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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This project is to develop practical co-prime and nested samplers and arrays for radar, radar sensor networks, and wireless communications. The proposed algorithms have been evaluated using real world radar and radar sensor network data, and have led to practical methodologies, algorithms and design tools with performance robust to uncertainty and adaptive to variations in dynamic operating conditions of radar and radar sensor networks. Major research tasks include: 1) Co-Prime and Nested Samplers for Radar Waveform Design, 2) Co-Prime and Nested Samplers for Non-stationary Signals, 3) Co-Prime and Nested Samplers and Arrays for Synthetic Aperture Radar Imaging, 4) Co-Prime and Nested Samplers and Arrays for Radar Sensor Networks, 5) Co-prime and nested arrays for wireless communications. 10 Ph.D students and 7 M.S. students have been supported by this ONR project and graduated with Ph.D and M.S. degrees. Of these 17 Ph.D/M.S. students, 4 Ph.D students and 2 M.S. students are women.

15. SUBJECT TERMS

Nested Array, Co-prime array, Nested Sampling, Co-prime Sampling, Radar Sensor Networks, Wireless Communications

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Practical Co-Prime and Nested Samplers and Arrays for Radar and Radar Sensor Networks Final Report

Qilian Liang
Department of Electrical Engineering
University of Texas at Arlington
Arlington, TX 76019-0016
phone: (817) 272-1339 fax: (817) 272-2253 email: liang@uta.edu

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LONG-TERM GOALS

The long-term goal of this project is to develop practical co-prime and nested samplers and arrays for radar, radar sensor networks, and wireless communications. The proposed algorithms will be evaluated using real world radar and radar sensor network data, so this project will lead to practical methodologies, algorithms and design tools with performance robust to uncertainty and adaptive to variations in dynamic operating conditions of radar and radar sensor networks.

OBJECTIVES

This project includes the objectives listed below.

1. Co-Prime and Nested Samplers for Radar Waveform Design.
2. Co-Prime and Nested Samplers for Non-stationary Signals.
3. Co-Prime and Nested Samplers and Arrays for Synthetic Aperture Radar Imaging.
4. Co-Prime and Nested Samplers and Arrays for Radar Sensor Networks.
5. Co-prime and nested arrays for wireless communications

APPROACH

Led by PI Liang, ten PhD students, Qiong Wu, Ishrat Maherin, Junjie Chen, Na Wu, Xin Wang, Zhuo Li, Hao Liang, Shitong Yuan, Longwei Wang, Ganlin Zhao, participated in this project during this report period and have received their Ph.D degrees. Qiong Wu mainly worked on co-prime sampling for nonstationary signals, co-prime sampling-based higher-order statistics; Junjie Chen worked on spectrum efficiency based on nested sampling and co-prime sampling; Ishrat Maherin worked on target detection in radar sensor networks; Na Wu worked on nested and co-prime array for Direction-of-Arrival (DoA) estimation; Zhuo Li worked on home area networks; Xin Wang worked on sensor selection; Hao Liang worked on nested array for underwater sensor networks; Shitong Yuan worked on 3-D nested array for 5G cellular networks; Longwei Wang worked on Massive MIMO; Ganlin Zhao worked on target detection using radar sensor networks.

Major approaches include the following aspects.

1. Sparse Nested Cylindrical Sensor Networks for Internet of Mission Critical Things

   In (1), two new structures of sparse cylindrical sensor network are proposed, which are one dimensional nested cylindrical sensor network (1D NCSN) and two-dimensional nested cylindrical sensor network (2D NCSN). Considering the development of Internet of Mission Critical Things (IoMCT), numerous of devices need to be interconnected and sharing information. Sparse structures of sensor networks will not only reduce the cost of deployment, but also decrease the quantity of data. The reason of choosing cylindrical sensor network is that cylindrical array has been widely used in wireless communication and underwater target detection. According to the characteristic of cylindrical array, the one-dimensional and two-dimensional nested array is extended to build the 1D and 2D sparse cylindrical sensor networks respectively. Comparing with the one-dimensional nested cylindrical sensor network, the two-dimensional structure could save more elements, while it's hard to derive the beampattern expression of the two-dimensional nested cylindrical sensor network. Simulation results show that the 1D nested cylindrical sensor network has a higher resolution than the uniform cylindrical sensor network. In addition, through augmented matrix MUSIC approach, 2D NCSN could detect all targets in the range, even if the number of targets is larger than the number of real elements in the network. However, both the uniform cylindrical sensor network and the 1D NCSN couldn't find all the sources.

2. Efficient Sensor Selection Schemes for Wireless Sensor Networks in Microgrid

   Integration of distributed energy resources (DERs) into microgrid makes the power supply more reliable and reduces the cost. However, the connection of a large number of DERs among the load on middle-voltage/low-voltage feeders can result in severe voltage regulation problems. These challenges motivate the application of wireless sensor networks into microgrid. In (3), several sensor selection schemes are heuristically proposed to improve the voltage measurement performance, prolong the sensor network lifetime, and guarantee the real-time communication between the distributed sensors and the intelligent control center. First, aiming to accurately monitor the real-time voltage level, we propose an opportunistic sensor selection scheme under equal power allocation and investigate the asymptotic behaviors of the voltage measurement performance. Furthermore, we address the sensor selection scheme under optimal power allocation and derive a reminiscent of ?water-filling? solution. The proposed sensor selection schemes are applied and verified in the context of voltage regulation. In addition, we present the studies on the tradeoff between the voltage measurement and the sensor power consumption. Finally, we explore the joint power and spectrum allocation schemes to maximize the transmission rate between the sensors and the control center based on sensor selection. The theoretical analysis and proof are instrumental to the future wireless network design in microgrid.

