega^{(1)}$, $\Pi^{(1)}$, when deploying smaller EMSs consisting of (a) $L = (25 \times 25)$ and (b) $L = (12 \times 12)$ unit cells.

Figure 14. Numerical Assessment ($f = 3.5$ [GHz], $P_{th} = -65$ [dBm], $S = 2$, $K = 20$) - Picture of the thresholded power map in the neighboring of the RoI $\Omega^{(1)}$, $\Pi^{(1)}$, when deploying the EMSs at a quota of $z_w^{(s)} = (H_w^{(s)} - 7)$ [m].

Figure 15. Numerical Assessment ($f = 3.5$ [GHz], $P_{th} = -65$ [dBm], $S = 2$, $K = 20$) - Picture of the thresholded power map in the neighborhood of the RoI $\Omega^{(1)}$, $\Pi^{(1)}$, measured at (a)/(b) $h = 0.5$ [m], (c)/(d) $h = 1.0$ [m], and (e)/(f) $h = 2.0$ [m] when considering (a)/(c)/(e) the absence and (b)/(d)/(f) the presence of the optimally-planned EMSs.

According to the proposed planning method (Sect. II), a set of $W(s)$ ($W^{(1)} = 8$ [Fig. 8(c)]; $W^{(2)} = 12$ [Fig. 8(d)]) building facades has been chosen into each neighboring square region, $\Pi^{(s)}$, of a RoI $\Omega^{(s)} (s = 1, \ldots, S)$. Then, the complete set of $K = 20$ EMSs has been off-line synthesized in the EMSD block (Fig. 3 - Sect. III-A) by assuming an installation quota of $z_w^{(s)} = (H_w^{(s)} - 2)$ [m] from the ground level (Fig. 4), $H_w^{(s)}$ being the height of the $(w, s)$-th wall ($w = 1, \ldots, W^{(s)}$, $s = 1, \ldots, S$) wall, $\tau_w^{(s)}$, in the OSM database [50]. More specifically, each EMS has been implemented [4] with a properly-tailored pattern of $L = (50 \times 50)$ square-shaped unit cells (i.e., $O = 1$) printed on a support of $A (\Gamma_w^{(s)}) = (2.14 \times 2.14)$ [m$^2$] ($w = 1, \ldots, W^{(s)}$, $s = 1, \ldots, S$) over...
a Rogers RT/duroid 5870 substrate ($\varepsilon_r = 2.33$, $\tan \delta = 1.2 \times 10^{-3}$) of thickness $3.7 \times 10^{-2} \, [\lambda]$. For completeness, the physical layout of one of the synthesized EMSs (i.e., $\Gamma_4^{(2)}$) is shown in Fig. 9. Similarly to the BTS, each synthesized EMS has been modeled in the RT simulator as an equivalent source by importing the corresponding radiation pattern at the correct location/orientation within the simulated scenario.

The OPP at hand is then solved by sampling the $B$-size ($B \approx 1.05 \times 10^6$ - Tab. I) solution space of the admissible EMSs deployments with the ShbD-based approach ( Sect. III). Towards this end, the GP-based DT of the fitness function has been built exploiting RT-simulated training samples according to the procedure in Sect. III-C (FFE Block), while the ShbD control parameters have been set according to the state-of-the-art guidelines [3][35]: $T = 4 \times 10^3$, $P = 40$, $I = 10^3$, $\delta^2 = 8 \times 10^{-1}$, $\delta_1^M = 10^{-1}$, and $\delta_2^M = 10^{-2}$. The final (i = I) outcome of the planning process is summarized in Fig. 10 where the thresholded maps of the distribution of power received in $\Pi^{(1)}$ [Fig. 10(a)] and $\Pi^{(2)}$ [Fig. 10(b)] are reported along with the positions of the selected EMSs. There are $Q^{(\text{opt})} = 7$ EMSs (i.e., $\Gamma_1^{(1)}$, $\Gamma_2^{(1)}$, $\Gamma_3^{(1)}$, $\Gamma_4^{(2)}$, $\Gamma_5^{(2)}$, $\Gamma_6^{(2)}$, $\Gamma_7^{(2)}$ - Tab. I), $Q^{(\text{opt})} = 3$ [i.e., $\Gamma_1^{(1)}$, $\Gamma_2^{(1)}$, $\Gamma_3^{(1)}$] - Fig. 10(a)] and $Q^{(\text{opt})} = 4$ [ $\Gamma_1^{(2)}$, $\Gamma_2^{(2)}$, $\Gamma_3^{(2)}$, $\Gamma_4^{(2)}$] - Fig. 10(b)] for $\Omega^{(1)}$ and $\Omega^{(2)}$, respectively. Thanks to the reduction of the coverage term (3) of about two orders of magnitude with respect to the “nominal” scenario without EMSs (i.e., $\Phi_{\text{w1}}(\chi_{\text{th}}) = 1.19 \times 10^{-2}$ - Tab. I), there is a remarkable enhancement of the level of the power received in the Rolls. Indeed, the coverage condition holds true in $\Omega^{(1)}$ [i.e., $P(\chi_{\text{th}}) \chi^{(\text{opt})}) > P_{\chi_{\text{th}}, \chi \in \Omega^{(1)}$ - Fig. 10(a)] vs. Fig. 8(a)], while only few locations of $\Omega^{(2)}$ are under the power threshold $P_{\chi_{\text{th}}, \Delta(\Omega^{(2)})} = 86\%$ of the received power [ $\Omega^{(1)}$ - Fig. 10(a) vs. Fig. 8(a)]

