Through-Wall Tracking of Human Movers Using Joint Doppler and Array Processing

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***Abstract*—In this letter, a radar combining Doppler processing and spatial beamforming is presented for tracking humans through walls. Multiple targets are tracked by resolving the targets in the Doppler and bearing space. To overcome the high sidelobes associated with an array of limited size, the CLEAN and RELAX algorithms are implemented, and their performances are compared with standard beamforming. The radar is tested in indoor line-of-sight and through-wall scenarios for multiple loudspeakers and human subjects.**

***Index Terms*—CLEAN, Doppler, RELAX, spatial beamforming.**

I. Introduction

THROUGH-WALL detection and tracking of human movers is an important problem of current interest in security and surveillance operations. Ultrawideband radars for this application with down-range resolution of the order of centimeters have been reported in [1]–[7]. These radar systems utilize impulse [1]–[4], frequency-modulated continuous-wave (FMCW) [5], stepped frequency [6], or noise [7] waveforms to realize a high-range resolution. An alternate development was a low-complexity Doppler radar with a two-element receiver array [8]–[10]. Multiple moving targets were first resolved based on their Doppler returns. The direction of arrival (DOA) of each target was then estimated using the phase difference of the scattered signal at the two receiver elements. This system has very low complexity but is based on the assumption that no two targets have the same Doppler returns. When the targets are not well resolved in the Doppler dimension, the error in the DOA estimation is found to increase significantly. This problem is particularly acute for human tracking, since micro Doppler returns from human arm and leg motions have a broad Doppler spread [11]. In this letter, we present a four-element array radar that combines Doppler processing with software beamforming to resolve targets along both the Doppler and DOA space. This enables the detection of targets with overlapping Dopplers. However, in an array of limited size, the sidelobes due to strong targets can prevent the detection of weaker targets when the targets are not resolvable in the Doppler domain. We implement the CLEAN algorithm [12] in the beamformer to iteratively remove the sidelobe features of the strong target to enable the detection of weaker targets. The RELAX algorithm [13], an enhancement of CLEAN, is also implemented to further improve the accuracy of the target-parameter estimation. Some preliminary results based on measurements conducted for loudspeakers and human subjects in line-of-sight (LOS) scenarios were presented in [14]. In this letter, we present the detailed algorithms and results of tracking multiple humans through walls.

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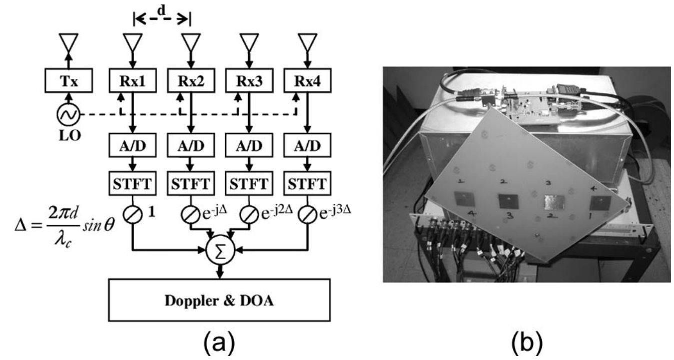

Fig. 1. (a) Radar architecture. (b) Photograph of the receiving array.

II. Radar Design and Processing

Fig. 1(a) shows the radar architecture. The testbed consists of a CW transmitter operating at a frequency of 2.4 GHz and four receiving microstrip patch antennas fabricated on a 1.6-mm FR-4 substrate. The antennas are separated by 0.56λ, where $\lambda =$ 12.5 cm, to provide the maximum resolution while avoiding any grating lobes within the range -45° to 45°. Off-the-shelf quadrature receiver boards (Analog Devices AD8347) are used to downconvert the received signals, which are then digitized for software processing. A photo of the receiving array is shown in Fig. 1(b).

