DARPA SC2
Spectrum Collaboration Challenge

Division 6 Seminar

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LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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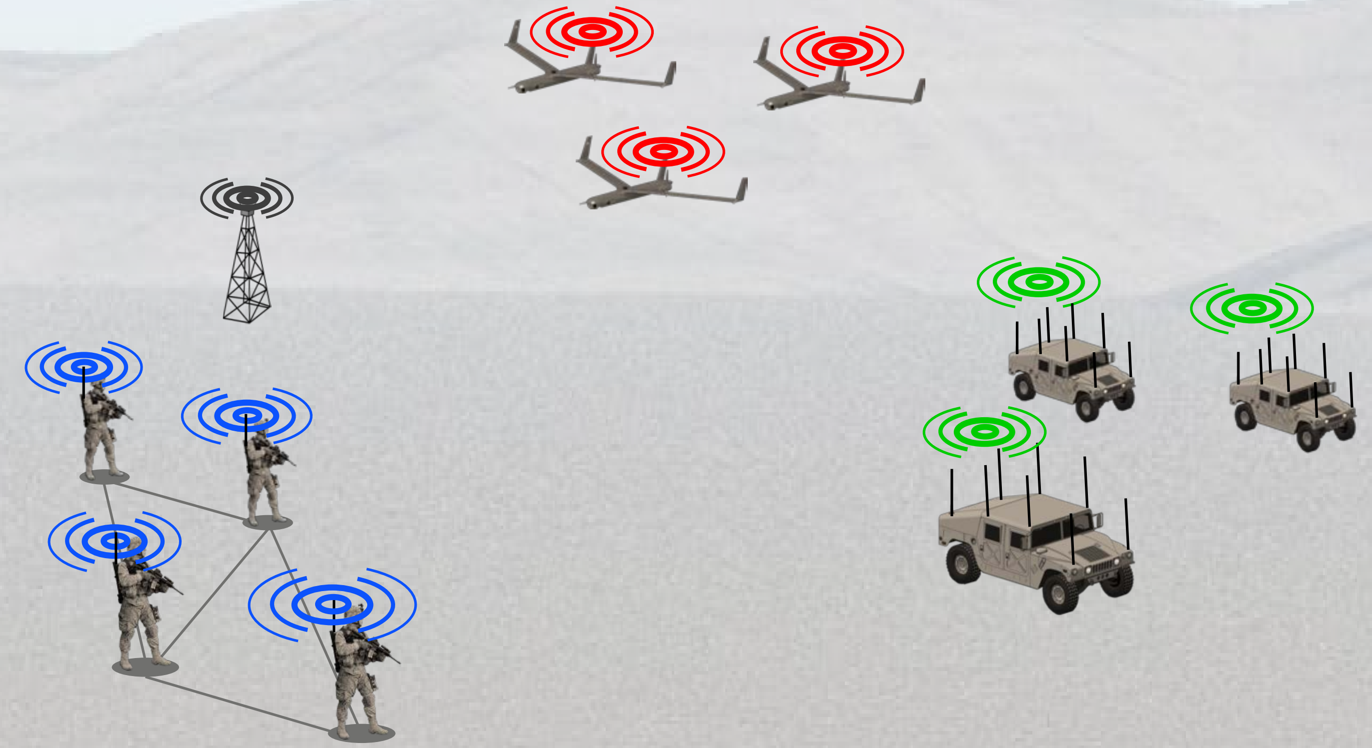
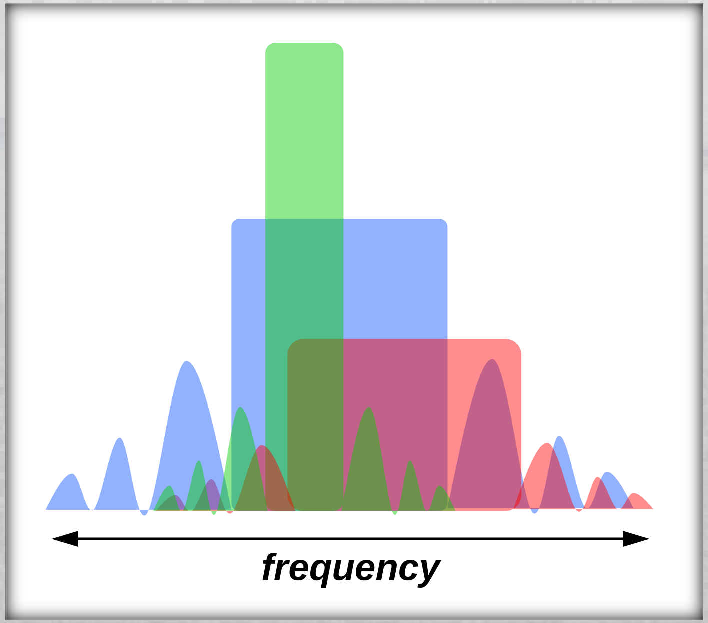
Motivating Example

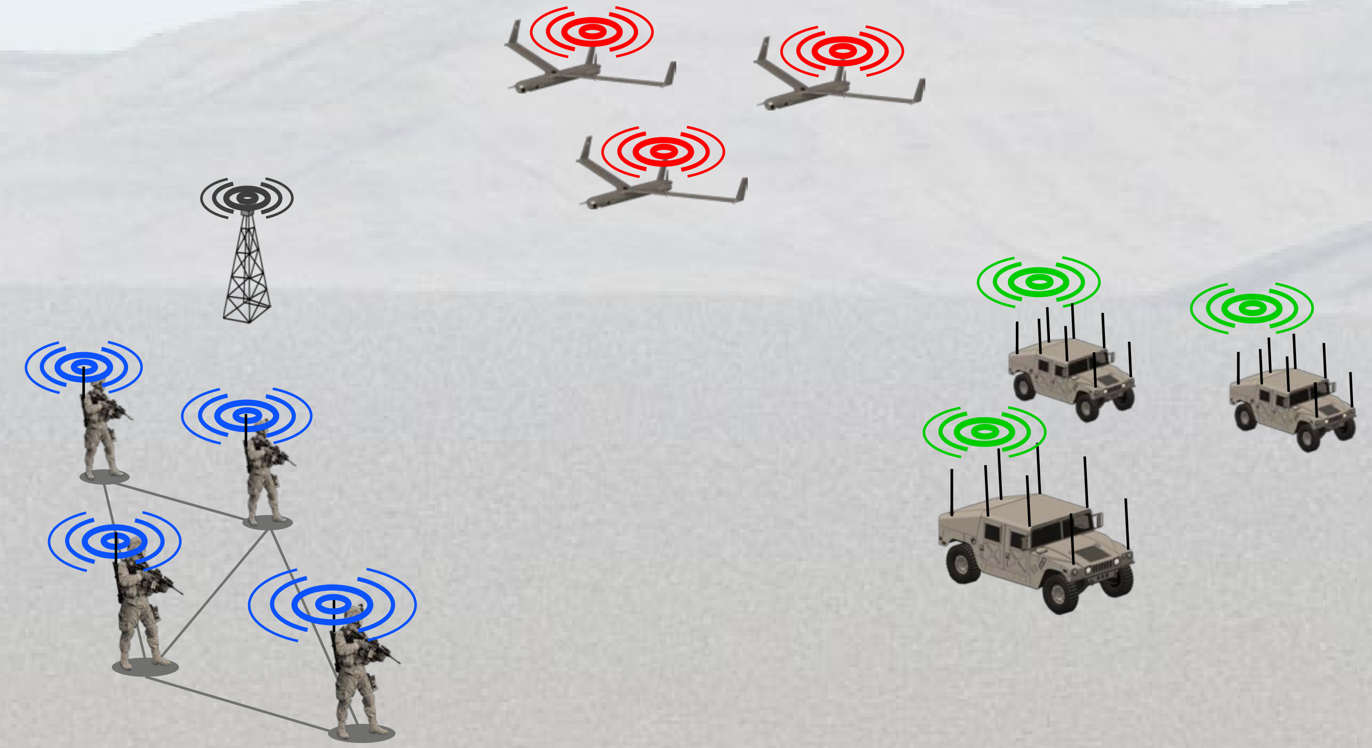


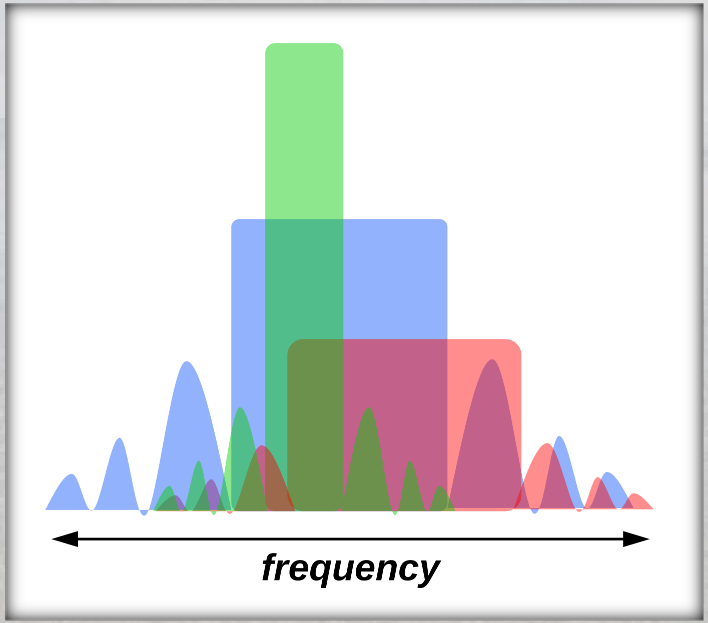


Motivating Scenario:

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

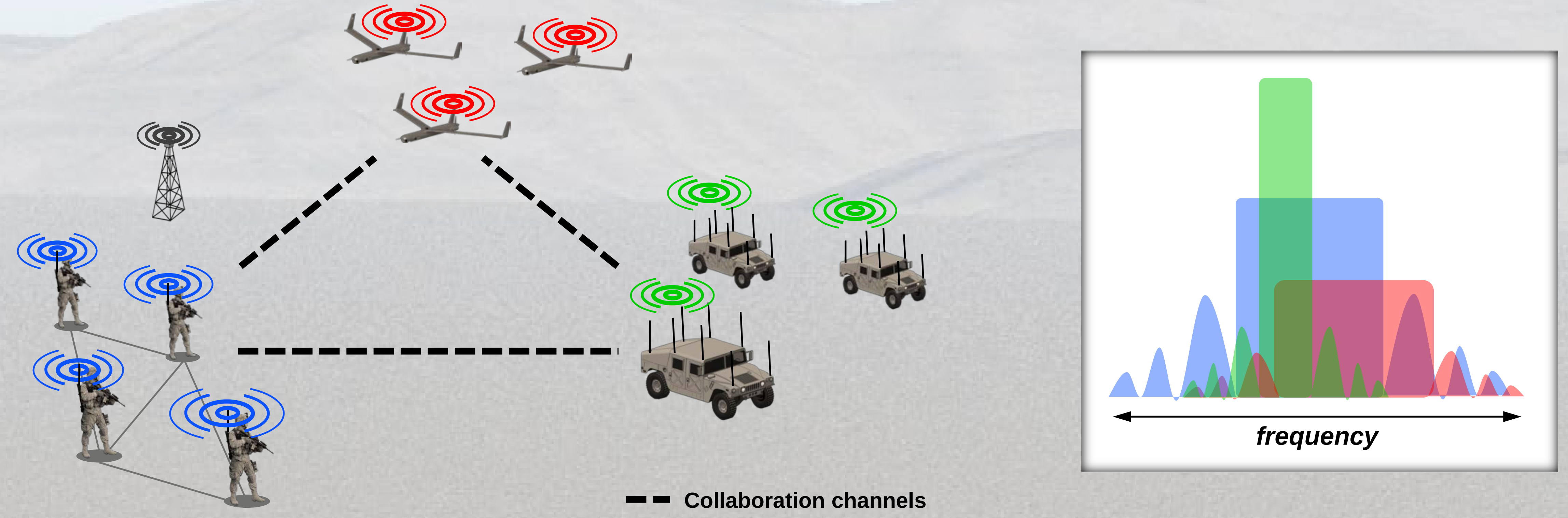
Motivating Example





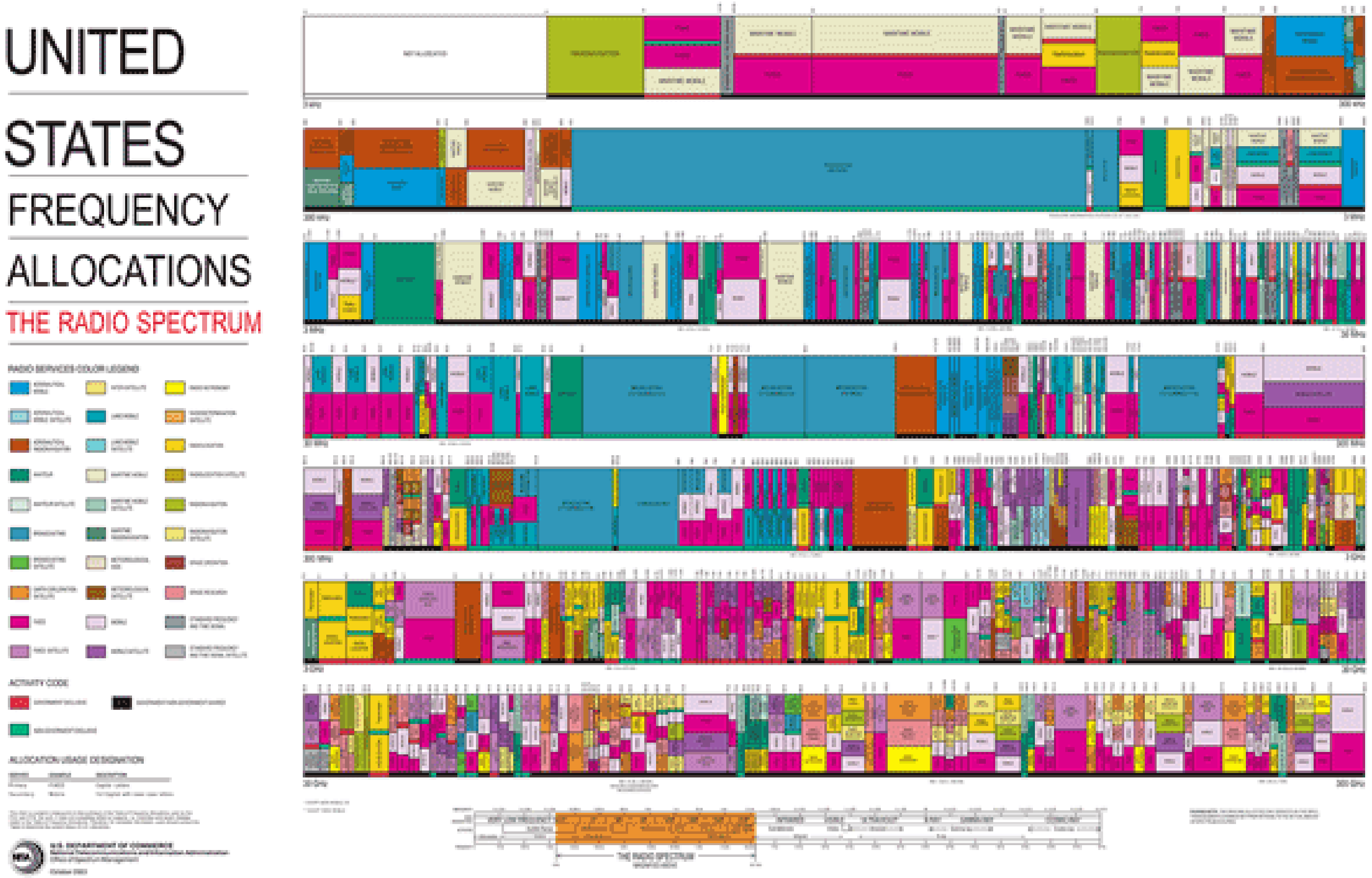
- **Key Challenges:**
  - **Networks are heterogeneous** ⇒ *coordination without co-design*
  - **Interference environment is dynamic** ⇒ *spectrum usage must adapt accordingly*
  - **Networks are all secondary users** ⇒ *networks must make their own rules for sharing*