To point out the coverage improvement enabled by the EMSs, the thresholded maps of the power gap $\Delta P(\chi)$ $[\Delta P(\chi) = P(\chi_{\text{th}}) - P_{\chi_{\text{th}}, \chi \in \Omega^{(1)}})]$ are shown, as well [Figs. 10(c)-10(d)].

One can observe that the received power has been increased (i.e., $\Delta P(\chi) > 0$) over a wide region around both the Rolls centers, while the red pixels always correspond to limited/negligible reductions of power level (i.e., $\Delta P(\chi) \leq -1.5 \, [\text{dBm}]$).

Let us now focus on $\Omega^{(1)}$ to investigate on the “effect/impact” of each $q$-th ($q = 1, ..., Q^{(\text{opt})}$ - Tab. I) EMS on the wireless coverage. Towards this purpose, Fig. 11 gives the behavior of the cumulative density function (CDF) of the received power, $\Theta$, which is defined as

$$\Theta \{ P(\chi) \geq \hat{P} \} = Pr \{ P(\chi) \leq \hat{P} \} \quad (12)$$

$^5$It is worth pointing out that the coverage improvement in $\Omega^{(2)}$ is intrinsically a harder task than that for $\Omega^{(1)}$ because of the larger distance, $R$, of the BTS from $\Omega^{(2)}$ (i.e., $R \chi_{\text{th}}^{(1)} \approx 123 \, [\text{m}]$ vs. $R \chi_{\text{th}}^{(2)} \approx 405 \, [\text{m}]$ - Fig. 7).

Figure 16. Numerical Assessment ($f = 3.5 \, [\text{GHz}]$, $P_{\chi_{\text{th}}} = -65 \, [\text{dBm}]$, $S = 2$, $K = 20$) - Plot of the CDF of the received power, $\Theta \{ P(\chi) \geq \hat{P} \}$, within a circular region centered on the Roll $\Omega^{(2)}$, $r_{\chi_{\text{th}}}^{(2)}$, of radius $\zeta = 40 \, [\text{m}]$.

Figure 17. Numerical Assessment ($f = 3.5 \, [\text{GHz}]$, $P_{\chi_{\text{th}}} = -65 \, [\text{dBm}]$, $S = 2$, $K = 20$) - Picture of the thresholded power map in the neighborhood of the Roll $\Omega^{(2)}$, $\Pi^{(2)}$, when deploying (a) $Q^{(2)} = 1$, (b) $Q^{(2)} = 2$, and (c) $Q^{(2)} = 3$ EMSs according to the ShbD-based planning method.

