Using Network QoS to Optimize Control System Operation

Background

- Control of networked systems popular area of research over last decade
- Usually assumes network introduces stochastic disturbance that is either **fixed and known** or **slowly varying and learnable**
- Many mobile communication channels suffer from disturbances that **change rapidly**, such as multipath fading and interference/jamming
- Most interestingly, communication systems can adapt to channel impairments in different ways, offering tradeoffs in reliability/latency/throughput

Example: Fading

- Consider mobile communications over a fading multipath channel
- Movement of the vehicle through the environment produces variations in signal strength as signal paths combine constructively or destructively
- Received signal power can be modeled and predicted using Hidden Markov Model (HMM)

Example: Jamming

- Future jammers may often be small, mobile devices such as UAVs or mobile robots
- Such jammers will use strategies to maximize their impact on network performance while maximizing the achievable jamming time (battery life)
- For example, such jammers will turn on and off or hop across frequency bands used by the communications network
- The on-off pattern and hopping pattern are typically pseudo-random, but the dwell time can be modeled as Markov

Physical-Layer Adaptation

- Modern communications systems offer multiple ways to adapt to channel changes:
- **Transmitted power**
  - Can reduce channel error rate at expense of reducing battery life and increasing interference to other parts of the network
- **Modulation and code rate**
  - Can reduce channel error rate at expense of lower data rate

Higher-layer Adaptation

- **Link Layer: ARQ**
  - Can detect erroneous packets and request retransmission at expense of additional latency
- **Medium-Access Control (MAC)**
  - Can prioritize some packets at expense of higher latency/contention/collisions
- **Routing**
  - Can tradeoff between longer routes that offer high reliability but longer latency vs. shorter routes with low latency but lower reliability

Simple Case Study

- Control system with two initial states:
  - Stable (**S**)
  - Unstable (**U**)

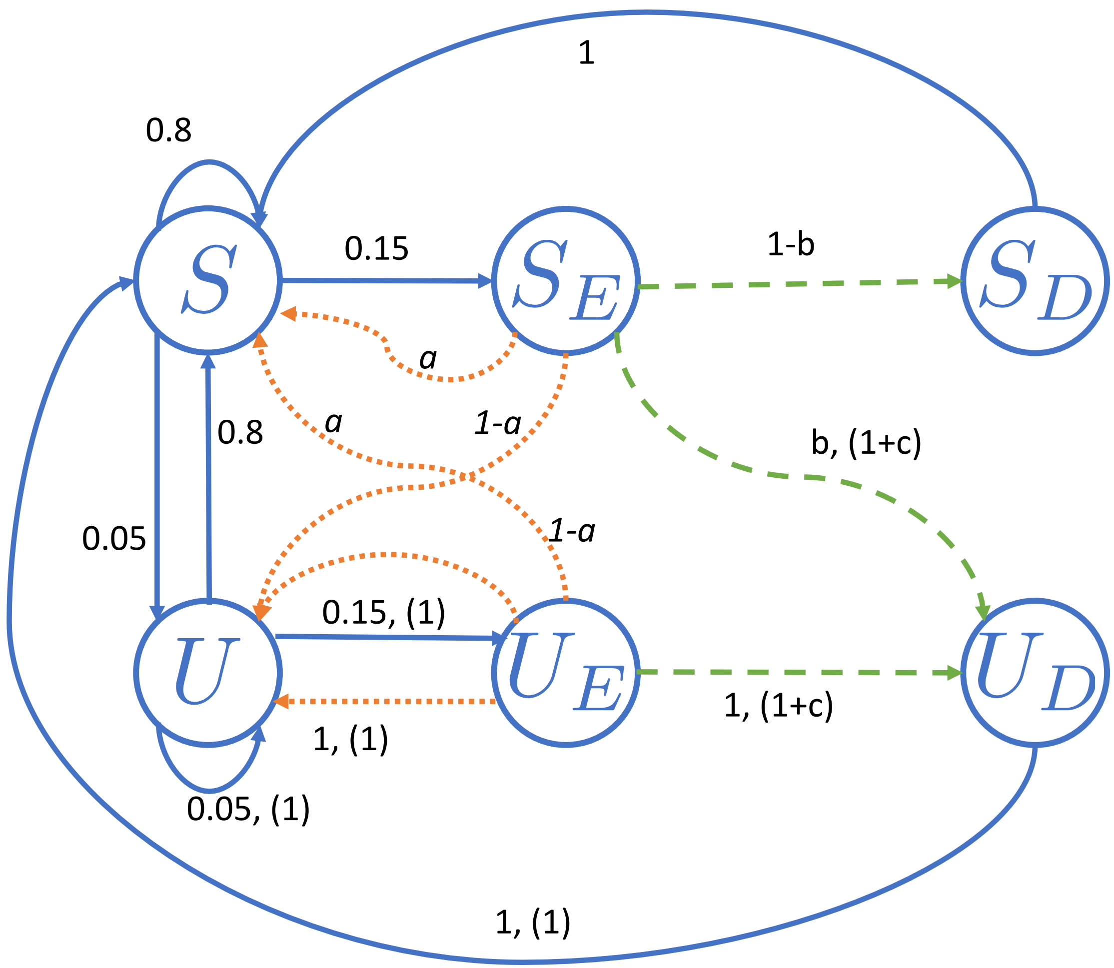
- Unreliable communications system
  - Correct information with prob. 0.8
  - Noisy information with prob. 0.15
  - No useful information with prob. 0.05
- No information makes system go unstable

