IEEE ICC 2021: Student Grant Application Statement of Purpose

Bharath Keshavamurthy | PhD Student | Purdue University
IEEE Student Member (95181635) | IEEE ComSoc Student Member

24 April, 2021

1 Enrollment

Doctor of Philosophy (PhD), School of Electrical & Computer Engineering, Purdue University, West Lafayette, IN [June 2020 - Present]

2 My Research & Technical Symposia Impact

My past and current research interests are detailed here – along with the impact of attending relevant IEEE ICC 2021 Technical Symposia on them.

- **DARPA Spectrum Collaboration Challenge (SC2)** & **MS Thesis**:
  - Adaptive, Intelligent Spectrum Sensing & Dynamic Channel Access in Cognitive Radio Networks: HMMs and Approximate POMDPs;
  - E2E Cognitive Radio Design: Cross-Layer Optimization strategies (MCS Adaptation, Rate Adaptation, Tx Power Control, Hybrid ARQ, Prioritized Flow Scheduling, Channel & Bandwidth Allocation, and Multi-hop Routing);
  - Over-The-Air Implementation of our Cognitive Radio Network on the NSF POWDER Testbed (USRP X310s and USRP B210s) in the CBRS Spectrum (3.4GHz - 3.8GHz);
  - Symposia Impact: Spectrum Sensing & User Detection (CRAIN-1)
    - Presenting our paper titled, "Learning-based Cognitive Radio Access via Randomized Point-Based Approximate POMDPs"
    - Extremely interested in perusing the research on CPD-driven Spectral Cartography (G Zhang, et al.) and Grant-Free NOMA via Generative Neural Networks (Y Zou, et al.)

- **NSF EARS, NSF POWDER, NSF AERPAW, & PhD Research**:
  - Adaptive, Multi-Tier Scheduling and Trajectory Optimization for Power-Constrained UAV Relays: Hierarchical Competitive Swarm Optimization, Rate Adaptation, SMDP Formulation, and Multiple UAV settings with additional Control Heuristics;
  - 28GHz Propagation Modeling in Urban and Suburban Radio Envs on the NSF POWDER Testbed: Custom Horn Antennas & Up/Down Converter Design, Sliding Correlator Channel Sounder, and a Fully Autonomous Antenna Rotating Platform for Beam Tracking;
  - mmWave Communications: Algorithms enriched by the Radio Env Map constructed from the 28GHz Measurement Campaign data;
  - mMIMO (Sounder, Beacon Beam-Sweeping): Experiments on the NSF POWDER Testbed (Skylark mMIMO: Iris SDRs, Faros Hub, 64x64 BS), and Laboratory Implementations using pi-radio SDRs;
  - 3D Coverage: A Joint-Optimization Problem constituting Trajectory Optimization for Power-Constrained UAV Relays, and Positioning & Scheduling Optimization for HAPs and LEOs, in Next-Generation Multi-Tier Heterogeneous Networks;
  - V2X Implementation of our mmWave Communication Systems, and Scheduling & Trajectory Optimization for Power-Constrained UAV Relays on the NSF AERPAW Testbed;
  - Symposia Impact and Associated Interested Papers:
    - UAVs-II (MWN-6) and Satellite Networking-I (SAC-SSC-2)
      - RSS based UAV-BS Mobility Mgmt via Policy Gradient DRL (M Khoshkholgh, et al.)
      - Network Simulator for Large Low Earth Orbit Satellite Nets (B S Kempton and Anton Riedl)
      - Optimizing Data Transmission in High Altitude Balloon Nets with Multi-beam Directional Antennas (Y Wang, et al.)
    - mmWave and TeraHertz Networks (MWN-11)
      - A Full-Stack Framework for Antenna and Beamforming Eval in mmWave 5G NR (M Lecci, et al.)
    - mmWave and MIMO (SAC-MLC-2)
      - DeepRx MIMO: Convolutional MIMO Detection with Learned Multiplicative Transformations (D Korpi, et al.)

3 Coursework

Stochastic Processes, Queuing Theory, Estimation & Detection Theory, Convex & Non-Convex Optimization, Lumped System Theory, Mobile Communication Networks, Real Analysis & Measure Theory, Algorithms, and Error Control Coding.

