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13. ABSTRACT *(Maximum 200 Words)*
Recent advances in sensor technology have created great interest in building networked sensor systems for both civilian and military applications employing low-cost, low-power, multi-functional sensor nodes which carry their own power sources. Our results show the significant potential of joint optimization of distributed sensor processing and networking for Air Force applications. In particular, we focus on target detection and estimation applications requiring energy efficiency, like MIMO radar systems with unmanned vehicle sensor nodes, which are of great interest to the Department of Defense and in particular to the Air Force, but our research will also benefit nonmilitary applications and provide improvements beyond energy efficiency. This research has produced several important research contributions to the communications, signal processing and data fusion communities. It was shown that if the sensors know that their data is to be used to solve a specific target detection and estimation problem, they are able to determine what data is necessary to accurately solve these problems and which data which is already well described by previously observed data. Thus joint design can enable a new generation of technologies for solving important real-world problems related to large-scale networks of monitoring sensors spread over large regions.

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NETWORKING SENSORS FOR INFORMATION DOMINANCE - JOINT SIGNAL PROCESSING AND COMMUNICATION DESIGN
AFOSR grant No. FA9550-09-1-0576
Annual Report (Submitted Dec. 2011)

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1. Objectives

Multiple UAV sensor/radar nodes, connected by wireless communication networks, offer tremendous potential surveillance performance. However, this comes with some inherent limitations. The most severe limitation is likely that each UAV has limited data rate and energy supply. In some of the work completed under this grant, we were able to demonstrate that these challenges can be addressed by jointly designing the signal processing and communications. Thus the communication network exploits the knowledge of the particular signal processing application (for example target detection, estimation, classification) the network is aiming to perform to obtain greatly improved performance.
As a particular example of our joint design work, we developed a joint Communications and signal processing approach where each sensor is able to individually, without consulting the other sensors, judge the importance of its data. Those sensors with the most informative data transmit this data first and the sensors with less important data can save energy by not transmitting any data. With a proper transmission stopping rule, this approach yields the same performance as if all sensors transmit and yet very impressive energy/rate savings are achieved in many cases of interest (significant SNR or number of sensors or proper system design). Our first results on this topic focused on signal/target detection problems and on joint design employing the lower levels of the communication network. We later investigated appropriate higher layer designs to capitalize on these gains and we also studied estimation, classification and general optimization problems. We demonstrated the approach on MIMO radar networks. Along the way, we made some fundamental contributions to the theory of MIMO radar and the high citation rates and great interest from the radar community indicate the importance of this work. Lately we have also received great interest from DoD contractors, indicating that MIMO radar seems to have achieved an even greater level of acceptance. There are indications that MIMO radar technology is on the verge of appearing in the next generation of defense equipment.

2. Executive Summary

We are very proud of the great progress we have made towards studying the joint design of signal processing and communication strategies where we focus on networks of sensor/radar nodes that are widely dispersed over space. One early major area of focus of this project was on developing appropriate signal processing and communication strategies for networks which focus on target detection or hypothesis testing problems. Many important military and non-military applications are specific cases of this general problem. Hypothesis testing, or signal detection, is a fundamental sensor networking application which is employed for solving many important problems including improved monitoring, control and repair of the human body, buildings, bridges, energy production facilities, the environment and other critical infrastructure, while also providing important contributions to homeland security, law enforcement, disaster prediction/avoidance and defense related problems. As an example, we collaborated with faculty in the civil engineering department at Lehigh University on monitoring the health of large structures (for example bridges, buildings and airplanes) to detect problems before they occur. There are many applications of this type which directly fit our paradigm and there are some other applications that indirectly fit our paradigm. As an example, we collaborated with scientists in the Biological Sciences department at Lehigh University, who were studying cells from a basic scientific perspective. In their scientific experiments they typically pose hypothesis testing problems and attempt to make decisions based on sensor measurements. In these applications it is important to limit the number of measurements to avoid damaging the living organisms under study and so we limit sensor measurements for a different reason, as opposed to trying to save precious battery power, but our general theory still applies.

