Dynamic Spectrum Sharing: Lessons from the DARPA Spectrum Collaboration Challenge

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SPECTRUM COLLABORATION CHALLENGE

USING AI TO UNLOCK THE TRUE POTENTIAL OF THE RF SPECTRUM

SC2 Design Challenge–
Want Spectrum Management to:

- Respond in real time as users and traffic evolve:
  - Requires **autonomous intelligent** agents (take humans out of the loop)
  - Time scales of **seconds** (vs. one day in CBRS)
- Support diverse users and applications
  - Frequency channelization **not predetermined** (vs. 10 MHz channels in CBRS)
  - Need **scaffolding** to support information interchange: channels and protocols
  - Must **incentivize** accurate reporting and spectrum sharing
  - Greater **intelligence** needed => **more than traditional resource optimization**

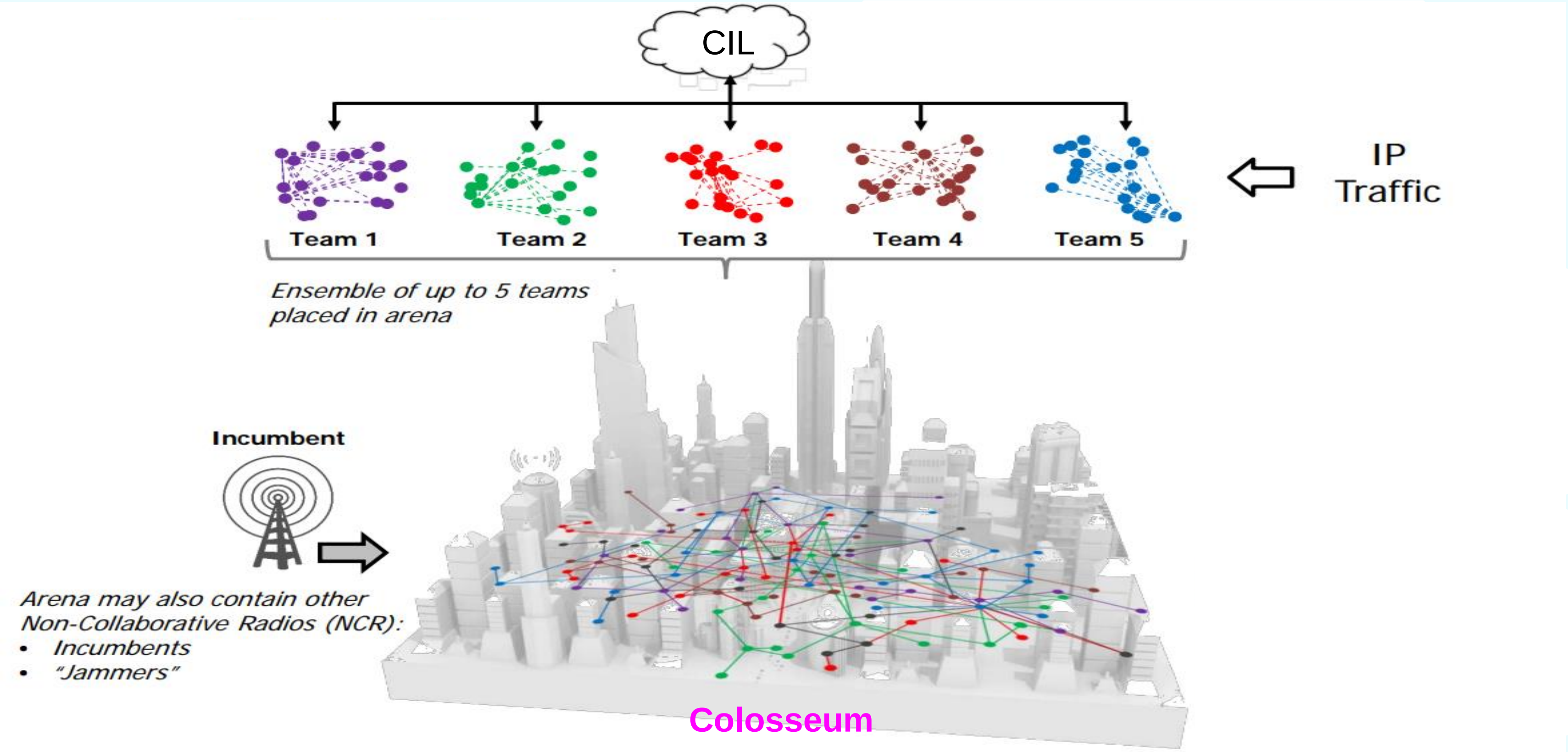
SC2 Design Challenge: Want Spectrum Management to

- Require minimal infrastructure and optimize spectrum usage across users' spatial distributions
  - **No central infrastructure** (i.e., SAS in CBRS)
  - Spectrum management should be **distributed** and **collaborative**
- Operate in presence of incumbents and interferers
  - Need **distributed sensing and reporting**

Conclusions from SC2:

- These goals can be achieved with existing technologies
- Much work to be done:
  - Efficiency?
  - Security / Privacy?
  - Incentivizing and enforcing?

