Reference-Free Passive RF Imaging Using Near-Field Spatial Processing

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Passive radar imaging has been extensively studied and is based on an illuminator-of-opportunity, such as a wireless access point, providing a signal that scatters from targets and is incident on a receiving node(s) in order to infer information on the range and velocity of the target scene. Such systems universally require reference signal regeneration, from a dedicated channel, that is cross-correlated with the received signal in order to extract the range/Doppler information of the target. This paper presents one of several techniques developed by the authors to achieve passive radar (or RF) imaging without any requirement for extraction of the reference signal. The concept is analogous to optical systems in which various source(s) provide general illumination of a target scene, the scattered signals of which are gathered and processed at an optical sensor in order to reconstruct the image, but without any requirement to extract the illumination (reference) source itself. Such an approach offers numerous practical advantages in achieving imaging from a single passive sensor without the additional requirement of precise, or indeed any, regeneration of the illuminating source: a reference-free approach. This paper presents one such technique based on sampling of the complex signal distribution over an antenna aperture and near-field processing to form a two/three-dimensional reconstruction of the target scene. The fundamental principles of the technique are described along with analysis of basic performance limits. Modelling is presented to illustrate the capability of the technique, which is validated by experimental measurement with a WiFi access point-based prototype system.

Keywords—passive radar, reference-free WiFi sensing, near-field spatial processing

I. Introduction

Passive radar systems exploit illuminators of opportunity [1-4] and since their inception in the 1930s have been primarily used for military and defense applications. However, passive radar has experienced a resurgence of research interest over the last two decades for a range of new civil applications, which have been driven by the rapid development of new digital communications such as GSM cellular networks and digital audio broadcasting (DAB) [5, 6]. The typical architecture [7], depicted in Fig. 1, is a bistatic arrangement comprising a receive channel with a directional antenna pointing at an illuminator-of-opportunity (such as a WiFi access point or a broadcast transmitter) in order to generate a near-perfect copy of the illumination signal and a surveillance channel with an antenna gathering scattered signals from the target scene. Cross-correlation

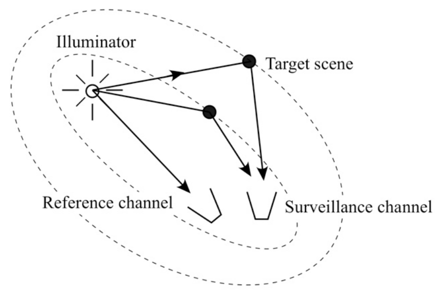

Fig. 1. Arrangement of a typical passive radar using an illuminator-of-opportunity.

processing is then used in order to derive range-Doppler information on the target scene [8], which establishes target range/Doppler characteristics according to the bistatic ellipse, indicated in Fig. 1.

Until now, efforts have focused on enhancing the regeneration of the reference signal by demodulating the received signal, and regenerating a less noisy synthetic version based on the retrieved symbols [2].

The general vision of the work described here is to explore techniques to perform passive radio-frequency (RF) imaging using an illuminator - or illuminators - of opportunity, but without any requirement to isolate or regenerate the reference signal. This may be achieved by sampling the signal distribution over a suitable aperture. The aperture may be a linear or planar array of antennas, uniformly or sparsely distributed, with coherent or non-coherent sampling. The concept is analogous to optical systems in which various source(s) provide general illumination of a target scene, the scattered signals of which are gathered and processed at an optical sensor in order to reconstruct the image, but without any need to extract the illumination (reference) source itself. This offers numerous practical advantages in achieving imaging from a single passive sensor without the additional requirement of precise, or indeed any, regeneration of the illuminating source such as those described in [9-11]. We term these new approaches reference-free techniques. These are based on the premise that the signal distribution over a given aperture may be used to infer the target scene in the vicinity of the aperture, which is the basis of all optical sensing systems. This method offers both cross-range and range resolution, by means of spatial processing, the limits of which are derived in this paper.

