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14. ABSTRACT
We have made excellent progress on studying appropriate signal processing and communication strategies for networks of dispersed nodes where each node may be equipped with a sensor. One area of focus has been on developing appropriate signal processing and communication strategies for networks which focus on target detection or hypothesis testing problems. There are many important military and non-military applications of this paradyme. In particular, hypothesis testing, often called signal detection, is a fundamental sensor networking application which is key 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. We have developed very promising approaches for saving battery power for important military applications employing sensors. For example, we developed a highly efficient approach which achieves the same performance as the optimum energy unconstrained approach but 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 without any loss in performance.

15. SUBJECT TERMS
Multiple-input multiple output (MIMO) systems, MIMO Radar, Sensor networks, Energy efficient signal detection, hypothesis testing

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Performance Limits and Design of MIMO for Sensor and Ad Hoc Wireless Networks
AFOSR grant No. FA9550-06-1-0041
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1. Objectives

Multiple colloborating nodes can provide significant performance improvement over nodes that operate autonomously. The improvements are much like one can obtain when transmit and receive antenna arrays used to form multiple-input multiple-output (MIMO) channels. Provided at least as many transmit as receive antennas are used, recent research shows that performance scales linearly with the number of antennas. The main difference between our research and the research on standard point-to-point MIMO is that are nodes are distributed in space and they may be equipped with sensors. Not having the antennas co-located at a single location complicates the problem significantly but also sets up some great research challanges that have captured our interest. Is it possible to exploit the positions of the nodes, dispersed over space and not co-located, so that we can obtain performance which is even better than what one can obtain with co-located antennas. Our results indicate this is indeed the case.

2. Executive Summary

We have made excellent progress on studying appropriate signal processing and communication strategies for networks of dispersed nodes where each node may be equipped with a sensor. One area of focus has been on developing appropriate signal processing and communication strategies for networks which focus on target detection or hypothesis testing problems. There are many important military and non-military applications of this paradyme. In particular, hypothesis testing, often called signal detection, is a fundamental sensor networking application which is key 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. For example, we have been collaborating 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. In fact there are many applications of this type which directly fit our paradigm. There are also some applications that indirectly fit our paradigm. For example, we have been collaborating with scientists in the Biological Sciences department at Lehigh University, who are working on understanding biological systems. In their scientific experiments they typically pose hypothesis testing problems and attempt to test the hypothesis using sensor measurements. Interestingly, in these applications it is important to limit the number of measurements to avoid damaging the living organisms under study. In this case we limit sensor measurements for a different reason, as opposed to trying to save precious battery power, but our general theory still applies. We have developed very promising approaches for saving battery power for important military applications employing sensors. For example, we 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.

A second area of focus has been on applying MIMO communications and signal processing technology to ad hoc and sensor networks. Wireless ad hoc and sensor networks have attracted significant attention in recent years due to their ability to be deployed without the need for any established infrastructure. This lack of infrastructure also creates many challenging problems, because no centralized control is available to coordinate between users. Multipath fading and the broadcast nature of these wireless channels further complicates matters. We study a new MIMO radar paradyme we invented which is now a hot topic being investigated by many other groups also. We also study MIMO communications for networks, which still seems to be a very open topic.

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

We have made a number of contributions to MIMO radar including research on basic concepts [12], waveform design [2,13,20,25], direction finding [3], moving target [14,17c] and high resolution [15,18]. Next, we provide some more detailed discussion reviewing our recent MIMO radar research.

Multiple-input multiple-output (MIMO) channels formed by using multiple transmit and receive antennas have lead to a revolution in communications research and development. Recent research [12] indicates that one can exploit similar ideas in radar using what we call a MIMO radar approach.

