Multipath analyses of moving targets in enclosed structures using
Doppler radars

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ABSTRACT

In through-the-wall radar and urban sensing applications, detection, localization, and classification of targets are highly desirable. The presence of the targets inside buildings, and in close proximity of walls, floors, and ceilings, leads to a rich multipath environment. Multipaths can introduce false targets, thereby degrading target detection, localization, and classification performances. A multipath model based on the principles of ray tracing is advocated in this paper. We consider a diffused target moving in an enclosed urban structure being observed by a stationary Doppler radar. The model is verified using both simulated and experimental data. Further, we address the inverse problem of identifying the true Doppler peak given the Doppler spectrum, and show that the solution exists under partial knowledge of the angles of arrival.

Keywords: Multipath identification, through-the-wall radar, Doppler radar.

1. INTRODUCTION

Through-the-wall (TTW) radar imaging and urban sensing address the desire to obtain the internal layout of a building along with traditional radar capabilities, namely detection, classification, and localization of both stationary and moving targets inside the building1-4. Recent literature on urban sensing and TTW radar has focused on detecting, locating, and classifying both moving and stationary targets, without any consideration for multipath. The presence of targets in close proximity of walls, floor, and/or ceiling can introduce several multipaths in addition to the direct arrival in the radar return, leading to degradation in performance. It is, therefore, imperative that multipath for the problem at hand be thoroughly investigated.

Existence of multipath has been demonstrated recently for stationary targets behind walls5-7. In 5, a SAR image of a stationary human inside a room is shown along with ghost targets resulting from multipath. In 6, the authors use distributed fusion to remove the false targets caused from multipath and target interactions, when access to imaging from multiple sides of the building is available. In 7, time reversal techniques are employed to alleviate ghosting and clutter from the target scene. However, no rigorous multipath analysis is presented in the aforementioned references or their citations.

In this paper, we first derive a multipath model using a rigorous ray tracing approach for a moving target. The target is assumed to be diffused and present inside an enclosed structure, in close proximity of the front and side walls. Monostatic Doppler radar operation is considered and a priori knowledge of the building layout is assumed. The model can incorporate various target motion types, such as linear, accelerating, and micro-Doppler. The derived multipath model is then used to identify the true Doppler frequency of the target from the spectrum of the radar return. For pulse-Doppler radar, the multipaths appear at ranges farther than the direct path in the range-Doppler map, thereby identifying the true Doppler frequency. However, for a Doppler radar, such conclusions cannot be made due to lack of range resolution capability. We show that the inverse problem of true Doppler identification for Doppler radars can be solved under certain conditions, such as when partial knowledge of the angles of arrival is available. In this case, Doppler identification is equivalent to tagging the angles to the respective multipaths, and can be solved using simple maximum likelihood (ML) type decision rules. It is noted that the use of CW waveforms in conjunction with an array offers many advantages, which have been demonstrated experimentally in 8. Finally, simulation and experimental results are provided to validate the multipath analysis and proposed Doppler identification algorithm.

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The paper is organized as follows. In Section 2, the multipath model is derived. In Section 3, the inverse problem of Doppler identification is formulated and solved. Supporting simulation and experimental results are provided in Section 4. Section 5 contains concluding remarks.

2. MULTIPATH MODEL

Consider Fig. 1, which shows the two-dimensional (2D) scene under consideration at a discrete time instant, \( n \). The moving target is located in close proximity of the front wall (wall-1) and a side wall (wall-2). The walls are assumed to be homogeneous. Wall-1 has thickness \( d_1 \) and permittivity \( \varepsilon_1 \), while wall-2 has thickness \( d_2 \) and permittivity \( \varepsilon_2 \). In Fig. 1, the origin is marked as \( O \), and the stationary radar is located at point \( R \), whose coordinates in the \( x-y \) plane are given by \((-D_x, 0)\). The target is at location \( T \), given by \((-x(n), y(n))\). The standoff distance of the radar from wall-1 is denoted by \( D_y \). We will assume, for now, that the radar and the target are at the same height. The direct non-line-of-sight (NLOS) path from the radar to the target is denoted as Path-A in Fig. 1. Likewise, the first and second order multipaths are denoted as Path-B and Path-C, respectively. The first order multipath consists of one transmission through wall-1 and one exterior reflection at wall-2, while the second order multipath consists of one transmission through wall-1 and one internal reflection at wall-2. There also exist higher order signal transmissions through wall-1; an example of such a transmission is captured by Path-D in Fig. 1. We note that inclusion of Path-C in the analysis obligates us to include Path-D since both of these paths have similar strengths due to an equal number of reflections and transmissions, albeit through different walls. Some points of interest, such as \( B' \), \( C' \), and \( C'' \), pertaining to the respective paths \( B \) and \( C \) are shown in Fig. 1, and have the following coordinates

\[
B' = (y_1(n), 0), \quad C' = (y_3(n), 0), \quad C'' = (y_5(n), 0) \tag{1}
\]