Techniques that may achieve location, Doppler and imaging without explicitly extracting a reference signal have appeal in offering passive RF imaging with greater simplicity of operation and reduced complexity. Moreover, ghosting and increased sidelobe levels that arise from contamination of the reference channel with target responses are altogether eliminated. Being an array-based approach, the spatial processing lends itself to imaging in two dimensions with a linear aperture or three dimensions with a planar aperture, rather than the more limited range-Doppler plot that is produced with a typical passive bistatic radar. The illuminators do not need to be modulated and can be numerous, analogous to an optical system in which multiple or diffuse light sources typically illuminate a target scene.

This paper describes a particular passive, reference-free RF imaging technique investigated by the authors, based on near-field matched-filtering (NFMF). Section II describes the basic concept, with analysis of the fundamental resolution and bandwidth limits. Forward modelling is then performed in Section III to illustrate likely outputs of a practical system. Next, Section IV presents results from a prototype 5 GHz WiFi access point based system developed during this work, validating the concept. Finaly, Section V outlines our conclusions.

II. Near Field Spatial Processing

The basic geometry of the reference-free approach considered in this paper is shown in Fig. 2, comprising an illuminator or illuminators that provide general illumination, with a scattered field from the target scene that is gathered by an antenna array. Coherent, near-field matched-filter processing across the array signals yields a value for each pixel corresponding to the coherent summation of the array signals originating from that point. The illuminators should ideally be to the side or rear of the array normal in order to minimise direct signal interference [12], similar to minimising the effect of 'glare' in optical imaging systems, though background suppression or moving target indicator (MTI) techniques may be employed if required.

To achieve the necessary matched filter focusing, a phase correction is applied for each (x, y) pixel in the image, based on the distance of each array element, at w_n, from the pixel using basic geometry:

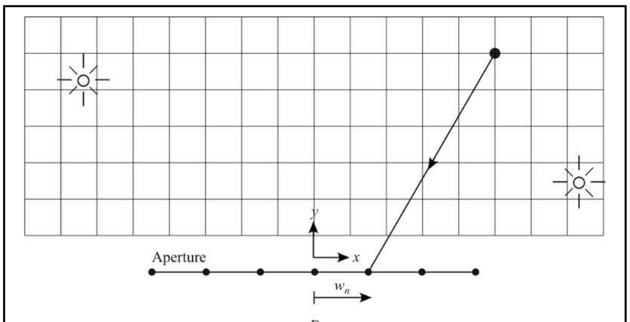

Fig. 2. Setup for near-field matched-filter processing.

$$\text{phase correction} = \frac{2\pi}{\lambda}\sqrt{(x-w_n)^2+y^2} \tag{1}$$

Amplitude correction may also be applied:

$$\text{amplitude correction} = \frac{1}{\sqrt{(x-w_n)^2+y^2}} \tag{2}$$

and suitable windowing, as required, to control sidelobes. This yields an (X x Y x N) matched-filter that is used in a straightforward matrix process to form the image, where the image size is X x Y pixels and there are N array elements. Extension to three-dimensional imaging may be achieved with a planar array. The approach thus produces a spatial map of targets, which arguably offers more practically-useful information than the classic range-Doppler map [13].

The angular resolution, $\Delta\theta$, and the cross-range resolution, Δx, depend on the aperture dimension in the usual way [14, 15]:

$$\Delta\theta = \frac{\lambda}{D\sin\alpha} \tag{3}$$
$$\Delta x = \lambda\frac{Y}{D} \quad \text{at distance } Y \text{ from the centre of the aperture}$$

where α is the angular bearing relative to the normal.