3. Coprime Interpolation and Compressive Sensing for Future Heterogeneous Network Towards 5G

   Because of enormous amount of images and videos to be transmitted in 5G, it is quite desirable to do aggressive downsampling in the transmission side. As a consequence, the co-prime-interpolated compressive sensing approach, which could recover the downsampled data in the receiver side, is proposed in (4). The co-prime structure, interpolation, and compressive sensing are combined in order to improve the resolution of reconstructed images through compressive-sensing. The numerical analysis of root mean square error and peak signal-to-noise ratio is examined, respectively. This new approach is applied on the test image and real data. The results prove that our approach provides a potential solution for future heterogeneous network toward 5G.

4. Channel estimation for massive MIMO with 2-D nested array deployment

   The problem of channel estimation in 5G is regarded as the one of the bottleneck problems due to its complexity related with large number of antenna elements at the BS side and more narrower beams when choosing high frequency such as millimeter wave. In (5), we study the channel estimation problem for massive MIMO with a new antenna array at the base station (BS) side. The randomly deployed single antenna user equipments (UEs) within a single cell in the cellular network comprise of a random array. Based on the geometric channel model, using multiple snapshots of beamforming and combining vectors at the BS and UEs side respectively, the problem is formulated as a sparsity-aware problem and the coordinate descent algorithm is employed to retrieve the significant channel gain. Simulation results show the effective of the algorithm under two different scenarios with high SNR and low SNR respectively and for both cases, we can find the significant paths with properly chosen penalization parameter λ.

5. Low Complexity Optimization for User Centric Cellular Networks via Large Dimensional Analysis

   Users near cell edges suffer from severe interference in traditional cellular networks. In (6), we consider the scenario that multiple nearby base stations (BSs) cooperatively serve a group of users which is referred to as the cell free networks. A low complexity optimization method based on the large dimensional analysis is proposed. The advantage of the cell free networks is that the interference caused in the cell edge users can be converted into intended signal. It is not easy to obtain the optimal solution to the network due to coupled relations among the users? rates. To obtain a suboptimal solution, a precoder that balances signal and interference is adopted to maximize the network capacity. In traditional optimization, it requires instantaneous channel state information. We try to optimize the network sum rate based on the large dimensional analysis. In this way, the optimization can be transformed into another problem that merely depend on the large scale channel statistics. Large dimensional analysis is leveraged to derive the asymptotic signal to interference plus noise ratio that only depends on large scale channel statistics. Based on this result, the power allocation problem does not need to adapt as frequently as the instantaneous channel state information. By this means, signal exchange overhead can be greatly reduced. Numerical results are provided to validate the efficacy of the proposed optimization method.

6. On the Uplink Outage Throughput Capacity of Hybrid Wireless Networks with Massive MIMO

   In (7), we investigate theoretical transmission capacity limit of the uplink hybrid wireless network under infrastructure mode. Massive MIMO technology is assumed to be equipped on the base station to further increase the whole network throughput. Multi-user MIMO is preferred over Point-to-Point MIMO to achieve improved scalability and simplify UE design. Another perspective of this paper is to include the fading effect on capacity. Under favorable propagation condition, Massive MIMO greatly mitigates small scale fading effect between each user and base station antenna. Then closed-form outage capacity over large scale fading channel is derived in both low SNR and high SNR scenarios.

7. Sense-Through-Foliage Target Detection Based on EMD and UWB Radar Sensor Networks

   In (8), we propose to apply Empirical Mode Decomposition (EMD) approach to detect target hidden in foliage clutter based on data collected by Ultra Wide Band (UWB) radar. The EMD based target detection approach performs well when the radar signal quality is good. However, EMD approach fails to detect target when the radar signal quality is poor. In such case, Rake structure in RSN is applied to combine different radar echoes as preprocessing before EMD to achieve target detection task.

8. Spatial Spectrum Analysis of Proposed Two-dimensional Nested Cylindrical Array

   In (9), a new two-dimensional nested cylindrical array is proposed. According to the characteristic of cylindrical array, the two-dimensional rectangular nested array is extended to build the 2D sparse cylindrical array. Comparing with the one-dimensional sparse cylindrical arrays, this new structure could save more elements than the 1D sparse cylindrical array. Moreover, simulation results show that through augmented matrix MUSIC approach, 2D sparse cylindrical array could also detect all targets in the range, even if the number of targets is larger than the number of real elements in the array. However, both the uniform cylindrical array and the 1D sparse cylindrical arrays couldn't find all the sources.

9. Increasing Capacity of Multi-Cell Cooperative Cellular Networks with Nested Deployment

   In (17)(2), we proposed a novel deployment for multi-cell cooperative cellular networks based on the two-dimensional (2D) nested co-array, and analyzes its sum-rate capacity and spectrum efficiency. The system model is based on the traditional hexagonal cellular array, in which each hexagon represents a marcocell. We take advantage of the invariance in the difference co-array so that the 2D nested array is able to calculate all elements in the covariance matrix of channel fading coefficients. Based on this premise, we demonstrate that the derivation procedure of average sum-rate capacity for the cooperative cellular networks is still valid for the nested distributed base stations (BSs) in the non-fading and Rayleigh fading channels. In numeric simulations, the derived formulas are consistent with the results from previous references. More importantly, given the same number of BSs, the proposed distribution significantly increases the sum-rate capacity of the system.

