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14. ABSTRACT A multiple-input multiple-output (MIMO) radar system, unlike a standard phased-array radar, can transmit via its antennas linearly independent waveforms. We have made significant contributions on exploiting the waveform diversity offered by MIMO radar to achieve superior performance. First, we have considered a MIMO radar system where both the transmitter and receiver have multiple well-separated subarrays with each subarray containing closely-spaced antennas. Because of this general antenna configuration, both the waveform diversity gain and the spatial angular diversity gain can be simultaneously achieved. Second, we have devised a cyclic optimization algorithm for the synthesis of signal waveform matrix X whose covariance matrix R is equal or close to a previously optimized covariance matrix. Third, we have developed a weighted least-squares based non-parametric and user parameter-free iterative adaptive approach (IAA), which can work well for MIMO radar applications, such as space-time adaptive processing (STAP) for ground moving target indication (GMTI). We have listed papers that provide details.					
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MIMO Radar
- Diversity Means Superiority

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1. Summary

A multiple-input multiple-output (MIMO) radar uses multiple antennas to simultaneously transmit several linearly independent waveforms. It also uses multiple antennas to receive the reflected signals. It has been shown that by exploiting this waveform diversity, MIMO radar can overcome performance degradations caused by radar cross section (RCS) fluctuations, achieve flexible spatial transmit beam pattern designs, provide high-resolution spatial spectral estimates, and significantly improve the parameter identifiability. The MIMO radar can be grouped into two classes according to their antenna configurations. One class is the conventional radar array, in which both the transmitting and receiving antennas are closely spaced for coherent transmission and detection. The other class is the diverse antenna configuration, where the antennas are separated far away from each other to achieve spatial diversity gain.

The waveform diversity offered by MIMO radar is the main reason for its superiority over standard phased-array radar, which transmits scaled versions of a single waveform. For colocated transmit and receive antennas, for example, MIMO radar has been shown to have the following appealing features: higher resolution, superior moving target detection ability, better parameter identifiability, and direct applicability of adaptive array techniques; in addition, the covariance matrix of the probing signal vector transmitted by a MIMO radar system can be designed to approximate a desired transmit pattern – an operation that, once again, would be hardly possible for conventional phased-array radar. An interesting current research topic in this area of MIMO radar system is the optimal synthesis of the transmitted waveforms. Optimization of a performance metric directly with respect to the signal matrix can lead to an intractable problem even under a relatively simple low peak-to-average-power ratio (PAR) constraint. For this reason, we proposed the following strategy: first optimize the performance metric of interest with respect to the signal covariance matrix \mathbf{R} ; and then synthesize a signal waveform matrix that, under low PAR constraint, realize (at least approximately) the optimal covariance matrix derived in the first step. We presented a cyclic optimization algorithm for the synthesis of a signal waveform matrix to (approximately) realize a given covariance matrix \mathbf{R} , under the constant modulus constraints or low PAR constraint. The output of the cyclic algorithm can be used to obtain either a waveform matrix whose covariance matrix is exactly equal to \mathbf{R} but whose PAR is slightly larger than the imposed value, or a waveform matrix with the imposed PAR but whose covariance matrix may differ slightly from \mathbf{R} – the type of application will dictate which one of these two kinds of waveforms will be more useful.

As a MIMO radar can transmit different waveforms, reflected signals from scattering points will lack coherency, which facilitates the application of adaptive array techniques. When the array steering vectors are accurately known, existing approaches, such as Capon and APES, have been shown to offer increased resolution and better interference rejection. However, when high levels of noise or model errors are present, the performance of these existing adaptive approaches can degrade significantly.

Recently, a weighted least-squares based non-parametric and user parameter-free iterative adaptive approach (IAA) was proposed in array processing and other sensing applications. IAA can work with few snapshots (even one) under considerable noise, arbitrary array geometries, and uncorrelated as well as correlated sources. The Bayesian information criterion (BIC) can be used to sparsify the IAA estimates. Further improvements in performance can be achieved by employing the last step of the parametric RELAX algorithm initiated by the estimates of IAA with BIC. The RELAX extension also allows IAA to estimate off-grid sources more accurately. Although IAA is derived and analyzed under the passive array processing framework, it can also be applied to active sensing applications, such as single-input single-output (SISO) radar range-Doppler imaging, and space-time adaptive processing (STAP), due to the similarities of the underlying data models. We showed via simulations that IAA outperforms the most competitive methods in the literature in the corresponding application areas. It is important to note that IAA can be applied to all discussed application areas without any essential modifications. IAA appears to be a viable candidate for practical applications as it does not require any user parameter, has a simple formulation, provides superresolution, facilitates parallel processing and shows good performance and robustness.