Doppler and spatial beamforming are performed on the received signals according to as follows:

$$\chi(t,f,\theta) = \frac{1}{N}\sum_{n=1}^{N}\int\left\{x(n,t')h(t'-t)e^{-j2\pi ft'}dt'\right\} \times e^{-j(n-1)\frac{2\pi d}{\lambda}\sin\theta}. \quad (1)$$

The short-time Fourier transform (STFT) is first applied to the time-domain signal $x(n,t)$ of receiver element n to capture the instantaneous Doppler f of the targets. A time window $h(t)$ of 0.25 s is used in the STFT. Spatial beamforming is next performed by introducing a phase shift that is proportional to

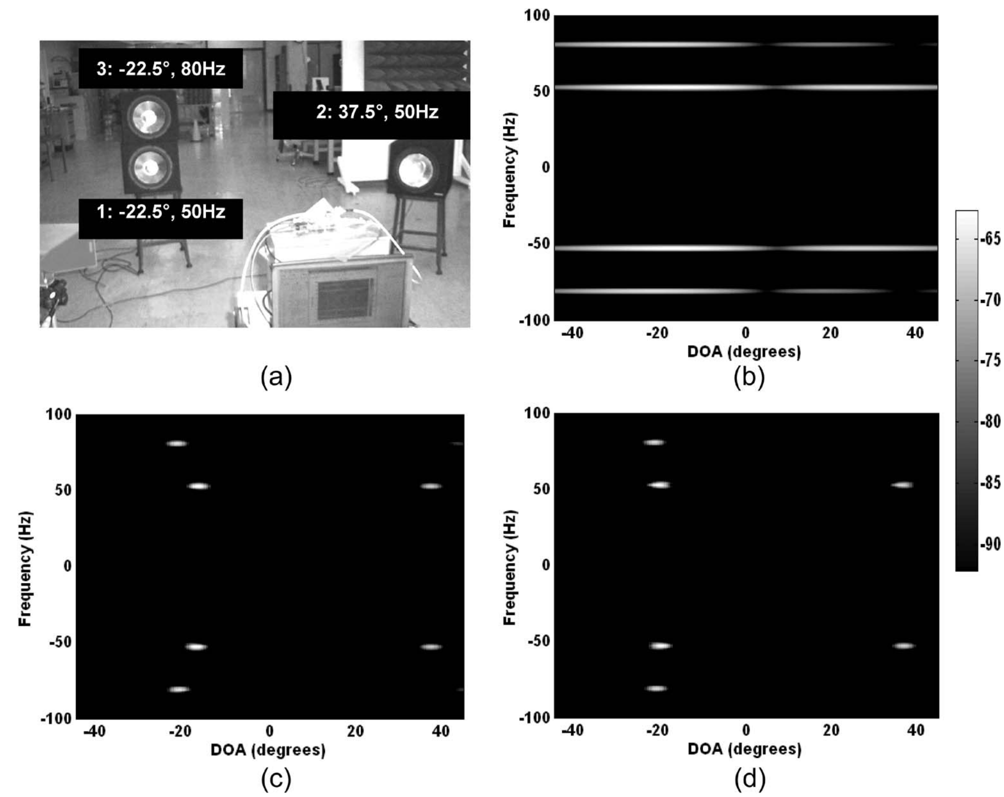

Fig. 2. Three loudspeaker targets in indoor LOS resolved in the Doppler–DOA space, in decibel scale. (a) Experimental setup. (b) Beamforming result. (c) CLEAN result. (d) RELAX result.

the sine of the beam-steering angle θ from the boresight to the signals at each of the receiver elements followed by summation of the phase-shifted signals. These two steps help resolve the target returns along the Doppler and DOA dimensions for each time instant t. Here, λ is the wavelength of the radar, and N is the total number of elements in the antenna array.

