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This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:
Catapano, I., Gennarelli, G., Imperatore, P., Barbiroli, M., Soldovieri, F. (2024). Multipath Propagation Influence on Retrievable Information in Indoor Electromagnetic Imaging. New York : IEEE [10.1109/ICEAA61917.2024.10701643].

Availability:
This version is available at: https://hdl.handle.net/11585/1026897 since: 2025-10-29

Published:
DOI: http://doi.org/10.1109/ICEAA61917.2024.10701643

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(Article begins on next page)

08 November 2026

Multipath Propagation Influence on Retrievable Information in Indoor Electromagnetic Imaging

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***Abstract*—Indoor sensing of non-cooperative targets by means of systems mainly designed for wireless communication is a topic attracting huge interest. In this frame, since few years, several studies have addressed the interaction of electromagnetic waves with the surrounding environment to improve the detection and tracking performance. As a contribution to this filed, the present work focuses on a linear microwave imaging approach and conducts a theoretical analysis to investigate how multipath reflections, experienced when the electromagnetic signal propagation occurs in an indoor environment, affect the imaging capabilities. The analysis is carried out in terms of the retrievable spectral content and explores how this quantity is influenced by multipath propagation effects. As a preliminary study, a canonical indoor scenario is considered, and a 2D ray-based scalar model is adopted to model the signal propagation.**

Keywords—Indoor sensing, microwave imaging, inverse scattering, multipath

I. INTRODUCTION

The attempt to satisfy the requirements of the next generation society, where telecommunication systems cover a more and more central role, is driving towards the design of novel communication paradigms, where the surrounding environment is regarded no more as an obstacle but as a cooperative tool to be exploited for improving the signal coverage [1], [2]. In addition, a significant interest is devoted towards the design of smart radio environments (SREs) where reconfigurable intelligent surfaces are used to meet the required performances while keeping the necessity of green technologies [1], [3].

Furthermore, the exploitation of telecommunication devices not only to connect people and allow data exchange but also for the not foreseen aim of improving security and safety of citizens appears as an amazing challenge. Accordingly, huge attention is given to the design of innovative dual use technological solutions suitable both for communication and sensing purposes [4]-[6].

Focusing the interest on this last issue, this communication deals with a preliminary study regarding the possibility of detecting a non-cooperative target located in an indoor environment. More in detail, the study investigates how multipath propagation contributions, also included in the signal propagation model, influence the imaging capabilities with respect to the free space propagation.

It should be stressed that the multipath propagation exploitation to enhance imaging performance has been considered in a number of previous works [7]-[11]. However, these works address specific radar configurations, which are characterized by a relatively large measurement aperture and operate over a wide frequency range.

This study addresses the more challenging case of a limited number of microwave sources operating at a single frequency, among those exploited for wireless communication devices. The analysis is carried out in a 2D geometry and by adopting a ray-based model to describe the signal propagation [12]. The imaging is faced as an inverse scattering problem, whose formulation is simplified by exploiting the Born Approximation [13], with the aim of detecting and localizing the target. The linear inverse scattering problem at hand is discretized by using the Method of Moment (MoM) and solved by adopting the Truncated Singular Valued Decomposition (TSVD) of the scattering matrix as a regularization scheme [14]. The performance of the imaging approach is analyzed by resorting to the spatial spectral content, which is a general tool to evaluate the reconstruction capabilities of a linear inverse scattering algorithm [9], [10], [15]. Although the spectral content is a general tool, its computation depends on the scattering matrix relating the measured electric field to the electromagnetic features of the target. Hence, the reference scenario at hand must be defined to compute the spectral content. In the following, a simple indoor scenario consisting in an empty room is considered.

II. SIGNAL PROPAGATION MODEL

A. Incident field computation

Let us consider the 2D geometry depicted in Fig.1, which sketches an empty room, and let Ω be the domain under investigation, i.e. the region where the target can be located. The electromagnetic sensing system is an array of evenly spaced transmitting and receiving antennas modelled as filamentary line sources polarized along z (TM polarization), working at the angular frequency ω and located close to one of the walls. The array is represented by red circles in Fig. 1. The incident filed E_{inc} radiated at the generic point $\mathrm{r} = (x, y) \in \Omega$ when the antenna is located at $\mathrm{r_s}$ is computed by

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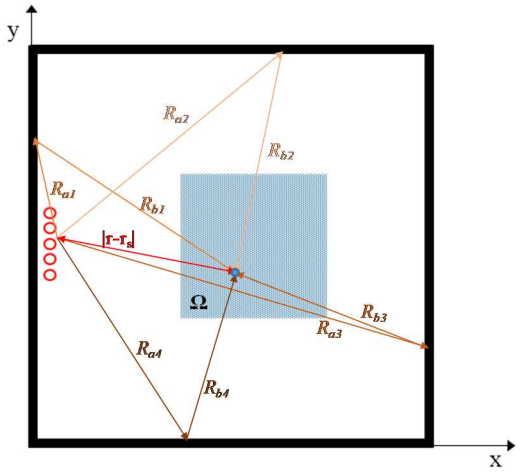

