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Networked guidance and control for mobile multi-agent systems: a multi-terminal (network) information theoretic approach (Renewal)

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14. ABSTRACT
Our results are categorized into two groups: (Group A was the main focus, and B are preliminary results creating the foundation for future research)
A) We discovered new methods to analyze and design optimal distributed estimation systems and decentralized controllers. We have discovered new principles and insights that have contributed to systematic methods for the design of more efficient distributed tracking and decentralized control systems.
More recently, we obtained new methods to design and analyze the performance of systems in which the operation of a constitutive component incurs additional costs or is contingent on shared resources or utilization levels that depend on previous actions. Examples include 1) remote estimation (or distributed tracking) systems in which the wireless transmission of data from the sensors to a base station is either costly or is powered by batteries recharged by energy harvesting and 2) Remote sensing in which information is sent from the sensors to a base-station across a shared wireless network in which simultaneous transmissions cause a destructive interference event commonly called 'collision'. Our published articles describe our overarching formulation and progressively more general results on these problems. Our focus is on structural results that can be leveraged to reduce the complexity of the design process significantly.

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Contents

1 Summary of research outcomes (Sept 1, 2015 - Aug 31, 2016)

We have successfully completed three important research objectives, for which we had only preliminary results prior to the start of this grant. With funding provided by grant FA9550-15-1-0367, we were able to complete the following goals:

R1 We have completed the characterization of the optimal transmission policies of a remote estimation problem in which sensors communicate their measurements to a fusion center via a shared wireless channel. The channel is affected by the interference that occurs when two or more sensors transmit simultaneously. As a result of our work, this became one of the very few team decision problems, with non-classical information structure, for which an optimal solution is known. Our work is reported in [J1, C1]. The methods we developed may be applicable to other currently unsolved team-decision problems with non-classical information structure.

R2 We have determined necessary and sufficient conditions for the convergence of a new generalized dynamic consensus scheme that can be used to track time varying processes. Our analysis is valid for arbitrary communication graphs, is constructive, and it also provides a systematic method to obtain low order scalable solutions. Our work is reported in [J2].

R3 In collaboration with my former student S. Sabau (Stevens I.T.) and M. C. Rotkowitz (UMD), we have proposed a new convex method to design decentralized controllers that, unlike prior results, does not require complicated factorizations. Our algebraic approach remains valid for multi-dimensional systems, and systems with delays. Our work is reported in [J3].

2 Summary of research outcomes (Sept 1, 2016 - Aug 31, 2017)

R4 The work reported in [J1, C1] is mainly for sensor measurements drawn from continuous random variables. We have found that optimal policies may be completely different when the measurements are discrete. We have completed the characterization of optimal policies for the problem in [J1, C1], for the case when measurements are discrete.

R5 We are investigated problems in which mobile sensors must operate in partially denied environments, where state information is either completely lacking or is available with very high distortion. In our formulation, sensors have the option to request state information from a base-station and incur a communication/security cost. We have found a tractable framework to analyze this problem when the denied area is symmetric set and the goal is to keep agent centered, in the presence of stochastic disturbances. We use renewal theory and optimization techniques to find the optimal waiting time for requesting information. Our solution provides the best trade-off between deviation from the center and the security cost of information request.

R6 In collaboration with my colleague R. La (UMD), we are also investigated optimal task allocation policies subject to use-dependent resource constraints. Our work is applicable to supervisory control problems, subject to energy harvesting, communication constraints and it can also be used to model the performance limitations inherent to supervisory control systems governed by human operators. In this reporting period, we developed a new tractable framework to investigate a task allocation system that comprises an unbounded queue, a non-preemptive server, and a stationary scheduler. For the first time, we consider that the server

has an action-dependent state, which evolves according to a given MDP whose input is the action chosen by the scheduler. The action-dependent state determines the probability that a task can be completed within an epoch. We were able to show that stability, whenever viable, can be achieved by a simple scheduler that operates based on the availability state, a threshold applied to the action-dependent state and a flag that indicates when the queue is empty. The lowest upper-bound on the service rates that are achievable by the system, subject to the requirement that the queue remains stable, can be determined by a finite search.

R7 We also investigated remote estimation problems formed by sensors and estimators that are not collocated. Information is transmitted from the sensors to the estimators via a shared network, whose reliability may change with prior workload - such as when communicating nodes are battery powered. Our goal is to design a Markovian scheduler that selects among various modes of operation, each prioritizing a transmission to the estimators from a subset of the sensors. Transmissions from sensors with lower priority are more likely to be dropped. We show that this problem is, in general non-convex, but we propose algorithms with varying degrees of generality and convergence guarantees.

3 Summary of research outcomes (Sept 1, 2017 - Aug 31, 2018)

R8 The work reported in R4 above was completed, submitted for publication in the IEEE Transactions on Automatic Control and recently accepted (see [J4]).

R9 The work reported in R5 above was completed, submitted for publication in the IEEE Transactions on Automatic Control and recently accepted (see [J5]).

R10 The work reported in R6 above, focuses on maximizing the rate at which tasks can be serviced, subject to action-dependent performance effects on the server. In this reporting period, we investigated the problem of minimizing "workload" subject to a pre-selected service rate. We are currently working on two drafts describing these results, which we plan to submit to Automatica as a two-part article.

R11 We completed work on R7 and validated our results numerically. A preliminary version of our results was accepted for publication in the IEEE CDC 2018 (see [C4]).

R12 Based on our work in R6 and R7, I was invited to co-author (jointly with Prof. Varun Jog (UW) and Prof. Richard La (UMD)) a tutorial article for the IEEE Transactions on Information Theory (see [J7]).

