Proceedings of ISAP 2014, Kaohsiung, Taiwan, Dec. 2-5, 2014

Enumeration of Unresolved Radar Targets with Beamspace Post-Doppler CFAR

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***Abstract*— In this paper, enumeration method for unresolved radar targets containing in one specific Doppler bin in radar array antenna is proposed. The proposed method uses adaptive threshold to detect targets in beamspace and post-Doppler domain to improve target enumeration accuracy in lower SNR with respect to conventional MDL (Minimum Description Length) based method. Moreover, unlike those conventional methods, threshold in the proposed method is controlled to maintain the user-specified probability of false enumeration. By computer simulation, the proposed method achieved 62.3 % of enumeration accuracy in the scenario of two highly-correlated mainbeam target of respective SNR = 20 dB while MDL achieved 9.1 % of the accuracy.**

I. Introduction

Unresolved multiple radar targets in one specific detection cell degrade radar measurement accuracy by conventional measurement techniques. This is because that those techniques such as monopulse angle measurement are assuming single radar target in the detection cell. Thus enumeration of unresolved radar targets is crucial for accurate radar measurement as well as situational awareness.

MDL and AIC (Akaike Information Criteria) are well-known signal enumeration method used in array signal processing [1]. For radar application, SIGNED-MDL (Signal Number Detection by Eigenbeamforming and Doppler Filter with MDL), where MDL applied in beamspace and post-Doppler domain, is proposed [2][3]. SIGNED-MDL shows improvement of enumeration accuracy in lower SNR condition successfully with respect to MDL. Those methods, however, utilize a sufficient statistic with a penalty function, i.e. information theoretic criteria, rather than threshold. In essence, probability of false enumeration is determined uniquely thus one could not specify probability of false enumeration by controlling threshold level which should be set corresponding to user's requirement.

In this paper, a threshold-based enumeration method for unresolved radar targets containing in one specific Doppler bin is proposed. As with the SIGNED-MDL, received signal is fed into multiple eigenbeamformer followed by slow-time FFT (Fast Fourier Transform) to integrate target power into one specific Doppler bin. Subsequently, CFAR (Constant False Alarm Rate) threshold maintaining the user-specified false enumeration rate is applied to test the target Doppler bin for each eigenbeam so that targets enumeration is accomplished by picking up the target-detected eigenbeams.

II. Proposed Enumuration Method

A. Signal Model in Beamspace and Post-Doppler Domain

Received signal vector containing $K(\leq M)$ targets from direction $\mathbf{u}_k=[u_k,v_k]^T$ impinging on array antenna with M spatial channel is defined as $\mathbf{x}(n)=\mathbf{A}\mathbf{s}(n)+\mathbf{n}(n)$, where n and $\mathbf{n}(n)$ are coherent pulse number and Gaussian receiver noise vector respectively. $\mathbf{s}(n)$ is consist of complex amplitude of the k-th target $s_k(n)$. The k-th steering vector $\mathbf{a}(\mathbf{u}_k)$ is stored in $\mathbf{A}=[\mathbf{a}(\mathbf{u}_1)\ \cdots\ \mathbf{a}(\mathbf{u}_K)]$. Sample covariance matrix is given as $\hat{\mathbf{R}}_{\mathbf{xx}}=N^{-1}\sum_{n=1}^{N}\mathbf{x}(n)\mathbf{x}(n)^H=\hat{\mathbf{E}}\hat{\mathbf{\Lambda}}\hat{\mathbf{E}}^H$, where $\hat{\Lambda}$ is a diagonal matrix consist of eigenvalues in descending order $\hat{\lambda}_m$ and $\hat{\mathbf{E}}=[\hat{\mathbf{e}}_1,\cdots,\hat{\mathbf{e}}_M]$ is consist of the corresponding eigenvector $\hat{\mathbf{e}}_m$. $\hat{\lambda}_1,\cdots,\hat{\lambda}_K$ and $\hat{\mathbf{e}}_1,\cdots,\hat{\mathbf{e}}_K$ are termed as signal eigenvalue and eigenvector respectively. $\hat{\lambda}_{K+1},\cdots,\hat{\lambda}_M$ and $\hat{\mathbf{e}}_{K+1},\cdots,\hat{\mathbf{e}}_M$ are termed as noise eigenvalue and eigenvector respectively. MDL and AIC enumerate target signals using respective information theoretic criteria for the eigenvalue distribution $\hat{\lambda}_1\geq\cdots\geq\hat{\lambda}_K\gg\hat{\lambda}_{K+1}\geq\cdots\geq\hat{\lambda}_M$ when $K<M$.