Fig. 1 Reference scenario

considering and omitting the time factor $exp\{j\omega t\}$. Under the ray based model here considered and able to account for only the first order reflections, the expression of E_{inc} is obtained by means of simple geometrical optics concepts [12]:

$$E_{inc}(\mathrm{r},\mathrm{r_s},\omega) = E_0 \frac{e^{-jk|\mathrm{r}-\mathrm{r_s}|}}{\sqrt{|\mathrm{r}-\mathrm{r_s},|}} + \sum_{p=1}^{4} E_0 \Gamma_w(\theta_p) \frac{e^{-jk(R_{ap}+R_{bp})}}{\sqrt{R_{ap}+R_{bp}}} \quad (1)$$

where k denotes the free space propagation constant, $\Gamma_w(\theta_p)$ is the wall reflection coefficient, θ_p is the local incidence angle at the wall p (p = 1,…,4), R_{ap} and R_{bp} are the distances from $\mathrm{r_s}$ and r to the wall p, respectively. The first term on the right-hand side of eq. (1) represents the line of sight (LoS) contribution, while the summation accounts for the first order multipath terms due to the four room walls.

B. Forward scattering problem

Under the Born Approximation, the field scattered by a target arbitrary located in Ω is expressed by the integral relationship [13]:

$$E_s(\mathrm{r_s},\omega) = \int_\Omega G(\mathrm{r_s},\mathrm{r},\omega) E_{inc}(\mathrm{r},\mathrm{r_s},\omega)\chi(\mathrm{r})d\mathrm{r} \quad (2)$$

where G is the Green's function, i.e. the field radiated at $\mathrm{r_s}$ by an elementary source located in r, whose expression for the Lorentz reciprocity [12],[13] is the same of that of E_{inc} in eq. (1). Moreover, $\chi(\mathrm{r})$ is the electric contrast function accounting for the target, which is modeled as an equivalent dielectric permittivity anomaly with respect to the free space. The integral operator defined by eq. (2) is referred to as scattering operator, whose kernel is the product between G and E_{inc}. Let us note that the scattering operator defined only by the LoS contribution in eq. (1) corresponds to the free space scattering operator.

III. Microwave Imaging Approach

A. Inverse problem solution

The imaging is faced as the solution of the linear inverse scattering problem described by eq. (2), where E_s denotes the data and χ the unknown. Specifically, the problem is discretized according to the MoM and by using a pixel base representation for χ. Therefore, in each pixel $(x_q, y_q) \in \Omega$, with $q = 1, \dots Q$ ($Q$is the number of pixels discretizing Ω), a regularized solution is given in a closed form by means of the TSVD of **L**, which is the matrix representing the discrete version of the scattering operator (see eq. (2)):

$$\hat{\chi}(x_q, y_q) = \sum_{n=1}^{T} \frac{\langle \mathrm{E_s}, \mathrm{u}_n \rangle}{\sigma_n} \mathrm{v}_n(x_q, y_q) \quad (3)$$

In eq. (3), the tern $\{\mathrm{u}_n, \sigma_n, \mathrm{v}_n\}$ defines the SVD of **L,** $\langle\cdot,\cdot\rangle$ denotes the scalar product and T is the truncation index [14].

B. Spatial spectral content

A general tool to investigate the reconstruction capabilities of the TSVD based approach described in the previous section is given by the spectral content [15]. If k_x and k_y denote the spatial spectral variables, the spectral content is defined as:

$$sp(k_x, k_y) = \sum_{n=1}^{T} |\tilde{\mathrm{v}}_n(k_x, k_y)| \quad (4)$$

where $|\tilde{\mathrm{v}}_n(k_x, k_y)|$ is the modulus of the Fourier transform of the singular vectors $\mathrm{v}_n(x_q, y_q)$:

$$|\tilde{\mathrm{v}}_n(k_x, k_y)| = \left|\sum_{i=1}^{Q} \mathrm{v}_n(x_q, y_q) exp[-i(k_x x_q + k_y y_q)]\right| \quad (5)$$

As stated in eq. (4), only the singular vectors referred to the singular values before the truncation index T are considered.

Since the set of vectors $\{\mathrm{v}_n\}$ form an orthogonal basis for the space wherein the discrete contrast χ is defined, $sp(k_x, k_y)$ defines the set of the spatial frequencies retrievable by means of the regularized inversion of **L** [15].