10. Higher-Order Statistics in Co-prime Sampling with Application to Channel Estimation

    We studied higher-order statistics of non-Gaussian signal using temporal co-prime sampling(10). We extended co-prime sampling to pairwise co-prime sequence (PCS) to derive higher-order statistics (HOS), and analyzed the computational complexity of PCS-HOS algorithm for both parametric and nonparametric methods. Compared to the existing HOS algorithms, the proposed algorithm vastly reduces the complexity by several orders in terms of the length of segmentation window. We also applied PCS-HOS to estimate the orders and coefficients of fading channels, which are modeled as autoregressive moving average (ARMA) processes. In particular, we analyzed the variance of thirdorder cumulants as the output of this fading channel model, and use it to determine the orders for both autoregressive and moving average model. In simulations, the proposed algorithm reduces the computational complexity to 17% of the existing HOS algorithms with negligible performance loss in high noise-to-signal ratio (SNR) environment. In low SNR scenario, it is more sensitive to order mismatch in terms of the variances of expectations, which makes it a more reliable indicator to confirm the correct order. Furthermore, we also developped overdetermined matrix representation for moving average (MA) system, and apply PCS-HOS algorithm to estimate its parameters only based on the outputs. Our simulation results showed that 3rd-order PCS-HOS achieves 80% performance gain versus the existing HOS with the same computational complexity, or it has 12% performance loss with 85% reduction in complexity compared to the counterpart processing the same length of signal.

11. Multi-Step Information Fusion for Target Detection using UWB Radar Sensor Network

    In (11), we proposed a multi-step information fusion scheme for target detection through foliage and wall, using ultra wide-band (UWB) radar sensor networks (RSN). We applied information theory to detect target with poor signal quality in dynamic forest-environment. This method is motivated by the fact that echoes from the stationary target that is obscured by foliage has strong random characteristics. This is resolved by three steps of information fusion. For first step of information fusion, we use Kullback-Leibler (K-L) divergence based weighting and generated a modified histogram. In the second step, we use entropy and mutual information based information fusion. Finally, we use three different fusion methods: Dempster and Shafer (DS) theory of evidence, proportional conflict redistribution rule 5 (PCR5) and Bayesian network for decision fusion. Results show that when echoes are in poor quality, accurate detection can be achieved by applying our method. To demonstrate that our algorithm could be applied to other scenarios, we apply it to sense-through-wall human detection using different UWB radars, and simulation results show that our approach works well.

12. Game Theoretical Method for Sum-Rate Maximization in Full-Duplex Massive MIMO Heterogeneous Networks

    In (16), we consider massive MIMO in twolayer Heterogeneous Networks. The system has a large selfinterference and co-channel interference due to operating in fullduplex mode. By using Game Theory, an optimized sum-rate is achieved. We investigate the potential sum-rate before and after the optimization under the power constraints. It is shown that the game theoretical method performed a very good access scheduling. Compared to non-optimized model, game theoretical method can achieve higher sum-rate.

13. Self-Similarity and Modeling of LTE/LTE-A Data Traffic

    Forecasting and modeling the network traffic can help optimize it further. Extensive work has been done on Self-Similarity of Ethernet and Ad-Hoc networks data traffic as Self-Similar time-series can be forecasted. In (12), we emphasize the Self-Similarity of fast growing LTE and LTE-A networks which was left un-explored. It demonstrates Self-Similarity in live LTE and LTE-A networks data traffic. The degree of Self-Similarity is also evaluated and compared. Traffic modeling is very important in optimizing the network with efficient utilization of resources. Modeling of user arrival in live LTE network is performed in this work, which is important since the incoming users are predominantly using data traffic compared to that of traditional voice traffic.

14. Underwater DoA Estimation Based on Nested Array

    In (14), we generalized a new algorithm for Direction of Arrival (DoA) estimation in one and two dimensional (1D and 2D) underwater non-uniform sensor array. The extension of augmented matrix approach from the minimum redundancy array (MRA) to the nested array and co-prime array is the main issue addressed in this work. We elaborate numerical examples of how to construct these new structures of the non-uniform array. The performances of classic MUSIC method and the augmented matrix MUSIC approach are also compared. We also analyze the Cramer-Rao bound (CRB) in the non-uniform sensor deployment and it decreases about 10dB comparing to the uniform linear array (ULA). Additionally, the sparse array can exploit more virtual sensors which are able to detect more sources and have a large dynamic range of the signal peaks to the background. Finally, we provide the detailed performance simulations of 1D and 2D nested array and co-prime array respectively.

15. Efficient Sampling for Radar Sensor Networks

    Compressive sensing (CS) is an excellent technique for data acquisition and reconstruction in radar sensor networks (RSNs) with a high computational capability. We presented a new efficient and effective signal compression and reconstruction algorithm based on CS principles for applications in real-world RSNs (18), in which the signals are obtained in real-world experiment of RSNs. The proposed algorithm neither requires any new optimisation method, nor needs complex pre-processing before compression. This method considers correlation between radar sensor signals to reduce the number of samples required for reconstruction of the original radar signals. We compare our algorithm's performance and complexity with some existing work, such as joint PCA & CS, DCS, and traditional CS. Numerical results show that the proposed algorithm performs more efficiently and effectively without introducing any more computation complexity. With more sensor nodes, our algorithm is more efficient, which significantly reduces the number of samples required per sensor.

16. Nested Sampling for Higher-Order Statistics with Application to LTE Channel Estimation

    In (19), we studied higher-order statistics based on nested sampling. We proposed multilevel nested sampling (MNS) algorithm to obtain higher-order statistics (HOS), and analyzed the computational complexity of the MNS-HOS algorithm for both parametric and nonparametric methods. Compared to the existing HOS algorithms, the proposed algorithm vastly reduces the complexity by several orders in terms of the length of segmentation window. We also applied MNS-HOS algorithm to estimate the coefficients of a simplified LTE spatial channel model blindly without using any training sequences. Our simulations showed that compared with pairwise coprime sampling HOS algorithm, MNS-HOS produces less variance and converges faster in estimating higher-order cumulants, and achieves 17% performance gain for channel estimation. The proposed MNS-HOS algorithm is also able to reduce computational complexity by 98% with a trade-off of 22% performance loss in contrast with the HOS algorithm without sparse sampling.

17. Opportunistic Sensing in Wireless Sensor Networks: Theory and Applications

    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 (20), 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 showed 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.

