Wireless Tomography, Part I: A Novel Approach to Remote Sensing

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***Abstract*—Wireless tomography, a novel approach to remote sensing, is proposed in Part I of this series. The methodology, literature review, related work, and system engineering are presented. Concrete algorithms and hardware platforms are implemented to demonstrate this concept. Self-cohering tomography is studied in depth. More research will be reported, following this initiative.**

***Index Terms*—radio frequency tomography, remote sensing, cognitive radar, cognitive radio.**

I. INTRODUCTION

The ever increasing demand on remote sensing capabilities directly conflicts with the accelerating awareness of loss of spectrum allocation [1]. Increased spectral awareness and waveform diversity can be applied to solve this problem. The FCC recommends spectrum policy [2] that makes 500 megahertz of spectrum newly available for broadband within 10 years, of which 300 megahertz should be made available for mobile use within five years. The need for dynamic spectrum access using cognitive radio [3] is real and immediate. This paper series [4], [5] is going to bring together wireless communications with remote sensing, especially radio frequency tomography. This is Part I.

A. Cognitive Radio and Cognitive Radar: A Convergence

Future applications demand that we limit the number of radio platforms. There is a need to integrate cognitive radio and cognitive radar into one flexible radio platform [6]. This kind of convergence (for voice and data) has been the driver in the wireless industry. This trend seems to be reasonable for management of the next generation energy grid—the smart grid. Cognitive radar (remote sensing) can be used for smart grid applications as well. The idea of using cognitive radio in the smart grid seems be proposed in the literature, for the first time, in [7]–[10][1].

B. Wireless Tomography—A Novel Approach to Remote Sensing

Every radio frequency (RF) signal needs spectrum access. The whole industry is around $700 billions in the US alone. Wireless phone and Internet access consumes the lion's share. It is natural to leverage this huge investment in the wireless industry. If the huge scale of the wireless market can be used to replace Ad Hoc devices for RF tomography [12], the cost will be driven down ruthlessly by Moore's Law and Metcalf's Law. To reflect this vision, we are justified in coining a new acronym "wireless tomography", to differentiate between old and new. More precisely, we argue that only COTS communications components should be used for this purpose.

Ideally, necessary consideration for sensing needs should be made in the initial design. This is not the case, however, in the real world. Vendors want to reduce cost by avoiding multi-functional radio applications. The advent of programmable radio platforms, such as software-defined radio (SDR), makes this vision more realistic. Today's technology—using FPGA and DSP—is still too costly for this purpose. Our focus is to develop tomorrow's technology, by using today's science to design and build a prototype and demonstrate the system concept.

C. Software-Defined Radio Based System Testbed

A new generation of general purpose SDR, called universal software radio peripheral (USRP2) provided by Ettus Research [13], is currently available in the market. This platform meets our needs. Hardware testbed development is on-going at Tennessee Technological University (TTU). The initial results will be released in several months. Part II [5] of this series will address the key designs and algorithms.

II. LITERATURE REVIEW AND RELATED WORK

In the context of wireless tomography, it seems that only two groups, [14]–[16] and [17], have conducted research on incoherent tomography. In the following, the availability of phase information, is used for classification in the literature.

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[1] In particular, one of the three objectives of the submitted proposal [7] in 2009 is "apply the proposed network testbed for the smart grid". The two-page white paper [11] is undated and was not brought to our attention (through Qiu's student) until June 2010.

A. Incoherent Tomography

First generation computerized tomography (CT) algorithms use attenuation only [18], [19]. ZigBee sensors (IEEE 802.15.4) are used in pairs to sense the attenuation between a pair of sensors in [14]–[16] and [17].

B. Coherent Tomography

Diffraction tomography requires both phase and signal intensity (amplitude) of the transmitted packets. Phase is not easily obtained in the ZigBee-like network the above.

Wicks and his colleagues [12], [20]–[30] used tomography for remote sensing, in particular, for tunnel detection [31], [32]. Geometric diversity obtained through multistatic radar operations is the central idea, especially for discrete ultra narrowband (UNB) frequencies. The information content (or degrees of freedom) of the temporal spatial signal is the ultimate concern. So, spatial diversity can be traded for signal bandwidth. For some special needs, such as noise radar, ultra-wideband (UWB) waveforms are preferred.