Using the supplied funding, we have developed promising approaches for saving battery power and data rate for important military applications employing sensors. We initially developed a highly efficient suboptimum approach which saves energy proportional to the number of sensors employed provided the signal to be detected is observed with sufficient signal-to-noise ratio. For such cases, the average number of sensor transmissions saved over the optimum unconstrained energy approach is larger than half the number of sensors employed. For the large and very important case of noncoherent detection, using the supplied funding we were able to show the gains are much larger. We later extended our approaches for non-target detection applications including estimation, classification and optimization problems. We generally found even larger gains in these cases, when compared to signal detection, for typical scenarios of interest (for example well designed systems).

A second major area of focus has been on developing MIMO radar signal processing technology and also similar ideas for more general sensor networks. Some of this work was done in collaboration with some other PIs that were funded by AFOSR. The original MIMO radar ideas were developed under AFOSR funding and we since the topic is so new there are still many open questions. Thus, we continued to develop the theory of MIMO radar and this work continues to attract great attention from the research community. This is evidenced by the high citation rates of our papers and the large number of papers on MIMO radar at conferences and in journal publications. More recently we are getting lots of interest from DoD contractors who want to employ MIMO radar ideas into future DoD radar systems which is very exciting.

3. Accomplishments (all references from list in Section 5)

We are very excited about our very recent work on applying joint design to estimation and optimization problems [14,22,26]. For the case where data is obtained from a set of dispersed sensor nodes and the overall metric is a sum of individual metrics computed at each sensor, a discretized version of a continuous optimization problem is considered. Maximum likelihood estimation based on statistically independent sensor observations is an example of such a problem [4,5,9,16,20,32]. By ordering transmissions from the sensor nodes, a technique we call ordering, a method for achieving a saving in the average number of sensor transmissions is described. While the average number of sensor transmissions is reduced, the approach always yields the same solution as the optimum approach where all sensor transmissions occur. The approach is valid for a general optimization or estimation problem provided the overall metric is a sum of individual metrics computed at each sensor. A maximum likelihood target location and velocity estimation example for a multiple node non-coherent MIMO radar system was investigated in great detail [14,22,26]. In particular, for cases with N good quality sensors with sufficiently well designed signals and sufficiently large signal-to-interference-plus-noise ratio, the average percentage of transmissions saved approaches 100 percent as the number of discrete grid points in the optimization problem Q becomes significantly large. In these same cases, the average percentage of transmissions saved approaches (Q-1)/Q x 100 percent as the number of sensors N in the network becomes significantly large. Similar savings are illustrated for general optimization (or estimation) problems with sufficiently well designed systems where the overall metric is a sum of individual metrics computed at each sensor. Savings can be even larger in some cases for systems with some poor quality sensors. One important result is that timing errors, clock errors and unknown communication delays can be overcome without significant impact in many applications [14].

We have also made some contributions to the topic of applying ordering to signal detection problems under this grant. The robustness due to timing errors, clock errors and unknown communication delays described in [14] for estimation and optimization problems also applies to detection problems since [14] describes a general method to put "out of order" transmissions back in order. We have also shown that the ordering for detection ideas we published earlier do apply to MIMO radar systems [29]. Further, the gains for the MIMO radar application are even larger than the gains reported earlier. First, we have provided [29] an improved ordering approach for any noncoherent processing approach and the MIMO radar system considered in [29] is one such approach. Second, we show [29] that the gains are very large for practical systems with very small false alarm probabilities. Finally, we have discussed [8,23] a useful methodology for efficiently implementing ordering approaches in radar systems by describing an efficient implementation of some of the important subsystems required.

We have made considerable progress in developing the theory for networks of radar sensors. First showing [9,16,20,32] that we can control the performance of both the noncoherent and coherent approaches by the number of antennas employed. Thus the improvements in the position and velocity estimation scale directly in proportion to the product of the number of transmitter antennas times the number of receiver antennas as shown in

[9], and to a lesser extent [1,4,5,11,15,16,17,20,32]. Similar gains occur for detection problems [2,10,13,21,28,29]. The results in [9,16] are very important in justifying the value of the noncoherent approach by showing [32] that the noncoherent approach can be made to perform as close as desired to a coherent approach if a sufficient number of properly placed antennas are employed. Our fundamental investigations on the accuracy of the approaches for target estimation in ideal [1,5,9,11] and nonideal [4] settings have also demonstrated significant potential for MIMO radar. In fact, our results indicate that slow oscillator phase drifts or static phase errors may not be such a big problem [4] for MIMO radar.

