Spatial Channel Sounding Based on Bistatic Synthetic Aperture Radar Principles

Lin-Li Cui* | David G. Michelson | Wen-Qin Wang

Abstract—In this paper, we propose a simplified spatial channel sounding method by utilizing bistatic synthetic aperture radar (BiSAR) principles. Despite the different deployment geometries compared with a conventional BiSAR system, the feasibility of the approach is established by 1) the proposed method achieves a better spatial resolution than conventional directional channel sounders and 2) reconstruction algorithms based on time-domain back-projection in conjunction with a digital elevation model provide a good imaging performance and are suitable for reconstructing the spatial distribution of scatterers. Simulations of a high-speed rail (HSR) scenario demonstrate that the estimated power delay profiles (PDPs) and power angle profiles (PAPs) are close to the actual values.

Index Terms—Bistatic synthetic aperture radar (bistatic SAR), channel sounding, spatial channel modeling.

1. Introduction

Most conventional approaches to characterizing spatial channels with measured channel response data require either mechanically steerable directional antennas or multiple antenna systems at both transmitter (Tx) and receiver (Rx) to resolve directions of arrival and departure (DoA and DoD) of the wireless signals [1]-[4]. However, the mechanical approach is both time-consuming and restricted to static channels or the channels with low Doppler frequencies. For multiple antenna systems, the computational burden increases dramatically with the increasing number of antenna elements [5]. In addition, it is not easy to deploy either class of antenna in some special scenarios (e.g. high-speed railway (HSR)).

As the development of the long-term evolution for railways (LTE-R) system, the characterization of wireless channels in HSR scenarios has attracted considerable interests [6][7]. However, conventional spatial channel measurement approaches suffer from cost, size, and performance limitations, making them unsuitable in railway environments. Because the safety regulations imposed by train operators have restricted the vast majority of previous work to single-antenna measurement systems.

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It showed that a single antenna mounted aboard a moving high-speed train can be used to realize a virtual array for multiple-input multiple-output (MIMO) channel measurement\(^8\). The maximum array size is limited by 1) each sampling interval is between \(\lambda/4\) and \(\lambda/2\) and 2) the total sampling interval cannot exceed the coherence time of the channel. Therefore, different from conventional virtual arrays that operate in static or quasi-static environments, the useful size of a virtual moving array is limited to a few elements. This limitation dramatically reduces the angular resolution using classical DoA estimation algorithms such as multiple signal classification (MUSIC)\(^9\), estimating signal parameter via rotational invariance techniques (ESPRIT)\(^{10}\), and space alternating generalized expectation maximization (SAGE)\(^{11}\).

The similarities and correspondence between wireless channel sounding and bistatic synthetic aperture radar (BiSAR) are apparent. However, most of the previous work on BiSAR focused on Earth observation scenarios, where both the transmitter and receiver were above the Earth’s surface\(^{12}\). Recent work demonstrates the possibility of using terrestrial transmitter orthogonal frequency division multiplexing (OFDM) signals for Earth surface BiSAR imaging\(^{13}\).

The wireless channel measurement scheme for high speed orbits has a geometry that is very different from the previously considered BiSAR case. In \(^{14}\), the SAR concept was applied to implement a virtual antenna array. Kirchhoff migration was adopted in \(^{15}\) to obtain the geometrical parameters of a ray-optical propagation model. However, neither of these methods represents the system application of SAR technology in channel detection. Although the similarities between bistatic synthetic aperture radar and channel sounding are immediately apparent, it is necessary to verify the feasibility of channel sounding with BiSAR.

1) Resolution capability analysis: BiSAR is typically working in the far-field scenario such as remote sensing, rather than in the near-field such as channel sounding where the scatterers are close to the transmitter and receiver. Because the range resolution and Doppler resolution in BiSAR are dependent on the transmitter-receiver geometry and the topography of the scene, it is necessary to confirm that BiSAR can work well in a channel sounding geometry to meet the requirements of range-Doppler resolution.

2) Effective imaging algorithm with acceptable computation burden: In conventional remote sensing applications, BiSAR is utilized to create large geographical images, where the imaging areas may extend for tens of kilometers. In channel measurement applications, BiSAR is used to create scatterer maps which only extend for several kilometers or less. Meanwhile, an efficient imaging algorithm should be developed to reconstruct the distribution of scatterers in three-dimensional space for wireless communications.