18. Capacity Optimization in Heterogeneous Home Area Networks with Application to Smart Grid

    In (21), we studied the problem of optimizing the downlink capacity in a heterogeneous Home Area Network (HAN) with beamforming technique at the smart meter for Smart Grid application. We model the communication scenario between the smart meter and in-home appliances as a heterogeneous multi-user network. The optimal power allocation algorithm is developed under the constraints that 1) each user satisfies individual signal to interference and noise ratio (SINR) requirement for successful heterogeneous communication; 2) the sum of transmit power allocated to each user is equal to the permissible total transmit power at the smart meter; 3) the allocated transmit power to each user is feasible. The optimization problem is mathematically shown to be convex and the optimal power allocation is thus derived. By employing the theorem that the sum of independent exponentially distributed random variables follows Erlang distribution, the probability distribution function (PDF) of the smallest allocated transmit power is mathematically obtained from the properties of downlink indoor Saleh-Valenzuela (S-V) channels. It is analytically shown that the allocated transmit power has a lower limit which is determined by the SINR threshold as well as the total number of active users in the HAN. Furthermore, numerical results verify the capacity performance improvements of the proposed optimal power allocation scheme. It is also shown that beamforming technique contributes to the optimal power allocation scheme.

19. Nested Sparse Sampling and Co-prime sampling in Sense-Through-Foliage Target Detection

    In (24), we applied nested sampling and co-prime sampling to target detection in UWB radar sensor networks (RSN), based on a differential approach. The non-stationary UWB signal needs to be decomposed into several approximate wide sense stationary (WSS) signals so that nested sampling could be used in this situation. We also compared the performance of nested sampling and co-prime sampling against uniform under-sampling. The results show that in terms of good quality data and poor quality data, both nested sampling and co-prime sampling work better.

20. Target Detection using 3-D Sparse Underwater Senor Array Network

    Underwater target detection has been widely used nowadays. In (15), we show that the 3-D nested-array system can provide $O(N^2)$ degree of freedom(DOF) by using only N physical sensors when the second order statistics of the received data is used, which means we can use less sensors to get a better performance. A maximum likelihood (ML) estimation algorithm for underwater target size detection is also proposed. Mathematical analysis illustrates that our underwater sensor network can tremendously reduce the variance of target estimation. It is shown that the maximum-likelihood estimator is unbiased and the Cramer-Rao lower bound can be achieved for the variance of parameter estimation. Simulations further validate these theoretical results.

21. Scaling Laws for the Ergodic Capacity of Hybrid Wireless Networks with Distributed Base

Stations

In (13), we considerred the problem of how the ergodic throughput capacity scales in hybrid wireless networks under the infrastructure mode. As opposed to the existing hybrid wireless networks in which the base station only serves individual cell area, the concept of distributed base stations (DBS) is introduced to achieve transmit/receive diversity in this paper. We model the hybrid wireless network with DBS as a multi-cell virtual MIMO system. In addition, a successive interference cancelation (SIC) strategy and the frequency reuse scheme are employed to limit the intra-cell interference and other-cell interference (OCI), respectively. The ergodic throughput capacity, which is an indicator of spectrum efficiency, is investigated over the independent but not identically distributed composite fast fading channels. It is analytically shown that compared to the traditional hybrid wireless network, the ergodic throughput capacity of hybrid wireless networks with DBS scales with gain with NxNBS.

22. Self-Similarity and Modeling of LTE/LTE-A Data Traffic

Forecasting and modeling the network traffic can help optimize it further. Extensive work has been done on Self-Similarity of Ethernet and Ad-Hoc networks data traffic as Self-Similar time-series can be forecasted. In (12), we emphasize the Self-Similarity of fast growing LTE and LTE-A networks which was left un-explored. It demonstrates Self-Similarity in live LTE and LTE-A networks data traffic. The degree of Self-Similarity is also evaluated and compared. Traffic modeling is very important in optimizing the network with efficient utilization of resources. Modeling of user arrival in live LTE network is performed in this work, which is important since the incoming users are predominantly using data traffic compared to that of traditional voice traffic.

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25. Rate Distortion Performance Analysis of Nested Sampling and Coprime Sampling

    In (22), rate distortion performance of nested sampling and coprime sampling was studied. It was shown that with the increasing of distortion, the data rate decreases. With these two sparse sampling algorithms, the data rate is proved to be much less than that without sparse sampling. With the increasing of sampling spacings, the data rate decreases at certain distortion, which is because with more sparse sampling, less number of bits is required to represent the information. We also proved that with the same sampling pairs, the rate of nested sampling is less than that of coprime sampling at the same distortion. The reason is that nested sampling collects a little less number of samples than coprime sampling with the same length of data, which is a little sparser than coprime sampling.

26. Spectrum Efficiency of Nested Sparse Sampling and Co-Prime Sampling

    We proposed new spectral efficiency methods using nested sparse sampling and co-prime sampling (30). The original works on nested sampling and coprime sampling only showed that these new sub-Nyquist sampling algorithms could achieve enhanced degrees of freedom, but did not consider its spectrum efficiency. Spectral efficiency describes the ability of a communication system to accommodate data within a limited bandwidth. In (30), we provided the procedures of applying nested and coprime sampling structure to estimate the QPSK signal autocorrelation and PSD using a set of sparse samples. We also provided detailed theoretical analysis of the PSD of these two sampling algorithms with the increase of sampling intervals. Our theoretical results show that the mainlobe of PSD becomes narrower as the sampling intervals increase for both nested and coprime sampling. The simulation results also show that by making the sampling intervals, i.e., N_1 and N_2 for nested sampling, and P and Q for coprime sampling, large enough, the main lobe of PSD obtained from these two sub-Nyquist samplings are much narrower than the original QPSK signals, which means the bandwidth occupancy of the sampled signal is smaller and it improves the spectrum efficiency. The enhanced spectrum efficiency is a new advantage for both nested sparse sampling and coprime sampling, which could be used in wireless networks to fully use the available spectrum with more and more devices communicating over the wireless communication band.