Our publications on MIMO radar have brought new attention to the diversity gains that occur in radar systems that are similar to the diversity gains that occur in communication systems. We have recently demonstrated that one needs complex targets to get these gains [2] but that orthogonal signals, Gaussian reflections and Gaussian clutter are not needed [13]. In particular, our results in [13] show that the diversity gain of the noncoherent MIMO radar approach is not dependent on the particular clutter-plus-noise distribution for any well behaved (finite power) clutter-plus-noise distribution. We are particularly excited about our findings on diversity in non-Gaussian clutter-plus-noise [13]. For a radar system adopting the Neyman-Pearson (NP) criterion, we have derived the diversity gain for a general scalar hypothesis test statistic and a general vector hypothesis testing problem.

For a MIMO radar system with M transmit and N receive antennas, used to detect a target composed of Q random scatterers with possibly non-Gaussian reflection coefficients in the presence of possibly non-Gaussian clutter-plus-noise, in [13] we considered a class of test statistics, including the optimum test for Gaussian reflection coefficients and Gaussian clutter-plus-noise, and applied the previously described general (last paragraph) results to compute the diversity gain. It was found that the diversity gain for the MIMO radar system is dependent on some specific properties of the cumulative distribution function (cdf) of the reflected signal (and thus it depends on the distribution of the reflection coefficients) while being invariant to the exact cdf of the bounded variance clutter-plus-noise. If the transmitted waveforms span a space of dimension L, the largest possible diversity gain is no greater than p min(NL,Q), where p is the lowest order coefficient of a Taylor series expansion of the cdf of the reflected signal and L can be no greater than M. Thus orthogonal signals are not need to achieve the largest possible diversity gain of p min(NM,Q), only linear independence. In some cases of interest (independent reflections), it is shown that the maximum possible diversity gain can be achieved.

We were also able to demonstrate [10] a new gain, called geometry gain, in MIMO radar moving target detection applications that looks a bit like a diversity gain but which is distinctly different. It comes from viewing the motion of the target from different directions and developing the estimated (fused) motion to be consistent with all these views. We have received some significant interest from industry in these results due to the practical importance and difficult nature of this problem.

Industry and academia are both very interested in waveform design for MIMO radar. They need these designs in real implementations and theory is lacking. We have studied this problem for classification and high resolution estimation applications in [6,18,19]. Here we were able to extend some of our previous theoretical results which showed equivalence (in the design of the waveform correlation matrix) between optimizing for mean-square error and mutual information. The previous results demonstrated the equivalence without producing the actual waveforms. In [6,18,19], we provided an algorithm to produce actual waveforms and we showed these practical waveforms produced results that were indistinguishable from our previous theoretical predictions in a large number of example cases considered. Thus, these practical waveforms jointly optimized mean-square error and mutual information for the example cases considered to the highest accuracy we could achieve in our computations. We were recently the first group to demonstrate large potential gains in tracking performance from MIMO radar systems and in [17,33] we study the effect of the antenna positions, target location, path loss, target reflectivity, and the number of antennas (radar nodes) employed.

Some other contributions to image fusion, MIMO radar, communications and smart grid are reported in [3,7,12,25,27,30,31]. Here we have tried to use some of the ideas and techniques studied under this funding for some different applications from those previously considered, mainly radar and sensor networking.

4. Personnel Supported

Rick S. Blum, (PI) Professor of ECE
Xun Chen, Research Assistant
Jim Davis, Research Assistant
Ziad Rawas, Research Assistant
Zhemin Xu, Research Assistant
Qian He, Research Assistant
Yang Yang, Research Assistant
Anand Srinivas Guruswamy, Research Assistant
Joe Baker, Research Assistant
Chuanming Wei, Research Assistant
Liang Zhao, Research Assistant
Qian He, postdoc
Yang Yang, Postdoc

5. Technical Publications

Journal Papers
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1. Hana Godrich, Alexander Haimovich, Rick S. Blum, ``Target Localisation Techniques
and Tools for multiple-input multiple-output radar,'' Radar, Sonar & Navigation, IET,
Vol. 3, Issue 4, pp. 314-327, Aug. 2009.