3) Spatial channel characteristic extraction: The final stage of channel sounding is extracting channel characteristics, including both temporal and spatial information. Based on the scatterer map obtained by reconstruction of the scene, it is not difficult to extract these parameters. However, the efficiency and accuracy of the scheme must be verified.

The objective of this paper is to demonstrate the feasibility of channel sounding through BiSAR imaging and to show some preliminary results of the investigated spatial channel characteristics is based on scatterer images. The remainder of the paper is organized as follows. In Section 2, the system model is presented, along with the chosen scene reconstruction algorithm. A simulator is built in Section 3 to show the analysis procedure of the proposed channel sounding technique. Section 4 gives the simulation results, and discussions derived from these results are developed in Section 5. Conclusions are drawn in Section 6.

2. System Model

2.1. Problem Geometry

Fig. 1 (a) shows a typical high-mobility wireless channel measurement scenario for HSR. The transmitter (i.e.,
the base station, Tx) is stationary and generally located between 10 m and 50 m away from the railway track. The receiver (i.e., the train, Rx) is running on the railway track at a constant high speed (e.g., 360 km/h or 100 m/s). Scatterers, including trees, buildings, and terrain are distributed on both sides of the track.

A BiSAR with a stationary transmitter (ST-BiSAR) is depicted in Fig. 1 (b). The stationary transmitter (Tx) is located at \( r_T \). The receiver (Rx) is moving along the direction of positive \( y \) with a constant velocity \( v \) m/s. At the moment \( \eta \) (\( \eta \) denotes the azimuth time), the receiver is at \( r_R \) and the scatterer \( P \) is located at \( r_P \). Once all the scatterers have been identified by a suitable ST-BiSAR image reconstruction algorithm, the characteristics of the wireless channel can be determined.

2.2. Resolution Analysis

The reconstructed image is a map of the scatterers that comprise the scene. The resolution of the map must be appropriate in order to assess the impact of channel impairments on the performance of the wireless system. Therefore, it is necessary to study the impact of the scenario layout and geometry on the imaging resolution of the ST-BiSAR.

The imaging resolution in a conventional BiSAR is specified by the range resolution, Doppler resolution, and cross range resolution. These parameters are determined by three factors: The bandwidth of the probing signal emitted by the transmitter, the length of the synthetic aperture, and the bistatic geometry—the relative locations of the stationary transmitter and the track followed by the moving receiver.

Using gradient theory\(^{[16]}\), the range resolution \( \rho_r \) at the moment \( \eta \) is given by

\[
\rho_r = \frac{c}{B |\nabla R_\eta|} \tag{1}
\]

where \( B \) is the bandwidth and \( c \) is the speed of light. And \( \nabla R_\eta \) is the gradient of the bistatic distance \( R_\eta \), where \( R_\eta \) is

\[
R_\eta = |r_T - r_P| + |r_R - r_P| \tag{2}
\]

Ellipsoids with foci at Tx and Rx present a constant bistatic distance \( R_\eta \). Because the range history varies faster along the focal axis, a BiSAR can acquire a better range resolution than a conventional channel sounder.

The Doppler resolution at the moment \( \eta \) is given by

\[
\rho_d = \frac{1}{|\nabla f_\eta|} \tag{3}
\]
where $T$ is the synthetic processing time and $\nabla f_\eta$ is the gradient of the Doppler frequency. Based on the ST-BiSAR geometry in Fig. 1, the Doppler frequency is given by

$$f_\eta = -\frac{1}{\lambda} \left[ \mathbf{v} \cdot \left( \mathbf{r}_R - \mathbf{r}_P \right) \right]$$

(4)

where $\lambda$ is the wavelength. Higher velocity and closer distance to the scatterers cause quicker changes of Doppler frequency. This means that the Doppler resolution depends on the angular rate of the receiver.

Defining $\theta$ is the angle between the range resolution and the Doppler resolution, the cross-range resolution is

$$\rho_{XR} = \frac{\rho_r}{\sin \theta}$$

(5)

The best performance will be obtained when the range resolution and the Doppler resolution are orthogonal.

The projection of $\rho_r$, $\rho_d$, and $\rho_{XR}$ at the ground plane are $\rho_{rG}$, $\rho_{dG}$, and $\rho_{XRG}$, which will be the performance for the motion in the ground plane.