2. Selected Paper Abstracts

L. Xu and J. Li, "Iterative Generalized Likelihood Ratio Test for MIMO Radar," *IEEE Transactions on Signal Processing*, Vol. 55, No. 6, pp. 2375-2385, June 2007.

We consider a multiple-input multiple-output (MIMO) radar system where both the transmitter and receiver have multiple well-separated subarrays with each subarray containing closely-spaced antennas. Because of this general antenna configuration, both the coherent processing gain and the spatial diversity gain can be simultaneously achieved. We compare several spatial spectral estimators, including Capon and APES, for target detection and parameter estimation. We introduce a generalized likelihood ratio test (GLRT) and a conditional generalized likelihood ratio test (cGLRT) for the general antenna configuration. Based on GLRT and cGLRT, we then propose an iterative GLRT (iGLRT) procedure for target detection and parameter estimation. Via several numerical examples, we show that iGLRT can provide excellent detection and estimation performance at a low computational cost.

P. Stoica, J. Li, and X. Zhu, "Waveform Synthesis for Diversity-Based Transmit Beampattern Design," *IEEE Transactions on Signal Processing*, Vol. 56, No. 6, pp. 2593-2598, June 2008.

Transmit beampattern design is a critically important task in many fields including defense and homeland security as well as biomedical applications. Flexible transmit beampattern designs can be achieved by exploiting the waveform diversity offered by an array of sensors that transmit probing signals chosen at will. Unlike a standard phased-array, which transmits scaled versions of a single waveform, a waveform diversity based system offers the flexibility of choosing how the different probing signals are correlated with one another. Recently proposed techniques for waveform

diversity-based transmit beampattern design have focused on the optimization of the covariance matrix \mathbf{R} of the waveforms, as optimizing a performance metric directly with respect to the waveform matrix is a more complicated operation. Given an \mathbf{R} , obtained in a previous optimization stage or simply pre-specified, the problem becomes that of determining a signal waveform matrix \mathbf{X} whose covariance matrix is equal or close to \mathbf{R} , and which also satisfies some practically motivated constraints (such as constant-modulus or low peak-to-average-power ratio constraints). We propose a cyclic optimization algorithm for the synthesis of such an \mathbf{X} , which (approximately) realizes a given optimal covariance matrix \mathbf{R} under various practical constraints. A numerical example is presented to demonstrate the effectiveness of the proposed algorithm.

J. Li, L. Xu, P. Stoica, D. Bliss, and K. Forsythe, "Range Compression and Waveform Optimization for MIMO Radar – A Cramer-Rao Bound Based Study," *IEEE Transactions on Signal Processing*, Vol. 56, No. 1, pp. 218-232, January 2008.

A multi-input multi-output (MIMO) radar system, unlike standard phased-array radar, can transmit via its antennas multiple probing signals that may be correlated or uncorrelated with each other. This waveform diversity offered by MIMO radar enables superior capabilities compared with a standard phased-array radar. One of the common practices in radar has been range compression. We first address the question of "to compress or not to compress" by considering both the Cramér-Rao bound (CRB) and the sufficient statistic for parameter estimation. Next, we consider MIMO radar waveform optimization for parameter estimation for the general case of multiple targets in the presence of spatially colored interference and noise. We optimize the probing signal vector of a MIMO radar system by considering several design criteria, including minimizing the trace, determinant, and the largest eigenvalue of the CRB matrix. We also consider waveform optimization by minimizing the CRB of one of the target angles only or one of the target amplitudes only. Numerical examples are provided to demonstrate the effectiveness of the approaches we consider herein.

X. Tan, W. Roberts, J. Li, and P. Stoica, "Range-Doppler Imaging Via a Train of Probing Pulses," *IEEE Transactions on Signal Processing*, Vol. 57, No. 3, pp. 1084-1097, March 2009.

