DARPA SC2
Spectrum Collaboration Challenge

Division 6 Seminar

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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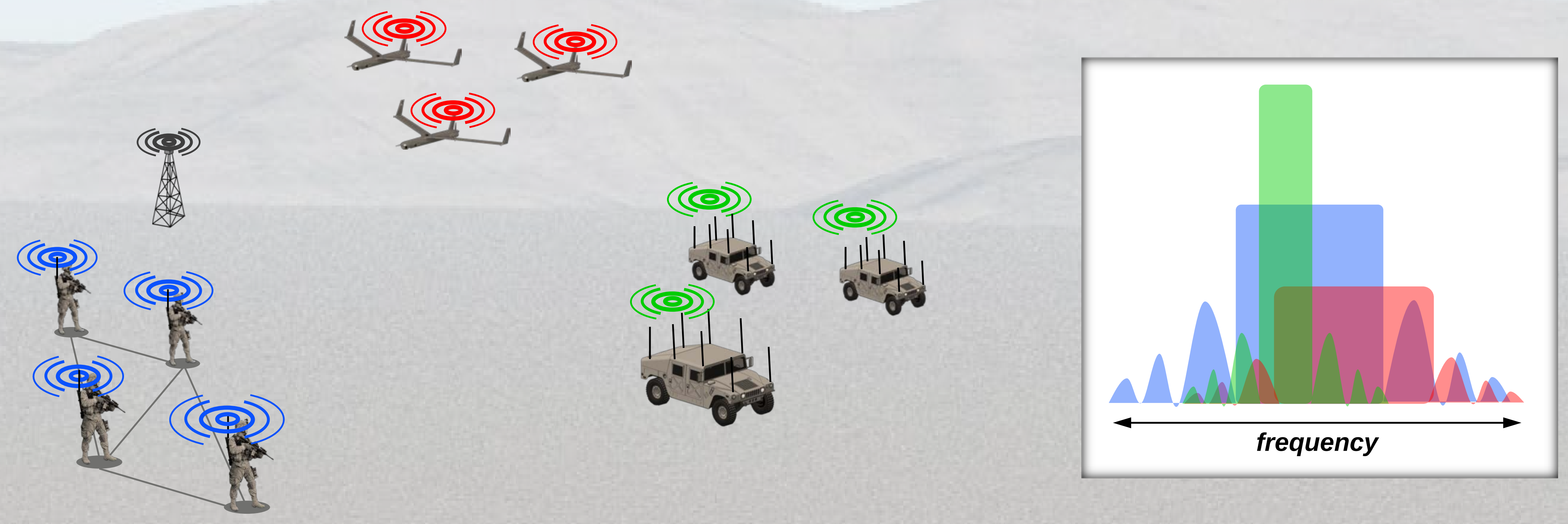
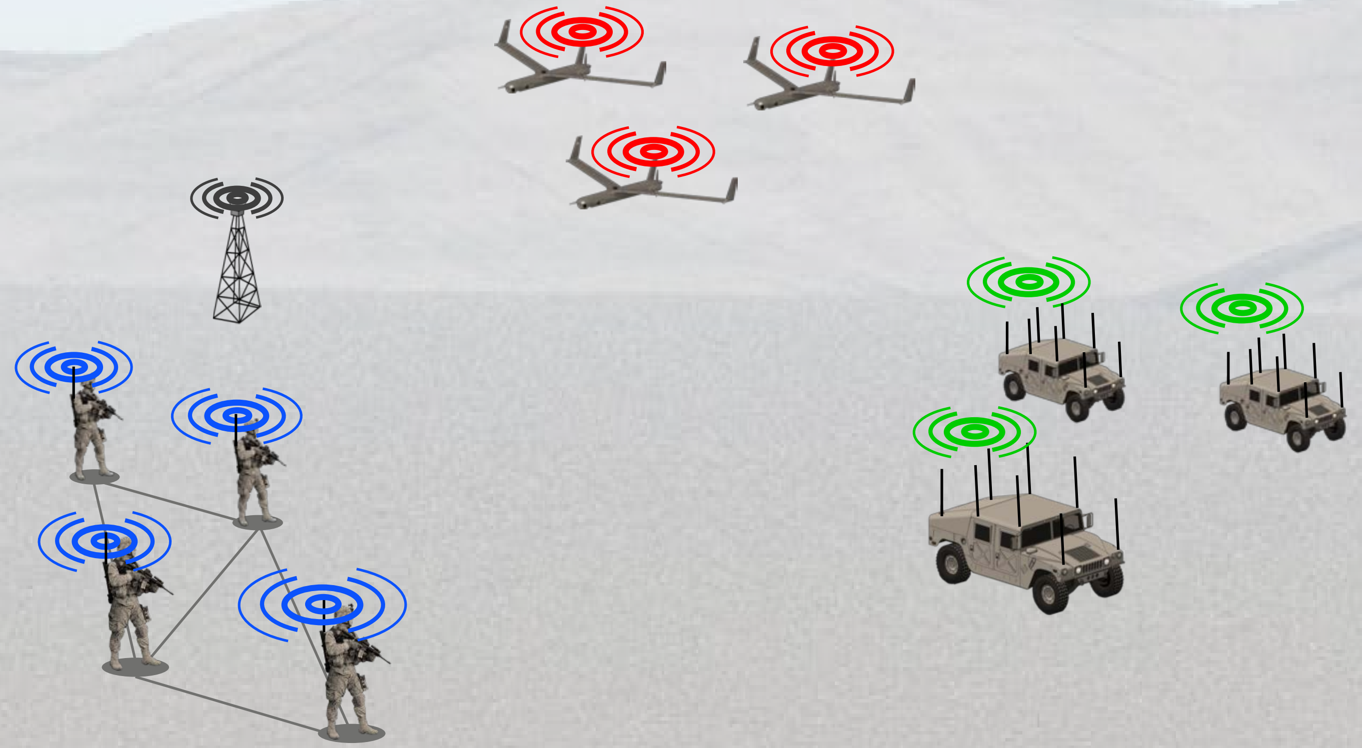
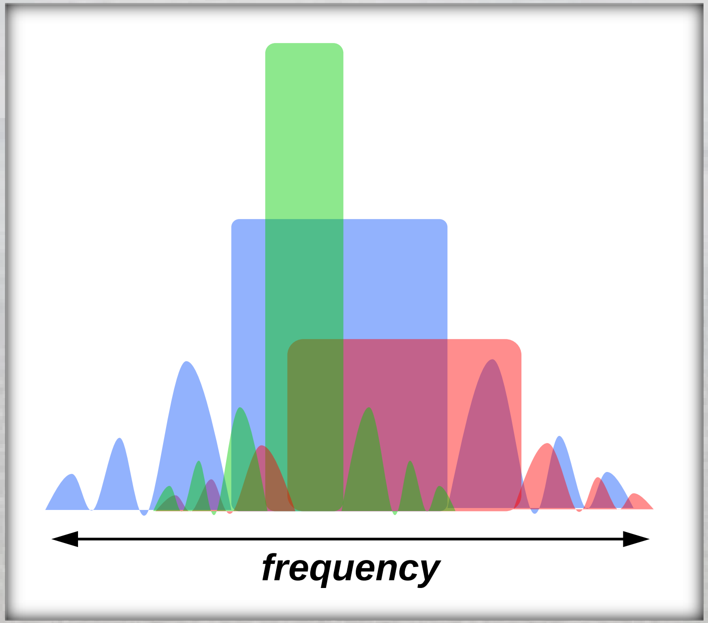
Motivating Example



Motivating Scenario:
Spatial convergence of allied, heterogeneous networks operating in the same frequency band

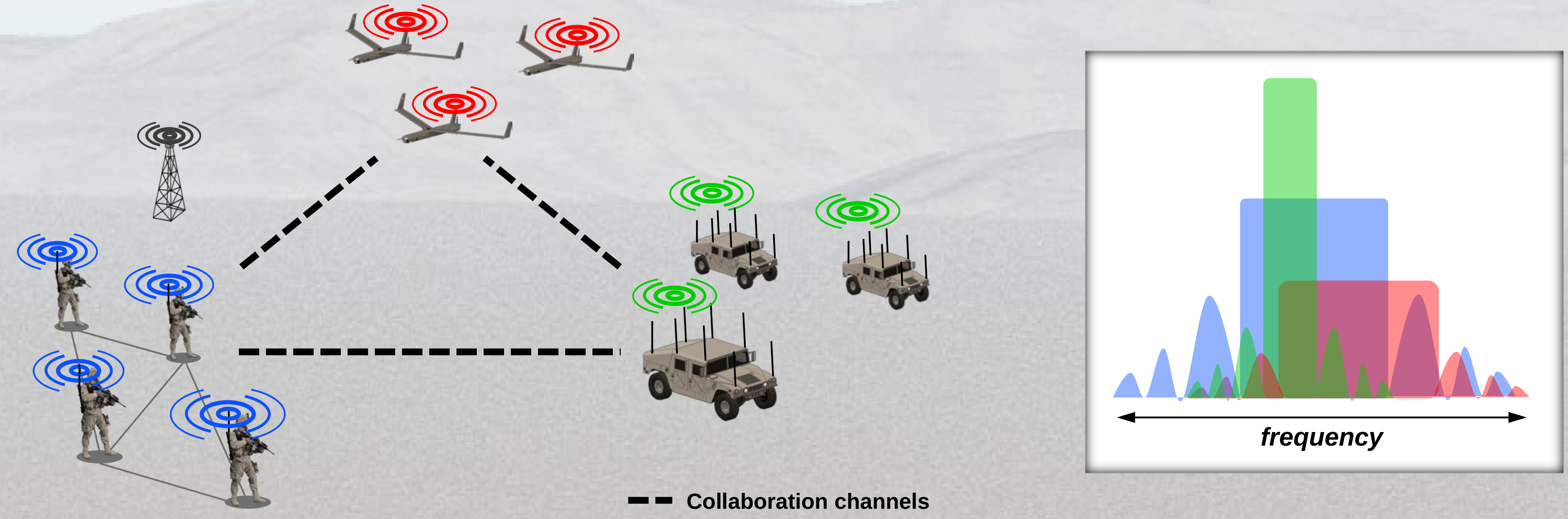
Motivating Example





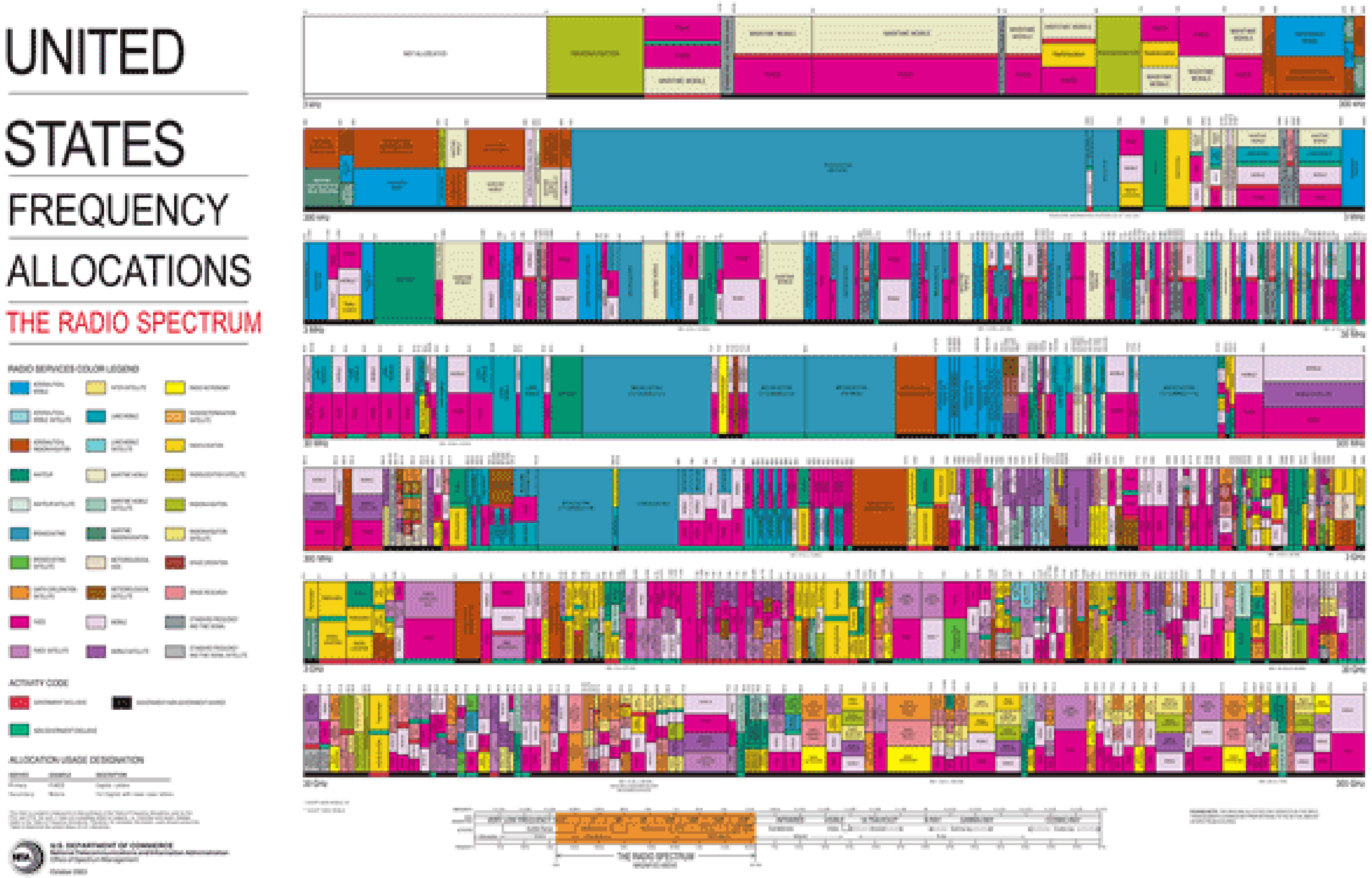
- **Key Challenges:**
  - **Networks are heterogeneous** ⇒ *coordination without co-design*
  - **Interference environment is dynamic** ⇒ *spectrum usage must adapt accordingly*
  - **Networks are all secondary users** ⇒ *networks must make their own rules for sharing*

Motivating Example



Out-of-band collaboration anticipated to be a key enabler of effective spectrum sharing among heterogeneous networks

Current Solution



Static allocation is an inefficient solution to ever-increasing demand for spectrum.

DARPA Spectrum Collaborative Challenge (SC2)

- **DARPA MTO organized a three-year "Challenge" competition to spur innovation in *dynamic* spectrum sharing**

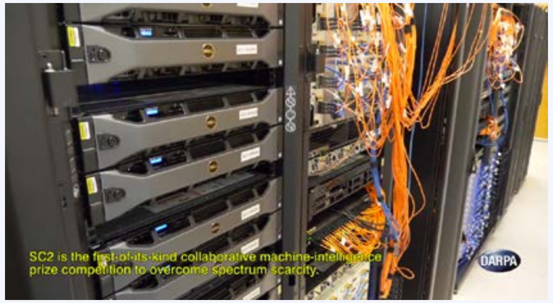
PRIZE AWARDS:

WHO?

30 Teams
US and International

WHERE?

Colosseum
Virtual wireless environment



- **IP Traffic generation and full-mesh channel emulation for 128 radio nodes**
- **Channel Emulator built by Ettus Research Systems Integrator: JHU/APL**

HOW?

COTS Software-Defined Radio
100 MHz BW, 2x2 MIMO

Ettus Research
USRP X310

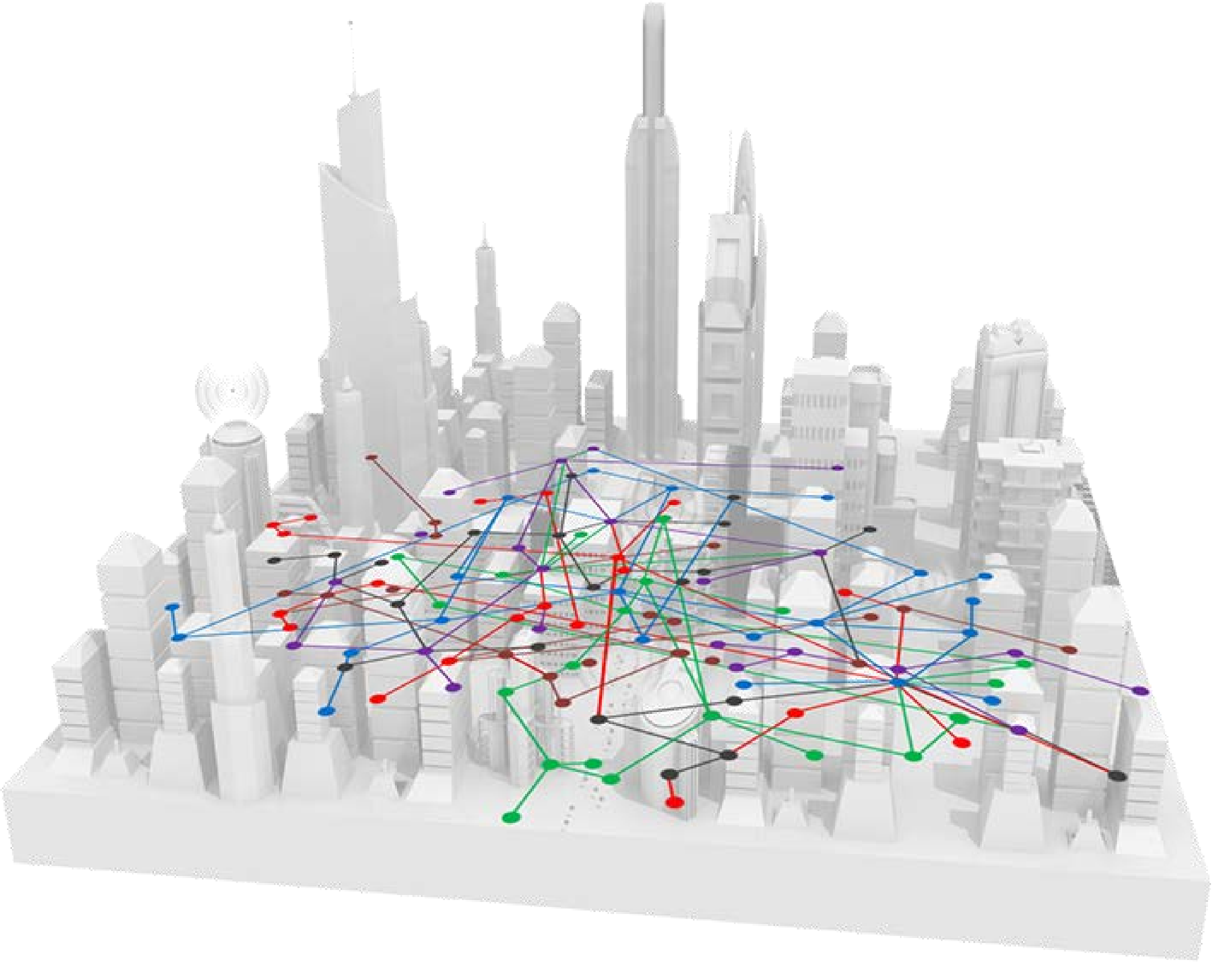
Goal: Teams program their radios to create *Collaborative Intelligent Radio Networks (CIRNs)* which share spectrum dynamically.

Figures from DARPA SC2 Competitor Kickoff Presentation

Outline

- **MIT LL Scenario Development for SC2**
  - Motivating Questions
  - Implementation Tools and Challenges
- **MIT LL Training Bot Development**
  - Cognitive Algorithm Development
  - Simulation Results
- **Phase 1 Competition in Review**

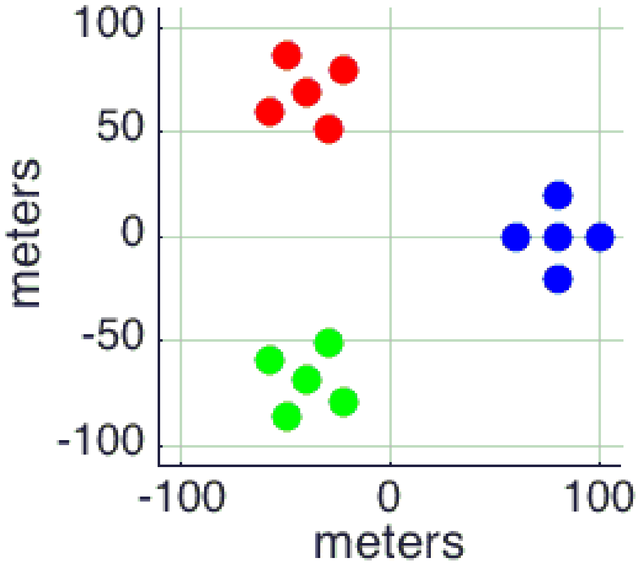
MIT LL Task #1: Scenario Development



- MIT LL was one of two Scenario Developers for the Competition (along with Federated Wireless)
- Goal: Create realistic situations from commercial and military realms in which heterogeneous networks must share the same spectrum
  - Emphasize situations which incentivize collaboration and machine learning
- Three principal components:
  - Emulated node positions over time
  - RF channel models
    - Large-scale and small-scale fading
  - IP traffic profiles
    - Deterministic and stochastic packet arrivals
    - Constant and variable mean rate

Example Q1: Can CIRNs Determine When They Need to Coordinate Spectrum Access?

