Effect of Waveform Bandwidth and Array Size on Time Reversal Processing in TWIR Radar

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***Abstract*—Time Reversal (TR) processing is very effective for imaging applications in scatterer rich environment such as Through-the-wall Imaging (TWI). In this paper, a typical Through-the-Wall imaging scenario i.e the reflections from the walls are exploited to improve the image focusing using Time Reversal (TR) techniques. After extensive MATLAB based simulation it was found that the proposed TR based image reconstruction scheme outperforms the conventional processing both in down range and cross range focusing performance. In addition, TR focusing performance with respect to bandwidth and array size is also compared. It was observed that wall reflection multipaths can be exploited to reduce the size of TWIR array and to use lesser bandwidth waveform for a reasonable focusing performance.**

***Index Terms*—Through-the-Wall Imaging Radar (TWIR), Stepped Frequency Continuous Wave (SFCW), Time Reversal (TR), Multiple-Input-Multiple-Output (MIMO).**

I. Introduction

Ultra-Wide Band (UWB) radars are popular in through-the-wall(TTW) sensing. UWB Through-the-Wall Imaging Radars (TWIR) are used for hostage rescue operation, rescue of earth quake victims and fire fighting personnel. The primary challenge of TTW imaging is to provide a clean image of objects inside a building. In addition, the size and weight of the radar should desirably be small for portability and speedy surveillance. One way is to improve the resolution is to increase the size of the array, but that will increase the weight and the portability of the radar gets affected. Time Reversal (TR) is an emerging technique which exploits the multipath environment [1] and is promising to meet the aforementioned challenge. More numbers of multipaths better will be the image focusing with TR, which goes against the conventional wisdom. The TR improvement factor is the function of ratio of the coherence bandwidth of the medium to the bandwidth of the waveform [2]. If a wideband pulse is transmitted, the pulse gets broaden up due to the multipath reflections in a scatterer rich environment. The coherence bandwidth is inversely proportional to the time spread of the target response. It is the function of randomness of scattering of the medium which is often referred as random medium. However, TR signal processing is very simple technique which exploits the degrees of freedom provided by the mulitpaths to improve the down range focusing, cross range focusing and improved side lobe performance. In a typical TWIR, the effect of various length of antenna, bandwidth on TR processing is studied. In TWIR the important resources are the waveform band width and the number of antenna elements. In SFCW modulation, large band width provides better resolution but it takes longer time for scanning the room. Similarly, for ease of portability, smaller antenna is always better.TR based image reconstruction techniques for TWIR radar like scatterer rich environment a smaller bandwidth waveform and smaller antenna can be used to obtain reasonable image focusing.

The paper is organized in the following manner. Section II explains about the typical TWIR through-the-wall environment and multipaths due to walls, roofs and floor. The theory of TR as a matched filter is discussed in section III. Section IV covers the Time Reversal processing. Section V presents the simulation and interpretation of the results followed by the conclusions in section VI.

II. Multipaths in a Through-the-Wall Imaging Radar

The practical TWIR radar system with closely spaced transmit and receive array known as co-located MIMO mode of operation is shown in Fig.1. Separate transmit and receive arrays provide the adequate isolation for continuous wave operation. As the echo signal is the superposition of reflected echo from the targets and the reflections from the walls, roof and floor as shown in Fig. 2. There is transmit array consisting of N_t number of transmitters and N_r number of receivers, depending upon the resolution requirement and quick surveillance. However, this portable class of radars suffer from poor resolution both in cross range and down range dimension. It results in defocused and blurred image. Further, small antenna leads to poor cross range resolution and speedy surveillance and long depth of surveillance puts constraint on the bandwidth of the waveform, hence poor down range resolution. Poor resolution causes the interference of targets echoes and scatterers echoes. It results in defocused image, ghosts and finally position of the target gets shifted from the actual position. SFCW UWB signal is being increasingly used for TWIR application for ease of generation and coherent processing. The main intent for the introductory explanation about TWIR is to dwell on the design issue in the context of practical TWIR and resultant image degradation due to both design constraint and environment in which radar operates. It explains about propagation of signal i.e angle of incidence, angle of refraction and multipath scattering from walls of the room. But for the sake of simplicity, only the multipath reflections from the walls are considered here. However, it does not affect the research findings.

