Features and Potentialities of Static Passive EM Skins for NLOS Specular Wireless Links

Giacomo Oliveri, Senior Member, IEEE, Marco Salucci, Senior Member, IEEE, and Andrea Massa, Fellow, IEEE

Abstract — The ability of passive flat patterned electromagnetic skins (EMSs) to overcome the asymptotic limit of the total path attenuation (TPA) of flat metallic reflectors in non-line-of-sight (NLOS) specular point-to-point fixed wireless access applications is assessed. For the first time, the best of our knowledge, closed-form expressions of the achievable TPA in EMS-powered NLOS links are stated. The condition on the panel size of EMS screens to overcome the performance of flat passive conductive screens (PCSs) with the same aperture is derived and numerically validated.

Index Terms — Access, fixed wireless, inverse problems, inverse scattering, metamaterials, next-generation communications, point-to-point wireless link, smart electromagnetic environment (SEME), static passive EM skins.

I. INTRODUCTION AND MOTIVATION

Wireless systems exploiting carriers at mmWave frequencies and beyond are becoming more and more popular both for fixed wireless access (e.g., 802.11ay) [1], [2] and mobile applications (e.g., 5G, B5G, 6G) in outdoor [3] and indoor [4] scenarios. Indeed, increasing the carrier frequency allows one to exploit wider portions of the spectrum to deliver high-speed broadband communications, while avoiding complex and costly cabled infrastructures [1], [2], [3], [4].

Unfortunately, the path loss and the attenuation experienced at higher and higher frequencies become increasingly severe especially in non-line-of-sight (NLOS) conditions [5], [6], [7] and suitable countermeasures [7], [8], [9] are mandatory to guarantee a suitable quality-of-service (QoS) at the users by recovering adequate signal levels even on large distances. Toward this end, one option is the exploitation of reflections from suitably located flat passive conductive screens (PCSs) [7], [10]. The possibility of establishing reliable wireless links in NLOS conditions, thanks to such a technology, is well-known since decades [10], [11]. In fact, PCSs have been successfully used for telemetry and voice communications [12] and, more recently, to enhance the indoor and the outdoor 5G coverage [7], [13]. The working principle of PCSs is that of redirecting the incident power toward the receiver through a specular reflection according to the first Snell’s law [Fig. 1(a)] [7], [10], [12], [13]. Therefore, the overall attenuation (namely, the total path attenuation (TPA)) experienced by the EM wave that travels from the transmitter to the receiver, thanks to the PCS reflection, depends on the size of the same screen [7], [10], [12], [13]. Unfortunately, the TPA cannot be arbitrarily reduced by increasing the PCS aperture [7] and its value is known to converge to the free-space loss of a virtual transmitter–receiver LOS link with the same overall length [Fig. 1(a)] [7], [14] in the asymptotic case of a perfect electric conductor (PEC) screen with infinite extension. This limit, which is as a consequence of the classical theory of images [14], implies that PCSs cannot be used to overcome the free-space attenuation in point-to-point links, but they only allow to bypass obstacles [Fig. 1(a)].

Flat electromagnetic skins (EMSs) [15], [16], [17], [18], [19], [20] may be profitably considered to address such a limitation by deriving new practical guidelines for NLOS point-to-point wireless communications. EMSs are indeed a class of inexpensive static passive devices that recently have enabled an advanced control of the wireless propagation [16], [17], [18], [19], [20] in several instances of the so-called smart electromagnetic environment (SEME) [15], [21], [22], [23], [24]. Toward this end, the EMS microscale physical descriptors have been set to guarantee that the macroscale performance of the device at hand complies with the user-defined requirements [16], [17]. Up to now (i.e., current EMS applications), anomalous reflections toward non-Snell angular directions have been yielded, thanks to EMSs to generate collimated [18], [19] or contoured footprints [16], [17]. On the other hand, there are no theoretical motivations that prevent
the design of EMSs that focus on the reflected power along the standard Snell’s specular direction.

According to this line of reasoning, this article proposes a technological solution based on EMS specular screens to overcome the asymptotic limit of the TPA of PCSs. Using the synthesis method presented in [20], EMSs are designed to outperform PCSs in terms of TPA. Furthermore, an innovative theoretical derivation is presented to enable the closed-form computation of the upper bound for the achievable TPA. User-oriented guidelines are also drawn from a numerical assessment concerned with different NLOS point-to-point propagation scenarios.

To the best of the authors’ knowledge, the main methodological innovations of the proposed research work with respect to the state-of-the-art include the following.

1) The introduction of EMSs as a technological solution for the implementation of highly efficient backhaul point-to-point fixed wireless links that overcome the free-space path loss limit and the assessment of the margin of improvement that can be achieved in such an application scenario.

2) A theoretical and numerical proof of the possibility to overcome the asymptotic TPA limit of standard metallic screens with EMSs.

3) The derivation of the closed-form analytical expression for the upper bound of the TPA achievable when using EMS-based screens as a function of the screen aperture, the transmitter/receiver features, and the NLOS link setup, which, unlike state-of-the-art available derivations, enables the designer to determine (through simple calculations) a) whether an indirect link including an EMS can outperform a comparable free-space link and b) what is quantitatively the expected margin of improvement on the TPA.

4) The derivation of operative guidelines and an “optimality condition” on the design of EMSs that improve the performance of standard metallic panels of the same size in terms of NLOS power transfer efficiency.

The outline of this article is as follows. Starting from the formulation of the problem of a wireless NLOS specular link, the values of the TPA theoretically achievable by PCSs and EMSs are derived (Section II). A set of results from an exhaustive numerical study are then presented to assess the performance of the synthesized EMSs in comparison to that yielded with standard PCSs under the same operative conditions (Section III). Finally, some conclusions are drawn (Section IV).

II. PROBLEM FORMULATION

Let us consider the propagation scenario in Fig. 1(a) where a pair of transmitting and receiving antennas, respectively centered at \( r_{TX} \triangleq \{r_{TX}, \theta_{TX}, \phi_{TX}\} \) and \( r_{RX} \triangleq \{r_{RX}, \theta_{RX}, \phi_{RX}\} \), operate in NLOS conditions, the direct path between them being obstructed. Both the antennas are oriented so that the direction of their maximum gain (i.e., \( G_{TX} \) and \( G_{RX} \)) is toward a square \( L \) being the side) flat passive reflecting screen centered in the origin of the global system of coordinates \( (x, y, z) \) [Fig. 1(a)].

Without any other obstacle between the transmitter/receiver and the screen, a wireless link between the two antennas can be established, thanks to the reflection by such a screen (i.e., \( \theta_{TX} = \theta_{RX} = \theta_0 \)) if the first Fresnel zone clearance condition holds true [25], [26].

Under these hypotheses and considering a time-harmonic dependence on the working frequency \( f \), the problem of designing a passive flat screen to establish an NLOS wireless link between the transmitter and the receiver can be formulated as that of finding the set \( d \) of screen descriptors, \( d \triangleq \{d_i; s = 0, \ldots, S - 1\} \) (e.g., the screen side, the details of its geometrical/physical properties), so that the power at the
receiver (i.e., $r = r_{RX}$) [14]

$$P_{RX}(r_{RX}; d) = \frac{\lambda^2 G_{RX}|E_{RCS}(r_{RX}; d)|^2}{8\pi \eta}$$

(1)

is maximized. In (1), $\lambda$ and $\eta$ are the wavelength ($\lambda \triangleq (c/f)$) and the impedance ($\eta \triangleq \sqrt{(\mu_0/\varepsilon_0)}$) of the free-space with permittivity and permeability equal to $\varepsilon_0$ and $\mu_0$, respectively, while $c$ is the free-space speed of light ($c \triangleq \sqrt{1/(\mu_0\varepsilon_0)}$). Moreover, $E_{RCS}(r_{RX}; d)$ is the electric field reflected in $r = r_{RX}$ by the flat screen, described by the vector $d$, when illuminated by the incident electric field $E_{inc}(r)$ generated by the transmitter, the time dependence $\exp(j2\pi ft)$ being omitted hereinafter for the sake of notation compactness.