Spectrum Sharing Scenario in SC2



SC2 Scoring Structure

- Each team scores points by delivering IP traffic flows achieving certain QoS mandates (throughput, latency, hold time, etc.)
- Team's match score $= \begin{cases} \text{min score} & \text{if min score} \leq \text{scoring threshold} \\ \text{achieved score} & \text{if min score} > \text{scoring threshold} \end{cases}$

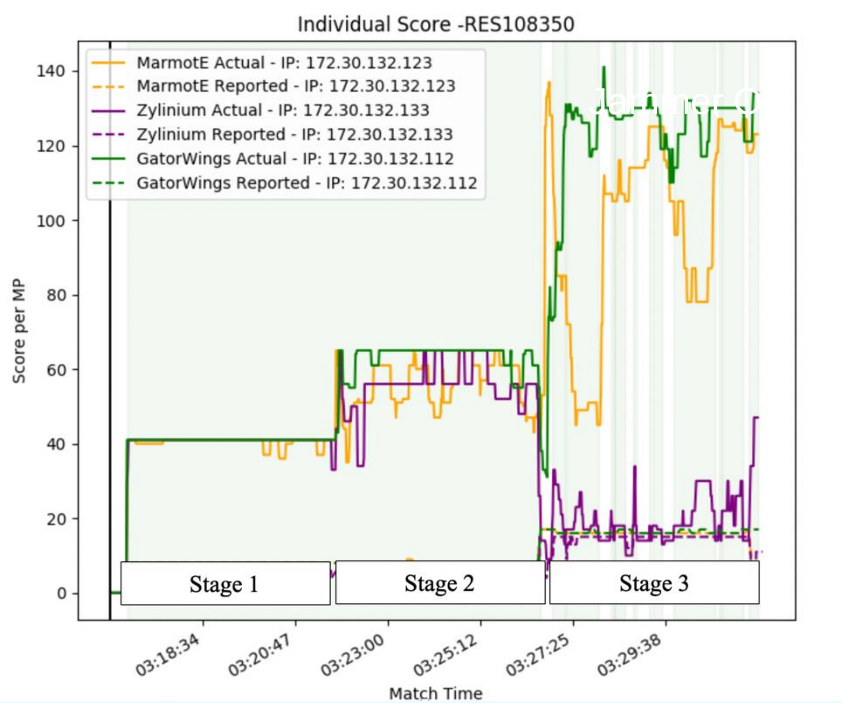
  where min score = minimum among all 5 teams' achieved scores
- A mixed cooperative/competitive game

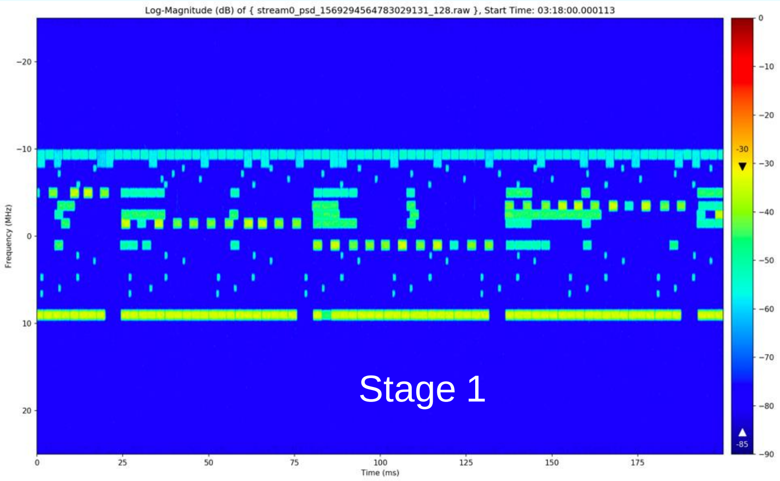
Information for Spectrum Sharing in SC2

- Adapt strategy in presence of **rich but incomplete information**:
  - Do not know, but may learn, other teams' waveforms, protocols, strategies
  - No online scoring information, other than teams' estimates
  - Teams use CIL to report frequency use, radio locations, performance (score) estimates
    - Some CIL veracity checks on spectral use, scores
    - Teams do not have to report their true scores when their scores are above the threshold
  - Incumbents report channel usage, interference received and threshold, threshold violations
  - Spectrum sensing to estimate peer channel usage and detect jamming and active incumbents