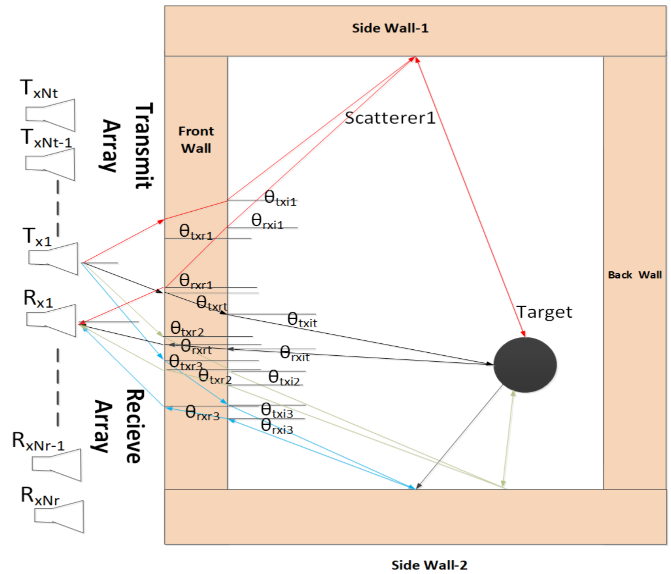
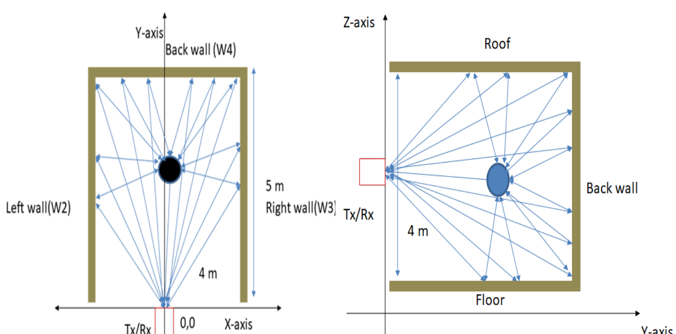


Fig. 1. TWIR radar with multipath reflections from walls

N_t is the numbers of transmitters, N_r is the numbers of receivers $\theta_{txi}(s)$ is the angle of incidence w.r.t transmitter, $\theta_{rxi}(s)$ is the angle of incidence w.r.t receiver $\theta_{txr}(s)$ is the angle of refraction w.r.t transmitter, $\theta_{rxr}(s)$ is the angle of refraction w.r.t receive s : numbers of scatterers, $(s = 1, 2, 3, ..., N_{sc})$.



(a) (b)

Fig. 2. Multipath reflections from walls, roof, floor(a) Multipaths due to walls (b) Multipath due to floor and roof

III. Time Reversal as a Matched Filter

Time reversal is similar to matched filtering used in signal processing. The following section explains that in the presence of highly scattered media the expression of TR is same as matched filter. If the signal $s_r^f(t)$ is transmitted by a transmitter and received by N_r numbers of receiver.

$$s_r^f(t) = s_t^f(t) * h_i(t) \tag{1}$$

$$s_r^{TR}(t) = s_r^f(-t) * h_i(t) \tag{2}$$

$$s_r^{TR}(t) = s_t^f(-t) * h_i(-t) * h_i(t) \tag{3}$$

$$s_r^{TR}(t) = s_t^f(t) * Rii(t) \tag{4}$$

where, $s_t^f(t)$ is the transmit signal,$h_i(t)$ is impulse response of the medium, $s_r^f(t)$ is the received signal after forward probing, $s_r^{TR}(t)$ is the received signal after Time Reversal (TR), $Rii(t)$ is the auto-correlation function of the room for each receiver and $i = 1, 2, 3, ..., N_r$.