To determine the received power (1), the computation of the field reflected by the screen, $E_{RCS}(r; d)$, is carried out with the method developed in [20] for the analysis of EMMs, but suitable for PCSs, as well. By discretizing the square flat screen area, $\Theta$, in $P \times Q$ ($P = Q$) square cells, $\{\Theta_{pq}; p = 0, \ldots, P - 1; q = 0, \ldots, Q - 1\}$, of side $\Delta$ ($\Delta \triangleq (L/Q)$), it turns out that [20]

$$E_{RCS}(r; d) \approx \frac{j \exp(-jkr)}{2\lambda r} \Delta^2 \text{sinc}\left(\frac{\pi \Delta \sin\theta \cos\varphi}{\lambda}\right) 
\times \text{sinc}\left(\frac{\pi \Delta \sin\theta \sin\varphi}{\lambda}\right) \sum_{p=0}^{P-1} \sum_{q=0}^{Q-1} \exp\left[j \frac{2\pi}{\lambda} \beta_{pq}(r) \right]$$

$$\times \left[\eta \cos\theta \cos\varphi(J_p^x)_{pq} + \eta \cos\theta \sin\varphi(J_p^y)_{pq} 
+ \sin\varphi(J_m^x)_{pq} + \cos\varphi(J_m^y)_{pq}\right]$$

$$+ \left[-\eta \sin\varphi(J_p^x)_{pq} + \eta \cos\varphi(J_p^y)_{pq} 
+ \cos\theta \cos\varphi(J_m^x)_{pq} + \cos\theta \sin\varphi(J_m^y)_{pq}\right]$$

(2)

where $\theta, \varphi$ are the spherical angles in the global coordinate systems, $\text{sinc}(\cdot) \triangleq (\sin(\cdot))/\theta(\cdot)$, and the phase term $\beta_{pq}(r)$ is given by

$$\beta_{pq}(r) = x_p \sin\theta \cos\varphi + y_q \sin\theta \sin\varphi$$

$$+ \frac{\cos^2\theta (x_p^2 + y_q^2)}{2r}$$

$$- \frac{(x_p \sin\theta \sin\varphi - y_q \sin\theta \cos\varphi)^2}{2r}$$

$$\sinh(\eta \Delta r)$$

(3)

($J_{pq}^\alpha$ ($\alpha \in \{e, m\}$, $l = x, y$) being the discretized electric ($\alpha = e$) or magnetic ($\alpha = m$) surface current coefficients induced on $\Theta_{pq}$ by the incident field $E_{inc}$ [20], which are the functions of $d$ [the dependency is not made explicit in (2) for the sake of notation compactness].

It is worth remarking that (2) is accurate and reliable for predicting the received power in $r = r_{RX}$ (1) as long as the Fresnel condition holds true [20]

$$r \geq r_{FR}$$

(4)

where $r_{FR} \triangleq \max\{10 \times L/\sqrt{2}; 0.62 \times \sqrt{(2 \times L^3/\lambda^3)/10\lambda}\}$ being $r \triangleq |r|$. As detailed in Appendix B, this implies that (2) and the associated derivations can be reliably used only if the screen side is small enough [i.e., not beyond the Fresnel side length (16)]. The reflected field $E_{RCS}$ is known once the $\alpha$-th ($\alpha \in \{e, m\}$) surface current, $J_{\alpha}(r) = \sum_{l=x, y} \sum_{p=0}^{P-1} \sum_{q=0}^{Q-1} (J_{pq}^\alpha) \hat{\Pi}_{pq}(r)\hat{\eta}$, induced on the screen surface (i.e., $r \in \Theta$) is available. Toward this end, the generalized sheet transition condition (GSTC) method can be applied (refer to [20] for additional details).

### A. PCS Case

By considering specular reflections [i.e., $\psi_{tx} = 180$ [deg], $\psi_{rx} = 0$ [deg], $\theta_{tx} = \theta_{rx} = \theta_0$—Fig. 1(a)] from the screen, the design of an ideal [i.e., composed by a PEC] PCS consists in the definition of the panel side $L$ (i.e., $S = 1, d_0 = L$).

1) Finite-Size PCS Model: Since the contribution to the reflection by each $(p, q)$th ($p = 0, \ldots, P - 1; q = 0, \ldots, Q - 1$) cell of an ideal PCS can be seen as a canonical scattering problem from a PEC plate with area $\Theta_{pq}$, standard approaches such as those based on the induction equivalent or the physical equivalent approximations [14] can be reliably applied. Using this latter, the surface currents on the screen aperture (i.e., $r \in \Theta$) can be computed for PCSs as [14]

$$J_{\alpha}(r) = 2 \sum_{p=0}^{P-1} \sum_{q=0}^{Q-1} \hat{\eta} \times \hat{H}_{pq}^\alpha \hat{\Pi}_{pq}(r)$$

$$J_{\alpha}(r) \approx 0$$

$$\hat{\Pi}_{pq}(r) \triangleq \begin{cases} 
1, & r \in \Theta_{pq} \\
0, & r \notin \Theta_{pq}
\end{cases}$$

(5)

and sequentially substituted first in (2) and then in (1) to determine the amount of power reflected by the PCS at the receiver, $P_{RCS}(r_{RX}; d) \triangleq \frac{P_{PCS}(r_{RX}; L)}{P_{TX}}$, as well as the corresponding TPA

$$A_{PCS}(r_{RX}; L) \triangleq \frac{P_{PCS}(r_{RX}; L)}{P_{TX}}$$

(7)

this latter being defined in general as follows:

$$A_{PCS}(r_{RX}; L) \triangleq \frac{P_{RCS}(r_{RX}; d)}{P_{TX}}$$

(8)

where $P_{TX}$ is the transmitted power.

2) Asymptotic PCS Model: When $L \rightarrow \infty$, the problem at hand can be studied neglecting (2) and rather using the theory of images [14] as the interaction between a source and a flat infinite PEC.

By introducing the virtual source symmetrically to the original transmitting antenna as shown in Fig. 1(a) and recalling that there is no direct link between the transmitter and the

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1Several effective methodologies have been recently proposed for the analysis of wave-manipulating surfaces [27], [28], [29]. The approach in [20] is adopted in the following since: 1) it enables to consider nonisotropic elementary units and it directly accounts for their mutual coupling, unlike [27]; 2) it does not only enable the computation of asymptotic path loss formulas, unlike [28]; and 3) it can be straightforwardly adopted in the far-field and in the radiative near-field, unlike [29]. Moreover, it has been demonstrated to provide an excellent matching with full-wave simulated results [20].
receiver, the power reflected at the receiver location, \( r = r_{RX} \), is given by the canonical Friis’ transmission equation provided that the two antennas are mutually in far-field [14]. Accordingly, the asymptotic value of the TPA for a PCS of infinite extension (\( L \to \infty \)), \( A^{PCS}_{\infty}(r_{RX}) \), \( A^{PCS}_{\infty}(r_{RX}) \triangleq \lim_{L \to \infty} \left( \frac{\mathcal{P}^{PCS}_{RX}(r_{RX}; L)}{\mathcal{P}_{TX}} \right) \), can be derived

\[
A^{PCS}_{\infty}(r_{RX}) = \left[ \frac{\lambda}{4\pi(r_{RX} + r_{TX})} \right]^2 G_{RX} G_{TX}.
\]

(9)

It is worth remarking that (9) models the asymptotic behavior of the PCS (i.e., \( A^{PCS}(r_{RX}; L) \to A^{PCS}_{\infty}(r_{RX}), L \to \infty \)), but it is not an upper bound for the TPA of a PCS valid regardless of the PCS side \( L \). Indeed, TPA values greater than \( A^{PCS}_{\infty}(r_{RX}) \) can be reached by finite aperture PCSs as numerically proved in Section III.