"N-Corners"



Compare sum throughput for greedy vs. altruistic spectrum access

- Regime 1: When their interference environments are isolated, CIRNs benefit from greedy spectral usage
- Regime 2: Congestion necessitates coordination (e.g., "global" FDMA)
- Several SC2 scenarios test the ability to detect and adapt to such regime changes

Example Q1: Can CIRNs Determine When They Need to Coordinate Spectrum Access?

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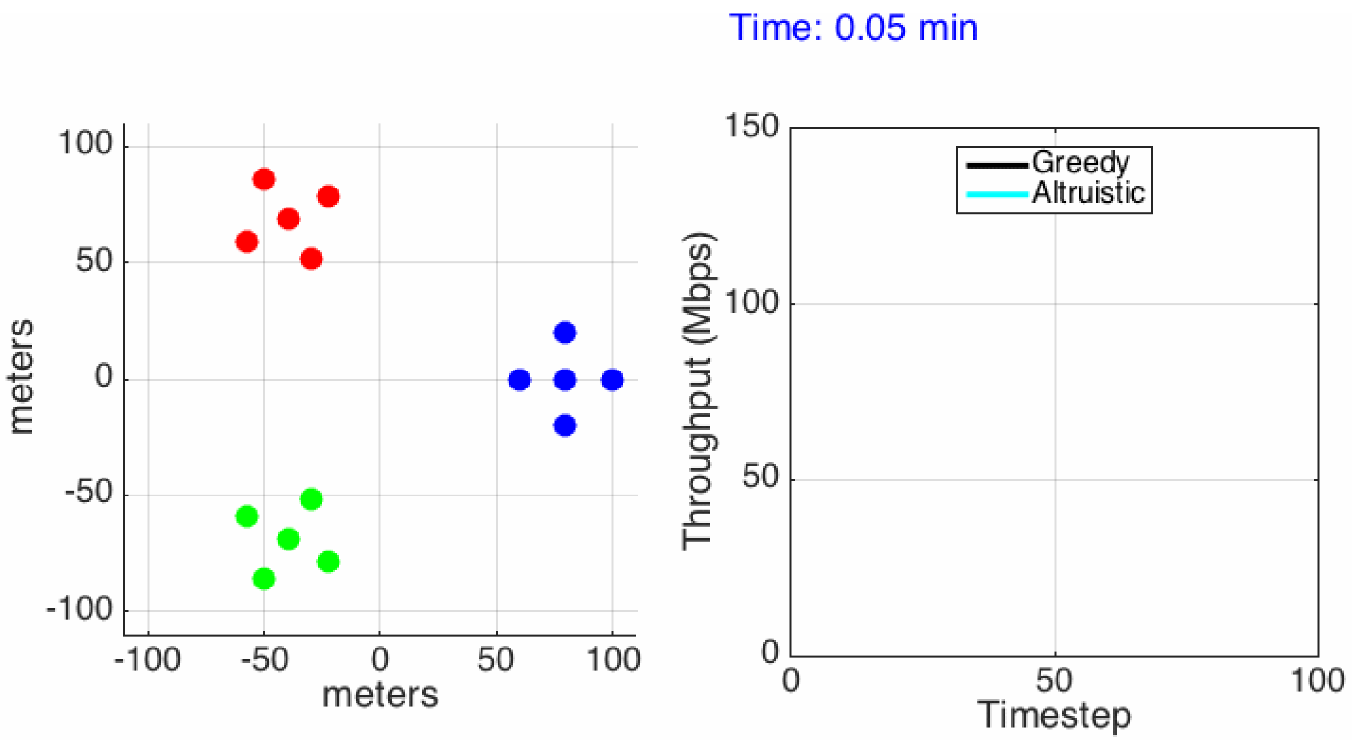

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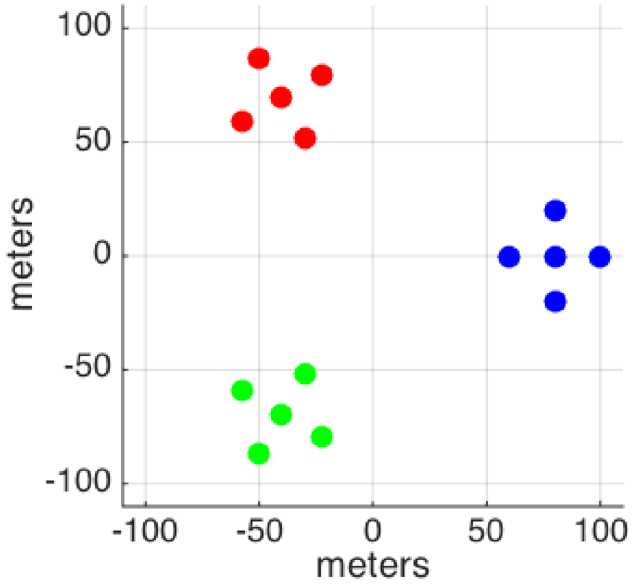
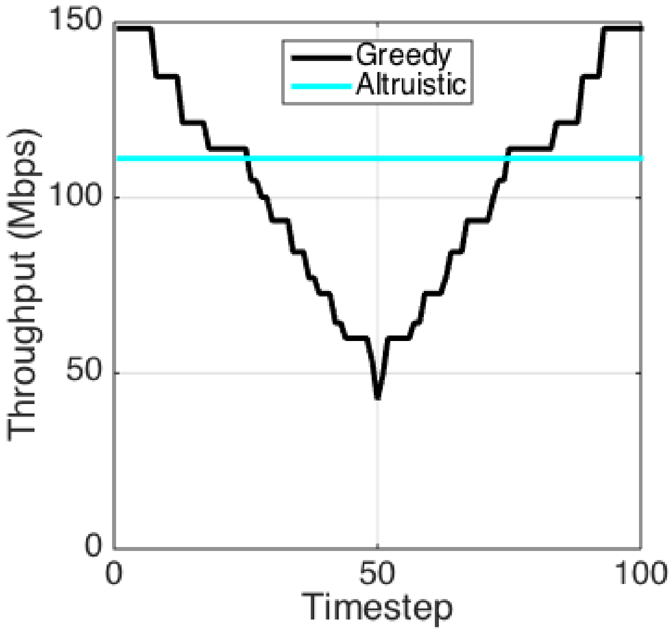


Time: 9.95 min



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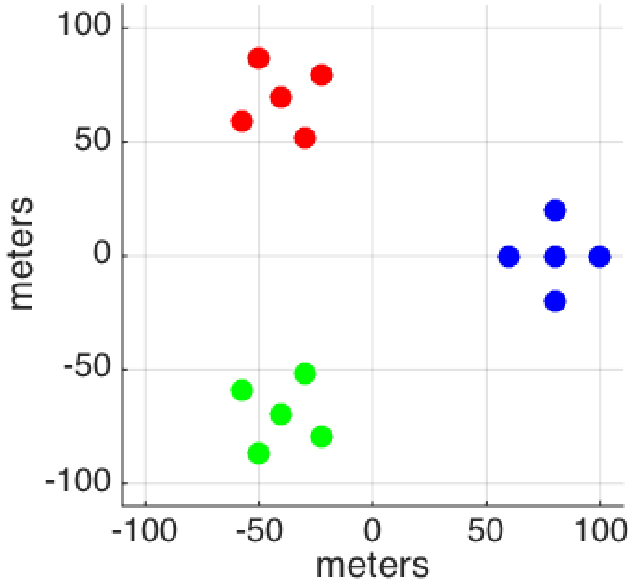

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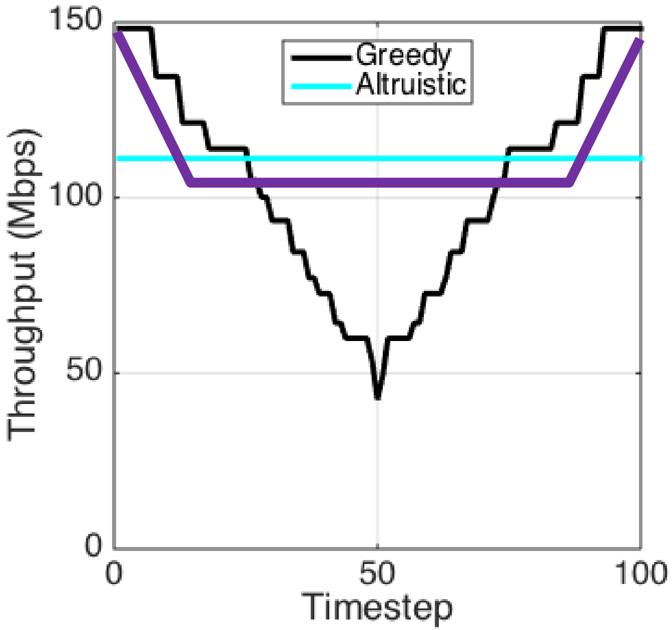

Traffic Demand

- **Regime 1: When their interference environments are isolated, CIRNs benefit from greedy spectral usage**
- **Regime 2: Congestion necessitates coordination (e.g., "global" FDMA)**
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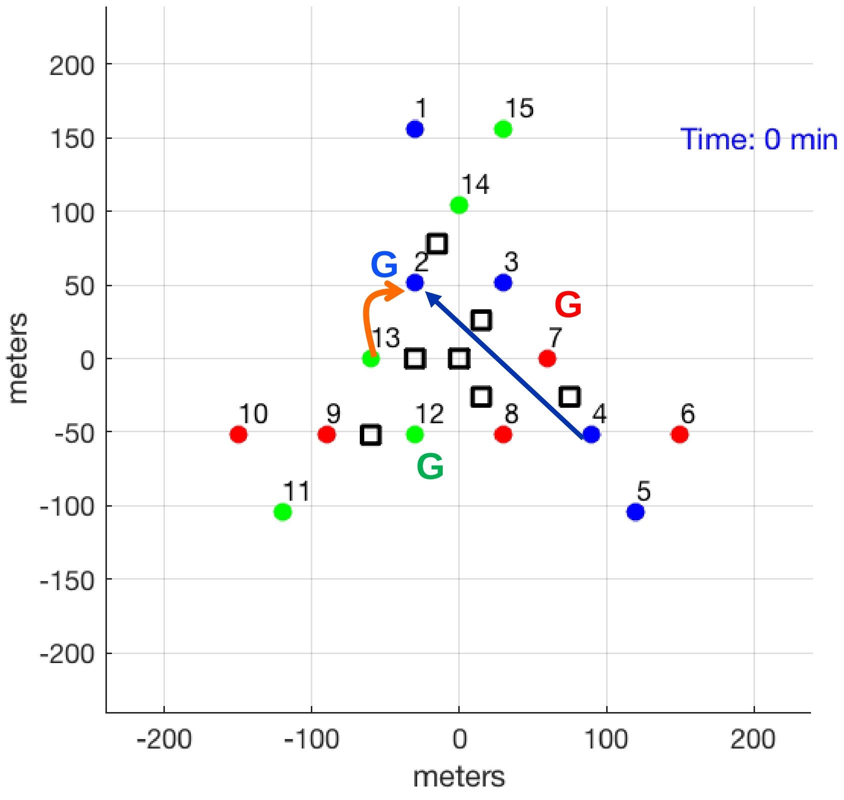
Example Q2: Can CIRNs Collaboratively Adapt to Complex Interference Environments?

"Interference Detective"



- **Real-world interference environments can be highly *asymmetric***
  - **Suppose CIRNs collide in time-frequency space**
  - **Impact severity may differ greatly among colliding parties**
    - **Simple reactive schemes can be highly sub-optimal**
    - **In contrast, collaboration is a key mechanism for solving inter-CIRN *hidden node* problems**

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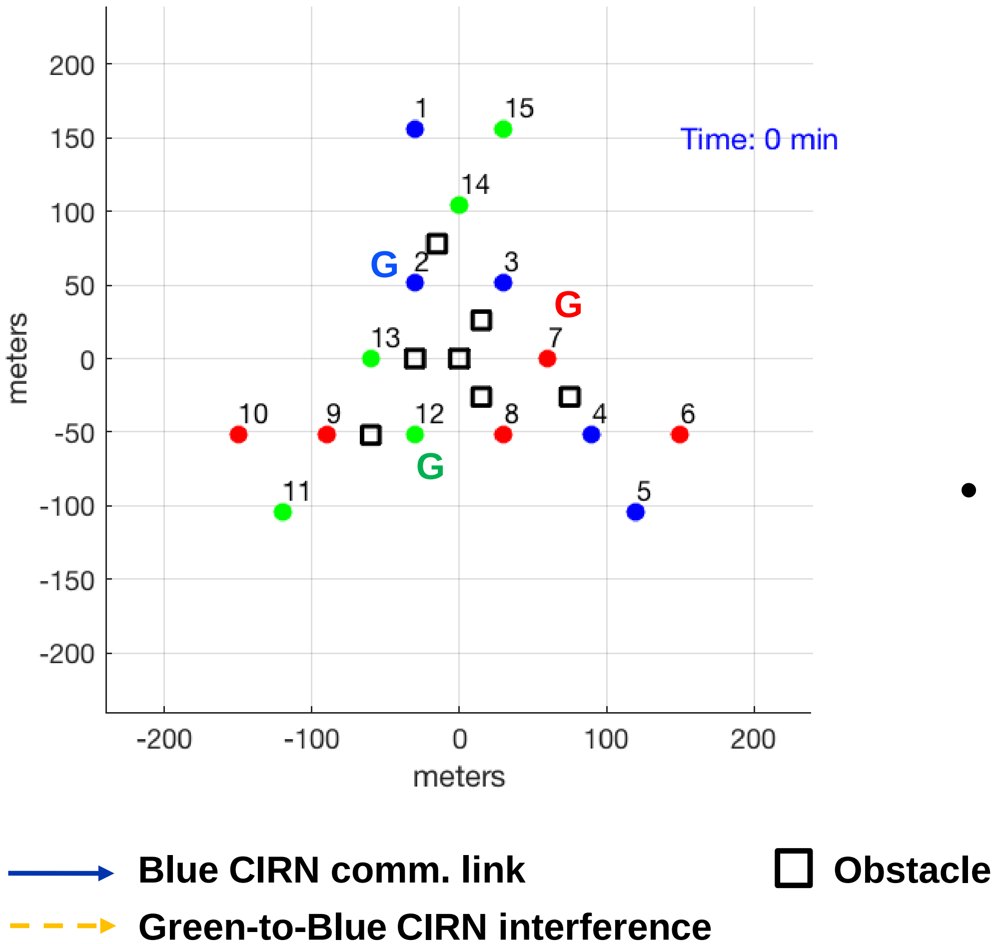

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- **Propagation obstacles can provide opportunities for spatial re-use of spectrum**
  - **Environment may naturally segregate interference zones associated with each receiver**

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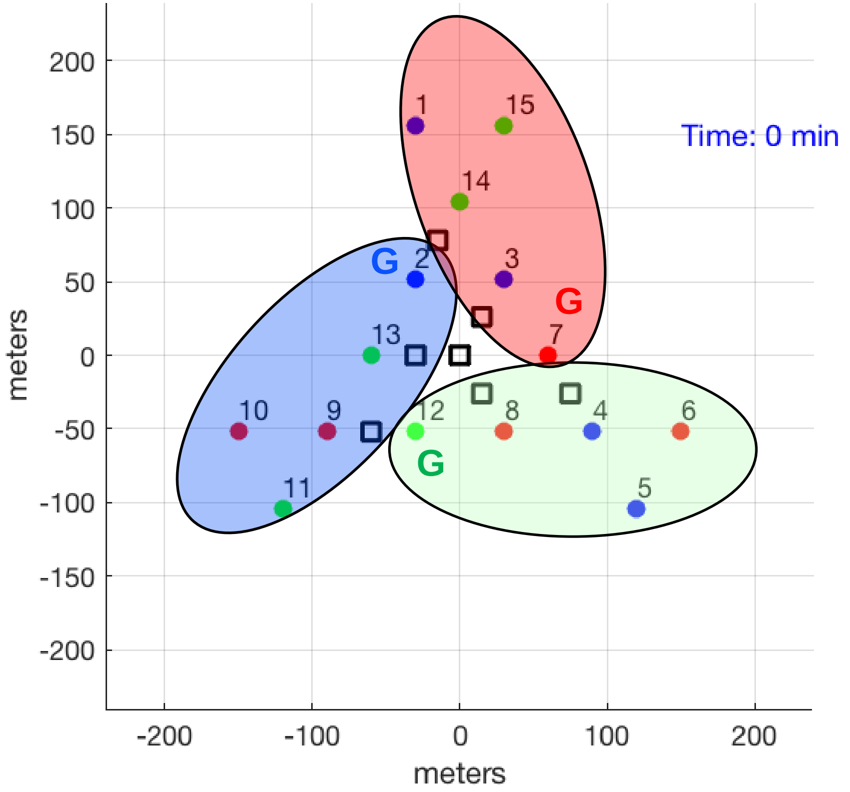