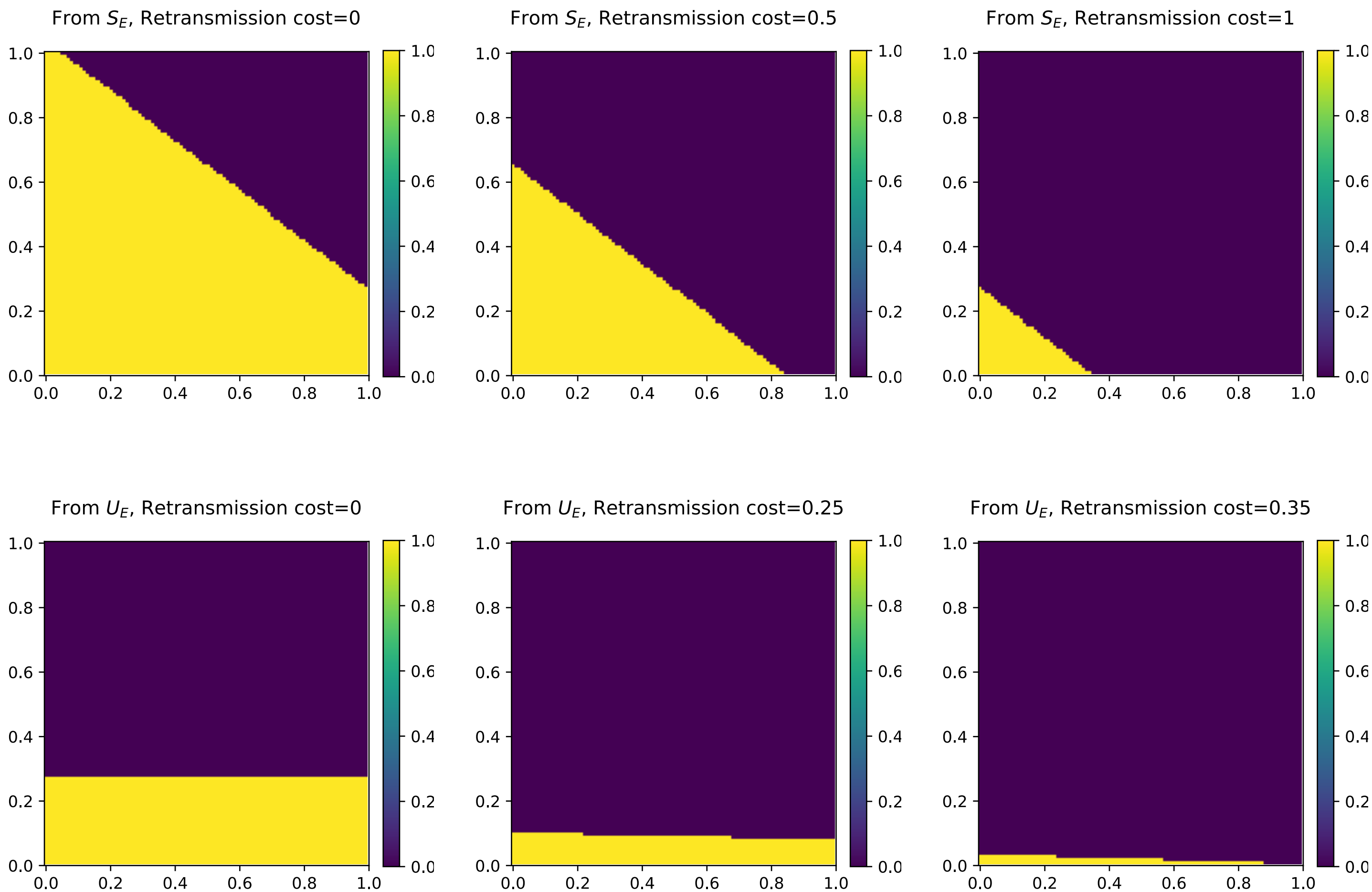
- Effect of erroneous information captured by transition to new states $\mathbf{S_E}$ or $\mathbf{U_E}$

