Through Wall Imaging at Microwave Frequencies using Space-Time Focusing

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I. Introduction

Imaging inside of buildings to detect human signature has become a problem of great importance to law enforcement agencies. Existing technology based on infrared cameras, although can provide high resolution images, has limited applicability to situations where the building opacity is low. Therefore imaging is only possible through thin non-absorbing material such as imaging through curtains and single walls without insulations, etc. Electromagnetic (EM) spectrum in the range of 100MHz-100GHz offers a unique opportunity for mapping of an unknown area including interior of a building because of its penetration capability through building materials. While the real part of the relative dielectric constant of non-metallic building materials at VHF through W-Band ranges from 2-4 and their loss tangent is of the order of 0.1 or less, human body present certain unique features as a scatterer of EM waves, because of its very high dielectric constant. In addition characteristic voluntary and involuntary movements affecting scattered signal such as Doppler shift, could be exploited for detection and identification. In this paper a physics based wave propagation simulation tool is employed to investigate the phenomenology of wave propagation inside complex building structures such as statistics of path loss, angel of arrival, spatial and spectral field coherence, etc. In addition the application of a space-time focusing method for detecting objects inside a building is examined. The focus of this investigation is mainly on the forward problem to better understand the physics of the problem which can be utilized to simplify the inverse problem. The result of this study will be used in the development of novel radar-based detection algorithms as well as detection methods based on multi-modality.

II. Imaging Algorithm

At low microwave frequencies, scattering and attenuation of EM waves through buildings and vegetation is relatively low. Hence the signal will survive over relatively long distances in an urban environment. Although the backscatter signal level may be sufficiently above the noise level, target detection and location in a highly scattering environment, where the signal between a target and radar may experience many reflections and diffractions, is not straightforward. To remedy this difficulty a multi-static sensor configuration is considered. In this approach an ad hoc array of cooperative transceivers is proposed. Assuming the locations of the transceiver nodes can be determined using a combination of differential GPS and laser triangulation, the backscatter and multi-static responses of the scene can be generated. The delay profiles obtain from this array of sensors can be used in an inverse scattering algorithm to generate the radar image of the scene. Time reversal methods can offer a unique opportunity for solving the inverse scattering problem of EM wave propagation and focusing in a spatially varying (inhomogeneous) medium.

While the concept of time reversal to focus waves in spatially varying media is new to the field of EM wave propagation, it has been applied in the area of acoustic and ultrasonic for several years [1-3]. The basic premise is quite simple. Let an impulse source (in time and space) be transmitted into some general inhomogeneous medium, and the tangential surface fields determined on a closed surface surrounding the impulse. It can be shown mathematically that if these surface fields are conjugated and re-radiated in time reversed sequence, that the incoming wave, generated by the surface fields is identical to the outgoing wave, and the returning energy focuses on the original source point. This is an application of reciprocity and can be shown to be similar to a matched filter commonly applied in radar and communications. In any finite size array that occupies a limited spatial area the system is diffraction limited, however, it is shown that in an

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inhomogeneous medium a time reversal array is not always diffraction limited and can achieve super-resolution as the scatterer in the vicinity of the transmitter array and the focal point increases. As shown in Figure 1, the imaging algorithm is constructed of four major tasks: 1) Mapping the building structures, 2) Solving forward scattering problem, 3) Space focusing by adaptive transmission from transceivers, and 4) Time focusing for measuring backscattering. In this paper it is assumed that the building structure is known.

III. Forward Scattering Problem

A typical scenario considered for through wall imaging can be viewed as a combination of outdoor-indoor environment which can potentially create an extreme multipath environment for the wave propagation. In these scenarios usually the direct paths between target and detectors are not the dominant paths. Therefore forward propagation problem must be solved to find the optimum transmission paths between the target and the detectors. Each of these paths may include few reflections, transmissions and diffractions. A wave propagation simulator based on a 3D ray-tracing algorithm [4, 5] has been used for this purpose.

IV. Space Focusing Technique

The first focusing technique used in this paper in order to maximize the field intensity at the target point will be referred to as space focusing. In a typical scenario the target is located inside a building, shown in Figure 2, surrounded by a set of sensors located randomly around the building. The proposed space focusing method works similar to standard arrays. However each sensor has a scanning array capable of focusing its beam into desired direction for the purpose of final focusing at the target location. On the other hand each sensor (transmitter at this moment) points its signal to few preferred direction which are found from forward scattering solution for the same scenario. The phases and amplitudes of the signals for transmission in desired directions are also determined from the solution of forward scattering problem.

V. Time Focusing Method

The space focusing algorithm helps to balance phase and transmission direction from transmitters such that all arrive at the target constructively. However the uniqueness of the solution for inverse problems is not guaranteed. A simple case for explaining the lack of uniqueness is when backscattering of transmitted signal from an adjacent object to the detector is much stronger than actual backscattering from target. Therefore additional mechanism is required to filter the actual backscattering of the real target from false alarms because of the early and late responses of other objects in the search area.