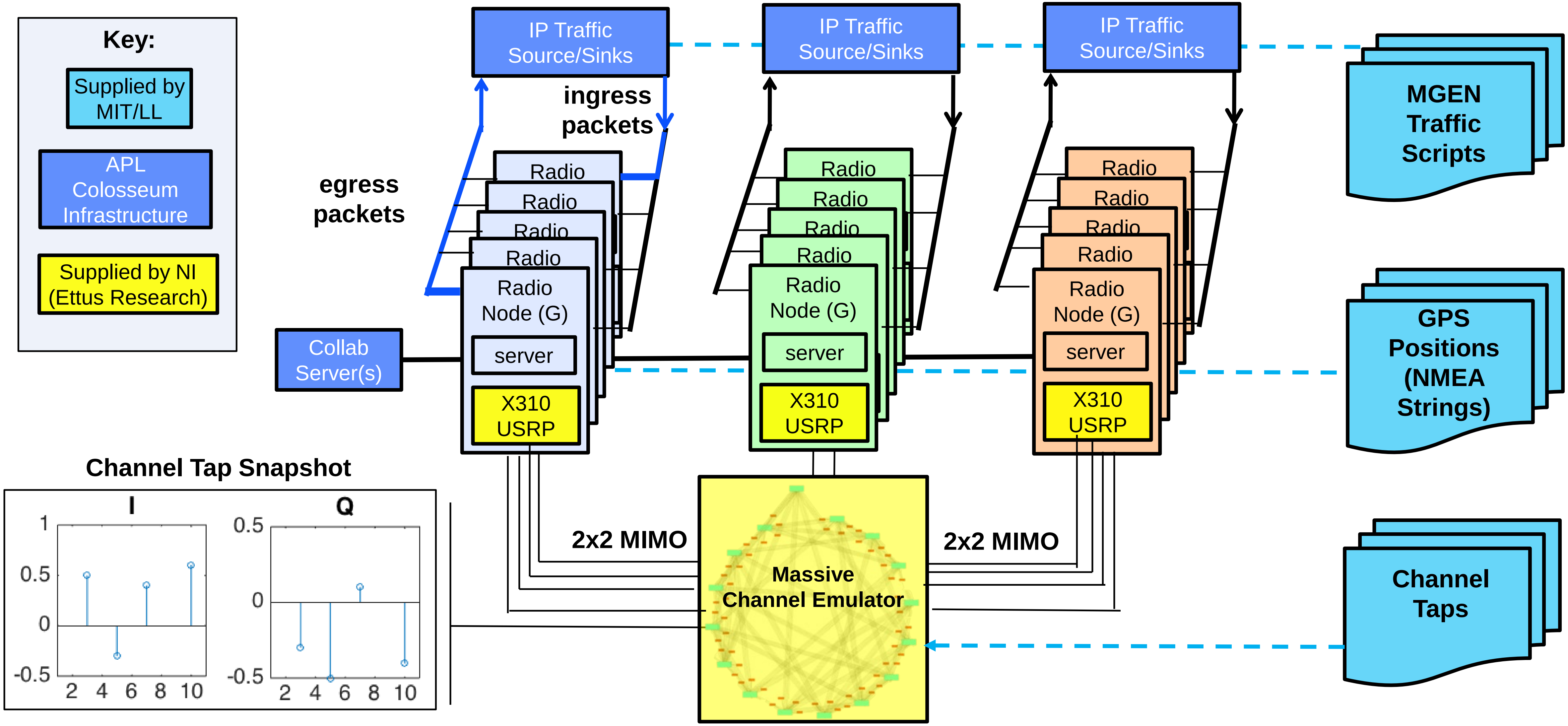
Blue CIRN comm. link

Obstacle

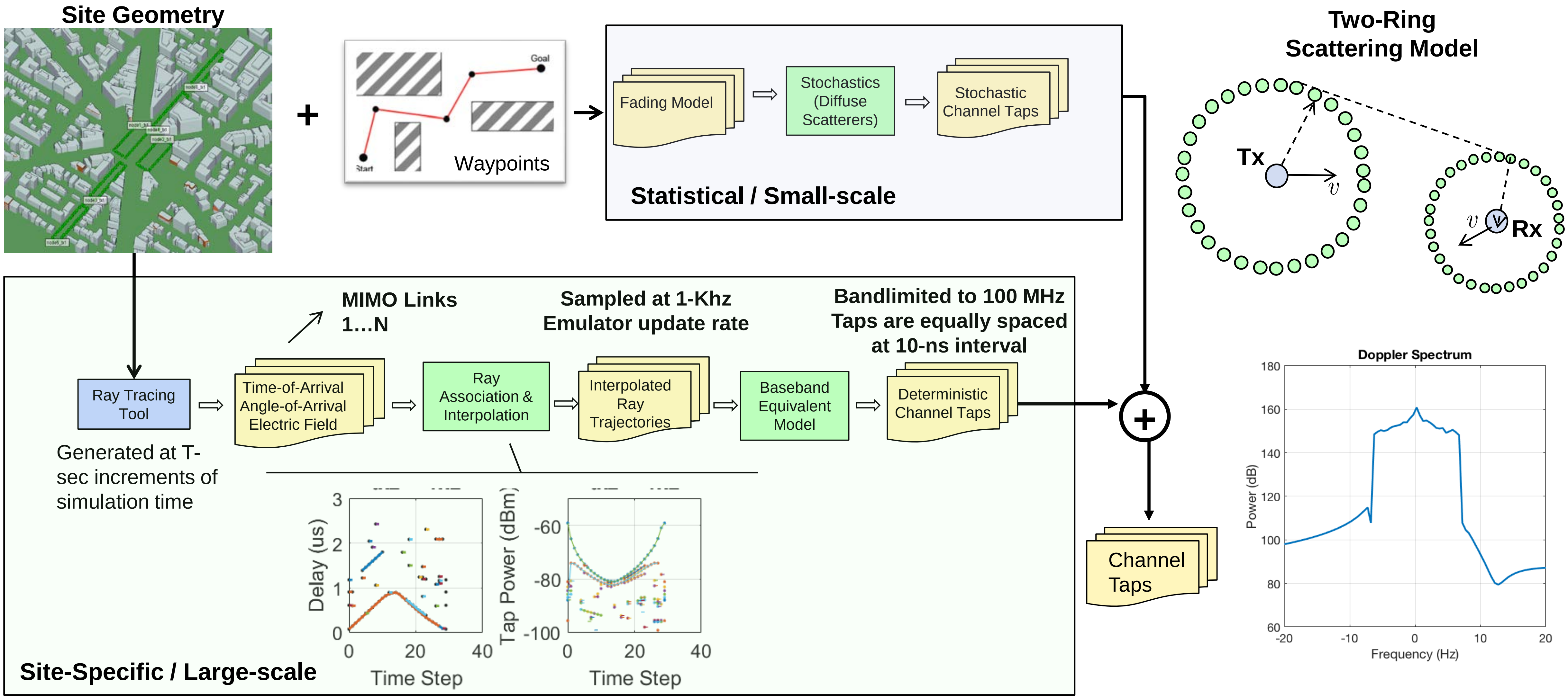
Green-to-Blue CIRN interference

- **Real-world interference environments can be highly *asymmetric***
  - **Suppose CIRNs collide in time-frequency space**
  - **Impact severity may differ greatly among colliding parties**
    - **Simple reactive schemes can be highly sub-optimal**
    - **In contrast, collaboration is a key mechanism for solving inter-CIRN *hidden node* problems**
- **Propagation obstacles can provide opportunities for spatial re-use of spectrum**
  - **Environment may naturally segregate interference zones associated with each receiver**
  - **De-confliction only necessary within each zone separately ⇒ opportunities for spatial re-use across zones**

Scenario Instantiation in Colosseum



RF Channel Modeling



Outline

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- **MIT LL Training Bot Development**
  - Cognitive Algorithm Development
  - Simulation Results
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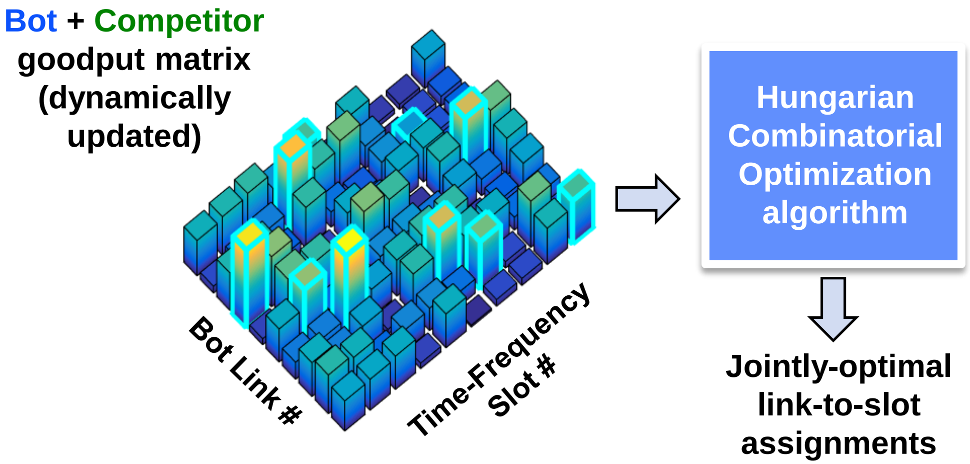
MIT/LL Training Bot Overview

- **Purpose of Bots: provide an SDR implementation for Competitors to practice against (and collaborate with)**
- **Bot components:**
  - **Fully functional transceiver (GNURadio-based)**
  - **Centralized Bot "brain" (Python-based)**
    - **Adapts spectrum access in time and frequency based on performance**
    - **Supports basic elements of the SC2 collaboration protocol (Developed in Python)**
- **Bot also used as reference implementation in Colosseum demo tutorials provided to the Competitors**

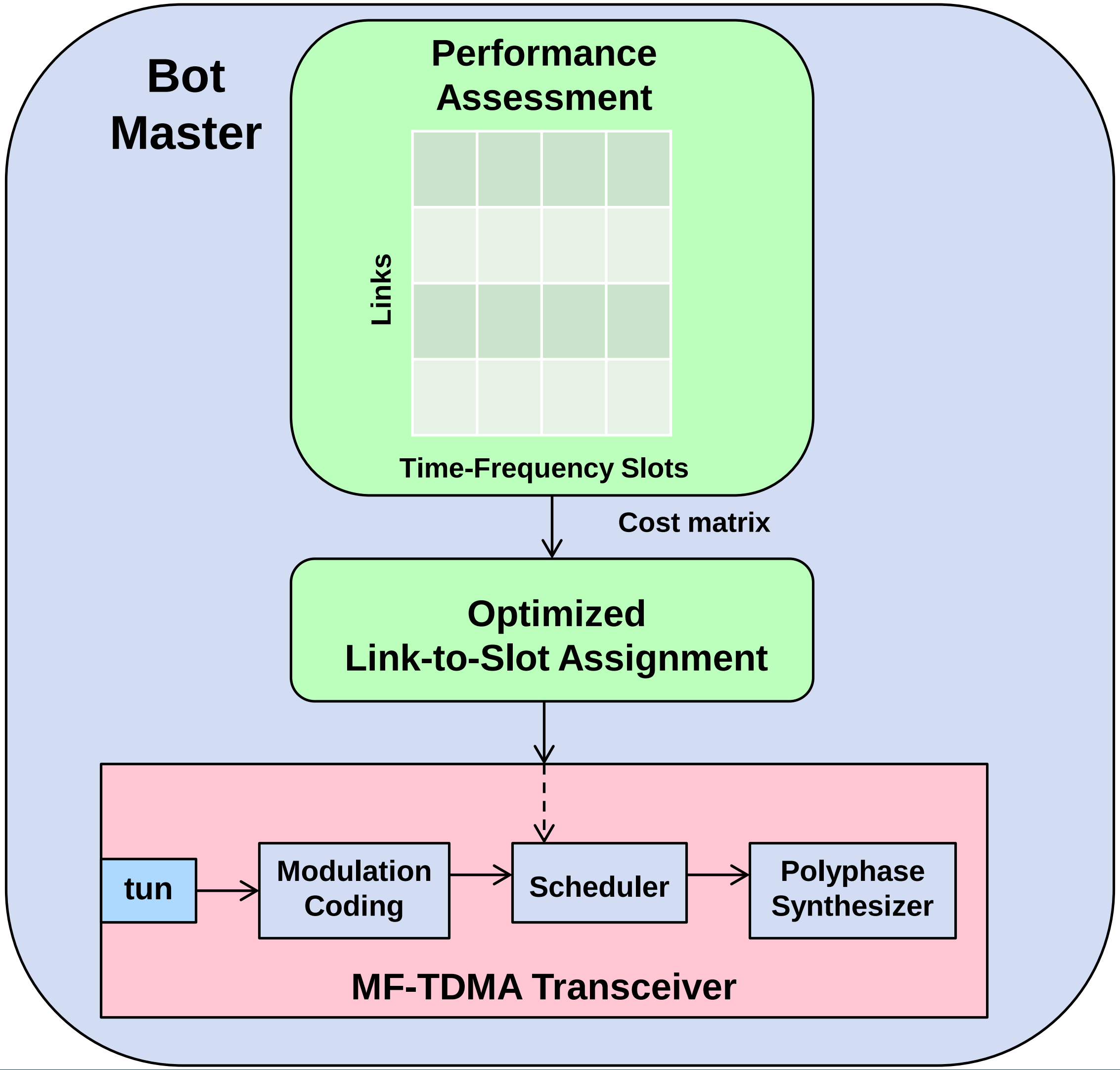
Table of Bot PHY/MAC Parameters

Parameter	Bot Implementation
Modulation	QPSK
Coding / Decoding	Convolutional / Viterbi
MAC Scheme	Multi-Frequency TDMA (MF-TDMA)
Access Slots	5 Frequency Slots, 4 Time Slots per frame

Bot Cognitive Approach



Bot Network Design
Intra-Network Coordination



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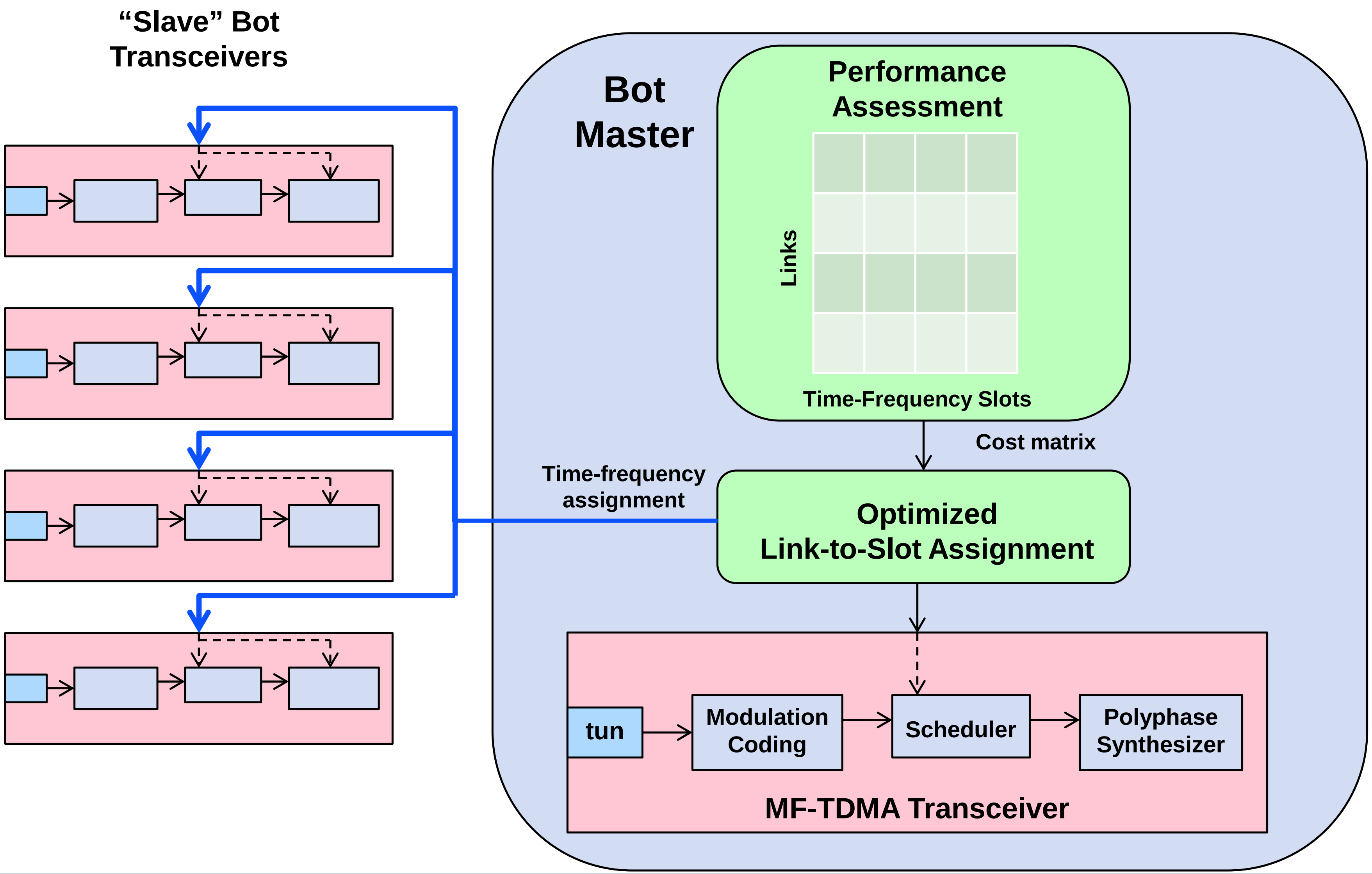
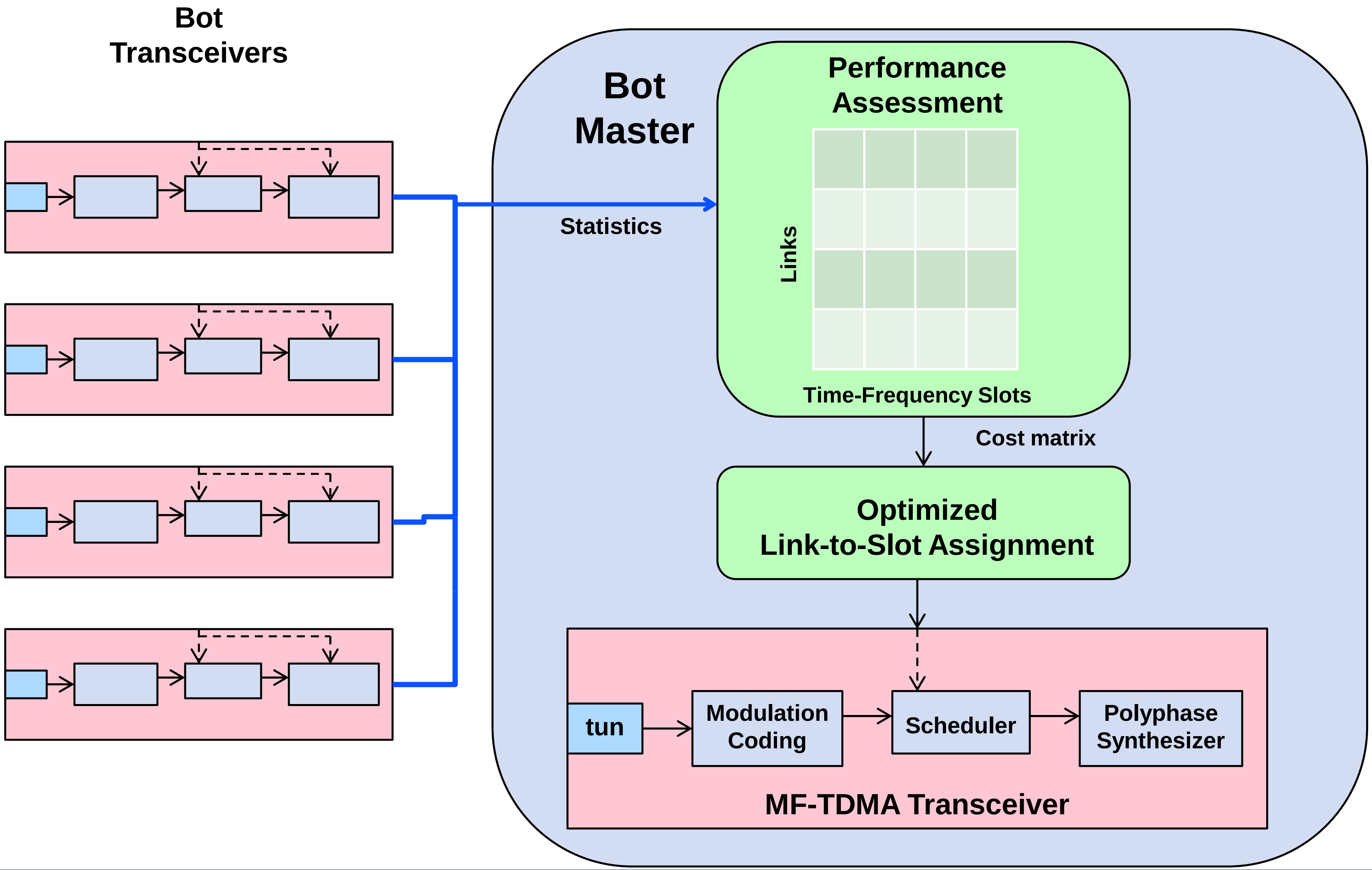
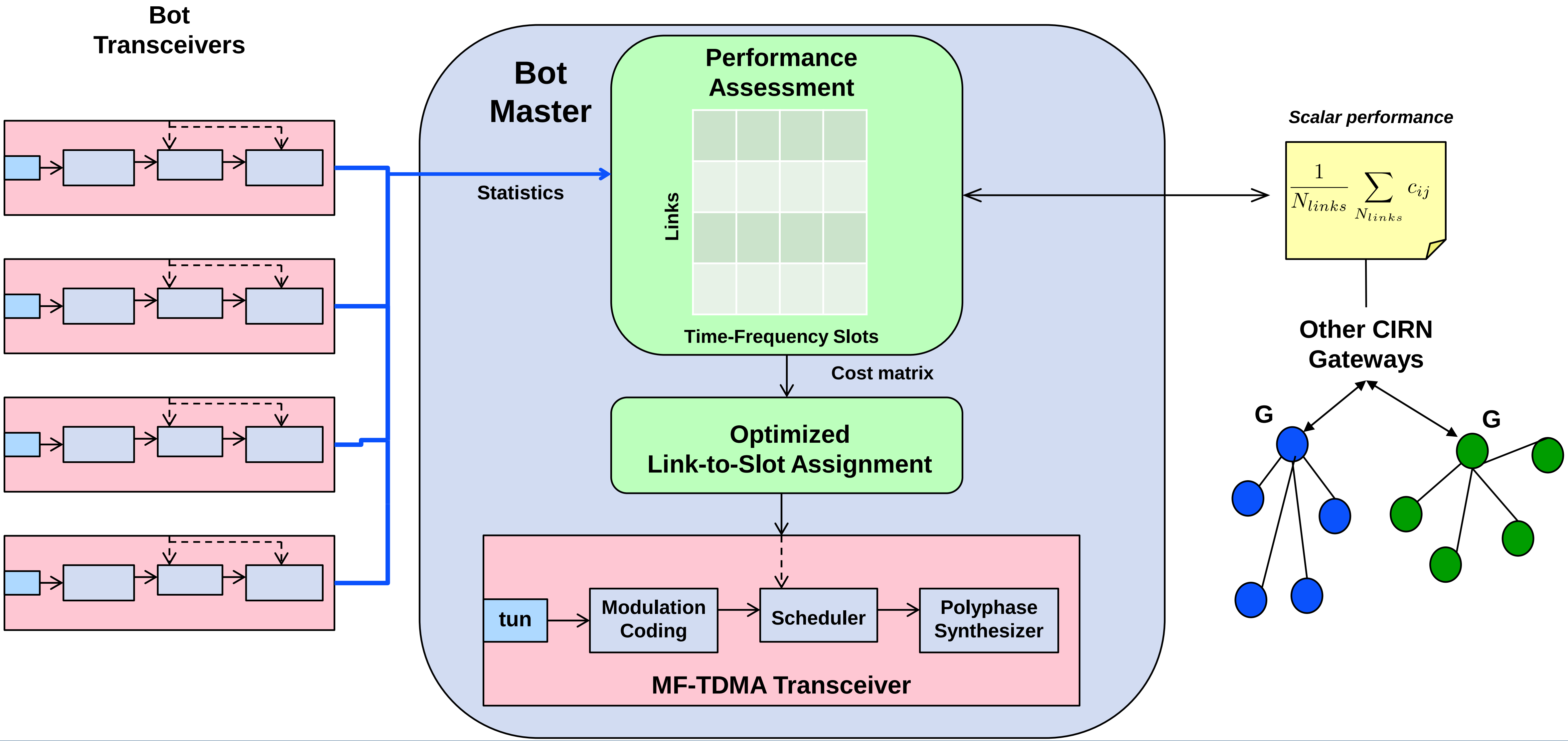