27. Theoretical Performance Limits for Compressive Sensing with Random Noise

    In (34), we analyzed the performance of noisy compressive sensing theoretically, and derived both the lower bound and upper bound of the probability of error for compressive sensing, with the assumption that both the original information and the noise follow Gaussian distribution. Both the lower bound and upper bound of the probability of error for the general case without special requirement of the measurement matrix Φ are provided. It has been shown that under some condition, perfect reconstruction of the information vector is impossible, as there will always be certain error. Specially, when the Bernoulli matrix is chosen as the measurement matrix, the corresponding lower bound and upper bound of the probability of error are given with a much neat and clear expression. The corresponding Cramer-Rao lower bound is also provided. These results provide some theoretical reference of the probability of error of compressive sensing.

28. Coprime Sampling for Nonstationary Signal

Estimating the spectrogram of non-stationary signal relates to many important applications in radar signal processing. In recent years, coprime sampling and array attract attention for their potential of sparse sensing with derivative to estimate autocorrelation coefficients with all lags, which could in turn calculate the power spectrum density. But this theoretical merit is based on the premise that the input signals are wide-sense stationary. In (27), we discussed how to implement coprime sampling for non-stationary signal, especially how to attain the benefits of coprime sampling meanwhile limiting the disadvantages due to lack of observations for estimations. Furthermore, we investigated the usage of coprime sampling for calculating ambiguity function of matched filter in radar system. We also examined the effect of it and conclude several useful guidelines of choosing configuration to conduct the sparse sensing while retain the detection quality.

29. Secure Transmission for Big Data Based on Nested Sampling and Coprime Sampling with Spectrum Efficiency

Big data presents critical requirements for security in data collection and transmission of selected data through a communication network. A new secure transmission for big data based on nested sparse sampling and coprime sampling was presented in (32). With nested sampling and coprime sampling, besides the advantage of higher spectrum efficiency, big data could also achieve higher power spectral density for binary frequency shift keying (BFSK) signal. When the sampling spacing pairs are big enough, the spectrum of BFSK signal performs like frequency hopping. This property has great advantage in the security of big data collection and transmission using FH/BFSK, as it could achieve low error probability. With the same multitone interfering signal added to FH/BFSK, the error probability becomes much lower using nested sampling and coprime sampling compared with the original FH/BFSK signal. This proves that both nested sampling and coprime sampling could be used in big data transmission to resist interference, while guaranteeing the transmission performance.

30. Decision Fusion in Target Detection using UWB Radar Sensor Network

Ultra wide band radar sensor network can be used to detect target in foliage environment. Information theoretic algorithms like entropy, relative entropy and mutual information are proven methods that can be applied to data collected by various sensors. However, the complexity of the environment posses uncertainty in fusion center and correct decision can only be made by decision fusion. In (28), we proposed two methods Dempster and Shafer (D-S) theory of evidence and bayesian network for combining the decision of target detection. We resolved the conflict of decision by applying these methods. We also introduce the improved version of D-S theory for conflicting evidence and compared the performance with D-S and bayesian network. Accurate detection can be achieved by applying these methods, when echoes are in poor quality. The performance of the algorithm was evaluated, based on real world data.

31. Radar Sensor Network for Target Detection using Chernoff Information and Relative Entropy

In (23)(29), we proposed to apply information theory to Ultra wide band (UWB) radar sensor network (RSN) to detect target in foliage environment. Information theoretic algorithms such as Maximum entropy method (MEM) and mutual information are proven methods, that can be applied to data collected by various sensors. However, the complexity of the environment poses uncertainty in fusion center. Chernoff information provides the best error exponent of detection in Bayesian environment. In this paper, we consider the target detection as binary hypothesis testing and use Chernoff information as sensor selection criterion, which significantly reduces the processing load. Another strong information theoretic algorithm, method of types, is applicable to our MEM based target detection algorithm as entropy is dependent on the empirical distribution only. Method of types analyzes the probability of a sequence based on empirical distribution. Based on this, we can find the bound on probability of detection. We also proposed to use Relative entropy based processing in the fusion center based on method of types and Chernoff Stein Lemma. We study the required quantization level and number of nodes in gaining the best error exponent. The performance of the algorithms were evaluated, based on real world data.

32. Higher-Order Statistics in Co-prime Sampling with Application to MA System Identification

In (10), we studied higher-order statistics of non- Gaussian signal using temporal co-prime sampling. We extend co-prime sampling to pairwise co-prime sequence (PCS) to study higher-order statistics (HOS), and analyze the computational complexity of PCS-based HOS algorithm for both parametric and nonparametric methods. Compared to the existing HOS algorithms, the proposed algorithm vastly reduces the computation complexity by several orders in terms of the length of segmentation window. We develop overdetermined matrix representation for moving average (MA) system, and apply PCSbased HOS algorithm to identify MA systems only based on their outputs. Our simulation results show that 3rd-order PCSbased HOS could achieve 80% performance gain for MA system identification, compared to the existing HOS with the same computational complexity, or it has 12% performance loss with 15% complexity compared to the counterpart processing the same length of signal. We also apply PCS-based HOS algorithm to estimate the coefficients of simplified LTE spacial channel model only based on its outputs (26). Further, we apply co-prime Sampling-based third-order cumulants for UWB channel order determination (25).