B. EMS Screen Case

1) Finite-Size EMS Screen Model: The synthesis of an EMS screen to maximize the power reflected toward the receiver (1) requires the setup of the \( B \) geometrical descriptors, \( \{p^b; b = 0, \ldots, B - 1\} \), of each \((p, q)\) th \((p = 0, \ldots, P - 1; q = 0, \ldots, Q - 1)\) meta-atom [Fig. 1(d)] within the screen aperture \( \Theta \), hence in the overall the synthesis of the \( S \)-dimensional \((S \triangleq 1 + B \times P \times Q)\) descriptor vector \( \mathbf{d} \) whose entries are defined as follows:

\[
\begin{align*}
    d_s &= L, \quad s = 0 \\
    d_{1+b+(p+q)\times B} &= g_{pq}, \quad b = 0, \ldots, B - 1; \\
    p &= 0, \ldots, P - 1; \quad q = 0, \ldots, Q - 1.
\end{align*}
\]

(10)

The values of these descriptors (10) are chosen with the method detailed in [20] so that the resulting surface currents approximate a set of “ideal currents” (i.e., those that maximize the power reflected at the receiver position) [20]. It is worth remarking that despite its formulation in a static framework (Fig. 1), the synthesis methodology can be directly adopted in dynamic wireless communications scenarios [30], [31] provided that the meta-atom descriptors encode the reconfiguration status of the cell (e.g., the diode/varactor setting) rather than its geometrical properties [31].

Once \( \mathbf{d}^{EMS} \) has been determined and under the hypothesis that there is a perfect phase matching between the surface current supported by the EMS screen and the ideal one, the amount of power reflected by the EMS screen at the receiver, \( \mathcal{P}^{EMS}_{RX}(r_{RX}; \mathbf{d}) \), \( \mathcal{P}^{EMS}_{RX}(r_{RX}; \mathbf{d}) \triangleq \mathcal{P}^{EMS}_{RX}(r_{RX}; \mathbf{d}^{EMS}) \), is equal to

\[
\mathcal{P}^{EMS}_{RX}(r_{RX}; \mathbf{d}) \approx G_{RX} A^{\Delta \sin^2 \left( \frac{\pi \Delta \sin \theta \cos \varphi}{\lambda} \right)} \sin(\frac{\pi \Delta \sin \theta \sin \varphi}{\lambda})
\]

\[
\times \sum_{p=1}^{P} \sum_{q=1}^{Q} \left[ \eta \cos \theta \cos \varphi \left( J_m^{pq} \right) + \eta \cos \theta \sin \varphi \left( J_m^{pq} \right) \right]
\]

\[
- \sin \varphi \left( J_m^{pq} \right) + \cos \varphi \left( J_m^{pq} \right)^2
\]

\[
+ \eta \sin \varphi \left( J_m^{pq} \right) + \eta \cos \varphi \left( J_m^{pq} \right)
\]

(11)

and the corresponding path attenuation, \( A^{EMS}_{RX}(r_{RX}; \mathbf{d}^{EMS}) \), is given by

\[
A^{EMS}_{RX}(r_{RX}; \mathbf{d}^{EMS}) = \frac{\mathcal{P}^{EMS}_{RX}(r_{RX}; \mathbf{d}^{EMS})}{\mathcal{P}_{TX}}
\]

(12)

according to (8). The approximation adopted to obtain (11) refers to the assumption that the phases of all the components of the surface currents can be perfectly controlled in each meta-atom according to the phase conjugation condition [20]. It is worthwhile to point out that both the value of \( \mathcal{P}^{EMS}_{RX}(r_{RX}; \mathbf{d}) \) and, consequently, the corresponding path attenuation, \( A^{EMS}_{RX}(r_{RX}; \mathbf{d}^{EMS}) \), depend on the meta-atom structure since this latter affects the surface currents on the EMS screen, which are involved in (11).

2) EMS Screen Performance Upper Bound: While (12) gives the actual achievable link performance by taking into account the full-wave modeling of the finite-size EMS screen at hand, it is of interest to know in advance (i.e., before the actual synthesis phase) the performance bound achievable by an optimal/ideal EMS able to collect and reflect to the receiver all the incident power. Such an information, which is not available in the state-of-the-art concerning EMS engineering, is of fundamental importance for the designer in order: 1) to evaluate the expected margin of improvement enabled by an EMS without the need to perform a full design and 2) to define the correct layout size while avoiding excessive optimization processes.

By considering the working principle of EMSs, such an upper bound can be deduced by noting that: 1) the incident power on the EMS, \( \mathcal{P}_{INC} \), is proportional to both the gain and the aperture of the transmitting antenna by also fulfilling the condition \( \mathcal{P}_{INC} \leq (G_{TX} P_{TX})/(4\pi r_{TX}^2 \cos(\theta_{TX}) L^2) \); 2) the EMS screen behaves as a transmitting antenna with input power \( \mathcal{P}_{INC} \) and gain \( (4\pi \cos(\theta_{TX}) L^2)/\lambda^2 \) [14] in ideal conditions since it redirects all the incident power along the receiver direction; and 3) the propagation toward the receiver can be faithfully modeled with the Friis’ transmission equation [14]. Therefore, it is possible to infer, as detailed in Appendix A, that the upper bound for the TPA of an ideal EMS square screen of size \( L \) (i.e., \( A^{EMS}_{opt}(r_{RX}; L) \triangleq \max_{\{d^{EMS}; s = 1, \ldots, S\}} \left\{ A^{EMS}(r_{RX}; \{L, \{d^{EMS}; s = 1, \ldots, S\}\}) \right\} \)) is

\[
A^{EMS}_{opt}(r_{RX}; L) = G_{TX} G_{RX} \frac{\cos^2(\theta_L) L^4}{(4\pi \mathcal{P}_{TX} r_{RX}^2)^2}.
\]

(13)
The value of \( A^{EMS}_{opt}(r_{RX}; L) \) only depends on the screen size \( L \), but not on the EMS unit-cell shape and/or material. However, one should consider that (13) provides an ideal upper bound without taking into account edge effects, local periodicity approximations, material losses, imperfect local phase control, and illumination tapering/spillover effects. Nevertheless, it can be a very useful tool for roughly sizing an EMS screen starting from the user needs in terms of QoS at the user located at \( r = r_{RX} \). It is also worth mentioning that edge-diffraction contributions, which could be accounted for by...

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generalizing the previous formulation [32], have typically a marginal effect on the TPA when very large EMSs are at hand, as numerically shown in [20]. On the other hand, the presence of a mounting structure such as a supporting wall [29] may provide a further TPA improvement owing to the specular nature of the addressed fixed wireless links.