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**

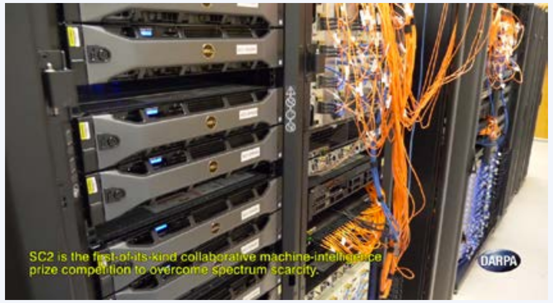
PRIZE AWARDS:

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

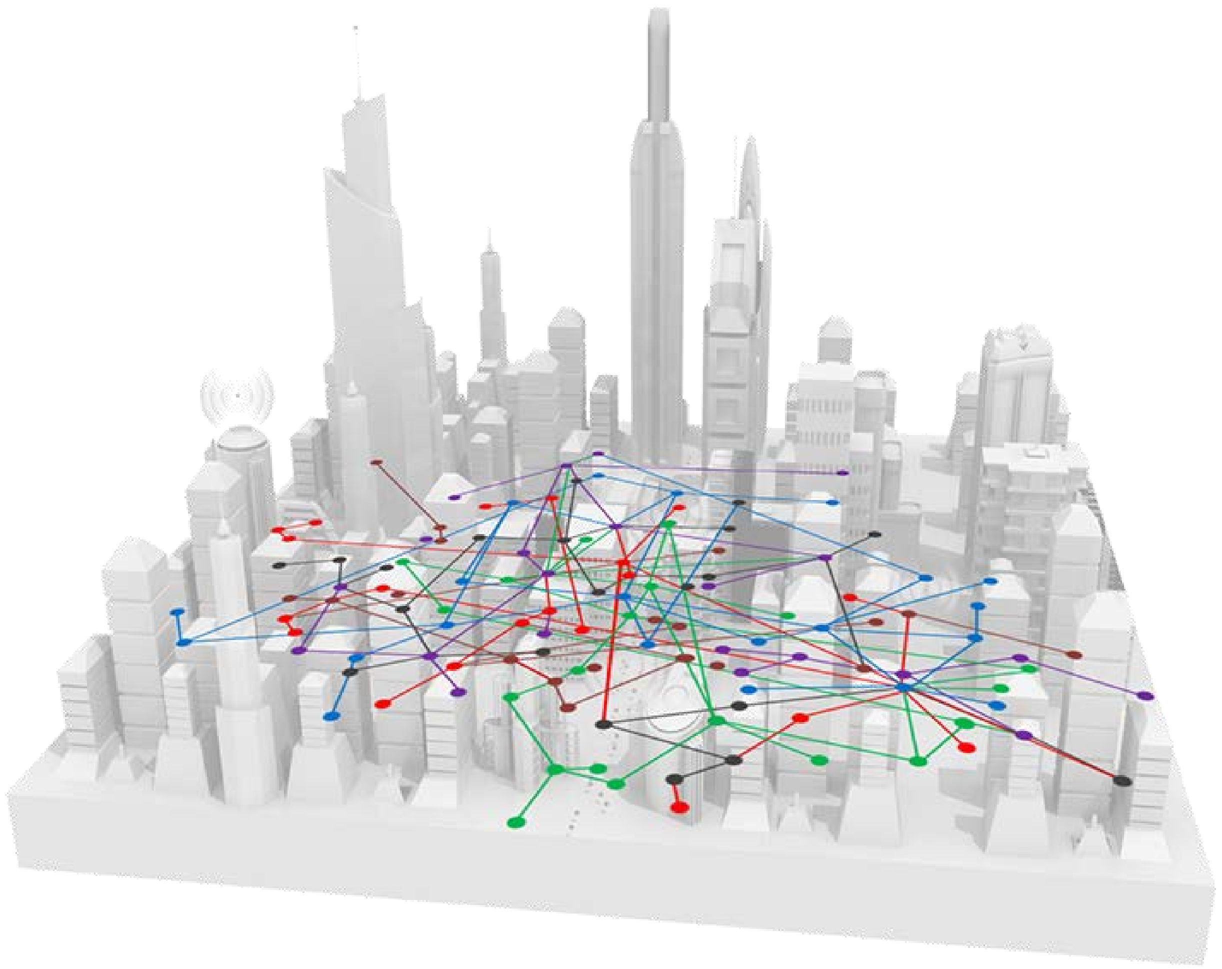
Goal: Teams program their radios to create *Collaborative Intelligent Radio Networks (CIRNs)* which share spectrum dynamically.

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

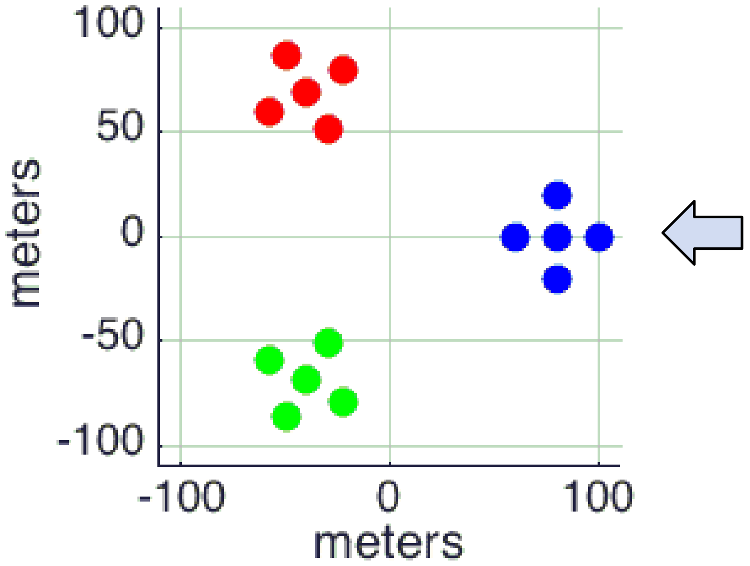
MIT LL Task #1: Scenario Development



- 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**

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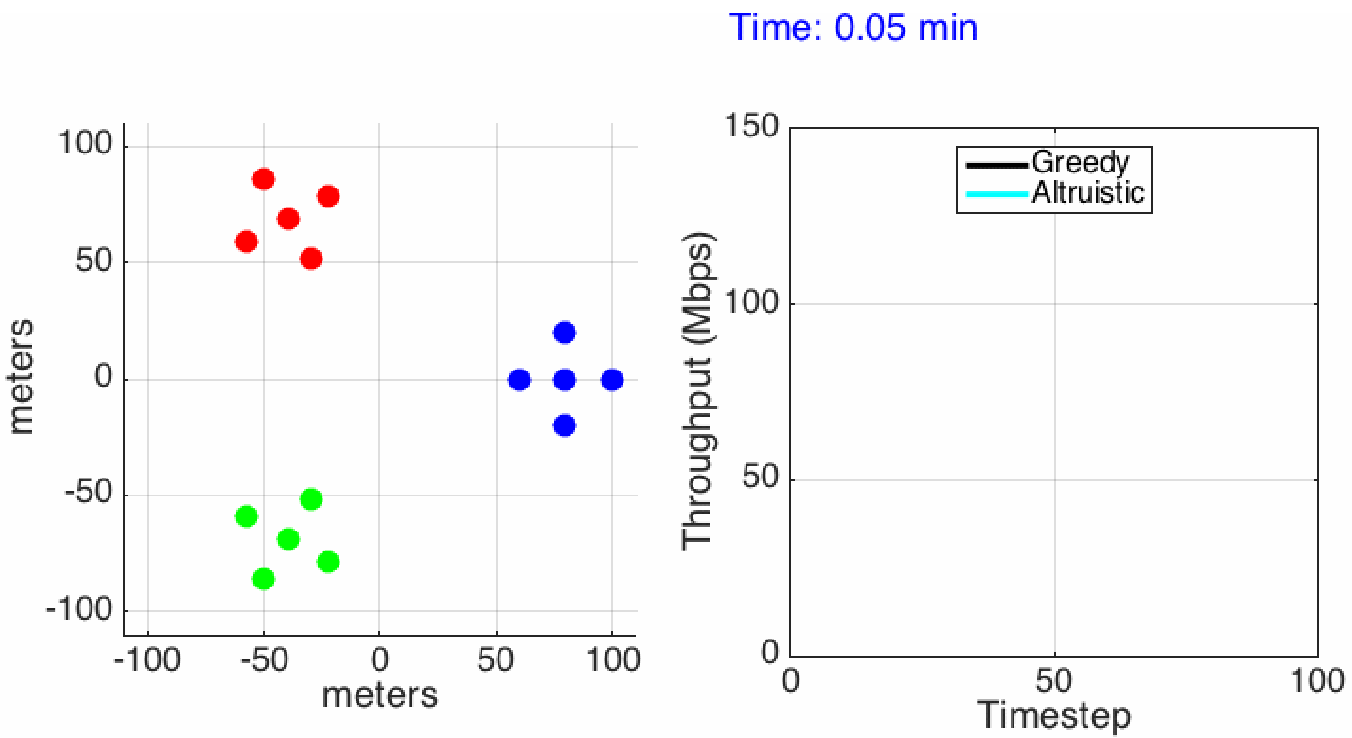

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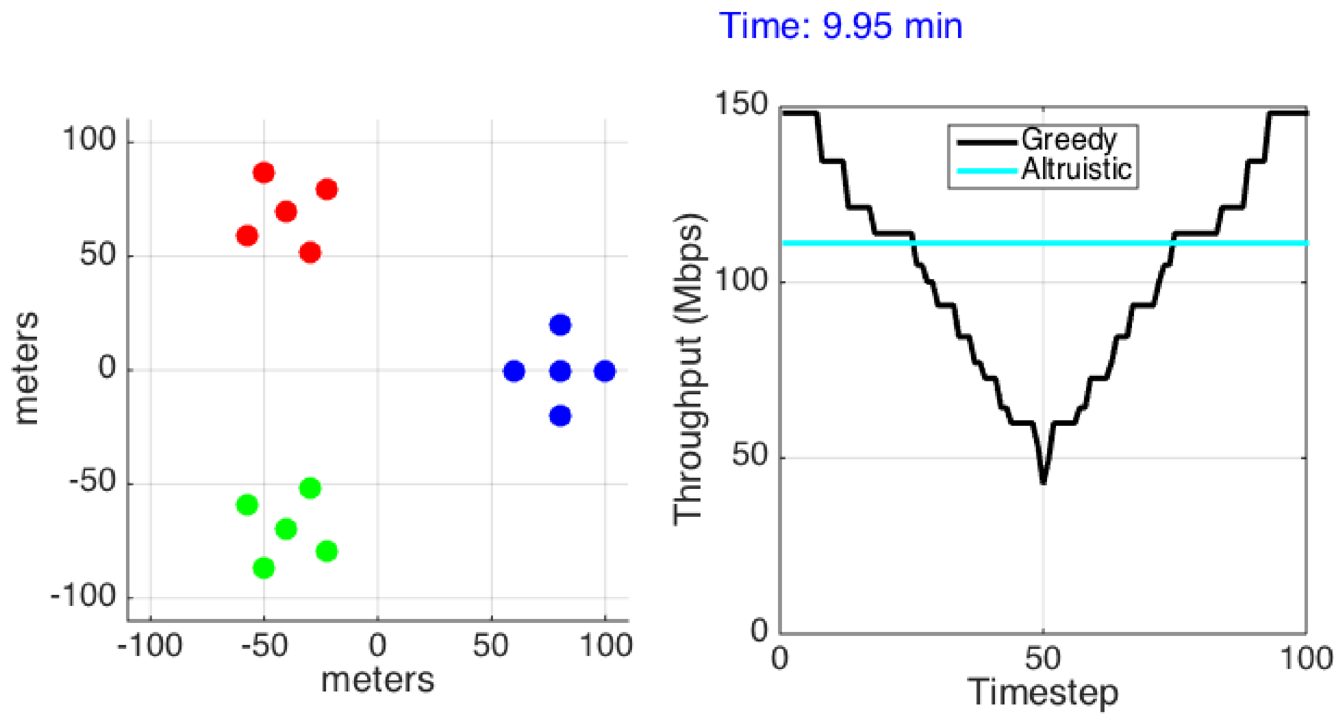

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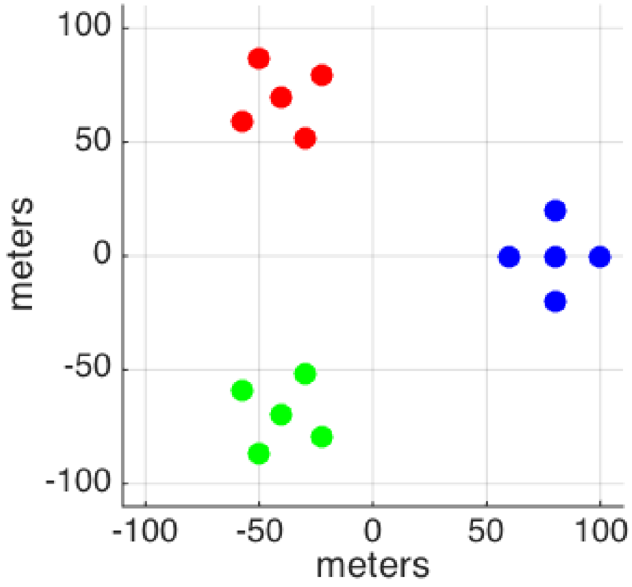
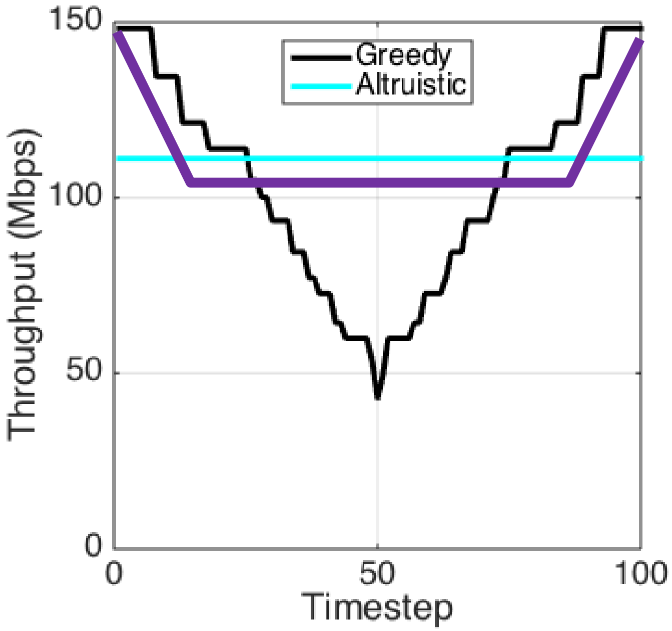


Time: 9.95 min



Traffic Demand

- **Regime 1: When their interference environments are isolated, CIRNs benefit from greedy spectral usage**
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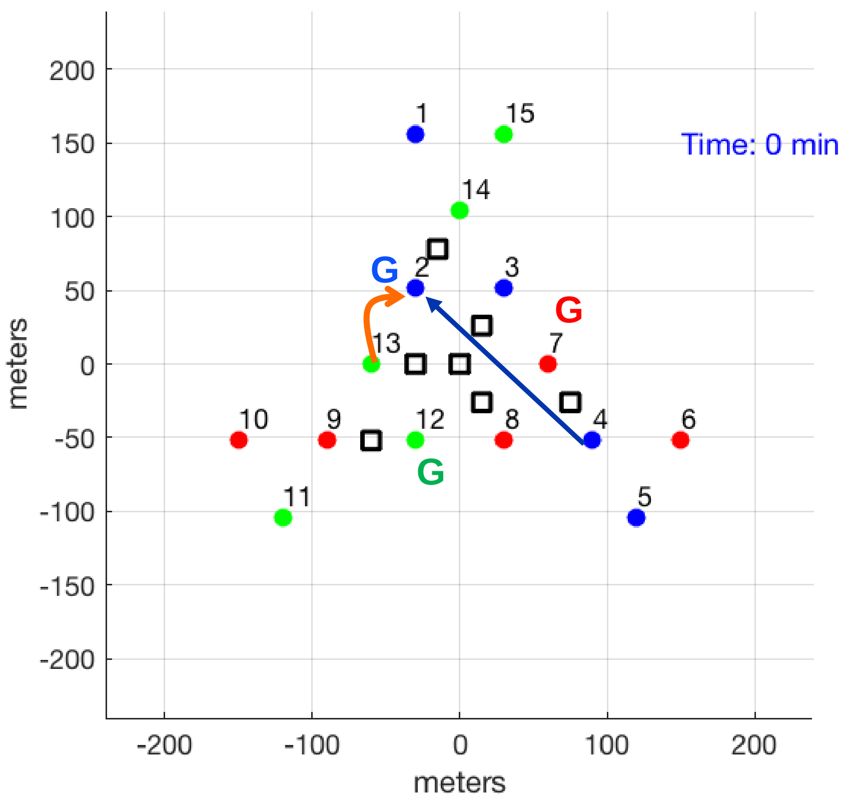
Example Q2: Can CIRNs Collaboratively Adapt to Complex Interference Environments?

