Passive Multi-Array Image Fusion for RF Tomography by Opportunistic Sources

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Abstract—The large diffusion of wireless infrastructures in public and private areas is currently stimulating research on surveillance radar systems capable to exploit network transmissions as potential sources of opportunity. Since these sources are generally narrow band, we propose in this letter a single-frequency approach for imaging targets by using passive arrays deployed around the scattering scene. Single-frequency data allow casting the imaging as an inverse source problem, which avoids the need to retrieve information about the sources prior to imaging. The drawbacks of the highly coarse resolution and blinding effects due to the sources are overcome by employing a multi-array image fusion strategy in conjunction with a change detection scheme for imaging moving targets. The proposed approach is tested via numerical experiments based on full-wave synthetic data corresponding to an indoor scenario.

Index Terms—inverse source, multistatic radar, opportunistic sources, urban sensing.

I. INTRODUCTION

The use of passive multistatic radars systems [1] for surveillance have recently attracted considerable attention owing to their low cost, covertness, anti-jam, and effective exploitation of opportunistic sources in both heavy and scarce population areas. In urban environments, these sources constitute direct illuminators to the target and can be local to the target surroundings, such as Wi-Max and Wi-Fi, or non-specific, serving large communities such as FM radio, DAB, cell phone base stations, and satellite borne illumination.

The signals originated from a single or multiple sources are scattered from targets and successively collected by single or multiple receivers operating in a multi-static modality. Unlike active radars, passive radars mostly exploit narrow frequency bands as dictated by the radiation modalities of the opportunistic sources. Another important challenge is the low signal to clutter ratio underlying these applications.

Based on different properties of the reference and received (surveillance) signals, such as the Time of Arrival (TOA), the Direction of Arrival (DOA), and the Received Signal Strength Indicator (RSSI), passive radars can prove effective in target localization [2-4]. In particular, the potential of uncooperatively and covertly detecting people in motion behind walls using passive bistatic Wi-Fi radar at standoff distances was shown in [2]. Another practical feasibility study on the Wi-Fi transmissions based passive bistatic radar was presented in [3] for local area surveillance of vehicles and personnel. A localization method for a system, using TOA information of the signals received from multiple illuminators, has been recently developed in [4], where approximated maximum-likelihood optimization has been applied based on semi-definite relaxation plus bisection methods.

The aforementioned methods exploit non-cooperative sources, but assume a-priori knowledge of the source positions and attempt to acquire the signals emitted by the sources through a dedicated channel. This stage helps in properly setting the focusing strategy and in mitigating the masking effects due to the strong (with respect to the signals scattered by the targets) “direct” signal.

In this letter, we present an alternative imaging approach tailored for moving targets, when the narrowband non-cooperative sources are stationary, and the data are collected by a passive array of receivers placed around the scene of interest. We consider the limit case of narrowband sources, namely, single frequency sources. In this framework, the imaging problem can be thought as the reconstruction of the secondary sources (currents induced on the targets under the incidence of the field radiated by the non-cooperative sources) and can be cast as an inverse source problem. In so doing, the only necessary information about the non-cooperative source is the operating frequency. However, blinding effects due to the primary sources and a dramatic loss of range resolution still remain crucial issues to be tackled. To solve these problems, a multi-array change detection strategy is here proposed. In particular, we apply change detection to remove static clutter and eliminate the primary source contribution. The multi-array strategy instead allows to partially compensate for the resolution loss. Note that change detection has been previously considered for tracking moving targets in through wall imaging and urban sensing scenarios by active radar configurations [5, 6].

The letter is organized as follows. In Sec II, the general formulation of the inverse source problem is presented. The
reconstruction performance of the inverse source approach is performed in Sec. III. The imaging approach and reconstruction results are shown in Sec. IV. Conclusions follow in Sec. V.

II. THE INVERSE SOURCE MODEL

In the following, we will refer to the simplified 2D scattering scenario depicted in Fig. 1. A target residing in the investigation \( D \) is illuminated by the incident field radiated by a set of opportunistic sources (gray squares) located around the object at positions \( P_s \). The sources can be placed both inside and outside \( D \). A volumetric or surface current distribution is induced over the target depending on its electromagnetic properties (e.g. dielectric or perfectly conducting). These currents re-irradiate the scattered field, which is collected by a set of passive receivers placed at positions \( P_o \) outside the assumed scattering scene and around the target (black triangles). Both the sources and receivers are modeled as filamentary electric lines polarized along the \( y \)-axis, so that the problem becomes scalar since only the \( y \)-component of the electric field is nonzero.