- Can use erroneous information, but more likely to make system go unstable
- Can wait for retransmission via incremental redundancy ARQ, but more likely to transition to **U** while waiting and costs in terms of additional energy

- Capture behavior as MDP:

MDP for Example





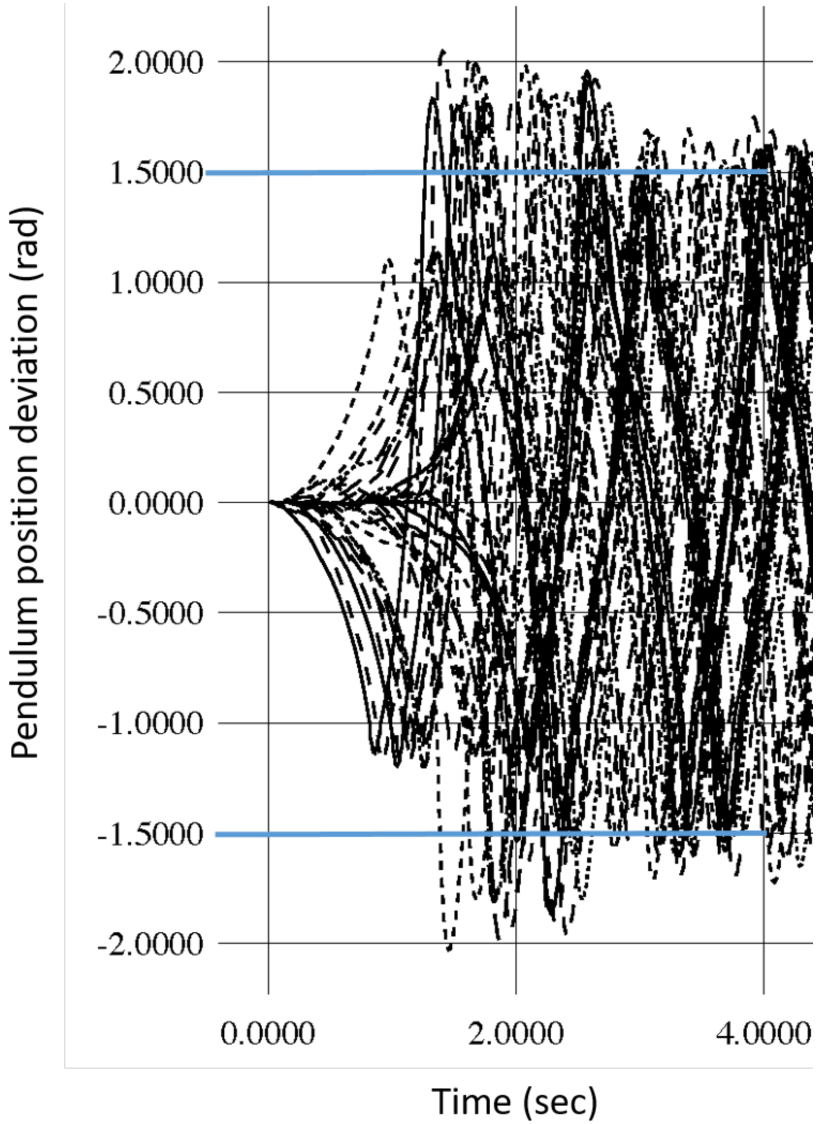
Yellow=wait for retransmission, Purple=Use noisy information

Future Work

- Develop methods to exchange detailed QoS information from network to control applications
- Develop methods for control systems to adapt operation based on QoS
- Develop methods for control systems to adapt how the network reacts to errors/delays
- Analyze and incorporate into decision processes the effects of such strategies on networks as a whole: requesting retransmissions increases contention
- Apply multi-agent optimization techniques to determine globally optimal strategies in presence of priorities, adversaries, ...