However, this approach is also capable of range resolution by virtue of the spatial processing, without any explicit radar range processing and with a continuous wave (CW) illuminating source. Referring to Fig. 3, the depth of focus of an aperture of width D at vertical distance Y may be deduced by considering the change in phase of signal contributions from a point displaced distance $\Delta R/2$ from the focus in the y-direction. It is apparent that the variation in path length at the mis-focussed point is given by:

$$\Delta L = \frac{\Delta R}{2}(1-\cos\alpha) \tag{4}$$

which for small α approximates to:

$$\Delta L \approx \frac{\Delta R\alpha^2}{4} \approx \Delta R\frac{D^2}{16Y^2} \tag{5}$$

A path length variation, ΔL, of a quarter of a wavelength is a good bound on the region of focus, equating to −3.9 dB signal reduction, with an associated range resolution of:

$$\Delta R = \frac{16Y^2}{D^2}\frac{\lambda}{4} = 4\lambda\left(\frac{Y}{D}\right)^2 \tag{6}$$

where Y is the perpendicular distance from the centre of the aperture. Range resolution thus depends on the square of the distance from the aperture rather than being proportional to this distance in the case of cross-range resolution (Equation (3)). This result suggests that the technique may offer useful range resolution at higher operating frequencies, above 5 GHz or so, which may particularly suit future beyond-5G (B5G) implementations in the mm-wave band

and operation in an indoor environment at relatively short range. The practical limit on for useable range resolution to be obtained is found by equating range to half the range resolution,

$$Y_{\max} = \Delta R/2 = 2\lambda\left(\frac{Y_{\max}}{D}\right)^2 \Rightarrow Y_{\max} = \frac{D^2}{2\lambda} \tag{7}$$