A long line of research, called time reversal imaging, addresses two basic ingredients: (1) multiple input, multiple output (MIMO)—multistatic radar operations; (2) the methodology of treating sensors as part of propagation channel. Time reversal imaging is analogous to wireless tomography in the sense that MIMO lies at the heart of these two distinct frameworks. The seamless combination of sensors and radio propagation is made possible by low-cost computing and exploited by waveform diversity through the use of programmable waveform generators.

Indeed, MIMO ties together wireless tomography and time reversal imaging, and includes the latter two as special cases—in a mathematical framework. The three, however, have different meanings and implementations. MIMO radar or sensing is analogous to MIMO wireless communication. MIMO radar and communications requires the phase synchronization between different waveforms on transmit and receive. Wireless tomography and time reversal imaging, on the other hand, impose no such constraint. Also, the matrix size in wireless tomography is much larger than that of traditional MIMO communication and MIMO radar.

C. Self-Coherent Tomography—Phase Reconstruction

If we want to use communications components only, phase information may be inaccurate or very difficult to obtain. A different approach, called self-coherent tomography, is required to acquire the phase information, through the process of phase reconstruction. Two steps [33] are needed: (1) Phase reconstruction and (2) standard coherent tomographic processing, such as time reversal imaging, are used for image formation.

An exhaustive search has been made in IEEE *Xplore*, using the key words “amplitude only”, “intensity only”, “phaseless”, “phase retrieval”, etc. A similar search has been made in optics but the papers are not listed here. To highlight the evolution of the central idea, all papers are sorted in chronological order in [33]–[215]. In general, papers are traced back to 1981. Earlier comparison of algorithms is made in [34], [35]. No attempt is made herein to compare and treat these papers. We comment, however, on the key conceptual development that is relevant to our interest—the first self-coherent system using wireless tomography. We do this in chronological order.

Practical considerations in microwave diagnostics are made in [36], [39], [42]. A long line of work [77], [84], [90], [91], [99], [104], [105], [108], [110], [128], [133], [216]–[218] has led to algorithms that are practical. The algorithm, called Fourier Harmonics Method proposed in [157], [166], [169], [179], has been implemented and is reported in Section III-A.

Another algorithm, called Radiating Currents Method proposed in [206], [213], is also implemented and is reported in Section III-B. The goal is to find out if there is any practical application.

The use of multi-frequency data [139], [143], [164], [166], [187], [212] is an important idea relevant to our problem at hand. Non-contiguous-orthogonal frequency division multiplexing (NC-OFDM) offers flexible spectrum access in cognitive radio and cognitive radar: through the control of carriers power allocation. The above multi-frequency formalism is compatible with NC-OFDM. This line of thought will be explored, in depth, in the next paper of this series.

The Born approximation and Rytov approximations [18], only valid for weak scatterer assumptions, are the main stream frameworks in the literature. Metallic targets are of our interest, however, can not be treated using these frameworks. The inverse problems of metallic targets have been treated in [198], [219]–[225].

The use of phaseless tomography is reported in millimeter- and sub-millimeter-wave [204], [214] and in terahertz frequencies [177], [226]. The idea of compressed sensing is connected to the phase retrieval problem in [177]. Sampling in space and time is essential in tomographic imaging: compressed sensing is essential. The low signal-to-noise-ratio (SNR) paradigm for this problem is an unsolved problem.

Experimental data that is made available, online by [168], has been used to test the algorithms in [33], [166], [193]. The TE and TM database is from 2 to 10 GHz and even 18 GHz for the most complex targets.

D. Time Reversal Imaging—A Coherent Tomography Approach

Once the phase is retraced during phase reconstruction, standard coherent algorithms are applied. This two-step approach [33] facilitates the management of the non-linearity of the inverse problem.

Time reversal imaging has been chosen for several reasons: (1) Using a testbed, TTU has experimentally demonstrated (for the first time) time reversal techniques in the context of ultra-wideband communications. The hardware platform[2] [227], [228] can be leveraged for wireless tomography, especially in the context of noise radar that is ultra-wideband in nature. (2)

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[2] This work has been funded in the last seven years by ARL, ARO, NSF and ONR.