Closing the loop between control and network

- Research in previous section provides basic feedback between network and control
- However, performance of networked control applications will be limited if network is not optimized to requirements of the applications
- More importantly, applications may suffer catastrophic performance degradation when conditions degrade

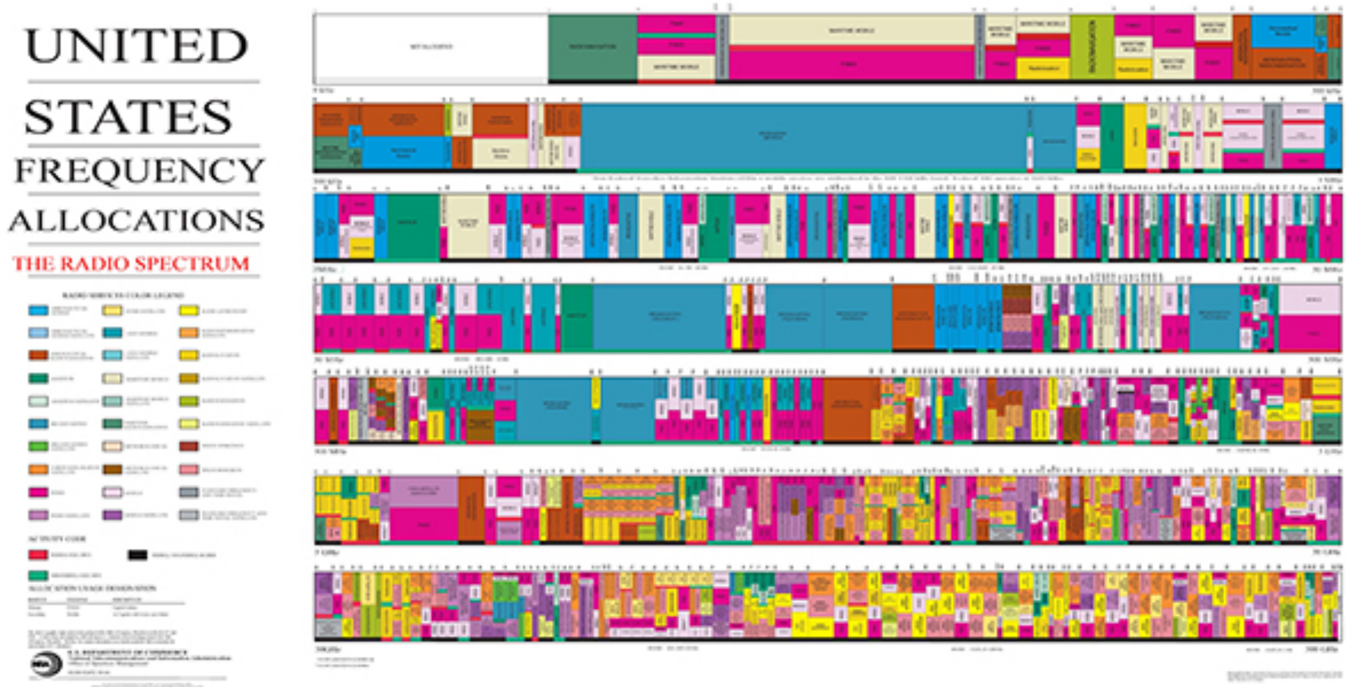

2.0000
1.5000
1.0000
0.5000
0.0000
-0.5000
-1.0000
-1.5000
-2.0000
0.0000
2.0000
4.0000
Pendulum position deviation (rad)
Time (sec)

Goals

- Optimize network operation to mix of control applications in presence of:
  - multiple coalitions with limited information exchange
  - time-varying spatial distribution of communicators
  - time-varying mission priorities
  - time-varying channels
  - time-varying interference and/or jamming
  - presence of incumbent users