We consider range-Doppler imaging via transmitting a train of probing pulses. We present two methods for range-Doppler imaging. The first one is based on the instrumental variables (IV) filter and the second one is based on the iterative adaptive approach (IAA). Numerical results show that both methods can suppress interference from neighboring range and Doppler bins. An attractive feature of the IV filter is that it can be computed offline. IAA has better performance than IV and has super resolution, but at the cost of a higher computational complexity.

J. Li, P. Stoica, and X. Zhu, "MIMO Radar Waveform Synthesis," *2008 IEEE Radar Conference*, Rome, Italy, May 2008, invited.

A multi-input multi-output (MIMO) radar system, unlike a standard phased-array radar, can transmit multiple probing signals that are correlated or uncorrelated with each other. This waveform diversity offered by the MIMO radar is the main reason for its superiority over the standard phased-array radar. An interesting current research topic in MIMO radar is the optimal synthesis of the transmitted waveforms. Recently proposed techniques for MIMO radar waveform synthesis have focused on the optimization of the covariance matrix \mathbf{R} of the waveforms, as optimizing a performance metric directly with respect to the waveform matrix is a more complicated operation. Given an \mathbf{R} , the problem becomes that of determining a signal waveform matrix \mathbf{X} whose covariance matrix is equal or close to \mathbf{R} , and which also satisfies some practically motivated constraints. We propose a cyclic optimization algorithm for the synthesis of such an \mathbf{X} , which (approximately) realized a given optimal covariance matrix \mathbf{R} under various practical constraints, and which also has good auto- and cross- correlation properties in time, if desired. A number of numerical examples are presented to demonstrate the effectiveness of the proposed algorithm.

J. Li, X. Zhu, P. Stoica, and M. Rangaswamy, "High Resolution Angle-Doppler Imaging for MTI Radar," *IEEE Transactions on Aerospace and Electronic Systems*, to appear.

To reduce the need for training data or for accurate prior knowledge of the clutter statistics in space-time adaptive processing (STAP), we consider high resolution angle-Doppler imaging by processing each range bin of interest independently. Specifically, we use a weighted least squares based iterative adaptive approach (IAA) to form angle-Doppler images of both clutter and targets for each range bin of interest. The resulting angle-Doppler images can be used with localized detection approaches for moving target indication (MTI). We show via numerical examples that the robust and non-parametric IAA algorithm can be used to enhance the MTI performance significantly as compared to existing approaches.

M. Xue, D. Vu, L. Xu, J. Li, and P. Stoica, "On MIMO Radar Transmission Schemes for Ground Moving Target Indication," *The 43rd Asilomar Conference on Signals, Systems and Computers* (invited), Pacific Grove, CA, November 2009.

We compare several multiple-input multiple-output (MIMO) radar transmission schemes, including code division, time division, and Doppler frequency division approaches, for Ground Moving Target Indication (GMTI). To obtain probing waveforms with low sidelobe levels for range compression, we transmit sequences specifically designed to have low correlation levels. At the receiver side, we apply the Iterative Adaptive Approach (IAA), which uses only the primary data, to form high resolution angle-Doppler images. To mimic real world scenarios, we apply our algorithms to a simulated dataset which contains high-fidelity, site-specific, simulated

ground clutter returns. By combining the usage of intelligent transmission schemes, probing waveforms with good correlation properties, and the adaptive angle-Doppler imaging approach, we show that slow moving targets can be more clearly separated from the clutter ridge in the angle-Doppler images by MIMO radar than by the conventional single-input multiple-output (SIMO) radar.

3. Awards

The Second Place Best Student Paper Award at the 41st Asilomar Conference on Signals, Systems and Computer in Pacific Grove, California, for the paper:

X. Zhu, J. Li, P. Stoica, and J. R. Guerci, "Knowledge-Aided Space-Time Adaptive Processing", *41st Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, November, 2007.

Lockheed-Martin Best Student Paper Award at 2009 SPIE Defense, Security, and Sensing Conference (invited), Orlando, Florida, for the paper:

W. Roberts, H. He, X. Tan, M. Xue, D. Vu, J. Li and P. Stoica, "Probing waveform synthesis and receive filter design for active sensing systems," *2009 SPIE Defense, Security, and Sensing Conference* (invited), Orlando, Florida, April 13-17, 2009.

4. Students

Xumin Zhu (graduated with Ph.D.), Xing Tan, Duc Vu, Arsen Ivanov, William Roberts (SMART Fellowship).