Basic Dynamic Spectrum Sharing: Alleys of Austin

- 3 / 5 squads (networks) of solders sharing 20 MHz spectrum
- 3 stages of increasing IP traffic demands
    - Stage 1: VOIP & C2 streams
    - Stage 2: Stage 1 + video stream & file
    - Stage 3: Stage 2 + more video streams & files


Individual Score -RES108350
MarmotE Actual - IP: 172.30.132.123
MarmotE Reported - IP: 172.30.132.123
Zylinium Actual - IP: 172.30.132.133
Zylinium Reported - IP: 172.30.132.133
GatorWings Actual - IP: 172.30.132.112
GatorWings Reported - IP: 172.30.132.112
Score per MP
0
20
40
60
80
100
120
140
Stage 1
Stage 2
Stage 3
03:18:34
03:20:47
03:23:00
03:25:12
03:27:25
03:29:38
Match Time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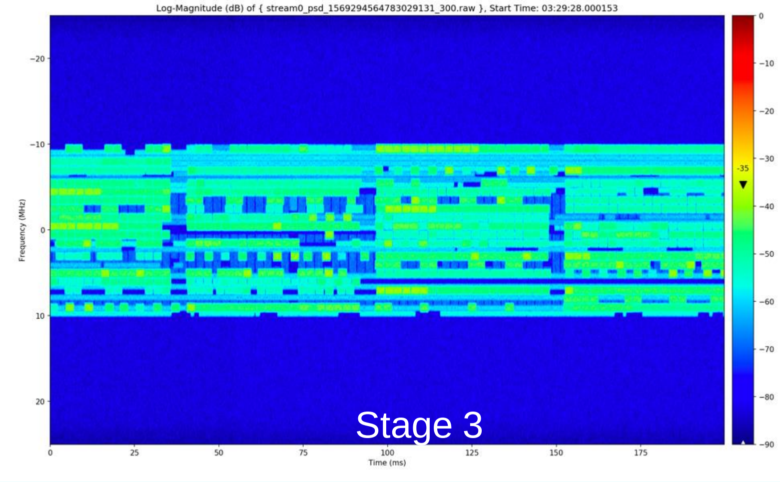
Frequency (MHz)
Time (ms)
Stage 1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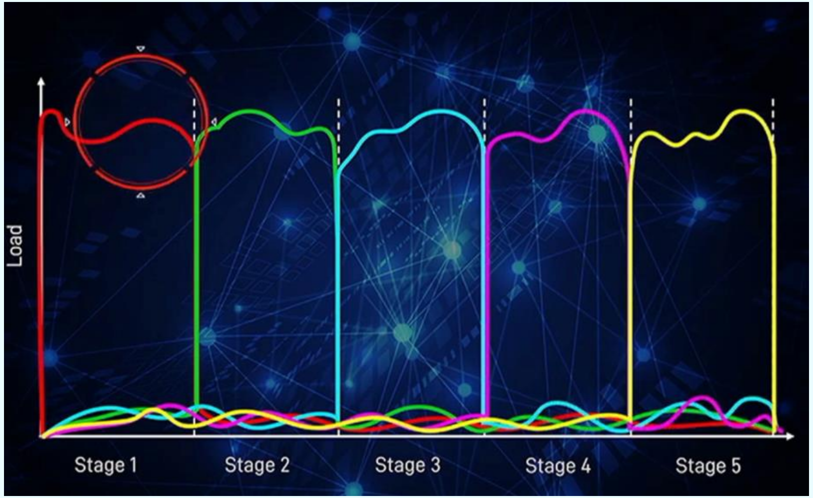
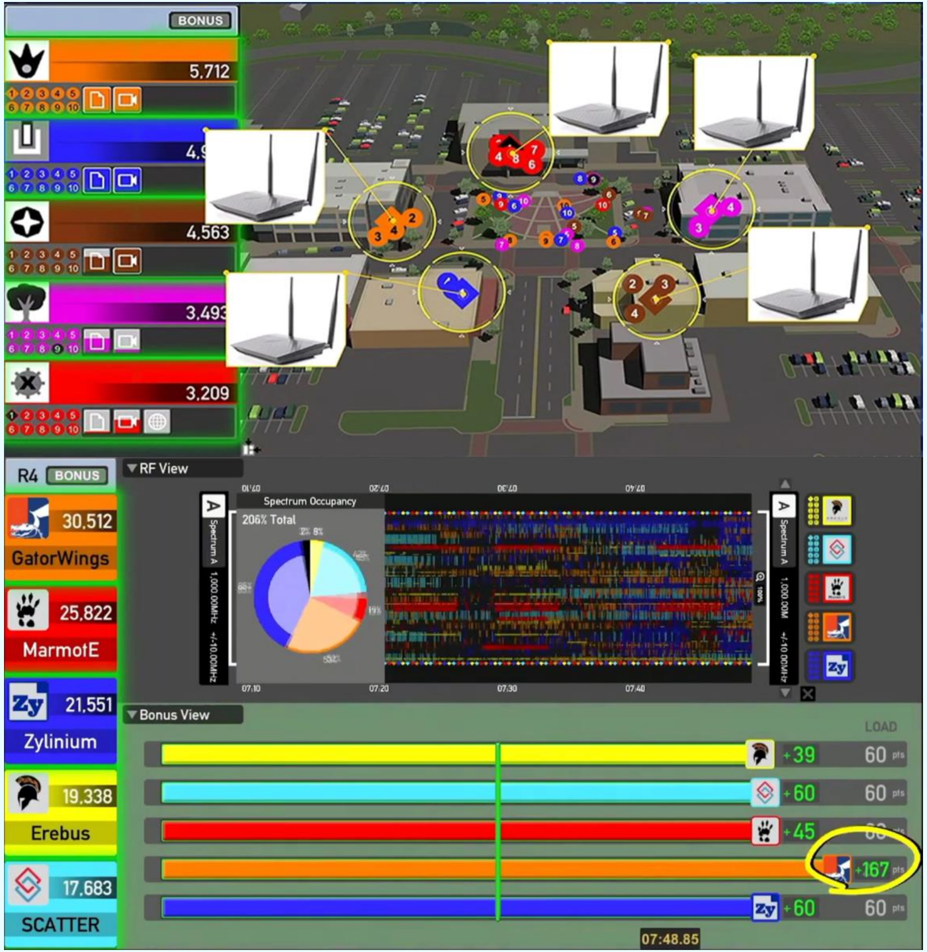
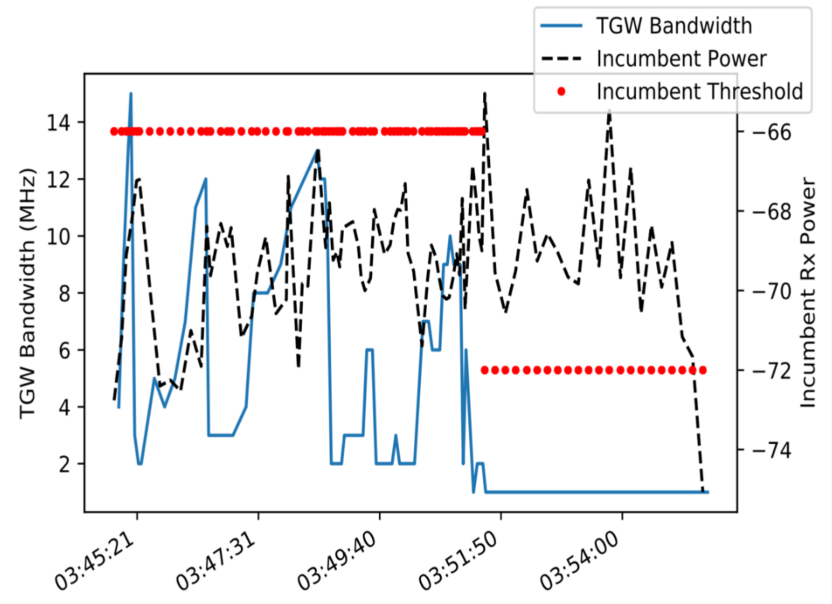
Frequency (MHz)
Time (ms)
Stage 3