4 Statement on Conference Attendance

In addition to presenting our paper titled, "Learning-based Cognitive Radio Access via Randomized Point-Based Approximate POMDPs" at the CRAIN-1 symposium, I am looking forward to learn more about the exciting research endeavors that are set to be detailed by researchers from both academia and industry.

Firstly, in the arena of cognitive radio networks, I am excited to study more about CPD-based Spectral Cartography and Grant-Free NOMA via Generative Neural Networks.

Secondly, in the domain of UAV communications & mobility management, I cannot wait to learn more about the use of Policy Gradient Deep RL for UAV Mobility Orchestration. I am also looking forward to peruse the capabilities & the performance of the Network Simulator for Large Low-Earth Orbit Satellite Networks – and potentially use it in my PhD research.

Finally, focusing on mmWave communications and MIMO, I am thrilled to be able to listen to presentations on DeepRx MIMO and mmWave 5G NR Antenna & Beamforming Evaluation Framework.

The privilege and opportunity to listen to these works presented by researchers and industry professionals is something for which I am truly grateful.

Learning-based Cognitive Radio Access via Randomized Point-Based Approximate POMDPs

Bharath Keshavamurthy *Student Member, IEEE* and Nicolò Michelusi *Senior Member, IEEE*

***Abstract*—In this paper, a novel spectrum sensing and access strategy based on approximate Partially Observable Markov Decision Processes (POMDPs) is proposed, wherein a cognitive radio learns the time-frequency correlation model defining the occupancy behavior of incumbents, via the Baum-Welch algorithm, and concurrently devises an optimal strategy to perform spectrum sensing and access that exploits this learned correlation model. To ameliorate the complexity of the POMDP optimization, the PERSEUS algorithm, a randomized point-based value iteration method, is designed, with fragmentation and Hamming distance state filters. Evaluating the cognitive radio throughput against incumbent interference, we demonstrate that, with sensing restrictions, our framework achieves a 6% performance gain over that attained by a maximum a-posteriori (MAP) state estimator with prior model knowledge, and outperforms correlation-coefficient based clustering algorithms by an average of 60%; additionally, it surpasses a Neyman-Pearson Detector that assumes independence among channels with no sensing restrictions, by an average of 25%. Furthermore, unlike state-of-the-art algorithms, the proposed design facilitates the regulation of the trade-off between cognitive radio throughput and incumbent interference via a penalty parameter in the underlying MDP.**

***Index Terms*—Cognitive Radio, HMM, POMDP**

I. Introduction

With the advent of fifth-generation wireless communication networks, the problem of spectrum scarcity has been exacerbated [2]. For some time now, cognitive radio technologies have been in the spotlight as a potential solution to this problem in commercial and military applications. Cognitive radio networks facilitate efficient spectrum utilization by intelligently accessing *white spaces* left unused by the sparse and infrequent transmissions of licensed users while ensuring rigorous incumbent non-interference compliance [3].

A crucial aspect underlying the design of cognitive radio networks is the channel access protocol in the MAC layer of the stack. Additionally, physical design limitations are imposed on the cognitive radio node's spectrum sensor because of quick turnaround times and energy efficiency [4], which restrict the number of channels that can be sensed at any given time. This has led to research in algorithms that first determine which channels to sense and then, via aggregation or correlation exploitation, use the gathered information to perform optimal channel access. In this regard, the current state-of-the-art involves channel sensing and access strategies dictated by multi-armed bandits [5], reinforcement learning agents [6], and other custom heuristics [7], [8]. Yet, almost all these works, such as [5], [6], assume independence across frequencies in the discretized spectrum, which is imprudent because licensed users exhibit correlation across both frequency and time in their channel occupancy behavior: the primary users frequently occupy a set of adjacent channels (frequency correlation), repeating similar motifs in behavior over time (temporal correlation) [9]–[11]. This pattern in the occupancy behavior of the incumbents imputes a high correlation among channels, which may be learned and leveraged for more accurate predictions of spectrum holes. In this paper, we propose a parameter estimation algorithm to learn the aforementioned correlation model, and an algorithm based on approximate POMDPs to determine the optimal channel sensing and access policy that exploits this learned correlation structure.