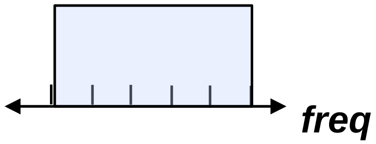
Bot Network Design
Collaboration

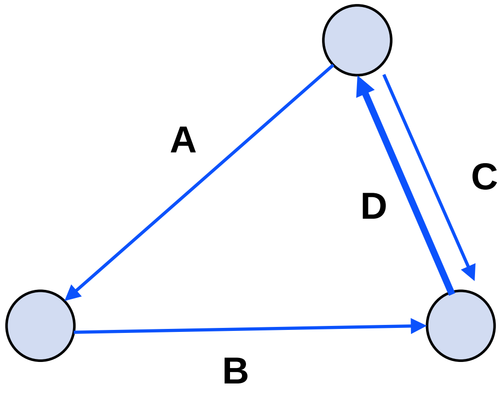


Bot Network Design
Collaboration



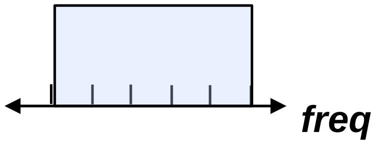
Lincoln Algorithm: Example

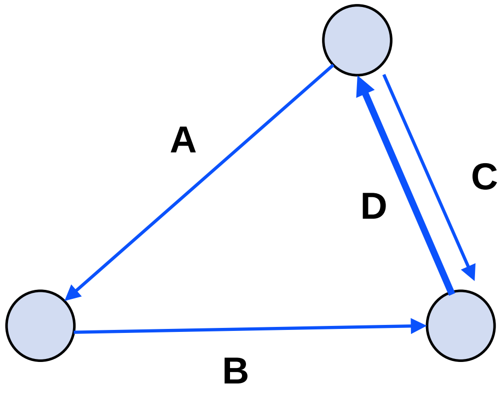




Token	Link	Frequency Slot #				
		1	2	3	4	5
1						
2						
3						
4						
5						

Lincoln Algorithm: Example

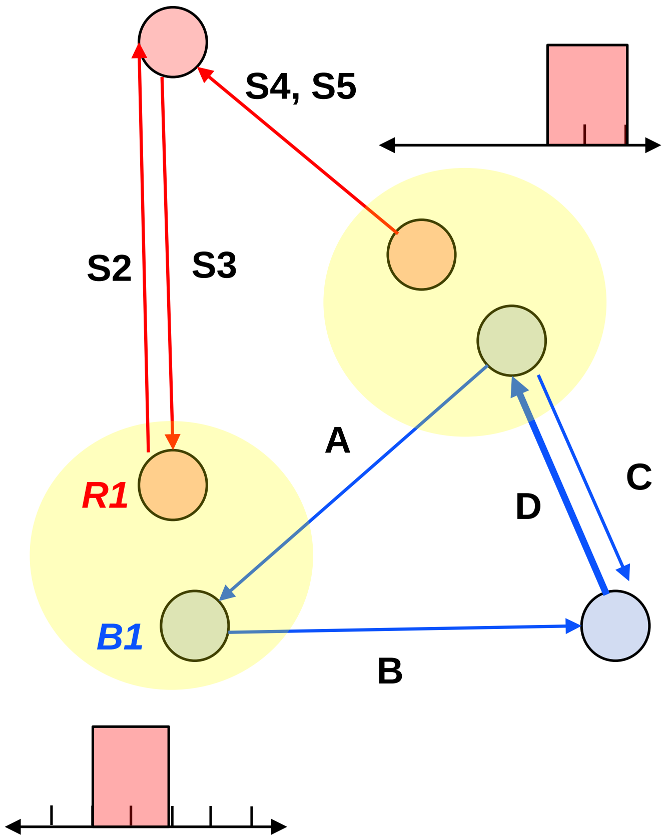


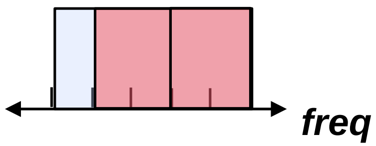


Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A					
2	B					
3	C					
4	D					
5	D					

First, tokens are assigned to links in proportion to traffic demand

Lincoln Algorithm: Example



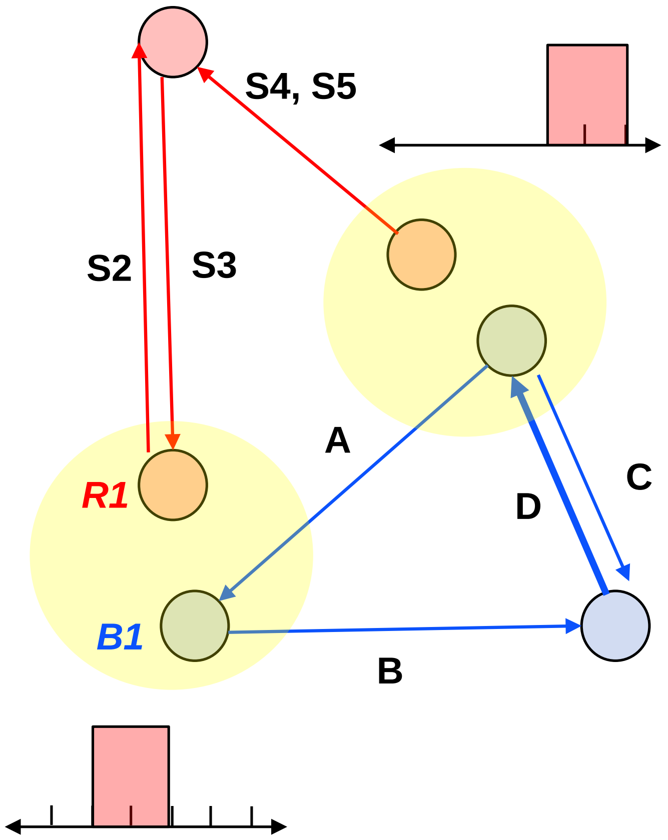


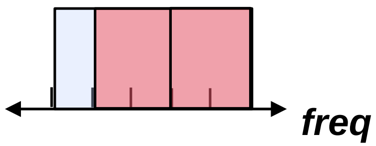
Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A		1, 0			
2	B			0, 1		
3	C					
4	D				1, 0	1, 0
5	D				1, 0	1, 0

Cost = 1 – rx packets / tx packets

Then, costs are assigned to each link-to-slot pairing based on performance.
Format: (own cost, collaborative cost)

Lincoln Algorithm: Example





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1	A		1, 0			
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3	C					
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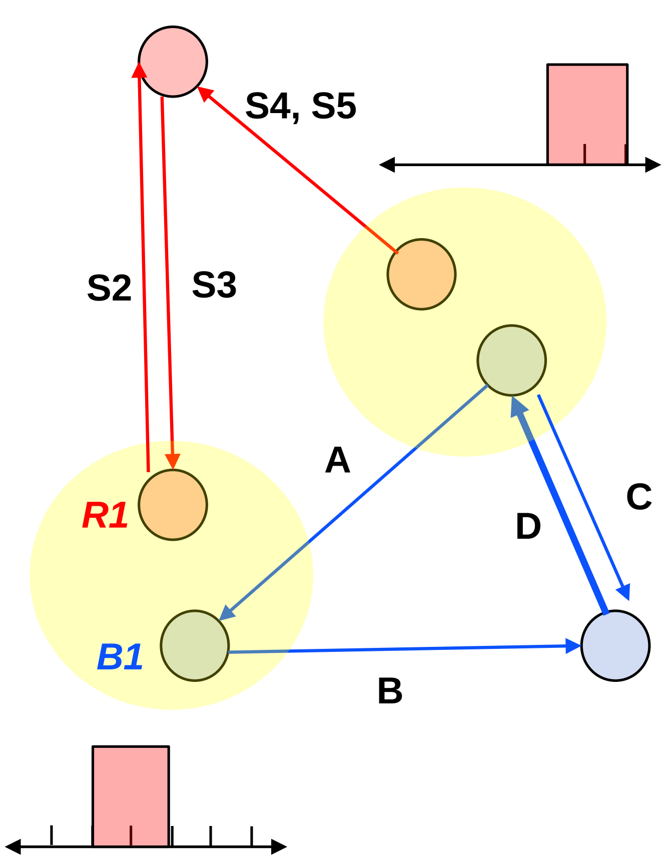
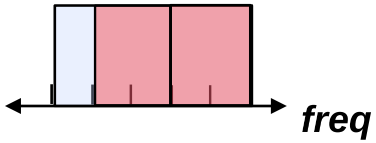


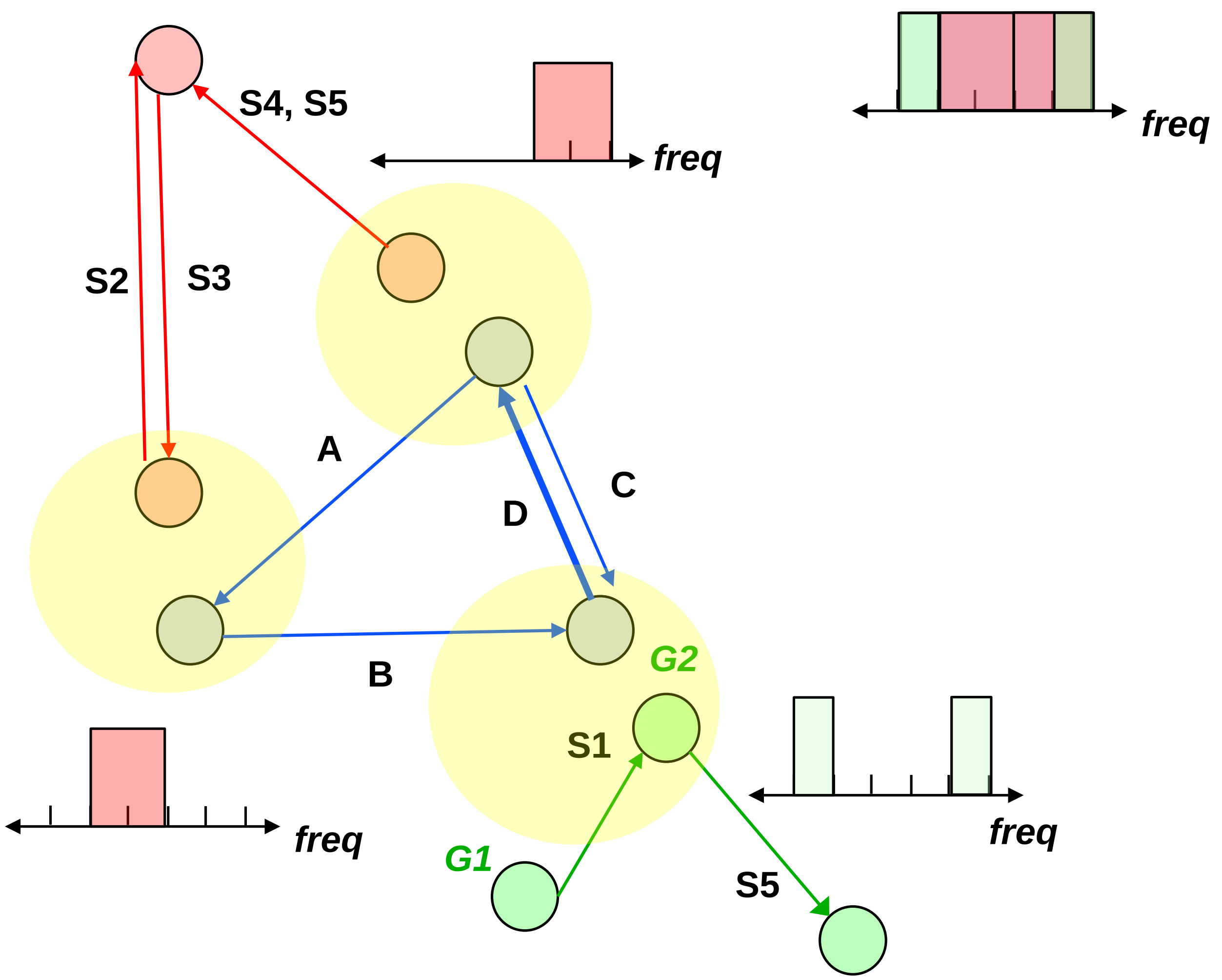


Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0, 0	1, 0	0, 0	0, 0	0, 0
2	B	0, 0	0, 0	0, 1	0, 0	0, 0
3	C					
4	D				1, 0	1, 0
5	D				1, 0	1, 0

Cost = 1 – goodput / offered_load

Then, costs are assigned to each link-to-slot pairing based on performance.
Format: (own cost, collaborative cost)

Lincoln Algorithm: Example



Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0, 0	1, 0	0, 0	0, 0	0, 0
2	B		0, 0	0, 1	0, 0	1, 0
3	C					1, 0
4	D	0, 1			1, 0	1, 0
5	D	0, 1			1, 0	1, 0

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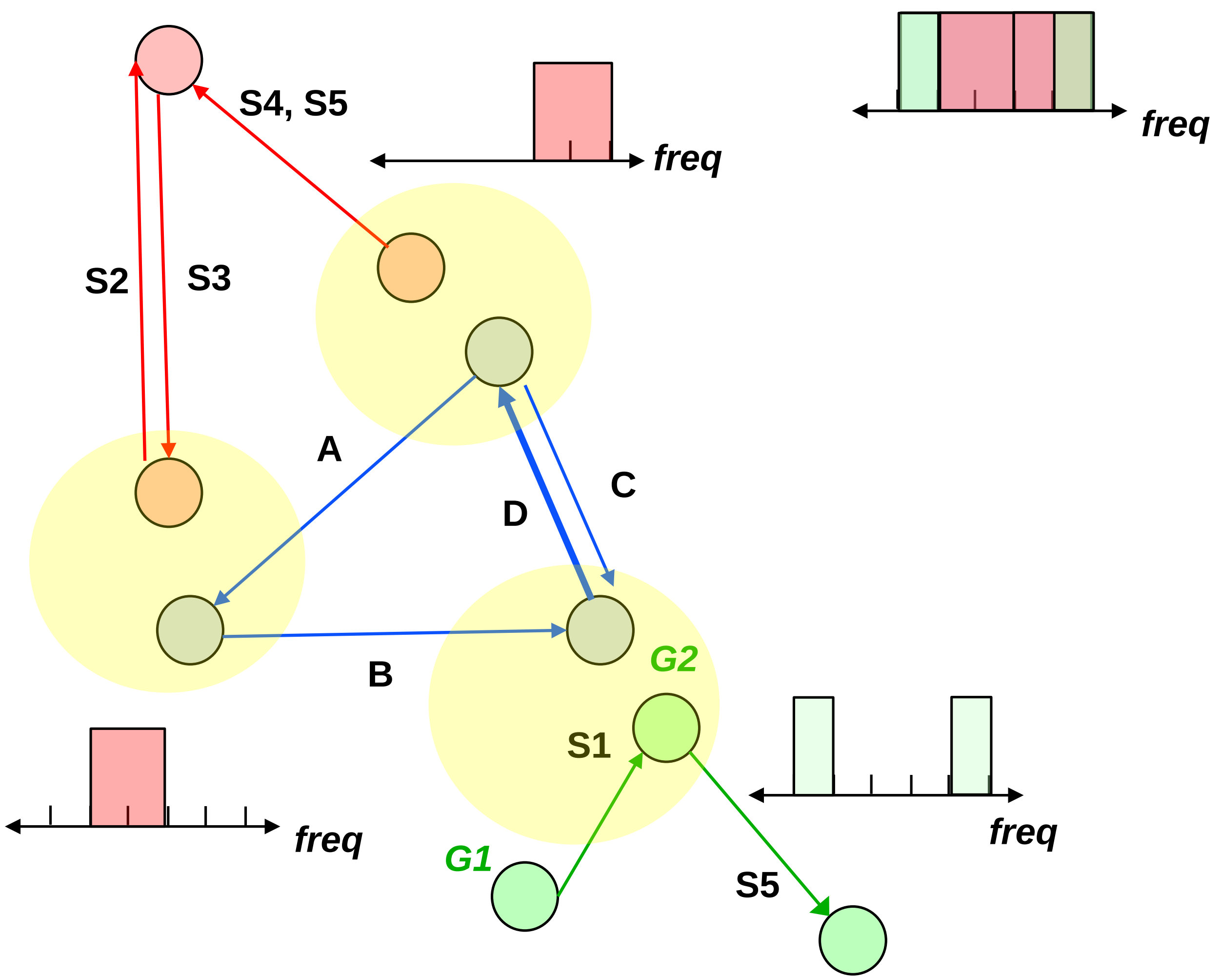

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2	B	0, 0	0, 0	0, 1	0, 0	1, 0
3	C	0, 0	0, 0	0, 0	0, 0	1, 0
4	D	0, 1	0, 0	0, 0	1, 0	1, 0
5	D	0, 1	0, 0	0, 0	1, 0	1, 0

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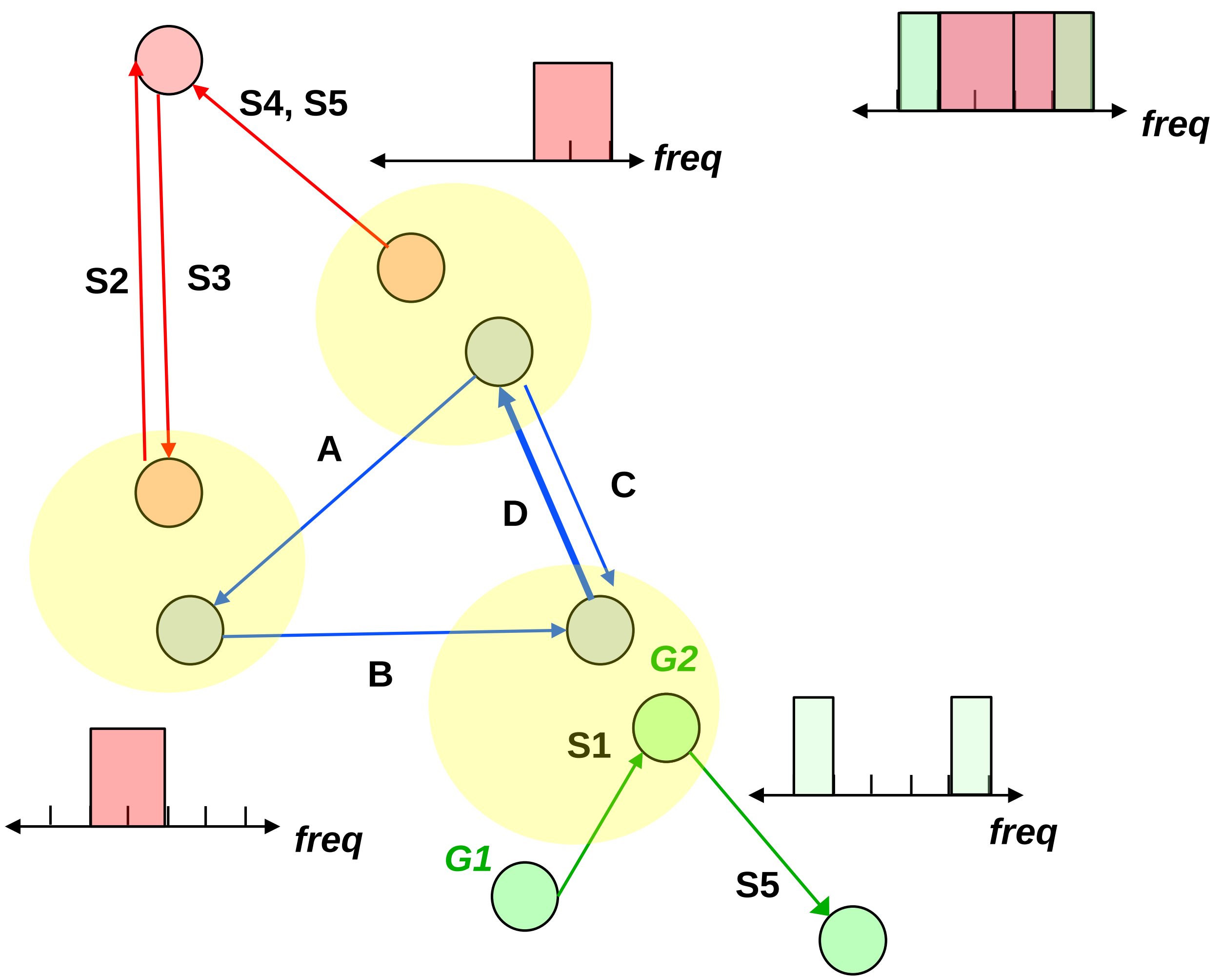
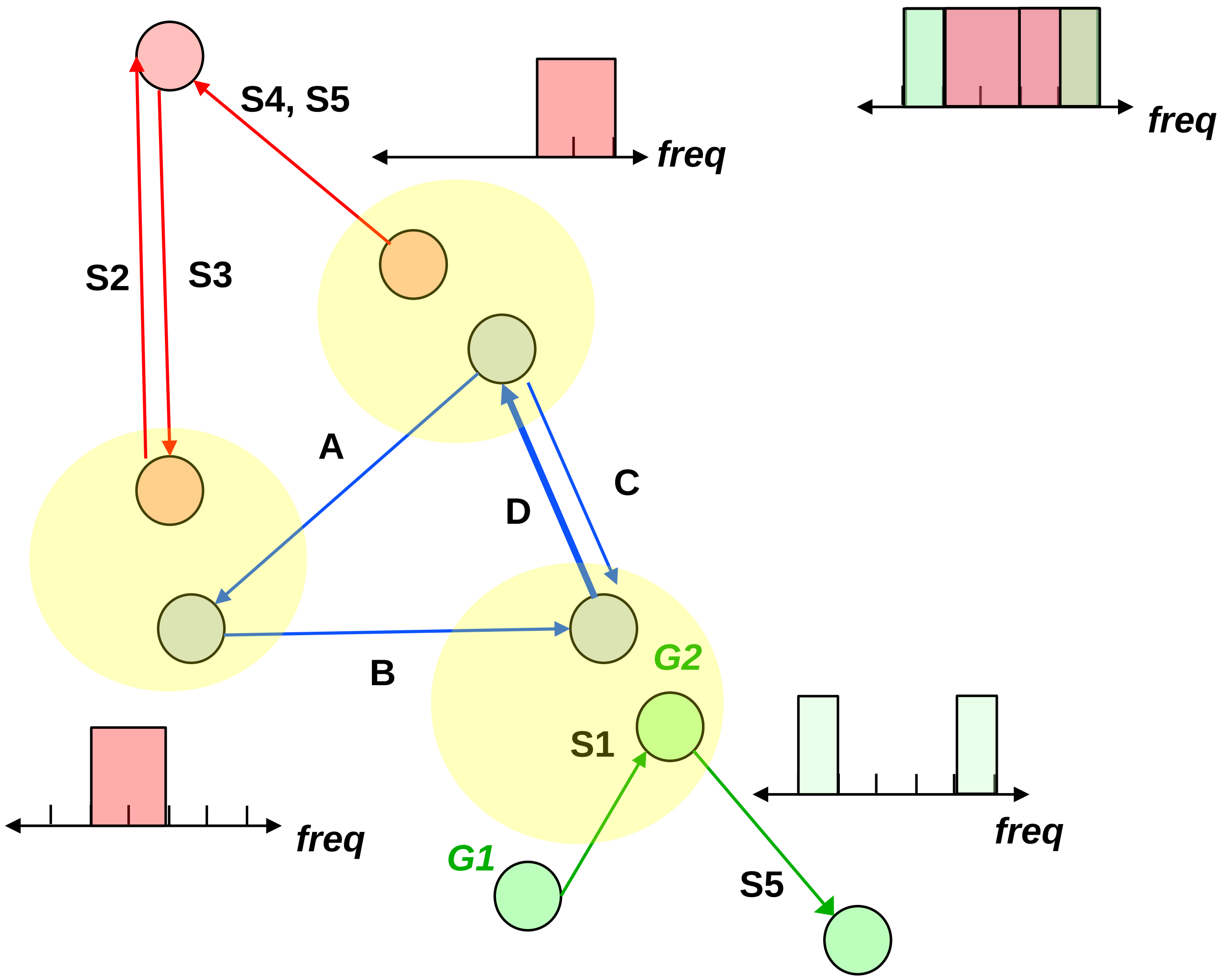


Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0	1.0	0	0	0
2	B	0	0	0.5	0	1.0
3	C	0	0	0	0	1.0
4	D	0.5	0	0	1.0	1.0
5	D	0.5	0	0	1.0	1.0

Total Cost = Own Cost + 0.5 * Collab Cost

Composite inter-network costs are computed.