### 2.3. Scene Reconstruction with Back-projection Algorithm

 Several BiSAR scene reconstruction or imaging algorithms have been developed in recent years\cite{ref}. The time-domain back-projection (BP) is the most flexible BiSAR imaging algorithm. It reconstructs the scene on a pulse-by-pulse, pixel-by-pixel basis, and can perfectly accommodate both azimuth-variance and topography-dependence.

The basic concept of the back-projection algorithm is described below. For convenience, the locations of transmitter (Tx) and receiver (Rx) are $(x_r, y_r, h_r)$ and $(x_R, y_R, h_R)$, respectively. Assuming the pixel set of the imaging area of interest is $(x_i, y_j, h_k)$, and the transmitting signal is $s(t)$. The received signal from the point scatterer $(x_i, y_j, h_k)$ is given by

$$s_{r,i,j,k} = \sigma_{i,j,k} \cdot s \left( t - \frac{R_{T,i,j,k} + R_{R,i,j,k}}{c} \right)$$

(6)

where $\sigma_{i,j,k}$ is the scattering coefficient of the point scatterer $(x_i, y_j, h_k)$. $R_{T,i,j,k}$ is the distance between Tx and the point scatterer $(x_i, y_j, h_k)$:

$$R_{T,i,j,k} = \sqrt{(x_T - x_i)^2 + (y_T - y_j)^2 + (h_T - h_k)^2};$$

(7)

$R_{R,i,j,k}$ is the distance between Rx and the point scatter $(x_i, y_j, h_k)$

$$R_{R,i,j,k} = \sqrt{(x_R - x_i)^2 + (y_R - y_j)^2 + (h_R - h_k)^2};$$

(8)

So, the received signal is

$$s_r(t, \eta) = \sum_{i,j,k} \sigma_{i,j,k} \cdot s \left( t - \frac{R_{T,i,j,k} + R_{R,i,j,k}}{c} \right).$$

(9)

The BP imaging process can be described by

$$s_r(t, \eta) = \int \int s_{r,i,j,k}(t, \eta) \delta^* \left( t - \frac{R_{T,i,j,k} + R_{R,i,j,k}}{c} \right) \, dt \, d\eta = \int \int s_{r,i,j,k}(t, \eta) \delta^* \left( t - t_{i,j,k}(\eta) \right) \, dt \, d\eta$$

(10)

where $\delta^* \left( t - t_{i,j,k}(\eta) \right)$ is the matched filter for the point scatterer at $(x_i, y_j, h_k)$. The image pixel $(x_i, y_j, h_k)$ generated by the process is the convolution of the received BiSAR signal and the matched filter for the corresponding scatterer.

Range compression technique achieves a better resolution than the conventional pulse radar. Range compression is usually performed in the frequency domain with matched filters to increase computational
efficiency\textsuperscript{[18]}. In addition, various fast back-projection methods have been developed to use sub-aperture processing or parallel multi-core processing to improve performance\textsuperscript{[19],[20]}.

Most BiSAR reconstruction algorithms need to know the height of the scatterer at a particular location to ensure optimal Doppler focus. Digital elevation models (DEMs) of the terrain are generally provided for this purpose. For channel sounding applications, the height of the strongest scatterers can be refined using a 2-1/2-D approach. A multiplicity of scenes is reconstructed for different assumed scatterer heights. The height at which the primary scatterer comes into the sharpest focus will correspond to its correct height. This may not be practical for imaging applications, however, this approach is suitable for channel sounding applications because of less stringent resolution requirements and more attention to the main scatterers than the scene details.

3. Simulator

3.1. Methodology

The goal of this work is to verify the feasibility of the channel sounding based on the ST-BiSAR technique.

Firstly, the achievable resolution across the scene is analyzed based on selected ST-BiSAR geometry of HSR propagation scenario. Then, a simulator is built to extract the spatial channel parameters based on ST-BiSAR imaging, and to evaluate the feasibility and performance of the proposed channel sounding technique. As shown in Fig. 2, the simulation process is distributed across four stages. Each stage is described in details in the following subsections. Finally, the simulation results obtained are used to draw some conclusions concerning future research strategies.

3.2. Setup Simulation Scenarios

The first stage of the channel simulation process is to set up simulation scenarios. The detailed parameters of the simulator in this HSR geometry with ST-BiSAR mode are listed in Table 1.