2. Rick S. Blum, "Limiting Case of a Lack of Rich Scattering Environment for MIMO Radar Diversity'', IEEE Signal Processing Letters, Volume 16, Issue 10, Oct. 2009, pp. 901-904.

3. Chuanming Wei and Rick S. Blum,``Theoretical analysis of correlation-based quality measures for weighted averaging image fusion,''Information Fusion (10 November 2009).

4. Qian He, Rick S. Blum, "Cramer-Rao Bound for MIMO Radar Target Localization with Phase Errors'', IEEE Signal Processing Letters, vol. 17, no. 1, pp. 83-86, Jan 2010.

5. Qian He, R. S. Blum, H. Godrich, and A. M. Haimovich, "Target Velocity Estimation and Antenna Placement for MIMO Radar with Widely Separated Antennas'', IEEE Journal of Selected Topics in Signal Processing, Special Issue on MIMO Radar, Vol. 4, Issue 1, pp. 79-100, Feb. 2010.

6. Y. Yang, R. S. Blum, Z. S. He, and D. R. Fuhrmann, ``MIMO radar waveform design via alternating projection,'' IEEE Transactions on Signal Processing, Vol. 58, Issue 3, Part 1, pp. 1440-1445, 2010.

7. Zhemin Xu, Sana Sfar, Rick S. Blum, ``Receive Antenna Selection for Closely-Spaced Antennas with Mutual Coupling'', IEEE Transactions on Wireless Communications., Vol. 9, Issue 2, pp. 652-661, Feb. 2010.

8. Y. Yang, R. S. Blum and B. M. Sadler, "A Distributed and Energy-Efficient Framework for Neyman-Pearson Detection of Fluctuating Signals in Large-Scale Sensor Networks," IEEE Transactions on Selected Areas in Communications, vol. 28, no. 7, September 2010.

9. Qian He, Rick S. Blum, and Alexander M. Haimovich, "Non-coherent MIMO Radar for location and velocity estimation: More antennas means better performance'', IEEE Transactions on Signal Processing, vol. 58, no. 7, pp. 3661-3680, Jul 2010.

10. Qian He, Nikolaus H. Lehmann, Rick S. Blum, and Alexander M. Haimovich, "MIMO Radar Moving Target Detection in Homogeneous Clutter,'' IEEE Trans. on Aerospace and Electronic Systems, vol. 46, no. 3, pp. 1290-1301, Jul 2010.

11. Hana Godrich, Alexander M. Haimovich, and Rick S. Blum, ``Target Localization Accuracy Gain in MIMO Radar Based Systems,'' IEEE Trans. on Information Theory, Vol. 56, No. 6, pp. 2783-2803, June 2010.

12. Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum, "Diffuse Prior Monotonic Likelihood Ratio Test for Evaluation of Fused Image Quality Measures", IEEE Trans. on Image Processing, Vol. 20, No. 2, pp. 327-344, Feb. 2011.

13. Qian He and R. S. Blum. ``Diversity Gain for MIMO Neyman-Pearson Signal Detection,'' IEEE Transactions on Signal Processing, Vol. 59, No. 3, pp 869-881, March 2011.

14. Rick S. Blum, "Ordering for Estimation and Optimization in Energy Efficient Sensor Networks", IEEE Transactions on Signal Processing, vol. 59, issue 6, pp. 2847-2856, June 2011.

15. Min Jiang, Ruixin Niu, and Rick S. Blum,``Bayesian target location and velocity estimation for multiple-input multiple-output radar'', IET Radar, Sonar & Navigation, Volume 5, Issue: 6,
pp. 666 - 670, 2011.

Conf. papers
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16 Qian He and R. S. Blum, ``Performance and complexity issues in noncoherent and coherent MIMO radar,'' invited paper for the 43rd IEEE Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, Nov 2009.

17 Hana Godrich , Alexander M. Haimovich and Rick S. Blum, A MIMO Radar System Approach to Target Tracking, invited paper for 2009 Asilomar Conference on Signals, Systems and Computers.