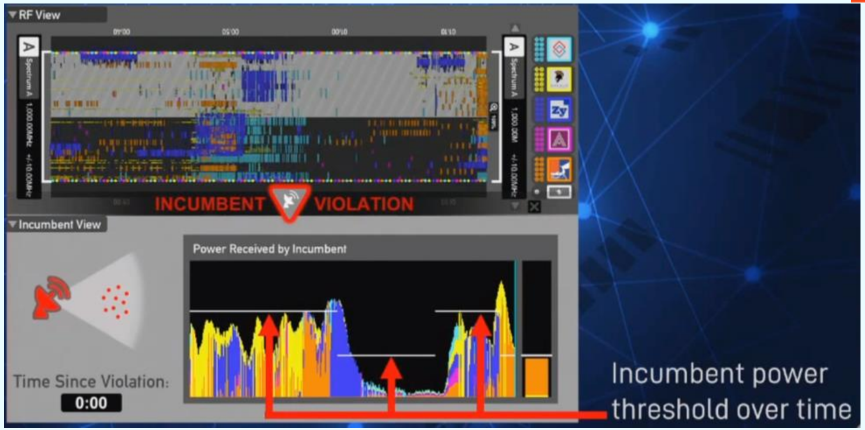
Traffic Surges (Slice of Life)

