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University of Texas at Arlington
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PO Box 19145
Arlington, TX 76019

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Office of Naval Research
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14. ABSTRACT

In this project, compressive sensing for radar and radar sensor networks were studied. Significant results have been achieved in the following aspects: Compressive Sensing in Radar Sensor Networks Using Pulse Compression Waveforms; Theoretical Performance Bounds for Compressive Sensing with Random Noise; Compressive Sensing in Radar Sensor Networks for Target RCS Value Estimation; Rate Distortion Performance Analysis of Compressive Sensing; etc. Three PhD students were directly supported by this project, and have graduated. Major recognitions and awards associated with the sponsored research were conferred to the PI. 21 journal papers and 30 conferences papers were published or presented, and a complete list is attached in this report.

15. SUBJECT TERMS

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Final Technical Report for ONR Award under Grant N00014-11-1-0071 (11/15/2010 – 9/30/2013) Compressive Sensing for Radar and Radar Sensor Networks

Qilian Liang
Department of Electrical Engineering
University of Texas at Arlington
E-mail: liang@uta.edu

Abstract

In this project, compressive sensing for radar and radar sensor networks were studied. Significant results have been achieved in the following aspects: Compressive Sensing in Radar Sensor Networks Using Pulse Compression Waveforms; Theoretical Performance Bounds for Compressive Sensing with Random Noise; Compressive Sensing in Radar Sensor Networks for Target RCS Value Estimation; Rate Distortion Performance Analysis of Compressive Sensing; etc. Three PhD students were directly supported by this project, and have graduated. Major recognitions and awards associated with the sponsored research were conferred to the PI. 21 journal papers and 30 conferences papers were published or presented, and a complete list is attached in this report.

1 Most Significant Research Results

1.1 Compressive Sensing in Radar Sensor Networks Using Pulse Compression Waveforms

Inspired by recent advances in compressive sensing (CS), we introduce CS to the radar sensor network (RSN) using the pulse compression technique in order to efficiently compress, restore and recover the radar data [7]. For the sake of simplicity but without losing generality, we study an RSN consisting of a number of transmit sensors and one receive sensor. Our idea is to employ a set of Stepped-Frequency waveforms as pulse compression codes for transmit sensors, and to use the corresponding Stepped-Frequency (SF) waveforms as the sparse matrix in the receive sensor due to the orthogonality of the basis. We conclude that the signal samples along the time domain could be largely compressed so that they could be recovered by a small number of measurements. In addition, a diversity gain could also be obtained at the output of the set of the matched filters in the receive sensor. Simulation results show that even if the signal could not be perfectly reconstructed, the probability of miss detection of target could be kept zero. In the future, the reconstructed signal would further be applied to the study of target recognition.

1.2 Theoretical Performance Bounds for Compressive Sensing with Random Noise

In [1], we study the performance of compressive sensing theoretically in the presence of random noise. Different from other literature, we consider exact reconstruction of the signal, but not the recovery of the support of the signal. Both the lower bound and upper bound of the probability of error for compressive sensing are provided, with the assumption that both the original signal and the noise follow Gaussian distribution. It has been shown that under some condition, perfect reconstruction of the signal vector is impossible, as there will always be certain error. Our results provide some theoretical reference of noisy compressive sensing.

1.3 Compressive Sensing in Radar Sensor Networks for Target RCS Value Estimation

In [8], we introduce CS to radar sensor network (RSN) within the pulse compression technique in order to efficiently compress, restore and then reconstruct the radar data. We employ a set of Stepped-Frequency waveforms as pulse compression codes for transmit sensors, and to use the same set of Stepped-Frequency (SF) waveforms as the sparse matrix for each receive sensor. We conclude that the signal samples along the time domain could be largely compressed so that they could be recovered by a small number of measurements which depend on the number of transmit sensors. In addition, we develop a Maximum Likelihood (ML) Algorithm for radio cross section (RCS) parameter estimation and provide the Cramer-Rao lower bound (CRLB) to validate the theoretical result. We also provide simulation results illustrating that the variance of RCS parameter estimation theta satisfies the CRLB and our ML estimator is an accurate estimator on the target RCS parameter.