3) EMS Screen Optimality Condition: Under the assumption that $r_{TX} > 10\lambda$, by combining (9) and (13) as detailed in Appendix B, it is possible to yield the following condition (denoted as “optimality condition”) on the side $L$ of an EMS so that $A_{opt}^{EMS}(r_{RX}; L) \geq A_{opt}^{PCS}(r_{RX})$

$$L_{TH} \leq L \leq L_{FR}.$$  \hspace{1cm} (14)

In (14), $L_{TH}$ and $L_{FR}$ are the threshold and the Fresnel side lengths, respectively, equal to

$$L_{TH} \triangleq \frac{\lambda}{\cos(\theta_0)} \left( \frac{r_{TX} \times r_{RX}}{r_{TX} + r_{RX}} \right)$$  \hspace{1cm} (15)

and

$$L_{FR} \triangleq \min \left\{ \frac{r_{RX}}{10\sqrt{2}}, \frac{\lambda}{2\sqrt{2}} \left( \frac{r_{RX}}{0.62} \right)^2 \right\}.$$  \hspace{1cm} (16)

III. NUMERICAL RESULTS

The objective of this Section is manifold. On one hand, it is aimed at comparing the specular reflection efficiency of PCSs and EMSs in terms of TPA under the same operative conditions using the derived expressions (7) and (12) as well as to check the reliability and the accuracy of the EMS screen optimality condition (14) to overcome the end-to-end free-space TPA. On the other hand, it is devoted to assess the actual optimality condition (14) to overcome the end-to-end free-space TPA. Toward this end, the benchmark scenario models $L_{an}$ $NLOS$ link performance of different classes of screen panels, space TPA. On the other hand, it is aimed at comparing the specular reflection efficiency of different classes of screen panels, space TPA.

In (14), $L_{TH}$ and $L_{FR}$ are the threshold and the Fresnel side lengths, respectively, equal to

$$L_{TH} \triangleq \frac{\lambda}{\cos(\theta_0)} \left( \frac{r_{TX} \times r_{RX}}{r_{TX} + r_{RX}} \right)$$  \hspace{1cm} (15)

and

$$L_{FR} \triangleq \min \left\{ \frac{r_{RX}}{10\sqrt{2}}, \frac{\lambda}{2\sqrt{2}} \left( \frac{r_{RX}}{0.62} \right)^2 \right\}.$$  \hspace{1cm} (16)

The first numerical experiment compares the performance of an $L = 0.8$ [m]-sided square PCS with that from an equal-size EMS screen when illuminated by a $G_{TX} = 15.4$ [dBi] horn antenna (Table I), which is located $r_{TX} = 15$ [m] far from $\Theta$ along the direction $\theta_{TX} = \theta_0 = 30$ [deg]. The transmitter has been supposed to operate at $f = 27$ [GHz] and to radiate a power of $P_{TX} = 20$ [dBm] for generating the incident $y$-polarized electric field with magnitude and phase distributions shown in Fig. 3(a) and (c), respectively. The aperture of the patterned panel has been discretized in a half-wavelength uniform lattice (i.e., $\Delta = 5.556 \times 10^{-3}$ [m]) and the design of the EMS screen has been carried out by considering a $B = 1$ meta-atom composed by a canonical square-shaped patch [Fig. 1(d)] of side $g_{b}^b = \{b \} = g_s(1) \rightarrow d_1 + q \times r \times O \times B = d_2 + q \times r \times O \times B = s_{q1}^b (p = \alpha, \ldots, P - 1; q = 0, \ldots, Q - 1)$, while $d_0 = L$ printed on a single-layer Rogers RO4350 substrate with thickness $\tau = 5.08 \times 10^{-4}$ [m]. Moreover, the receiver has been located along the specular direction $\theta_{RX} = \theta_0$ [deg] and $r_{RX} = 15$ [m] far from the panel to comply with (14).\footnote{The $L = 0.8$ m-side EMS may be implemented in a single standard RO4350 panel commercially available by Rogers [34].}

Suboptimal performance would be obtained if neglecting the receiver distance in the design phase and performing a traditional “far-field” EMS synthesis, as discussed in [20].

![Fig. 2. Problem formulation. Sketch of the reference pyramidal horn antenna.](image)

![Fig. 3. Numerical validation ($f = 27$ [GHz], $P_{TX} = 20$ [dBm], $G_{TX} = 15.4$ [dBi], and $\theta_{TX} = 30$ [deg])—Plots of the distribution of (a) and (b) magnitude and (c) and (d) phase of $E_r^{\mu}$ within the screen aperture $\Theta$ when the transmitter in located (a) and (c) $r_{TX} = 15$ [m] and (b) and (d) $r_{TX} = 50$ [m] far from the reflective panel.](image)

| Table I | Numerical Validation—HORN ANTENNA DESCRIPTORS |
|---------|-----------------------------------------------|
| Low Gain | High Gain |
| $f$ (GHz) | 27 |
| $a$ (m) | $8.636 \times 10^{-3}$ |
| $b$ (m) | $4.315 \times 10^{-3}$ |
| $p$ (m) | $1.3839 \times 10^{-2}$ |
| $r_{TX}$ (m) | $2.3663 \times 10^{-2}$ |
| $\rho_e$ (m) | $2.4441 \times 10^{-2}$ |
| $\rho_h$ (m) | $2.8563 \times 10^{-2}$ |
| $\beta_1$ (m) | $2.1722 \times 10^{-2}$ |
| $G^r$ (dBi) | 15.4 |
| $Q^r$ (dBi) | 25.5 |

![Sketch of the reference pyramidal horn antenna.](image)
Fig. 4. Numerical validation \(f = 27 \text{ GHz}, \; P_{TX} = 20 \text{ [dBm]}, \; G_{TX} = G_{RX} = 15.4 \text{ [dB]}, \; \theta_{TX} = \theta_{RX} = 15 \text{ [m]}, \; \theta_{0} = 30 \text{ [deg]}, \; \text{and} \; L = 0.8 \text{ [m]}\)—EMS layout.

The layout of the EMS screen features a concentric pattern (Fig. 4) as actually expected since a “lensing” effect [Fig. 1(b)], which cannot be realized with a standard PCS [Fig. 1(c)], has to be afforded to focus the power at the receiver. Such patterning bears resemblance with that of devices such as annular strip gratings, radial line slot arrays, or Fresnel zone plates, which are well-known for their focusing capabilities [33], hence further motivating the “lensing” feature of the synthesized EMSs [Fig. 1(b)]. This behavior is pictorially highlighted by the plots of the magnitude of the dominant component of the reflected field (i.e., \(\|E_\varphi^m(r)\|\)) in the “transversal cut” [Fig. 5(c) versus (d)], which is the \(z' = 0\) plane in the receiver local coordinate system \((x', y', z')\) [Fig. 1(b)]. Thanks to a proper control of the surface currents induced on the panel [Fig. 5(a) versus (b)], the EMS screen focuses the power toward the receiver region better than a standard PCS of the same size [Fig. 5(c) versus (d)], which generates a suboptimal power distribution at the receiver position\(^5\) owing to diffraction. This is also pointed out by the comparison of the corresponding distributions of the field magnitude in the “longitudinal cut” [i.e., \(\|E_\varphi^m(r)\|\)] in the “transversal cut” [Fig. 5(e) versus (f)], which is the \(z' = 0\) plane in the receiver coordinate system—Fig. 1(b)], which once again shows that a “specular” reflection (as afforded by the PCS) is not adequate to enable the best power focusing, in general [e.g., Fig. 5(e) versus (f)]. Moreover, Fig. 5(d)–(f) enables to show the type of beam generated by the engineered surface, which, unlike other types of focusing approaches (e.g., Bessel beams), exhibits diffraction patterns before and after the receiver region [e.g., Fig. 5(f)].