Related Work: The works [5], [12], [13] develop spectrum sensing and access algorithms under the assumption that the occupancy behavior of incumbents is independent across both time and frequencies. In our work, we exploit both frequency and temporal correlations. In [14], a compressed spectrum sensing scheme is devised that exploits sparse temporal dynamics in the occupancy of licensed users; in [15], an efficient spectrum sensing strategy is proposed for dense multi-cell cognitive networks, that also exploits the spatial structure of interference; yet, both works neglect frequency correlation.

Spectrum sensing and access strategies in a distributed multi-agent cognitive radio setting have been considered in [6] and solved using TD-SARSA with Linear Function Approximation (LFA). However, frequency correlation is precluded, and errors in state estimation are neglected in the decision process. Unlike [6], we consider a model with correlation across frequencies, and we account for uncertainty in the occupancy state via a POMDP formulation. Although the spectrum sensing algorithms detailed in [7] consider the correlation in incumbent occupancy behavior across frequencies, the authors assume a perfect, noise-free observation model; instead, we account for the impact of noisy observations in our design. In both [7], [8], the authors account for occupancy correlation across both time and frequencies, yet their algorithms use a data-driven strategy wherein pre-loaded databases are employed offline to estimate the correlation models – which is impractical in non-stationary settings; instead, we present a *fully online framework* that learns the correlation model and simultaneously solves for the optimal channel sensing and access policy.

Non-adaptive strategies like the Viterbi algorithm in [8] employ a fixed channel sensing set throughout their period of operation and require a-priori knowledge of the transition model of the underlying MDP. In contrast, our solution learns this transition model and concurrently adapts the channel sensing set based on the estimated occupancy transitions and reward/penalty feedback. Next, highlighting our solution against the model-free RL model described in [16] which frames the problem under an unknown Markovian time-frequency correlated incumbent occupancy structure,

Extensions to this work have been submitted to IEEE TCCN [1].
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B. Keshavamurthy is with ECE, Purdue University, West Lafayette, IN.
N. Michelusi is with the School of ECEE, Arizona State University, AZ.
Email: bkeshava@purdue.edu, nicolo.michelusi@asu.edu

Bharath Keshavamurthy

Research Assistant | PhD Student | Purdue Communications Research Lab

+1-765-7758910 | bkeshava@purdue.edu | IEEE Student Member ID: 95181635 | IEEE ComSoc Student Member

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Summary

The objective of my life is to pursue state-of-the-art research in the arena of Electrical and Computer Engineering and strive to facilitate significant contributions to Science and Technology. Having an optimum level of understanding in the end-to-end development of communication & networking technologies, I hope to achieve path-breaking success and in doing so, solve some of the greatest problems plaguing mankind today such as Climate Change, Global Conflicts, Public Safety, and the need for Sustainable Development.

Experience

Research Assistant, NSF EARS Grant, Communications Research Lab, Purdue University [Oct 2020 - Present]

Stochastic modeling of communication networks | mmWave Propagation Modeling | UAV Trajectory Optimization

Research Assistant, DARPA Make-It Grant, Bindley Bioscience Center, Purdue University [Jan 2020 – Oct 2020]

High-throughput analytics | Structure elucidation via VAEs | Intelligent Reaction Preparation via RL | Visualization

Research Assistant, DARPA SC2 Grant, Communications Research Lab, Purdue University [Aug 2018 – Dec 2019]

DARPA Spectrum Collaboration Challenge | Intelligent Spectrum Sensing and Access via Approximate POMDPs

Graduate Engineering Intern, DC NX-OS Platform, CISCO, San Jose, CA, USA [May 2019 - Aug 2019]

A.I. models in the CISCO Nexus data center product portfolio: RNNs | DL classifiers | Sensitivity analyses | A3C DDPG

Senior Engineer, Digital Operations R&D, NOKIA, Bangalore, KA, India [June 2016 - July 2018]

Software development | DevOps | Correlated reasoning ML | Computer networking | Telecommunications R&D

Networking Intern, Ericsson India Global Services Pvt. Ltd, Bangalore, KA, India [Feb 2016 - July 2016]