Besides the field scattered by the targets, the receivers collect the direct signal coming from the source and also possible multipath contributions due to the scattering scene. Here, we assume that all these signals are removed by change detection, and as such, we focus on the scattered field model. Under a linear scattering model, the field scattered by the targets can be written as

\[
E_s\left( P_o, \omega \right) = \int_{D} G\left( P_o, P', \omega \right) O\left( P' \right) \sum_{n} E_{inc}\left( P', P_{sn}, \omega \right) dP'
\]

where \( \omega \) is the angular frequency, \( O\left( P' \right) \) is the target function (related to the target spatial support and material properties) assumed to be frequency independent, the index \( n \) denotes the \( n \)-th source, and \( G\left( P_o, P', \omega \right) \) is the Green’s function pertinent to the scattering scenario. The formulation in eq. (1) is general and can be applied in complex scenarios (e.g. with inhomogeneous background) provided that the relevant Green’s function is available under an analytical or numerical form [7]. The summation inside the integral represents the incident field provided by the non-cooperative sources. It must be noticed that, unlike the receiver positions \( P_o \), the source positions \( P_s \) are usually unknown. The transmitted waveform is also unknown, then in order to achieve imaging through the inversion of the scattering operator in eq. (1), the kernel part related to the incident field should be estimated. Since opportunistic sources in urban areas typically transmit narrow-band signals (e.g. Wi-Fi, Bluetooth, etc.), we choose to consider data at a single frequency. By doing so, eq. (1) can be rewritten as [8]

\[
E_s\left( P_o \right) = \int_{D} G\left( P_o, P' \right) J\left( P' \right) dP'
\]

in which the frequency has been dropped out from notation. In eq. (2), \( J\left( P' \right) = O\left( P' \right) \sum_{n} E_{inc}\left( P', P_{sn}, \omega \right) \) is the induced electric current density supported over the targets’ regions. It is realized that the incident field enters only as a complex amplitude of such a current. This was not the case in eq. (1), where the induced current and the scattered field data were both dependent on the frequency. In essence, the incident field should be known/estimated in advance in order to set up an imaging scheme that exploits the spatial and frequency diversity.

Eq. (2) can be rewritten in a more compact operator notation as

\[
E_s = AJ
\]

where \( A: U \rightarrow V \) is a linear operator acting between the unknown and data spaces \( U \) and \( V \), assumed Hilbert space of square integrable functions. The imaging is cast as the inverse source problem of eq. (3), and a standard and straightforward way to invert eq. (3) is provided by

\[
RJ = A^\dagger E_s
\]

with \( A^\dagger \) being the adjoint of \( A \). Inversion through eq. (4) is basically a migration scheme. It is known that migration allows obtaining stable reconstructions with respect to noise effects, but it suffers from an intrinsic limitation on the achievable resolution [9, 10]. Conversely, inverse filtering could allow better resolution. However, for the case at hand, the operator in eq. (3) is not injective because of the so-called non-radiating sources [11] (this is true even if data were collected continuously around the target). Therefore, an intrinsic limitation on the achievable resolution exists even by adopting an inverse filtering method. Moreover, the singular values of \( A \) exhibit an almost flat behavior before experiencing an abrupt exponential decay. As a result, migration leads to results similar to inverse filtering methods, while being much more efficient from the computational viewpoint [9, 10].

Fig. 1. General representation of the inverse source problem pertaining to a 2D scattering scene. A target in the investigation region \( D \) is illuminated by opportunistic RF sources (gray squares). The total field is collected by a set of passive receivers (black triangles).
III. ANALYSIS OF THE INVERSE SOURCE APPROACH

In this Section, we examine the system performance associated with eq. (4). As the aim is to obtain information about the achievable point spread function (PSF) while solving the inverse source problem, we assume that all the contributions (i.e., source field, multipath signals) different from the field scattered by the target have been removed from the data. Accordingly, the PSF is given by

$$PSF = A^\dagger A^T$$

where $J$ is an impulsive current distribution located at the point target.