where $Pr \{ \ldots \}$ denotes the probability function and $\hat{P} \in [-70, -50] \, [\text{dBm}]$, computed over a circular region of radius $\zeta = 40 \, [\text{m}]$ and centered in $r_{\chi_{\text{th}}}^{(1)}$ [Fig. 10(a)]. It turns out that there is a progressive improvement of the wireless coverage (i.e., $\Theta \{ P(\chi) \geq \hat{P} \} \approx 1 \%$ to $\Theta \{ P(\chi) \geq \hat{P} \} \approx 7 \%$ to $\Theta \{ P(\chi) \geq \hat{P} \} \approx 80 \%$ - Fig. 10(a)) starting from the “nominal” case [i.e., $\Theta \{ P(\chi) \geq \hat{P} \} = 30.2 \%$ - Fig. 8(a)] up to the EMSs planning at convergence [i.e., $\Theta \{ P(\chi) \geq \hat{P} \} \approx 100 \%$ - Fig. 10(a)]. For completeness, Fig. 12 shows the thresholded maps for the two intermediate sub-optimal configurations comprising $Q^{(1)} = 1 \{ \Theta \{ P(\chi) \geq \hat{P} \} \approx 14.2 \% \quad \text{Fig. 12(a)} \}$ and $Q^{(1)} = 2$ [EMSs $\Theta \{ P(\chi) \geq \hat{P} \} \approx 20 \%$ - Fig. 12(b) and Fig. 11]
2.5 % - Fig. 12(b) and Fig. 11.

To provide more insights on the impact of the EMS size on the achievable coverage improvement, the thresholded power map within \( \Pi^{(1)} \) is shown in Fig. 13 when deploying smaller skins consisting of \( L = (25 \times 25) \) [\( \Delta A (\Omega^{(1)}) \)]_{L=25} = 81.6 % - Fig. 13(a) and \( (b) L = (12 \times 12) \) [\( \Delta A (\Omega^{(1)}) \)]_{L=12} = 40.8 % - Fig. 13(b)] unit cells. As expected, a smaller area of the EMS determines a lower (but still noticeable) increase of the power level within \( \Omega^{(1)} \) because of (i) the reduced amount of collected energy from the BTS and (ii) the lower focusing capability.

On the other hand, the installation of the EMSs at a different height on the building facades does not significantly impact the overall quality of the obtained OPP solution, provided that their layout is properly re-designed to take into account the different incident/reflection angles (see Appendix I). As an illustrative example, the thresholded power map within \( \Pi^{(1)} \) is shown in Fig. 14 when considering a lower installation quota (i.e., \( s_w = (H_w - 7) \) [m]). As it can be observed, the performance of the SBd solution is only slightly reduced \([\Delta A (\Omega^{(1)})]_{s_w=7} = 89.8 \% - \text{Fig. 14}\) because of the non-optimized planning for such a skin deployment.

Finally, it is worth pointing out that the coverage improvement has been achieved at different measurement heights from the ground, as well. As a matter of fact, there is a remarkable improvement of the received power level also at a field sampling quota of \( h = 0.5 \) [m] \([\Delta A (\Omega^{(1)})]_{h=0.5} = 100 \% - \text{Fig. 15(a)}\) vs. \( h = 1.0 \) [m] \([\Delta A (\Omega^{(1)})]_{h=1.0} = 100 \% - \text{Fig. 15(b)}\), \( h = 2.0 \) [m] \([\Delta A (\Omega^{(1)})]_{h=2.0} = 94.3 \% - \text{Fig. 15(c)}\) vs. \( h = 1.3 \) [m] \([\Delta A (\Omega^{(1)})]_{h=1.3} = 75 \% - \text{Fig. 15(f)}\).

Similar results have been yielded for the RoI\(^{(2)}\) (Fig. 16), as well. More in detail, the SBd-derived EMSs distribution reduces the probability of being below the coverage threshold \( \mathcal{P}_{th} = -65 \) [dBm] from \( \Theta \{ \mathcal{P}(r | \mathcal{P}_{th}) \}_{Q^{(2)}=0} = 26.0 \% - \text{Fig. 8(b)}\) down to \( \Theta \{ \mathcal{P}(r | \mathcal{P}_{th}) \}_{Q^{(2)}=4} = 4.7 \% - \text{Fig. 10(b)}\), being \( \Theta \{ \mathcal{P}(r | \mathcal{P}_{th}) \}_{Q^{(2)}=1} = 25.2 \% - \text{Fig. 17(a)}\), \( \Theta \{ \mathcal{P}(r | \mathcal{P}_{th}) \}_{Q^{(2)}=2} = 17.2 \% - \text{Fig. 17(b)}\), and \( \Theta \{ \mathcal{P}(r | \mathcal{P}_{th}) \}_{Q^{(2)}=3} = 9.3 \% - \text{Fig. 17(c)}\).