This technique has many advantages. For example, it can be used for both weak scatterers and metallic scatterers. It uses the active MIMO array, in which each element in the array can both transmit a waveform and record a reflected signal—enabling waveform diversity. Multipath can be exploited to improve image resolution. It is valid for both point scatterers and extended targets.

An attempt has be made to list all the papers that are sorted in chronological order [143], [158], [184], [229]–[321]. We know many papers are missing in this list. It is hoped that the most significant papers have been included. Our selection of a particular scheme for implementation is based upon this list. We have taken a system engineering approach. No attempt has been made to develop new algorithms. Our top concern is to develop a first generation system that works.

The first paper is Prada and Fink [229]. The time reversal operator—a MIMO matrix or linear integral operator (continuous-time case)—has all the information about the circuitry, antenna, background medium and scatterer (target). In particular, the eigenvalue(s) of this (matrix) operator depends on the reflectivity of the target, while its eigenvector provides the phase and amplitude law to focus to the target. These eigenvectors are important for low SNR such as -25 dB where only the leading eigenvectors are reliable features [10], [322]. Cognitive radio and cognitive radar [3], [6] often exhibit low SNR. The time reversal operator can be viewed as providing cooperative sensing in cognitive radar. We will demonstrate, elsewhere, that time reversal can be used in low SNR.

The second conceptual breakthrough [239], [240], [246], [263], [269], [277], [284] is to tie together, *in a closed form*, the target geometry and the eigenvalues/eigenvectors. The eigenvalues/eigenvectors can be calculated from the time reversal matrix that is formed, directly, from sensor measurements. Experiments are reported in [315]. The advent of cost-effective sensors and computing, especially robots as distributed sensors [28], [323] and cloud computing [324], makes this approach powerful.

The third conceptual breakthrough is to use a sub-space based approach in time reversal MIMO to develop MUSIC-like algorithms. This is achieved independently by [259] and by [158], [253], [255], [265], [266], [272], [273], [292], [293], [305], [317], [319]. The key is to treat this MIMO matrix as a covariance matrix—random matrix theory (RMT) [310], [313], [314], in general. The matrix size in traditional MIMO communications and radar is small, typically two times four. The matrix size of the time reversal imaging matrix is much larger. Often, only the asymptotic limit of random matrix theory is available in a closed form. As a result, random matrix theory may be suitable for our problem at hand.

Interestingly, time reversal MUSIC is also valid for intensity only (incoherent tomography) imaging [184].

III. PHASE RECONSTRUCTION

As mentioned before, phase reconstruction is the first step in self-coherent tomography. In wireless tomography, phase reconstruction means reconstructing the scattered field from the information in the incident field and squared amplitude of the total field. The problem considered herein differs from the standard phase reconstruction problem [128] as both the amplitude and phase information have to be reconstructed.

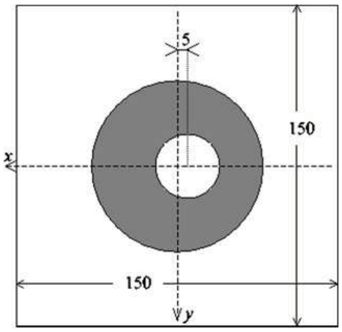

Fig. 1. Extended target.

The scenario in the problem considered, shown in Fig. 1, has the following properties: the investigated domain Ω is a circle with radius a which encloses one or more targets; the incident TM wave from angle θ_i impinges on the investigated domain Ω; the measurement domain Γ is a circle with radius b; there are L receivers with angle θ_0 on the circle; Ω and Γ are concentric; the background medium is assumed to be homogeneous with dielectric permittivity of ε_b and magnetic permittivity of μ_0. The scattering equations based on above assumptions are [169]

$$\begin{aligned} E(\mathbf{r}) &= E_{\mathrm{inc},i}(\mathbf{r}) + k^2 \times \int_{\Omega} G(\mathbf{r}-\mathbf{r}')\chi(\mathbf{r}')E(\mathbf{r}')d\mathbf{r}' \\ &= E_{\mathrm{inc},i}(\mathbf{r}) + A_i\left[\chi E\right], \mathbf{r} \in \Omega \end{aligned} \tag{1}$$