The angles of incidence and refraction are shown in the Fig. 1 subscripted by their respective paths. For example, the angle of incidence pertaining to Path-A is denoted as \( \psi_{ab}(n) \), and the corresponding angle of refraction is denoted by \( \psi_{ra}(n) \). The angles are clearly a function of the time instant, \( n \). Other angles are denoted using similar naming convention. From Snell’s law, we have the following,

\[
\psi_{pa}(n) = \sin^{-1}\left(\frac{\sin(\psi_{pa}(n))}{\sqrt{\varepsilon_i}}\right), \quad p \in \{A, B, C, D\} \tag{2}
\]

\[
\psi_{ra}(n) = \sin^{-1}\left(\frac{\cos(\psi_{ra}(n))}{\sqrt{\varepsilon_2}}\right)
\]

Using the fact that the radar standoff distance does not change with time, \( n \), we obtain the following expressions after projecting the four paths onto the \( x \)-axis.

\[
d_1 \tan(\psi_{ba}(n)) + (y(n) - d_1) \tan(\psi_{ra}(n)) = D_x - x(n) \\
d_1 \tan(\psi_{ca}(n)) + (y(n) - d_1) \tan(\psi_{ra}(n)) = D_x \\
d_1 \tan(\psi_{cb}(n)) + (y(n) - d_1) \tan(\psi_{ra}(n)) = D_x \\
3d_1 \tan(\psi_{ba}(n)) + (y(n) - d_1) \tan(\psi_{ra}(n)) = D_x - x(n) \tag{3}
\]

Considering the reflection at wall-2 and using simple geometry, we obtain

\[
y_1(n) = y(n) - x(n) \cot(\psi_{ba}(n)) \\
y_2(n) = y(n) - x(n) \cot(\psi_{cb}(n)) \\
y_3(n) = y_2(n) - 2d_1 \tan(\psi_{cb}(n)) \tag{4}
\]

Equation (3), after substitution from (2) and (4), can be solved numerically for the various angles of incidence, and the angles of refraction can then be computed using (2).
In order to obtain the Doppler, it is important to obtain the time delays experienced by the radar returns corresponding to the various paths in Fig. 1. In this regard, the one-way time delays for the various paths can be readily derived, and are given by

\[
\tau_a(n) = \frac{1}{c} \left( \frac{d_1 \sqrt{\varepsilon_i}}{\cos(\psi_{ia}(n))} + \frac{y(n) - d_i}{\cos(\psi_{ia}(n))} \right) \\
\tau_b(n) = \frac{1}{c} \left( \frac{d_1 \sqrt{\varepsilon_i}}{\cos(\psi_{ib}(n))} + \frac{y_i(n) - d_i}{\cos(\psi_{ib}(n))} + \frac{x(n)}{\sin(\psi_{ib}(n))} \right) \\
\tau_c(n) = \frac{1}{c} \left( \frac{d_1 \sqrt{\varepsilon_i}}{\cos(\psi_{ic}(n))} + \frac{y_i(n) - d_i}{\cos(\psi_{ic}(n))} + \frac{2d_2 \sqrt{\varepsilon_i}}{\cos(\psi_{ic1}(n))} + \frac{x(n)}{\sin(\psi_{ic}(n))} \right) \\
\tau_d(n) = \frac{1}{c} \left( \frac{3d_1 \sqrt{\varepsilon_i}}{\cos(\psi_{id}(n))} + \frac{y(n) - d_i}{\cos(\psi_{id}(n))} \right) \\
\]  

(5)

