Simulation of Passive Time-Reversal Surveillance System for Detection of Target Invasion Inside Forested Environment

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***Abstract* –Since time-varying and random components of channel response can be suppressed by using a passive time-reversal scheme, the scheme can efficiently decrease the clutter responses in a rich-clutter environment such as forest. Simulations are performed based on a realistic forest channel model to demonstrate the time-reversal scheme can be used to detect a target.**

***Index Terms* —Passive time-reversal, phase conjugation, target detection, rich-clutter environment.**

1. Introduction

A passive time-reversal (TR) scheme is a simplified TR technique [1-2]. A general TR system resends the TR signals that are previously received channel responses reversed in time domain. But in a passive TR scheme, such reversion and retransmission are performed in the post-processing with the convolution operation. Thus, it is known for the passive TR system to provide some advantages such as a simple system complexity and pulse compression [1].

A feasibility study of the passive TR scheme for target detections in time-varying rich-cluttered environments was performed in [2]. In this paper, we use a more realistic channel model, swaying vegetation model to characterize the detection performance of the passive TR system in more detail.

2. Target Detection Scenario

As shown in Fig. 1, multiple transceivers are placed with the equal space in the aperture direction (the direction of the *y*-axis). At a distance from the array in the range direction (the direction of the *x*-axis), there is a forest that consists of uniformly distributed trees. Then, the transceiver array monitors the forest by transmitting and receiving a pulse to and from the forest repeatedly in a given period (time resolution) of Δt. If a target enters from outside, then we may detect the target invasion. Moreover, using passive TR scheme, the clutter responses can be effectively suppressed. In this section, a forest channel model is used to generate forest channel signals. Then, a simulation of a target invasion scenario is performed.

(1) Forest Channel Model

Each tree is usually modeled by N independent point clutters whose position are uniformly distributed within

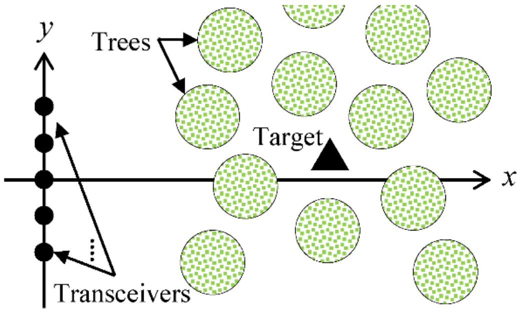

Fig. 1. Passive time-reversal detection scenario.

acylinder-shaped volume. Based on the multiple scattering theory [3], the magnitude of the scattering coefficient of the nth point clutter is

$$A_n = \sqrt{E\left[\sigma_{\text{Tree}}\right] / (4\pi N)}. \quad (1)$$

where $E[X]$ is the mean of a random variable, X and σ_{Tree} is the radar cross-section (RCS) of one tree [3].

The motion of each point clutter can generated by a mass-spring system expressed by the following differential equation [4]:

$$m_n \frac{\partial^2 \mathbf{r}_n(t)}{\partial t^2} + c_n \frac{\partial \mathbf{r}_n(t)}{\partial t} + k_n \mathbf{r}_n(t) = \mathbf{F}_n(t), \quad (2)$$

where the subscript n denotes the nth clutter. m_n, c_n, and k_n are the mass, damping factor, and spring constant, respectively. $\mathbf{r}_n$ is the positional vector. $\mathbf{F}_n$ is the external force applied to the corresponding clutter and can be generated by

$$\mathbf{F}_n(t) = C_d \rho w^2(t) A_n / 2, \quad (3)$$

where C_d is the drag coefficient, ρ is the air density, and A_n is the surface area of the nth clutter [4]. Von Karman power spectrum is used to generate $w(t)$, which is the wind speed profile. In addition, tree parameters such as A_n, m_n, c_n, and k_n are given in [5]. Fig. 2 shows a generated forest channel signal and its autocorrelation function for a 0.04 tree/m^2 density forest. The calculated channel coherence time is 48.1 ms, which is well matched with a known measurement data, 19.65 to 56.64 ms [6].