$$\begin{aligned} E_{\mathrm{tot}}(\theta_0) &= E_{\mathrm{inc},e}(\theta_0) + E_d(\theta_0) \\ &= E_{\mathrm{inc},e}(\theta_0) + k^2 \times \int_{\Omega} G(\mathbf{r}-\mathbf{r}')\chi(\mathbf{r}')E(\mathbf{r}')d\mathbf{r}' \\ &= E_{\mathrm{inc},e}(\theta_0) + A_e\left[\chi E\right], \mathbf{r} \in \Gamma \end{aligned} \tag{2}$$

in which $k = \omega\sqrt{\mu_0\varepsilon_b}$, Green's function $G(\mathbf{r}-\mathbf{r}') = -(j/4)H_0^{(2)}(k\left|\mathbf{r}-\mathbf{r}'\right|)$ ($H_0^{(2)}$ is a Hankel function of zero order and second kind) , contrast function $\chi(\cdot) = [\varepsilon_r(\cdot) - 1]$ and objects' dielectric permittivity $\varepsilon_r(\mathbf{r})\varepsilon_{\mathbf{b}}$. In the above two formulas, E_d is the scattered field needed to be reconstructed. Moreover, integral operators A_i , A_e, incident fields $E_{\mathrm{inc},i}$, $E_{\mathrm{inc},e}$ and total fields E, E_{tot} are the quantities evaluated in Ω and observation circle, respectively.

The considered problem herein amounts to retrieving $E_d(\theta_0)$ from the knowledge of $E_{\mathrm{inc},e}(\theta_0)$ and $\left|E_{\mathrm{tot}}(\theta_0)\right|^2$. In order to solve the phase reconstruction problem, a sequence of non-linear equations will be constructed. However if the number of variables to be solved is similar to or larger than the number of equations, the problem will be underdetermined, which will make the solution non-unique. Thus, we should find the key variables, which are called degrees of freedom, inside the equations to reduce the number of variables to be solved. This is our way to deal with phase reconstruction.

A. Fourier Harmonics

The $B(\cdot)$ operator, related to the scattered field defined by [169], is defined as:

$$\mathrm{B}[E_d(\theta_0)] = |E_d(\theta_0)|^2 + 2\mathrm{Re}[E_d(\theta_0)E_{\mathrm{inc},e}(\theta_0)^*] \tag{3}$$

in which $*$ stands for matrix conjugate, and can be rewritten as

$$\mathrm{B}[E_d(\theta_0)] = |E_{\mathrm{tot}}(\theta_0)|^2 - |E_{\mathrm{inc},e}(\theta_0)|^2 . \tag{4}$$

It has been thoroughly shown [113] that the scattered field under the above scenario can be accurately represented with $2ka$ Fourier harmonics. Thus the scattered field

$$E_d(\theta_0) = \sum_{n=-ka}^{ka} c_n e^{jn\theta_0} = \sum_{n=-ka}^{ka} (x_n + jy_n) e^{jn\theta_0} \tag{5}$$

in which $c_n = x_n + jy_n$. The Fourier harmonic coefficients x_n and y_n are the actual variables which are going to be retrieved. A series of nonlinear equations will be established by substituting Fourier series expansion Eq. (5) of scattered fields into Eq. (3) with the equation number equal to L. In order to make the problem overdetermined, the variable's number of $4ka + 2$ should be less than L. The built-in MATLAB function **fsolve** will be applied to give the solution to the established non-linear equations.

B. Radiating Currents

The radiating currents exhibits finite degrees of freedom, the number of which is bounded by the number of dominant singular values of the Green's function [213].