Since a four-element array has a rather poor angular resolution, weaker targets can be easily buried within the sidelobes of stronger targets, particularly for targets with overlapping Dopplers. The CLEAN algorithm [12] is, hence, implemented to facilitate the DOA estimation of weaker targets. For each Doppler bin and at each time instant, the algorithm first identifies the strength a_1 and DOA θ_1 of the strongest target from the spatial-beamforming pattern χ

$$|a_1|^2 = \max_{\theta_1} |\chi_{(\theta)}|^2. \quad (2)$$

Then, the main-lobe and sidelobe features of the strongest target are removed from the spatial-beamforming pattern as follows:

$$\chi_{\text{residual}}\Big|_1 = \chi - \frac{1}{N}\sum_{n=1}^{N} a_1 e^{-j(n-1)\frac{2\pi d}{\lambda}(\sin\theta - \sin\theta_1)}. \quad (3)$$

From the residual pattern $\chi_{\text{residual}}|_1$, the next strongest target is identified, and the procedure is iterated until the residual energy $|\chi|^2_{\text{residual}}|_M$ falls below the noise floor. This iterative procedure enables us to better detect the parameters of the weaker targets in the presence of strong targets.

It is known that the DOA estimation using CLEAN is inherently biased due to the sidelobe interference between the targets. This error can be further minimized by introducing the RELAX procedure at each CLEAN step [13]. Assuming that M (greater than one) targets have been detected in a particular CLEAN step, RELAX reextracts the strength and DOA (a_p, θ_p) of each target p after removing the other targets' $(m = 1 : M, m \neq p)$ contributions in the beamformer output

$$|a_p|^2 = \max_{\theta_p} \left| \chi - \frac{1}{N}\sum_{n=1}^{N}\sum_{m\neq p} a_m e^{-j(n-1)\frac{2\pi d}{\lambda}(\sin\theta - \sin\theta_m)} \right|^2. \quad (4)$$

The reextraction of target parameters is iterated until the residual energy at that step $|\chi|^2_{\text{residual}}|_M$, computed using

$$|\chi|^2_{\text{residual}}\Big|_M = \left| \chi - \frac{1}{N}\sum_{n=1}^{N}\sum_{m=1}^{M} a_m e^{-j(n-1)\frac{2\pi d}{\lambda}(\sin\theta - \sin\theta_m)} \right|^2 \quad (5)$$

converges. This procedure is repeated for each CLEAN step. The RELAX algorithm enables a more accurate estimate of the target DOA at the price of increased computation time.

III. Measurement Results

Measurement is first conducted for three loudspeaker test targets in indoor LOS conditions, as shown in Fig. 2(a). The vibration of the speaker diaphragm results in a radar return that is frequency modulated. Speakers 1 and 2 are driven at the same audio frequency but have different DOAs, while