1.4 Zero Correlation Zone Sequence Pair Sets for MIMO Radar

Inspired by recent advances in MIMO radar, we apply orthogonal phase coded waveforms to MIMO radar system in order to gain better range resolution and target direction finding performance [2]. We provide and investigate a generalized MIMO radar system model using orthogonal phase coded waveforms. In addition, we slightly modify the system model to improve the system performance. Accordingly, we propose the concept and the design methodology for a set of ternary phase coded waveforms that is the optimized punctured Zero correlation Zone (ZCZ) sequence-Pair Set (ZCZPS). We also study the MIMO radar ambiguity function of the system using phase coded waveforms, based on which we analyze the properties of our proposed phase coded waveforms which show that better range resolution could be achieved. In the end, we apply our proposed codes to the two MIMO radar system models and simulate their target direction finding performances. The simulation results show that the first MIMO radar system model could obtain ideal target direction finding performance when the number of transmit antennas is equal to the number of receive antennas. The second MIMO radar system model is more complicated but could improve the direction finding performance of the system.

1.5 Opportunistic Sensing in Radar Sensor Networks

In real world, wireless heterogeneous sensor network (HSN) design and information integration are necessary in different applications. Traditionally, wireless sensor networks information integration is set up to passively fuse all received data. Such an approach is computationally challenging and operationally ineffective because improvements in information accuracy are not guaranteed. Opportunistic Sensing (OS) refers to a paradigm for signal and information processing in which a network of sensing systems can automatically discover and select sensor platforms based on an operational scenario. In [3], we proposed theory and algorithms of OS to simplify the HSN design and promote more efficient information integration. We proposed an information theoretical criterion for opportunistic sensing in HSN, and show that HSN with correlated modalities needs less number of codewords than that with independent modalities. Our OS algorithm advances autonomous sensing that not only ensures effective utilization of sensing assets but also provides robust optimal performance. We applied our OS algorithm to radar sensor networks for surveillance and monitoring, and showed that our approach works very well and much better than other approaches.

1.6 Radar Sensor Wireless Channel Modeling

In [4], we study the radar sensor wireless channel modeling in foliage environment, a rich scattering and time-varying environment, based on extensive data collected using ultra-wideband (UWB) and narrowband (200 and 400 MHz) radar sensors. We apply two approaches to the wireless channel modeling: Saleh and Valenzuela (S-V) method for UWB channel modeling and CLEAN method for narrowband and UWB channel modeling. We validated that UWB echo signals (within a burst) do not hold self-similarity, which means the future signals cannot be forecasted based on the received signals and channel modeling is necessary from statistical point of view. Based on the S-V method for UWB channel modeling, in foliage UWB channel, the multipath contributions arriving at the receiver are grouped into clusters. The time of arrival of clusters can be modeled as a Poisson arrival process, while within each cluster, subsequent multipath contributions or rays also arrive according to a Poisson process. At different distance (near distance, medium distance, and far distance), we observe that the Poisson process parameters are quite different. We also observe that the amplitude of channel coefficient at each path follows Rician distribution for medium and far distance, and it is non-stationary for paths from short distance (one of two Rician distributions), and these observations are quite different with the IEEE indoor UWB channel model and S-V indoor channel model. Based on the CLEAN method, the narrowband (200 and 400 MHz) and UWB channel impulse responses have many similarities: both can be modeled as linear time-variant filter channel. We also studied the large-scale fading using path-loss and log-normal shadowing model for foliage enviroment, and observed that the path-loss exponent is very high because it has rich scattering.

1.7 Radar Sensor Network Using New Ternary Codes

In the radar sensor network (RSN), the interferences among different radar sensors can be effectively reduced when waveforms are properly designed. In [5], we perform some theoretical studies on coexistence of phase coded waveforms in the RSN. We propose a new ternary codes-optimized punctured zero correlation zone sequence-pair set (ZCZPS)-and analyze their properties. Applying the new ternary codes and equal-gain combination technique to the RSN, we study the detection performance versus different numbers of radar sensors under the different conditions. The simulation results show that the RSN using our optimized punctured ZCZPS performs better than the RSN using the same number of common codes such as the Gold codes and much better than the single radar system no matter whether or not the Doppler shift is considered.