"Interference Detective"



Blue CIRN comm. link

Green-to-Blue CIRN interference

Obstacle

- **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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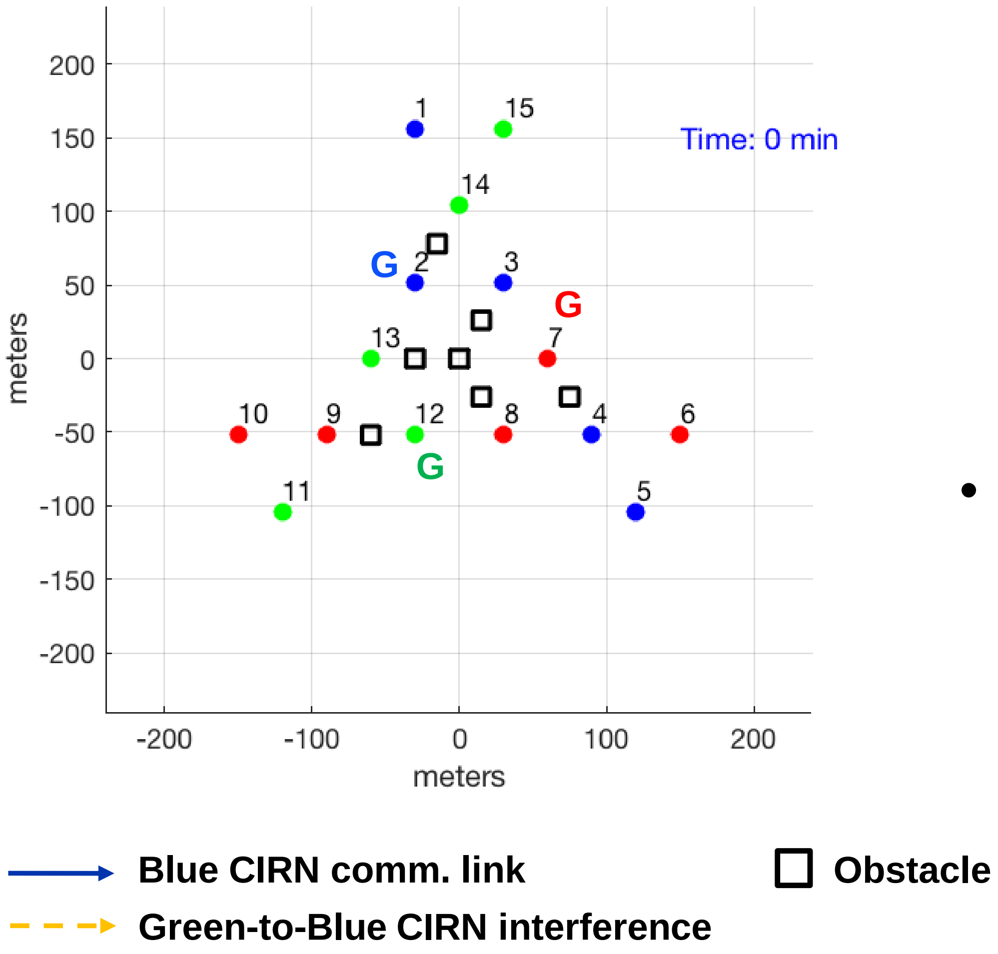

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- **Propagation obstacles can provide opportunities for spatial re-use of spectrum**
  - **Environment may naturally segregate interference zones associated with each receiver**

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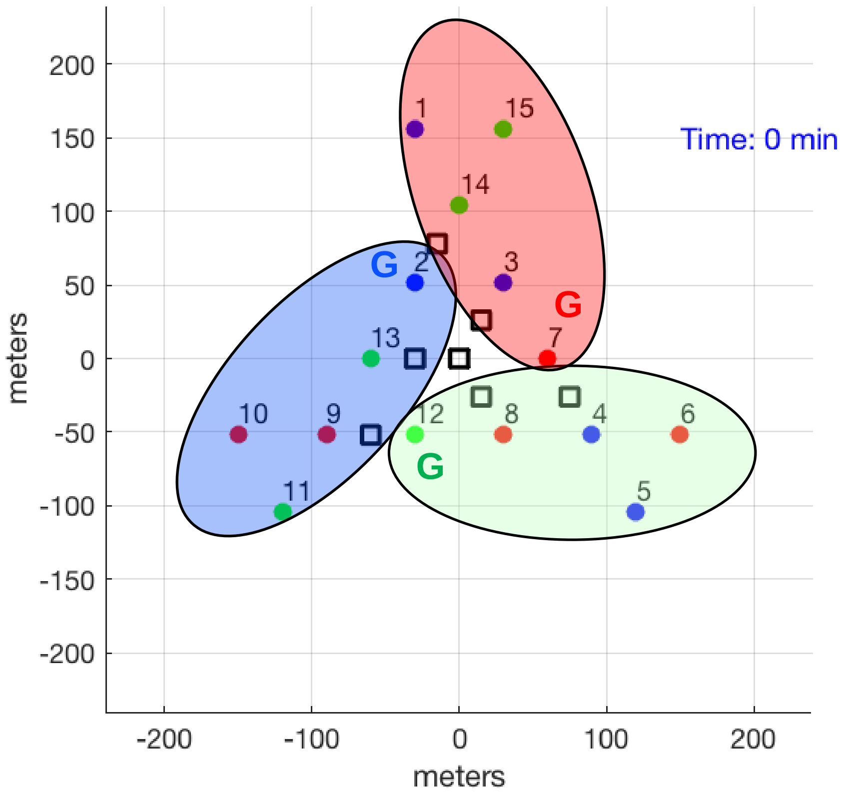

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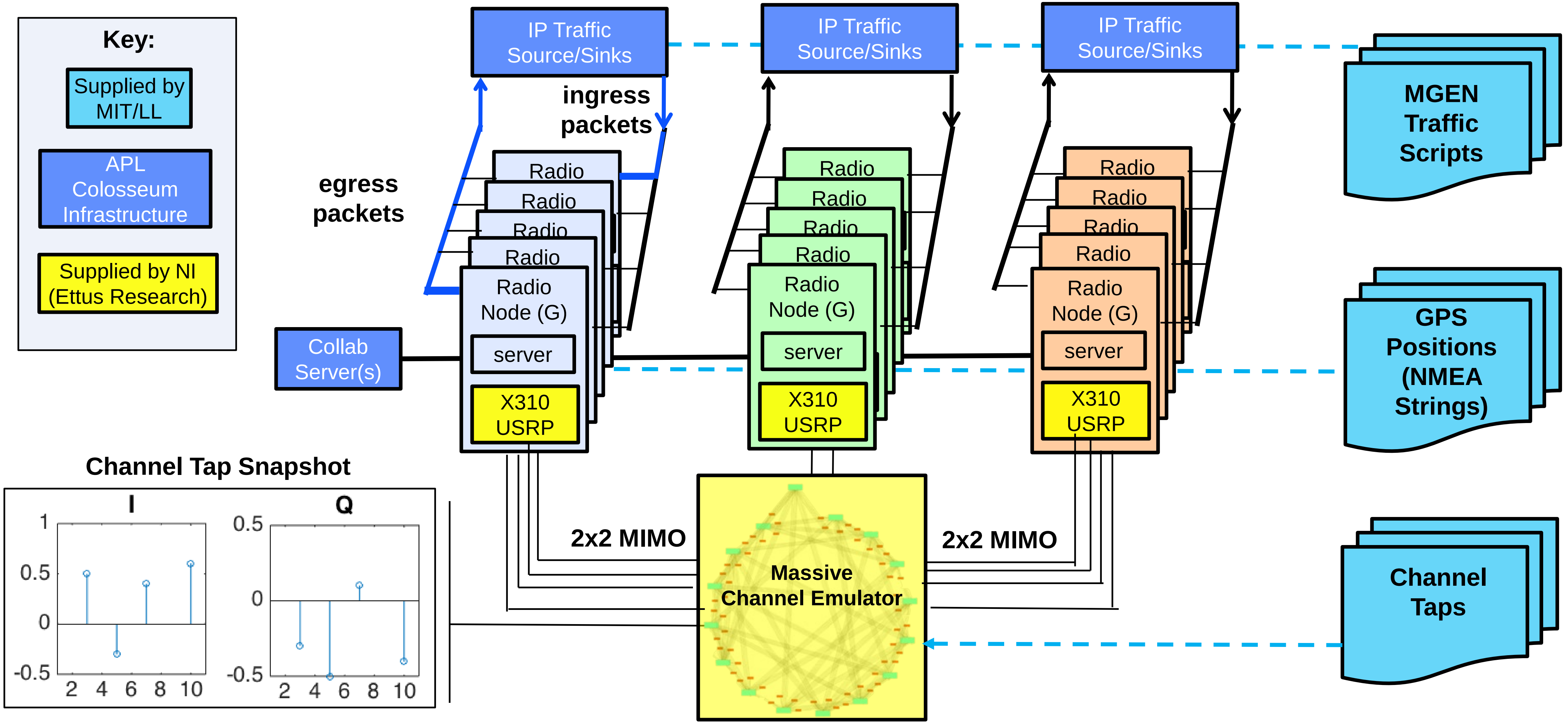
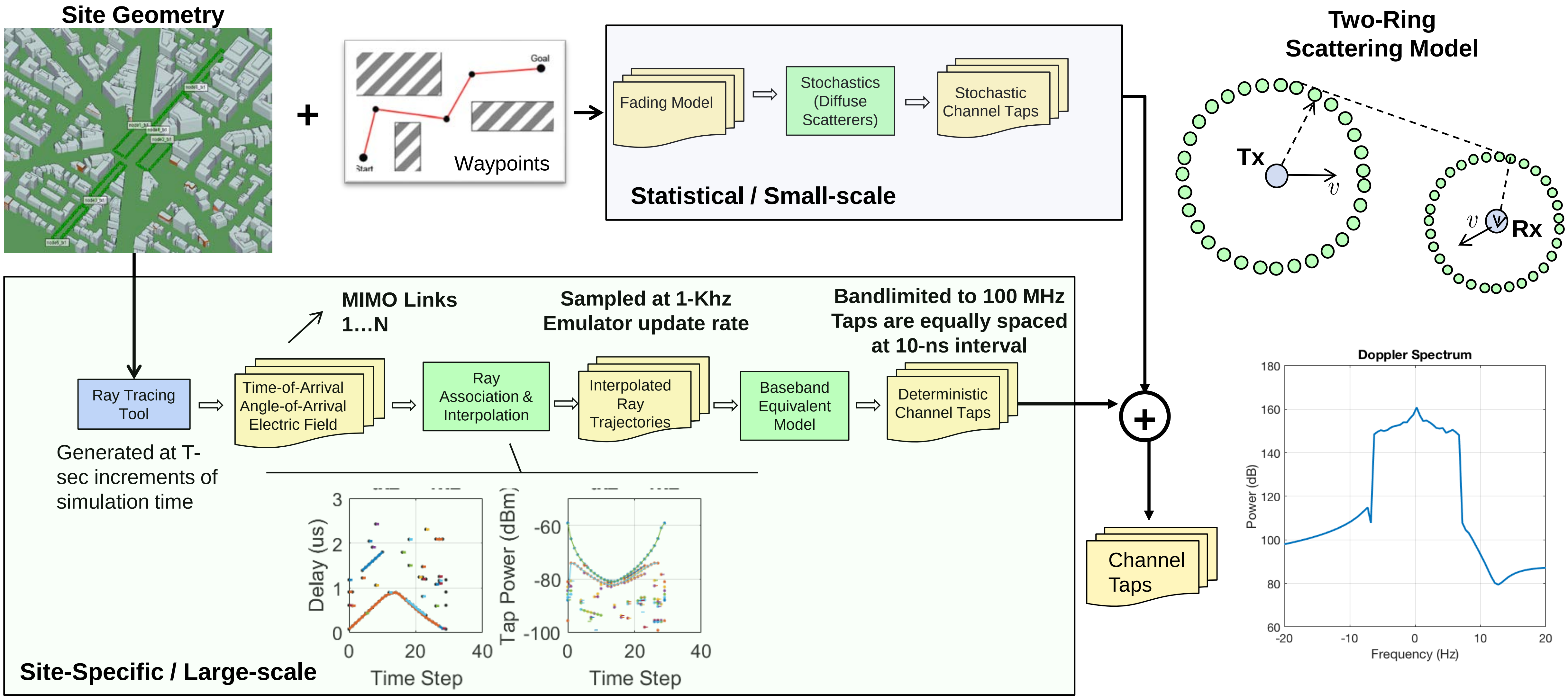
- **Propagation obstacles can provide opportunities for spatial re-use of spectrum**
  - **Environment may naturally segregate interference zones associated with each receiver**
  - **De-confliction only necessary within each zone separately $\Rightarrow$ opportunities for spatial re-use across zones**

Scenario Instantiation in Colosseum



RF Channel Modeling



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  - Cognitive Algorithm Development
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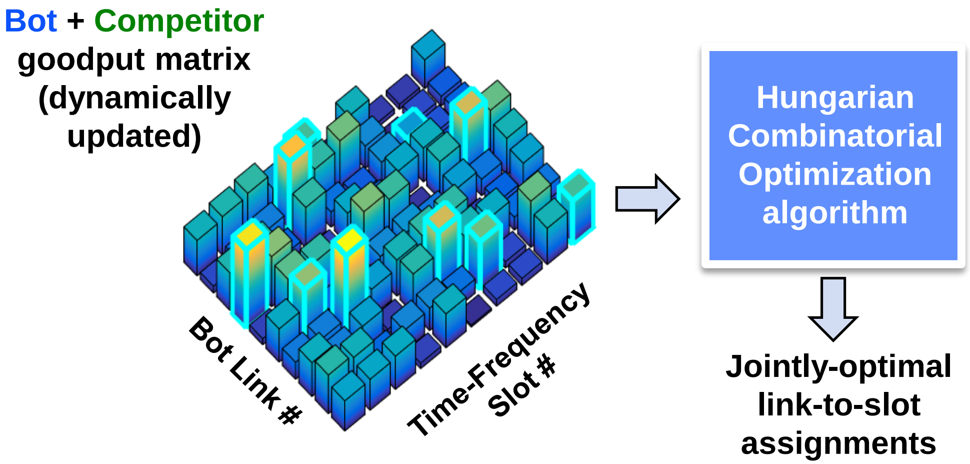
MIT/LL Training Bot Overview