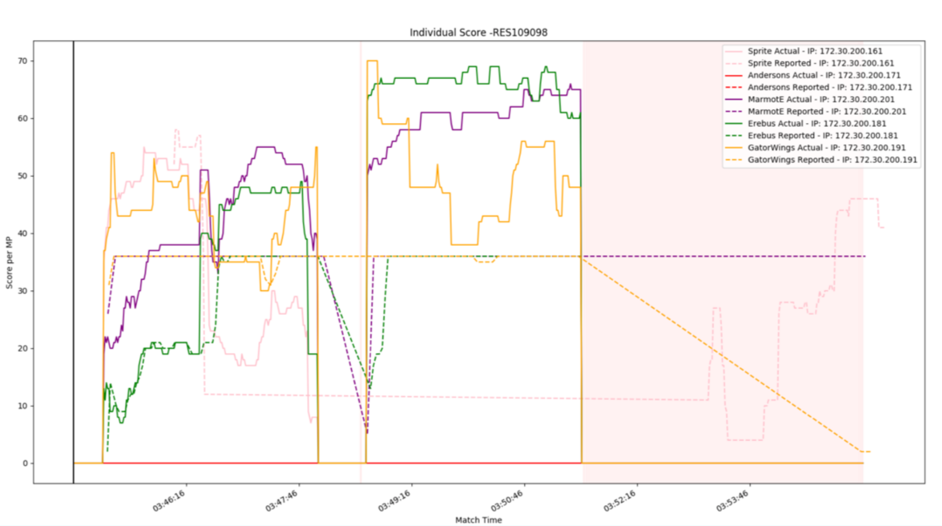




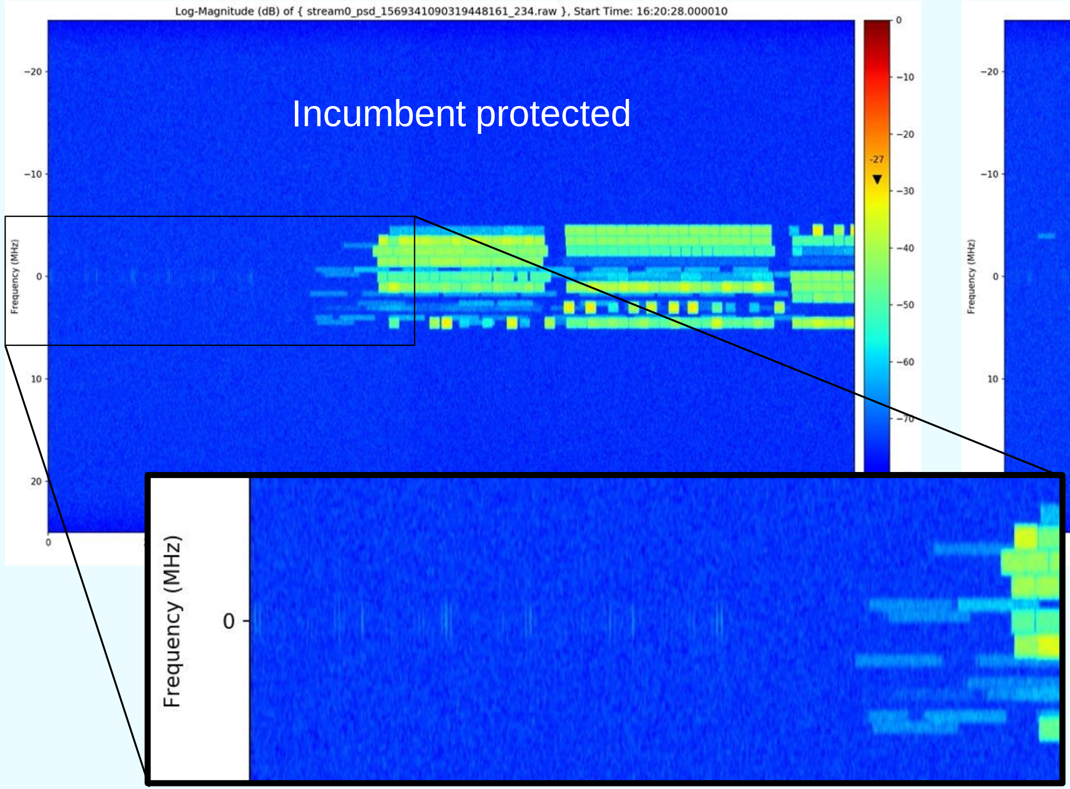
Passive Incumbent Protection

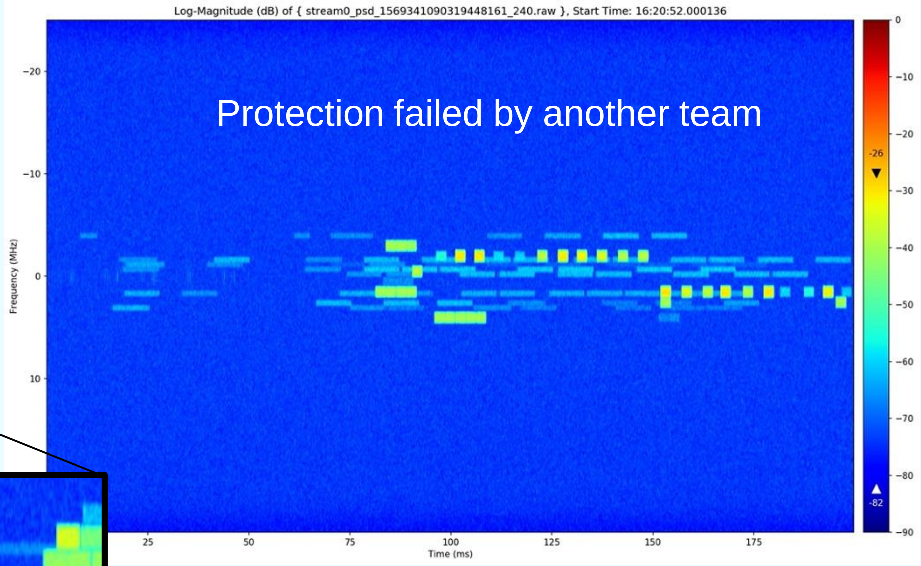


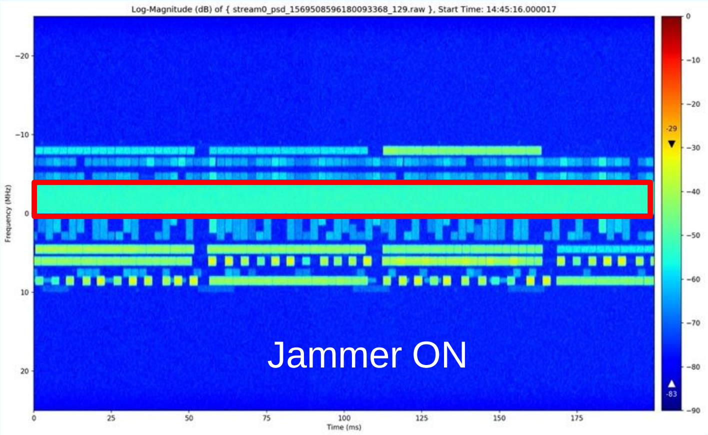




Active Incumbent (Vehicular Radar) Protection