For quite some time, it has been understood that radar targets provide a rich scattering environment that produces from 5 to 25 dB target fluctuations. Further, targets produce essentially independently scattering returns when radiated from sufficiently different directions (see [12] for a mathematical illustration of this using a reasonable model). Thus if we distribute receivers over a wide enough area, the premise of MIMO radar, it seems clear that we can exploit the angular spread of the scattering to obtain improved performance by combining these independent looks at the target. This is essentially what is known as diversity gain in MIMO communications and it is exploited extensively in space-time coding and related MIMO techniques. The key is that while any individual look at the target might have a small amplitude return with a significant probability, the probability that all the looks have small amplitude returns can be made very small with a reasonable number of looks. Surprisingly, we exploit what is normally considered to be a deficiency, target fluctuations, to improve performance. In fact, other effects that are also normally considered to hurt performance, such as reflections of the returns off the ground or other objects, can also be exploited to improve performance in a similar way.

Diversity gain is only one of two key gains that MIMO communications can provide. The other gain is called a spatial multiplexing or capacity gain and this is entirely different from diversity gain. In communications, this difference, essentially the difference between space-time coding and the BLAST approach, is well understood. Spatial multiplexing in MIMO communications is based on the ability to use the multiple transmit and receive antennas to set up a multidimensional space for signaling. Then, by the proper signaling, for example signaling down the eigenvectors of the multidimensional space if the channel is known at the transmitter, one can form uncoupled, parallel channels that allow the rate of communication to be increased in direct proportion to the number of such channels. The maximum number of such channels is the dimension of the multidimensional space which is set by the smaller of the number of transmit and receive antennas. In MIMO radar these same ideas can be employed to use a set of Q dispersed transmit and receive antennas (or radars) to resolve Q closely spaced targets even if these targets are too closely spaced to be resolved by single antenna radars. The key is to work in the multidimensional space set up by the multiple antennas. In fact, we have shown that the rank of the multidimensional channel matrix is equal to the number of closely spaced targets. Clearly, this shows this information is not available in standard radars with either single antennas or closely spaced antennas since in these cases the rank of the matrix is unity. We have recently verified in [18] that these spatial multiplexing type gains lead to much higher resolution in MIMO radar. This is the first such verification and seems to be a very important milestone.

Radars, in particular MIMO radars, are also useful for target identification or classification, and, in these applications, one is interested in estimating the impulse response of a spread target using a high resolution radar. Here we describe some recent work on optimum MIMO radar waveform design for these applications. Note that single transmitter and receiver waveform design is a special case. Here we consider two criteria for designing waveforms. The first one is to find transmitted waveforms that minimize the minimum mean-square error (MMSE), between the estimate and the target response given a fixed transmitted waveform. The second criterion is to design a waveform that will maximize the conditional mutual information (MI), between the target response and the reflected waveforms given a fixed transmitted waveform. For either criterion we impose a constraint on the signal power. It is very interesting that the optimum solution for either problem is essentially the same [2,20]. While some authors postulated this was true, we seem to be the first to demonstrate this fact. The optimum solution employs what is commonly called water-filling to allocate the limited power appropriately. We note that the solution requires a complete statistical description of all the random quantities describing the observations. We have shown that if either the number of receive or transmit antennas (or the length of the target impulse response) goes to infinity, then we do not require full knowledge. Instead we just require certain samples of the power spectral density (PSD). Further, we have shown [13,25] that even for cases where the required samples of the PSD are not exactly known we can still find robust methods for signal design that work very well.

Another aspect of our investigations focuses on communications [1,4-11,14-17] [19,22-24] with some emphasis on MIMO communications in networks. For brevity, we focus in what follows on our recent work considering the capacity of a set of dispersed single antenna nodes who collaborate to communicate [4].