33. Spectrum Efficiency of Nested Sparse Sampling and Co-Prime Sampling

We proposed new spectral efficiency methods using nested sparse sampling and co-prime sampling (30). The original works on nested sampling and coprime sampling only showed that these new sub-Nyquist sampling algorithms could achieve enhanced degrees of freedom, but did not consider its spectrum efficiency. Spectral efficiency describes the ability of a communication system to accommodate data within a limited bandwidth. In (30), we provided the procedures of applying nested and coprime sampling structure to estimate the QPSK autocorrelation and power spectral density (PSD) using a set of sparse samples. We also provided detailed theoretical analysis of the PSD of these two sampling algorithms with the increase of sampling intervals. Our theoretical results show that the mainlobe of PSD becomes narrower as the sampling intervals increase for both nested and coprime sampling. The simulation results also show that by making the sampling intervals, i.e., N_1 and N_2 for nested sampling, and P and Q for coprime sampling, large enough, the main lobe of PSD obtained from these two sub-Nyquist samplings are much narrower than the original QPSK signals, which means the bandwidth occupancy of the sampled signal is smaller and it improves the spectrum efficiency. The enhanced spectrum efficiency is a new advantage for both nested sparse sampling and coprime sampling, which could be used in wireless networks to fully use the available spectrum with more and more devices communicating over the wireless communication band.

34. Coprime Sampling for Nonstationary Signal

    Estimating the spectrogram of non-stationary signal relates to many important applications in radar signal processing. In recent years, coprime sampling and array attract attention for their potential of sparse sensing with derivative to estimate autocorrelation coefficients with all lags, which could in turn calculate the power spectrum density. But this theoretical merit is based on the premise that the input signals are wide-sense stationary. In (27)(31), we discuss how to implement coprime sampling for non-stationary signal, especially how to attain the benefits of coprime sampling meanwhile limiting the disadvantages due to lack of observations for estimations. Furthermore, we investigate the usage of coprime sampling for calculating ambiguity function of matched filter in radar system. We also examine the effect of it and conclude several useful guidelines of choosing configuration to conduct the sparse sensing while retain the detection quality.

35. Secure Transmission for Big Data Based on Nested Sampling and Coprime Sampling with Spectrum Efficiency

    Big data presents critical requirements for security in data collection and transmission of selected data through a communication network. A new secure transmission for big data based on nested sparse sampling and coprime sampling was presented in (32). With nested sampling and coprime sampling, besides the advantage of higher spectrum efficiency, big data could also achieve higher power spectral density for binary frequency shift keying (BFSK) signal. When the sampling spacing pairs are big enough, the spectrum of BFSK signal performs like frequency hopping. This property has great advantage in the security of big data collection and transmission using FH/BFSK, as it could achieve low error probability. With the same multitone interfering signal added to FH/BFSK, the error probability becomes much lower using nested sampling and coprime sampling compared with the original FH/BFSK signal. This proves that both nested sampling and coprime sampling could be used in big data transmission to resist interference, while guaranteeing the transmission performance.

36. Decision Fusion in Target Detection using UWB Radar Sensor Network

    Ultra wide band radar sensor network can be used to detect target in foliage environment. Information theoretic algorithms like entropy, relative entropy and mutual information are proven methods that can be applied to data collected by various sensors. However, the complexity of the environment posses uncertainty in fusion center and correct decision can only be made by decision fusion. In (28), we proposed two methods Dempster and Shafer (D-S) theory of evidence and bayesian network for combining the decision of target detection. We resolved the conflict of decision by applying these methods. We also introduce the improved version of D-S theory for conflicting evidence and compared the performance with D-S and bayesian network. Accurate detection can be achieved by applying these methods, when echoes are in poor quality. The performance of the algorithm was evaluated, based on real world data.

37. Target Detection using Chernoff Information and Relative Entropy

    Complex environment of forest makes target detection through foliage an ongoing challenge. 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 environment posses uncertainty in fusion center. In (29), we considered the target detection as binary hypothesis testing and derive the best possible error exponents using Chernoff Information and Chernoff Stein Lemma. The error probabilities associated with the detection is crucial in understanding the performance of the detection. We also propose relative entropy based preprocessing in the fusion center based on an information theoretic algorithm known as method of types. We found the relation between the observation size, quantization level and number of nodes in gaining the best error exponent. The performance of the algorithm was evaluated, based on real world data.

WORK COMPLETED

1. Sparse Nested Cylindrical Sensor Networks for Internet of Mission Critical Things
2. Increasing Capacity of Multi-Cell Cooperative Cellular Networks with Nested Deployment
3. Higher-Order Statistics in Co-prime Sampling with Application to Channel Estimation
4. Nested Sampling for Higher-Order Statistics with Application to LTE Channel Estimation
5. Multi-Step Information Fusion for Target Detection using UWB Radar Sensor Network
6. Opportunistic Sensing in Wireless Sensor Networks: Theory and Applications
7. Rate Distortion Performance Analysis of Nested Sampling and Coprime Sampling
8. Capacity Optimization in Heterogeneous Home Area Networks with Application to Smart Grid
9. Nested Sparse Sampling and Co-prime sampling in Sense-Through-Foliage Target Detection
10. Radar Sensor Network for Target Detection using Chernoff Information and Relative Entropy
11. Target Detection using 3-D Sparse Underwater Senor Array Network
12. Game Theoretical Method for Sum-Rate Maximization in Full-Duplex Massive MIMO Heterogeneous Networks
13. Scaling Laws for the Ergodic Capacity of Hybrid Wireless Networks with Distributed Base Stations
14. Self-Similarity and Modeling of LTE/LTE-A Data Traffic
15. Underwater DoA Estimation Based on Nested Array
16. Higher-Order Statistics in Co-prime Sampling with Application to Channel Estimation
17. Opportunistic Sensing in Wireless Sensor Networks: Theory and Applications
18. Rate Distortion Performance Analysis of Nested Sampling and Coprime Sampling