- **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**

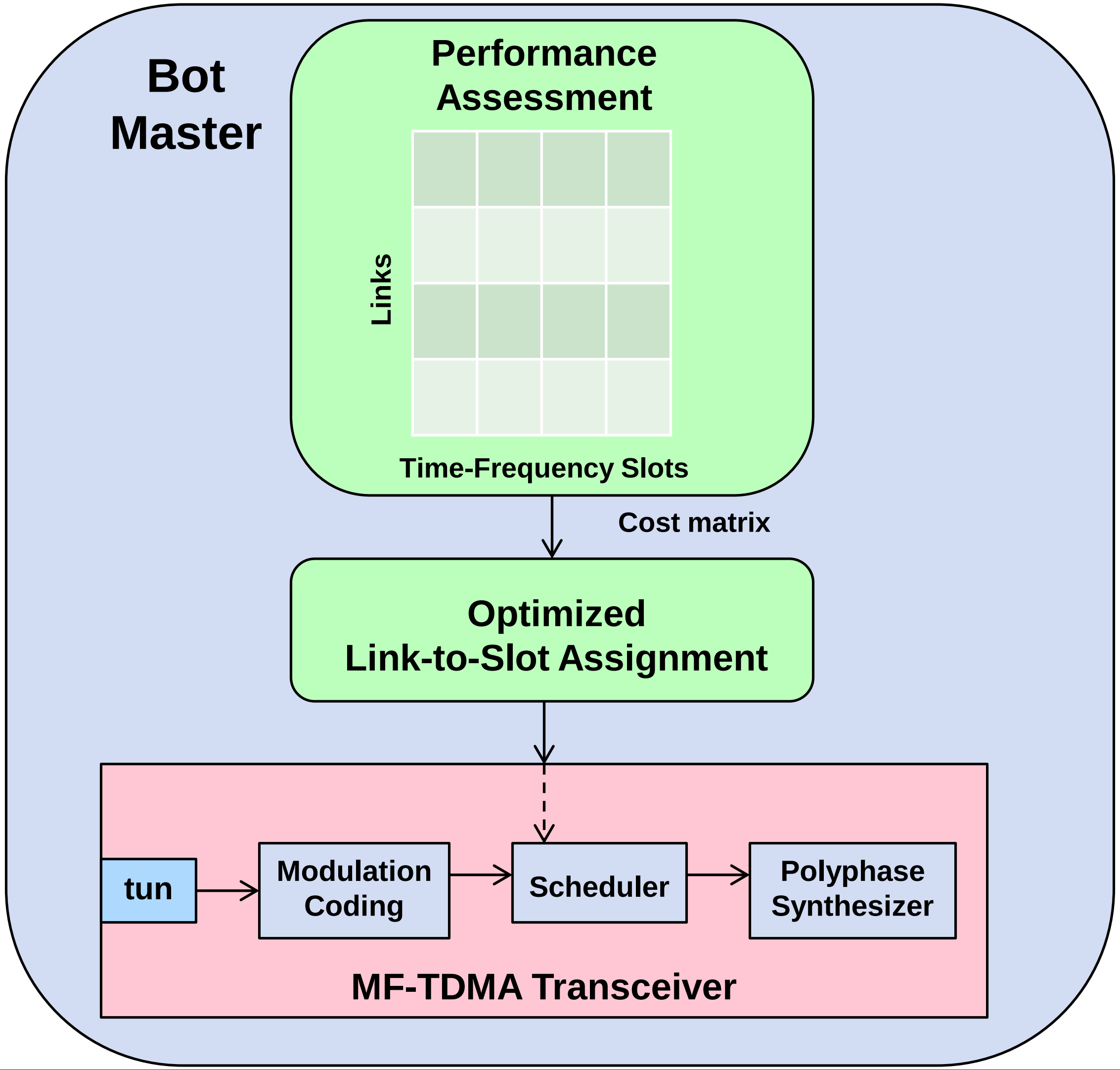
Table of Bot PHY/MAC Parameters

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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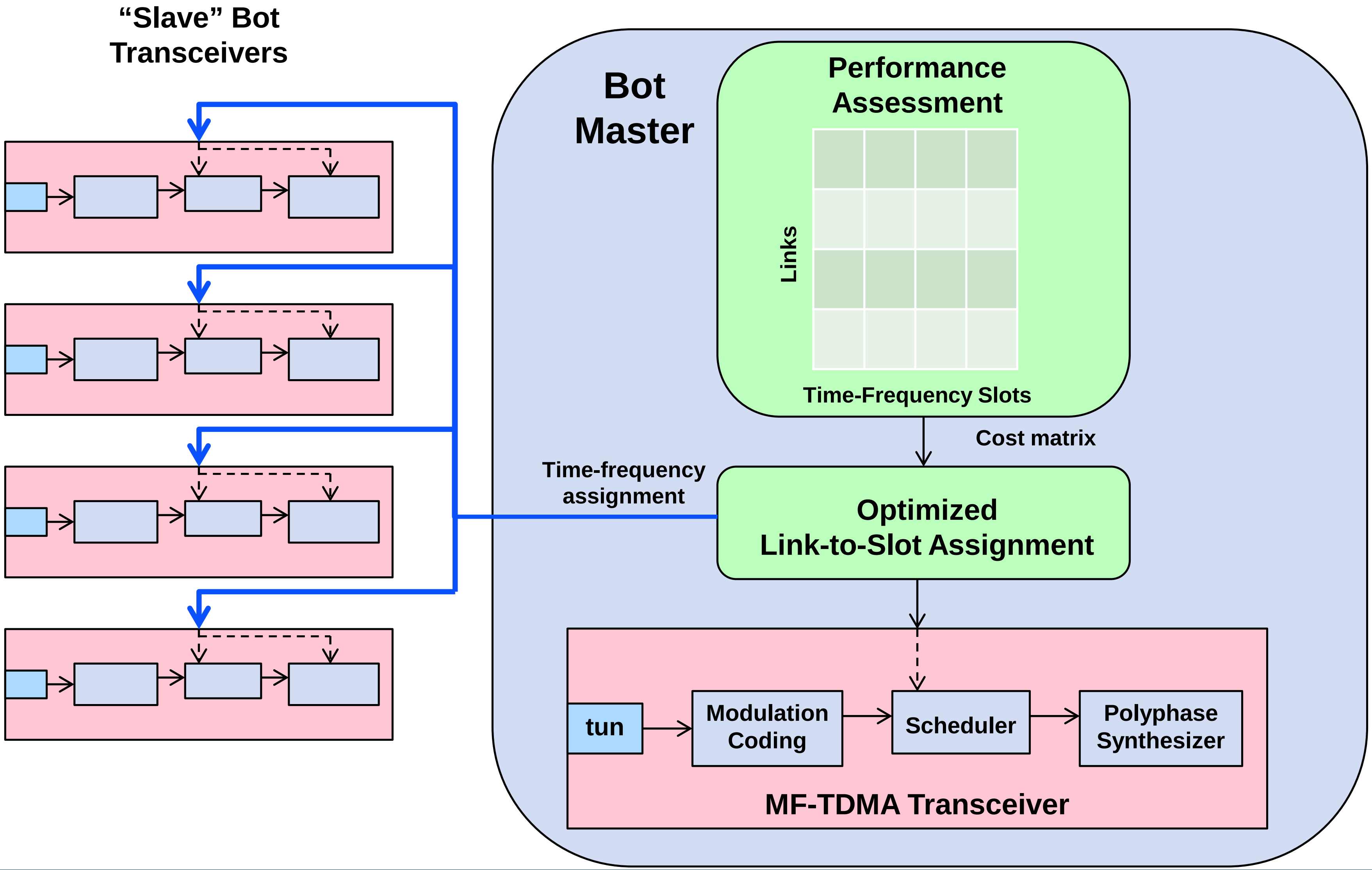
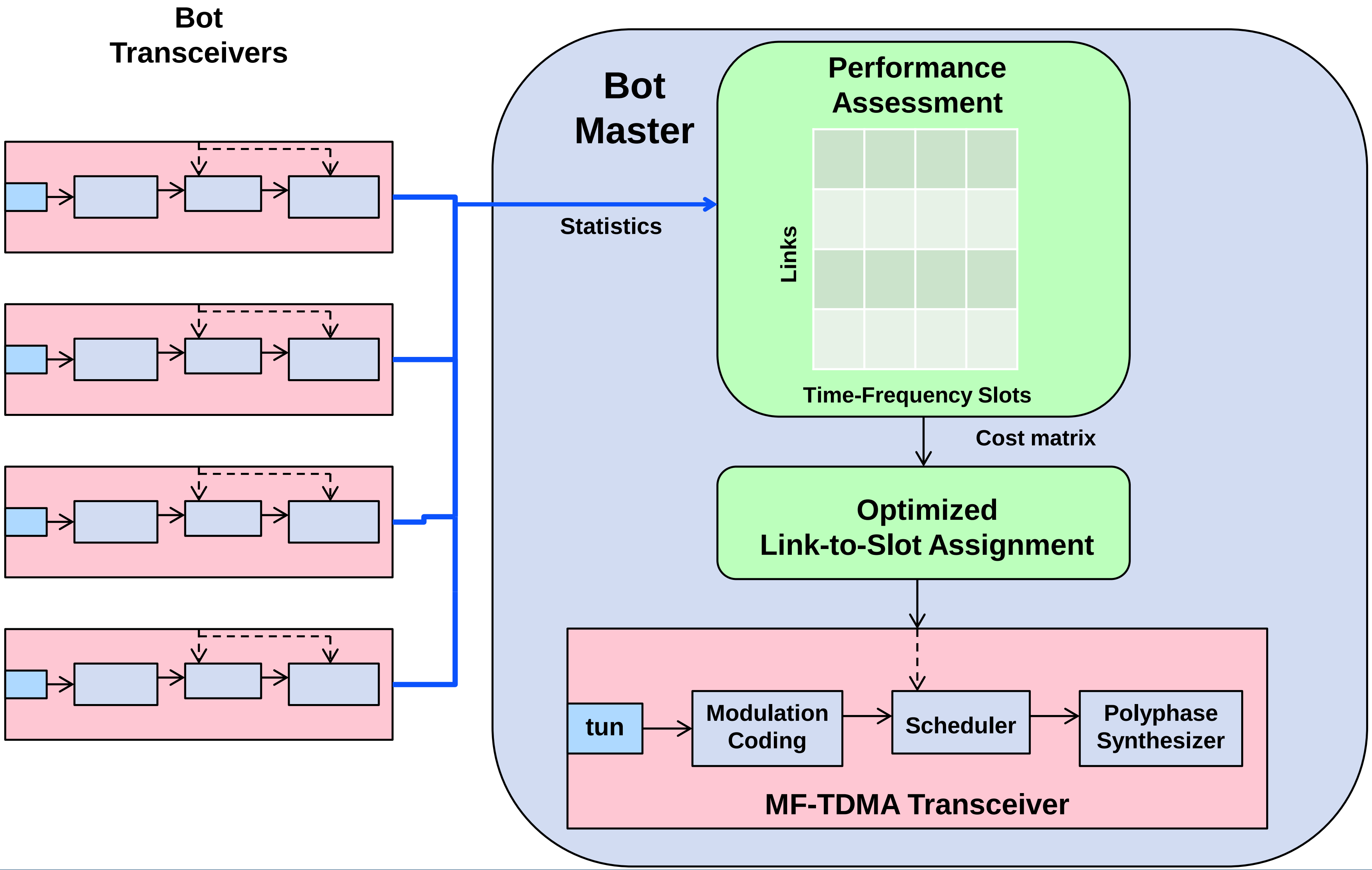


Bot Network Design
Collaboration



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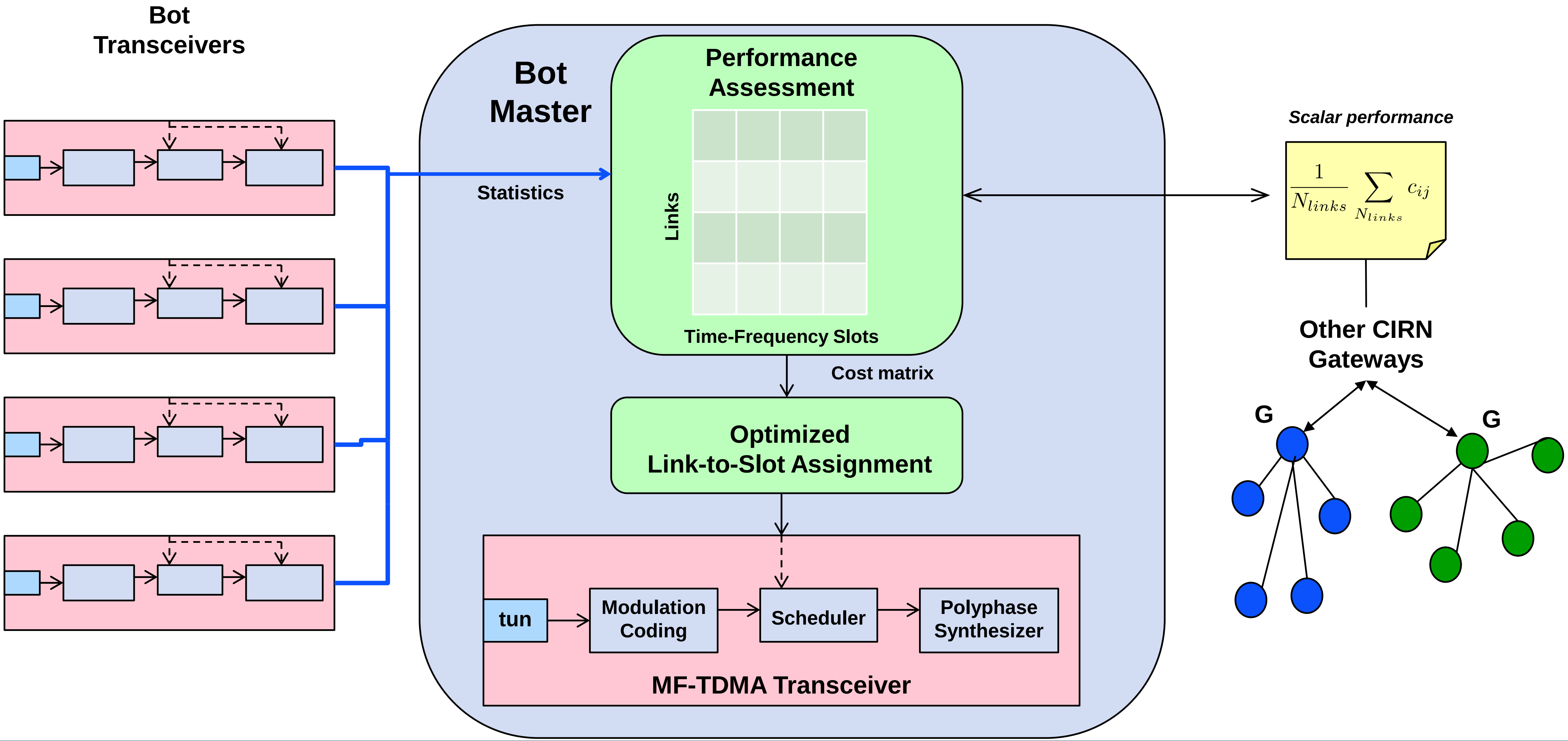
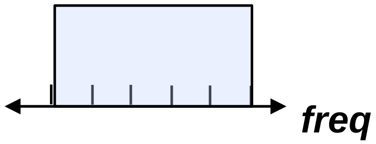
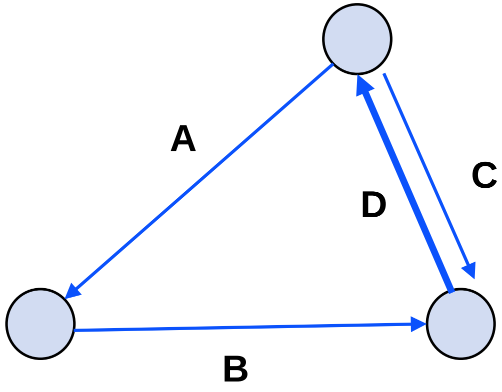