As for the TPA, Fig. 6 shows that such an \(L = 0.8\) [m]-sided EMS panel is significantly more effective than the PCS with the same size, since \(\Delta A_{PCS}^{EMS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.8[m]} \approx 15\) [dB], being

\[
\Delta A_{PCS}^{EMS}(r_{RX}; L) = A_{EMS}(r_{RX}; L) - A_{PCS}(r_{RX}; L). \tag{17}
\]

Moreover, it reaches a TPA value considerably better than that from an infinitely extended PCS (i.e., \(A_{EMS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.8[m]} \approx -48.5\) [dB] versus \(A_{PCS}(r_{RX})^{r_{RX}=15[m]}_{L=0.8[m]} \approx -59.8\) [dB] \(\Rightarrow \Delta A_{PCS}^{EMS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.8[m]} \approx 11.3\) [dB]). This latter result is not surprising since the EMS screen optimality condition (14) holds true, the values of the panel side, \(L\), the side-length threshold, \(L_{TH}\), and the Fresnel side length, \(L_{FR}\) being \(L = 0.8\), \(L_{TH} = 3.10 \times 10^{-1}\), and \(L_{FR} = 1.06\) [m], respectively. Furthermore, it is worth noting that the synthesized EMS screen affords a TPA which is only \(5\) [dB] below the theoretical upper bound for such an aperture size (i.e., \(A_{opt}^{EMS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.8[m]} \approx -43.4\) [dB]) despite the simple (i.e., single-layer and standard cheap off-the-shelf materials) meta-atom at hand [Fig. 1(d)].

The same scenario of the first experiment has been dealt with next by varying the panel side \(L\) to account for different screen sizes, but always fulfilling Fresnel limit \(L \leq L_{FR}\). Fig. 6 shows the plots of the TPA in the range 0.1 [m] \(\leq L \leq 1.0\) [m]. As it can be observed, the PCS and the EMS screen behave similarly, analogously to the “ideal” patterned panel, until \(L < L_{TH}\) by yielding close TPA values, which are also below the free-space asymptotic limit \(A_{PCS}(r_{RX})^{r_{RX}=15[m]}_{L=0.8[m]} \approx -59.8\) [dB]. The fact that \(A_{EMS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.8[m]} \approx A_{PCS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.8[m]} \approx A_{opt}^{EMS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.8[m]} \approx 15\) [dB] when \(L < L_{TH}\) suggests that (13) can be used to predict the TPA of small panels (i.e., \(L < L_{TX}\)) regardless of the design technology (e.g., patterned or metallic) and implementation. On the other hand, it turns out that an EMS screen of side \(L\) slightly above the marker \(L_{TH}^{EMS}\), defined as follows:

\[
L_{TH}^{EMS} \triangleq \arg \{A_{EMS}(r_{RX}; L) = A_{PCS}(r_{RX})\} \tag{18}
\]

which is here very close to \(L_{TH}\) (i.e., \(L_{TH}^{EMS} = 3.39 \times 10^{-1}\) [m] versus \(L_{TH} = 3.10 \times 10^{-1}\) [m], performs better than an infinite PEC screen (i.e., \(A_{EMS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.8[m]} > A_{PCS}(r_{RX})^{r_{RX}=15[m]}_{L=0.8[m]}\)) despite the simplicity of the chosen meta-atom. This result confirms that it is possible to overcome the limit dictated by the theory of images in point-to-point fixed wireless links by recurring to the wave manipulation properties of EMSs. Moreover, it shows that despite the simplicity of (13) and (14), which is a consequence of the exploitation of Friis’ transmission equation (see the Appendices), their results can be used as an accurate and reliable guideline for the design and preliminary performance evaluation of EMS-enabled wireless links. Moreover, the TPA improvement enabled by the patterned screen over the asymptotic PCS limit is greater and widening more and more the panel dimension \(\Theta\) [e.g., \(\Delta A_{PCS}^{EMS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.4[m]} \approx 1.76\) [dB] versus \(\Delta A_{PCS}^{EMS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.8[m]} \approx 15.19\) [dB] as well as solid red versus dashed green lines in Fig. 6] until the Fresnel threshold (\(L = L_{FR}\)). On the other hand, the use of an EMS screen, instead of a PCS of the same finite size, is also more and more convenient as \(L\) grows [e.g., \(\Delta A_{PCS}^{EMS}(r_{RX}; L)^{r_{RX}=15[m]}_{L=0.4[m]} \approx 0.0\) [dB] versus

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\(^5\)On the contrary, the PCS and EMS reflected beam would be more similar if considering smaller \(L\) values not complying with (14) [20].
Fig. 5. Numerical validation ($f = 27$ [GHz], $P_{TX} = 20$ [dBm], $G_{TX} = G_{RX} = 15.4$ [dBi], $r_{TX} = r_{RX} = 15$ [m], $\theta_0 = 30$ [deg], and $L = 0.8$ [m])—Maps of (a) and (b) phase of the electric surface current, $\Delta L^+$, induced on the panel aperture, $\Theta$, and (c)–(f) magnitude of the dominant component of the field reflected (i.e., $|E_{xx}|$) in (c) and (d) “transversal cut” and (e) and (f) “longitudinal cut” [Fig. 1(b)] by (a), (c), and (e) PCS and (b), (d), and (f) EMS screen in Fig. 4.

Fig. 6. Numerical validation ($f = 27$ [GHz], $G_{TX} = G_{RX} = 15.4$ [dBi], $r_{TX} = r_{RX} = 15$ [m], and $\theta_0 = 30$ [deg])—Plots of the TPA versus the side $L$ of the reflective panel.

$\Delta A_{PCS}^{EM}(r_{RX}; L)|_{r_{TX}=15[m]} \approx 14.91$ [dB] as well as red versus blue solid lines in Fig. 6) provided that $L > L_{PCS}^{EMS}$ ($L_{PCS}^{EMS} = 0.5$ [m]), $L_{PCS}^{EMS}$ being the threshold side for which the equality $A_{PCS}^{EMS}(r_{RX}; L) = A_{PCS}^{EMS}(r_{RX}; L)$ is fulfilled, that is,

$$L_{PCS}^{EMS} \triangleq \arg \left( A_{PCS}^{EMS}(r_{RX}; L) = A_{PCS}^{EMS}(r_{RX}; L) \right).$$

Of course, it is generally possible to reduce the value of $L_{PCS}^{EMS}$ (i.e., $L_{PCS}^{EMS} \rightarrow L_{TH}$) by implementing more sophisticated and performing meta-atoms.

The third experiment is then aimed at evaluating the EMS screen performance when the wireless link is established over longer distances. More specifically, the transmitter and the receiver have been placed $r_{TX} = r_{RX} = 50$ [m] from the panel so that the magnitude and the phase of the incident field over $\theta$ are those in Fig. 3(b) and (d), respectively. As expected, the plots of the TPA versus the screen side $L$ [Fig. 7(a)] confirm the outcomes from the previous benchmark with shorter distances (e.g., $A_{PCS}^{EMS}(r_{RX}; L)|_{r_{TX}=50[m]} \approx A_{PCS}^{EMS}(r_{RX}; L)|_{r_{TX}=50[m]}$ when $L < L_{TH}$, while $A_{PCS}^{EMS}(r_{RX}; L)|_{r_{TX}=50[m]} \geq 0$ [dB] and $A_{PCS}^{EMS}(r_{RX}; L)|_{r_{TX}=50[m]} \geq 0$ [dB] as long as $L > L_{TH}$ and $L > L_{PCS}^{EMS}$, respectively), but widening both the theoretical thresholds (Table I). This means that the greater the receiver distance, $r_{RX}$, the wider must be the patterned panel to yield improved performance with respect to the equivalent aperture PCS and to overcome the free-space path attenuation limit.