Lincoln Algorithm: Example

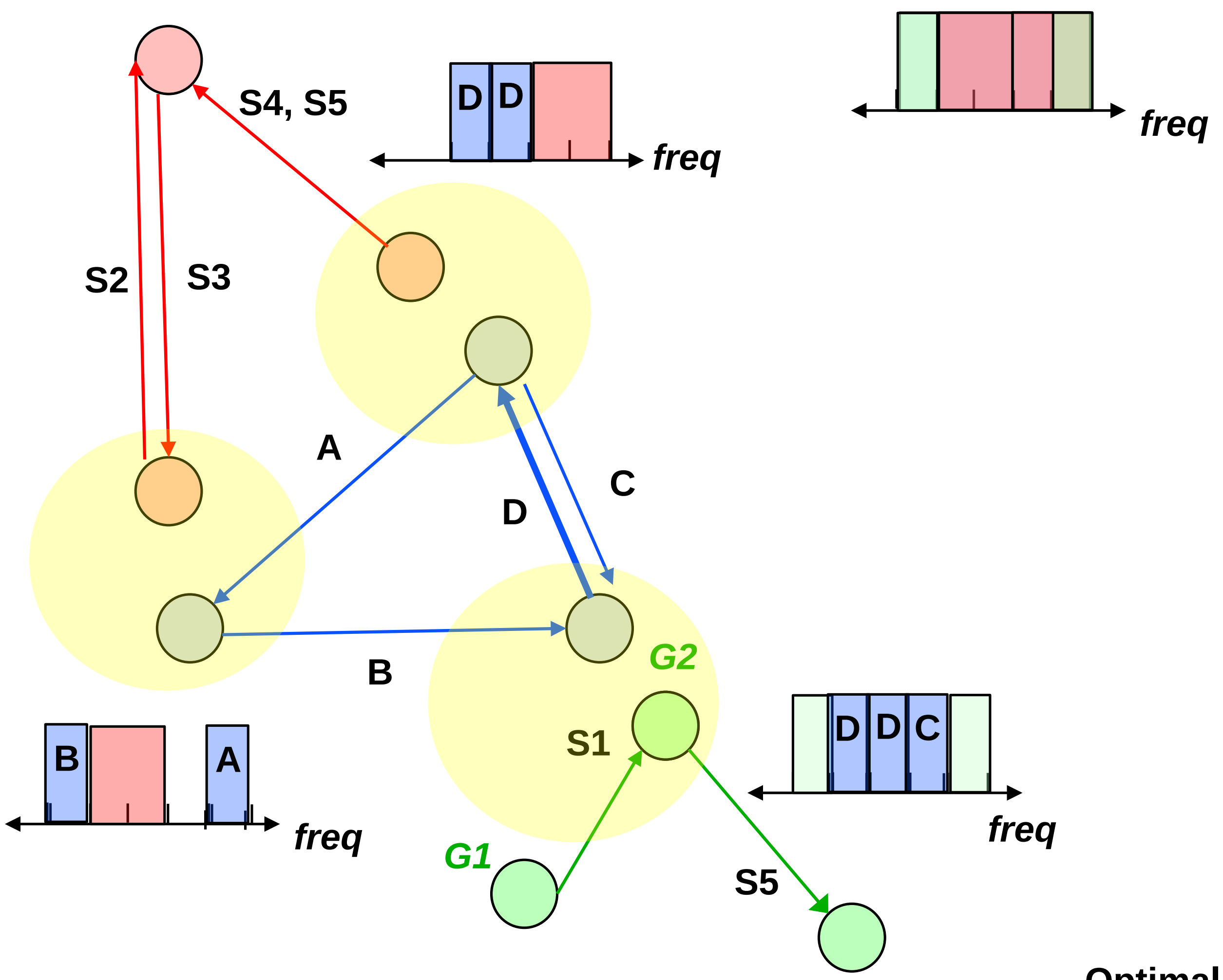


Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0	1.0	0	0	0
2	B	0	0	0.5	0	1.0
3	C	0	0	0	0	1.0
4	D	0.5	0	0	1.0	1.0
5	D	0.5	0	0	1.0	1.0

Total Cost = Own Cost + 0.5 * Collab Cost

Finally, Hungarian Assignment determines optimal assignment.

Lincoln Algorithm: Example

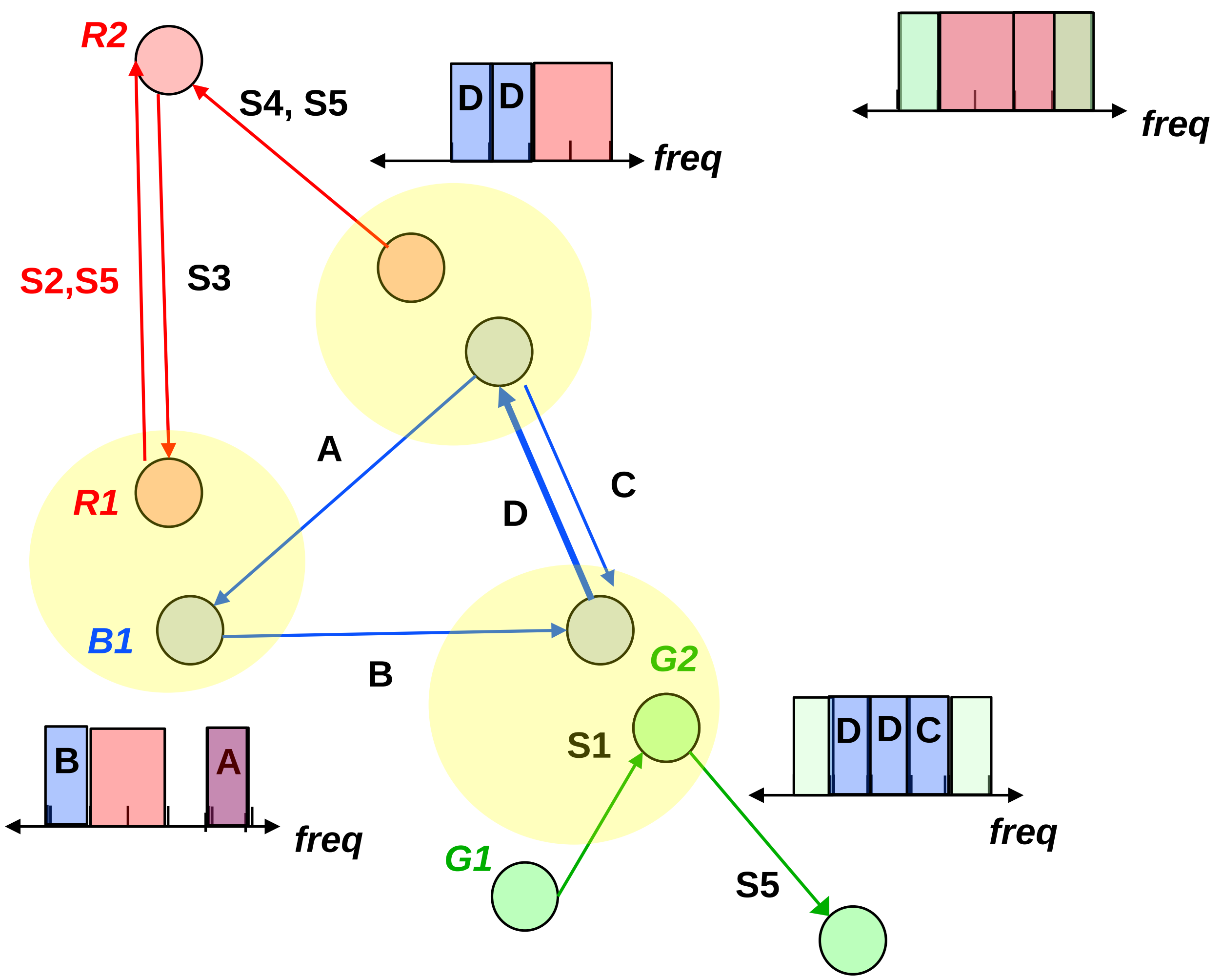


Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0	1.0	0	0	0
2	B	0	0	0.5	0	1.0
3	C	0	0	0	0	1.0
4	D	0.5	0	0	1.0	1.0
5	D	0.5	0	0	1.0	1.0

Total Cost = Own Cost + 0.5 * Collab Cost

Optimal frequency plan for Blue: B D D C A **(perfect deconfliction)**

A Harder Example



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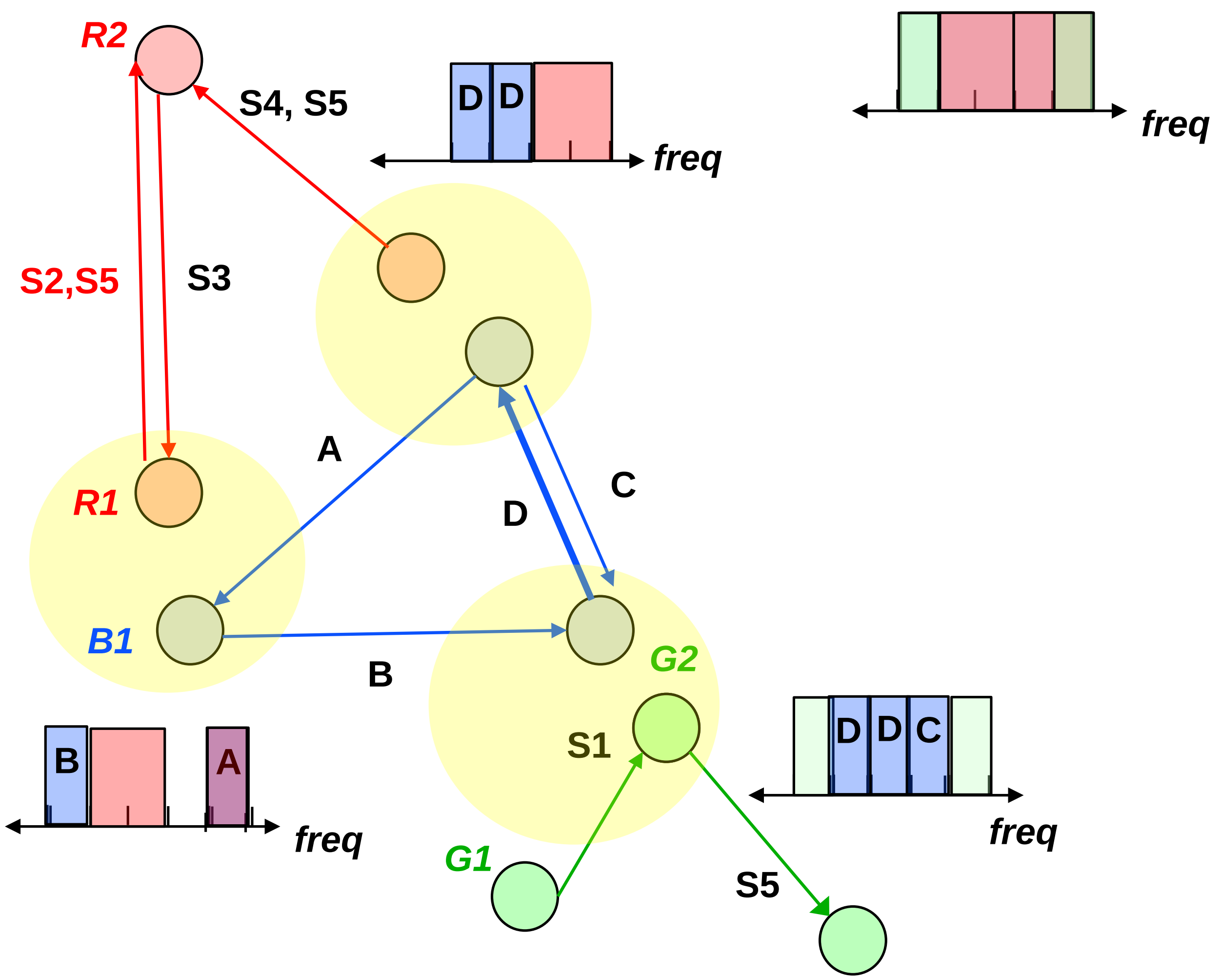
1	A	0	1.0	0	0	1.0
2	B	0	0	0.5	0	1.0
3	C	0	0	0	0	1.0
4	D	0.5	0	0	1.0	1.0
5	D	0.5	0	0	1.0	1.0

Interference present at all Blue nodes on Slot 5

A Harder Example



Token	Link	Frequency Slot #				
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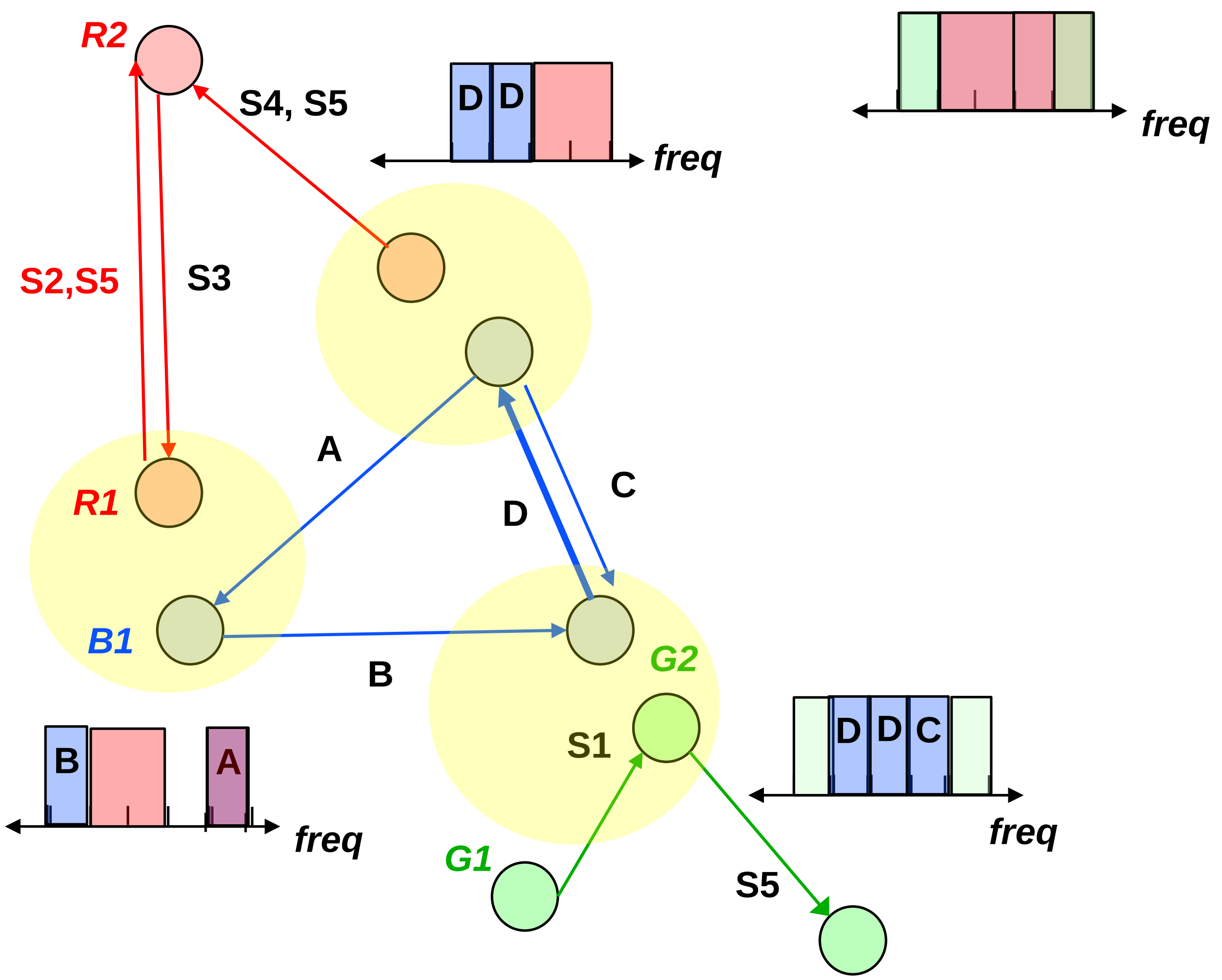
1	A	0	1.0	0	0	
2	B	0	0	0.5	0	
3	C	0	0	0	0	
4	D	0.5	0	0	1.0	
5	D	0.5	0	0	1.0	

Blue vacates Slot 5 since collaborative cost exceeds threshold on all links.