In [4], we analyze wireless ad hoc networks that use cooperative diversity from two complementary perspectives. The network we consider uses the amplify-and-forward (AF) cooperation protocol. We first determine the capacity region and rate matrices for these networks. Numerical results indicate that cooperation is beneficial when optimal multi-hop routing is not used, but can be ineffective when optimal multi-hop routing is employed. Secondly, we develop an analytical expression for the transmission blocking probability (TBP). The TBP allows us to draw insight into the possible benefits of cooperation. We determine that the TBP for networks that use cooperation is not noticeably larger than that for networks that employ only point-to-point communications. Taken together, these two results leads us to conclude that although the blocking probability does not significantly increase when cooperation is used, the capacity is only increased in certain scenarios, i.e. when optimal multi-hop routing is not used. The PI recently finished editing a special issue of the IEEE Journal of Selected Areas of Communications on cooperative networking and thus has seen the latest work on this topic. Based on this, we believe our results will be well received by the research community since they provide new insights that we have not seen provided elsewhere.

Our very latest research [16,24, 17a,17b], on energy efficient combined communication and signal detection has us very excited. Signal detection is one important application for which dedicated sensor networks have been proposed for both civilian and military applications. Joint signal processing and communication design of such networks has been of great interest recently. There are some aspects of wireless sensor networks that have not yet been exploited in previous studies. For example, sufficiently close nodes can hear each others' transmissions. Such considerations led us to devise new classes of energy efficient signal detection procedures. We have demonstrated that these new approaches require, on average, fewer sensor node transmissions and that the savings can be significant in cases of interest. The idea is to have each sensor decide the informativeness of its data, without consulting the other sensors, to facilitate a distributed approach. Then the sensors with the most informative data transmit first. When the fusion center has received overwhelming data to support a particular hypothesis the process is stopped which saves transmissions, and thus energy. We have shown that our approach saves an amount of energy which is proportional to the total number of sensors employed (including those not transmitting) 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. We feel these are important new findings. We presented this work at a joint AFOSR-Finland meeting and the group of researchers told us they also believe this is important work.

4. Personnel Supported

Rick S. Blum, (PI) Professor of ECE
Zhenyu Tu, Research Assistant
Danny Safi, Research Assistant
Zhemin Xu, Research Assistant
Xun Chen, Research Assistant
Yang Yang, Research Assistant
Sana Sfar, Postdoc

5. Technical Publications

Journal Papers
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1. Eugene Perevalov, R. S. Blum, Anthony Nigara and Xun Chen, ``Throughput Capacity of Ad hoc Networks with Route Discovery'', EURASIP Journal on Wireless Communications and Networking in a special issue on ``Wireless Mobile Ad Hoc Networks''. Volume 2007, Issue 1, 14 pages, January 2007.

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10. Xun Chen, Eugene Perevalov, Anthony Nigara and R. S. Blum, ``Effect of Routing on Throughput for Ad Hoc Networks'', submitted to IEEE Trans. on Networking.

11. Hamid R. Sadjadpour, Kyungmin Kim, Hongyun Wang, Rick S. Blum, and Yong H. Lee, ``Application of Randomization Techniques to Space-time Convolutional Codes'', IEEE Trans. on Signal Processing, Vol. 54, Issue 11, Nov. 2006, pp. 4484-4489.

12. Rick. S. Blum, Leonard J. Cimini, Alexander M. Haimovich, ``MIMO Radar: Part I - Widely Separated Antennas'', IEEE Signal Processing Magazine, Volume 25, Issue 1, pp. 116-129, 2008.

13. Yang Yang and R. S. Blum, ``Minimax Robust MIMO Radar Waveform Design,'' IEEE Journal of Selected Topics in Signal Processing, Vol. 1, Issue 1, June 2007, pp. 147-155.

14. Eugene Perevalov, Rick Blum and Danny Safi, "On the throughput capacity of large wireless ad hoc networks confined to a region," EURASIP Journal on Wireless Communications and Networking, Volume 4, Article No. 9, October 2007.

15. Eugene Perevalov, Danny Safi, Rick Blum and Lang Lin, "Spatial Multiplexing Gains for Realistic Sized Ad Hoc Networks with Directional Antennas," EURASIP Journal on Wireless Communications and Networking, vol. 2007, Article ID 98490, 12 pages, 2007.

16. Rick S. Blum and Brian Sadler,"Energy Efficient Signal Detection

in Sensor Networks using Ordered Transmissions,"
IEEE Transactions on Signal Processing.
Volume 56, Issue 7, Part 2, pp. 3229-3235, July 2008.