As for the computational issues, the SBd method assures a time saving of about \( \Delta t_{\text{sav}} \approx 90 \% \) (\( \Delta t_{\text{sav}} \triangleq \frac{(P_{\text{OPP}})}{(P_{\text{SBd}})} \)) [3] with respect to a standard optimization, mainly thanks to the exploitation of the DT for the coverage assessment (Sect. III-C) during the iterative process.

The second test case of the numerical validation is concerned with a more challenging OPP, the power threshold being set to \( \mathcal{P}_{th} = -60 \) [dBm]. Owing to the harder requirement, two additional RoIs appear on the same scenario (\( \Sigma \)) of the previous example (\( S = 4 - \text{Fig. 18}\), namely the RoI \( \Omega^{(3)} \) - Fig. 18\( (\Omega^{(3)}) = (313, 914, 1.5) \) [m], \( M^{(3)} = 74 \), and \( \Delta (\Omega^{(3)}) = 1850 \) [m\(^2\)]) and the RoI \( \Omega^{(4)} \) - Fig. 19\( (\Omega^{(4)}) = (363, 396, 1.5) \) [m], \( M^{(4)} = 59 \), and \( \Delta (\Omega^{(4)}) = 1475 \) [m\(^2\)]). Therefore, \( W^{(3)} = 10 \) [Fig. 19(a)] and \( W^{(4)} = 8 \) [Fig. 19(b)] new EMSs have been designed in the EMSD block (Sect. III-A) for a potential deployment on the “candidate” building facades in \( \Pi^{(3)} \) - Fig. 19\( (a)\) and \( \Pi^{(4)} \) - Fig. 19\( (b)\)]. Due to the higher cardinality of the solution space (i.e., \( K = 38 \rightarrow B = 2.75 \times 10^{10} \) - Tab. I), a bigger training set \( \mathcal{T} = 7.6 \times 10^{3} \) I/O pairs has been generated.

6Considering that the average simulation time for evaluating the received power distribution associated to one trial guess of the SBd-DoFs vector \( \chi \) is equal to \( \Delta t_{\text{sim}} = 75 \) [sec], it turns out that the time for a serial assessment of all \( B \) configurations would be equal to \( \Delta t_{\text{sim}} = (B \times \Delta t_{\text{sim}}) \approx 910 \) [days].
on the RoIs centers, \( \{ \text{RoI}(s) ; s = 1, \ldots, S \} \). The positive outcome on the EMSs planning is also confirmed, from a statistical viewpoint, by the CDFs in Fig. 21. For instance, let us analyze the case of the RoI \( \text{RoI}(4) \). It turns out that the deployment of \( Q^{(i)} = Q^{(\text{opt})} \mid \gamma = 3 \) EMSs reduces the probability of being below the QoS threshold of \( \text{Pr}_{\text{th}} = -60 \text{ [dBm]} \) from \( \Theta \{ \text{Pr}(x) \mid \text{Pr}_{\text{th}} \} \mid Q^{(i)} = 0 = 49.2 \% \) [Fig. 20(l)] down to \( \Theta \{ \text{Pr}(x) \mid \text{Pr}_{\text{th}} \} \mid Q^{(i)} = 3 = 8.3 \% \) [Fig. 20(n)] with a reduction of the “blind” area of about \( \Delta A \{ \text{RoI}(4) \} \approx 86.4 \% \).

V. CONCLUSIONS
In the framework of the emerging SEME paradigm, the planning of passive/low-cost EMSs to enhance the QoS in large-scale urban propagation scenarios has been addressed. An innovative Shb-based strategy has been proposed to solve the arising OPP by determining optimal trade-off solutions, which jointly maximize the level of power received within “no-coverage/low-QoS” RoIs and minimize the overall cost and environmental impact.

The numerical assessment, on a real-world test-bed, has proved the feasibility of the proposed strategy for the SEME implementation as well as the effectiveness of the proposed planning method. By considering both different RoIs and distances from the BTS as well as various values of the coverage threshold \( \text{Pr}_{\text{th}} \), effective EMSs deployments have been obtained with a significant computational efficiency, as well.