18 Y. Yang, R. S. Blum, Z. S. He, and D. R. Fuhrmann, ``Waveform design for MIMO radar using an alternating projection approach,'' in Proceedings of Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, November 2009.

19 Y. Yang, R. S. Blum, Z. He, and D. R. Fuhrmann, ``Alternating projection for MIMO radar waveform design,'' invited paper for CAMSAP 2009 (Dec. 2009), pp. 169-172.

20 Chuanming Wei, Qian He, and Rick S. Blum, "Cramer-rao bound for joint location and velocity estimation in multi-target non-coherent MIMO radars", CISS 2010.

21 Xun Chen, R. S. Blum, ``Non-coherent MIMO radar in a non-Gaussian clutter-plus-noise environment,'' CISS 2010.

22 R. S. Blum, ``Ordering for Estimation", CISS 2010.

23 Y. Yang, R. S. Blum, and B. M. Sadler, ``Distributed energy-efficient scheduling for radar signal detection in sensor networks,'' 2010 IEEE International Radar Conference, pp. 1094-1099, 2010.

24 Qian He and R. S. Blum, "Diversity gain for MIMO radar employing nonorthogonal waveforms", invited paper for the 4th International Symposium on Communications, Control and Signal Processing, pp. 1-6, Limassol, Cyprus, Mar 2010.

25 Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum, Diffuse Prior Monotonic Likelihood Ratio Test for Evaluation of Fused Image Quality Metrics, in proceeding of the 12th International Conference on Information Fusion, pp. 1076-1083, Seattle, WA, Jul. 6-9, 2009.

26 Rick S. Blum, ``Ordering for Estimation and Optimization", International Conference on Acoustics, Speech and Signal Processing (ICASSP) 2011.

27 Qian He and Rick S. Blum, ``Smart Grid Monitoring for Intrusion and Fault Detection with New Locally Optimum Testing Procedures", ICASSP 2011.

28 Qian He and Rick S. Blum, ``MIMO Radar Diversity with Neyman-Pearson Signal Detection in Non-Gaussian Circumstance with Non-orthogonal Waveforms'', ICASSP 2011.

29 Ziad Rawas, Qian He and Rick S. Blum, "Energy-Efficient Noncoherent Signal Detection for Networked Sensors Using Ordered Transmissions", Conference on Information Sciences and Systems, Johns Hopkins, March 2011.

30 Qian He and R. S. Blum, "New Hypothesis Testing-Based Methods for Fault Detection for Smart Grid Systems", Conference on Information Sciences and Systems, Johns Hopkins, March 2011.

31 Qian He and R. S. Blum. ``Smart Grid Fault Detection Using Locally Optimum Unknown or Estimated Direction Hypothesis Test,'' to appear, the 2011 IEEE International Conference on Smart Grid and Clean Energy Technologies (ICSGCE), Chengdu, China, Sep 2011.

32 Qian He, R. S. Blum, and Zishu He. ``Noncoherent Versus Coherent MIMO Radar for Joint Target Position and Velocity Estimation,'' to appear, the 2011 IEEE CIE International Conference on Radar, Chengdu, China, Oct 2011.

33. H. Godrich, V. M. Chiriac, A. M. Haimovich, and R. S. Blum, Target tracking in MIMO radar systems: Techniques and performance analysis, 2010 Radar Conference, pp. 1111 – 1116, 2010.

6. Interactions/Transitions

6.1 Conference Presentations

Qian He and R. S. Blum, ``Performance and complexity issues in noncoherent and coherent MIMO radar,'' invited paper for the 43rd IEEE Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, Nov 2009.

Hana Godrich , Alexander M. Haimovich and Rick S. Blum, A MIMO Radar System Approach to Target Tracking, invited paper for 2009 Asilomar Conference on Signals, Systems and Computers.

Y. Yang, R. S. Blum, Z. S. He, and D. R. Fuhrmann, ``Waveform design for MIMO radar using an alternating projection approach,'' in Proceedings of Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, November 2009.

Y. Yang, R. S. Blum, Z. He, and D. R. Fuhrmann, ``Alternating projection for MIMO radar waveform design,''
invited paper for CAMSAP 2009 (Dec. 2009), pp. 169-172.