The Doppler is proportional to the derivative of the time delays in (5) with respect to \( n \), which are given by

\[
\frac{d\tau_a}{dn} = \frac{1}{c} \left( \frac{d_1 \sqrt{\varepsilon_i} \sec(\psi_{ia}(n)) \tan(\psi_{ia}(n)) \frac{dy_{ia}}{dn} + (y(n) - d_i) \sec(\psi_{ia}(n)) \frac{dy_{ia}}{dn}}{\sec(\psi_{ia}(n))} \right) \\
\frac{d\tau_b}{dn} = \frac{1}{c} \left( \frac{d_1 \sqrt{\varepsilon_i} \sec(\psi_{ib}(n)) \tan(\psi_{ib}(n)) \frac{dy_{ib}}{dn} + (y_i(n) - d_i) \sec(\psi_{ib}(n)) \frac{dy_{ib}}{dn}}{\sec(\psi_{ib}(n))} \right) \\
\frac{d\tau_c}{dn} = \frac{1}{c} \left( \frac{d_1 \sqrt{\varepsilon_i} \sec(\psi_{ic}(n)) \tan(\psi_{ic}(n)) \frac{dy_{ic}}{dn} + (y_i(n) - d_i) \sec(\psi_{ic}(n)) \frac{dy_{ic}}{dn}}{\sec(\psi_{ic}(n))} \right) \\
\frac{d\tau_d}{dn} = \frac{1}{c} \left( \frac{3d_1 \sqrt{\varepsilon_i} \sec(\psi_{id}(n)) \tan(\psi_{id}(n)) \frac{dy_{id}}{dn} + (y(n) - d_i) \sec(\psi_{id}(n)) \frac{dy_{id}}{dn}}{\sec(\psi_{id}(n))} \right) \\
\]  

(6a, b)

In (6), the derivative of the angles with respect to \( n \) are required, which can also be derived in a straightforward manner, and are, therefore, not provided here.

The signal can propagate to and from the target along the paths defined in Fig. 1. The direct path is obtained when the signal propagates to the target and back along Path-A. All other combinations of the four paths on transmit and receive constitute either the multipaths or higher order signal transmissions through the front wall. Generally, if there are \( K \) possible one-way paths between the radar and the target, then the total number of round-trip paths is \( ^K C_2 \), where \( ^K C_q \) is the number of possible combinations for choosing \( q \) objects from a set of \( p \) objects. In our model, we have ten possible round-trip paths. The signals from these paths superpose and the radar return is given by
where $f$ is the carrier frequency of the Doppler radar, $\tau_p(0)$ and $\tau_q(0)$ are the delays corresponding to ranges at $n=0$ for the paths $p$ and $q$ respectively. The reflection coefficients, denoted by $\Gamma_p(n)$ and $\Gamma_q(n)$ for the paths $p$ and $q$ respectively, are time varying since the angles of incidence and refraction vary with time due to target motion. The reflection and transmission coefficients can be computed using the expressions in 9. It is noted that although the multipath model was derived for a Doppler radar, it is also applicable to pulse-Doppler radar systems 10.

3. TRUE DOPPLER IDENTIFICATION

The received signal spectrum may contain multiple peaks as a result of multipath. One of those peaks corresponds to the signal that has propagated to the target and back via the direct path only, and should be considered as indicating the true Doppler frequency. In this section, we apply the multipath model of Section 2 to identify the true Doppler peak amongst the multitude of peaks. The problem of Doppler peak identification is important because it can help reduce the false alarms, and may also aid in tracking the target using Doppler information. From the model, it is clear that the Doppler identification problem can be solved if and only if the angles are known. We thus assume that the angle of arrival information is available. In practice, this can be accomplished by using an array in conjunction with the Doppler radar system. The array need not be sophisticated since the simulation results show that precise knowledge of the angles is not required for the task at hand.

The estimated angles of incidence for the various paths in Fig. 1 are denoted by $\hat{\psi}_{ip}, p \in \{A,B,C,D\}$. The Doppler identification problem can be stated mathematically as follows. Given the angle estimates $\hat{\psi}_{ip}, p \in \{A,B,C,D\}$, the Doppler spectrum, the wall parameter pairs $(d_i, e_i), i=1,2$, and the standoff distances, $D_x$ and $D_y$, of the radar from both the walls, identify the peak corresponding to the target NLOS direct path. The target location $(-x(n), y(n))$ is unknown and has to be estimated from the angle information and the standoff distances. Consider Fig. 1, we obtain from simple trigonometric relations,

$$\cot(\psi_{ip}(n)) = \frac{y_i(n) - D_y - d_i}{D_i - D_x \tan(\psi_{ip}(n)) - d_i \tan(\psi_{ip}(n))}$$

$$\hat{\psi}_{ip}(n) = D_x \cot(\hat{\psi}_{ip}(n)) - d_i \cot(\hat{\psi}_{ip}(n)) \tan(\hat{\psi}_{ip}(n)) + d_i$$