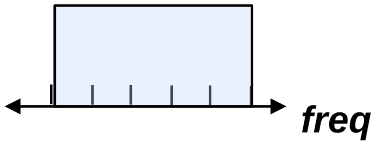
Lincoln Algorithm: Example

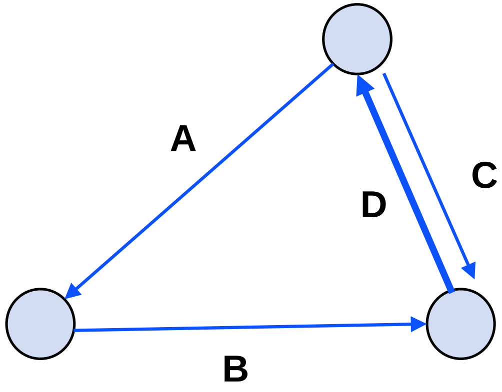




Token	Link	Frequency Slot #				
		1	2	3	4	5
1						
2						
3						
4						
5						

Lincoln Algorithm: Example

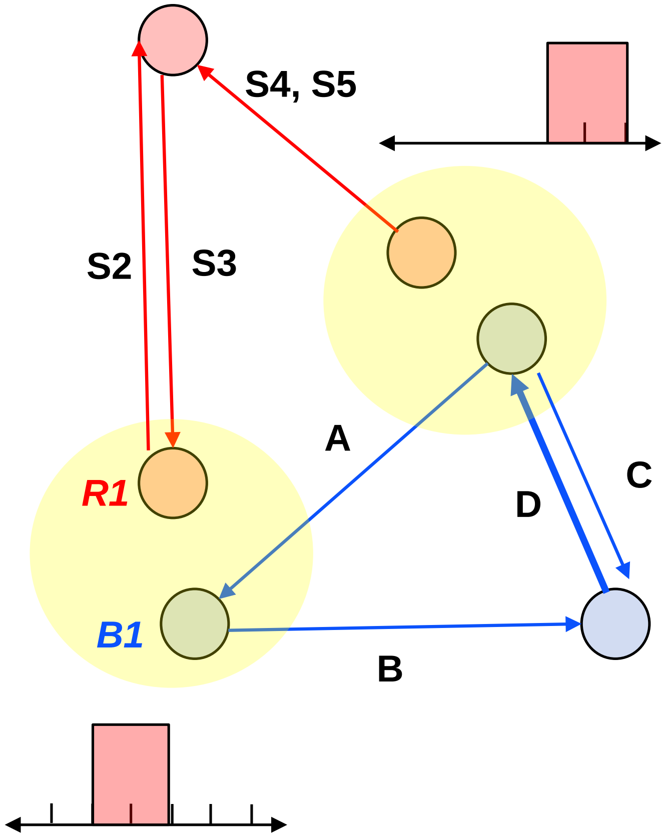


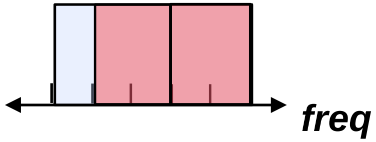


Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A					
2	B					
3	C					
4	D					
5	D					

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

Lincoln Algorithm: Example



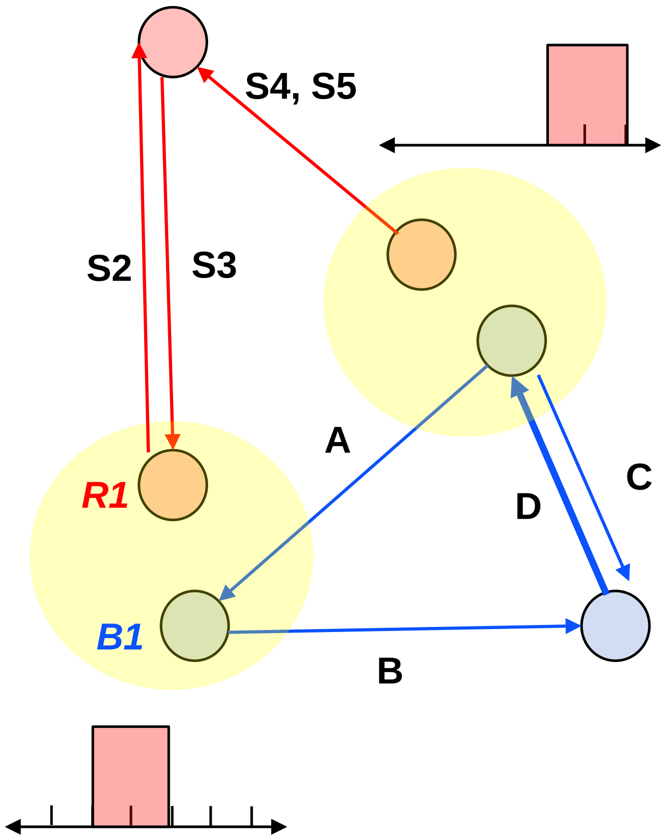


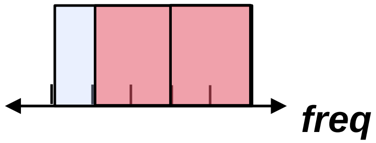
Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A		1, 0			
2	B			0, 1		
3	C					
4	D				1, 0	1, 0
5	D				1, 0	1, 0

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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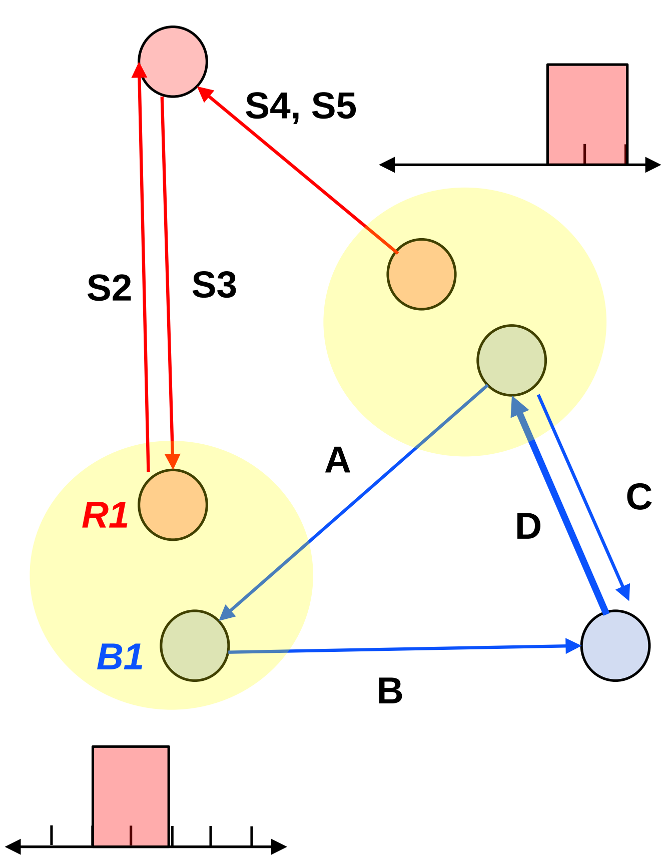
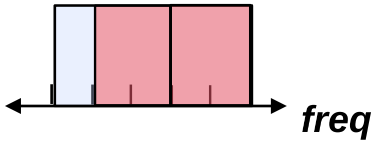


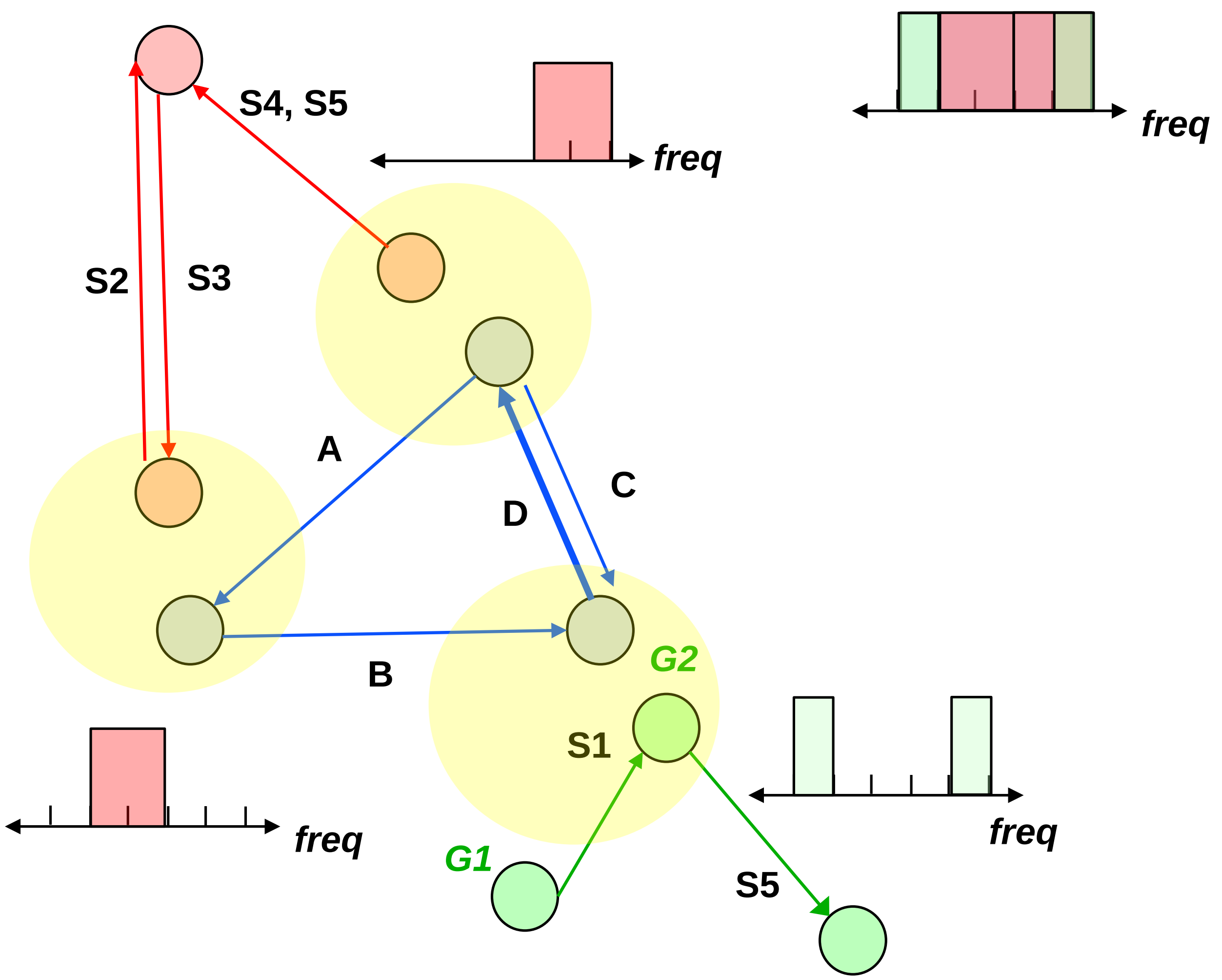


Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0, 0	1, 0	0, 0	0, 0	0, 0
2	B	0, 0	0, 0	0, 1	0, 0	0, 0
3	C					
4	D				1, 0	1, 0
5	D				1, 0	1, 0

Cost = 1 – goodput / offered_load

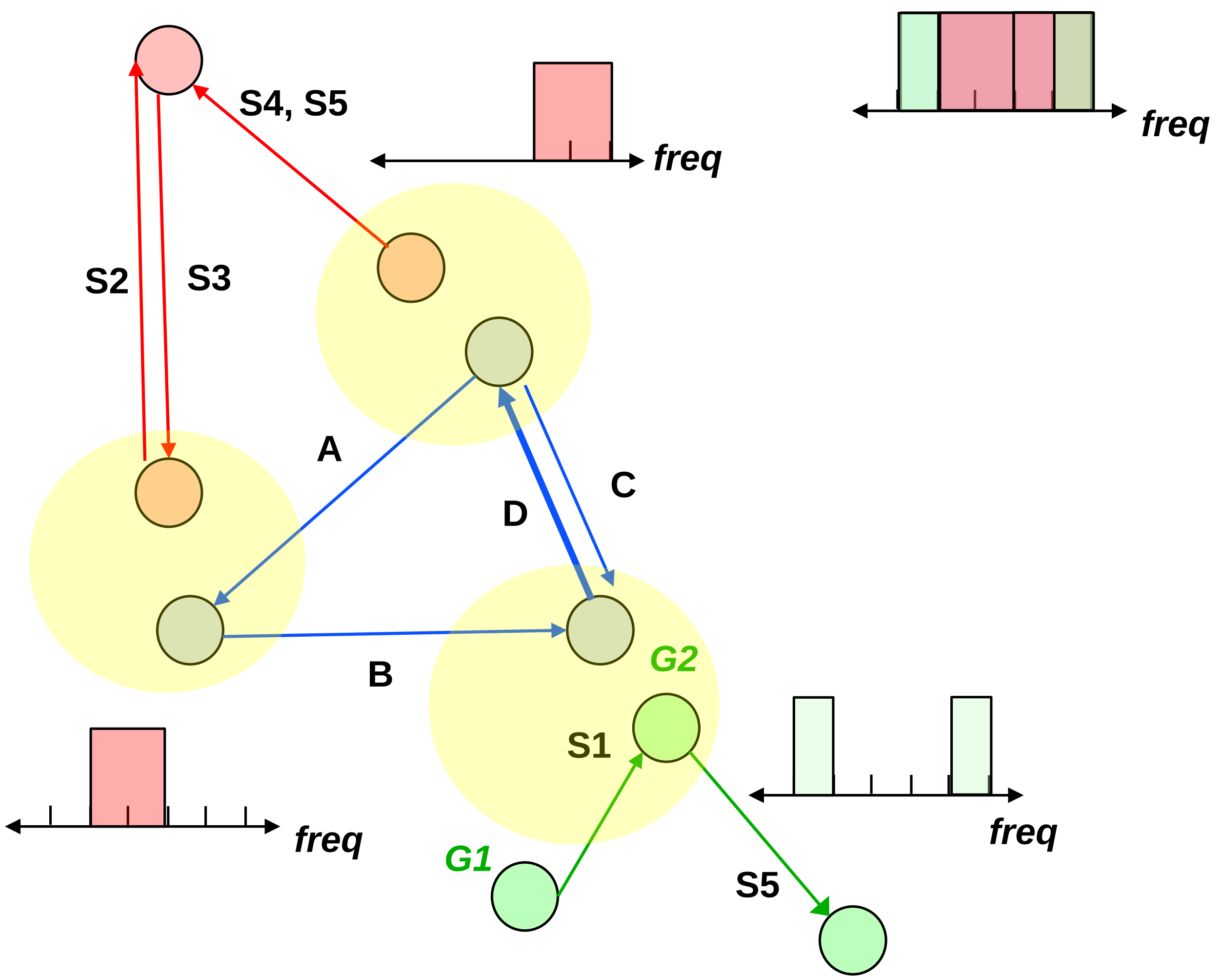
Then, costs are assigned to each link-to-slot pairing based on performance.
Format: (own cost, collaborative cost)

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

Lincoln Algorithm: Example



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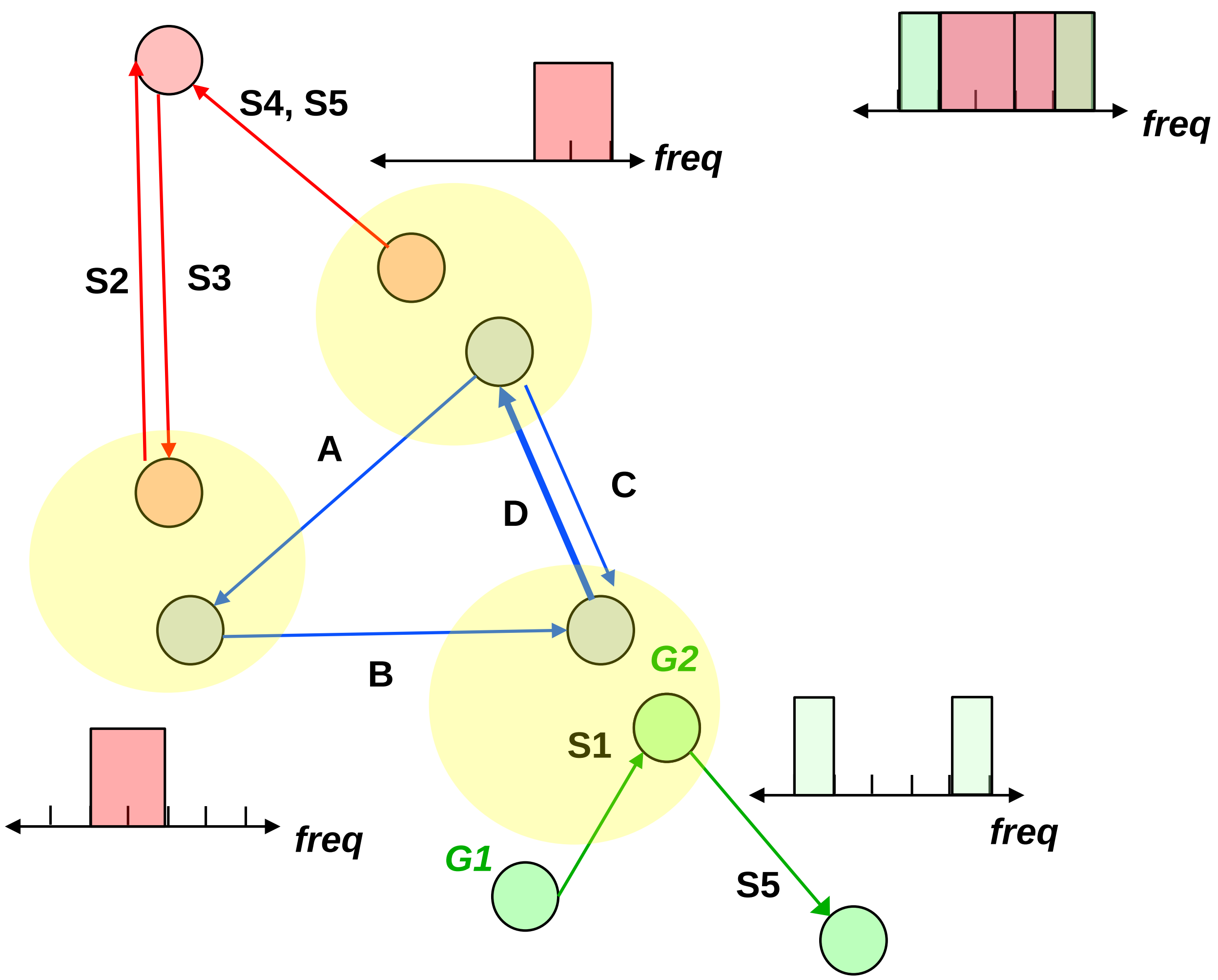
1	A	0, 0	1, 0	0, 0	0, 0	0, 0
2	B	0, 0	0, 0	0, 1	0, 0	1, 0
3	C	0, 0	0, 0	0, 0	0, 0	1, 0
4	D	0, 1	0, 0	0, 0	1, 0	1, 0
5	D	0, 1	0, 0	0, 0	1, 0	1, 0