To check the independence of previous outcomes on the transmitter type, the numerical analysis has been repeated with higher gain transmitting/receiving devices [i.e., $G_{TX} = G_{RX} = 25.5$ [dB]—Table I]. As expected, except for a scaling factor due to the different gains, the behavior of the TPA versus $L$ turns out to be almost identical to that of the lower gain horn in both $r_{TX} = r_{RX} = 15$ [m] [Figs. 6 versus 8(a)] and $r_{TX} = r_{RX} = 50$ [m] [Figs. 7(a) versus 8(b)] cases. Moreover, the values of the TPA markers are very close (Table II), as well, the thresholds being identical by definition (15) (16).

On the contrary, the patterns of the synthesized layouts when illuminated by the two different horns are significantly different [i.e., Figs. 7(c) versus 9(b)] since the design of an EMS layout depends on the incident field. Nevertheless, the fact that EMS layouts designed for different scenarios and working conditions yield satisfactory lensing effects and fulfill challenging targets in terms of TPA values (i.e., QoS at the receiver) is also an important and further proof of the reliability and the robustness of the synthesis process in Section II-B.

The next experiment has been performed to assess whether there is still an improvement in the TPA using EMS panels instead of PCSs and with respect to the free-space limit if moving the receiver farther and farther away from the screen.
Toward this purpose, the receiver distance has been varied from \( r_{RX} = 20 \) [m] up to \( r_{RX} = 300 \) [m] by keeping the same antenna type for the transmitter (i.e., \( G_{TX} = G_{RX} = 25.5 \) [dBi]), \( r_{TX} = r_{RX} = r_0 \), and \( \theta_0 = 30 \) [deg])—plots of (a) TPA versus the side \( L \) of the reflective panel and (b) and (c) layouts of the synthesized \( L \)-sided square EMS screens: (b) \( L = 0.5 \) [m] and (c) \( L = 2.9 \) [m].

The benefit of installing an EMS for a user located in a fixed position \( r_{RX} = r_0 \) increases as the size of the panel widens (Table III).

It is also interesting to note that the same target TPA of a standard metallic panel can be reached by an EMS screen of the same side \( L \) (i.e., equal aperture \( \theta \)) over longer end-to-end distances (i.e., \( A_{PC S}^{EMP}(r_{RX}; L) \approx A_{PC S}(r_{RX}; L) \approx 55[m] \) )—Fig. 10). This suggests that wireless links considerably longer than those achievable with traditional flat metallic reflectors can be established using EMS screens without increasing the transmitter/receiver gains, the input power, or the panel size.

To analyze the dependence of the performance of EMS-based screens on the angle of the specular reflection, two other \( \theta_0 \neq 30 \) [deg] angular directions have been considered, namely, \( \theta_0 = 20 \) [deg] and \( \theta_0 = 45 \) [deg], while the other scenario parameters have been kept unaltered from the benefit of installing an EMS for a user located in a fixed position \( r_{RX} = r_0 \) increases as the size of the panel widens (Table III).

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those of Fig. 8(a). Once again, it turns out [Fig. 11(a)] that it is advantageous (i.e., \( \Delta A_{\text{PCS}}^{\text{EMS}}(r_{\text{RX}}; L) \mid_{\rho=50[m]} \geq 0 \) adopting a suitably designed EMS screen if the panel aperture \( \Theta \) fulfills the condition \( L \geq L_{TH}^{\text{EMS}} \), being \( L_{TH}^{\text{EMS}} \approx L_{TH} \), whatever the \( \theta_0 \) value. However, the TPA value afforded by the EMS screen gets worse and worse as \( \theta_0 \) increases toward endfire (\( \rightarrow \theta_0 \to 90 \text{ [deg]} \)). For instance, \( A_{\text{EMS}}^{\text{opt}}(r_{\text{RX}}; L) \mid_{\theta_0=90[\text{deg}]} > A_{\text{EMS}}^{\text{opt}}(r_{\text{RX}}; L) \mid_{\theta_0=0[\text{deg}]} > A_{\text{EMS}}(r_{\text{RX}}; L) \mid_{\theta_0=0[\text{deg}]} > A_{\text{EMS}}(r_{\text{RX}}; L) \mid_{\theta_0=90[\text{deg}]} \) regardless of the aperture side, \( L \). Analogously, the performance enhancement granted by the EMS reduces when tilting more and more the incidence/reflection angle as shown in the representative plots in Fig. 11(c) for an EMS screen of side \( L = 1 \text{ [m]} \) \( (L \geq L_{TH}^{\text{EMS}}) \). Such behaviors are actually the result of two concurring effects. On one hand, the amount of power impinging on the panel aperture, \( P_{\text{INC opt}} \), grows as \( \theta_0 \to 0 \text{ [deg]} \) since the effective area intercepting the incident beams is maximum when the source is at broadside (i.e., \( \theta_0 = 0 \text{ [deg]} \)). On the other hand, there is an unavoidable degradation of the effectiveness of the unit cell as \( \theta_0 \to 90 \text{ [deg]} \) as it is well-known from EM surface engineering [35]. In fact, wider incidence angles require more abrupt phase variations within the \( \Theta \) aperture, which are more difficult to be realized when using simple unit cells with inherently reduced phase-control capabilities [35].

Vice versa, there is a closer and closer fitting between the ideal TPA, \( A_{\text{OPT}}^{\text{EMS}}(r_{\text{RX}}; L) \), and the actual one, \( A_{\text{EMS}}(r_{\text{RX}}; L) \), Fig. 11(a), as well as smaller and smaller deviations of \( L_{TH}^{\text{EMS}} \) from \( L_{TH} \) Fig. 11(b) as \( \theta_0 \) approaches broadside. For instance, Fig. 11(a) shows that \( \Delta A_{\text{EMS}}^{\text{opt}}(r_{\text{RX}}; L) \mid_{\theta_0=0[\text{deg}]} \approx 2.3 \text{ [dB]} \) versus \( \Delta A_{\text{EMS}}^{\text{opt}}(r_{\text{RX}}; L) \mid_{\theta_0=45[\text{deg}]} \approx 9.7 \text{ [dB]} \) being \( \Delta A_{\text{EMS}}^{\text{opt}}(r_{\text{RX}}; L) \triangleq A_{\text{EMS}}(r_{\text{RX}}; L) - A_{\text{OPT}}^{\text{EMS}}(r_{\text{RX}}; L) \). This means that simpler meta-atoms can yield a power focusing efficiency close to the ideal one as the incidence on the screen tends to the normal to the surface.

The last test case is aimed at assessing the feasibility and the benefit of NLOS specular links with EMS screens when increasing the end-to-end distance \( \rho (\rho \triangleq r_{\text{TX}} + r_{\text{RX}}) \). Therefore, the behavior of the TPA versus the screen side \( L \) has been analyzed when \( \rho = 400 \text{ [m]} \) and \( \rho = 2000 \text{ [m]} \) by setting \( r_{\text{TX}} = r_{\text{RX}} = (\rho/2) \). As expected, Fig. 12(a) and (b) shows that wider panels are necessary to overcome the asymptotic free-space limit as the link length \( \rho \) grows [e.g., \( L_{TH} \mid_{\rho=400[m]} = 1.132 \text{ [m]} \) versus \( L_{TH} \mid_{\rho=2000[m]} = 2.532 \text{ [m]} \)].—Plot of the TPA versus the receiver distance from the screen, \( r_{\text{RX}} \).