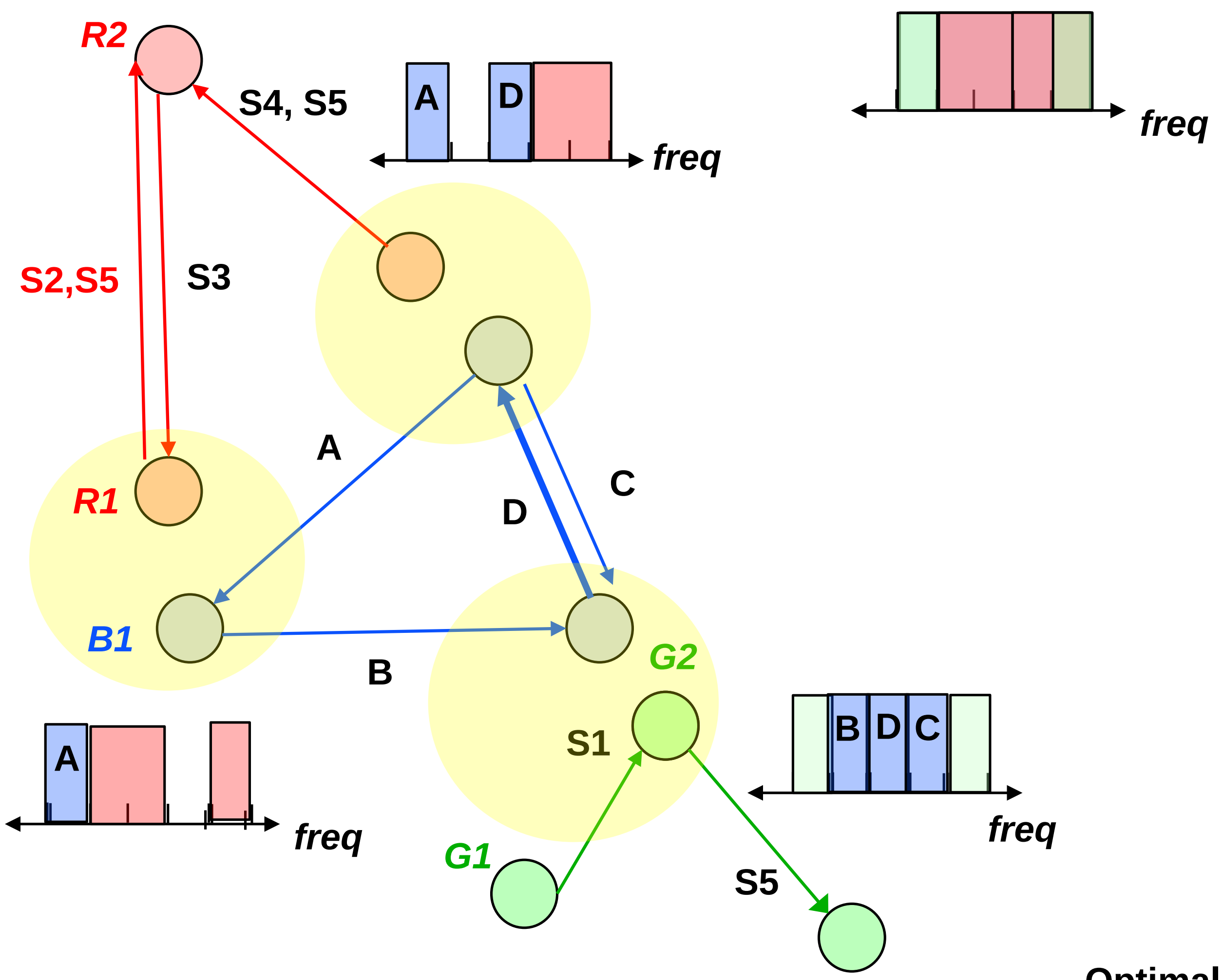
A Harder Example



Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0	1.0	0	0	
2	B	0	0	0.5	0	
3	C	0	0	0	0	
4	D	0.5	0	0	1.0	
~~5~~	~~D~~	~~0.5~~	~~0~~	~~0~~	~~1.0~~	

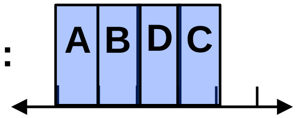
Link D loses one token, optimal assignment is re-computed.

A Harder Example



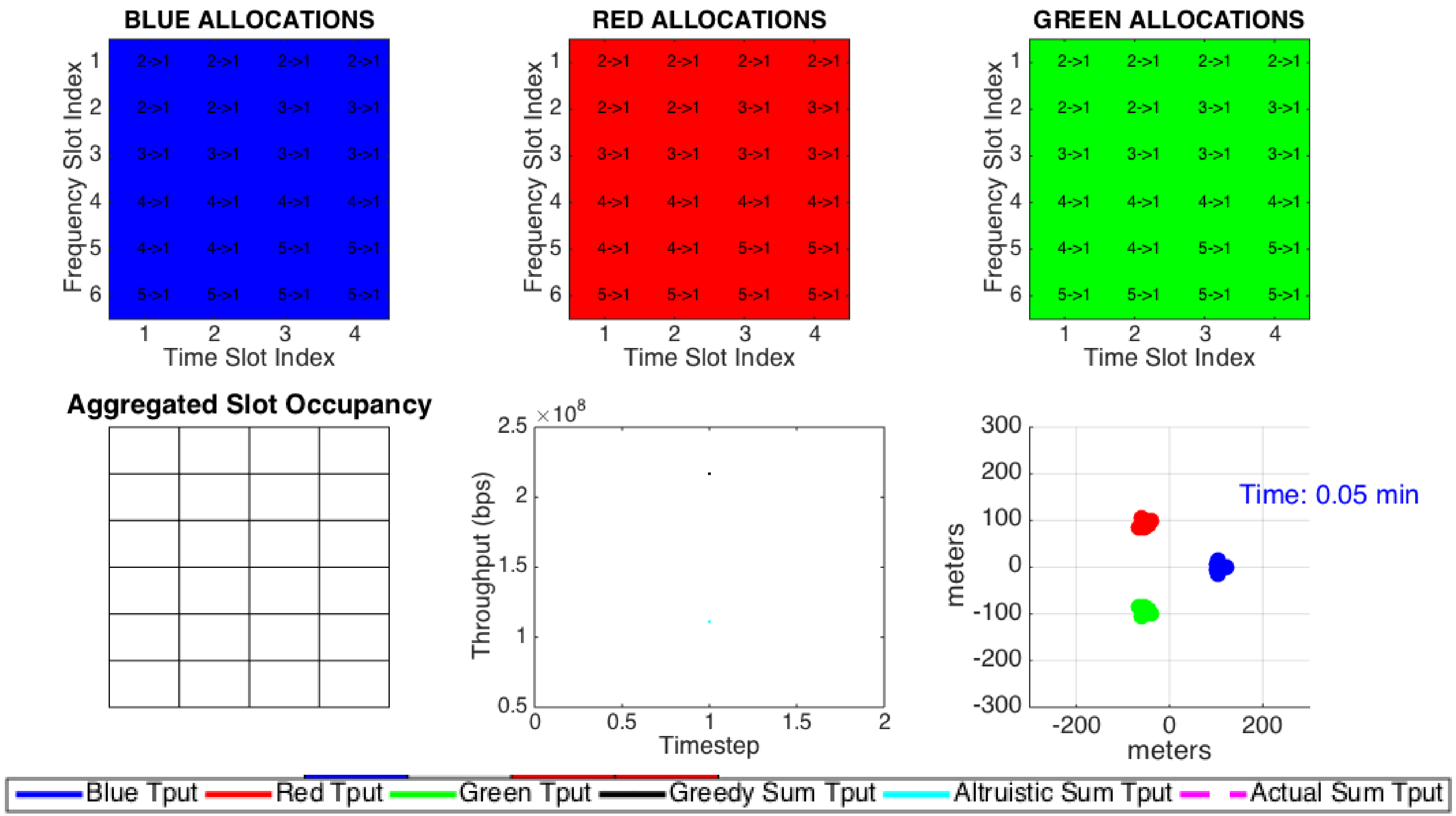
Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0	1.0	0	0	
2	B	0	0	0.5	0	
3	C	0	0	0	0	
4	D	0.5	0	0	1.0	
~~5~~	~~D~~	~~0.5~~	~~0~~	~~0~~	~~1.0~~	

Optimal frequency plan for Blue:

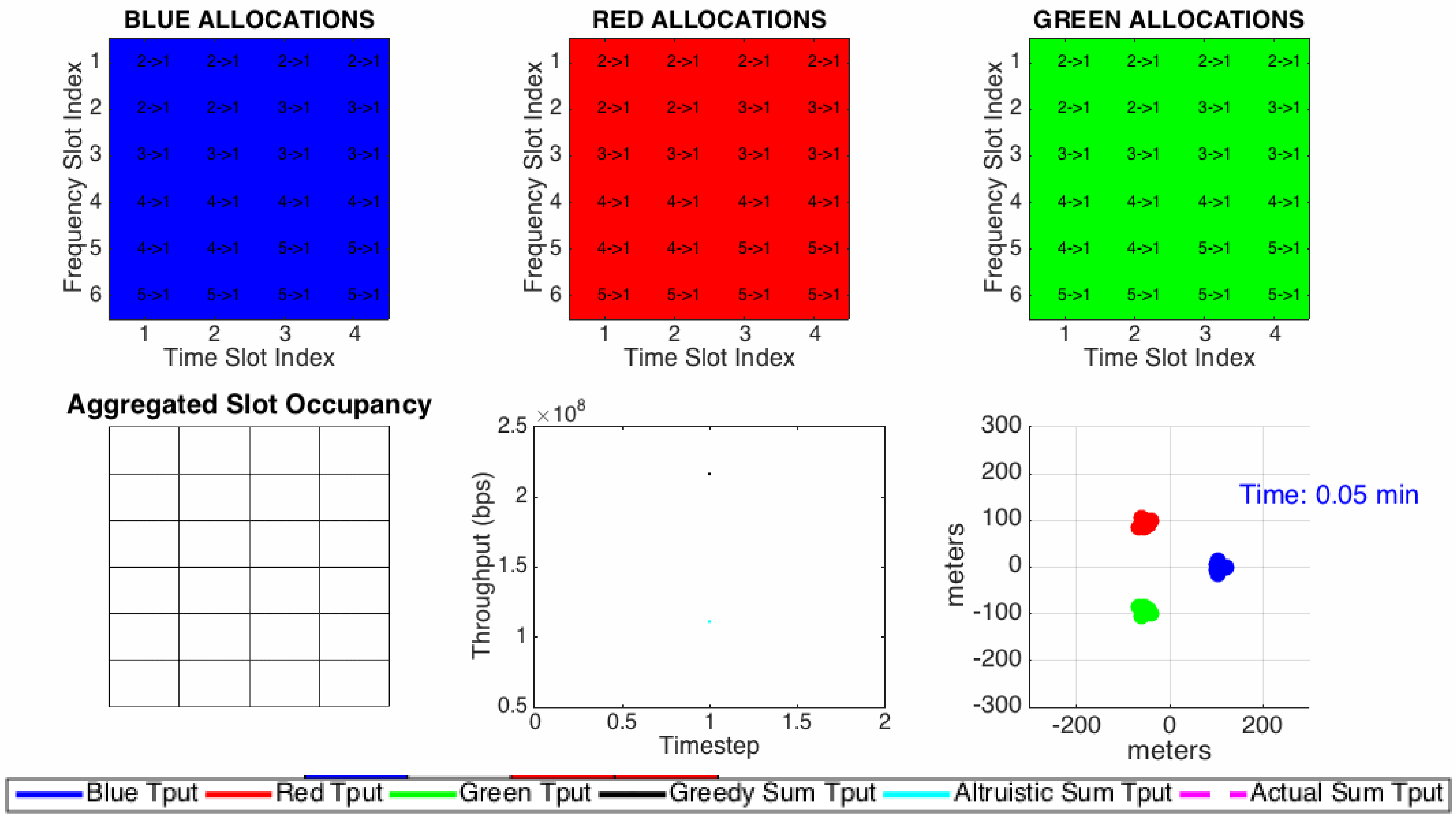


(perfect deconfliction)

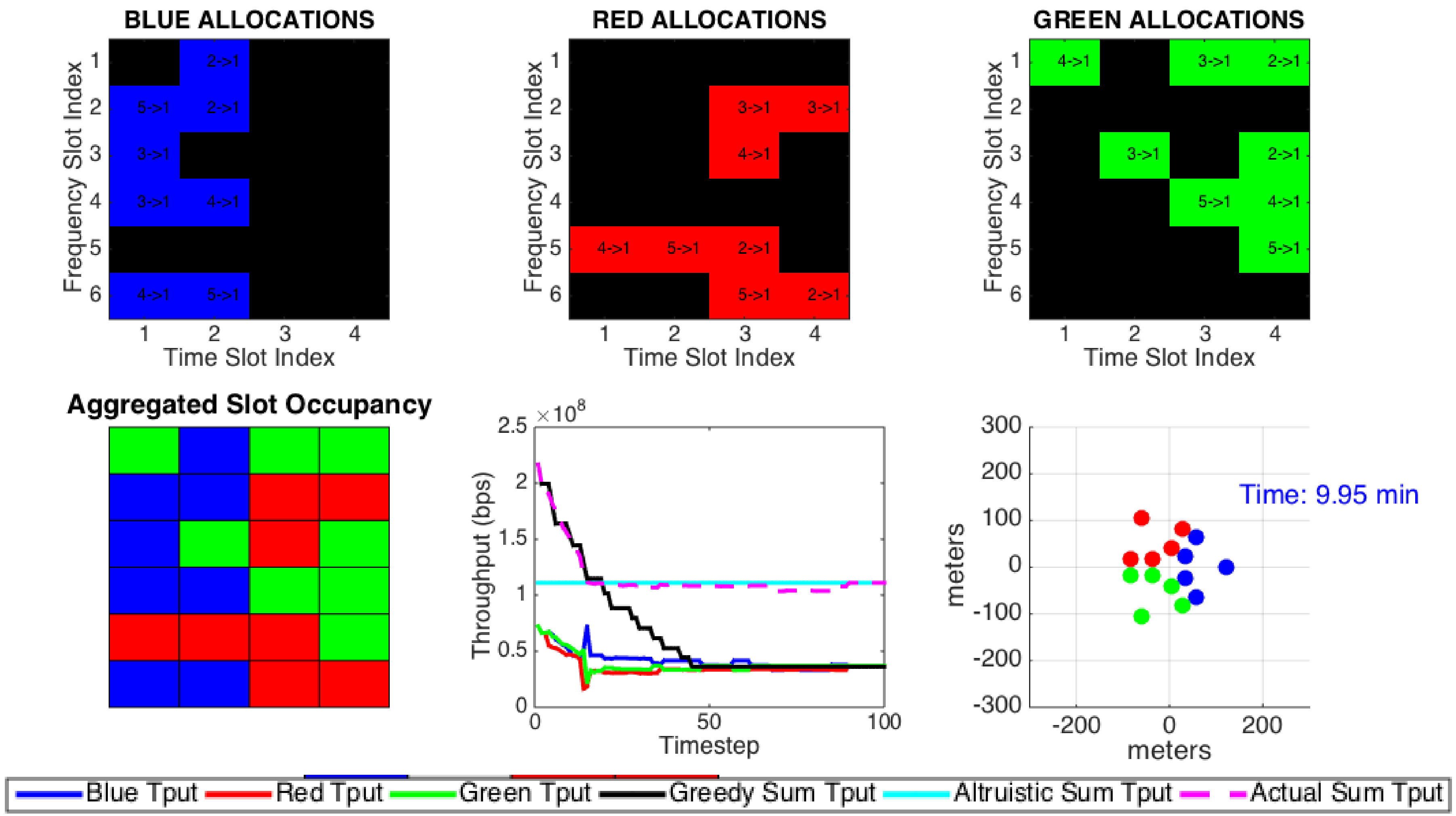
Simulated Algorithm Performance (N-Towers)



Simulated Algorithm Performance (N-Towers)



Simulated Algorithm Performance (N-Towers)



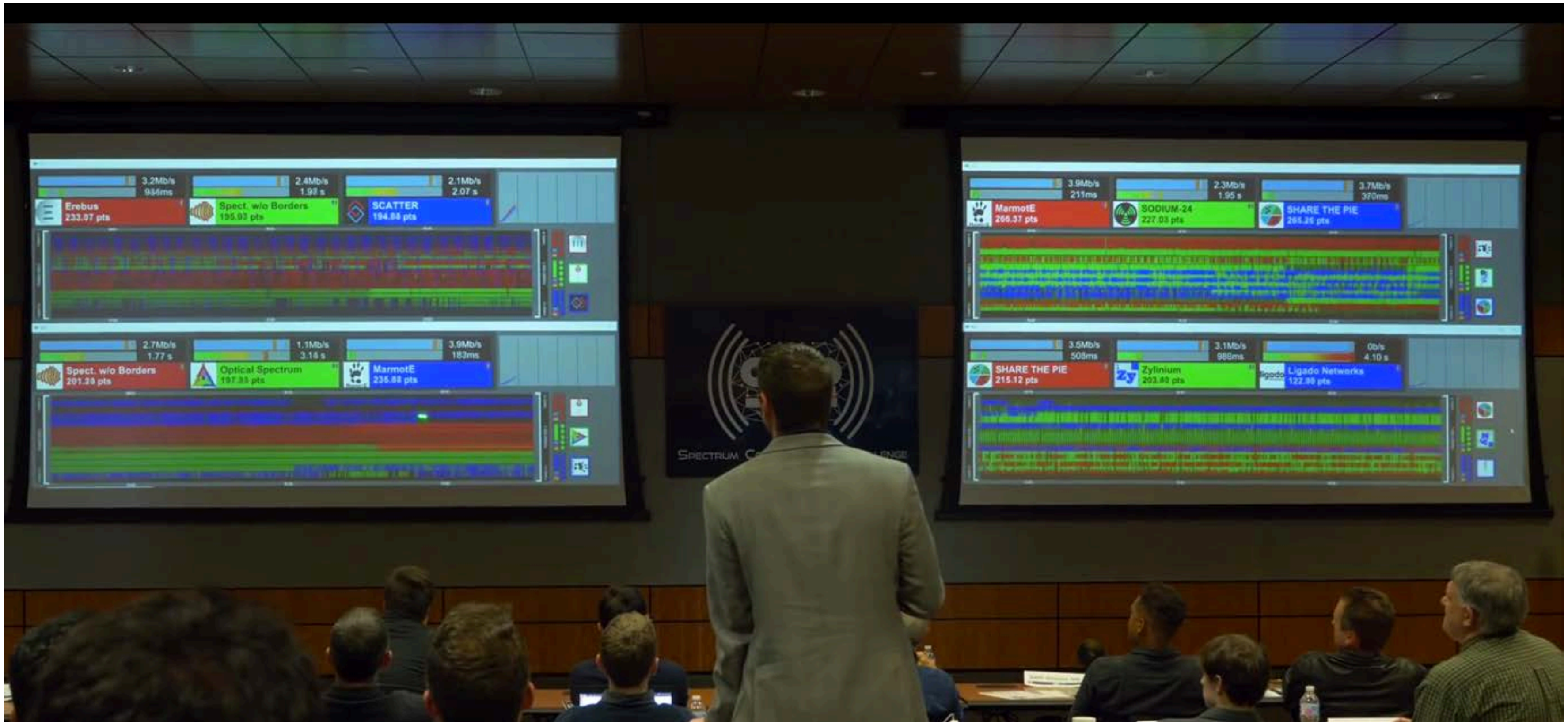
Outline

- **MIT LL Scenario Development for SC2**
  - **Motivating Questions**
  - **Implementation Tools and Challenges**

- **MIT LL Training Bot Development**
  - **Cognitive Algorithm Development**
  - **Simulation Results**

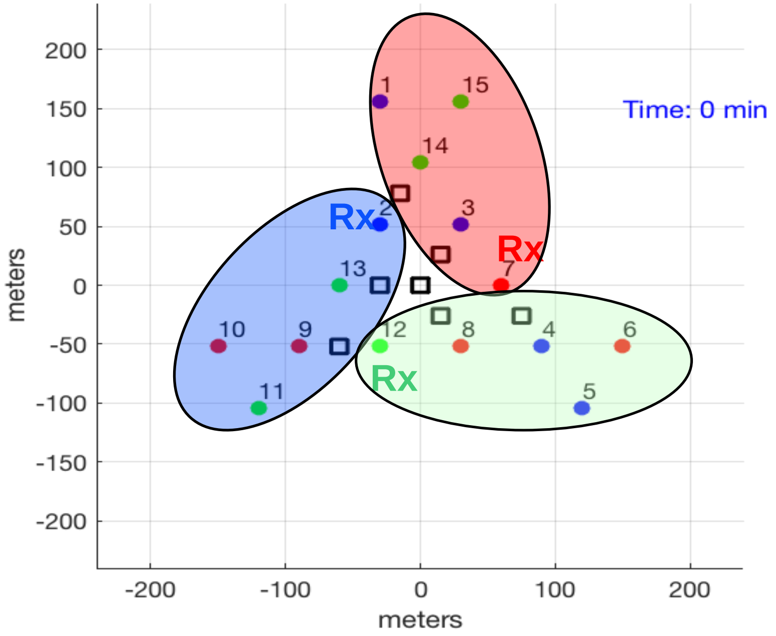
- **Phase 1 Competition in Review**

Preliminary Event 1

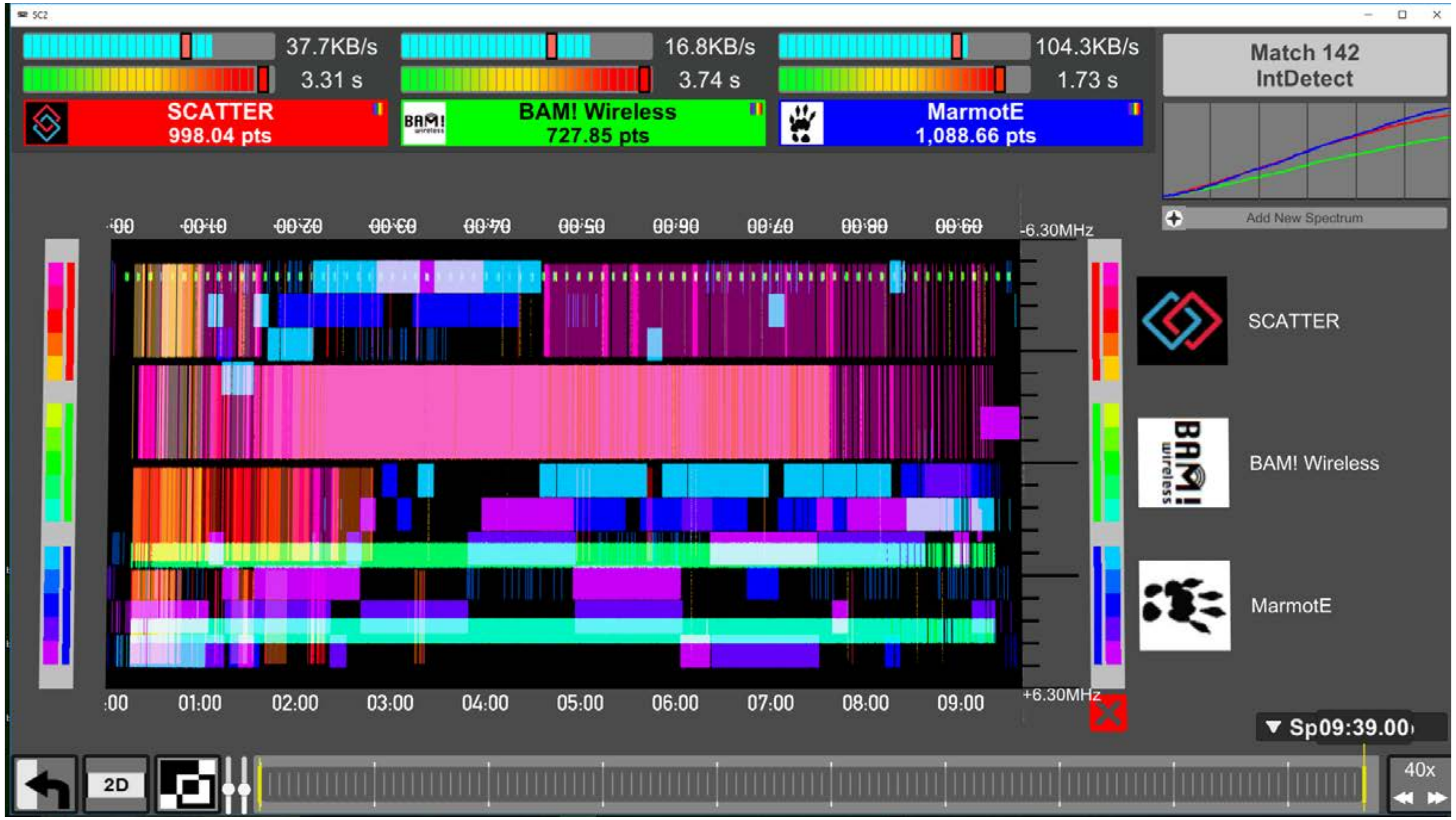


- All matches run in early December
- Results reveal: December 13th 2017, at JHU/APL (Laurel, MD)
- 26 Teams submitted SDR images (19 qualified to compete)