Table 1: Simulation parameters

<table>
<thead>
<tr>
<th>Transmitting signal</th>
<th>Multi-carrier signal</th>
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<tr>
<td>Center frequency (GHz)</td>
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</tr>
<tr>
<td>Signal bandwidth (MHz)</td>
<td>100</td>
</tr>
<tr>
<td>Carrier interval (kHz)</td>
<td>500</td>
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<tr>
<td>Height of Tx (m)</td>
<td>30</td>
</tr>
<tr>
<td>Height of Rx (m)</td>
<td>4.5</td>
</tr>
<tr>
<td>Distance between Tx and Rx track (m)</td>
<td>50</td>
</tr>
<tr>
<td>Moving speed of Rx (m/s)</td>
<td>100</td>
</tr>
<tr>
<td>Height of scatterers (m)</td>
<td>0 to 20</td>
</tr>
</tbody>
</table>

Tx antenna | Omnidirectional antenna
Rx antenna | 180-degree sector antenna

Fig. 2. Channel simulator with four stages.
The transmit signal is selected as the multi-carrier signal so that the channel sounder is as similar as possible to the LTE-R base station and the remote terminal. The central frequency is at 2.35 GHz, and the bandwidth is 100 MHz with a carrier interval of 500 kHz.

Supposing the base station (Tx) is fixed and located 50 m away the railway track. The high-speed train (Rx) is moving along the railway at a constant velocity 100 m/s. The heights of Tx and Rx are 30 m and 4.5 m, respectively. The Tx antenna is an omnidirectional antenna that continuously emits signals. The Rx uses a 180-degree-sector antenna to receive the signals reflected by the scatterers on the left-side (or right-side) of the train. In the simulation coordinate frame, the Tx is located at the origin with a 3D coordinate (0, 0, 30), and the Rx is moving along the line x=50, parallel to the y-axis. All scatterers are randomly distributed in the propagation environment with their heights ranging from ground to 20 m. All of the scatterers present an isotropic response.

To properly assess the imaging performance, both point scatterers (PSs) and cluster scatterers (CSs) are considered. For point scatterers, we assume that the point scatterers are uniformly distributed in the 3D propagation space. For cluster scatterers, we assume that there are 10 point scatterers uniformly distributed around one cluster center. Cluster centers form a grid network across the imaging area, as shown in Fig. 3.

3.3. Generate Scatterer Images

The second stage of the simulation process is to reconstruct an image of the scene, a map of the scatterers, by applying the BiSAR back-projection algorithm to the received data. The flowchart of the scatterer map reconstruction process is shown in Fig. 4.

The received raw data is processed to achieve range compression first. This forms a range normalized 2D matrix with azimuth time on one axis and bistatic range on the other axis. In this domain, a single scatterer follows a hyperbolic trajectory in range-Doppler space. This data is the input to the back-projection reconstruction process.

Back-projection focuses a single point in 3D space at one time. Firstly, the range timeline for the point is computed, which forms a 1D trajectory of range vs time for the point (it will be a hyperbola). This range timeline is used to compute the expected signal phase history vs time. The range corrected data is then interpolated at the points given by this range timeline, which means that the 2D data is interpolated onto the 1D trajectory.

This gives the measured signal history vs time for a scatterer at the focus position. At this point, the expected and measured signal histories (each a 1D vector) are correlated to derive a complex scalar backscatter value by coherent superposition.
A single scatterer from the 3D imaging space is projected as a single point in a 3D space. However, almost all the imaging space for conventional BiSAR geometry is 2D. Doppler focusing is used here to extract the height information among the multilayer images for each scatterer. Simulation results further suggest that comparing the degree of Doppler focusing observed for alternative trial heights can be used to refine the estimated heights of significant scatterers. Such an approach is impractical for imaging applications, but may be acceptable for channel sounding applications which focus on the strongest multipath components.

### 3.4. Extract Channel Characteristics

The third stage of the simulation process is to extract channel characteristics based on the generated scatterer images. Each pixel in the images represents a possible scatterer. From the generated images, the geometry location and the intensity of the scatterer can be determined. Note that higher intensity means the greater possibility of existence and larger reflection coefficients.