Future works, beyond the scope of this paper, will be aimed at extending the proposed approach to deal with the planning of mixed scenarios involving both RISs and IAB nodes.

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Appendix I

Without loss of generality and by assuming a local coordinate system \((x', y', z')\) with origin in \(r^{(s)}_{w}\) (Fig. 4), the EM wave radiated by the BTS towards \(\Gamma^{(s)}_{w}\) is modeled as a monochromatic plane wave at frequency \(f\) with incident wave vector equal to

\[
k^{(w,s)}_{\psi} = -\frac{2\pi}{\lambda} \left[ \sin (\theta^{(w,s)}_{\psi}) \cos (\varphi^{(w,s)}_{\psi}) + \sin (\theta^{(w,s)}_{\psi}) \sin (\varphi^{(w,s)}_{\psi}) \right]
\]

where \(\theta^{(w,s)}_{\psi}\) and \(\varphi^{(w,s)}_{\psi}\) are the elevation and the azimuth coordinates of the angle of incidence, respectively, whose expressions are

\[
\begin{aligned}
\theta^{(w,s)}_{\psi} &= \mathcal{F}_{\theta} (r'_{\psi}) \\
\varphi^{(w,s)}_{\psi} &= \mathcal{F}_{\varphi} (r'_{\psi})
\end{aligned}
\]

\((13)\)

\(\mathcal{F}_{\theta}(r)\) and \(\mathcal{F}_{\varphi}(r)\) being the Cartesian-to-Polar operators equal to

\[
\begin{aligned}
\mathcal{F}_{\theta}(r) &= \arccos \left( \frac{z}{\sqrt{x^2+y^2+z^2}} \right) \\
\mathcal{F}_{\varphi}(r) &= \arctan \left( \frac{y}{x} \right)
\end{aligned}
\]

\((15)\)

Moreover, \(r'_{\psi} [x'_{\psi}, y'_{\psi}, z'_{\psi}]\) denotes the position of the BTS as seen from the EMS \(\Gamma^{(s)}_{w}\) (Fig. 4) and its Cartesian coordinates are

\[
\begin{aligned}
G_{x} \left( r'_{\psi}, r^{(s)}_{w} \right) &= x - x^{(s)}_{w} \cos (\alpha^{(s)}_{w}) + y - y^{(s)}_{w} \times \\
G_{y} \left( r'_{\psi}, r^{(s)}_{w} \right) &= \frac{z - z^{(s)}_{w}}{\sin (\alpha^{(s)}_{w})} - y^{(s)}_{w} \times \\
G_{z} \left( r'_{\psi}, r^{(s)}_{w} \right) &= x - x^{(s)}_{w} \sin (\alpha^{(s)}_{w}) - y^{(s)}_{w} \times \\
\end{aligned}
\]

\((17)\)

where \(\alpha^{(s)}_{w}\) is the orientation angle of the building wall \(r^{(s)}_{w}\) with respect to the global \(x\)-axis (Fig. 4).

Analogously, the angular direction of the EM wave reflected from the EMS \(\Gamma^{(s)}_{w}\) towards the barycenter of \(\Omega^{(s)}\), \((\vec{\theta}^{(w,s)}_{\Omega}, \vec{\varphi}^{(w,s)}_{\Omega})\), turns out to be

\[
\begin{aligned}
\vec{\theta}^{(w,s)}_{\Omega} &= \mathcal{F}_{\theta} (r^{(s)}_{\Omega}) \\
\vec{\varphi}^{(w,s)}_{\Omega} &= \mathcal{F}_{\varphi} (r^{(s)}_{\Omega})
\end{aligned}
\]

\((18)\)

\(r^{(s)}_{\Omega} = \left[ G_{x} \left( r^{(s)}_{\Omega}, r^{(s)}_{w} \right), G_{y} \left( r^{(s)}_{\Omega}, r^{(s)}_{w} \right), G_{z} \left( r^{(s)}_{\Omega}, r^{(s)}_{w} \right) \right]\) being the position of \(\Omega^{(s)}\) in the EMS local system of coordinates (Fig 4).
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