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14. ABSTRACT

This project is to develop practical co-prime and nested samplers and arrays for radar, sensor networks, and wireless communications. Major research tasks include: 1) Representation Learning and Nature Encoded Fusion for Heterogeneous Sensor Networks; 2) Sparse Nested Cylindrical Sensor Networks for Internet of Mission Critical Things; 3) Information Theoretic Bounds for Sparse Reconstruction in Random Noise; 4) Increasing Capacity of Multi-Cell Cooperative Cellular Networks with Nested Deployment; 5) Coprime Interpolation and Compressive Sensing for Future Heterogeneous Network Towards 5G; 6) Channel estimation for massive MIMO with 2-D nested array deployment. 4 Ph.D students have been supported by this ONR project and 2 have graduated with Ph.D degrees.

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

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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, sensor networks, and wireless communications. 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 sensor networks and wireless communications.

OBJECTIVES

This project includes the objectives listed below.

1. Co-Prime and Nested Samplers and Arrays for Sensor Networks.
2. Co-Prime and Nested Samplers for Non-stationary Signals.
3. Co-prime and Nested Arrays for Wireless Communications

APPROACH

Led by PI Liang, four PhD students, Longwei Wang, Ganlin Zhao, Fangqi Zhu, Chengchen Mao participated in this project during this report period and two students have received their Ph.D degrees. Major approaches include the following aspects.

1. Representation Learning and Nature Encoded Fusion for Heterogeneous Sensor Networks

   Target detection based on heterogeneous sensor networks is considered in (1). Fusion problem is investigated to fully take advantage of the information of multi-modal data. The sensing data may not be compatible with each other due to heterogeneous sensing modalities, and the joint PDF of the sensors is not easily available. A two-stage fusion method is proposed to solve the heterogeneous data fusion problem. First, the multi-modality data is transformed into the same representation form by a certain linear or nonlinear transformation. Since there is a model mismatch among the different modalities, each modality is trained by an individual statistical model. In this way, the information of different modalities is preserved. Then, the representation is used as the input of the probabilistic fusion. The probabilistic framework allows data from different modalities to be processed in a unified information fusion space. The inherent inter-sensor relationship is exploited to encode the original sensor data on a graph. Iterative belief propagation is used to fuse the local sensing belief. The more general correlation case is also considered, in which the relation between two sensors is characterized by the correlation factor. The numerical results are provided to validate the effectiveness of the proposed method in heterogeneous sensor network fusion.

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

   In (2), 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.

3. Bandwidth Allocation Based on Personality Traits on Smartphone Usage and Channel Condition

   How to allocate resources in the era of Big Data in telecommunications becomes a new issue. Smartphone data could be a function of personality, as the smartphone supports interpersonal interaction, and the data collected from the smartphone usage often contains rich customer opinion and behavioral information. A bandwidth allocation method based on smartphone users' personality traits and channel condition is studied in a unified mathematical framework in (3). Personalizing bandwidth allocation could be done by analyzing smartphone users' personality traits, resulting in business intelligence, a smarter and more efficient usage of the limited bandwidth, while taking channel fading conditions into account. Using the diagnostic inference, the service provider could calculate the user's probability of having each personality trait stand on its data usage. One step further, its bandwidth usage of the following period can be predicted using predictive inference. For our proposed bandwidth allocation scheme, both the outage capacity and outage probability are studied in fading channel. Therefore, the service providers shall better allocate the limited bandwidth, provide more personal service to each user, and adjust the bandwidth allocation further on account of the real channel condition.

4. Information Theoretic Bounds for Sparse Reconstruction in Random Noise

   Compressive sensing (CS) plays a pivotal role in the signal processing and we address on the issues, i.e., the information-theoretic analysis of CS under random noise in (4). To distinguish from existing literature, we aim at providing a precise reconstruction of the source signal. From the analysis of the recovery performance, we calculate the lower band upper bound of the probability of error for CS. To be more specific, we provide more discussions for the case where both the source and the noise follow Gaussian distribution. It has been proved that perfect reconstruction of the signal vector is impossible if the corresponding conditions are not satisfied, which can be served as the theoretical reference of noisy CS. In terms of the necessary proofs, we leverage the results from information theory and estimation theory. The compression of real underwater acoustic sensor network (UWASN) data is applied to verify the theoretical bounds derived in this work.