Since $\mathbf{a}(\mathbf{u}_k)$ spans signal subspace, following equality holds

$$\hat{\mathbf{E}}_N{}^H\mathbf{a}(\theta_k)=\mathbf{0}_{M\times 1} \tag{1}$$

where $\hat{\mathbf{E}}_N=[\hat{\mathbf{e}}_{K+1},\cdots,\hat{\mathbf{e}}_M]$ spans noise subspace. Eigenbeams are given as $\hat{y}_m(n)=\hat{\mathbf{e}}_m{}^H\mathbf{x}(n)$, i.e. beamspace processing. Specifically, signal eigenbeams containing K targets, i.e. $\hat{y}_m(n)$ for $1\leq m\leq K$, is expressed as $\hat{y}_m(n)=\sum_{k=1}^{K}\hat{c}_k^{(m)}s_k(n)+n_m(n)$, where $\hat{c}_k^{(m)}=\mathbf{a}_k{}^H\hat{\mathbf{e}}_m$ and $n_m(n)=\mathbf{e}_m{}^H\mathbf{n}(n)$. The rest of eigenbeans is expressed as $\hat{y}_m(n)=n_m(n)$ from (1) for $K+1\leq m\leq M$, i.e. noise eigenbeams. Note that noise subspace and noise eigenbeams are not defined when $K=M$.

Radar target signal observed in slow-time domain is expressed as a sinusoidal signal, $s_k(n)=A_k\exp(j2\pi f_k n)$, where are A_k and f_k are complex-amplitude and normalized Doppler frequency respectively for the k-th target. In this study, $f_1,\ldots,f_K$ are constrained to be within Doppler resolution. Thus $s_k(n)$ is highly-correlated or coherent signal. Now signal eigenbeam $\hat{y}_m(n)$ is expressed as

$$\hat{y}_m(n)=\sum_{k=1}^{K}\hat{c}_k^{(m)}A_k\exp(j2\pi f_k n)+n_m(n) \tag{2}$$

By noticing that signal eigenbeam $\hat{y}_m(n)$ of (2) is a linear combination of K sinusoidal signals, slow-time FFT, aka pulse Doppler filter bank, is applied to coherently integrate target signals into one specific Doppler bin. Doppler power spectrum, i.e. post-Doppler data, is obtained as $\left|\hat{Z}_m(l)\right|^2$, where $\hat{Z}_m(l)$ is the *l*-th FFT output in the *m*-th eigenbeam.

B. *Target Enumuration with CFAR Threshold*

CFAR detection is widely used in radar system to maintain a constant probability of false alarm under heterogeneous and changing interference environment. CFAR threshold is adaptively obtained from an estimate of the average interference power in the reference bins and CFAR coefficient adjusted to maintain the probability of false alarm.

In our proposed enumeration method, CFAR threshold is applied to $\left|\hat{Z}_m(l)\right|^2$ to test the integrated target power in the Doppler bin. By assuming that target Doppler bin is known in advance by conventional target detection process, an estimate of the average receiver power is obtained from reference Doppler bins surrounding the target Doppler bin under test and the adjacent guard bins. By expressing the CFAR detection result for the *m*-th eigenbeam as

$$b(m)=\begin{cases}1 & \text{for signal detection}\\ 0 & \text{for othwewise}\end{cases}, \tag{3}$$

target enumeration is given as $\hat{K}=\sum_{m=1}^{M} b(m)$.