Applying similar trigonometric relations to another triangle comprising of Path-B, we have

$$\tan(\psi_{ib}(n)) = \frac{x(n)}{y(n) - y_i(n)}$$

$$\hat{x}(n) = (\hat{y}(n) - \hat{y}_i(n)) \tan(\hat{\psi}_{ib}(n))$$

The following can also be readily shown,

$$\hat{y}(n) = \frac{D_x - d_i \tan(\hat{\psi}_{ib}(n)) + \hat{y}_i(n) \tan(\hat{\psi}_{ib}(n)) + d_i \tan(\hat{\psi}_{ib}(n))}{\tan(\hat{\psi}_{ib}(n)) + \tan(\hat{\psi}_{ib}(n))}$$

Substituting (10) in (12), and using (12) in (11), we can obtain the target location estimate. Also,
\[
\hat{y}_2(n) = \hat{y}(n) - \hat{x}(n) \cot(\hat{\psi}_c(n)) \\
\hat{y}_3(n) = \hat{y}_2(n) - 2d_z \tan(\hat{\psi}_c(n))
\] (13)

The above inverse problem formulation assumes that the angles generated by the phased array have already been tagged to their respective paths. In practice, however, only four angle estimates \(\psi_i(n), i = 1, \ldots, 4\) are available without any means of tagging each estimate to its respective path, i.e., \(\psi_i(n) = \hat{\psi}_{id}(n)\), \(\psi_2(n) = \hat{\psi}_{ic}(n)\) so on and so forth. We note that if the angles have been tagged to their respective paths, then true Doppler identification is established from the model. Therefore, the problem of Doppler identification is identical to tagging the angles to their respective paths. The algorithm below describes the Doppler identification /angle tagging technique.

a) Obtain the four angles for each time instant, as \(\psi_i(n), i = 1, \ldots, 4\).

b) Out of the \(4!\) permutations of the angles \(\psi_{id}, \psi_{ib}, \psi_{ic},\) and \(\psi_{id}\), consider one permutation and let the angles, \(\psi_i, i = 1, 2, 3, 4\), be tagged as such. For example \(\psi_1 = \hat{\psi}_{id}, \psi_2 = \hat{\psi}_{ib}, \psi_3 = \hat{\psi}_{ic}, \) and \(\psi_4 = \hat{\psi}_{ic}\).

c) Using the multipath model advocated in Section 2, obtain the Doppler spectrum with the peaks being indexed by the vector,

\[
\omega_k, k \in (1, 2, \ldots, 4!), \quad \omega_k = [\omega_{1k}, \ldots, \omega_{4k}]^T
\] (14)

d) Compute and store the mean square error between the frequency peak vector \(\omega_k\) and the frequency peak vector \(\omega\) obtained from the radar returns.

e) Repeat b) to d) selecting a different permutation of the angles, \(\psi_{id}, \psi_{ib}, \psi_{ic},\) and \(\psi_{id}\) to tag \(\psi_i, i = 1, 2, 3, 4\), to the four paths, until all such permutations are exhausted.

The true Doppler/angle tagging can be inferred from the index, \(\hat{k}\) corresponding to frequency vector \(\omega_k\) which yields the minimum mean square error (MSE), i.e.,

\[
\hat{k} = \arg \min_k \| \omega_k - \omega \|^2
\] (15)

Although this completes the Doppler identification solution, there exist other technical challenges that need to be addressed. We found from our extensive simulations (see Fig. 2(d) for example), that, for practical systems, the angles corresponding to Path-A and Path-D cannot be resolved; likewise, the angles corresponding to Path-B and Path-C are unresolved. This implies that the angles estimates obtained using the array could be less than 4. The algorithm as described in a)-e) can be readily tailored for this scenario. In fact, the algorithm will have reduced complexity in this case. In other words, instead of \(4!\) permutations, we only have to decide between \(2! = 2\) permutations. Specifically, the two permutations are,

\[
\psi_1 = \hat{\psi}_{id}, \psi_2 = \hat{\psi}_{id}, \psi_3 = \hat{\psi}_{ib}, \psi_4 = \hat{\psi}_{ib} \\
\psi_1 = \hat{\psi}_{ib}, \psi_2 = \hat{\psi}_{ib}, \psi_3 = \hat{\psi}_{ic}, \psi_4 = \hat{\psi}_{ic}
\] (16)

In (16), we note that the assumption \(\hat{\psi}_{id} = \hat{\psi}_{id}\), and \(\hat{\psi}_{ic} = \hat{\psi}_{ib}\) has been enforced since only two angles are resolved.