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

   In (5), 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.

6. 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 (6), 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.

7. 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 (7). 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.

8. 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 (8), 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.

9. 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 (9), 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.

WORK COMPLETED

1. Representation Learning and Nature Encoded Fusion for Heterogeneous Sensor Networks
2. Sparse Nested Cylindrical Sensor Networks for Internet of Mission Critical Things
3. Bandwidth Allocation Based on Personality Traits on Smartphone Usage and Channel Condition
4. Information Theoretic Bounds for Sparse Reconstruction in Random Noise

5. Increasing Capacity of Multi-Cell Cooperative Cellular Networks with Nested Deployment
6. Efficient Sensor Selection Schemes for Wireless Sensor Networks in Microgrid
7. Coprime Interpolation and Compressive Sensing for Future Heterogeneous Network Towards 5G
8. Channel estimation for massive MIMO with 2-D nested array deployment
9. Low Complexity Optimization for User Centric Cellular Networks via Large Dimensional Analysis

RESULTS

Significant results were achieved during this report period. We have added the following "new capabilities" because of our works.

1. Since cylindrical sensor arrays are often made use of only a part of elements at a time, we have extended the 1-D and 2-D nested array structure to the cylindrical sensor network in order to reduce the number of nodes. In (2), we first propose the sparse sensor network constructed by 1-D nested cylindrical sensor network (1-D NCSN), which combined the nested linear array (NLA) with uniform circular array. Based on the previous work, the new beampattern of the proposed sparse sensor network is derived, and also compare it with the uniform cylindrical array-based sensor network. Furthermore, the 2-D nested array-based sensor network structure is also applied to reduce more sensors. To the best of our knowledge, this is the first time that the nested array structure is combined with the cylindrical sensor network. The detailed analysis of the DOA estimation is provided as well. Since the ability of an array to distinguish signals arriving from different angles is important in measuring the resolution of an array, we compared the performance of 1-D NCSN, and 2-D NCSN. Besides, the augmented matrix MUSIC approach is applied in order to detect multiple sources. Simulation results showed that the 2-D sparse cylindrical sensor network could achieve highest resolution with fewer elements comparing with other cylindrical sensor networks.
2. Heterogeneous sensor networks with multiple sensing modalities are gaining increasing popularity because they can provide several advantages for performance improvement in different realistic scenarios. Fusion of data from heterogeneous modalities, observing a certain phenomenon, has been shown to improve the performance of many surveillance and monitoring tasks. The key motivation is that sensors of different modalities will provide richer information than a single sensor, or even several sensors of the same modality. Because of our works (1), a two-stage framework for fusing information from heterogeneous sensors is proposed. The representation learning stage transforms the data into a unified data form. The nature encoded fusion allows data from different modalities to be processed in a unified probabilistic space. The inherent inter-sensor relationship is exploited and it can be seen as a nature encoded sensing with heterogeneous sensors. Then iterative belief propagation is used to refine and fuse the local individual belief. Instead of estimating the joint PDF, we just need to abstract the local log-likelihood ratio from each sensor. Then the local log-likelihood ratio is sent to the fusion center for processing. Further the more general correlation case is considered, in which the relation between two sensors is characterized by the correlation factor. The belief propagation provides intuitive insights as to how the probabilistic updates reinforce beliefs with the help of

correlation factor.

3. Wireless network capacity increases because of our work on nested base stations deployment (5). 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.

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

N/A.

HONORS/AWARDS/PRIZES

Outstanding Associate Editor, IEEE Access, 2018.

GRADUATED PH.D/M.S. STUDENTS

2 Ph.D students have graduated during this project:

1. Longwei Wang, Large Dimensional Analysis and Optimization for Massive MIMO Wireless Networks, December 2017.
2. Ganlin Zhao, Massive MIMO Performance Analysis and Radar Sensor Networks Based Target Detection, December 2017.

PUBLICATIONS

The publications are listed in the following references section, of which 9 journal papers have been published.

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[5] Qiong Wu, Qilian Liang, "Increasing the Capacity of Cellular Network with Nested Deployed Cooperative Base Stations," *IEEE Access*, vol. 6, no. 1, pp. 35568-35577, 2018.

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