Motivation

- DARPA Spectrum Collaboration Challenge (SC2)
  - 5th Grand Challenge
  - Develop new approaches to spectrum management by autonomous, intelligent agents (take humans out of the loop)



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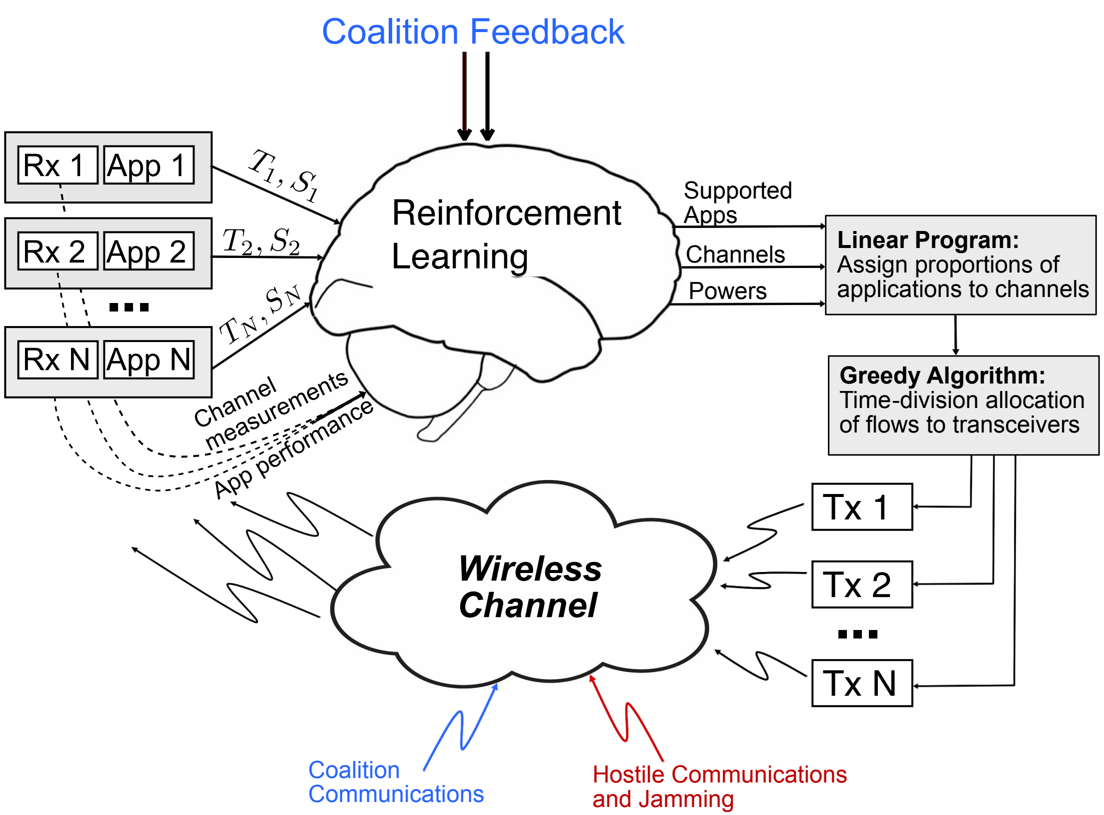
Example: Resource Allocation

- Centralized allocation within each coalition
- Coalition feedback channel for distributed resource allocation across coalitions
- Sensing for incumbent users, jammers



Allocation of Traffic to Channels

- Consider first known set of channels to use
- Given set of flows with specified throughput (T_j) and latency (S_j) requirements
- Find time-frequency allocation to channels over periodic *epochs*
  - η_i= expected maximum throughput per epoch of channel *i*
  - n_s = slots per epoch
  - t_s = time per slot

  - $\widetilde{T}_j$ = normalized latency (in slots)
  - $P_{i,j}$ = proportion of flow *j* mapped to channel *i*

$$
\begin{aligned}
\text{minimize} \quad & \sum_i \sum_j P_{i,j} & \\
\text{subject to} \quad & 0 \leq P_{ij} & \text{for all } i, j \\
& \sum_j P_{i,j} \leq 1 & \text{for all } i \\
& \sum_i \eta_i P_{i,j} \geq T_j & \text{for all } j \\
& \sum_i P_{i,j} \geq \left\lceil \frac{n_s}{\tilde{T}_j} \right\rceil \frac{1}{n_s} & \text{for all } j.
\end{aligned}
$$