which is a quarter of the classic Rayleigh far-field distance. The approach requires formation of the matched-filter matrix, V_{match}, which has three dimensions (in x, y and across the N array elements, w), which is then used in a simple matrix process with the N complex signals sampled from the array elements, V_{array}, in order to form the image. The image formation process is not computationally-intensive and can be performed quickly in real-time since the matched-filter matrix is calculated just once and then applied successively for each frame of the image. This may be implemented, for instance, in the following simple matrix process (in Matlab notation):

```
Vimage = squeeze(sum(Vmatch.*Varray,2));      (8)
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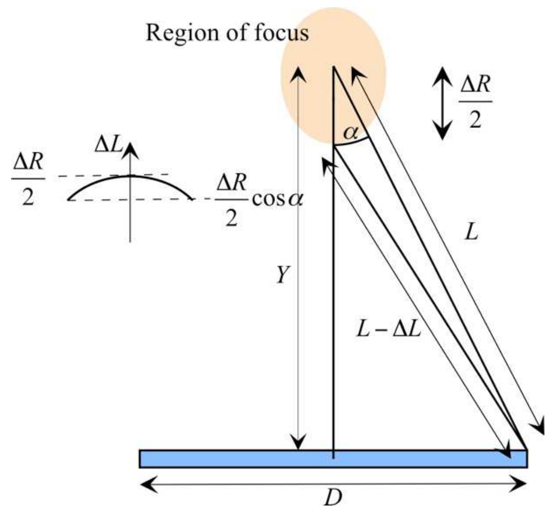

Fig. 3. Construction to determine depth of focus.

III. Forward Modelling

The technique described in Section 2 is demonstrated in a forward model comprising two targets and an illuminating source (a hypothetical WiFi access point) at the following locations:

(-20, 30)λ	0.5 amplitude	Target 1
(20, 40)λ	0.5 amplitude	Target 2
(40, 15)λ	1 amplitude	AP illuminating source

where locations are expressed normalised to the operating wavelength. Fig. 4 shows the result for an aperture 64 wavelengths wide with two sample points (antennas) per wavelength and Hamming windowing. The aperture is depicted as a black rectangle at the bottom of the image. The two targets are evidently located with high precision; from Equations (3) and (6) angular and range resolutions of 0.9º and 1.6 wavelengths at 40 wavelengths range would be expected, and the result is consistent with these values. The direct signal is quite evident though does not impact target detection, discrimination or location. This example uses a wide aperture (equivalent to 32 cm at 60 GHz), which may be suitable for many indoor applications such as TV set top location devices and public spaces such as shopping malls, transport hubs etc.

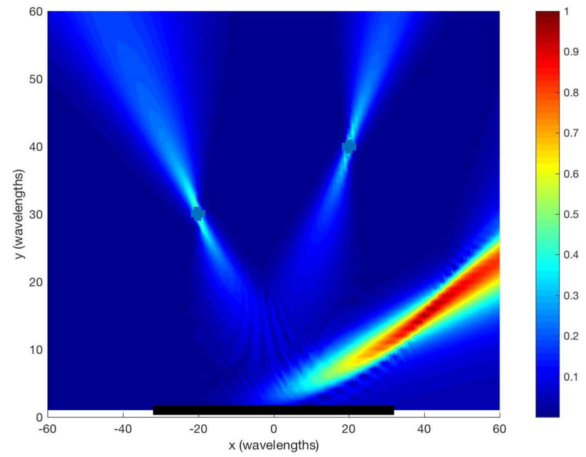

Fig. 4. Forward model of near-field matched-filter imaging, 64-wavelength, 128 antenna aperature, Hamming window.

In the 5-6 GHz band, an aperture size of around 8 wavelengths (41 cm at 5.8 GHz) is more suitable for a TV set-top type application. For the same target and access point illuminator locations, and with no windowing, the result is now as shown in Fig. 5. Clearly the resolution is reduced relative to the much larger 64-wavelength aperture, in particular the range resolution, but it is still possible to detect and locate the two targets in the presence of the DSI from the access point and in the absence of any means of DSI or clutter suppression.

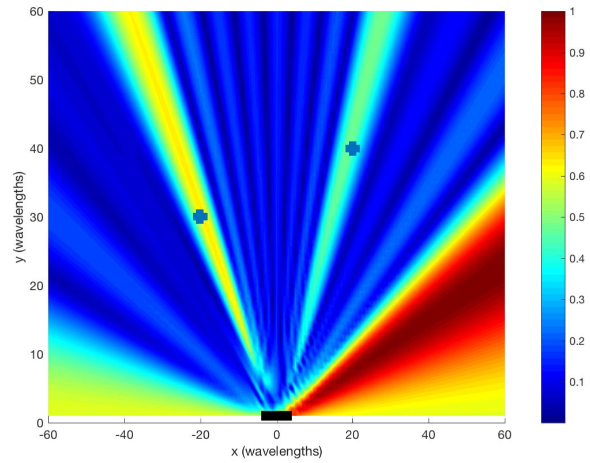

Fig. 5. Forward model of near-field matched-filter imaging, 8-wavelength, 16-antenna aperture, no window.

Direct signal interference from the illuminating source may well be an issue. This could possibly be managed by using directional antennas (maybe cardioid pattern) with the illuminating source to the side of or behind the antenna array, or by carefully orienting a null in the antenna (cardioid) pattern towards the illuminating source. However, MTI type techniques such as background clutter suppression or temporal high-pass filtering are likely to be more effective and appropriate for suppressing clutter and DSI.

