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MATHEMATICAL AND ALGORITHMIC CHALLENGES FOR FULLY ADAPTIVE RADAR (Preprint)

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14. ABSTRACT
Several factors such as difficult targets, embedded in complex clutter and competing background target settings and coupled with increasingly severe intentional and unintentional RF interference continue to increase the complexity and challenges of modern high performance radars. The cognitive fully adaptive radar (CoFAR) was introduced to meet the challenges of increasingly complex operating environments. The CoFAR features fully adaptive transmit, receive, and controller/scheduler functions by learning and understanding the complete multi-dimensional radar channel (targets, clutter, interference, etc.) via a sense-learn-adapt (SLA) approach. The system enables to jointly optimize the adaptive transmit and receive functions by estimating the radar channel comprising of clutter and other interfering signals.

15. SUBJECT TERMS
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LABORATORY ANNUAL TASK REPORT

LRIR: 20RYCOR051

Title: Mathematical and Algorithmic Challenges for Fully Adaptive Radar

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Research Objective:

Several factors such as difficult targets, embedded in complex clutter and competing background target settings and coupled with increasingly severe intentional and unintentional RF interference continue to increase the complexity and challenges of modern high performance radars. The cognitive fully adaptive radar (CoFAR) was introduced to meet the challenges of increasingly complex operating environments. The CoFAR features fully adaptive transmit, receive, and controller/scheduler functions by learning and understanding the complete multi-dimensional radar channel (targets, clutter, interference, etc.) via a sense-learn-adapt (SLA) approach. The system enables to jointly optimize the adaptive transmit and receive functions by estimating the radar channel comprising of clutter and other interfering signals.

The radar waveforms and receiver filters of the CoFAR for subsequent pulses or coherent pulse intervals (CPIs) are essentially computed using knowledge of the radar channel compromising of clutter and other interfering signals. In practice, the channel information is unknown and should be estimated from probing signals. Hence, the effectiveness of these CoFAR systems is highly dependent on the stationarity of the radar channels as well as the accuracy of the channel estimation algorithms. We developed new channel estimation algorithms that exploit the relationship between the channel impulses responses of adjacent pulses. The proposed algorithm outperforms a traditional unconstrained least squares solution.

We also address the next step where the framework involves an adversarial signal processing problem comprising “us” and an “adversary.” “Us” refers to an asset such as a drone/UAV or electromagnetic signal that probes an “adversary” cognitive radar. A cognitive sensor observes our kinematic state in noise as the observation. It then uses a Bayesian tracker to update its posterior distribution of our state and chooses an action based on this posterior. We observe the sensor’s action in noise. Given knowledge of “our” state sequence and the observed actions taken by the adversary’s sensor, we focus on the following inter-related aspects. We consider the adversary radar choosing its transmit waveform for target tracking by implementing a Wiener filter to maximize its signal-to-clutter-plus-noise ratio (SCNR). By observing the optimal waveform chosen by the radar, we will develop a smart strategy to estimate the adversary cognitive radar channels followed by signal dependent interference generation mechanism to confuse the adversary radar.

Summary:

The research in FY 20 is reported under two broad thrusts.

1. **Constrained Channel Estimation Algorithm**

Our principal aim is to develop a new channel estimation algorithm to improve the unconstrained least squares solution particularly in low SNR regimes since the least squares solution without any constraint suffers from low SNR values. We propose constrained least squares problem under the cosine similarity constraint and the inner product constraint between a channel impulse response of the previous pulse and the current pulse for which the channel impulse response is being estimated.

We first investigate the cosine similarity measurement and the inner product value between the channel impulse responses of adjacent pulses from RFView dataset and observe that the channel impulse responses between closer pulses show higher values of the cosine similarity and the inner product. We also observe that the unconstrained least squares solution shows much lower value of the cosine similarity especially for the low SNR environment.

Then we propose a new constrained least square problem with the cosine similarity constraint to improve the least squares solution. Since the least squares solution does not meet a desired value of the cosine similarity constraint, we enforce the estimated channel impulse response to have a desired cosine similarity measurement. The resulting optimization problem is a non-convex problem, however, we convert it to a non-convex quadratically constrained quadratic program for which strong duality holds. Furthermore, we observe that the inner product value between adjacent channel impulse responses does not vary regardless of the SNR level. We add the inner product constraint to the non-convex QCQP with the cosine similarity constraint then derive a convex optimization problem.

We provide numerical results of the proposed methods comparing to the traditional unconstrained lease square solution using a real dataset from RFView. We show that both the proposed methods outperform the least squares solution. It is also shown that the convex problem with the cosine similarity constraint and the inner product constraint shows the best performance even though computational complexity is much lower than the non-convex QCQP with the cosine similarity constraint. We also provide simulation results using RFView challenge dataset and the convex problem with the inner product constraint works well for the challenge dataset.