- Solution to linear program not necessarily implementable due to radio constraints:
  - Limits on number of channels radio can simultaneously transmit or receive on
  - Allocated proportions incompatible with achievable proportions via time-division
- Apply greedy algorithm to take result of linear program and create implementable schedule

Channel Selection

- Channel selection based on:
  - Own network geolocation information and channel quality feedback
  - Coalition Feedback:
    - Frequency usage
    - Peer flow performance
    - Geolocation information
  - Passive incumbent information reported by collation feedback
  - Sensing information for active incumbents and jammers
  - Priorities of own traffic flows and requests from peer networks
  - Estimated transmit power required and estimated impacts on SINRs of peer networks

- Large state space, large action space
- Choices affect future actions of peers and incumbents
- Model as MDP and apply reinforcement learning (RL)
- Problem: feedback is limited and slow
  - Need feature selection to reduce state space
  - Apply matrix completion or function approximation via neural network to fill in missing state information
  - Decompose action space into choosing number of channels via RL and choosing particular channels via greedy algorithm

- Problem: feedback is unreliable
  - Coalitions have incentives to underreport resource usage and performance
  - Uses machine learning to deanonymize coalition feedback and estimate performance of peer networks

SC2 Competition

- DARPA SC2 provides opportunity to test strategies in similar environments
- Over 90 teams enrolled, down-selected to 15 teams in final year
- Matches consist of 3-5 teams, with 10 radios/team
- Massive channel emulator (Colosseum) emulates scenarios in which teams perform missions, moving through real-world locations (Austin, San Diego, San Juan, …)

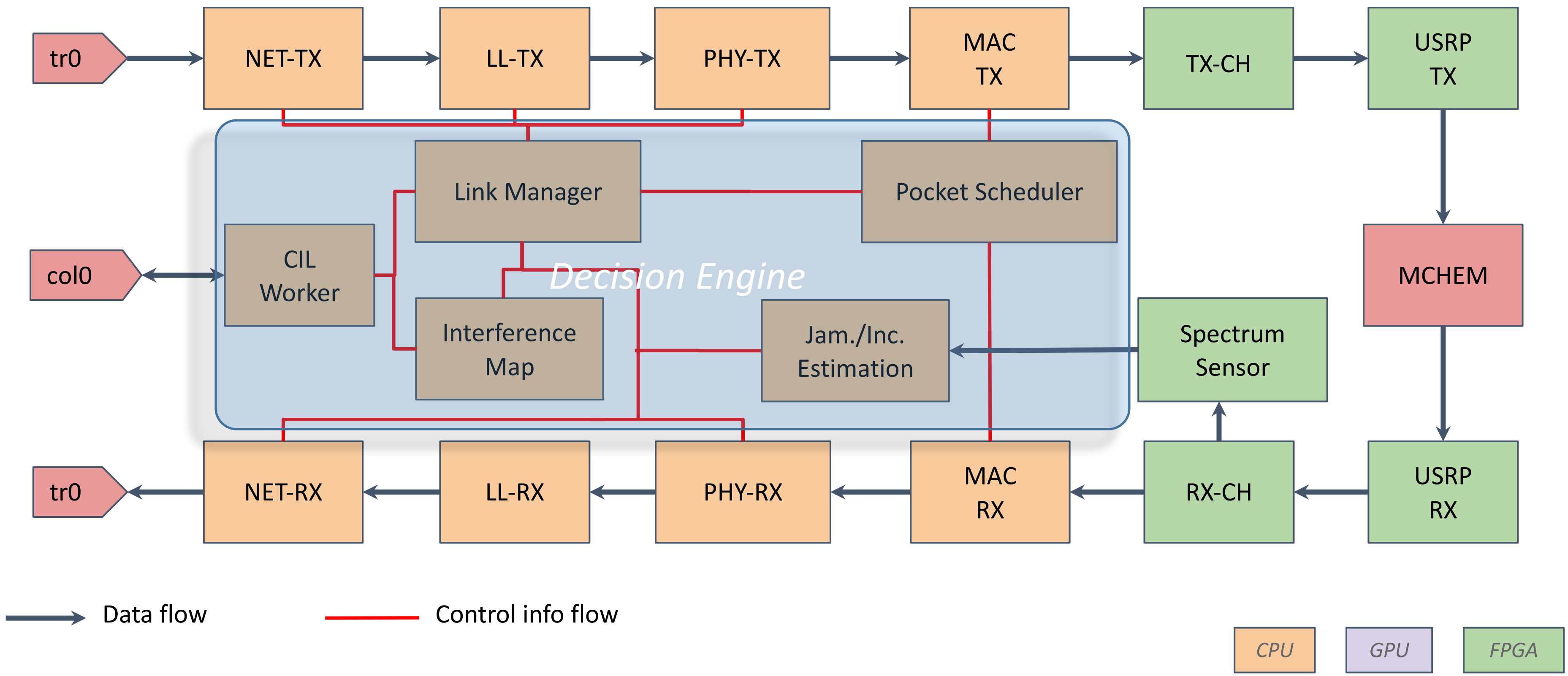
- Teams are scored based on how successful they and other teams are at delivering the flows offered to them
  - PE1: competitive only, teams try to maximize their own flows
  - PE2: cooperative only, score is the lowest number of flows delivered by any team in match
  - SCE: mixed cooperative and competitive, score limited by worst performing team until threshold met, then teams get differentiated scores based on flows they deliver