Based on user-specified probability of false enumeration P_{fe}, the corresponding probability of false alarm $P_{fa}^{(\mathrm{CFAR})}$ in CFAR detectors is given by using following equation.

$$P_{fa}^{(\mathrm{CFAR})}=1-\left(1-P_{fe}\right)^{-M} \tag{4}$$

The function block diagram of the proposed enumeration method is given in Fig.1. Since interference in $\mathbf{x}(n)$ is Gaussian receiver noise, CA (Cell Averaging) -CFAR is used to minimize CFAR loss in this study.

It should be noted that the proposed method can enumerate targets when $K=M$ due to using threshold unlike the information criteria based method. This would be great advantage since one could enumerate targets up to $K=2$ in minimum $M=2$ channels monopulse radar.

III. Computer Simulation

Element antenna position of a linear array antenna is illustrated in Fig.2 for computer simulation to highlight the effectiveness of the proposed enumeration method. Inter-element space is half-wavelength of operating frequency 10 GHz and thinning taper is applied to achieve lower antenna sidelobes and 1.7 deg of the antenna beamwidth. Total 54 elements antennas are grouped into four non-overlapping subarray as seen in the Fig.2. Two target signals are separated by half-beamwidth and 1/3 of normalized Doppler frequency in one specific Doppler bin. Sample covariance matrix with 32 coherent pulses is obtained with forward/backward averaging [4] to decorrelate the two signals and Hamming window is applied for slow-time FFT.

Target enumeration accuracy, i.e. probability of correct enumeration, is obtained for SNR through 10000 trials in Fig.3. Note SNR is defined at post-FFT stage for respective target. Performance of the proposed method is improved by increasing of P_{fe} from 0.01 to 0.1 as seen in the Fig 3. This is natural result because the corresponding thresholds in CFAR detectors are lowered. Especially the proposed method for the case of $P_{fe}=0.1$ outperforms both of SIGNED-MDL and MDL. For SNR = 20 dB, the proposed method achieved 62.3 % of enumeration accuracy while SIGNED-MDL and MDL achieved 57.3 % and 9.1 % respectively.

IV. Concluding Remark

Enumeration method for unresolved targets containing in one specific Doppler bin is proposed. The method uses threshold maintaining the user-specified probability of false enumeration and test targets in beamspace and post-Doppler domain. By computer simulation, the proposed method achieved 62.3 % of enumeration accuracy in the scenario of two highly-correlated mainbeam target of respective SNR = 20 dB while MDL achieved 9.1 % of the accuracy.

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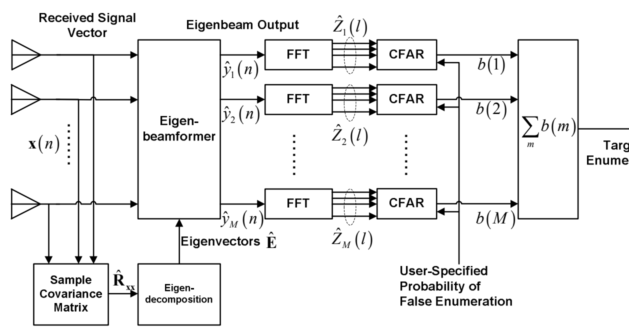

Figure 1. The function block diagram of the proposed method.

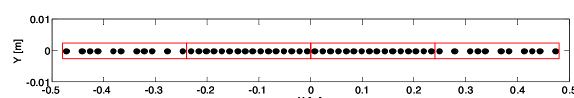

Figure 2. Element antenna position indicated by black color circle and four subarray divided by red color line.

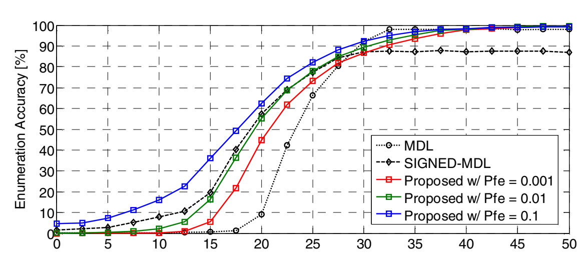

Figure 3. Target enumeratoin accuracy vs. SNR for two highly-correlated mainbeam target