The effect of the multipath on the imaging performance is investigated by computing the spectral content corresponding to different expressions of the matrix **L**, computed as a discrete counterpart of the scattering operator defined for different propagation conditions. Specifically, the kernel of the scattering operator is at first computed by accounting only for the LoS term in E_{inc} expression and, thus, in that of the Green's function. Thereafter, the terms of the summation at the right hand side of eq. (2) are progressively added and considered in the computation of the product between G and E_{inc}.

IV. Performance Analysis

Regarding the 2D reference scenario depicted in Fig.1, let us assume a square shaped room with size $10\ m \times 10\ m$. The investigated domain Ω is $4\ m \times 4\ m$, located in front of the sensing system and centered with respect to both the sensing system and the room, as illustrated in Fig.1 The investigated domain is discretized into square pixels whose side is $0.02\ m$ long. The sensing system consists of an array of 11 antennas, which are evenly spaced of $0.05\ m$ each other and operate at 2.5 GHz, with a resulting probing wavelength of $0.12\ m$. The antennas are $0.20\ m$ far to the left room wall. The walls have relative dielectric permittivity $\varepsilon_w = 4$, electric conductivity $\sigma_w = 0.005\ S/m$, and thickness $0.25\ m$.

To understand the effect introduced by the presence of the walls, the spectral content corresponding to the free-space is initially considered (case a). Then, the contributions due to single reflections on the room walls are progressively added, by considering firstly the wall behind the antenna array (case b), then the walls behind and in front (case c), the lateral walls (case d) and, finally, all the four walls (case e).

In Fig. 2, the left panels show the scenario considered for the computation of the scattering operator, i.e. of the matrix **L**; while the right panels show the corresponding spatial spectral contents. These last depict the retrievable spatial frequencies

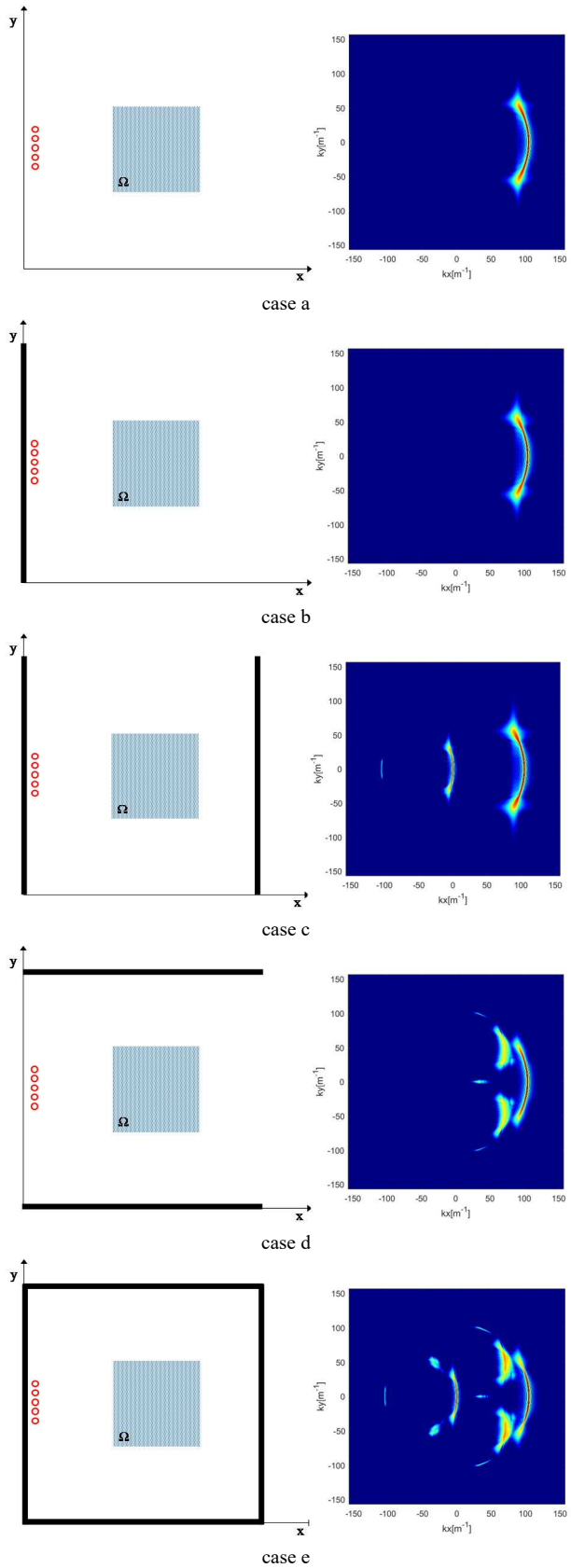

Fig. 2 Spectral contents for different scenarios: considered scenario (left panel); spectral content (right panel)

and thus the filtering effect introduced by the regularized inversion of **L**. Due to the reduced number of transmitting and receiving single frequency antennas, all the available singular values are considered in eq. (3) and thus in eq. (4). Moreover, the spectral contents in Fig. 2 right panels are given in dB scale considering the range [-30, 0] dB.