1.8 Compressive Sensing: To Compress or Not To Compress

In [12], we consider the compressive sensing scheme from the information theory point of view and derive the lower bound of the probability of error for CS when length N of the information vector is large. The result has been shown that, for an i.i.d. Gaussian distributed signal vector with unit variance, if the measurement matrix is chosen such that the ratio of the minimum and maximum eigenvalues of the covariance matrices is greater or equal to $4/(MK+1)$, then the probability of error is lower bounded by a non-positive value; which implies that the information can be perfectly recovered from the CS scheme. On the other hand, if the measurement matrix is chosen such that the minimum and maximum eigenvalues of the covariance matrices are equal, then the error is certain and the perfect recovery can never be achieved.

1.9 A Compressive Sensing Based MIMO Impulse Radio Ultra-wideband Communication System

Sampling rate is the bottleneck for ultra-wideband (UWB) wireless communication system. Compressive sensing (CS) is a natural framework to handle this problem, which claims a small collection of linear projections of a sparse signal contains enough information for stable, sub-Nyquist signal acquisition. In [13], our major contribution is to propose a novel impulse radio UWB communication system which is sparse in the time domain. MIMO is employed to introduce diversity gain in order to achieve better performance. Real-time channel estimation scheme is also proposed and there is no loss in the information throughput conveyed by the whole communication system.

1.10 Rate Distortion Performance Analysis of Compressive Sensing

Recent research in compressive sensing has shown that sparse signals can be recovered from a small number of random measurements using linear programming. This property raises the question of whether compressive sensing can provide an efficient representation of sparse signals in an information theoretic sense. In [11], we studied the performance of rate distortion function $R(D)$ of noisy compressive sensing in two cases: the noise follows Gaussian distribution or not (general noise). Our numerical results show that compressive sensing uses less bits to represent the same information compared to conventional information acquisition and reconstruction techniques. Besides that, we specify both uniform and non-uniform quantization for compressive sensing, and get the corresponding rate distortion functions in these two cases. We compared their performance and our results proved that nonuniform quantizers perform better than uniform quantizers when our original source X follows Gaussian distribution. In addition, we get the rate distortion function $R(D)$ in the case of combining general channel coding with compressive sensing, as channel coding process can make our final recovery of the original signal more accurate.

1.11 Compressive Sensing for Radar Sensor Networks

Motivated by recent advances on Compressive Sensing (CS) and high data redundancy among radars in radar sensor networks, we studied CS for radar sensor networks [10]. We demonstrated that the sense-through-foliage UWB radar signals are very sparse, which means CS could be applied to radar sensor networks to tremendously reduce the sampling rate. We applied SVD-QR and maximum likelihood algorithms to CS for radar sensor networks. SVD-QR could vastly reduce the number of radar sensors, and CS was applied to the selected radar sensors for data compression. Simulations were performed and our compression ratio could be 192:1 overall.

2 Narrative on Research Progress

2.1 Radar Sensor Network for Target Detection Using Chernoff Information and Relative Entropy

In [9], we considerred the target detection as binary hypothesis test- ing and derive the best possible error exponents using Chernoff Information and Chernoff Stein Lemma. The error probabilities associated with the de- tection is crucial in understanding the performance of the detection. We also propose relative entropy based processing in the fusion center, based on an information theoretic algorithm, known as method of types.Complex environment of forest makes target detection through foliage an ongoing chal- lenge. Ultra wide band (UWB), radar sensor network (RSN) can be used to detect target in foliage environment. Information theoretic algorithms like entropy and mutual information are proven methods that can be applied to data collected by various sensors. However, the complexity of the environ- ment posses uncertainty in fusion center. We found the relation between the quantization level and number of nodes in gaining the best error exponent. The performance of the algorithm was evaluated, based on real world data.