Cell planning | Network deployment & optimization | SONs | HETNETs | Small cells

Intern, MCSRDC, Hindustan Aeronautics Limited, Bangalore, KA, India [July 2015 - Aug 2015]

ATC Transponder for SSR with encoding altimeter and SLS | Aircraft navigation, communication, and combat systems

Education

Doctor of Philosophy, Electrical and Computer Engineering, 3.85/4.0, Purdue University [Jun 2020 – Present]

Master of Science, Electrical and Computer Engineering, 3.65/4.0, Purdue University [Aug 2018 – May 2020]

Bachelor of Engineering, 9.61/10, BMS College of Engineering, Bangalore, India [Sept 2012 - June 2016]

Pre-University, 96.1%, New Horizon Pre-University College, Bangalore, India [June 2010 - Mar 2012]

Matriculation (10th Grade), 95%, St. Thomas Public School (ICSE), Bangalore, India [June 2009 - Mar 2010]

Major Projects

Adaptive Multi-Scale Scheduling and Trajectory Design for Power-Constrained UAV Relays [Jan 2021 – Present]

28GHz Propagation Modeling in Urban and Suburban Radio Environments on NSF POWDER [Oct 2020 – Present]

Over-The-Air (CBRS) Operations of the BAM! Wireless DARPA SC2 Radio on NSF POWDER [Mar 2021 – Present]

Intelligent Spectrum Sensing and Access via Randomized Approximate POMDPs [Aug 2018 – Apr 2021]

High-Throughput Analytics and Structure Elucidation via DESI Mass Spectrometry [Jan 2020 – Oct 2020]
Multi-agent Swarm Optimization using e-puck2 robots in Fully Distributed Mesh WLANs [Oct 2019 - Oct 2020]
Purdue BAM! Wireless: DARPA Spectrum Collaboration Challenge (SC2) Cognitive Radio [Aug 2018 - Nov 2019]
A.I Models in the CISCO Nexus Data Center Networking Product Portfolio, CISCO [May 2019 - Aug 2019]
Cross-Layer Optimization in Decentralized Ad-hoc Cognitive Radio Networks [Jan 2019 - May 2019]
Automated Operations and Recovery (AOR), Digital Ops, Nokia Applications & Analytics [Jun 2016 – July 2018]
IEEE 802.11af: A Hardware Platform to utilize the TV White Spaces in India, BMSCE [Dec 2015 - Aug 2016]
Full Custom Design of a sensor node for Industrial WSNs, DRDO-BMSCE [Sept 2015 - May 2016]
IC Design of an OFDM Transceiver Architecture for LTE Downlink, BMSCE [July 2015 - Dec 2015]

Honors and Accomplishments

Nokia Applaud Excellence Award, Excellence in field of work, hard work, and innovation, Nokia, Oct 2017
Best Research Paper, 5th IEEE International Conference on Wireless Networks and Embedded Systems, Oct 2016
Best Paper Presentation, 5th IEEE International Conference on Wireless Networks and Embedded Systems, Oct 2016
Best Research Paper, 4th National Conference on Networking, Embedded and Wireless Systems, June 2016

Publications

Learning-based Cognitive Radio Access via Randomized Point-based Approximate POMDPs
Under Review at IEEE Transactions on Cognitive Communications and Networking (TCCN), 2021
Learning-based Cognitive Radio Access via Randomized Point-based Approximate POMDPs
IEEE ComSoc International Conference on Communications (ICC), 2021
VLSI implementation of a novel sensor architecture for Industrial Wireless Sensor Networks
2016 IEEE International Conference on Computational Intelligence and Computing Research (ICCIC), 2016
Conceptual Design of Proactive SONs based on the Big Data Framework for 5G Cellular Networks
5th IEEE International Conference on System Modeling & Advancement in Research Trends (SMART), 2016
Communication System Design for White-Fi (802.11af)
10th IEEE ComSoc International Conference on Advanced Networks and Telecommunication Systems (ANTS), 2016
Hardware-in-Loop simulation of a White-Fi system utilizing the TV White Spaces in India
5th IEEE International Conference on Wireless Networks and Embedded Systems (WECON), 2016
Feasibility Analysis of a Super Wi-Fi Network for Rural Broadband Deployment in India
4th National Conference on Networking, Embedded and Wireless Systems, 2016