2. **Channel/Parameter Estimation and Smart Interference Design via Inverse Filtering**

We consider inter-related adversarial inference problems involving cognitive radars and address how to engineer interference at the physical layer level to confound the radar which forces it to change the transmit waveform. The adversary radar chooses the transmit waveform for target tracking by implementing a Wiener filter to maximize its signal-to-clutter-plus-noise ratio (SCNR). By observing the optimal waveform chosen by the radar, we develop a smart strategy to estimate the adversary cognitive radar channels followed by signal dependent interference generation mechanism to confound the adversary radar.

Our objective is to minimize the signal power of the interference generated by us while ensuring the SCNR of the adversary radar does not exceed a pre-defined threshold. The setup is schematically shown in Figure 1.

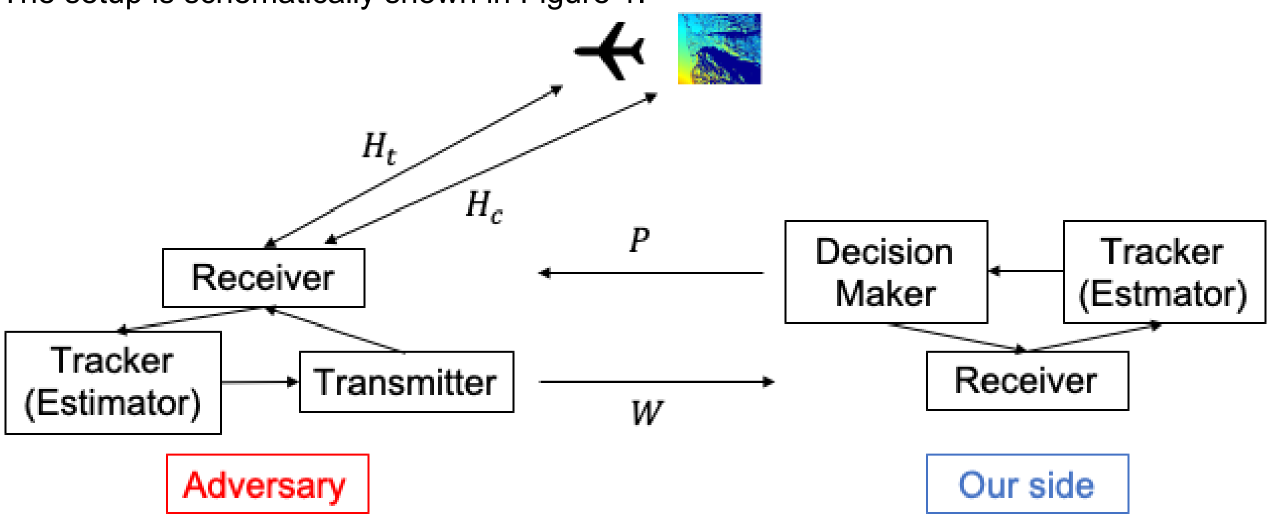

Figure 1. Schematic of transmit channel, clutter channel, and interference channel involving an adversarial cognitive radar and us. We observe the radar's waveform W in noise. The aim is to engineer the interference channel P to confuse the cognitive radar.

We first characterize how a cognitive radar optimally chooses its waveform based on its perceived interference. The radar's objective is to choose the optimal waveform that maximizes its SCNR. Then we design optimal interference signals to confuse the adversary cognitive radar by solving a probabilistically constrained optimization problem. The optimal interference signal minimizes its power such that the SCNR of the radar lies below a threshold with a prescribed probability. To solve a resulting non-convex optimization problem, we first estimate the transmit and clutter channel impulse response from the observation and use the estimated value of channel impulse responses to generate the interference signal.

The cognitive radar maximizes its energy in the direction of its target impulse response and transfer function. As soon as we have an accurate estimate of the target channel transfer function from the pulses, we can immediately generate signal dependent interference that nulls the target returns. Even if the clutter channel impulse response changes after we perform our estimation adaptively, since the target channel is stationary for longer durations. Therefore, signal dependent interference will work successfully for several pulses after we conclude the estimate. The main take away from this approach is that we are exploiting the fact that the cognitive radar provides information about its channel by optimizing the waveform with respect to its environment.