Lincoln Algorithm: Example

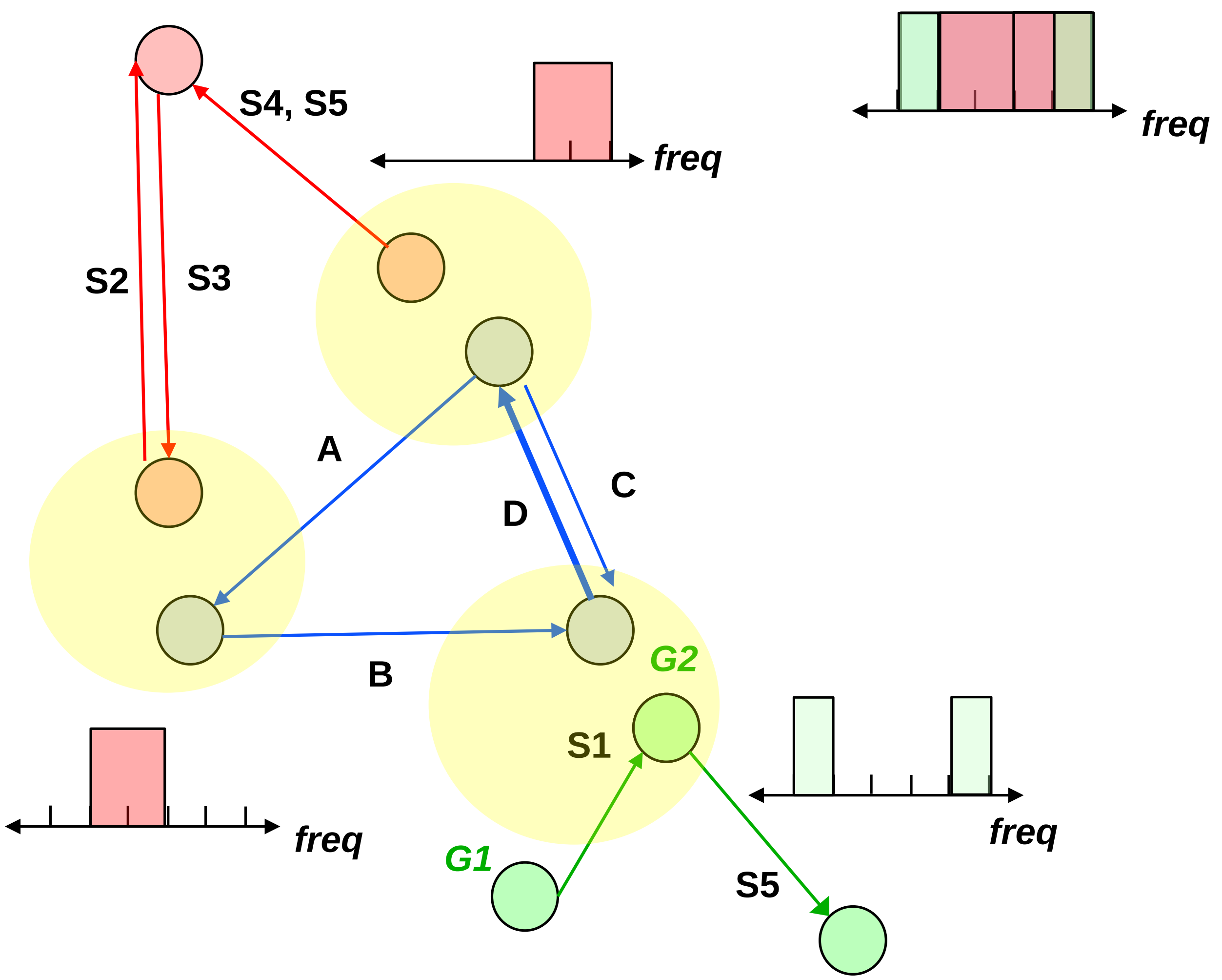


Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0	1.0	0	0	0
2	B	0	0	0.5	0	1.0
3	C	0	0	0	0	1.0
4	D	0.5	0	0	1.0	1.0
5	D	0.5	0	0	1.0	1.0

Total Cost = Own Cost + 0.5 * Collab Cost

Composite inter-network costs are computed.

Lincoln Algorithm: Example

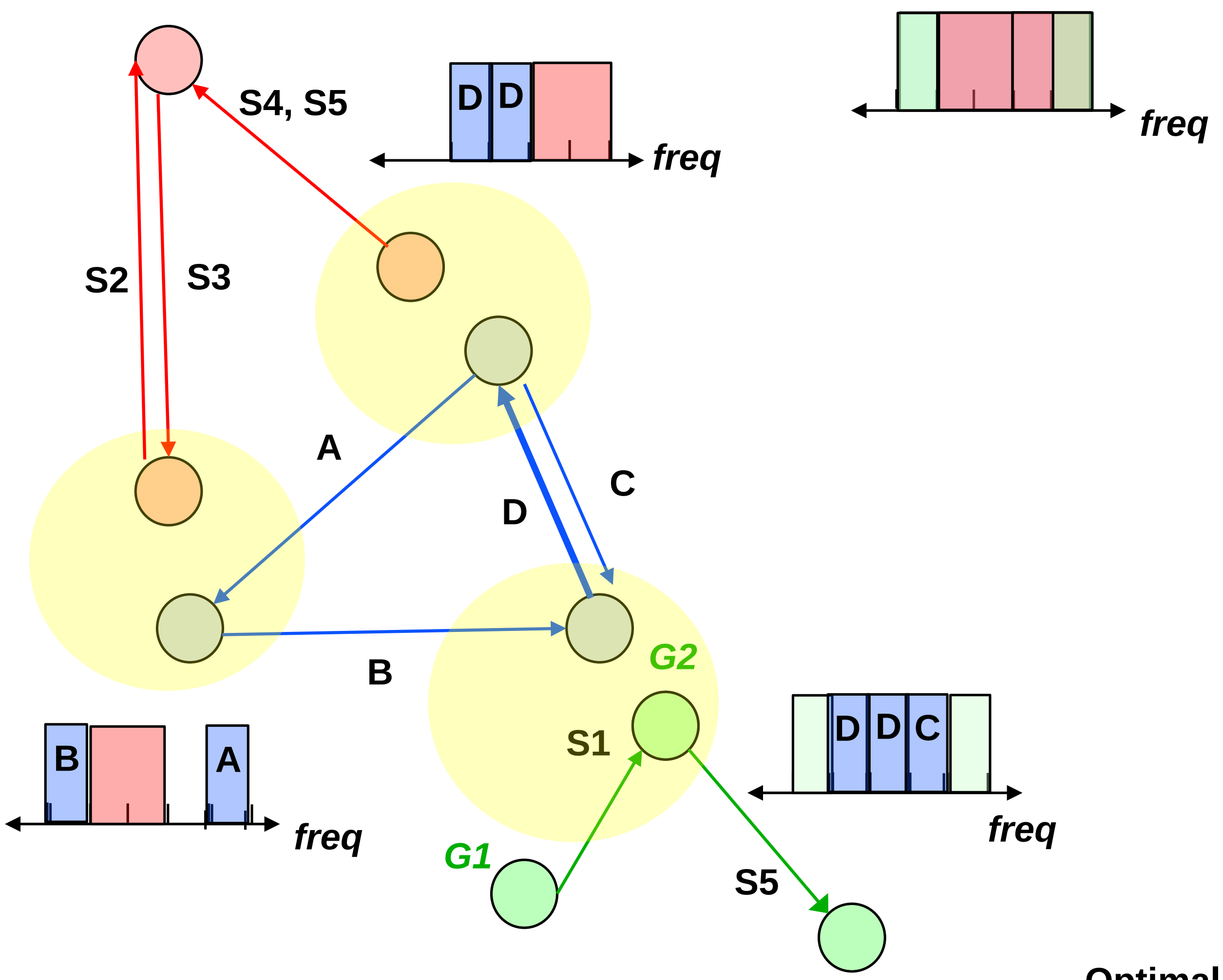


Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0	1.0	0	0	0
2	B	0	0	0.5	0	1.0
3	C	0	0	0	0	1.0
4	D	0.5	0	0	1.0	1.0
5	D	0.5	0	0	1.0	1.0

Total Cost = Own Cost + 0.5 * Collab Cost

Finally, Hungarian Assignment determines optimal assignment.

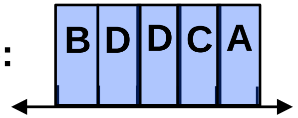
Lincoln Algorithm: Example



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

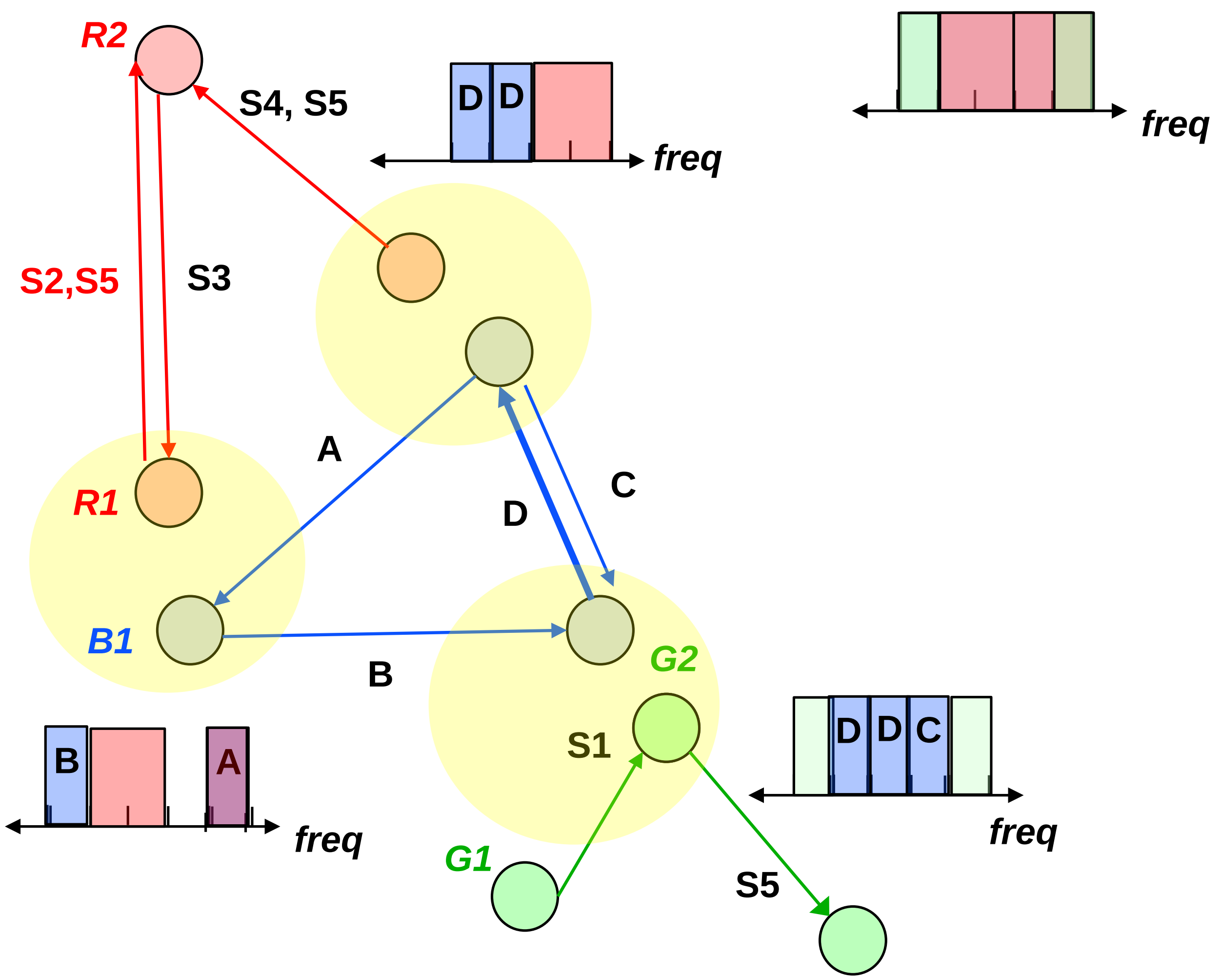
Total Cost = Own Cost + 0.5 * Collab Cost

Optimal frequency plan for Blue:



(perfect deconfliction)

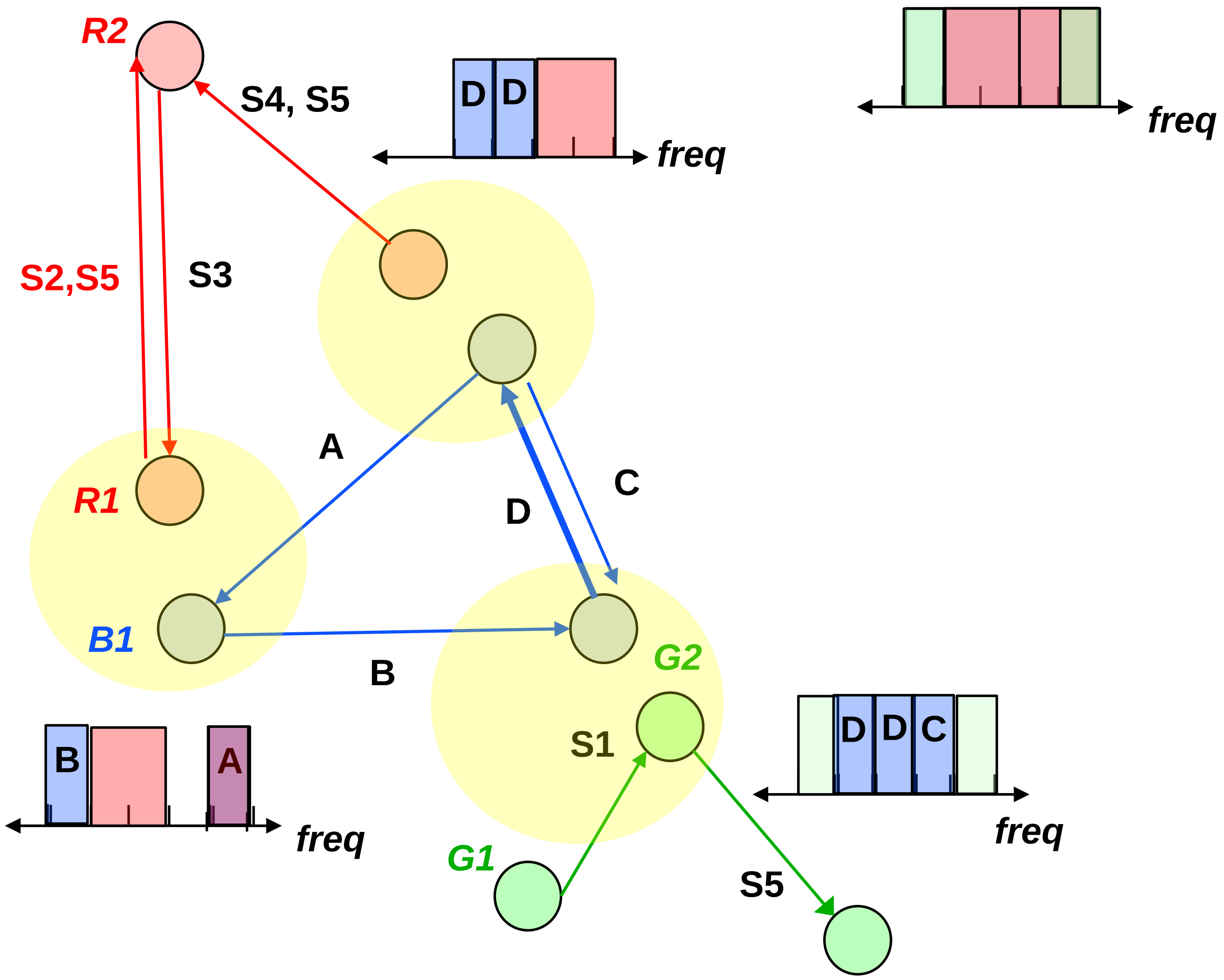
A Harder Example



Token	Link	Frequency Slot #				
		1	2	3	4	5
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