The advantage of ray-tracing algorithm used for solving forward scattering problem is determining delay profile as well as amplitude, phase and directions of paths at once. The last three sets of information were used for space focusing and now delay profile is used to perform time focusing. There are different ways which time focusing can be done. For the simplicity of detection system proposed in this paper, time focusing here is done by simultaneous transmitting from all transceivers and receiving at a time window around the mean value of all of the paths' delay. The width of time window is chosen proportional to standard deviation of the delay values, not less than 10 nsec to relax time gating procedure in practical applications.

VI. Simulation Results

For a five stories building shown in Figure 2, 75 sensors are placed around the building at 2 m above the ground, operating at 2.3 GHz. The forward problem has been solved for two different target position, in the 3rd and 5th floor. The results are used for optimum transmission from sensors. Figures 3 and 4 show angle of arrival for the rays arrived to the target positions. Then in order to filter spatially focused power at the target positions form undesired spikes at other positions, time focusing is done as described in section V. Field map at 3rd and 5th floors are shown in Figures 5 and 6 respectively. The white spot locates target's position, as it is shown focused field at desired position is at least 15 dB above field level at entire area at 3rd floor and 10 dB at 5th floor. The reduction in focus for 5th floor is because of higher signal attenuation and lower number of propagation paths.

References

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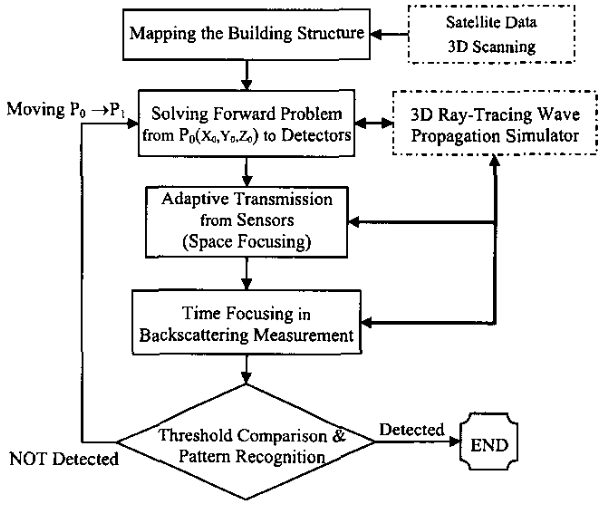

Figure 1. Flowchart of Imaging Method

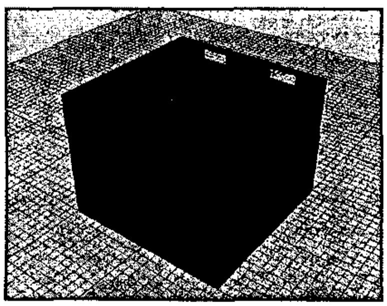

Figure 2. A typical five stories building used in simulation

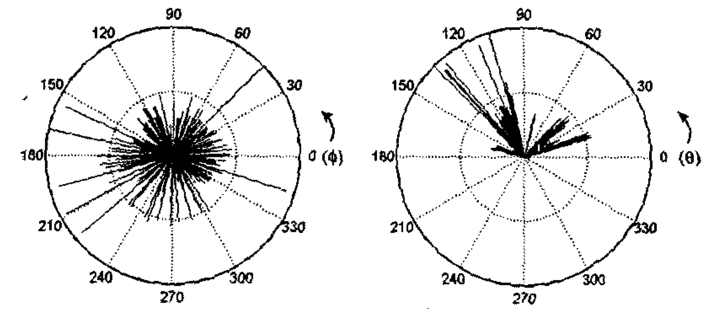

Figure 3. Angle of arrival for 3rd floor target

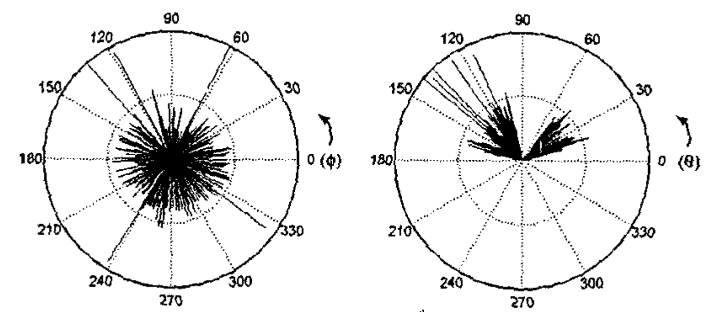

Figure 4. Angle of arrival for 5th floor target

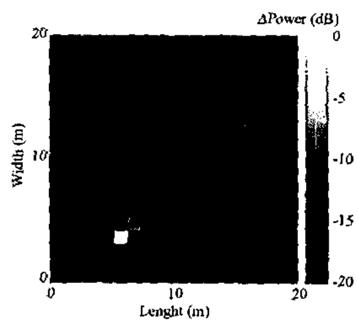

Figure 5. Field map at 3rd floor

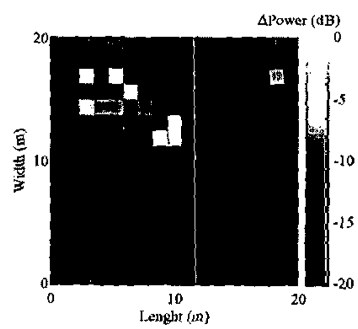

Figure 6. Field map at 5th floor