IV. TR Processing

(a) Forward Probing: (i)Transmission of signal $s_r^f(t)$ from N_t transmitters and reception by N_r receivers.(ii)Energy normalisation of the received signals for N_tNr transmit and receive pair. Signal undergoes multipath reflections from the walls, roofs and floor. Before retransmission in TR process energy normalisation is done to restore the signal energy. The energy normalisation parameter is

$$K_e = \frac{1}{N_{rc}} \sum_{i=1}^{N_{rc}} \| s_r^{TR}(t) \|^2 \tag{5}$$

where,N_{rc} is the number of range cells, K_e is the energy normalisation parameter.

(b) Time Reversal Transmit Signal: The received signal in forward probe is energy normalised and phase conjugated in frequency domain which equivalent to time reversal in time domain.

$$s_t^{TR}(t) = K_e s_r^{f*}(t) \tag{6}$$

(c) Time Reversal Received Signal: The TR transmit signal is multiplied with the response of the medium, which is called mathematical time reversal. Only assumption is the medium does not change or slowly change during the forward probing and time reversal processing.

$$s_r^{TR}(t) = K_e s_r^{f*}(t) s_r^f(t) \tag{7}$$

where, $s_r^{TR}(t)$ is the time reversal signal.

(d) TR reference signal: This signal required for matched filtering at the target location. TR process is dynamic and the spatio-temporal focusing takes place at the target (passive scatterer). There are various techniques used to estimate the TR time which depends on the location of the target. One of these techniques is the minimum entropy based method [3]. Here the peak detection for forward probed image is taken to generate the reference signal.

$$s_{ref}^f(t) = s^f(t - t_{tgt}) \tag{8}$$

s_{ref}^f is the reference signal which the estimated for TR focusing at so called $t = 0$ of time reversal and t_{tgt} is the time delay of transmitter to target and target to receiver.

(e) TR Matched Filtering:

$$s_{fil}^{TR}(t) = s_r^{f*}(t) s_{ref}^f(t) \tag{9}$$

$s_{fil}^{TR}(t)$ is the TR focused signal.

V. Simulation and Analysis

Time Reversal (TR) processing is very effective for imaging applications in scatterer rich environment. The TWIR radar used for the simulation is given in Table I.

TABLE I
TWIR scenario used for simulation and analysis

Simulation Parameters			
parameters	value	parameters	value
Room size	10 m x 10 m	Δf	3 MHz
Length of array	0.2m, 0.4m, 0.8m and 1.6m	Rang(max)	50m
No.s of Tx	2,4,8,16	Target	4 m
No.s of Rx	2,4,8,16	BW	(1-4) GHz
Rng. Res.	5 cm	Wall type	brick

Comparison of image focusing is depicted in Fig. 3. Comparion of TR focusing improvement for different frequencies and different length of antennas are depicted in Fig. 4, Fig. 5 and Fig. 6.

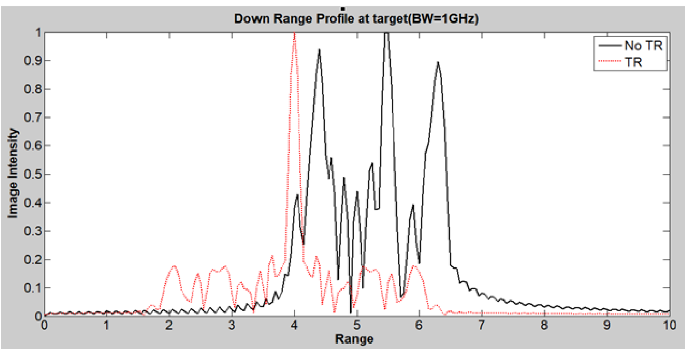
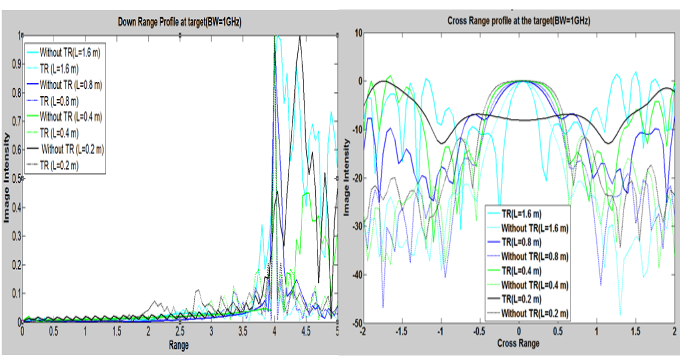