When a point target is located in the forest at a location of $\mathbf{r}_t$, then the channel signal can be expressed by using the Green's function as

$$H_m(f,t) = \frac{e^{-j\frac{4\pi f}{c}\left|\mathbf{r}_t - \mathbf{r}_m\right|}}{(4\pi)^2 \left|\mathbf{r}_t - \mathbf{r}_m\right|^2}\sigma_t + \sum_n \frac{e^{-j\frac{4\pi f}{c}\left|\mathbf{r}_n(t) - \mathbf{r}_m\right|}}{(4\pi)^2 \left|\mathbf{r}_n(t) - \mathbf{r}_m\right|^2} A_n, \quad (4)$$

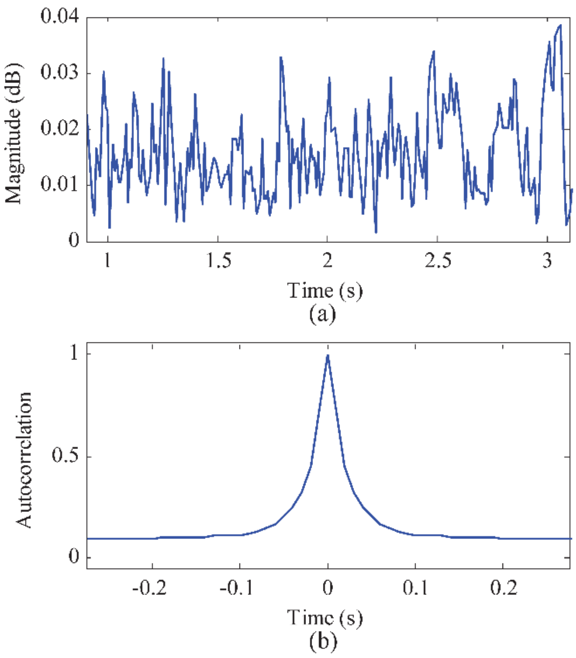

Fig. 2. Simulation result of (a) magnitude of forest channel signals at 5 m/s of average wind speed and its channel autocorrelation function.

where the subscript m denotes mth transceiver and σ_t is the scattering coefficient of the target. Since we are interested in the case that the target response is smaller than the overall clutter signal, the scattering coefficient σ_t is set to below A_n.

(2) Passive Time-Reversal Signals

Usually the presence of the target can be detected by comparing between (4) with and without the target. But the detection performance is not robust. In the proposed system, the channel signals are processed to divide the forest area into several sectors by using a multi-input-multi-output (MIMO) technique. First, the forest area is divided in the aperture direction using the uniform spacing and amplitude linear array factor [7] for the beamforming. Then, short-time Fourier transform (STFT) is applied to divide the signal in the range direction, which spatially divides channel signals, $H_{i,j}(f,t)$, where i and j are the indexes to denote the section location (e.g., $H_{1,1}(f,t)$ is the channel signal in the sector {1,1}). Fig. 3(a) shows the forest area divided into sectors. Next, the passive TR processing is individually applied to each sectors to suppress the clutter signals. The passive TR signal at the sector {i, j}, $S_{ij}(\Delta t,t)$, is given [2] by

$$S_{i,j}(\Delta t,t) = \frac{1}{C}\int_{f} H_{i,j}(f,t)H^{*}_{i,j}(f,t+\Delta t)\,df, \qquad (5)$$

where C is the normalizing factor [2], Δt is the difference in time between the two channel signals, and A^* is the complex conjugate of A.

In Fig. 3, the generated passive TR signals are shown. As can be seen, when $\Delta t = 0$, regardless of any sectors, the passive TR signals equal to 1. However, those signals approaches to different levels with Δt. For instance, the signal at the sector {4,2} approaches to a certain level and keep fluctuating. On the other hand, at the sector {4,3} or {4,4}, these signals approach to near zero. Those difference in magnitude mainly caused by the target. Since the target

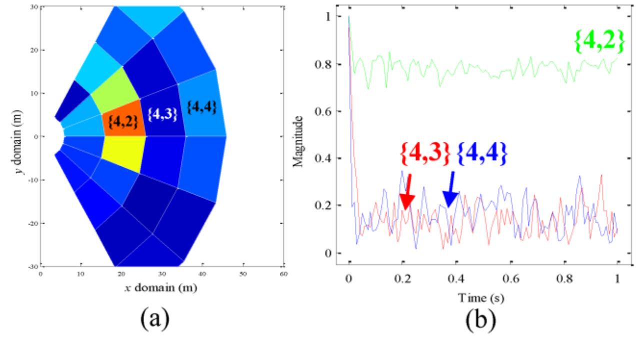

Fig. 3. Magnitude of passive time-reversal signals: (a) in 2D sector view at Δt = 0.2 s, and (b) time domain view at three sectors {4,2}, {4,3}, {4,4}.

and clutters are assumed time-invariant and time-varying objects, respectively, the passive TR system can efficiently decompose the responses.

3. Conclusion

A passive TR surveillance system is proposed and its performance simulation is provided. To generate realistic forest channel signals, a forest is realized by uniformly distributing multiple trees. Each tree consists of many point clutters and the motions of those point clutters are generated based on Newtonian mechanism with an input of the wind speed. To detect not only the invasion of a target into the forest but also the location of it, using a MIMO technique and the STFT, the forest area is divided into multiple sectors. Then, the passive TR scheme is applied to each divided channel signal. The target and its location can be identified with a high contrast.

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