An indoor scenario is considered, as shown in Fig. 2. All room walls have relative permittivity 4 and electric conductivity 0.005 S/m. The exterior walls are 3.3 m long and have thickness 0.3 m. The two internal walls are 1 m long and have thickness 0.15 m. The scene is illuminated by an opportunistic source (denoted by the blue asterisk) located at (0.3, 0.3) m and operating at frequency 2.45 GHz so as to mimic a Wi-Fi access point. A linear array of passive receivers (array A) is positioned outside the room at a stand-off distance of 0.3 m from the outer surface of the exterior wall. The array is 3 m long with an inter-element spacing of 0.05 m, which is lower than the Nyquist step $\lambda/2$, with $\lambda$ being the propagating wavelength. The investigation domain $D = [0.35, 3.25] \times [0.35, 3.25]$ m$^2$, nearly corresponding to the entire room, is discretized into square pixels having side 0.05 m along both directions.

Note that the use of a linear array of receivers is realistic and accommodates common usage in conventional through wall radar imaging applications [12].

In order to perform the imaging and in particular the resolution analysis, the Green’s function of the scattering scene is required. In principle, the computation of the exact Green’s function is possible [7], but it necessitates the knowledge of the layout (room with internal walls), which in general may not be available and should be estimated. In this work, we use instead the Green’s function pertinent to an infinite slab having the features of the front-wall [13].

An impulsive current distribution (point target) located at (1.5, 1.8) m is considered. The corresponding reconstruction (relative amplitude normalized to the maximum) obtained with array A is depicted in Fig. 3a. As can be seen, the image clearly peaks around the source. However, no resolution is achieved along the $z$-axis, which is an expected consequence of using a single frequency. It is well-known that inverting eq. (3) at single-frequency allows to retrieve only the spatial spectrum of the unknown supported over the Ewald circle [8], i.e., a circle of radius $k$ ($k$ being the wave-number) in the spectral plane $k_x - k_z$, $k_x$ and $k_z$ being the Fourier conjugate variables of $x$ and $z$, respectively. Furthermore, due to the aspect limited view, the retrievable Fourier spectrum is just supported over only a portion of the Ewald circle [8]. Therefore, a low-pass filtered version of the unknown can be retrieved along $x$ and there is no enough spatial band to focus along $z$. In this respect, an array B similar to A facing the left outer wall (see Fig. 2) would enable focusing the image along $z$ in lieu of $x$ (see Fig. 3b). This suggests adopting a multi-array strategy [14] where data gathered by two or more arrays deployed around the room (see Fig. 2) can be suitably exploited to improve the target localization performance.

Here, we adopt a simple multiplicative image fusion approach [15] consisting in the pixel-wise product of the amplitudes of the reconstructions obtained by each single array. The results shown in Fig. 3c confirm that it is possible to achieve a satisfactory localization of the point target.

IV. IMAGING APPROACH AND RESULTS

In this section, we present and validate the overall imaging method. The scattering scenario is still that shown in Fig. 2. For such a scene, synthetic data accounting for the complexity of the layout are generated by means of the full-wave forward solver GPRmax2D [16] based on the finite-difference time-domain (FDTD) method. As we mentioned above, the aim here is to detect and track moving targets.

![Fig. 3](image-url) Fig. 3. Normalized amplitude (dB) of the PSF relevant to a point target located at (1.5, 1.8) m. a) Image obtained with array A. b) Image obtained with array B. c) Multiplicative image fusion.
Nevertheless, we start the numerical analysis by first assessing the performance achievable by the multi-array inverse source method for the case of extended scattering objects. This is because it represents an important component of the imaging approach that will be introduced. To fulfill such a task, we use scattered field data obtained after a background subtraction, i.e. by subtracting from the total field the one computed in absence of targets. We recognize that this operation can be rarely performed in realistic cases, even more for the case at hand where the source is unknown. However, background subtraction allows removing the direct coupling signals between the source and receivers and studying the localization capabilities of the multi-array inverse source method.