Define,

$$c(\mathbf{r}) = \chi(\mathbf{r}) E(\mathbf{r}), \mathbf{r} \in \Omega \tag{6}$$

The investigated domain is divided into N small areas. In each small area $\Delta\Omega$, $c(\mathbf{r})$ is assumed to be identical. Thus, Eq. (2) can be represented as the matrix format,

$$\mathbf{E}_{\mathrm{tot}} = \mathbf{E}_{\mathrm{inc},e} + \mathbf{E}_d \tag{7}$$

$$\mathbf{E}_d = \mathbf{G}\mathbf{c} \tag{8}$$

and

$$(\mathbf{G})_{i,j} = k^2 \times \int_{\Delta\Omega} G\left(\mathbf{r}_i - \mathbf{r}'_j\right) d\mathbf{r}'_j \tag{9}$$

where $(\mathbf{G})_{i,j}$ denotes the i-th row and j-th column in the matrix $\mathbf{G}$. $\mathbf{r}_i$ denotes the i-th measurement and $\mathbf{r}'_j$ denotes the j-th small area in the investigated domain Ω.

The singular value decomposition (SVD) of $\mathbf{G}$ is,

$$\mathbf{G} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^H \tag{10}$$

where H means transpose conjugate operator.

Assume the number of dominant singular values of $\mathbf{G}$ is M, then

$$\mathbf{G} \approx \mathbf{U}_M \mathbf{\Lambda}_M \mathbf{V}_M^H \tag{11}$$

where $\mathbf{U}_M$ and $\mathbf{V}_M$ are the first M columns of $\mathbf{U}$ and $\mathbf{V}$ respectively. Besides,

$$\mathbf{\Lambda}_M = \begin{bmatrix} \lambda_1 & & \\ & \ddots & \\ & & \lambda_M \end{bmatrix} \tag{12}$$

where $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_M > 0$.

Define

$$\mathbf{x} = \mathbf{V}_M^H \mathbf{c} \tag{13}$$

then

$$\mathbf{E}_d \approx \mathbf{U}_M \mathbf{\Lambda}_M \mathbf{x} \tag{14}$$

It is easy to see that part of $\mathbf{c}$ contributes to the scattered field, which can be called a radiating current [213].

Thus,

$$\mathbf{E}_{\mathrm{tot}} \approx \mathbf{E}_{\mathrm{inc},e} + \mathbf{U}_M \mathbf{\Lambda}_M \mathbf{x} \tag{15}$$

and the non-linear equations can be obtained as,

$$|\mathbf{E}_{\mathrm{inc},e} + \mathbf{U}_M \mathbf{\Lambda}_M \mathbf{x}|^2 - |\mathbf{E}_{\mathrm{tot}}|^2 = \mathbf{0} \tag{16}$$

There are L equations and M variables to be solved in the above non-linear equations. Meanwhile M is less than L.

Besides, following [213], in order to solve the phase reconstruction problem, a cost function can be defined as,

$$f(\mathbf{x}) = \sum_{l=1}^{L} \left(\left| (\mathbf{E}_{\mathrm{inc},e} + \mathbf{U}_M \mathbf{\Lambda}_M \mathbf{x})_{l,1} \right|^2 - \left| (\mathbf{E}_{\mathrm{tot}})_{l,1} \right|^2 \right)^2 \tag{17}$$

The conjugate gradient method can be used to obtain the optimal value of $\mathbf{x}$ [213]. Then the scattered field can be reconstructed.

C. Numerical Results

The phase retrieval results obtained by aforementioned algorithms will be shown. The experimental data is provided by Institute Fresnel in France [168]. The file name is FoamDielIntTM.exp. The working frequency is 2GHz. $a = 0.15$m. $b = 1.67$m. $\theta_i = 0^o$. θ_0 is from 60^o to 300^0 with 1^o interval. Thus, L is equal to 241 and M is chosen to be 10. The reconstruction results are shown in Fig. 2 and Fig. 3 for phase and amplitude respectively. The reconstructed scattered field is very close to the true (measured) scattered field.

IV. FUTURE WORK

This series [4], [5] describes a new initiative to bring together two areas: wireless communications and radio frequency tomography. Although this vision seems natural, a systematic attack to this problem is for the first time presented here. The focus is to design a system that works. No effort is made to optimize this system design, or the algorithms. We emphasize the system engineering approach in our work. The architecture of a phase reconstruction algorithm to retrieve the phase of a communications signal, combined with time reversal imaging, seems promising at this point.