**Fig. 9.** Numerical validation \( (f = 27 \text{ [GHz]} \), \( G_{TX} = G_{RX} = 25.5 \text{ [dB]} \), \( r_{\text{RX}} = r_{\text{TX}} \), and \( \theta_0 = 30 \text{ [deg]} \))—Plots of (a) and (b) layouts of the EMS screens when \( (a) L = 1.0 \text{ [m]} \) and \( r_0 = 15 \text{ [m]} \) and \( (b) L = 2.9 \text{ [m]} \) and \( r_0 = 50 \text{ [m]} \).

**Fig. 10.** Numerical validation \( (f = 27 \text{ [GHz]} \), \( G_{TX} = G_{RX} = 25.5 \text{ [dB]} \), \( r_{\text{RX}} = 15 \text{ [m]} \), and \( \theta_0 = 30 \text{ [deg]} \))—Plot of the TPA versus the receiver distance from the screen, \( r_{\text{RX}} \).

| \( r_{\text{RX}} \mid_{\text{opt}} \) [m] \( 0.8 \) | \( 1.0 \) | \( 1.2 \) | \( \Delta A_{\text{EMS}}^{\text{PC}} \mid_{\text{opt}} \text{ [dB]} \) |
|---|---|---|---|
| 55 | 8.52 | 11.57 | 15.30 |
| 150 | 7.31 | 10.51 | 13.16 |
| 300 | 6.91 | 7.73 | 12.78 |
| 55 | 6.48 | 14.52 | 15.09 |
| 150 | 4.11 | 12.75 | 15.75 |
| 300 | 3.48 | 11.47 | 15.81 |

**Table III**

**Numerical Validation—Values of the Margins of TPA Improvement**
Fig. 11. Numerical validation ($f = 27$ [GHz], $G_{TX} = G_{RX} = 25.5$ [dBi], and $r_{TX} = r_{RX} = 15$ [m])—Plot of (a) TPA versus the side $L$ of the reflective panel along with (b) and (c) behavior of the side-length thresholds/markers and (c) margins of TPA improvement of the synthesized $L \in \{0.5, 6\}$ [m]-sized EMSs versus $\theta_0$.

Fig. 12. Numerical validation ($f = 27$ [GHz], $G_{TX} = G_{RX} = 25.5$ [dBi], $r_{TX} = r_{RX} = \rho/2$, and $\theta_0 = 30$ [deg])—Plot of (a) TPA versus the side $L$ of the reflective panel along with (b) and (c) behavior of the side-length thresholds/markers and (c) margins of TPA improvement of the synthesized $L \in [0.5, 6]$ [m]-sized EMSs versus the end-to-end distance $\rho$.

is on the square root of the end-to-end distance $\rho$ [i.e., $L_{TH} \propto \sqrt{\rho}$] and not directly on $\rho$, as pointed out by the corresponding line plot in Fig. 12(b) being $L_{TH} \approx 0.056 \times \sqrt{\rho}$. Moreover, Figs. 12(b) and 11(b) show that the value of the marker $L_{EM}^{TH}$ is generally very close to the threshold $L_{TH}$ with very similar dependence on both the end-to-end distance, $\rho$, and the specular reflection angle, $\theta_0$. This is a not trivial outcome since it implies that the use of the closed-form expression of the threshold $L_{TH}$ (15) is a reliable rule-of-thumb to quickly (i.e., without any synthesis process and/or full-wave numerical simulations) predict, for a given wireless link and incidence angle, the smallest panel size of an EMS screen that overcomes the free-space attenuation.

For completeness, Fig. 12(c) gives some insights on the efficiency of an EMS reflective panel of side $L = 6$ [m] ($L \geq L_{TH}^{EM}$) and $L = 0.5$ [m] ($L \ll L_{TH}^{EM}$) versus the link length $\rho$ to compare setups in which a TPA improvement is anticipated (i.e., $L = 6$ [m]) versus the case in which no such improvement is expected (i.e., $L = 0.5$ [m]).

As for the computation time of the proposed approach, the TPA evaluation for each design in Fig. 12(a) turns out very efficient (i.e., $\Delta t \leq 1$ [min]), as expected from [20], despite the large apertures at hand and the use of a nonoptimized MATLAB implementation of the method executed on a single-core CPU running at 1.6 [GHz].

IV. CONCLUSION

The feasibility of flat passive EMS screens to overcome the asymptotic TPA limit of flat PEC reflectors in NLOS specular conditions has been investigated. An extensive numerical
assessment has been performed to: 1) check the reliability and the accuracy of the theoretical deductions; 2) illustrate the EM features of EMSs for NLOS specular wireless links; c) give some insights on the potentialities of such a technological solution for NLOS point-to-point propagation; and 4) deduce user-oriented guidelines.

To the best of the authors’ knowledge, the main innovative methodological outcomes of this work include the below.

1) The use of flat static EMSs as reflective panels in point-to-point NLOS wireless links to yield a “lensing” effect toward the receiver [Fig. 1(b)] instead of the simple reflection of the incident beam [Fig. 1(c)] as done by PCSs.

2) The (numerically validated) proof that beyond well-known anomalous reflection applications [16], [17], flat patterned passive panels can be profitably used to improve the performance of traditional metallic screens in end-to-end NLOS wireless communications and the free-space limit derived by the theory of images, hence enabling the adoption of this technology in high-efficiency backhaul point-to-point links.

3) The analytic derivation of a simple closed-form upper bound (13) for the achievable TPA in an EMS-powered point-to-point reflective wireless links, which is valid also when dealing with dynamic scenarios [30], [31], not available in the state-of-the-art concerning wave propagation in SEME.

4) The definition of the optimality condition on the EMS screen aperture $\Theta$ of side $L$ (14) so that the corresponding TPA value is better than the asymptotic one from a PCS even of infinite extension ($L \to \infty$).

It is worth remarking that the conciseness and simplicity of the derived guidelines [e.g., (13), (14)] are a further benefit of the presented paradigm in view of its adoption of a practical strategy for backhaul wireless link design.

From the numerical validation and performance assessment, the following user guidelines can be drawn.

1) Subject to the EMS screen optimality condition (14), an $L$-side EMS screen outperforms a PCS with the same size in terms of TPA and it also overcomes the asymptotic end-to-end free-space TPA limit.

2) The advantage of using an EMS screen with respect to a PCS with the same aperture $\Theta$ becomes greater and greater when widening the panel side $L$.

3) Wider EMS panels are necessary to overcome the asymptotic free-space limit as the end-to-end distance of NLOS links $\rho$ grows, but the side $L$ of the squared EMS aperture increases proportionally to the square root of $\rho$.

Moreover, the following “tools” for the design of an EMS screen have been derived.

1) A minority (majority) relationship between the threshold length, $L_{TH}$, and the Fresnel one, $L_{FR}$ [i.e., $L_{FR} > L_{TH}$ ($L_{FR} < L_{TH}$)], is a condition of existence (nonexistence) of an $L$-size EMS screen better than a PCS of infinite extension ($L \to \infty$) for an NLOS wireless link at the frequency $f$ between a transmitter and a receiver located at a distance $r_{TX}$ and $r_{RX}$ from the reflective panel.

2) The closed-form expression (13) can be used to roughly size an EMS screen given the end-to-end NLOS wireless scenario (i.e., $G_{RX}$, $r_{RX}$, $G_{TX}$, $r_{TX}$, and $\theta_0$) or, vice versa, to derive the end-to-end NLOS wireless scenario given the $L$-sided EMS screen, starting from the user needs in terms of QoS (i.e., a TPA target).

3) The expression (15) is a reliable rule-of-thumb to quickly (i.e., without any synthesis process and/or full-wave numerical simulations) predict, for a given wireless link and incidence angle, the smallest panel size $L$ of an EMS screen that overcomes the free-space end-to-end attenuation limit.