Fig. 6 and Fig. 7 illustrates the result of the same target arrangement but now with non-coherent subtraction of the baseline scene comprising the access point alone, in the absence of any targets. The access point DSI is now absent from the image and the targets are clearly enhanced. More advanced MTI techniques such as IIR high-pass filtering may be readily applied to isolate moving features in the target. If windowing is applied then the sidelobe structure is very much suppressed at the cost of a modest reduction in resolution. This, of course, represents ideal conditions but is an indication of what might be possible in a well-designed and calibrated system.

IV. Results Obtained with Prototype System

A small-scale prototype system has been developed to investigate the NFMF technique presented here, as shown in Fig. 8 It comprises a 4-channel receive array of 0.75-wavelength spaced patches, connected to a USRP RIO software-defined radio (Model 2945), illuminated by a 5.6 GHz WiFi access point. The array contains dummy elements at each end to normalise the mutual coupling environment. The array inter-element spacing corresponds to an unaliased field of view of ±42º. Measurements were made inside a furnished room approximately 3 m x 4 m in size, representing a realistic indoor residential environment. The system was initially calibrated, through air, using a CW radiating source, in order to equalise the path lengths in each channel. From Equations (3) and (6) the expected resolution is 19º in azimuth and $4.7Y^2$ in range, where Y is the perpendicular distance from the array. The range resolution in this small-scale system is very poor due to the small array baseline, of two wavelengths, and the low operating frequency. Essentially, this system is able to measure angle-of-arrival and target intensity rather than range.

Fig. 9 shows a snapshot of a simulated and measured video images obtained with this system with a WiFi access point positioned at -70º to the array normal. 100 samples are taken per second with real-time non-coherent MTI processing combining a first order, IIR low-pass filter with 0.2 s time constant to perform averaging and noise filtering and a first order, IIR high-pass filter with 1 s time constant to provide sufficient persistence to track human targets in an indoor environment. The measured results are seen to closely resemble the simulation results, with similar azimuth resolution to the theoretical value of 19º at broadside. Suppression of direct signal interference is excellent with no evidence at all of the WiFi access point and there is ample sensitivity to detect human targets with few signal samples.

These results with a small-scale system are encouraging and validate system operation. Extrapolating to a 16-channel, 0.75-wavelength system, from Equations (3) and (6) a 4-fold increase in azimuth and range resolution is to be expected. Further improvement in resolution is possible using non-uniform array or sparse-sampled array topologies, within the coherence constraints of the target scene and operation at 60 GHz gives the potential for greatly increased resolution. An elevated sample rate and use of additional layers of image processing (for instance to mask the aliased angular range and to implement range-dependent scaling) are expected to result in enhanced images in future refinements of the system.