To build a spatial channel model of the propagation environment, both temporal dispersion and angular information are required. The temporal dispersion performance can be characterized by root mean squared (RMS) delay spread and power delay profile (PDP). Angular performance can be characterized by power angle profile (PAP) and RMS angle spreads (AS), including angle-of-arrival (AOA), angle-of-departure (AOD), angle-in-azimuth (AIA), angle-in-elevation (AIE). All these information can be easily calculated using information obtained by considering the size and location of the dominant scatterers that comprise the scene.

### 3.5. Evaluate Performance

At the same time, in order to evaluate the proposed channel sounding method, theoretical or actual channel characteristics are calculated from known geometric information of scatterers that have been placed throughout the propagation environment.

The final stage of the simulation process is to evaluate the feasibility and performance of the proposed channel sounding approach based on BiSAR technique by comparing the channel characteristics calculated from the generated scatterer images to the actual ones.

### 4. Results

#### 4.1. Resolution Analysis

Imaging resolutions from the stationary transmitter-bistatic synthetic aperture (ST-BiSAR) technique are the theoretical basis of the accuracy of location of scatterers in the propagation environment. The space resolution of scatterers depends on the spatial imaging resolution, which means to cover x-y plane, x-z plane, and y-z plane. However, there are very slight differences for those resolutions across different heights in space. Hence, Fig. 5 only gives the imaging resolutions projected on the ground plane (i.e., x-y plane) in the specific HSR scenario. The horizontal axis (x-axis) and the vertical axis (y-axis) both span across −200 m to 200 m. At the specific instant of interest, the Tx is stationary and located at (0, 0, 30), while the Rx is passing the location (50, 0, 4.5) at a constant speed of 100 m/s in the y-direction.

Fig. 5 (a) shows the range resolution on the ground plane. Due to the 100 MHz bandwidth of the system, the ideal range resolution for synthetic aperture radar (SAR) is about 1.5 m. So, it is easy to see that most of the area has a good performance, especially the area along the Tx-Rx focal axis but beyond the line of sight. The center region between Tx and Rx that gives a finer range resolution than the surrounding regions, for instance, 2.5 m shown in Fig. 5 (a), although the resolution of 2.5 m is just about 8 ns. As the distance between Tx and Rx...
increases, this region becomes larger. However, these regions will be overlapped by higher resolution values when the Rx is moving and multiple snapshots of the scene are taken.

Figs. 5 (b) and (c) show the Doppler resolution and cross range resolution, respectively. The region along the Rx moving track experiences much coarser resolution than other regions do. This is because that scatterers in these locations present a very slow angular rate to the moving Rx. Except for these specific regions, the Doppler resolution and the cross-range resolution generally exhibits a good performance. To achieve a resolution of 0.35 m at a range of 200 m with a directional antenna would require an impossibly small beamwidth of 0.1 degree. Meanwhile, the resolution of 1 m (~3 ns) is very acceptable for channel estimation when the power delay profile (PDP) duration may exceed a microsecond in an outdoor environment. So, the performance of the ST-BiSAR technique over most regions is much better than those that can be achieved with conventional channel sounding approaches, whether with highly directional antennas or using high resolution direction-of-arrival (DOA) algorithms.

The BiSAR technique achieves a good resolution across the vast majority of the scene. There are still some small regions, e.g., along the Rx track or along Tx-Rx axis within the line of sight, where the resolution is coarse. However, because the Rx is moving, these regions will be covered by normal areas, which will largely improve the imaging resolutions.

Fig. 5. Imaging resolution projected on the ground plane: (a) range resolution, (b) Doppler resolution, and (c) cross-range resolution.
4.2. Imaging Performance

Fig. 6 shows the imaging performance of two point scatterers along the x-axis, y-axis, and z-axis, respectively. The vertical axis is power, referring to the normalized image intensity in dB. Figs. 6 (a) to (c) depict the first point scatterer located at (–40, 80, 15), and Figs. 6 (d) to (f) are for another point scatterer located at (67, 20, 19). The

![Graphs showing imaging performances](image)

Fig. 6. Imaging performances of two point scatterers. The first point scatterer is located at (–40, 80, 50), and its imaging performances are shown in (a) along x-axis, (b) along y-axis, and (c) along z-axis. The second point scatterer is located at (67, 20, 19), and its performances are shown in (d) along y-axis, (e) along x-axis, and (f) along z-axis.
actual locations are easily identified in each case. Although each scatterer at each location will be imaged with different levels of quality and resolution, the actual locations of dominant scatterers are easily distinguished in the vast majority of cases.