Fig. 3. TR Image Focusing in range dimension



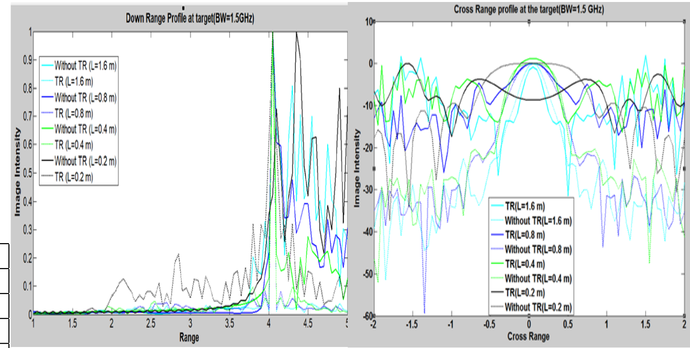
(a) (b)

Fig. 4. Down range and cross range profile for various length of antenna(a) Down range profile at 1 GHz (b) Cross range profile at 1 GHz

A. Discussions

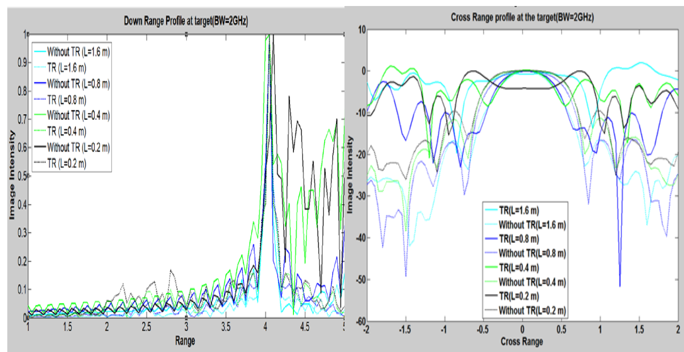
The down range focusing due to TR is given in table II. The down range focusing factor is in the order of 20 which extremely useful for TWIR application. It depends on the bandwidth of the waveform and the nature of the multipath scenario of the room.

Similarly as the length of the antenna increases, the sidelobe performance gets improved as shown in table III



(a) (b)

Fig. 5. Down range and cross range profile for various length of antenna(a) Down range profile at 1.5 GHz (b) Cross range profile at 1.5 GHz



(a) (b)

Fig. 6. Down range and cross range profile for various length of antenna(a) Down range profile at 2 GHz (b) Cross range profile at 2 GHz

TABLE II
Down Range Focusing for 1.6 m array

Down Range range focusing factor	
BW	Focusing Factor
1 GHz	16
1.5 GHz	20
2 GHz	24

TABLE III
Cross Range Sidelobe performance(BW: 1 GHz) comparison TR and Conventional processing

Side Lobe performance	
lenght of arrray	Side lobe level (SLL) Improvement
0.2m	20 dB
0.4m	22 dB
0.8m	22 dB
1.6m	24 dB

VI. Conclusions and Future Work

It is observed that for multipath reflections from wall results in large range spread and target image gets defocused. However, with the proposed TR based image reconstruction scheme the image gets focused. After extensive simulation, it was found that with TR, larger the bandwidth better is the down range focusing and longer the antenna better is the sidelobe compared to conventional processing. Wall reflection multipaths aids to image focusing in TR based image reconstruction scheme against the conventional wisdom. In future, it is planed to apply the aforementioned scheme for 3D resolution improvement in the MIMO TWIR radar.

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