19. Nested Sparse Sampling and Co-prime sampling in Sense-Through-Foliage Target Detection
20. Nested Sampling for Higher-Order Statistics with Application to LTE Channel Estimation
21. A Hybrid Approach of Sparse Sampling
22. Spectrum Efficiency of Nested Sparse Sampling and Co-Prime Sampling
23. Theoretical Performance Limits for Compressive Sensing with Random Noise
24. Coprime Sampling for Nonstationary Signal
25. Secure Transmission for Big Data Based on Nested Sampling and Coprime Sampling with Spectrum Efficiency
26. Decision Fusion in Target Detection using UWB Radar Sensor Network
27. Radar Sensor Network for Target Detection using Chernoff Information and Relative Entropy
28. Higher-Order Statistics in Co-prime Sampling with Application to MA System Identification
29. Secure Transmission for Big Data Based on Nested Sampling and Coprime Sampling with Spectrum Efficiency
30. Decision Fusion in Target Detection using UWB Radar Sensor Network
31. Target Detection using Chernoff Information and Relative Entropy

RESULTS

Significant results were achieved during this report period. 1) Increasing Capacity of Multi-Cell Cooperative Cellular Networks with Nested Deployment; 2) Higher-Order Statistics in Co-prime Sampling with Application to Channel Estimation; 3) Multi-Step Information Fusion for Target Detection using UWB Radar Sensor Network; 4) Rate Distortion Performance Analysis of Nested Sampling and Coprime Sampling. 5) Co-prime sampling for higher-order statistics; 6) Coprime Sampling for Nonstationary Signal; 7) Spectrum Efficiency of Nested Sparse Sampling and Co-Prime Sampling; 8) a hybrid approach which combines nested sampling and compressive sensing to reduce the number of symbols in data processing. 9) Co-prime sampling for higher-order statistics; 10) Coprime Sampling for Nonstationary Signal; 11) Spectrum Efficiency of Nested Sparse Sampling and Co-Prime Sampling. We have added the following "new capabilities" because of our works.

We have added the following "new capabilities" because of our works.

1. Wireless network capacity increases because of our work on nested base stations deployment (17). Given the high attenuation at higher frequency where the next generation cellular networks will be operated, it is expected that the 5G cellular network will operate using much smaller cells with radius size around 30 meters for indoor environment, and 200 meters in radius for outdoor environment. As the number of macro-cellular BSs (with cell radius around 1 mile or 1600 meters) reaching 50 million worldwide by 2015 for 4G and 3G celluar networks, it would need an extremely large number of BSs to deploy 5G cellular networks with cell radius 200 meters. Our BS deployment scheme based on nested array which will vastly reduce the number of BSs and increase wireless network capacity.

2. Simplied and more efficient HOS computation based on co-prime sampling. The parametric methods of HOS often fall into a dilemma in applications. On the one hand, they have high variance and require a large number of records to obtain smooth estimates. On the other hand, although they have better computational efficiency than nonparametric methods, increasing the number of segments is still demanding on computation, and may increase bias and introduce nonstationarities. Because of our work in (10), people are able to extend co-prime sampling calculating HOS and to develop PCS-based HOS algorithm processing non-Gaussian signal or using in nonminimum phase linear system. The major advantage of the proposed algorithm is to introduce new trade-off for the implementation of HOS–the algorithm is able to maintain the same degree of complexity but to achieve better HOS estimates; or it reduces the complexity by several orders with a mild performance loss.
3. We proposed a multi-step information fusion scheme for target detection through foliage and wall, using ultra wide-band radar sensor networks (11). Dynamic nature of the foliage imposes lot of challenges to detect target, while there is not enough statistical information. This has added new capability on sense-through-foliage target detection.
4. Rate distortion performance of nested sampling and coprime sampling. Because of our work in (22), people understand quantatively that with the increasing of distortion, the data rate decreases in nested sampling and coprime sampling. With these two sparse sampling algorithms, the data rate was proved to be much less than that without sparse sampling. With the increasing of sampling spacings, the data rate decreases at certain distortion, which is because with more sparse sampling, less number of bits is required to represent the information. It was also proved that with the same sampling pairs, the rate of nested sampling is less than that of coprime sampling at the same distortion.
5. Our work in (30) demonstrated that with the proper choice of sampling intervals in co-prime and nested sampling, i.e., making them large enough, the main lobe of PSD obtained from both nested sampling and coprime sampling is much narrower than the original QPSK signal. If we choose the sampling intervals larger, the bandwidth occupied will be narrower, which improves the spectrum efficiency. Besides the smaller average rate, the increased spectrum efficiency is a new advantage of both nested sparse sampling and coprime sampling.
6. The presumption to generate autocorrelation from the coprime sampled sequence is that the second-order expectations of the sequence remain unchanged over time, which is essentially the wide-sense stationary (WSS) signal. In the application of radar signal processing, however, this criteria cannot hold anymore. Because of our work in (27)(31), people are able to combine coprime sampling with short time Fourier transform (STFT-CS) to process non-stationary signal, and demonstrate this algorithm is useful to preserve both the original quality of the signal and at the same time dramatic decrease the sample rate.

IMPACT/APPLICATIONS

Results from this research could be integrated into emerging net-centric Navy and Marine Corps Command & Control and Intelligence, Surveillance, and Reconnaissance (C2 and ISR) acquisition programs. The algorithms from this project could be integrated into existing Navy and Marine Corps' radar sensor systems such as Tactical Remote Sensor System (TRSS), Joint Surveillance Target Attack

Radar System (JSTARS), Tier II Pioneer Unmanned Aerial System (UAS), Expeditionary Tactical Area Surveillance Sysem (ETASS), Critical Area Protection System (CAPS), etc. The proposed research will directly benefit DoD netcentricity based programs and concepts including Navy FORCEnet, Distributed Common Ground System (DCGS), Transparent Urban Structures (TUS) program, etc. This project will help to automate processes that provide small tactical units with more efficient data processing and sensor fusion.