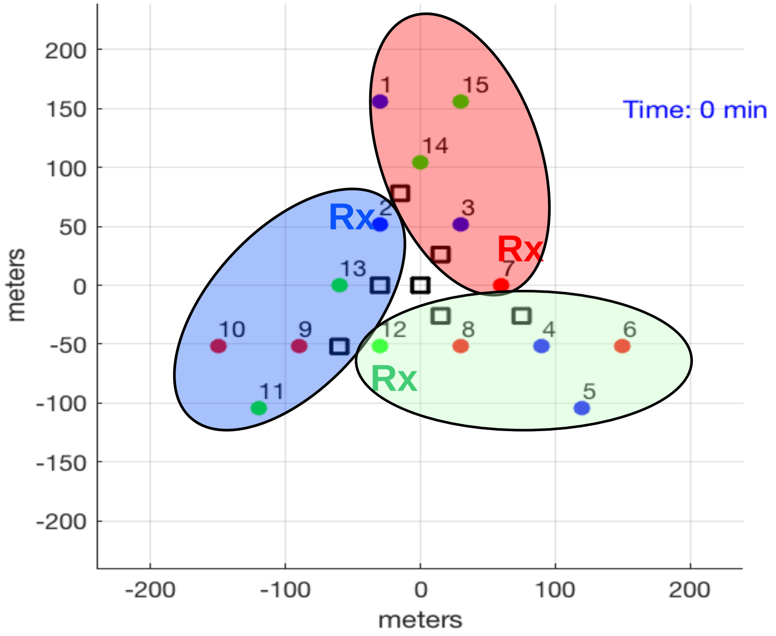
Interference Detective (Match 1)



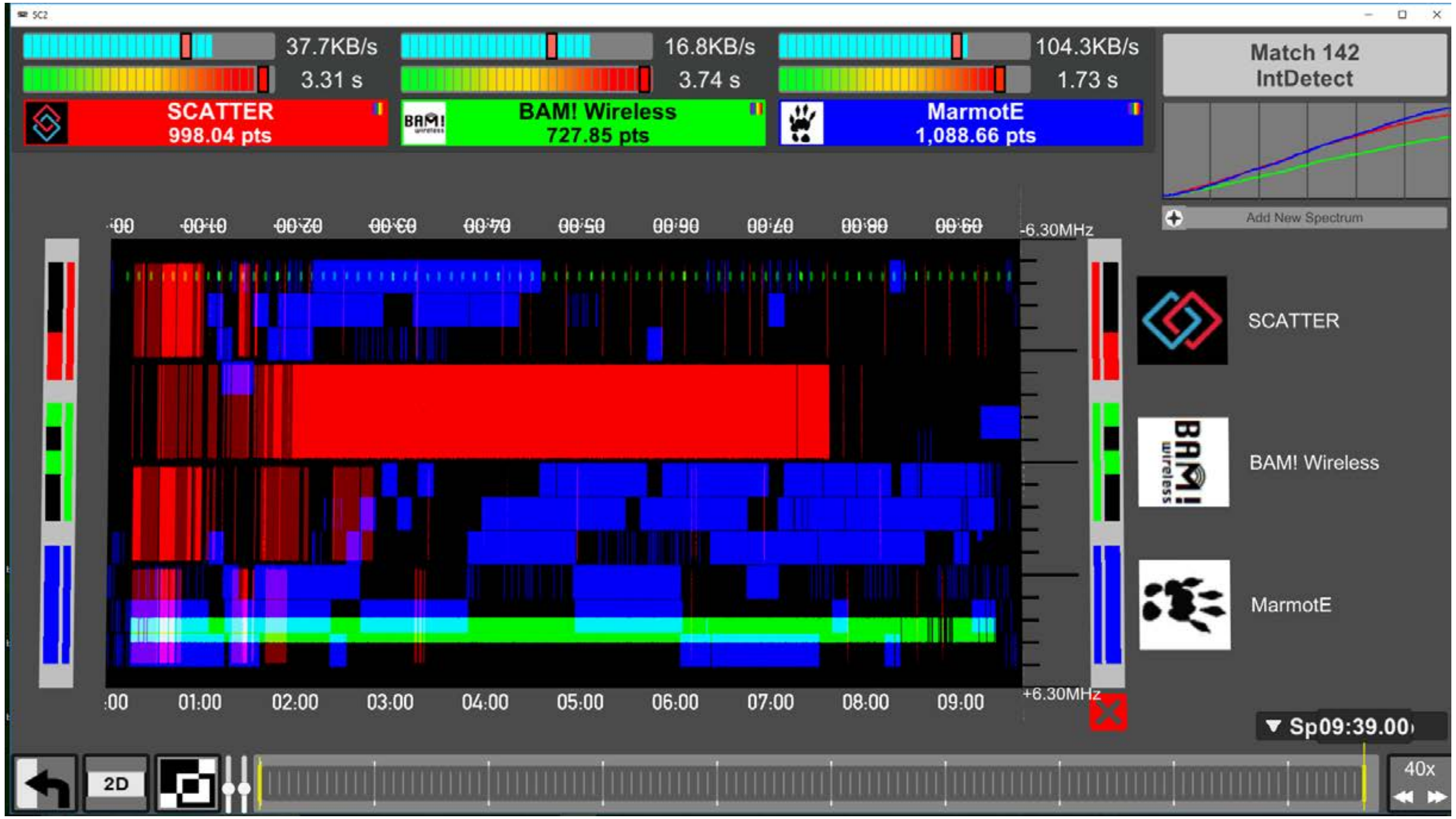
Composite Spectrum Overlay



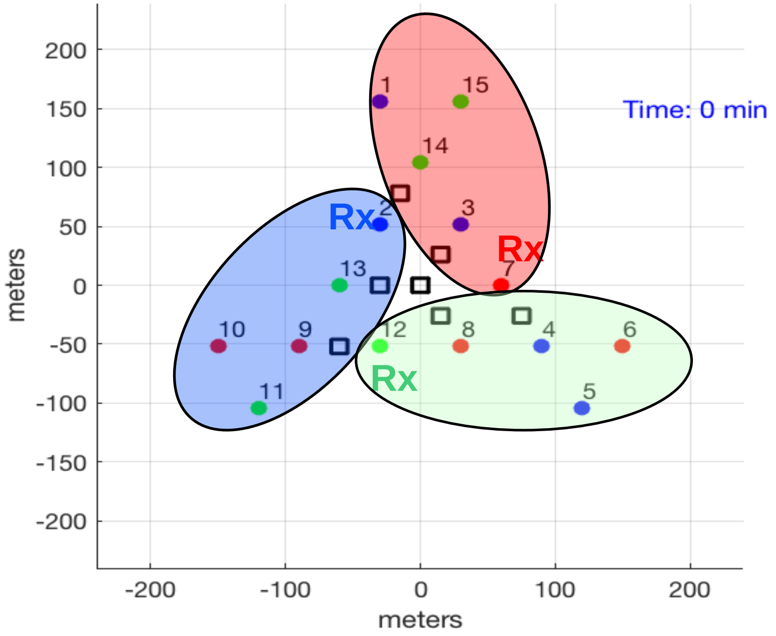
Interference Detective (Match 1)



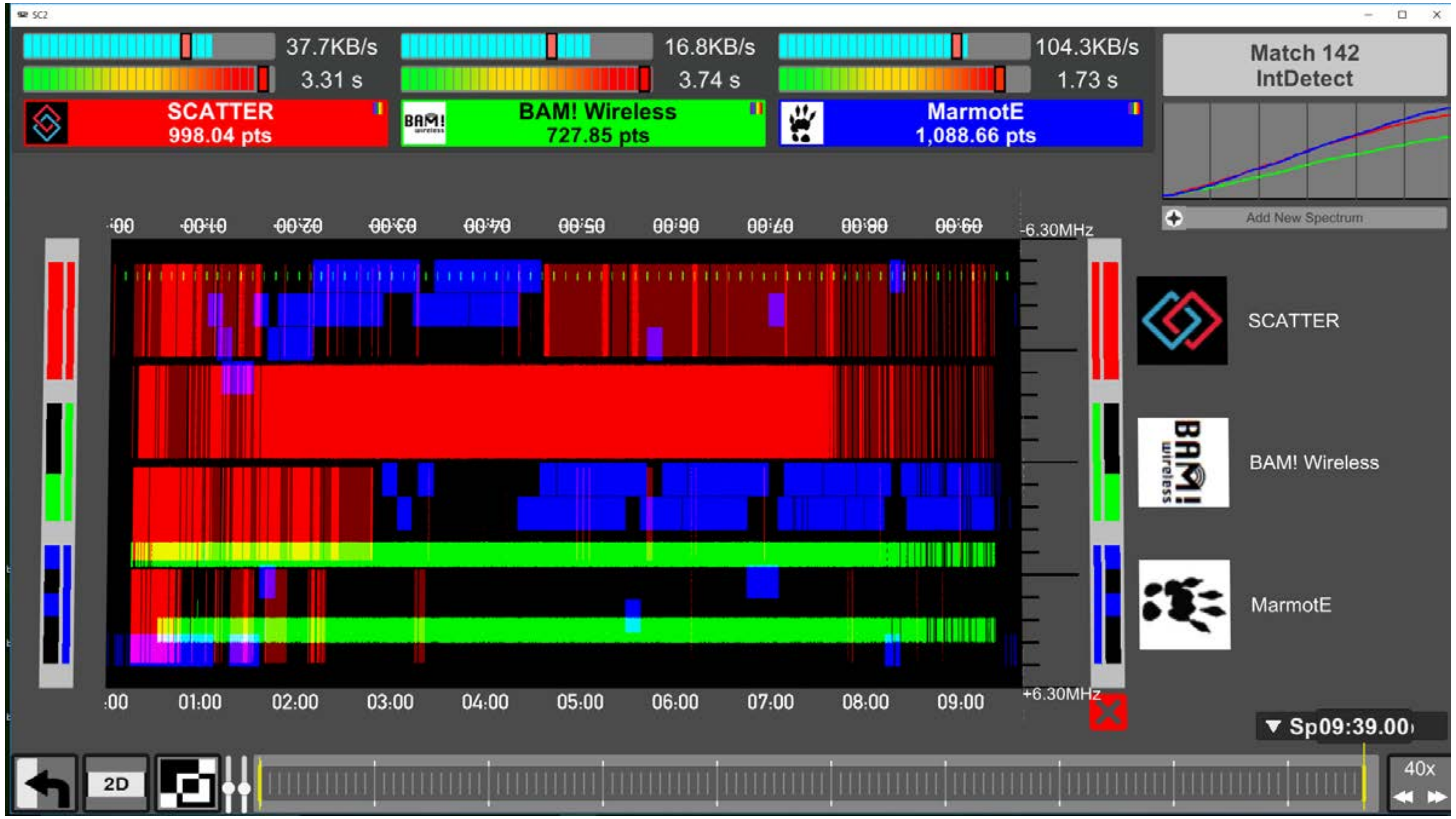
Blue Zone



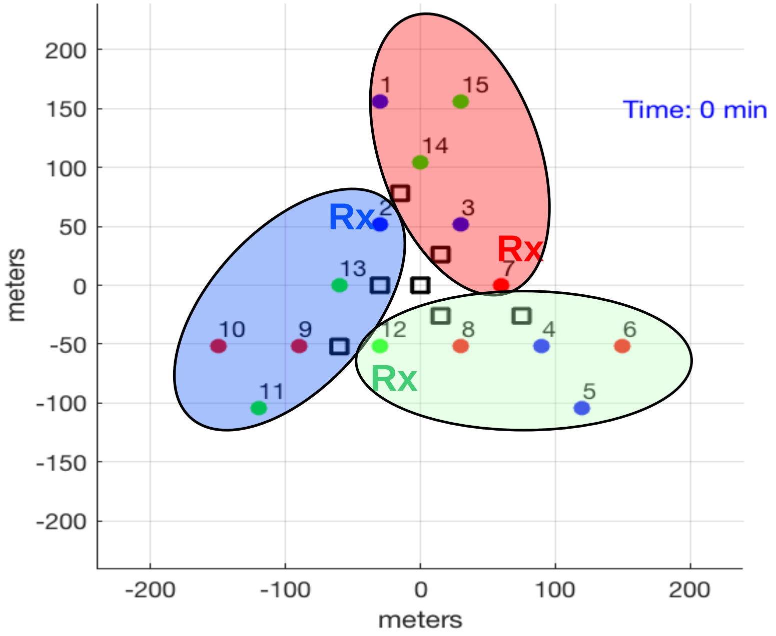
Interference Detective (Match 1)



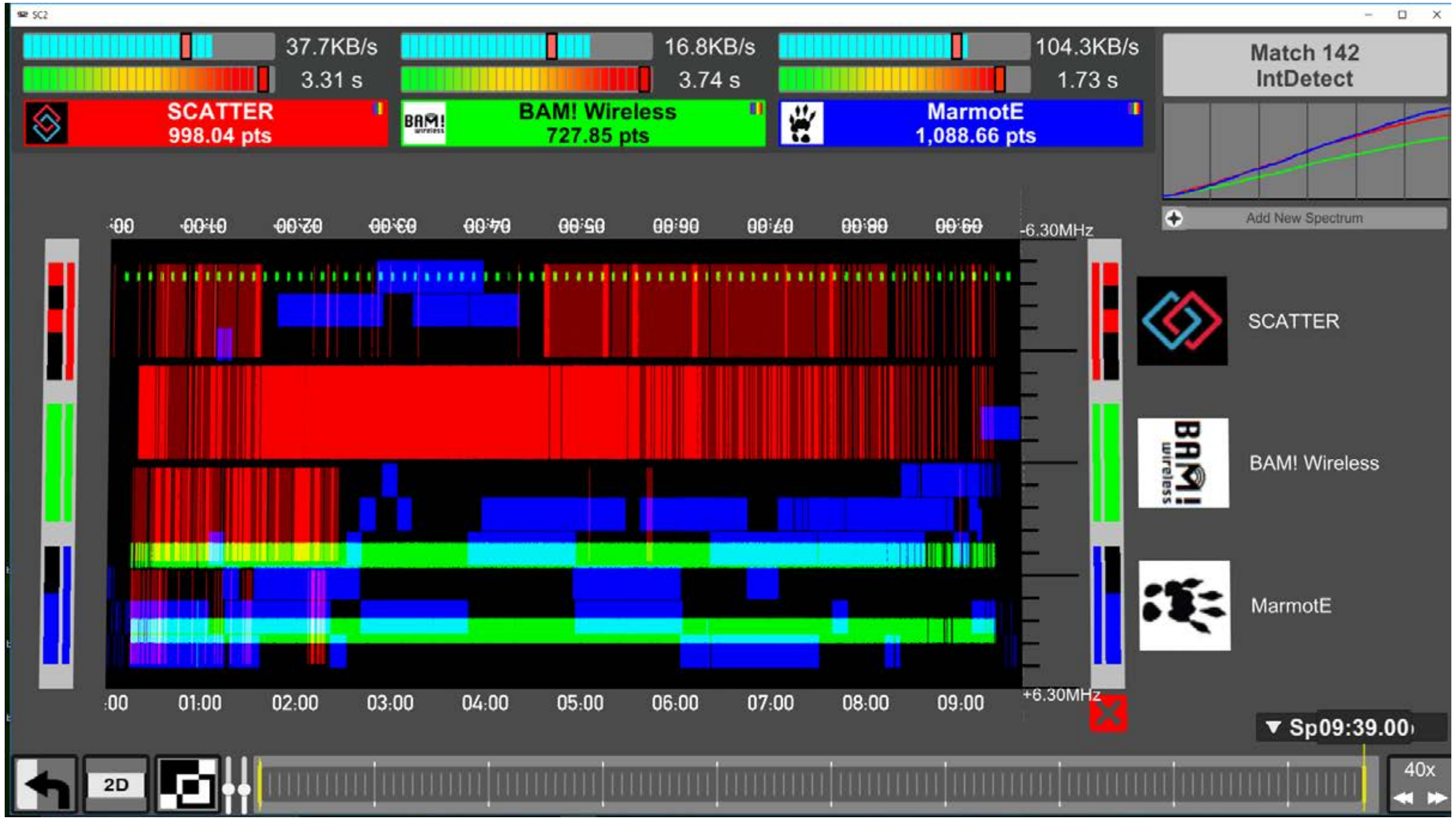
Red Zone



Interference Detective (Match 1)

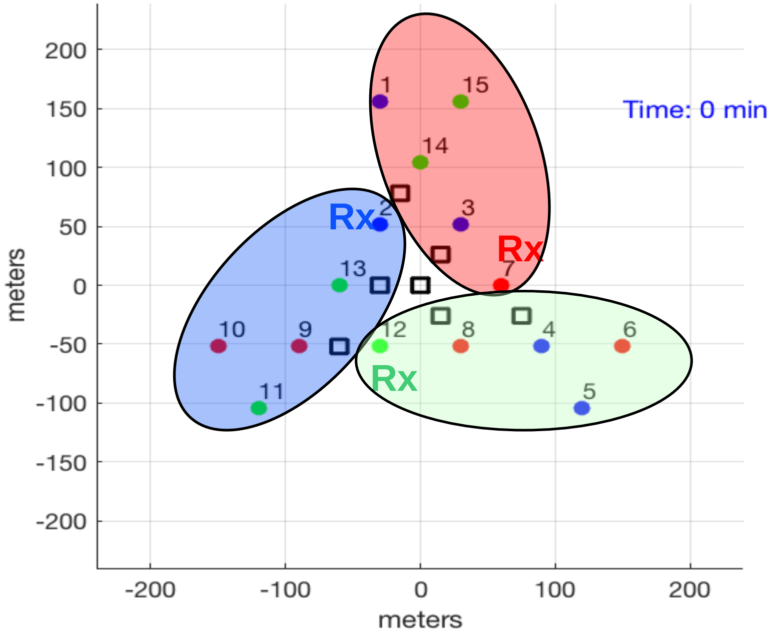


Green Zone

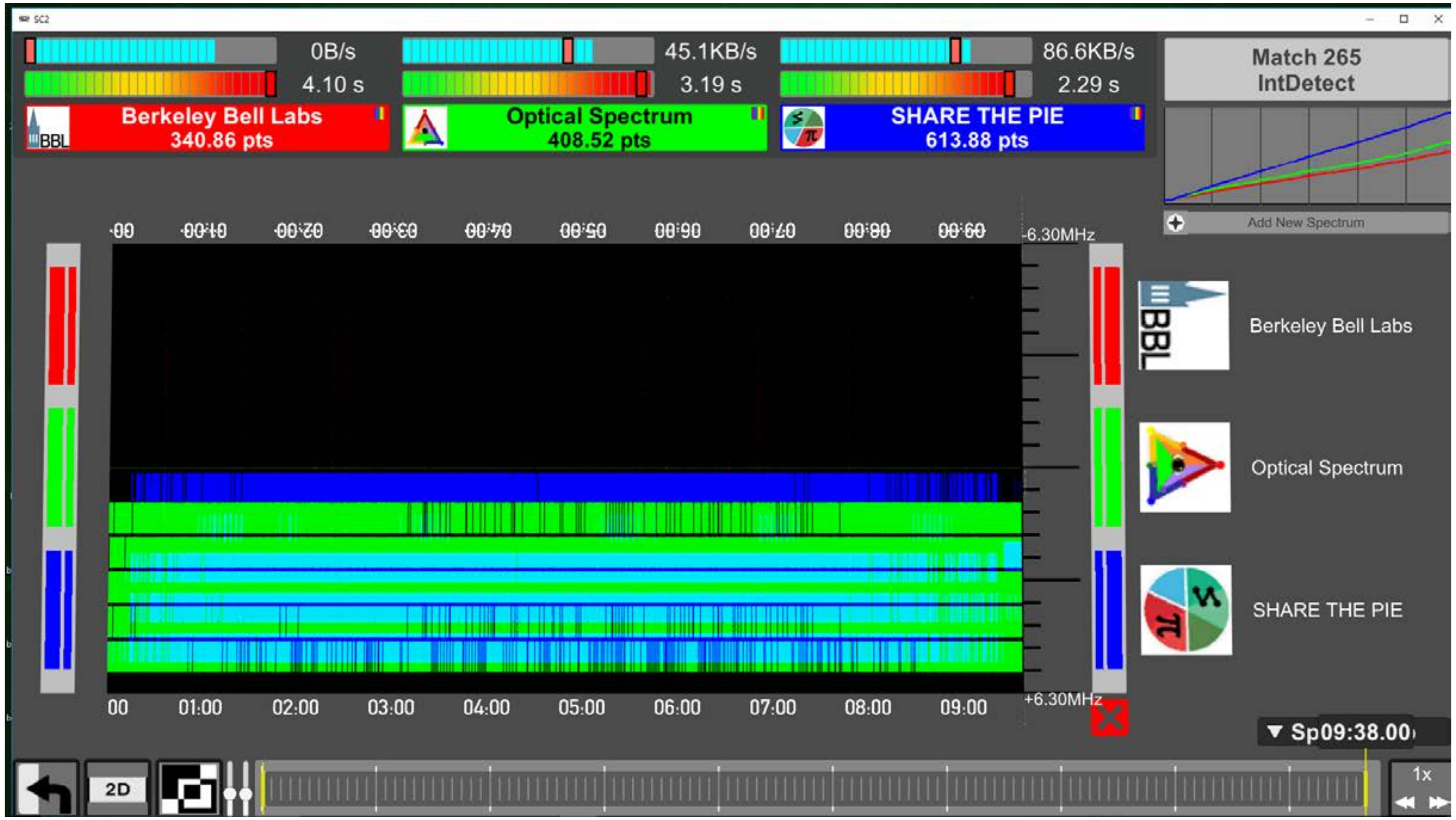


Some matches exhibited effective spatial re-use of the spectrum.