2.2 Experimental Study of Through-wall Human Being Detection Using Ultra-wideband (UWB) Radar

In [14], experiments on through-wall human being detection using ultra-wideband (UWB) radar PlusOn 220 in monostatic mode are carried out. For periodic respiratory motion of human target, the detection techniques employed are normalized difference square matrix method, and reference moving average method with Discrete Fourier Transform (DFT). The experimental results for human target detection behind gypsum wall and concrete wall have been separately demonstrated.

2.3 Situation Understanding Based on Heterogeneous Sensor Networks

Humans use multiple sources of sensory information to estimate environmental properties and has innate ability to integrate information from heterogeneous data sources. How the multi-sensory and multimodal information are integrated in human brain? There is consensus that it depends on the prefrontal cortex (PFC). The PFC has top-down control (favor weak) and rule-based mechanisms, and we propose to incorporate the favor weak mechanism into rule-based fuzzy logic systems (FLS) via using upper and lower membership functions in [6]. The inference engine of favor weak fuzzy logic system is proposed under three different categories based on fuzzifiers. We observe that the favor weak FLS is a special type-1 FLS which is embeded in an interval type-2 FLS, so it's much simpler in computing than an interval type-2 FLS. We apply the favor weak FLS to situation understanding based on heterogeneous sensor network, and it shows that our favor weak fuzzy logic system has clear advantage comparing to the type-1 FLS. The favor weak FLS can increase the probability of threat detection, and provides timely indication & warning (I& W).

2.4 Amplitude Based Compressive Sensing for UWB Noise Radar Signal

Compressive sensing(CS) is an emerging filed based on the revelation that a small collection of linear projections of a sparse signal contains enough information for stable, sub-Nyquist signal acquisition. UWB noise radar is one of the novel techniques which are widely used in various applications such as emergence rescues and military operations. One challenging problem in UWB noise radar operation is that huge amount of data will be received which requires tremendous storage space. Compressive sensing could easily handle this problem since it captures all the information we need from far fewer samples. In [15], we propose a novel amplitude based compressive sensing algorithm to compress data without any knowledge in advance. Simulation results indicate that 1/5 of original measurements are sufficient to recover original data, which also achieves a higher compression ratio than conventional compressive sensing.

2.5 Compressive Sensing for Synthetic Aperture Radar in Fast-Time and Slow-Time Domains

Compressive sensing (CS) is a new method to capture and represent compressible signals at a rate significantly below the Nyquist rate. To reduce the high data redundancy among different echoes in synthetic aperture radar (SAR), we apply compressive sensing to SAR in slow-time and fast-time domains [16]. Based on the reflectivity kernel analysis of SAR echoes, We demonstrate that the SAR signals are very sparse, which means CS could be applied to SAR to tremendously reduce the sampling rate. We apply SVD-QR to select a subset of SAR echoes in slow-time domain to reduce the redundancy, and compressive sensing to the selected echoes in fast-time domain. Simulations are performed and our compression ratio could be 47:1 overall.

2.6 Opportunistic Sensing in Wireless Sensor Networks

Opportunistic Sensing (OS) refers to a paradigm for signal and information processing in which a network of sensing systems can automatically discover and select sensor platforms based on an operational scenario. In [17], we propose theory and algorithms of OS for advancing autonomous sensing that not only ensures effective utilization of sensing assets but also provides robust optimal performance. We propose an information theoretical criterion for opportunistic sensing in wireless sensor networks and derive an algorithm for efficient OS. We apply our OS algorithm to radar sensor networks for sense-through-foliage target detection, and show that our OS algorithm works very well and much better than other approach.

3 Ph.D Training

Three PhD students were supported by this project, and have graduated.

- Davis Kirachaiwanich, PhD Dissertation: Compressive Sensing and Wireless Network Capacity with Performance Analysis, August 2011.
- Lei Xu, PhD Dissertation: Radar Sensor Networks: Waveform Design, MIMO, and Compressive Sensing, December 2011.
- Ji Wu, PhD Dissertation: Compressive Sensing in Wireless and Sensor Systems, August 2013.