R13 We have initiated and made significant progress on a new research direction on control-oriented approaches to population games and evolutionary dynamics. The overarching goal is to obtain new methods to analyze and promote resilient self-organizing continuous-time behavior for large swarms, subject to network reliability limitations. The swarms are partitioned into a finite number of populations, each of which is characterized by a finite set of strategies and a bounded-rationality rule (modeled by a protocol) specifying how their members (referred to as agents) revise their strategies over time. Each population is protocol-homogeneous, but is otherwise strategy-heterogenous because its members may adopt different strategies. The overall behavior of the swarms is governed by a distributed process in which each agent determines (independently of the others) when to revise its strategy and decides which strategy to adopt based on information available to it. The reward for adopting

each strategy is determined by a causal payoff mechanism in terms of the so-called social state, which at every instant comprises one vector per population whose entries are the percentages of the population adopting each strategy. In our formulation, the revision mechanisms, and consequently the protocols, are inspired on elementary evolutionary principles that can be easily implemented and for which there is a rich literature proposing insightful concepts and analysis methods. In most existing related work, the payoff mechanism is a memoryless map often called *population game*, which may account for adversarial effects among and/or within populations, such as in games of attrition that may model the competitive capture of resources. The class of congestion games is another example in the context of traffic assignment in which agents of multiple populations affect each other's travel-time from origin to destination. Population games can also follow a prescriptive scenario in which the payoff mechanism is designed to achieve a desired behavior and is computed and broadcast to the agents by a coordinator. Our research goals can be summarized as the development of a more general theory that not only introduces important dynamic effects in the payoff mechanism and evolutionary dynamic, but also accounts for network effects. An abridged version of our preliminary results are reported in [C3], which was recently published at the 2018 CDC. A more comprehensive discussion of our results can be found in [J6].

4 Published Journal Articles that acknowledge AFOSR Grant FA9550-15-1-0367

J1 Marcos M. Vasconcelos and Nuno C. Martins, Optimal Estimation over the Collision Channel, IEEE Transactions on Automatic Control 62 (1), 2017, pp. 321-336.

J2 Shinkyu Park and Nuno C. Martins, Design of Distributed LTI Observers for State Omniscience, IEEE Transactions on Automatic Control 62 (2), 2017, pp. 561-576.

J3 Serban Sabau, Nuno C. Martins and Michael C. Rotkowitz, A Convex Characterization of Multidimensional Linear Systems Subject to SQI Constraints, IEEE Transactions on Automatic Control 62 (6), 2017, pp. 2981-2986.

J4 Marcos M. Vasconcelos and Nuno C. Martins, "Optimal Remote Estimation of Discrete Random Variables Over the Collision Channel," IEEE Transactions on Automatic Control, 2018 (in press)

J5 Eduardo R. Arvelo and Nuno C. Martins, "Optimal Sensor Scheduling for Station-keeping in Denied Environments," Journal of the Franklin Institute (Special Issue on Distributed Event-Triggered Control, Estimation, and Optimization), 2018 (in press)

5 Journal Submissions that acknowledge AFOSR Grant FA9550-15-1-0367

J6 Shinkyu Park, Nuno C. Martins and Jeff S. Shamma, "Payoff Dynamic Models and Evolutionary Dynamic Models: Convergence to Equilibria", to be submitted in February 2019 to the Proceedings of the IEEE. (A version will be soon available in ArXiv)

J7 Varun Jog, Richard J. La and Nuno C. Martins (ordered alphabetically), "Communication, Networked Control, and Queueing Systems Subject to Action-Dependent Constraints: A

Unifying Framework", to be submitted in February 15th, 2019 to the IEEE Transactions on Information Theory (invited)

6 Conference Publications that acknowledge AFOSR Grant FA9550-15-1-0367

C1 Marcos M. Vasconcelos, Optimal Threshold Strategies for Remote Estimation Over the Collision Channel with Communication Costs, IEEE Conference on Decision and Control, 2015.

C2 Shinkyu Park and Nuno C. Martins, "Optimal Remote State Estimation for Self-Propelled Particle Models," IEEE Conference on Decision and Control, 2016.

C3 Shinkyu Park, Jeff S. Shamma and Nuno C. Martins, "Passivity and Evolutionary Game Dynamics," IEEE Conference on Decision and Control, 2018.

C4 Michael Lin, Richard J. La and Nuno C. Martins, "Remote State Estimation Across An Action-Dependent Packet-Drop Link," IEEE Conference on Decision and Control, 2018.

7 Invited Talks and Workshops

- Invited Seminar Series at UTRC (United Technologies Research Center), Hartford, Jan 16, 2017
- Invited talk[1] at the IMA Workshop on Distributed Control and Decision Making Over Networks, (The Institute for Mathematics and Its Applications - University of Minnesota) October 1, 2015
- Invited talk at the workshop Distributed Autonomy and Human-Machine Networks, IEEE Conference on Decision and Control, December 14, 2015

8 Potential Impact on DoD Activities

Our work on R1-R11 provided new methods to analyze and design optimal distributed estimation systems and decentralized controllers. We have discovered new principles and insights that have contributed to the design of more efficient distributed tracking and decentralized control systems.

Preliminary work described in R13 provides a foundation for future research on distributed coordination mechanisms for swarms. A proposal draft was submitted to Dr. Frederick Leve seeking AFOSR funding to continue this work.

9 Personnel

This grant has been used mostly to fund graduate research assistantships and PI salary to accomplish the research.

[1] Nuno C. Martins, Anders Rantzer and Naomi Leonard were the organizers of this 3-day IMA Workshop.