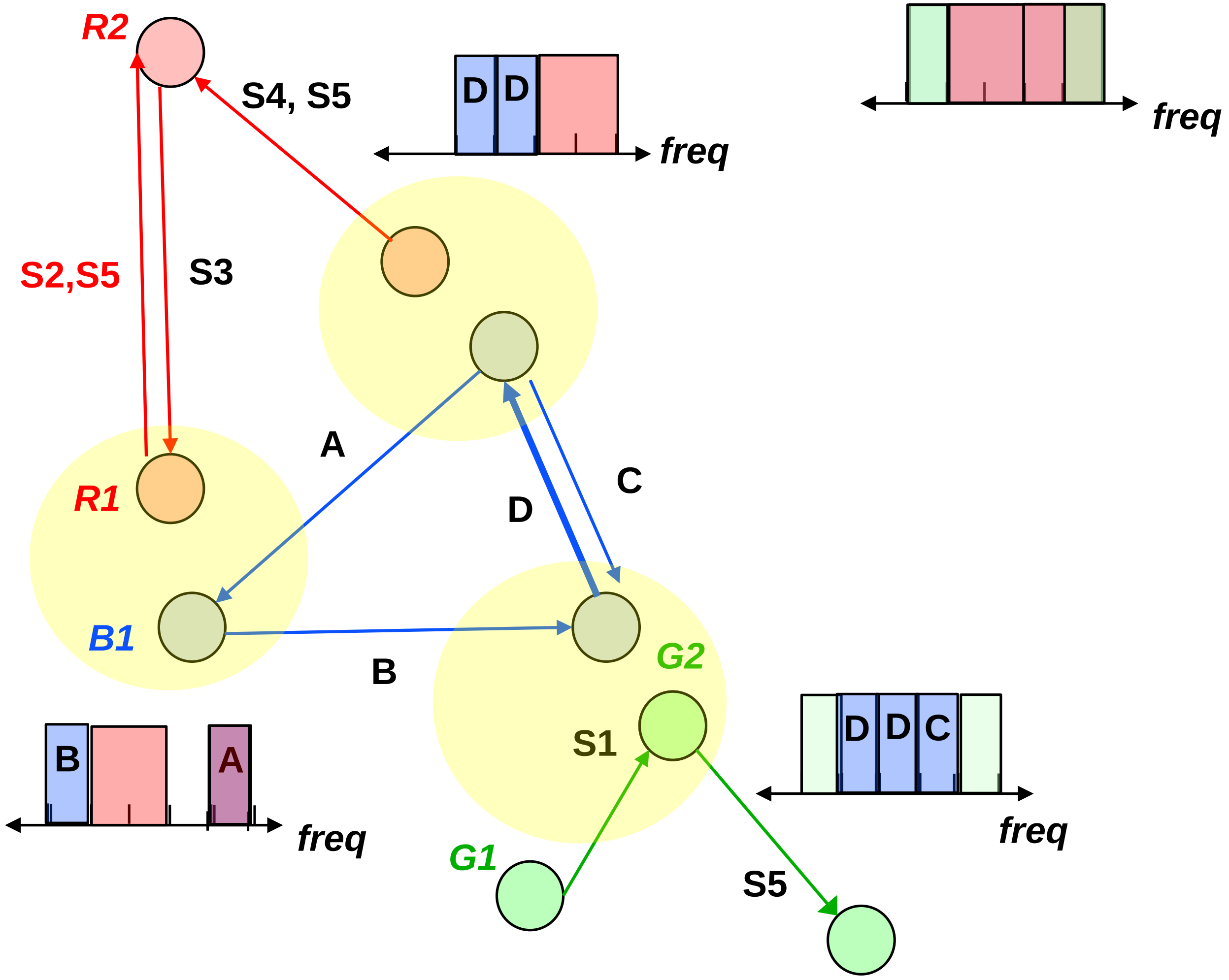
A Harder Example



Token	Link	Frequency Slot #				
		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	

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

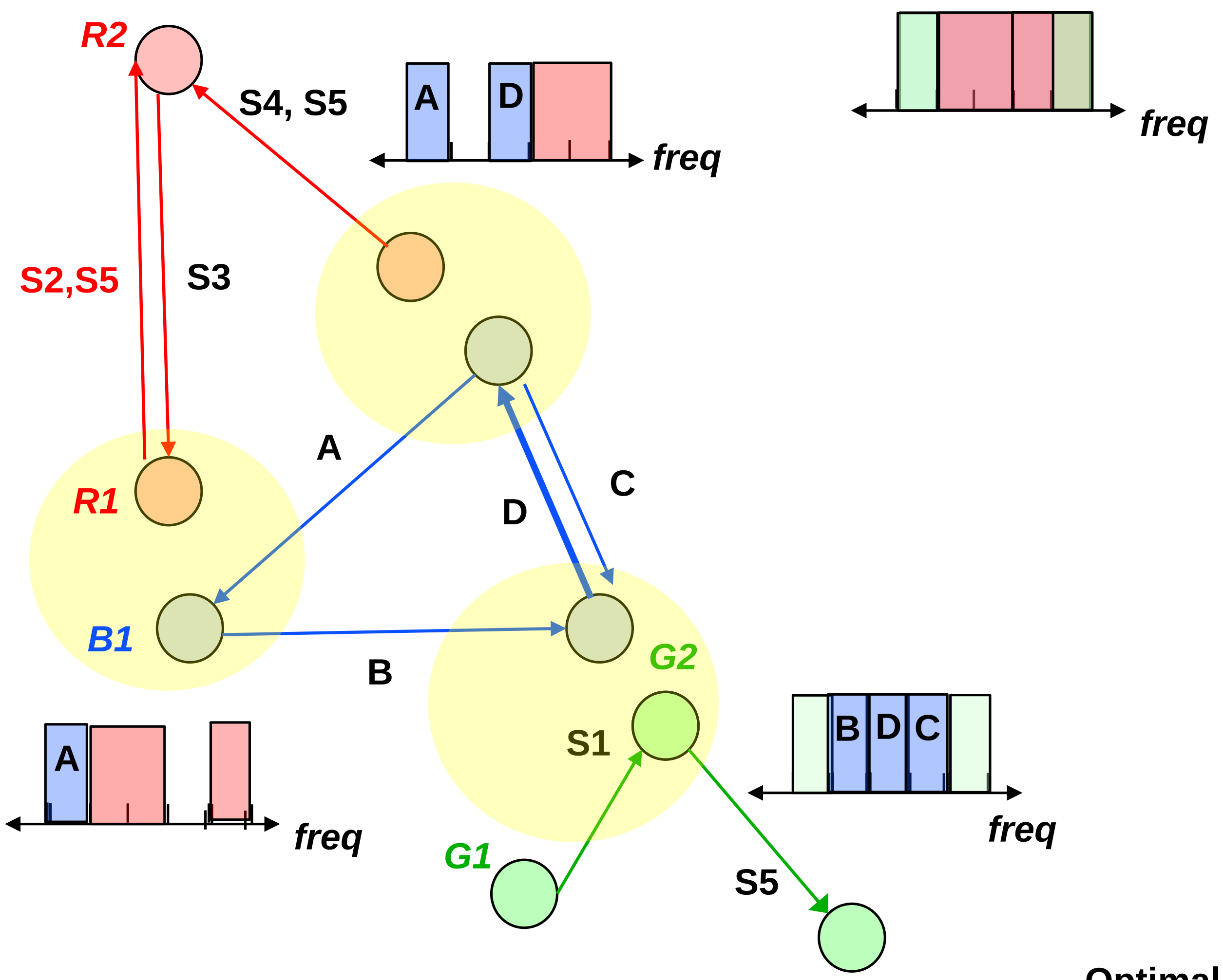
A Harder Example



Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	$\boxed{0}$	1.0	0	0	
2	B	0	$\boxed{0}$	0.5	0	
3	C	0	0	0	$\boxed{0}$	
4	D	0.5	0	$\boxed{0}$	1.0	
~~5~~	~~D~~	~~0.5~~	~~0~~	~~0~~	~~1.0~~	

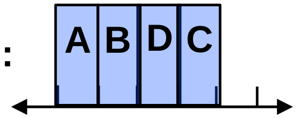
Link D loses one token, optimal assignment is re-computed.

A Harder Example



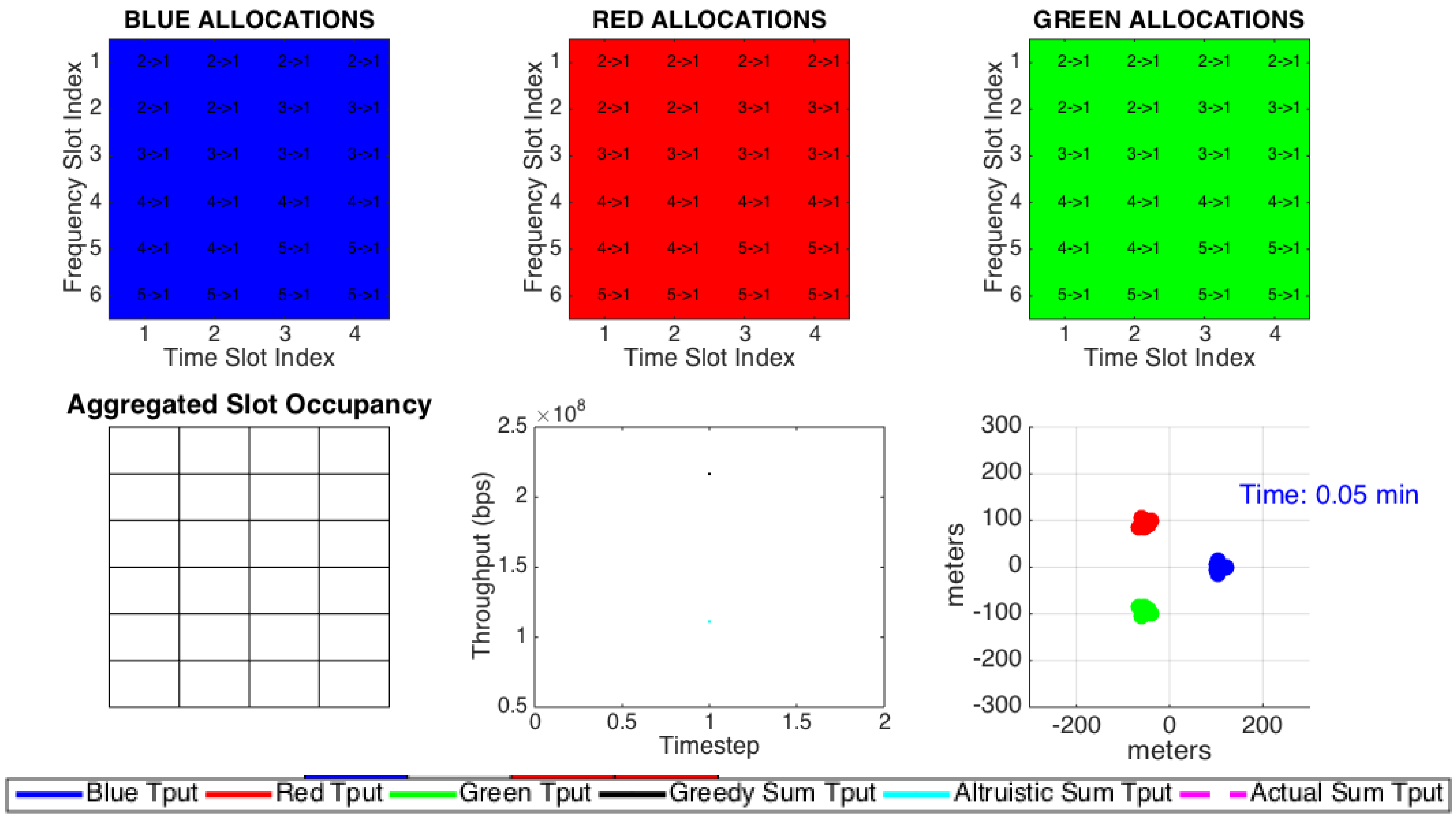
Token	Link	Frequency Slot #				
		1	2	3	4	5
1	A	0	1.0	0	0	
2	B	0	0	0.5	0	
3	C	0	0	0	0	
4	D	0.5	0	0	1.0	
~~5~~	~~D~~	~~0.5~~	~~0~~	~~0~~	~~1.0~~	

Optimal frequency plan for Blue:

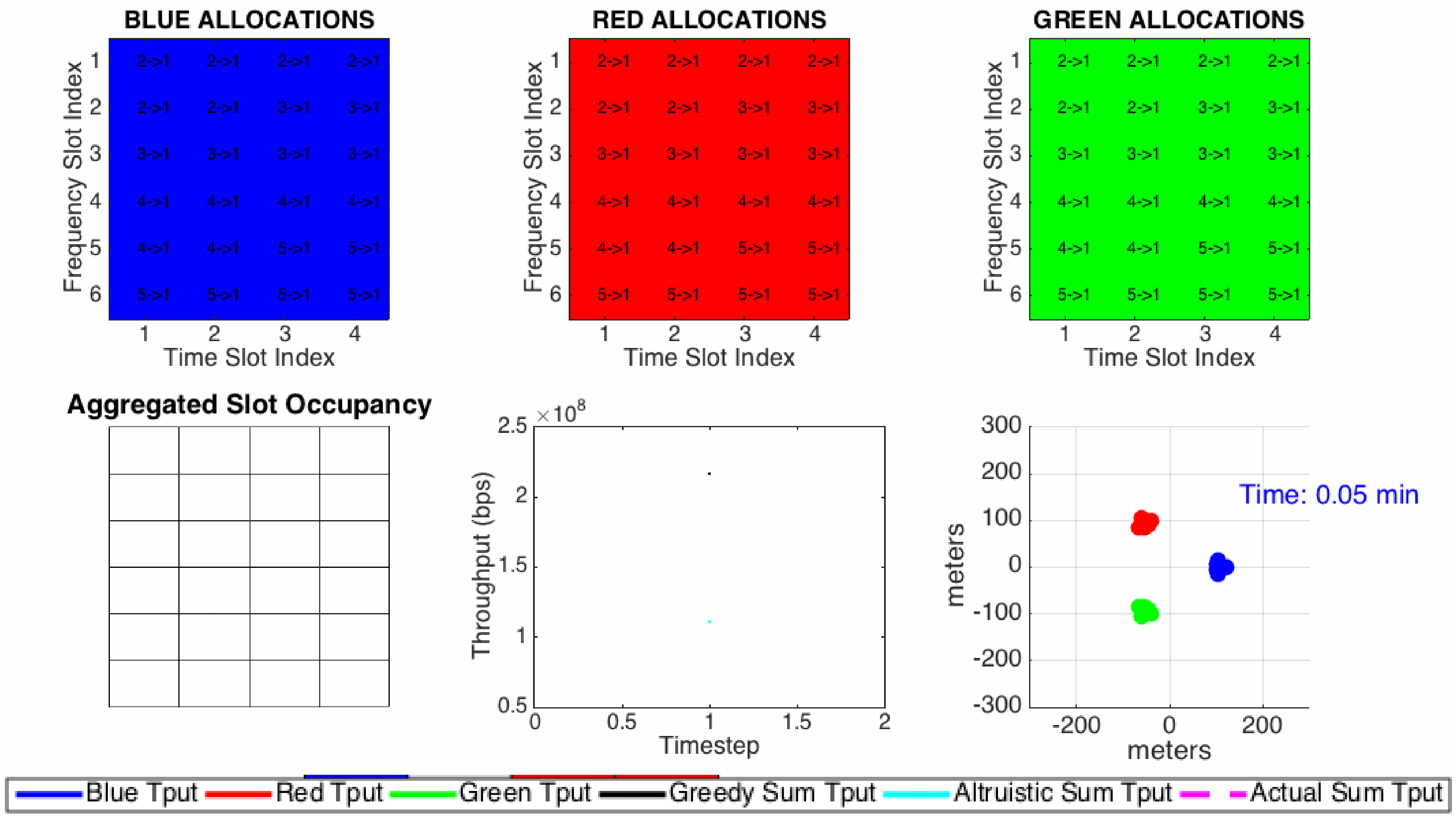


(perfect deconfliction)