List of Publications

Journal Papers:

1. V. Krishnamurthy and M. Rangaswamy, “How to Calibrate Your Adversary's Capabilities? Inverse Filtering for Counter-Autonomous Systems,” IEEE Transactions on Signal Processing, Vol. 67, no. 23, December 2019, pp. 6511-6525
2. S.Z. Gurbuz, H. Griffiths, A. Charlish, M. Rangaswamy, M. Greco, an K.L. Bell, “An Overview of Cognitive Radar: Past, Present, and Future,” IEEE AES Magazine, Vol. 34, no. 12, December 2019
3. B Geng, S Brahma, T Wimalajeewa, P.K. Varshney, M Rangaswamy, “Prospect Theoretic Utility Based Human Decision Making in Multi-Agent Systems,” IEEE Transactions on Signal Processing, Vol. 68, 2020
4. S.M. O’Rourke, P Setlur, M Rangaswamy, AL Swindlehurst, “Quadratic Semidefinite Programming for Waveform-Constrained Joint Filter-Signal Design in STAP,” IEEE Transactions on Signal Processing, Vol. 68, 2020
5. Sandeep Gogineni, Muralidhar Rangaswamy, Michael Wicks, “Performance bounds for two-channel delay-Doppler estimation using unknown waveforms,” Vol. 173, August 2020

Journal Papers Accepted for Publication

1. A. Liu, R.M. Narayanan, and M. Rangaswamy,” An Information Elasticity Framework for the Adaptive Matched Filter,” To appear in the IEEE Transactions on Aerospace and Electronic Systems

Journal Papers In Review

1. B. Kang and M. Rangaswamy, “Radar Waveform Design under Communication Sum Capacity Constraint,” *under review,* IEEE Transactions on Signal Processing.
2. V. Krishnamurthy, K. Pattanayak, S. Gogineni, B. Kang, and M. Rangaswamy, “Adversarial Radar Inference: Inverse Tracking, Identifying Cognition and Designing Smart Interference,” *under review*, IEEE Transactions on Aerospace and Electronic Systems

3. P. Singerman, S.M. O'Rourke, R.M. Narayanan, M. Rangaswamy, "Language-Based Cost Functions: Another Step Towards a Truly Cognitive Radar," under review in the IEEE Transactions on Aerospace and Electronic Systems

Journal Papers in Preparation:

1. B. Kang, S. Gogineni, M. Rangaswamy, and J. Guerci, "Constrained Maximum Likelihood Channel Estimation for Massive MIMO Radar," *in preparation*.

Conference Papers Publications

1. Y. Jiang, H. Li, and M. Rangaswamy, "Adaptive Signal Detection in Subspace Interference with Uncertain Prior Knowledge" Proceedings of the 53rd Asilomar conference on signals, systems and computers, Pacific Grove, CA, November 2019

2. S. Gogineni, M. Rangaswamy, J.R. Guerci, J.S. Bergin, D.R. Kirk, "Impulse Response Estimation for Wideband Multi-Channel Radar Systems," Proceedings of the IEEE Radar Conference, Washington D.C., April 2020

3. K.A. Alhujaili, V. Monga, and M. Rangaswamy, "Correlation-Gradient-Descent: Efficient Optimization Methods for Unimodular Waveform Design with Desirable Correlation Properties," Proceedings of the IEEE Radar Conference, Washington D.C., April 2020

4. P.G. Singerman, S.M. O'Rourke, R.M. Narayanan, and M. Rangaswamy, "Language-Based Cost Functions for Fully Adaptive Radar Under Imprecise Performance Standards," Proceedings of the IEEE Radar Conference, Washington D.C., April 2020

5. S. Gogineni, J. Guerci, J. Bergin, B. Watson, and M. Rangaswamy, " Modeling and Simulation of Cognitive Radars," Proceedings of the IEEE Radar Conference, Florence, Italy, September 2020

Professional Activities

M. Rangaswamy

1. Reviewer for IEEE Transactions on Signal Processing

2. Reviewer for IEEE Transactions on Aerospace and Electronic Systems

3. Guest Editor for IEEE Transactions on Aerospace and Electronic Systems, Special section on "Meta-level and Adversarial Tracking"

4. Organized inaugural workshop on High Fidelity RF modeling and simulation and distributed challenge dataset, August 2020

B. Kang

1. Reviewer for IEEE Transactions on Signal Processing

2. Reviewer for IEEE Transactions on Aerospace and Electronic Systems

Awards:

M. Rangaswamy

1. 2019 IEEE Dayton Section Fritz Russ Award, April 2020

2. 2019 International Science and Technology Award for ISTAR basic research, Office of Secretary of Defense, March 2020

3. AFOSR STAR Team award, March 2020

Technology Transition

High fidelity site specific physics based modeling and simulation tool developed under SBIR program as an outgrowth of LRIR research transitioned to a classified EP program under OSD support.