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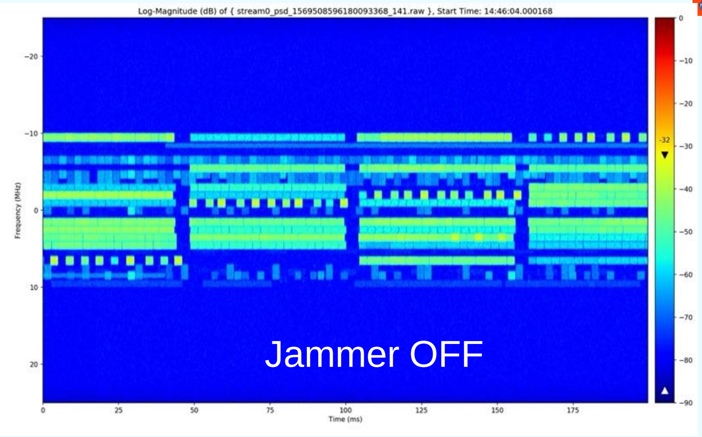
Frequency (MHz)
Time (ms)
Jammer ON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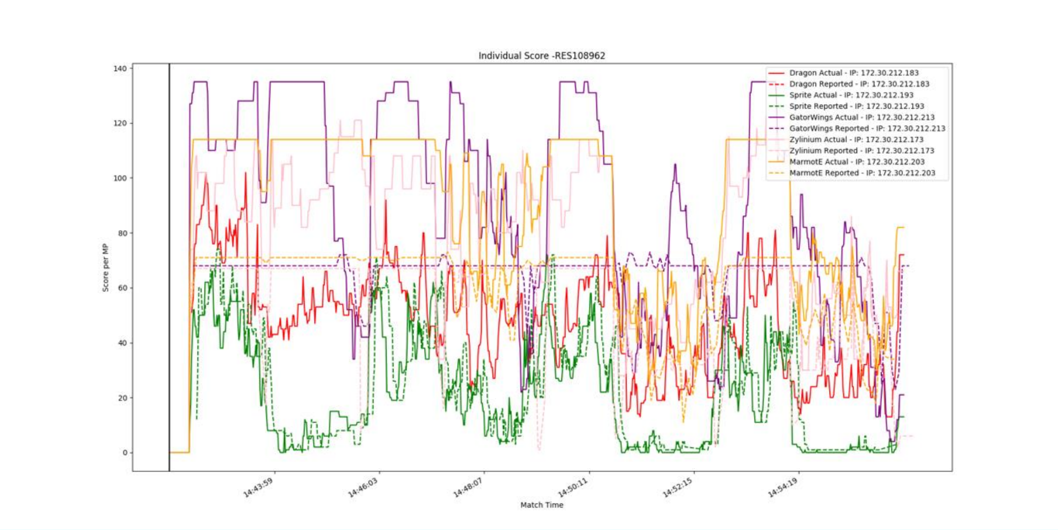
Frequency (MHz)
Time (ms)
Jammer OFF