17. Zhemin Xu, Sana Sfar, R. S. Blum, ``Analysis of MIMO Systems with Receive Antenna Selection in Spatially Correlated Rayleigh Fading Channels,'' IEEE Trans. on Vehicular Technology, Jan. 2009.

17a Y. Yang, R. S. Blum and B. M. Sadler,
Energy-Efficient Routing for Signal
Detection in Wireless Sensor Networks
IEEE Transactions on Signal Processing.

17b Zhenyu Tu and Rick S. Blum,
On the Limitations of Random Sensor Placement for Distributed Signal Detection, accepted, to appear in
IEEE Trans. on Aerospace and Electronic
Systems.

17c Nikolaus H. Lehmann, Qian He, Alexander M. Haimovich, Rick S. Blum, and Leonard J. Cimini, "Moving Target Detection in Homogeneous Clutter with a Stationary MIMO Radar", submitted to IEEE Trans. on Aerospace and Electronic Systems.

Conf. papers
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19. K. Kim, H.R. Sadjadpour, R. S. Blum, Y. Lee, ``Scalable Design of Space-Time Trellis Code with Low Decoding Complexity,'' IEEE Globecom 2006.

20. Y. Yang and R. S. Blum, ``Radar waveform design using minimum mean-square error and mutual information,'' in Proceedings of IEEE Workshop on Sensor Array and Multi-channel Processing (SAM), Boston, MA, 2006.

21. Yang Yang and R. S. Blum, "Energy-efficient Routing for Signal Detection under the Neyman-Pearson Criterion in Wireless Sensor Networks", IPSN 2007.

22. Zhenyu Tu and R. S Blum, On the Limitations of Random Sensor Placement for Distributed Signal Detection, ICC 2007.

23. Yang Yang and R. S. Blum, Routing for Emitter/Reflector Signal Detection in Wireless Sensor Network Systems, ICC 2007.

24. R. S. Blum and Brian Sadler, "A New Approach to Energy Efficient Signal Detection,'' CISS 2007.

25. Yang Yang and R. S. Blum, "Minimax Robust Waveform Design for MIMO Radar in the Presence of PSD Uncertainties,'' CISS 2007.

28. Meng Yu, Jing Li, and R. S. Blum, "Apply Network Coding in User Cooperation,'' ICC 2007.

29. Y. Yang and R. S. Blum, ``MIMO radar waveform design,'' in Proceedings of the IEEE Workshop on Statistical Signal Processing (SSP), pp. 468-472, Madison, WI, August 2007.

30. Y. Yang and R. S. Blum, ``Routing for emitter/reflector signal detection in wireless sensor network systems,'' in Proceedings of IEEE International Conference on Communications (ICC), pp. 4919-4924, Glasgow, UK, June 2007.

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32. Hana Godrich, Alexander Haimovich, Rick Blum, ``Cramer Rao Bound on Target Localization Estimation in MIMO Radar Systems,'' CISS 2008.

33. Yang Yang and Rick Blum, ``Sensor placement in Gaussian random field via discrete simulation optimization,'' CISS 2008.

34. Yang Yang and Rick Blum, ``A Simulation Study of Antenna Selection for Sensor placement in Gaussian,'' CISS 2008.

35. Qian He, Rick S. Blum, Hana Godrich, and Alexander M. Haimovich, ``Cramer-Rao Bound for Target Velocity Estimation in MIMO Radar with Widely Separated Antennas,'' CISS 2008.

36. Rick Blum, Yusuf Artan, and Brian Sadler, ``A New Approach to Energy Efficient Classification with Multiple Sensors based on Ordered Transmissions'' in proceedings of ICASSP 2008.

37. Hana Godrich, Alexander M. Haimovich and Rick S. Blum, "Target Localization Accuracy and Multiple Target Localization: Trade off in MIMO Radars", Invited paper for 2008 Asilomar Conference on Signals, Systems and Computers.