Chuanming Wei, Qian He, and Rick S. Blum, "Cramer-rao bound for joint location and velocity estimation
in multi-target non-coherent MIMO radars", CISS 2010.

Xun Chen, R. S. Blum, ``Non-coherent MIMO radar in a non-Gaussian clutter-plus-noise environment,''
CISS 2010.

R. S. Blum, ``Ordering for Estimation", CISS 2010.

Y. Yang, R. S. Blum, and B. M. Sadler, ``Distributed energy-efficient scheduling for radar signal detection in sensor networks,'' 2010 IEEE International Radar Conference.

Qian He and R. S. Blum, "Diversity gain for MIMO radar employing nonorthogonal waveforms", invited paper for the 4th International Symposium on Communications, Control and Signal Processing, pp. 1-6, Limassol, Cyprus, Mar 2010.

Chuanming Wei, Lance M. Kaplan, Stephen D. Burks and Rick S. Blum, Diffuse Prior Monotonic Likelihood Ratio Test for Evaluation of Fused Image Quality Metrics, in proceeding of the 12th International Conference on Information Fusion, pp. 1076-1083, Seattle, WA, Jul. 6-9, 2009.

Rick S. Blum, ``Ordering for Estimation and Optimization", International Conference on Acoustics, Speech and Signal Processing (ICASSP) 2011.

Qian He and Rick S. Blum, ``Smart Grid Monitoring for Intrusion and Fault Detection with New Locally Optimum Testing Procedures", ICASSP 2011.

Qian He and Rick S. Blum, ``MIMO Radar Diversity with Neyman-Pearson Signal Detection in Non-Gaussian Circumstance with Non-orthogonal Waveforms'', ICASSP 2011.

Ziad Rawas, Qian He and Rick S. Blum, "Energy-Efficient Noncoherent Signal Detection for Networked Sensors Using Ordered Transmissions", Conference on Information Sciences and Systems, Johns Hopkins, March 2011.

Qian He and R. S. Blum, "New Hypothesis Testing-Based Methods for Fault Detection for Smart Grid Systems", Conference on Information Sciences and Systems, Johns Hopkins, March 2011.

Qian He and R. S. Blum. ``Smart Grid Fault Detection Using Locally Optimum Unknown or Estimated Direction Hypothesis Test,'' 2011 IEEE International Conference on Smart Grid and Clean Energy Technologies (ICSGCE), Chengdu, China, Sep 2011 (to be presented).

Qian He, R. S. Blum, and Zishu He. ``Noncoherent Versus Coherent MIMO Radar for Joint Target Position and Velocity Estimation,'' the 2011 IEEE CIE International Conference on Radar, Chengdu, China, Oct 2011 (to be presented).

6.2 Transitions

There is great interest from Lockheed Martin in trying to employ the MIMO radar technology we developed under AFOSR funding into future DoD Radar systems. Lockheed Martin produces what is generally thought to be the most successful (most powerful) DoD radar system ever produced. They are involved in projects to design future DoD radar systems and are planning to propose the MIMO radar technology we developed. They feel the MIMO radar technology solves a number of critical issues that they face. Lockheed Martin is currently trying to put together some experimental demonstrations of our MIMO radar technology with the hope of later developing propducts. The contact at Lockheed is Micheal Luddy at Lockheed Martin in Moorestown, New Jersey. His email is michael.j.luddy@lmco.com.

It is also worth noting that Lockheed Martin has great interest in MIMO radar research which was supported by this grant:

Qian He, Nikolaus H. Lehmann, Rick S. Blum, Alexander M. Haimovich, and Leonard J. Cimini, "Moving Target Detection in homogeneous Clutter with a Stationary MIMO Radar,'' accepted in IEEE Trans. on Aerospace and Electronic Systems expected July 2010.

which demonstrates the gains of MIMO radar systems with widely spaced antennas for moving target detection which comes from observing the target from different directions. This leads to two distinct gains that we call geometry gain and diversity gain. They have great interest in implementing this technology in future DoD radar systems.

I have also heard that Raytheon has interest in testing MIMO radar technology. I heard this from Richard Loe, email: RLoe@androcs.com but we have not spoken for a while.

7. Patent Disclosures
None

8. Honors
The PI was named an IEEE Signal Processing Society distinguished lecturer.