### 4. SIMULATIONS AND EXPERIMENTAL RESULTS

#### 4.1 Multipath model

A point target is assumed to be at initial position \(x(0) = 4\) m, \(y(0) = 14\) m and moving with velocities \(dx(n)/dn = v_x = -1\) m/s, and \(dy(n)/dn = v_y = -0.5\) m/s. The front and side walls have the same thickness and permittivity, \((d_i, \varepsilon_i) = (0.2\) m, 7.6\), \(i = 1, 2\). The radar is located at \((-10\) m, 0 m). The radar has a standoff distance \(D = 4\) m. from wall-1. We choose the sampling frequency to be 100 Hz. The antenna is assumed to be omni-directional.
and noise-free radar returns are analyzed. Using the multipath model, we obtain Fig. 2. Fig. 2(a) shows the combined Doppler spectrum while the Doppler spectra corresponding to the individual round-trip paths are depicted in Fig. 2(b). The reflection coefficients and the time varying angles are shown in Fig. 2(c-d), respectively. One can clearly see from Fig 2(c) that the reflection coefficients are more or less time invariant. It is also noted that the higher order multipaths and signal transmissions are quite weak and hence, the considered paths are sufficient to capture the multipath phenomenon. The spectrum in Fig. 2(a) shows three distinct Doppler peaks, one of which is the direct path. However, it is not possible to ascertain which peak corresponds to the true Doppler. The presence of only three peaks can be attributed to the fact that some of the paths, such as path-A and path-D, have the same Doppler (see Fig. 2(b)). Also, the angles corresponding to path-C and path-D are close to the angles of path-B and path-A, respectively, and are un-resolvable, as evident from Fig. 2(d). We also observe that the Doppler shifts are non-overlapping and can be easily separated using simple filters. Multipath mitigation becomes straightforward once the Doppler peak corresponding to the target has been identified.

4.2 True Doppler ID

The target in the $x$-$y$ plane is located initially at $x(0) = 4m, y(0) = 14m$ and is moving with velocities given by $v_x = 1m/s$, and $v_y = −1m/s$. In this case, we again observed that only two angles were resolvable. Therefore the number of permutations to be tested for the scenario is 2. We consider two possibilities regarding angle estimates. In the first case, we assume that the angle estimates provided by the array at each time instant are imprecise. This is simulated by perturbing the angles with a normal random variable of zero mean and variance, $\sigma^2$. For example, in the first permutation corresponding to the true Doppler case, we have

$$\psi_1(n) = \psi_{1a}(n) + u_1(n), \psi_2(n) = \psi_{1b}(n) + u_2(n)$$

$$E[u_1(n)u_2(k)] = \sigma^2 \delta(n-k), E[u_1(n)u_1(k)] = 0, \forall n,k$$

The number of Monte Carlo trials was set to 400, and $\sigma^2$ was varied from 0 to 0.1 in non uniform increments. As expected, the probability of correct Doppler identification decreases with increasing variance, as shown in Fig. 3.

For the second case, we assume that the angles cannot be tracked by the array, that is, the angles output by the array are not updated for every time instant. Rather, the angle estimates are provided after the entire dwell time, meaning that the angular extent corresponding to the direct and the multipaths is provided. Consider Fig. 4, which shows the histograms of the angles obtained for path-A and B. The histograms are well approximated by a uniform distribution within their respective supports. Thus, we assume that the angles are uniformly distributed with supports equal to the supports of the paths. For the permutation corresponding to the true Doppler case, we have

$$\psi_1(n) = u_1(n), \psi_2(n) = u_2(n)$$

$$u_1 \sim U[\inf\{\psi_{1a}(n)\}, \sup\{\psi_{1a}(n)\}], u_2 \sim U[\inf\{\psi_{1b}(n)\}, \sup\{\psi_{1b}(n)\}]$$

$$E[u_1(n)u_2(k)] = E[u_1(n)]E[u_2(k)], \forall n,k$$

where $U[a,b]$ denotes the uniform probability density function having support in $a$, and $b > a$. Similarly, the other permutation can be considered by using appropriate angles in (18). Since the target is slowly moving, for a small dwell we can approximate the velocities to be

$$v_x = E_n[dx(n)/dn], v_y = E_n[dy(n)/dn],$$

$$\frac{dx(n)}{dn} \approx \frac{x(n) - x(n-1)}{1}, \frac{dy(n)}{dn} \approx \frac{x(n) - x(n-1)}{1}$$