38. Qian He, Rick S. Blum, Alexander M. Haimovich, Zishu He, "Antenna Placement for Velocity Estimation using MIMO Radar", Invited paper for 2008 Asilomar Conference on Signals, Systems and Computers.

39. Yang Yang and Rick S. Blum, "Distributed Routing in Wireless Sensor Networks for Signal Detection with Random Phase", 2008 Asilomar Conference on Signals, Systems and Computers.

40. Sana Sfar, Jerry Foschini, Reinaldo Valenzuela, Laurence Mailaender, Dimitri Chizikh, Kemal Karakayali, Rick Blum, Is Relayed collaborative Communication Worth it?, Invited paper at 2008 Asilomar Conference on Signals, Systems and Computers.

6. Interactions/Transitions

6.1 Conference Presentations

Nikolaus Lehmann, Alex Haimovich, Rick Blum, Dmitry Chizhik, Len Cimini, Reinaldo Valenzuela, ``High Resolution MIMO-Radar'', Asilomar, 2006.

K. Kim, H.R. Sadjadpour, R. S. Blum, Y. Lee, ``Scalable Design of Space-Time Trellis Code with Low Decoding Complexity,'' IEEE Globecom 2006.

Y. Yang and R. S. Blum, ``Radar waveform design using minimum mean-square error and mutual information,'' in Proceedings of IEEE Workshop on Sensor Array and Multi-channel Processing (SAM), Boston, MA, 2006.

Yang Yang and R. S. Blum, "Energy-efficient Routing for Signal Detection under the Neyman-Pearson Criterion in Wireless Sensor Networks", IPSN 2007.

Zhenyu Tu and R. S Blum, "On the Limitations of Random Sensor Placement for Distributed Signal Detection", ICC 2007.

Yang Yang and R. S. Blum, Routing for Emitter/Reflector Signal Detection in Wireless Sensor Network Systems, ICC 2007.

R. S. Blum and Brian Sadler, "A New Approach to Energy Efficient Signal Detection,'' CISS 2007.

Yang Yang and R. S. Blum, "Minimax Robust Waveform Design for MIMO Radar in the Presence of PSD Uncertainties,'' CISS 2007.

Meng Yu, Jing Li, and R. S. Blum, "Apply Network Coding in User Cooperation,'' ICC 2007.

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Qian He, Rick S. Blum, Alexander M. Haimovich, Zishu He, "Antenna Placement for Velocity Estimation using MIMO Radar", Invited paper for 2008 Asilomar Conference on Signals, Systems and Computers.

Yang Yang and Rick S. Blum, "Distributed Routing in Wireless Sensor Networks for Signal Detection with Random Phase", 2008 Asilomar Conference on Signals, Systems and Computers.

Sana Sfar, Jerry Foschini, Reinaldo Valenzuela, Laurence Mailaender, Dimitri Chizikh, Kemal Karakayali, Rick Blum, Is Relayed collaborative Communication Worth it?, Invited paper at 2008 Asilomar Conference on Signals, Systems and Computers.

6.2 Transitions

We are trying to use MIMO technology for radar and we had discussions with a Darpa program manager (Ed Baranoski) who thought MIMO Radar would be improtant for some of his new programs. We also briefed MDA on MIMO Radar and they also feel this is an important technology. In fact, MDA has funded an SBIR project on this topic and we were a member of the team. The effort showed the feasibility of MIMO radar to provide much higher resolution than anything currently possible with existing technology for use in target tracking.

7. Patent Disclosures
None

8. Honors
Gave a plenary talk at a popular recent sensor fusion conference. Invited by experts in the area. Giving an invited talk on sensor fusion/sensor networking at ICC next year. Our work on networking sensors seems to be getting recognition by the research community. The same is true for our MIMO radar work. We published an invited paper in IEEE Signal Processing magazine, gave tutorials at ICASSP and at the radar conference and organized invited sessions at the Asilomar and radar conferences.