4 Recognitions and/or Awards Associated with the Sponsored Research

- 2011, Promoted to a Full Professor at University of Texas at Arlington (UTA)
- 2012 Excellence in Research Award, UTA College of Engineering
- 2013 Outstanding Research Achievement Award, University of Texas at Arlington

5 Invited Talks at IEEE or Similar Level Conferences Associated with the Sponsored Research

- Plenary talk in IEEE International Conference on Communications, Workshop on Radar and Sonar Networks, June 2012, Ottawa, Canada.
- Plenary talk in International Conference on Wireless Algorithms, Systems, and Applications (WASA), August 2012, Yellow Mountain, China
- Keynote talk in IEEE Globecom, Workshop on Radar and Sonar Networks, Dec 2012, Anaheim, CA.
- Keynote talk in IEEE International Conference on Communications, Workshop on Radar and Sonar Networks, June 2013, Budapest, Hungary.

6 A List of Submitted, Presented and Published papers in This Project

In this project, 21 journal papers and 30 conferences papers were published or presented. A complete list is attached in this report.

References

[1] Junjie Chen, Qilian Liang, "Theoretical Performance Bounds for Compressive Sensing with Random Noise," submitted to *IEEE Trans on Information Theory.*

[2] Lei Xu, Qilian Liang, "Zero Correlation Zone Sequence Pair Sets for MIMO Radar," *IEEE Trans on Aerospace and Electronic Systems*, vol. 48, no. 3, pp. 2100 - 2113, July 2012.

[3] Qilian Liang, Xiuzhen Cheng, Scott Huang, Dechang Chen, "Opportunistic Sensing in Wireless Sensor Networks: Theory and Applications," *IEEE Transactions on Computers*, http://doi.ieeecomputersociety.org/10.1109/TC.2013.85, April 2013.

[4] Qilian Liang, "Radar Sensor Wireless Channel Modeling in Foliage Environment: UWB versus Narrowband," *IEEE Sensors Journal*, vol. 11, no. 6, June 2011, pp. 1448-1457.

[5] Lei Xu, Qilian Liang, "Radar sensor network using a set of new ternary codes: theory and application," *IEEE Sensors Journal*, vol. 11, no. 2, pp. 439-450, Feb 2011.

[6] Qilian Liang, "Situation Understanding Based on Heterogeneous Sensor Networks and Human-Inspired Favor Weak Fuzzy Logic System," *IEEE Systems Journal*, vol. 5, no. 2, pp. 156-163, June 2011.

[7] Lei Xu, Qilian Liang, "Compressive Sensing in Radar Sensor Networks Using Pulse Compression Waveforms," *IEEE Intl Conference on Communications*, Ottawa, Canada, June 2012.

[8] Lei Xu, Qilian Liang, Baoju Zhang, Xiaorong Wu, "Compressive Sensing in Radar Sensor Networks for Target RCS Value Estimation," *IEEE Globecom*, Workshop on Radar and Sonar Networks, Dec 2012, Anaheim, CA.

[9] I. Maherin, Q. Liang, "Radar Sensor Network for Target Detection using Chernoff Information and Relative entropy," accepted by *Physical Communications.*

[10] Qilian Liang, "Compressive Sensing for Radar Sensor Networks," *IEEE Globecom*, Dec 2010, Miami, FL.

[11] Junjie Chen, Qilian Liang, "Rate Distortion Performance Analysis of Compressive Sensing," *IEEE Globecom*, Nov 2011, Houston, TX.

[12] Davis Kirachaiwanich, Qilian Liang, "Compressive Sensing: to Compress or Not to Compress," *Asilomar Conference on Signals, Systems, and Computers*, Nov 2011, Pacific Grove, CA.

[13] Ji Wu, Wei Wang, Qilian Liang, Xiaorong Wu, Baoju Zhang, "Compressive Sensing-Based Signal Compression and Recovery in UWB Wireless Communication System," accepted by *Wiley Wireless Communications and Mobile Computing.*

[14] Ashith Kumar, Qilian Liang, Zhuo Li, Baoju Zhang, Xiaorong Wu, "Experimental Study of Through-wall Human Being Detection Using Ultra-wideband (UWB) Radar," *IEEE Globecom*, Workshop on Radar and Sonar Networks, Dec 2012, Anaheim, CA.