In the next set of results, a 200 m×200 m ground region is imaged around the base station and the train receiver, covering the range of x-axis from −50 m to 150 m and the range of y-axis from −100 m to 100 m. The height of the scatterers spans from ground level to 20 m. Because the antenna of the train-borne receiver uses a 180-degree-sector antenna, the propagation areas on the left and right sides of the moving track will be imaged separately. Fig. 7 shows a projected image of the scatterers on the ground plane. The horizontal or x-axis is transverse to the moving track, i.e., range or cross-track direction, with units in meters.

Meanwhile the vertical or y-axis is along the moving track also with units in meters. The imaged point scatterers from the left and right sides of the moving track are shown in Figs. 7 (a) and (b), respectively. The imaged cluster scatterers from the left and right sides of the moving track are shown in Figs. 7 (c) and (d), respectively. The corresponding actual scatterer images are shown in Figs. 7 (e) to (f). From the projected scatterer images, it can be seen that the strip close to the moving track, i.e., x=50, the imaged scatterers are blurred due to the coarser imaging resolution along the moving track, whether for point scatterers or cluster scatterers. By contrast, the imaged scatterers away from that strip can be clearly located.

Table 2 compares the channel characteristics obtained by BiSAR simulation with those obtained using actual scatterer sizes and locations. Both point scatterers (PSs) and cluster scatterers (CSs) are considered. The scatterers are distributed on the left side or right side of the railroad track. For point scatterers, 100 point scatterers are uniformly distributed in the 3D propagation space. For cluster scatterers, 16 cluster centers form a grid network across the imaging area, and 10 point scatterers are uniformly distributed around each cluster center, as shown in Fig. 3.

The notation “PS_L1” in Table 2 refers to point scatterers that are distributed on the left side of the moving track in the first simulation. The number 100 under PS_L1 refers to the total number of point scatterers. A similar notation is used in the column of the group name. The channel parameters include RMS delay spread (DS), RMS angular spread (AS), and the angle information including AOA in azimuth (AOA_az), AOA in elevation (AOA_el), AOD in azimuth (AOD_az), and AOD in elevation (AOD_el). For each group data, the actual values are shown against a light purple background to ease the task of comparing the estimated and actual values.

Fig. 8 gives five comparison charts for those channel parameters based on Table 2. The index number on the horizontal axis in these figures corresponds to the order of the group name. The black curves represent the calculated values; the red curves represent the theoretical ones. From Fig. 8, we can see that the overall delay spread performance is good, and the performance of point scatterers is better than that of the cluster scatterers. As to the space performances, the calculated values curves of AOA_az, AOA_el, and AOD_el match the theoretical values curves well. The relatively poor performance here is the comparison in AOD_az for scatterers located at the left of the moving track. Because the fixed transmitter is among the scatterers, whether point scatterers or cluster scatterers, the possibility of a blurred imaging scatterer may occur in a 360-degree round area, which easily increases the error range.

Figs. 9 and 10 give the power delay profiles (PDPs) and power angle profiles (PAPs) for the case PS_L1, respectively. In Fig. 9, the vertical coordinate “Power” is expressed on a linear scale. It can be seen that the simulation results match the theoretical values well. However, there are still many noisy components in the figures. It is not surprising that almost all of those noisy components are located on the ellipsoidal sphere of the known point scatterers, leading to the same time delay in the propagation channel. In Fig. 10, the power is normalized and expressed in dB. The shapes of the simulated PAPs are similar to the shapes of the theoretical values.
Fig. 7. Projected scatter images on the ground plane: The imaged pointed scatterers from the (a) left and (b) right sides of the moving track. The imaged cluster scatters from the (c) left and (d) right sides of the moving track, and (e) to (h) the corresponding theoretical scatter images.
To further compare the imaging performances for clusters of scatterers from different imaging regions, the cluster centers are formed into 16 groups across the whole imaging area, as shown in Fig. 11. And Fig. 12 gives the comparison charts for the groups of clusters of scatterers through two sets of simulation data.