The first test bed concerns the imaging of two metallic cylinders (\(T_1\) and \(T_2\) in Fig. 2) centered at (1.0, 2.5) m and (2.4, 2.6) m, and having radii 0.1 m and 0.2 m, respectively. The reconstruction reported in Fig. 4a is based on scattered field data collected by the array A (see Fig. 2). As expected, no focusing is achieved along the \(z\)-axis for both targets. Instead, while using data gathered by the array B (see Fig. 4b), focusing along \(z\) is possible but the two scatterers are no more resolvable. Finally, the multiplicative image fusion of these reconstructions displayed in Fig. 4c confirms the possibility to detect extended targets as it succeeds in detecting both \(T_1\) and \(T_2\). Actually, some residual clutter is present in the image mainly along the \(z\) direction probably due to the effect of the internal walls whose presence is not accounted for in the inverse model.

We now turn to address the more realistic situation where the total field (i.e., the field radiated by the non-cooperative sources, plus the field scattered by the scene and the field scattered by the targets) is collected by the receivers. Moreover, we assume that the targets are moving inside the room. The proposed imaging method combines the multi-array inverse source method with a coherent change detection approach [17]. Specifically, by exploiting the difference of total field data gathered at different times, it is possible to detect and track moving targets and reject the clutter introduced by static targets as well as the direct coupling between the source and receivers.

The imaging procedure is summarized in the block diagram reported in Fig. 5. \(M\) consecutive data frames are collected with array A and B at discrete times denoted by index \(m \in \{1, 2, ..., M\}\). For each \(m\), the difference \(\Delta E\) between the total fields at time \(m+1\) and \(m\) is inverted via eq. (4). At this stage, only the contribution of the moving objects is relevant as all static clutter is rejected. The amplitude of the images obtained at time \(m+1\) by processing the data collected with the array A and B are combined according to a multiplicative image fusion to produce the image \(I(m+1)\). Finally, a further multiplicative fusion stage between \(I(m+1)\) and \(I(m)\) follows to produce the overall image \(I^p(m)\). This latter operation is performed to retain only the common features among two consecutive images and to highlight the position of the scatterer at the \(m\)-th time instant. Indeed, \(I(m+1)\) would show the target’s positions at times \(m+1\) and \(m\) whereas \(I(m)\) at times \(m\) and \(m-1\); therefore the second stage multiplication allows emphasizing only the target’s position at time \(m\).

The change detection approach outlined in Fig. 5 is tested with regard to the scenario of Fig. 2. In particular, \(T_1\) moves from its initial position (1.0, 2.5) m to (1.8, 1.1) m following the trajectory sketched in Fig. 2, while \(T_2\) is stationary at (2.4, 2.6) m. The number of data frames \(M\) collected by the receivers is equal to 12. The tomographic images \(I^p(m)\) obtained with the change detection imaging procedure are illustrated in Fig. 6. Every image corresponds to a specific target position along the trajectory. It can be seen that a good localization of the target position is achieved, as also confirmed by the trajectory (Fig. 7) estimated by evaluating the position of the peak of \(I^p(m)\).

Note that a slow target may be invisible depending on the time interval between two consecutive datasets. A possibility to overcome this issue could be a change detection based on the difference between the current dataset and the one at a reference zero instant; however the effects of clutter are expected to be more significant in this case.
In this letter, we have proposed a strategy for imaging targets by means of a passive multistatic radar system, when non-cooperative sources are exploited as primary illuminators for the targets. Due to the narrowband nature of the opportunistic sources, imaging is formulated as a linear inverse source problem. No a-priori information on the sources is needed except their operating frequency. It has been shown that the limited bandwidth of the system generally yields a very poor resolution of the tomographic reconstructions. Furthermore, the blinding effects due to the primary sources and the lack of the background scene make the imaging of static targets a complicated task. On the other hand, the problem is greatly simplified if one is interested to track moving targets. In this circumstance, a simple coherent change detection approach combined with the multi-array inverse source method has been shown to provide satisfactory results with regard to an indoor scenario. The presented results should be meant as a proof of principle. Future work will be directed towards 3D scenarios in order to examine depolarization effects as well.

Fig. 6. Normalized amplitude (dB) of the reconstructions $I^m$ for different positions of the target $T_i$ by means of the change detection imaging procedure. Color scale [-20, 0] dB.

Fig. 7. Estimated target trajectory (circles). True trajectory (dashed line).

REFERENCES