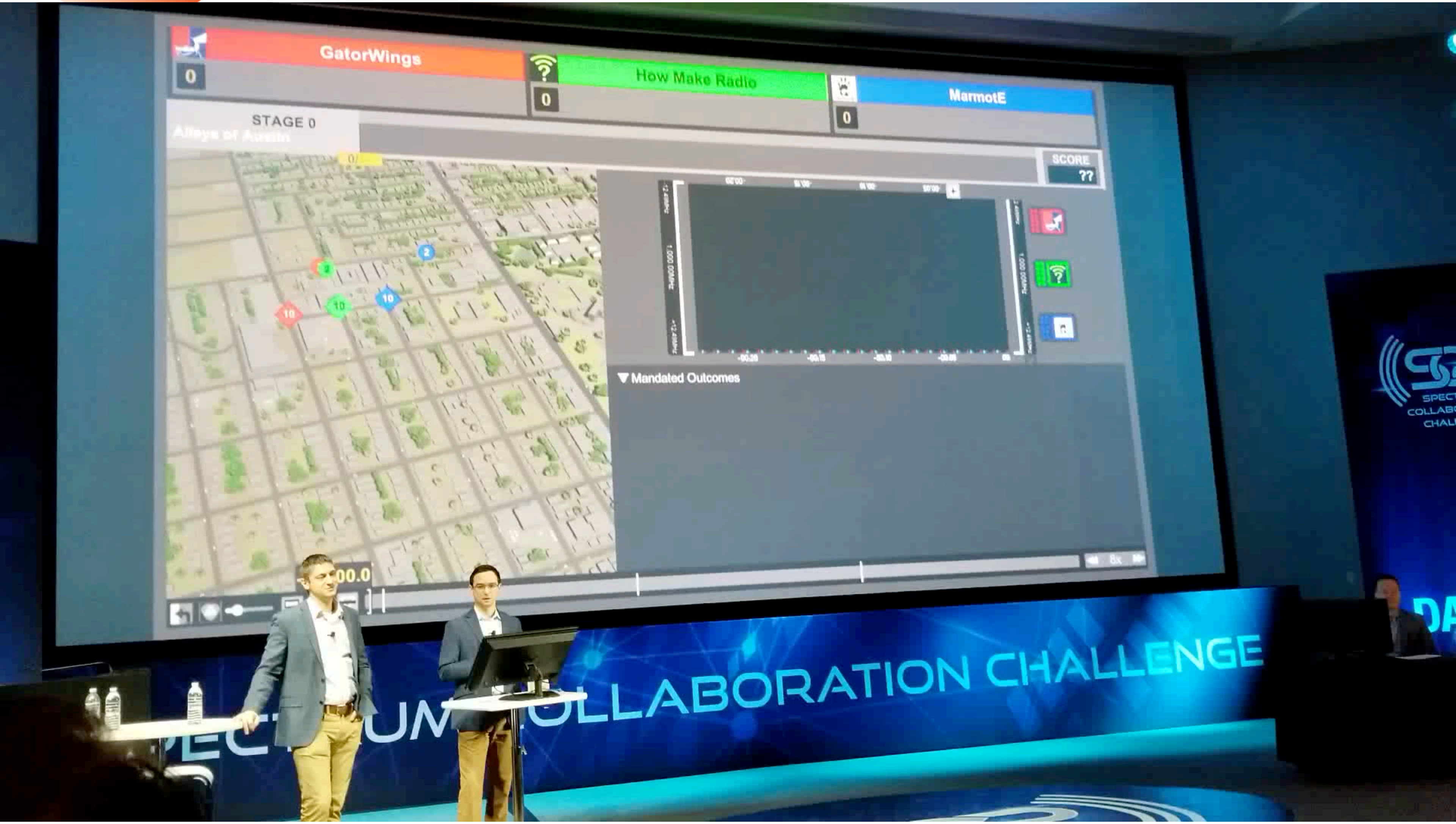
SC2 Challenges

- Wide variety of channel path losses, bandwidths, mobility levels
- Traffic with wide variety of QoS requirements:
    - Low latency <100 ms
    - High throughput > 1.5 Mbps
    - Huge file bursts > 1 Gbit
    - High fan-in/fan-out (traffic to/from one radio)
    - Stochastic traffic arrivals

- Need to coordinate spectrum usage with:
  - other teams
  - passive and active incumbents
  - jammers
- Interference with unknown characteristics from many different competitor teams, active incumbents, and jammers

Gatorwings Radio Design





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Future Research

- Develop resource allocation techniques that support mix of control and non-control flows
- Control systems may be able to operate in different regimes at different costs (i.e., highly stable vs marginally stable): develop methods to quantify and exchange with network resource allocation

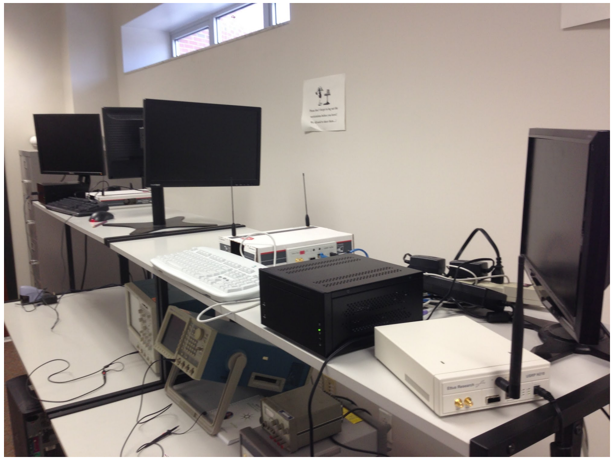
- Centralized resource allocation:
  - Usually at trusted node, vulnerable to physical and cyber attack
  - Cannot react quickly based on local information (changing interference/channel qualities)