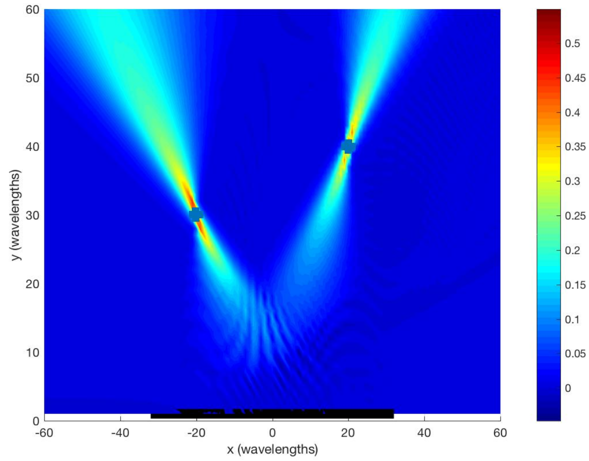

Fig. 6. Forward model as per Fig. 5, but with a non-coherent background supression.

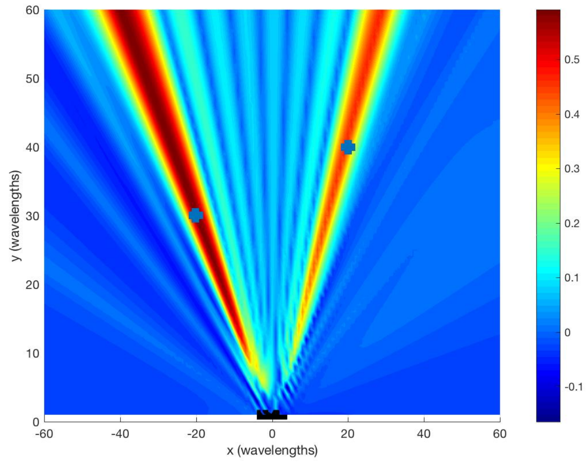

Fig. 7. Forward model as per Fig. 6, but with a non-coherent background supression.

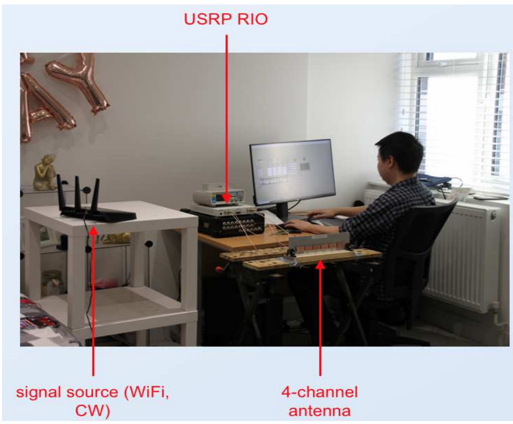

Fig. 8. NFMF test system setup.

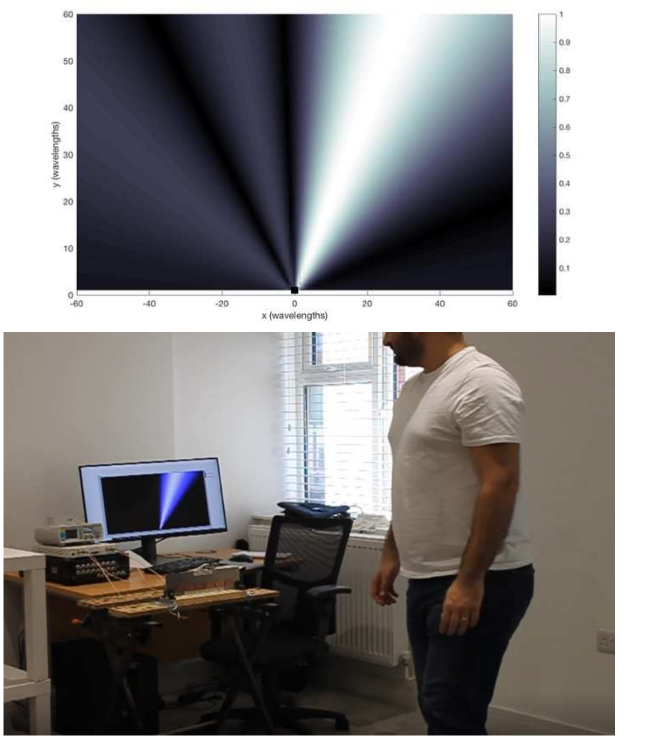

Fig. 9. Simulated (top) and measured (bottom) signatures, with AP at -70º, target at 20º, and non-coherent, high-pass MTI filtering.

V. CONCLUSIONS

This paper has introduced and explored the concept of passive RF imaging without the use of a reference signal: *reference-free* imaging. The elimination of a dedicated reference signal channel leads major practical benefits that include less dedicated hardware and no requirement for computationally expensive cross-correlation signal processing, affording real-time output of results.

The rationale is that the field distribution across a collecting aperture is a result of the adjacent target scene, irrespective of the exact nature of the illuminating source or sources, and hence there is information in this field distribution from which the target locations and motions may be deduced, in a similar manner to an optical system. The particular technique presented in this paper uses complex sampling across a linear array of antenna elements, with near-field matched-filter (NFMF) processing to focus the system on each specific point in order to form an image of the target scene. The technique is based on spatial processing and is able to image in two or three dimensions with a CW illuminating source, such as those from digital communications stations. Analytic results are obtained for the cross-range and range resolution of such a system in which it is shown that range resolution is obtained, which increases with the square of the distance from the array normal.

A small-scale, 4-channel prototype system illuminated by a 5.6 GHz WiFi access point has been constructed in order to validate the NFMF approach. The measured results and modelled results are found to agree well and confirm the resolution limits derived in this work. Extrapolation to a more realistic 16-channel system suggests that useful resolution is available for an imaging and location system that may be particularly suited to an indoor environment, and operation in the future 60 GHz band offers high precision indoor location and imaging. There are many potential extensions of the work, including investigation of interference pattern processing that requires only a sample of the amplitude distribution across an aperture; Doppler pattern processing; a planar aperture that offers three-dimensional imaging and a sparse-sampled array that offers greater resolution for a given number of channels. These variants are the subject of on-going work that shall be presented in future publications.

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