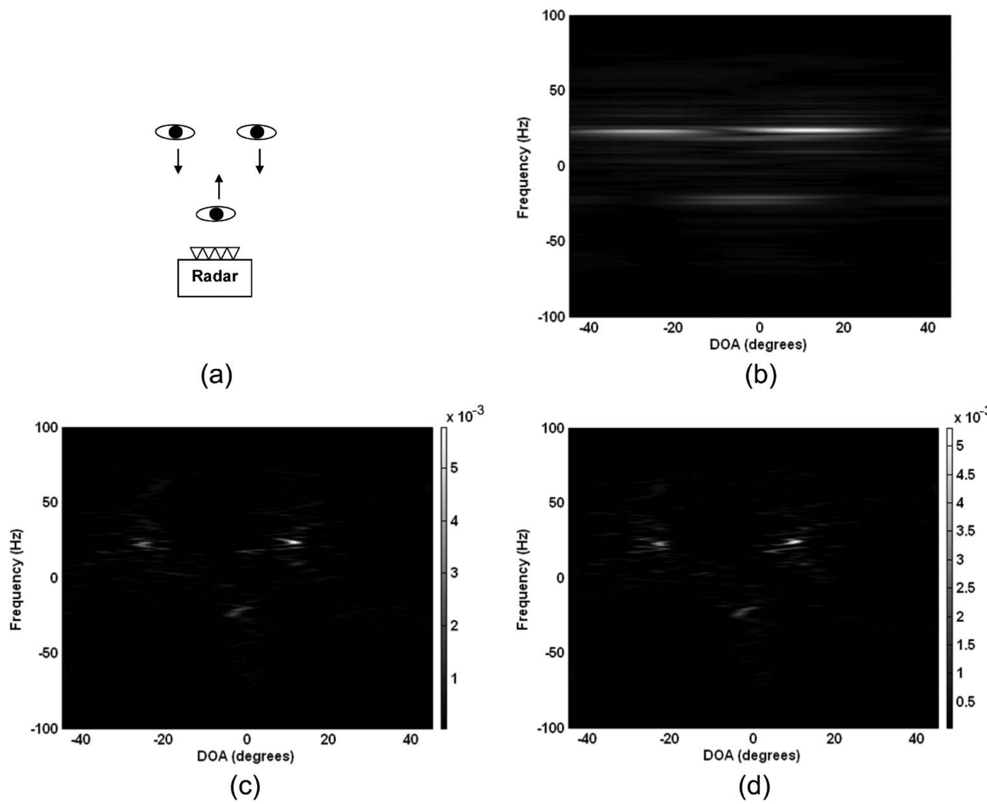

Fig. 3. Three human subjects in indoor LOS resolved in the Doppler–DOA space. (a) Measurement setup. (b) Beamforming result. (c) CLEAN result. (d) RELAX result.

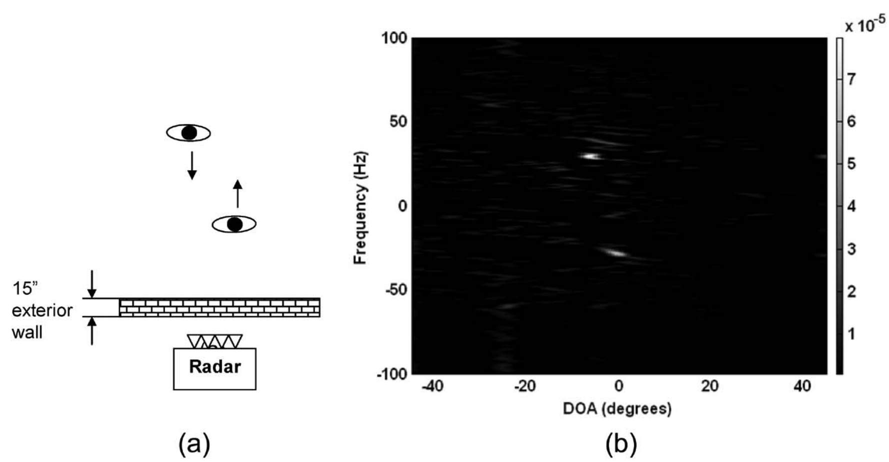

Fig. 4. Two human subjects in a through-wall scenario resolved in the Doppler space. (a) Measurement setup. (b) CLEAN result.

speaker 3 is driven at a different audio frequency but has the same DOA as speaker 1. After Doppler processing and spatial beamforming are performed, the three targets are resolved in the Doppler–DOA space, as shown in Fig. 2(b). However, the result is plagued by poor resolution and high sidelobes in the DOA dimension. Next, the CLEAN algorithm is tried on the same data. The discrete estimates of the DOA positions are obtained from the CLEAN algorithm. For display purpose, the extracted DOAs are convolved with a Gaussian point-spread function of 5° beamwidth and is shown in Fig. 2(c). The CLEAN algorithm leads to improved results over standard beamforming, but a small yet noticeable error of 5° exists in the DOA estimate of speaker 1 due to the effect of speaker 2 at the same Doppler. The RELAX algorithm is next applied, and the result is shown in Fig. 2(d). It is observed that the DOAs of the targets are estimated with greater accuracy (within 2°). The computational time, however, is increased by a factor of four when compared to CLEAN.