RELATED PROJECTS

PI: Qilian Liang, "Practical Co-Prime and Nested Samplers and Arrays for Radar and Radar Sensor Networks," Office of Naval Research (ONR), Award Number: N00014-17-1-2733, Total Grant: $159,501, 9/1/2017-9/30/2019.

HONORS/AWARDS/PRIZES

1. IEEE Fellow, 2016
2. IEEE Infocom Workshop Best Paper Award, 2016
3. Academy of Distinguished Scholars, University of Texas at Arlington, 2015.
4. Outstanding Research Achievement Award, University of Texas at Arlington, 2013

GRADUATED PH.D/M.S. STUDENTS

10 Ph.D students have graduated during this project:

1. Ishrat Maherin, PhD Dissertation: Target Detection and Cognitive Radio Capacity Analysis Based on Sensor Networks, May 2014.
2. Junjie Chen, PhD Dissertation: Sparse Sensing in Big Data, May 2014.
3. Xin Wang, PhD Dissertation: Hybrid and Smart Grid Wireless Networks: Capacity and Optimization, May 2014.
4. Zhuo Li, Ph.D Dissertation: Home Area Networks for Smart Grid Communications, May 2014.
5. Qiong Wu, PhD Dissertation: Sparse Sampling in Wireless Communications, May 2015.
6. Shitong Yuan, PhD Dissertation: Optimization of Heterogeneous Wireless Networks with Massive MIMO, May 2016.
7. Na Wu, PhD Dissertation, Sparse Sampling and Array in Signal Processing, May 2017.
8. Hao Liang, PhD Dissertation, Sparse Array for Wireless Sensor Networks and Wireless Communications, May 2017.
9. Longwei Wang, Large Dimensional Analysis and Optimization for Massive MIMO Wireless Networks, December 2017.
10. Ganlin Zhao, Massive MIMO Performance Analysis and Radar Sensor Networks Based Target Detection, December 2017.

7 M.S. students have graduated during this project:

1. Supreet Huilgol, Channel Coding Techniques for 5G Using Polar Codes, May 2017.
2. Netrapala, Sreevinay; Ststistical Analysis of Indoor UWB Channel Parameters in Different Wall Corridors and Through-Wall Environment, August 2015.
3. Katara, Karishma; Evaluation of Adaptive Video Optimization for Stall Minimization in Wireless Networks, August 2015.
4. Bangalore krishnamur, Shruthishree Channel Estimation and Statistical Analysis of Indoor Classroom Environment Using Ultra Wide-band Radio Technology, August 2015.
5. Roopeshkumar Polaganga, MS Thesis, Self-Similarity and Modeling of LTE/LTE-A Data Traffic, May 2015.
6. Zhaoheng Luo, MS Thesis, The Evaluation of RF Channel Impairments and Co-Channel Interference over Rician Fading Channel, Dec 2014.
7. Amit Deokar, MS Thesis, "Enhancement of Security and Reliability with MIMO Communication for Smart Grid," May 2013.

PUBLICATIONS

The publications are listed in the following references section, of which 20 journal papers and 14 conference papers have been published.

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[3] Xin Wang, Qilian Liang, "Efficient Sensor Selection Schemes for Wireless Sensor Networks in Microgrid," *IEEE Systems Journal*, vol. 12, no. 1, pp. 539-547, March 2018.

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[5] Fangqi Zhu, Na Wu, Qilian Liang, "Channel estimation for massive MIMO with 2-D nested array deployment," *Physical Communication*, vol. 25, pp. 432-437, Dec 2017.

[6] Longwei Wang, Qilian Liang, "Low Complexity Optimization for User Centric Cellular Networks via Large Dimensional Analysis," *Physical Communication*, vol. 25, pp. 412-419, Dec 2017.

[7] Ganlin Zhao, Qilian Liang, "On the Uplink Outage Throughput Capacity of Hybrid Wireless Networks with Massive MIMO," *(Elsevier)Ad Hoc Networks*, vol. 58, pp. 62-69, April 2017.

[8] Ganlin Zhao, Qilian Liang, "Sense-Through-Foliage Target Detection Based on EMD and UWB

Radar Sensor Networks," *International Conference on Communications, Signal Processing, and Systems*, July 2017, Harbin, China.

[9] Na Wu, Qilian Liang, "Spatial Spectrum Analysis of Proposed Two-dimensional Nested Cylindrical Array," *International Conference on Communications, Signal Processing, and Systems*, July 2017, Harbin, China.

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[11] Ishrat Maherin, Qilian Liang, "Multi-Step Information Fusion for Target Detection using UWB Radar Sensor Network," *IEEE Sensors Journal*, vol. 15, no. 10, pp. 5927-5937, Oct 2015.

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[13] Zhuo Li, Qilian Liang, "Scaling Laws for the Ergodic Capacity of Hybrid Wireless Networks with Distributed Base Stations," *IEEE Globecom*, Dec 2015, San Diego, CA.

[14] Na Wu, Qilian Liang, "Underwater DoA Estimation Based on Nested Array," *IEEE MILCOM*, Oct 2015, Tampa, FL.

[15] Hao Liang, Qilian Liang, "Target Detection using 3-D Sparse Underwater Senor Array Network," *IEEE MASS*, Oct 2015, Dallas, TX.

[16] Shitong Yuan, Qilian Liang, "Game Theoretical Method for Sum-Rate Maximization in Full-Duplex Massive MIMO Heterogeneous Networks," *(Elsevier) Signal Processing*, vol. 126, pp. 4-11, 2016.

[17] Qiong Wu, Qilian Liang, "Increasing Capacity of Multi-Cell Cooperative Cellular Networks with Nested Deployment," *IEEE International Conference on Communications*, June 2015, London, UK.

[18] Junjie Chen, Qilian Liang, "Efficient Sampling for Radar Sensor Networks," *International Journal of Sensor Networks*, vol. 17, no. 2, pp. 105-114, 2015.

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