Individual Score -RES108962
Dragon Actual - IP: 172.30.212.183
Dragon Reported - IP: 172.30.212.183
Sprite Actual - IP: 172.30.212.193
Sprite Reported - IP: 172.30.212.193
GatorWings Actual - IP: 172.30.212.213
GatorWings Reported - IP: 172.30.212.213
Zylinium Actual - IP: 172.30.212.173
Zylinium Reported - IP: 172.30.212.173
MarmotE Actual - IP: 172.30.212.203
MarmotE Reported - IP: 172.30.212.203
Score per MP
Match Time

Our Strategy – Custom Radio Stack

- **Flexible/agile:** able to exploit opportunities in time, frequency & space (cooperative + competitive)
- **Robust:** adaptive and capable of operating in presence of strong interference (competitive)
- **Everything adaptive:**
  - PHY: Acquisition, Modulation, Coding, TX Power, RX Gain
  - LL: Channels and Time Slots/Channel, Mapping of SRCs to Time Slots
  - NET: Supported flows, admission control granularity down to individual files/bursts
  - Other: Channels to jam

Spectrum Sharing Decision Engine

- Decision engine attempts to maximize our team's match score :
  - **which flows are transmitted**
  - **which channels are used and by which radios**
  - **which flows are sent in which pockets (time-frequency resource unit)**
- Action space is huge!
  - 40 channels x 10 time slots = 400 pockets
  - As many as 100+ flows
  - 100^{400} possible pocket schedules!

Inputs to Decision Engine

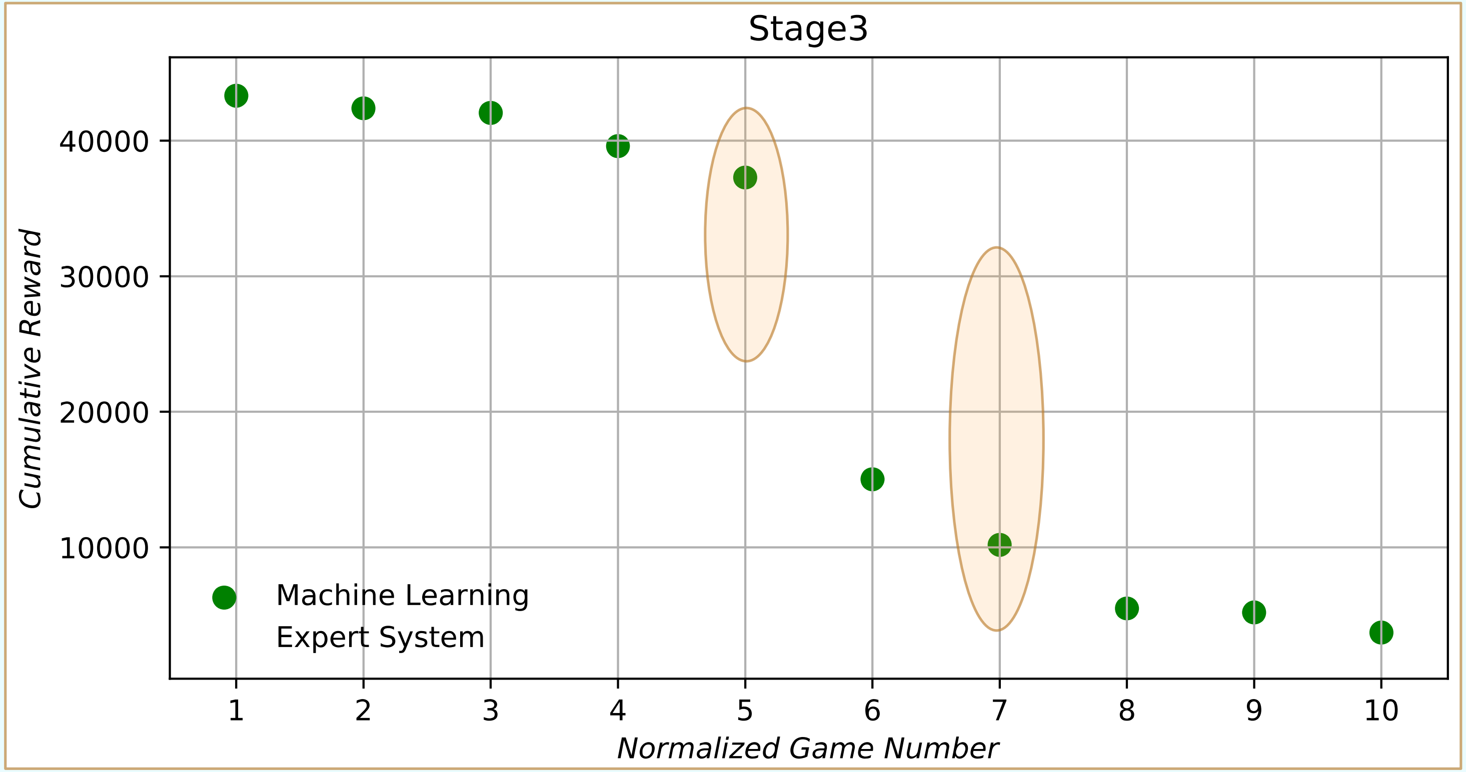
- Our team's **QoS Info and Performance**
  - QoS mandates for our team's flows
  - Estimated achieved mandates
- **Channel Info and Link Quality**
  - Estimated channel occupancies from our spectrum sensor (PSD measurements)
  - Channels used by our network and by peer networks
  - Computed SINRs from our interference map (GPS and voxel info from CIL messages)
  - Throughput per pocket expected between each SRC-DST pair
- **Peer IDs and Performance Info**
  - Inferred peer network IDs (based on CIL message characteristics)
  - Estimated achieved and total mandates (from CIL messages)