4) The difference between (13) and (9) gives a rough estimate of the maximum margin of improvement of an EMS screen with respect to a PCS.

Future works, beyond the scope of the current article, will be aimed at extending the formulation and the theoretical study to reconfigurable EMSs for managing dynamic scenarios and to shaped-beam reflecting EMSs for advanced holographic purposes. Moreover, the synthesis of more complex and efficient EMS meta-atoms is on the agenda to reach the TPA upper bound of an ideal EMS screen.

**APPENDIX**

A. Proof of (13)

With reference to the scenario in Fig. 1(b), the maximum incident power on an $L$-side square EMS screen is equal to

$$P_{INC}^{\text{opt}} = \frac{G_{TX} P_{TX} \cos(\theta_{TX}) L^2}{4\pi r_{TX}^2} \tag{20}$$

when the transmitter is in far-field and it has a uniform gain within the solid angle between the same transmitter and the EMS surface $\Theta$ [14].

In ideal conditions, the EMS operates as an aperture antenna with gain

$$G_{EMS}^{\text{opt}} = \frac{4\pi \cos(\theta_{RX}) L^2}{\lambda^2} \tag{21}$$

and input power $P_{INC}^{\text{opt}}$, since all the incident power is sent along to the receiver direction.

Accordingly, the Friis’ transmission equation reads as [14]

$$P_{RX}^{\text{EMS, opt}} = P_{INC}^{\text{opt}} \times G_{EMS}^{\text{opt}} \times G_{RX} \times \frac{\lambda^2}{4\pi r_{RX}^2} \tag{22}$$

where $G_{RX}$ is the gain of the antenna at the receiver location $r = r_{RX}$.

By simple substitution of (20) and (21) into (22), it turns out that

$$P_{RX}^{\text{EMS, opt}} = P_{TX} \frac{G_{RX} G_{TX}}{4\pi r_{TX}^2} \cos(\theta_{TX}) \cos(\theta_{RX}) L^4 \tag{23}$$

and the expression (13) for the upper bound of an ideal EMS square screen of side $L$ is yielded using (23) in (8).
B. Proof of (14)

By combining (9) and (13), one obtains

$$G_{TX} G_{RX} \cos(\theta_{TX}) \cos(\theta_{RX}) L^4 \geq \left( \frac{\lambda}{4\pi (R_{TX} + R_{RX})} \right)^2 G_{RX} G_{TX}$$

that solved with respect to $L$, becomes

$$L^4 \geq \frac{\cos(\theta_{RX}) \cos(\theta_{TX})}{\cos(\theta_{TX})} \left( \frac{R_{TX} \times R_{RX}}{R_{TX} + R_{RX}} \right)^2$$

(25)

The expression (25) can be further simplified into

$$L \geq L_{TH}$$

(26)

by taking into account that $\theta_{RX} = \theta_{TX} = \theta_0$.

Since the above considerations hold true if $R_{RX}$ complies with (4), let us rewrite this latter as a function of $L$

$$L \leq \frac{R_{RX}}{10\sqrt{2}}$$

(27)

$$L \leq \left( \frac{R_{TX} \times R_{RX}}{R_{TX} + R_{RX}} \right)^2 \frac{\lambda}{0.62 \sqrt{2}}$$

still under the hypothesis that $R_{RX} \geq 10\lambda$ to fulfill (4). The optimality condition (14) is then derived by combining (26) and (27).

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Marco Salucci (Senior Member, IEEE) received the M.S. degree in Telecommunication engineering from the University of Genoa, Italy, in 1992, and the Ph.D. degree in telecommunication engineering from the University of Genoa, Italy, in 2001. He is currently an Assistant Professor with the Department of Civil, Environmental, and Mechanical Engineering, (DICAM), University of Trento, Trento, Italy, and a Research Fellow of the ELEDIA Research Center.

Dr. Salucci was a Member of the COST Action TU1208 “Civil Engineering Applications of Ground Penetrating Radar.” He is a member of the IEEE Antennas and Propagation Society. He is an Associate Editor of Communications and Memberships of IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION.

Andrea Massa (Fellow, IEEE) received the Laurea (M.S.) degree in electronic engineering and the Ph.D. degree in EECs from the University of Genoa, Genoa, Italy, in 1992 and 1996, respectively. He is currently a Full Professor of electromagnetic fields with the University of Trento, Trento, Italy, where he teaches electromagnetic fields, inverse scattering techniques, antennas and wireless communications, wireless services and devices, and optimization techniques. He is also the Director of the Network of Federated Laboratories “ELEDIA Research Center” (www.eledia.org), Brunei, China, Czech, France, Greece, Italy, Japan, Peru, and Tunisia, with more than 150 researchers. He is holder of a Chang-Ijiang Chair Professorship withUESTC, Chengdu, China; a Visiting Research Professor with the University of Illinois at Chicago, Chicago, IL, USA; a Visiting Professor with Tsinghua University, Beijing, China; and Tel Aviv University, Tel Aviv-Yafo, Israel; and a Professor with CentraleSupélec, Paris, France. He has been holder of a Senior DIGITEO Chair with L2S-CentraleSupélec and CEA LIST, Saclay, France; UC3M-Santander Chair of Excellence, Universidad Carlos III de Madrid, Madrid, Spain; an Adjunct Professor with Penn State University, Pennsylvania, PA, USA; a Guest Professor with UESTC; and a Visiting Professor with the Missouri University of Science and Technology, Rolla, MO, USA; the Nagasaki University, Nagasaki, Japan, the University of Paris Sud, Orsay, France, the Kumamoto University, Kumamoto, Japan, and the National University of Singapore, Singapore. He has published more than 900 scientific publications among which more than 350 on international journals (>15,000 citations H-index = 65 [Scopus]; >12,000 citations H-index = 59 [ISI-Web}; >23,000 citations H-index = 89 [Google Scholar]) and more than 50 in international conferences where he presented more than 200 invited contributions (>40 invited keynote speaker) (www.eledia.org/publications). He has organized more than 100 scientific sessions in international conferences and has participated to several technological projects in the national and international framework with both national agencies and companies (18 international projects, >5 M€; 8 national project, >5 M€; 12 local project, >2 M€; 63 industrial project, >10 M€; 6 university project, >300 K€). His research activities are mainly concerned with inverse problems, analysis/synthesis of antenna systems and large arrays, radar systems synthesis and signal processing, cross-layer optimization and planning of wireless/RF systems, semantic wireless technologies, system-by-design and material-by-design (meta-materials and reconfigurable-materials), and theory/applications of optimization techniques to engineering problems (tele-communications, medicine, and biology).

Prof. Massa has been appointed IEEE AP-S Distinguished Lecturer (2016–2018). He is an IET Fellow and an Electromagnetic Academy Fellow. He served as an Associate Editor for IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION (2011–2014) and International Journal of Microwave and Wireless Technologies. He is a Permanent Member of “PIERS Technical Committee” and the “EuMW Technical Committee,” and an ESoA Member. He is a Member of the Editorial Board of Journal of Electromagnetic Waves and Applications. He has been appointed in the Scientific Board of the “Società Italiana di Elettromagnetismo (SIEm)” and elected in the Scientific Board of the Interuniversity National Center for Telecommunications (CNIT). He has been appointed in 2011 by the National Agency for the Evaluation of the University System and National Research (ANVUR) as a Member of the Recognized Expert Evaluation Group (Area 09, “Industrial and Information Engineering”) for the evaluation of the researches at the Italian University and Research Center 2004–2010. He has been elected as the Italian Member of the Management Committee of the COST Action TU1208 “Civil Engineering Applications of Ground Penetrating Radar.”

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