In Fig. 12, the index number of the horizontal axis corresponds to the group number in Fig. 11. The curves with dots represent the results obtained from simulation; the curves with rhombus represent the theoretical results. Figs. 12 (a) to (e) show the comparison results from the first simulation, meanwhile Figs. 12 (f) to (j) give the second simulation results. Obviously, the scatterers farther away from the moving track give a better performance due to better imaging resolutions, whether the temporal dispersion performances or the angular performances. However, the absolute differences between the curves with dots and the curves with rhombus are not large, which means that the overall performance is good.

The back-projection algorithm is known to produce a good imaging performance but is time-consuming. In order to image the 3D space of 100 m×200 m×20 m with an equal resolution of 1 m, 40000 points are needed to be calculated by the back-projection algorithm, which needs 34 minutes in MATLAB R2013a based on a 2.4 GHz Intel Core i5 PC. This is an acceptable computational burden.

5. Discussion

Some preliminary results for channel sounding based on ST-BiSAR technique are presented. The feasibility of the proposed method is explored. From the simulation results shown above, we can draw following conclusions:

1) The proposed channel sounding approach based on ST-BiSAR technique is feasible. Once the scatterers in the propagation environment are located based on ST-BiSAR technique, the temporal dispersion and spatial information can be successfully extracted from the imaged scatterers. In all trials, both PDPs/PAPs figures and delay spread/angle spread tables, the simulation results match well with the theoretical values.

2) Practical limitations associated with imaging resolution influence the characteristics of the propagation channel. From Fig. 5, most regions of the observed propagation environment yield a good performance. In some limited areas, e.g., along the Rx moving track or along Tx-Rx axis within the line of sight, the spatial resolution is much coarser than that in surrounding areas. This limitation can be mitigated by combining images formed using different transmitters or based upon data collected over different synthetic apertures.

3) Back-projection is an effective technique for reconstructing the distribution of scatterers in the scene or

<table>
<thead>
<tr>
<th>Group name</th>
<th>Channel characteristic parameters</th>
</tr>
</thead>
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<tr>
<td></td>
<td>DS (μs)</td>
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<tr>
<td>PS_L1(100)</td>
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<tr>
<td>CS_R1(160)</td>
<td>0.1753</td>
</tr>
</tbody>
</table>
propagation environment. Back-projection is known as the best performance algorithm in SAR imaging, while it is also a huge time-consuming algorithm. However, the imaging area in the channel sounding approach is limited in the propagation environment.
several kilometers range instead of tens or hundreds km in remote sensing system, which reduces the amount of data. Moreover, the parallel computing platform can accelerate the implementation of this algorithm.

4) Back-projection is also an effective way to build a 3D propagation environment based on Doppler focusing to obtain spatial information. In general BiSAR applications, the imaging area is limited to the ground plane. From Fig. 6, the 2D imaging area can extends to 3D. And the imaging performance is relatively good. The 3D coordinates make it easy to identify each point scatter from the scatter image. However, the performance varies with the change of the location of the point scatterer. The overall performance is at an acceptable level.

6. Conclusions

This paper shows that the hardware requirements of spatial channel sounding can be vastly reduced by replacing mechanically steered directional antennas or large antenna arrays with a virtual array formed by a single antenna carried aboard a moving platform and processing the received signals using ST-BiSAR technique. It also demonstrates that back projection is a suitable method for reconstructing the scene and extracting a 3D map of dominant scatterers from the received signal from which a spatial channel model can be derived.
Fig. 11. Cluster scatterers forming 16 groups across the imaging area.
An ST-BiSAR simulator is developed in order to examine the technical challenges associated with using the BiSAR approach. The feasibility of the technique in a specific high-speed railway scenario is validated. Our results show that the ST-BiSAR scheme successfully estimates the spatial, angular, and time dispersion characteristics of a simulated propagation environment with a good accuracy while incurring a tractable computational burden. This confirms that the proposed approach to channel sounding is feasible and paves the way for demonstration of a prototype ST-BiSAR in the field in the near future.

Fig. 12. Grouped cluster scatterers imaging performance comparisons: (a) delay spread comparison, (b) AOA-azimuth comparison, (c) AOA-elevation comparison, (d) AOD-azimuth comparison, (e) AOD-elevation comparison, (f) delay spread comparison, (g) AOA-azimuth comparison, (h) AOA-elevation comparison, (i) AOD-azimuth comparison, and (j) AOD-elevation comparison.
CUI et al.: Spatial Channel Sounding Based on Bistatic Synthetic Aperture Radar Principles

References


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