Figure 2 shows that a low pass filtering occurs along the *y* axis and a band bass one along the *x* axis in the cases a and b, i.e. when the signal propagation occurs in free space (panel a) and when a single reflection is taken into account on the wall behind the antenna array (panel b). Conversely, the filtering effects complicate when single reflections are also introduced due to the other walls. In details, a three-bands pass filtering occurs in case c (addition of a wall in front of the array – panel c). The filtering effect is even more complex when the two lateral walls are considered (panel d) and all the first order multipath contributions (all the four room walls – panel e) are taken into account.

These results suggest that the multipath contributions increase the amount of the retrievable spatial frequencies.

CONCLUSIONS

A preliminary theoretical study regarding the effect of electromagnetic multipath contributions on indoor imaging capabilities has been carried out. The achieved results suggest a non-trivial impact on the ability to properly detect and localize the target. Indeed, while a larger amount of spatial frequency is retrievable, it does not cover with continuity the spectral domain. Future activities will regard the computation of the point spread function as an additional tool for gathering detailed information on the imaging performance. This will also entail considering more complex environments, wherein floor and ceil are also taken into account resulting in a full 3D propagation environment, as well as the presence of an inner wall perturbing the LoS and the occurrence of higher-order multipath contributions beyond the first order.

ACKNOWLEDGMENT

This work has been supported by the European Union under the Italian National Recovery and Resilience Plan (NRRP) of Next Generation EU, partnership on "Telecommunications of the Future (PE0000001 – program "RESTART").

REFERENCES

[1] I. F. Akyildiz, A. Kak and S. Nie, "6G and Beyond: The Future of Wireless Communications Systems," in IEEE Access, vol. 8, pp. 133995-134030, 2020.

[2] C. D. Alwis et al., "Survey on 6G Frontiers: Trends, Applications, Requirements, Technologies and Future Research," in IEEE Open Journal of the Communications Society, vol. 2, pp. 836-886, 2021.

[3] E. C. Strinati et al., "Reconfigurable, Intelligent, and Sustainable Wireless Environments for 6G Smart Connectivity," in IEEE Communications Magazine, vol. 59, no. 10, pp. 99-105, October 2021,

[4] Y. Cui, H. Ding, L. Zhao and J. An, "Integrated Sensing and Communication: A Network Level Perspective," in IEEE Wireless Communications, vol. 31, no. 1, pp. 103-109, February 2024.

[5] C. De Lima et al., "Convergent Communication, Sensing and Localization in 6G Systems: An Overview of Technologies, Opportunities and Challenges," in IEEE Access, vol. 9, pp. 26902-26925, 2021

[6] F. Liu et al., "Integrated Sensing and Communications: Toward Dual-Functional Wireless Networks for 6G and Beyond," in IEEE Journal on Selected Areas in Communications, vol. 40, no. 6, pp. 1728-1767, June 2022.

[7] R. J. Burkholder, "Electromagnetic models for exploiting multi-path propagation in through-wall radar imaging," 2009 International Conference on Electromagnetics in Advanced Applications, Turin, Italy, 2009, pp. 572-575.

[8] P. Setlur, M. Amin, F. Ahmad, “Multipath model and exploitation in through-the-wall and urban radar sensing,” IEEE Trans. Geosci. Rem. Sens, vol 49, no 10, pp. 4021-4034, 2011.

[9] G. Gennarelli, and F. Soldovieri, “A linear inverse scattering algorithm for radar imaging in multipath environments,” IEEE Geosc. Rem. Sens. Letters, vol. 10, no. 5, pp. 1085-1089, 2013.

[10] G. Gennarelli and F. Soldovieri, “Radar imaging through cinderblock walls: achievable performance by a model-corrected linear inverse scattering approach,” IEEE Trans. Geosci. Rem. Sens., vol. 52, no. 10, pp. 6738–6749, 2014.

[11] P. Setlur, T. Negishi, N. Devroye, and D. Erricolo, “Multipath exploitation in non-los urban synthetic aperture radar,” *IEEE*

[12] C. Balanis, Advanced Engineering Electromagnetics, Wiley & Sons, 1989.

[13] W. C. Chew, Waves and fields in inhomogeneous media, IEEE Press, 1995.

[14] M, Bertero, P. Boccacci, Introduction to inverse problems in imaging. Institute of Physics, Bristol Philadelphia, UK, 1998.

[15] R. Persico, R. Bernini, and F. Soldovieri, “The role of measurement configuration in inverse scattering from buried objects under the Born approximation,” IEEE Trans. Antennas Propag., vol. 53, no. 6, pp. 1875– 1887, Jun. 2005.