Interference Detective (Match 2)

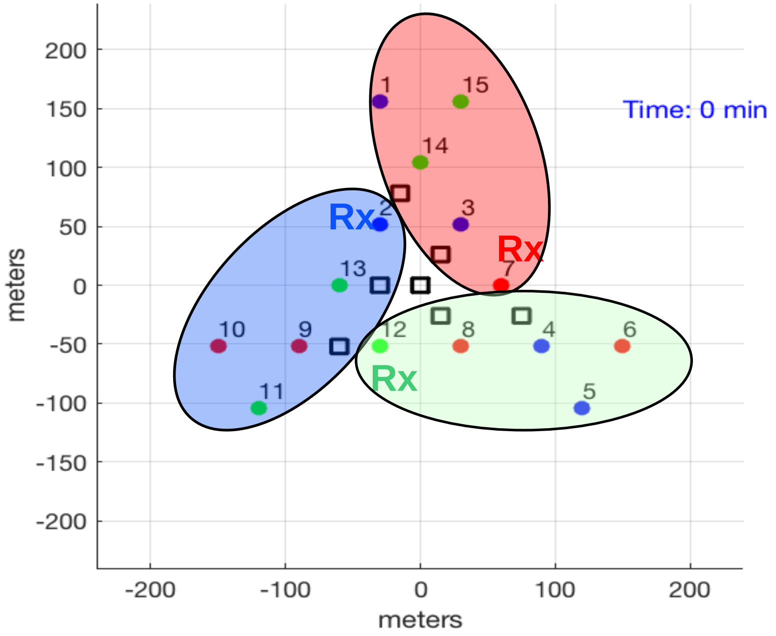


Composite Spectrum Overlay

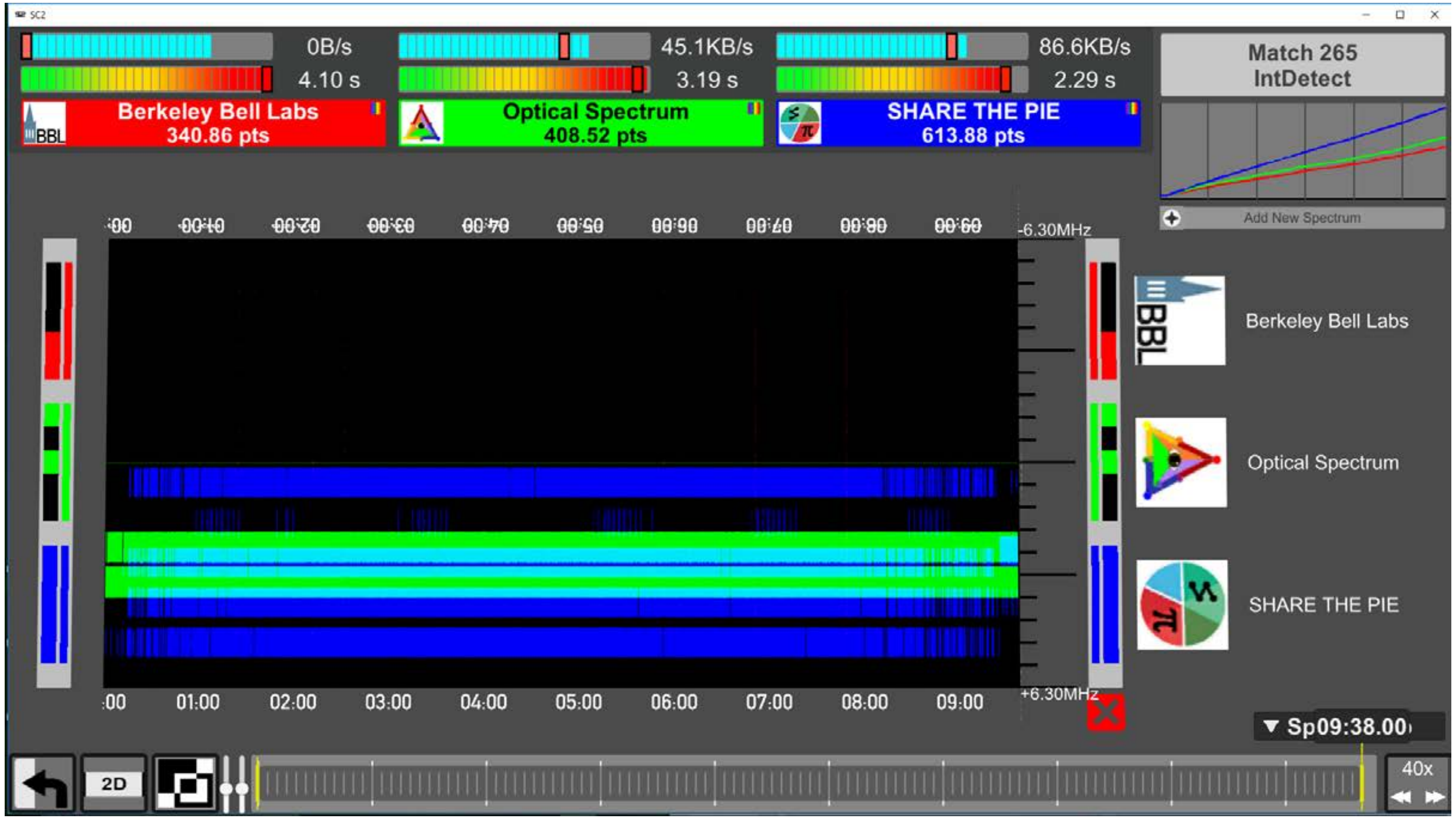


Some matches showed room for improvement in inter-network coordination.

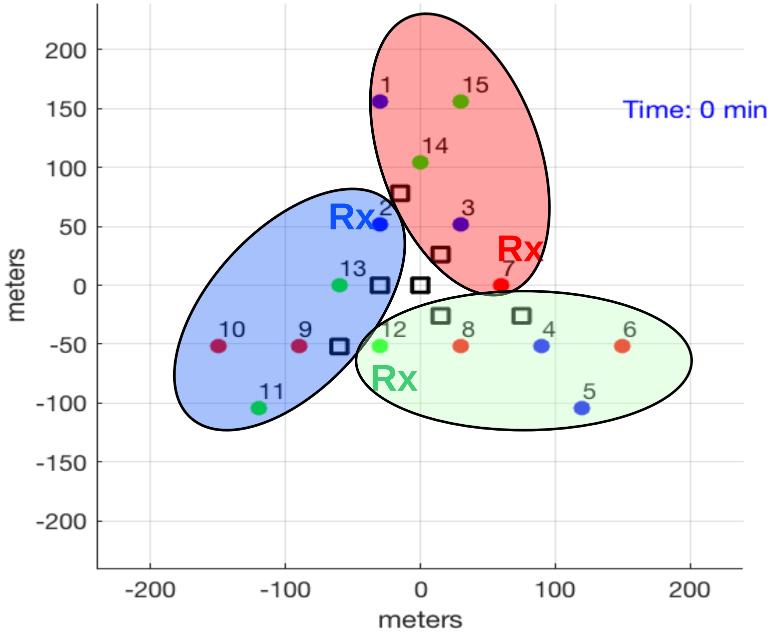
Interference Detective (Match 2)



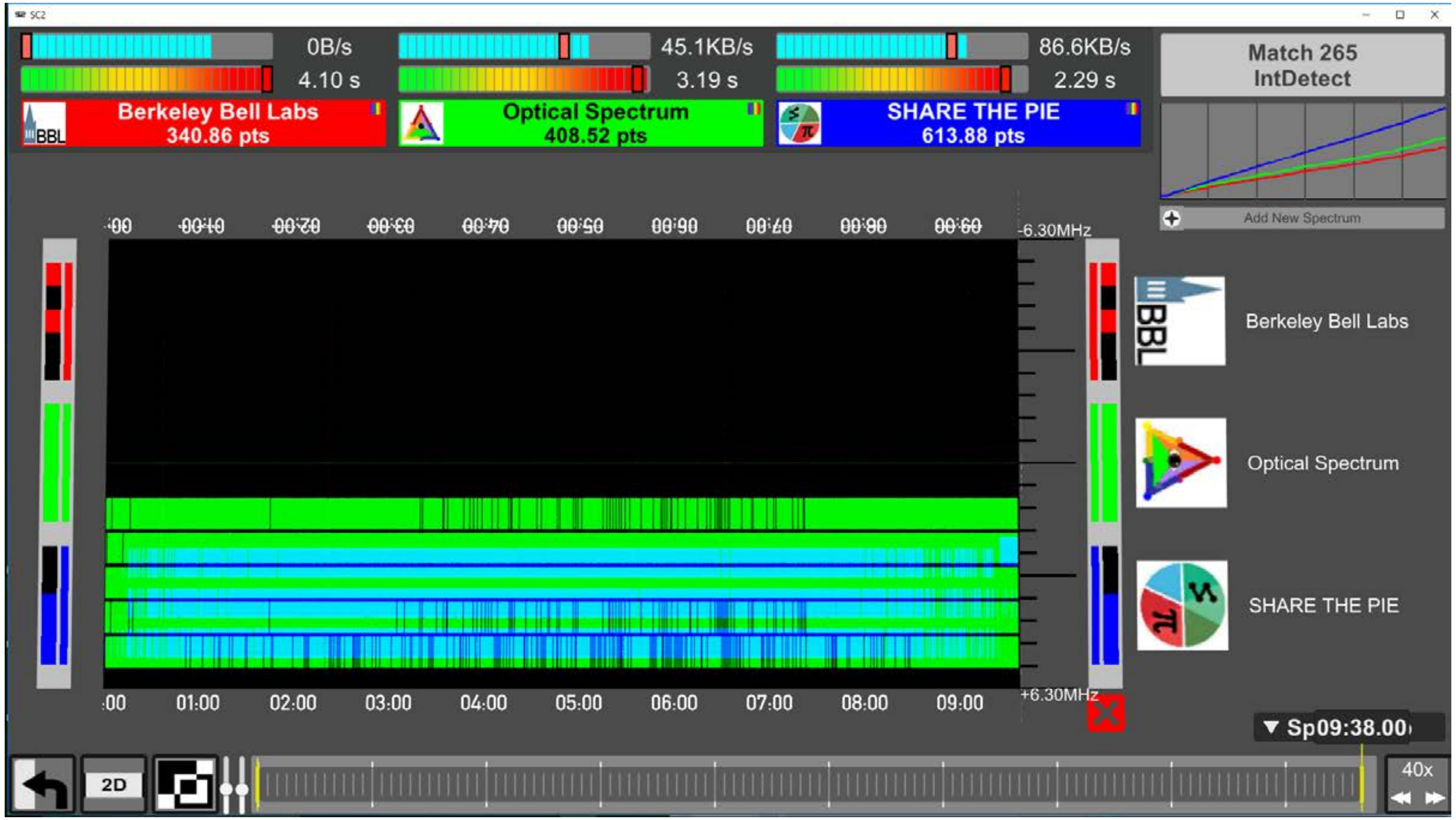
Blue Zone



Interference Detective (Match 2)

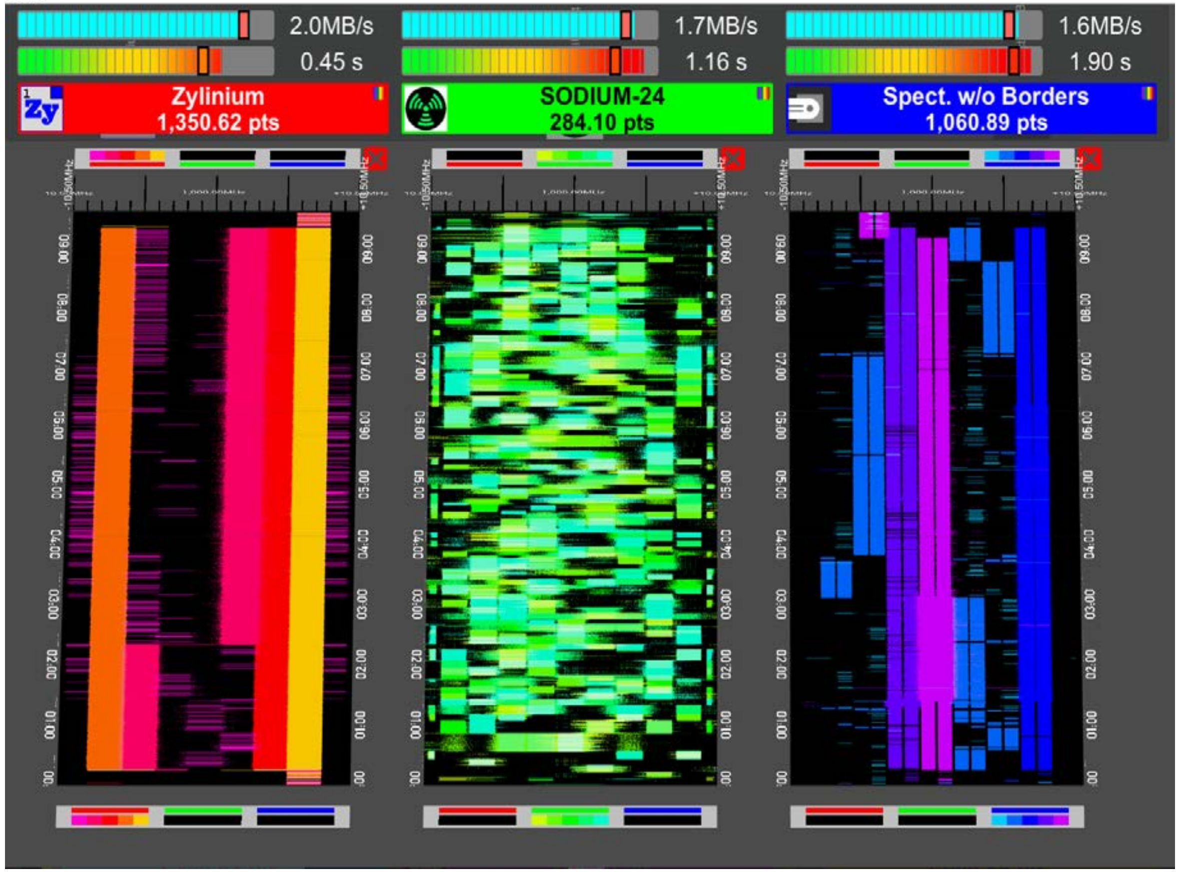


Green Zone

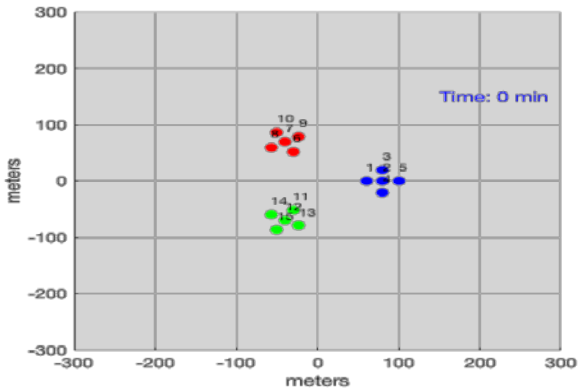


N-Corners

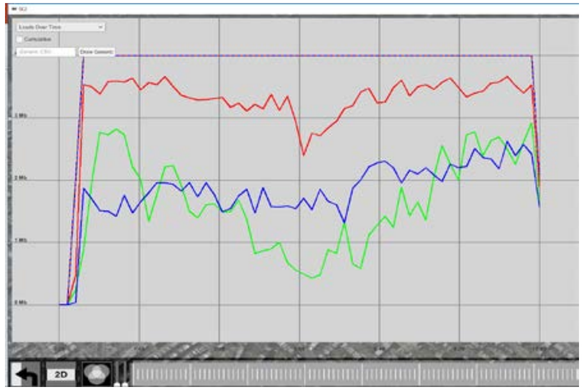
Spectrum Access Waterfall



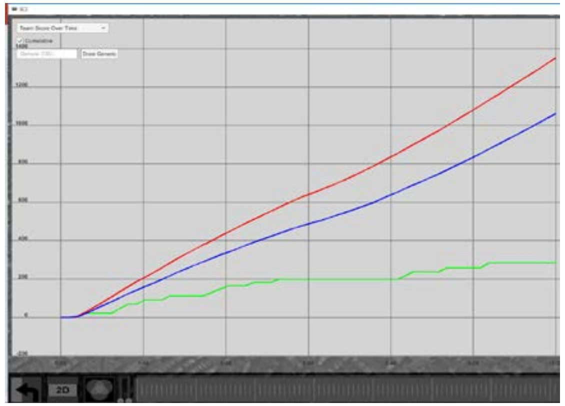
Scenario Map



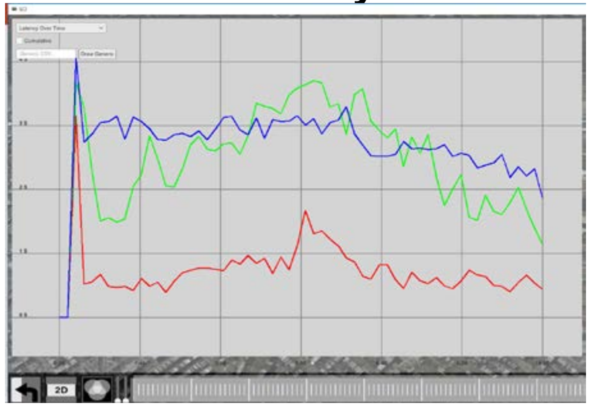
Throughput



Score



Latency



Two teams de-conflict to mitigate increasing mutual interference; the other suffers interference from both

Competition Final Leaderboard

Ranking	Team Name	Affiliation
1	MarmotE	Vanderbilt University
2	SHARE THE PIE	BAE Systems
3	Zylinium	Maryland-based startup
4	Erebus	Independent (3 engineers)
5	SCATTER	IDLab, Rutgers University
6	GatorWings	University of Florida
7	Sprite	Northeastern University
8	Strawberry Jammer	Northrup Grumman
9	Optical Spectrum	Independent (2 LIDAR engineers)
10	BAM! Wireless	Purdue University, Texas A&M University

Awarding of the PE1 Prizes

Summary*

- DARPA completed Year 1 of Spectrum Collaboration Challenge
- MITLL provided critical support in developing Challenge scenarios and providing Training Bots
- Developed capabilities will be used to enhance our group's spectrum operations capabilities on other programs
- Going forward: We will continue researching cognitive radio techniques

Acknowledgements

- **Bags Bhagyavati** *Group 51*
- **Devin Kelly** *Group 65*
- **John Mann** *Group 62*
- **Adam Margetts** *Group 62*
- **Kyle Morrison** *Group 51*
- **Jonathon Pendlum** *Group 62*
- **June Popielarz** *Group 62*
- **Michael Wentz** *Group 62*
- **Navid Yazdani** *Group 62*