- Develop privacy-preserving distributed resource algorithms
  - Apply distributed reinforcement learning, where each radio only knows part of the input state
- Develop techniques to improve performance in presence of unreliable and malicious information
  - Leverage research from other tasks on intermittent data integrity and context-aware filtering

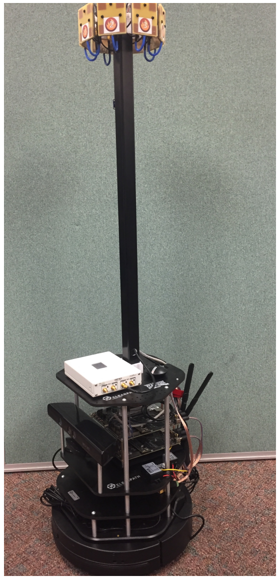
- Adapting resource allocation based on control system performance creates closed-loop system
  - For example, when channel quality degrades, control system performance may also degrade. Control systems then demand more resources, which further degrade network performance
  - Develop methods to model combined control applications and network as single system and ensure stability
- Develop methods to couple resource allocation with topology control

Conclusions

- Network performance is critical to performance of mobile autonomous systems
- To maximize performance, not sufficient to model network as stochastic disturbance with fixed statistics
- Potential for significant performance improvements by improving interface between control applications and network

Virtual Lab Tour





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