Decision Engine Design

- **No ML black box that can solve spectrum sharing problem**
- Decompose problem into smaller pieces:

1. **Channel selection**
    - Determines target set of channels *C* to be used by our network
    - ML and expert system/control/optimization approaches
2. **Admission control**
    - |*C*| determines number of pockets available
    - Estimates number of pockets needed to support each flow
    - Iterative process to determine set of flows to admit in order to maximize points scored
3. **Pocket schedule assignment**
    - Linear program to allocate number of pockets to satisfy latency requirements of all admitted flows
    - Greedy algorithm to assign pockets in each frame to satisfy mandates of all admitted flows
    - Maps to channels in *C* based on worst-case SINR over links of SRC-DST pairs in above assignments

Comparison of Expert System vs ML



Lessons Learned – Dynamic Spectrum Sharing

- A heterogeneous set of autonomous intelligent agents can manage spectrum in a distributed & collaborative fashion in time scales of seconds
- Dynamic sharing, traffic surge accommodation, passive and active incumbent protection can all be achieved with acceptable efficiency at the present time

- Essential to optimize strategy based on reward structure (scoring rules)

→ **Reward structure drives spectrum sharing behaviors**

Lessons Learned –
Machine Learning and AI for DSS

- No machine-learning black box that can solve spectrum sharing problem
- Domain-specific engineering to decompose problem
- Not enough training and validation data for ML
  - Need a less resource-intensive simulation environment to train ML algorithms
- Peer strategies (and probably radios) rapidly changed during last few weeks of SC2
  - ML algorithm (operation after training) couldn’t catch up
  - Switched to ES algorithm
  - Probably need more exploration and switching system to cope with rapid updates

Moving Forward – Technical Eco-system for DSS

- Suitable DSS system architecture (centralized, distributed, hybrid, geography, etc)
- Incentive frameworks to encourage desirable DSS behaviors
- Collaboration/information-sharing DSS protocols
- More efficient intelligent, autonomous agents to implement DSS strategies
- Radio & network design for DSS
- Privacy & security in DSS
- Monitoring and enforcement of DSS rules
- Performance metrics
- Test and experimentation
- Device/network certification

ML/AI Research Problems in DSS

- How to generate/collect suitable data sets for ML?
  - Simulation, RF emulation, or RF measurement?
- How to train multi-agent reinforcement learning agents with large state and action spaces?
- How to ensure ML solutions are robust to new situations?
- How can ML be used to police for noncompliant/abnormal behaviors?
- How to leverage ML in preserving privacy during exchange of collaboration information?
- Can ML adapt incentive structures over time to enhance overall network performance?

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Optimization

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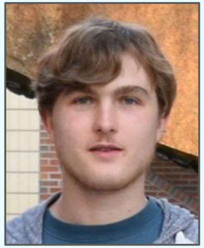
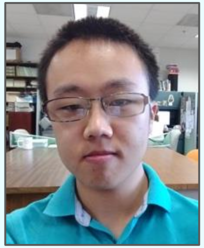


Caleb Bowyer

Machine Learning



Shiming Deng[1]

Analysis & Visualization Tools

Quan Pham[2]

Channel Emulation

Josh Agarth[3]

CIL Development

[1]Phases 1 & 2: Now with L3Harris

[2]Phases 1 & 2: Now pursuing Ph.D.

[3]Phase 1: Now with Lockheed-Martin

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