Measurements are next performed under the same indoor environment for three human subjects walking at a leisurely pace. Subjects 1 and 3 approach the radar and have positive Dopplers, while subject 2 walks away from the radar and has a negative Doppler, as shown in Fig. 3(a). Fig. 3(b)–(d) shows, respectively, the beamforming, CLEAN, and RELAX results for one captured time instant. In this figure, it is observed that additional micro Doppler components populate the Doppler

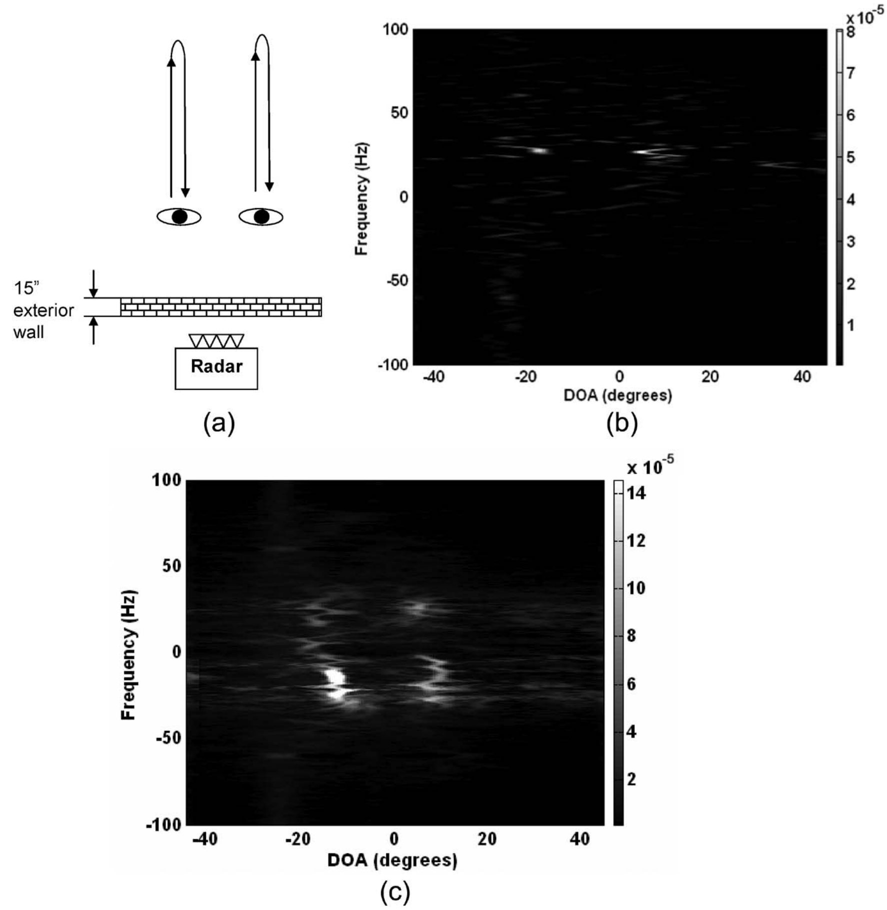

Fig. 5. Two human subjects in a through-wall scenario resolved in the DOA space. (a) Measurement setup. (b) CLEAN result for a single time instant. (c) Time-integrated CLEAN result.