In (19), the mean of the finite differences is used to obtain the velocities. In the simulation, we consider six independent Monte Carlo runs; each run comprises 400 independent Monte Carlo trials. As shown in Fig. 5, the probability of selecting the correct Doppler frequency is approximately 1 in every run. The results in Figs. 4 and 5 indicate that the Doppler identification problem can be effectively solved. This is in contrast to Fig. 3. This is because, in generating Fig. 3, the simulated angles at each time instant were inaccurate, while in Figs. 4 and 5, the angles are randomly chosen, thereby yielding random target locations. However, the finite difference operator along with temporal mean as advocated
in (19) smoothes such random variations in the target locations, yielding good true Doppler velocity estimates and thus good selection probabilities. This lack of smoothing explains the degraded performance for small perturbations in Fig. 3.

We now vary the angle support to see the effect on Doppler identification. For the first permutation corresponding to the true Doppler, we use (18) with the exception that

\[ u_i \sim U[E_{a \psi_{id}}(n) - a, E_{a \psi_{id}}(n) + a], u_j \sim U[E_{a \psi_{sd}}(n) - a, E_{a \psi_{sd}}(n) + a] \quad (20) \]

The probability of correctly selecting the true Doppler peak is shown in Fig. 6. The results are self explanatory but we notice that the performance degrades only for a large \( a (>0.5 \text{ rad}) \), which is approximately twice the support of \( a \) corresponding to the true angle as seen in Fig. 4.

4.3 Experimental results

A Doppler radar, operating at 2.4GHz, was used to illuminate a human target, moving along the bore sight to the radar. The initial distance of the target from the radar was 0.3m. The antenna was at a height of 1.22m from the ground. The received signal was sampled at a rate of 1 kHz. In this case, the true target velocity was estimated by measuring the total distance traveled and the time lapsed. The data were decimated by a factor 2 before further processing. The person walked away from the radar without moving his arms adjacent to a solid concrete block wall of thickness 0.142m and a dielectric constant of 7.6. The experimental layout is similar to that in Fig. 1 except that the front wall is absent and a floor is present. The normalized spectra of the measured and the modeled returns (with the floor returns incorporated in the model of Section 2) are shown in Fig. 7. The RCS of the human target, which varies with angle, was not incorporated in the model, and therefore, the magnitudes of measured and the modeled spectra do not match. The measured spectrum shows several peaks, the one corresponding to the true Doppler is indicated in Fig. 7. Comparing the measured and the modeled spectra, we observe that the spectral supports of the two spectra overlap. Moreover, the spectral peaks and nulls of the two spectra are well aligned, except for one peak indicated by an arrow in Fig. 7 which is slightly misaligned. Thus, the multipath model is validated using experimental data.

5. CONCLUSIONS

This paper provides the first model of multipath in TTW radar to be published in the open literature. The model is validated by both simulation and the use or experimental data. The multipath is described using a mathematically rigorous ray tracing approach that addresses the multipath arising from internal walls and may be extended to include the floor and ceiling. Both wideband radar and narrowband radar can be used with the advocated model. In addition to allowing prediction of the received radar signal, the model can also be used to solve the inverse problem—that is identifying the true target return in the presence of multipath. For such operation, a maximum likelihood computation is combined with use of a phased array that provides angular information. The Doppler identification algorithm is shown to perform well when we have partial knowledge of the angles of arrival and is robust to errors in the angle of arrival estimates. The presented experimental results validate the theoretical findings.

REFERENCES


MULTIPATH MODEL

Figure 1 Multipath 2D model.

Figure 2. (a) Doppler spectrum, (b) Individual Doppler profiles.
Figure 2. (c) Reflection coefficients vs. Dwell, (d) Angles vs. Dwell.

Figure 3. Gaussian perturbation errors in angles.

Figure 4. True histograms of angles.

Figure 5. Probability of choosing correct Doppler when angles are uniformly distributed with identical pdf as in Fig. 4.

Figure 6. Performance for angles uniformly varying as defined by parameter, $\alpha$ in eq. (18). X-axis is log scale.
Figure 7. Experimental results for human target walking away from radar.