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[16] Qilian Liang, "Compressive Sensing for Synthetic Aperture Radar in Fast-Time and Slow-Time Domains," *Asilomar Conference on Signals, Systems, and Computers*, Nov 2011, Pacific Grove, CA.

[17] Qilian Liang, Xiuzhen Cheng, Dechang Chen, "Opportunistic Sensing in Wireless Sensor Networks," *IEEE Globecom*, Nov 2011, Houston, TX.

[18] Qilian Liang, Ji Wu, Xiuzhen Cheng, Dechang Chen, Jing Liang, "Sparsity and Compressive Sensing of Sense-through-Foliage Radar Signals," *IEEE International Conference on Communications*, Workshop on Radar and Sonar Networks, June 2012, Ottawa, Canada.

[19] Junjie Chen, Qilian Liang, John Paden, Prasad Gogineni, "Compressive Sensing Analysis of Synthetic Aperture Radar Raw Data," *IEEE International Conference on Communications*, Workshop on Radar and Sonar Networks, June 2012, Ottawa, Canada.

[20] Ishrat Maherin, Qilian Liang, "A Mutual Information Based Approach for Target Detection through Foliage using UWB Radar," *IEEE International Conference on Communications, Workshop on Radar and Sonar Networks*, June 2012, Ottawa, Canada

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[25] Junjie Chen, Qilian Liang, "Information Theoretic Performance Bounds for Noisy Compressive Sensing," submitted to *IEEE Intl Conference on Communications*, June 2013, Budapest, Hungary.

[26] Jing Liang, Zinan Wang, Qilian Liang, "Adaptive Sensor Selection for Multitarget Detection in Heterogeneous Sensor Networks," *Ad Hoc & Sensor Wireless Networks*, vol. 12, no. 3-4, pp. 325-342, 2011.

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Appendix: Publications under the ONR Project N00014-11-1-0071.

A. Journal Papers

1. Junjie Chen, Qilian Liang, “Theoretical Performance Bounds for Compressive Sensing with Random Noise,” submitted to IEEE Trans on Information Theory.
2. Lei Xu, Qilian Liang, "Zero Correlation Zone Sequence Pair Sets for MIMO Radar," IEEE Trans on Aerospace and Electronic Systems, vol. 48, no. 3, pp. 2100 - 2113, July 2012.
3. Lei Xu, Qilian Liang, Xiuzhen Cheng, Dechang Chen, "Compressive Sensing in Distributed Radar Sensor Networks Using Pulse Compression Waveforms," EURASIP Journal of Wireless Communications and Networking, 2013, DOI: 10.1186/1687-1499-2013-36.
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19. Junjie Chen, Qilian Liang, “Efficient Sampling for Radar Sensor Networks,” accepted by International Journal of Sensor Networks.
20. Qiong Wu, Qilian Liang, “Coprime Sampling for Nonstationary Signal in Radar Signal Processing,” EURASIP Journal of Wireless Communications and Networking, doi:10.1186/1687-1499-2013-58, 2013.
21. Qilian Liang, Xiuzhen Cheng, Scott Huang, Dechang Chen, “Opportunistic Sensing in Wireless Sensor Networks: Theory and Applications”, IEEE Transactions on Computers, http://doi.ieeecomputersociety.org/10.1109/TC.2013.85, April 2013.

B. Conference Papers

1. Junjie Chen, Qilian Liang, "Theoretical Performance Limits for Compressive Sensing with Random Noise," IEEE Globecom, Atlanta, GA, Dec 2013.
2. Ishrat Maherin, Qilian Liang, "Decision Fusion in Target Detection using UWB Radar Sensor Network," International Conference on Communications, Signal Processing, and Systems, Sept 2013, Tianjin, China.
3. Ji Wu, Qilian Liang, Baoju Zhang, Xiaorong Wu, "Security Analysis of Distributed Compressive Sensing-Based Wireless Sensor Networks," International Conference on Communications, Signal Processing, and Systems, Sept 2013, Tianjin, China.
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