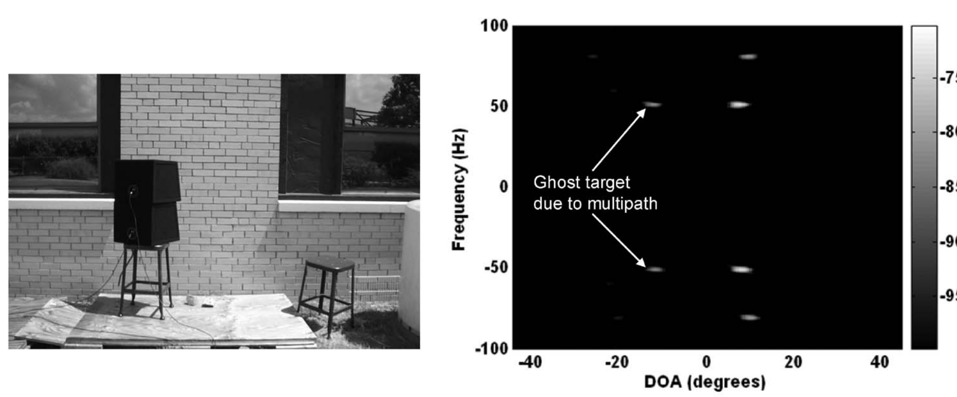

Fig. 6. Two loudspeaker targets in a through-wall scenario resolved in Doppler, in decibel scale. (a) Experimental setup. (b) CLEAN result.

spectrum due to the arm and leg motions of each subject. In spite of the Doppler overlap, the targets can be resolved in the Doppler–DOA space. The CLEAN results, again, show much better target separation than standard beamforming. The RELAX results, however, do not show any significant improvement over the CLEAN results. We believe that this is because each human is not a simple point target like the loudspeaker but is quite distributed in angle. Therefore, it is difficult to observe the improvement of $2^\circ - 3^\circ$ from the RELAX processing over the CLEAN processing. In subsequent processed data, only the CLEAN results are shown.

Next, measurements are conducted in a through-wall setup with two human subjects separated from the radar by an exterior brick wall of 15-in thickness. The distance between the radar and the wall is 3 ft. The transmit power used in the measurements is 15 dBm. Figs. 4 and 5 show the results from the CLEAN algorithm for two measurement cases. In the first case, two human subjects at distances of 5 and 15 ft from the wall walk in opposite directions with respect to the radar, as shown in Fig. 4(a). Fig. 4(b) shows the CLEAN result for a single time instant. Although there is significant attenuation caused by the wall, it is observed that subjects with nearly identical DOAs can be well resolved using Doppler processing. In the second case, the two subjects, separated from each other in bearing, walk together at the same pace, first away from the radar from 5 to 15 ft and, then, turn around and move toward the radar, as shown in Fig. 5(a). Fig. 5(b) shows the CLEAN result for a single time instant when the subjects approach the radar. It is shown that, while the subjects have similar Dopplers, they can be well resolved in the DOA domain. Fig. 5(c) shows the time-integrated Doppler–DOA map of the two subjects over the entire collection duration. Two clear tracks that are well resolved in the DOA space can be observed. Note that we did not compensate for the wall effect in the processing, and yet, no significant distortions on the DOA estimates were observed in our measurement. In general, however, the wall effect may be more significant, and additional deconvolution algorithms may be required to properly map the DOA.

Finally, we show that Doppler shifted multipath signals can sometimes be observed using the four-element array. In the setup, through-wall measurements are conducted with two loudspeakers separated from the radar by the same 15-in exterior brick wall as earlier. The two speakers are driven at different audio frequencies (50 and 80 Hz) but placed at the same DOA (10°), as shown in Fig. 6(a). The results of the measurements are shown in Fig. 6(b), where the two targets are well resolved in the Doppler space. However, we also observe a third ghost target at 50 Hz and a DOA position of -12°. This is most likely caused by multipath through the window. While wall phenomenology can, in general, be very complex, this case shows that spatial beamforming can be used to resolve environmental multipaths that would have been problematic for the two-element array described in [8]–[10].

IV. Conclusion

A four-element radar that combines Doppler processing with spatial beamforming for tracking multiple human subjects has been presented. The CLEAN and RELAX algorithms were implemented to improve the performance of standard beamforming. Results were demonstrated for human tracking in indoor LOS and through-wall scenarios. Our radar testbed operates in the CW mode. However, the concepts described in this letter should also be applicable to other waveforms such as linear FM or FMCW.

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