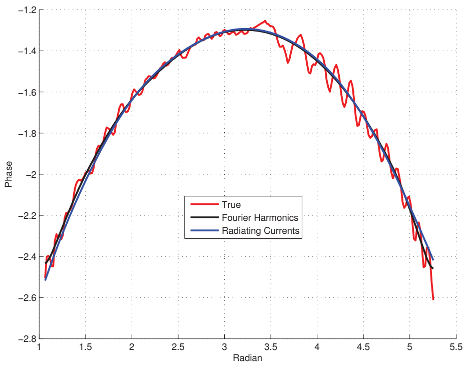

Fig. 2. Phase reconstruction.

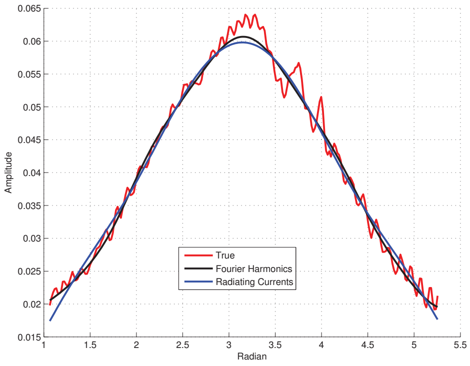

Fig. 3. Amplitude reconstruction.

Experimental data for extended targets have been used for phase retrieval in this paper. Also, two different algorithms are implemented to test this concept. A literature and history extending back more three decades has been exploited in our research and system architecture.

What is missing is a software-defined radio to measure the amplitude of the signal, and to confirm the phase retrieval algorithm. If the amplitude measurement is sufficiently accurate, the algorithm is expected to work. If not, these measurements errors must be accounted for, by regarding them as “noise”. Very likely, the errors (noise) are so large that a low signal to noise ratio is resultant. Fortunately, the time reversal matrix (operator) has the capability to filter these errors. The leading eigenvectors—obtained via principal components using dimensionality reduction in machine learning—are of interest. This practical system requirement ties together machine learning and low energy signal detection problem.

Sampling is critical to tomography. Close-in sensing is required to achieve high quality signal measurements [1]. Mathematically, the problem at hand is to retrieve the informational degrees of freedom. Compressive sensing is naturally connected to this problem; Signal, noise, sampling, and computing are all tied together.

On the other hand, wireless communication is moving to the era of cognitive radio and the use of dynamic spectrum access. Frequency diversity systems allow agile sensing in the presence of interference [1]. NC-OFDM is the scheme of choice in cognitive radio. Future networks will use this scheme [10]. The system engineering challenges have been addressed in Part II [5], of this series. In particular, NC-OFDM is used for spectrum fragmentation of the transmitted waveform to sense the environment. Waveform diversity and optimization are needed to achieve optimal imaging formation—the use of mutual information as the criteria simplifies the problem but may be suboptimal in terms of imaging formation.

Once phase is retrieved, standard coherent tomographic processing is followed. Time reversal imaging has been applied for coherent imaging. We can apply the method in [199] that exploits multipath in a wideband system. Ray-tracing method [325] can be applied. Maximum likelihood estimation of object location can be applied for strongly scattering objects [326]–[330].

Time reversal imaging is valid for inhomogeneous random medium. Basically, if the Green’s function of background medium is known, the problem is solved. The phase retrieval problem in inhomogeneous random medium seems be unsolved. In principle, the two algorithms in Section III are valid since only Green’s functions are used.

A hardware testbed is under development at TTU. Ultimately, wireless tomography will be implemented in this cognitive radio testbed [10].

V. CONCLUSION

Wireless tomography is a novel approach to remote sensing. This idea—combining wireless communications and remote sensing—is based on many years research insight. The methodology, literature review and related work, and system engineering are presented. When only communications components are used for system development, the phase of the signal is either inaccurate or very expensive to obtain.

We suggest a self-coherent wireless tomography, which has two steps. First, the phase retrieval is achieved using amplitude only data that are obtained through wireless sensors. Second, standard radio tomographic imaging algorithms are used. We emphasize time reversal imaging for two reasons: (1) TTU has a working experimental testbed; (2) this technique is the state-of-the-art. Our goal is to demonstrate the concept as quick as possible. No attempt has been made to optimize the system design and the algorithms.

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