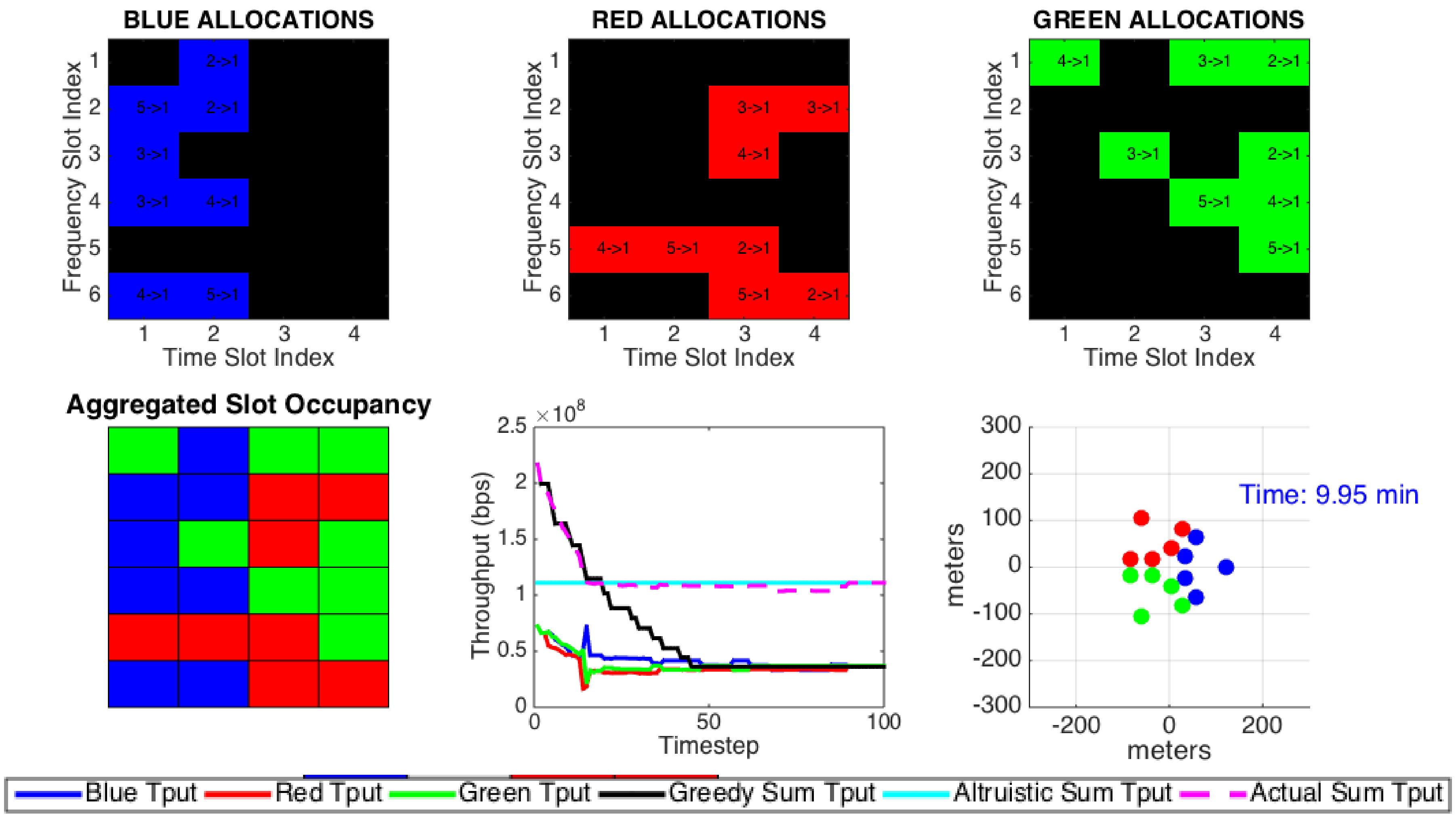
Simulated Algorithm Performance (N-Towers)



Simulated Algorithm Performance (N-Towers)



Simulated Algorithm Performance (N-Towers)



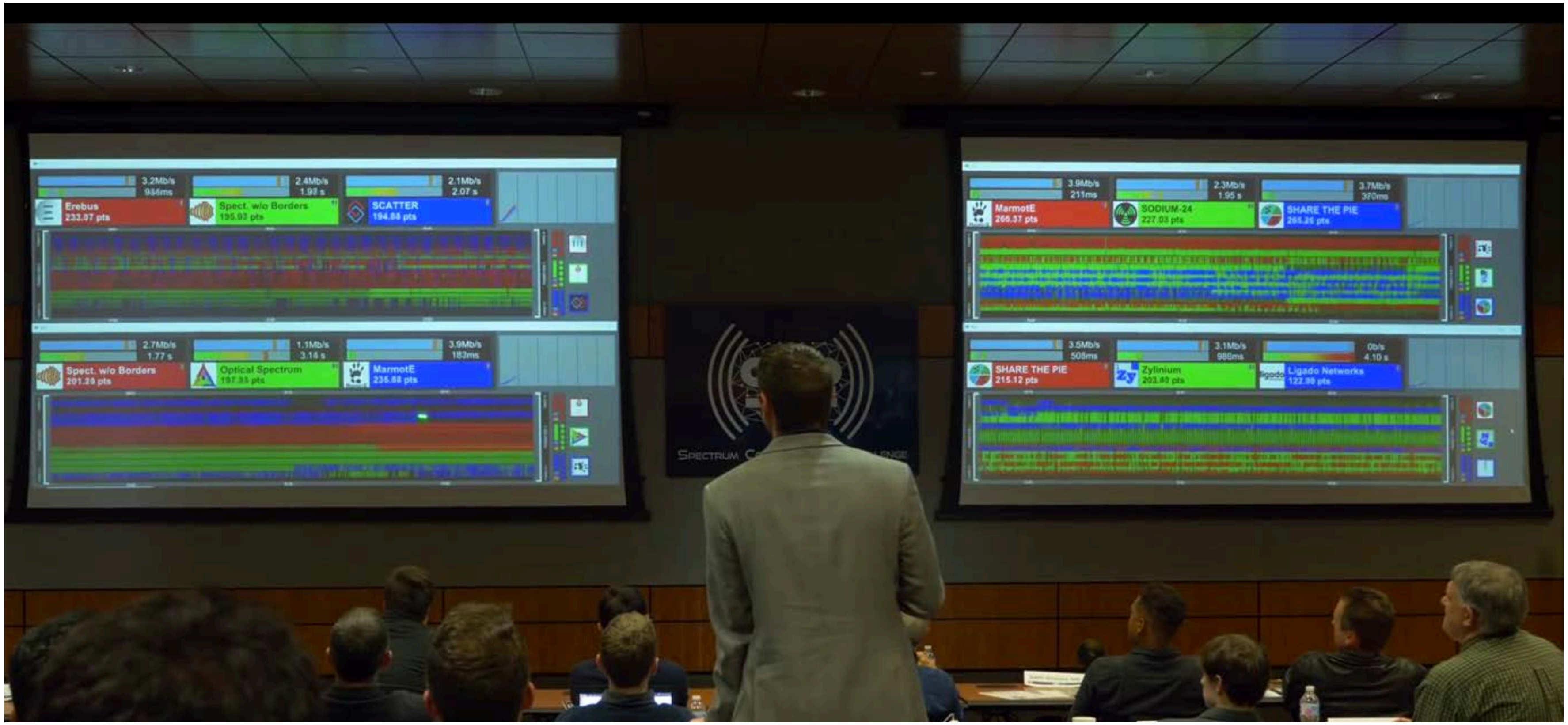
Outline

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

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

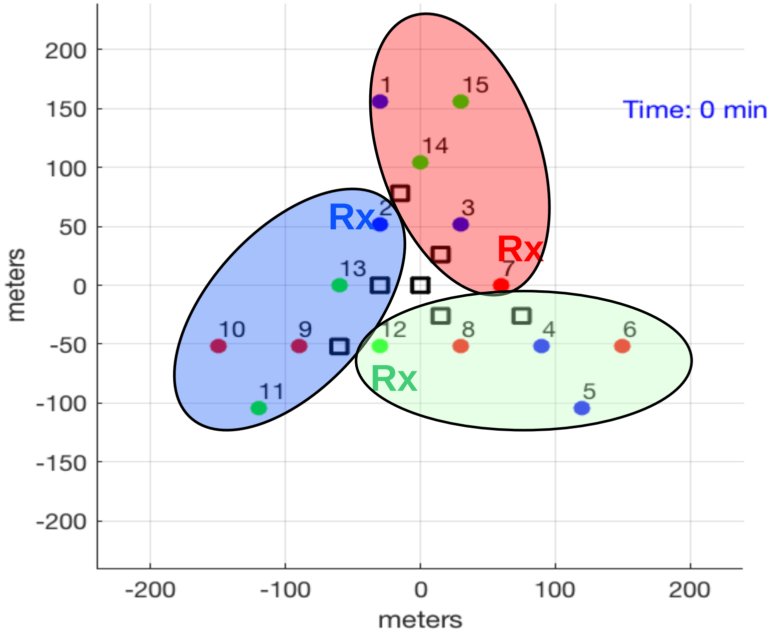
- **Phase 1 Competition in Review**

Preliminary Event 1

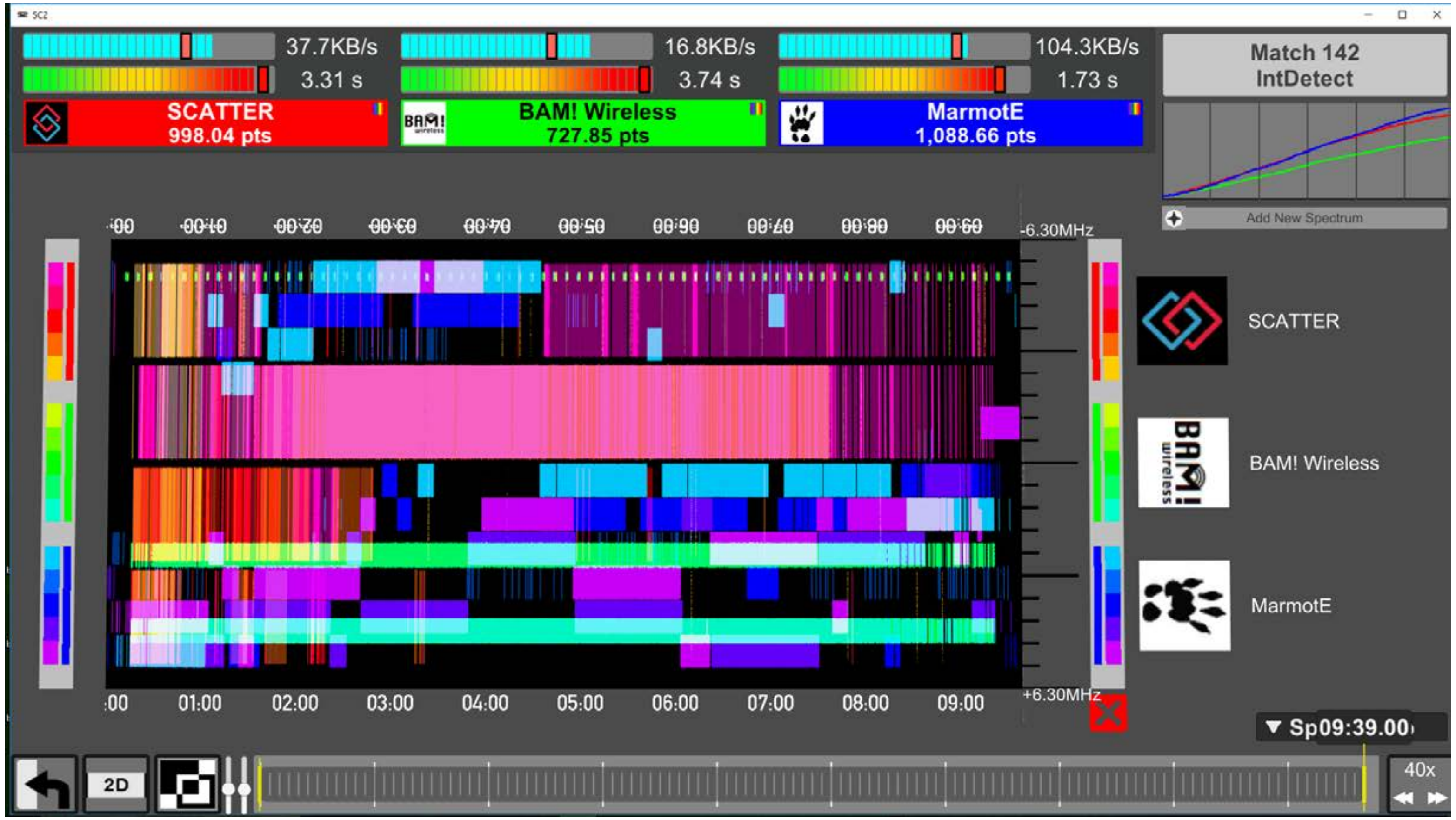


- All matches run in early December
- Results reveal: December 13th 2017, at JHU/APL (Laurel, MD)
- 26 Teams submitted SDR images (19 qualified to compete)

Interference Detective (Match 1)



Composite Spectrum Overlay



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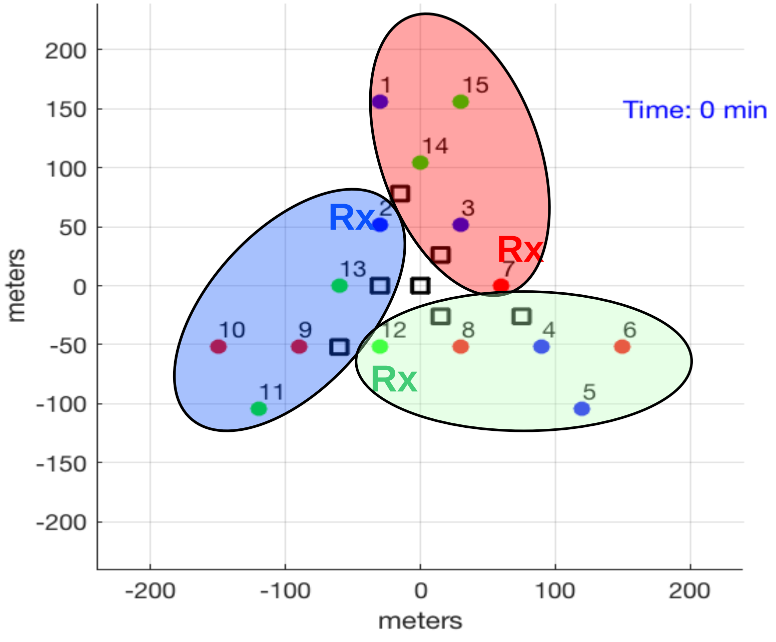
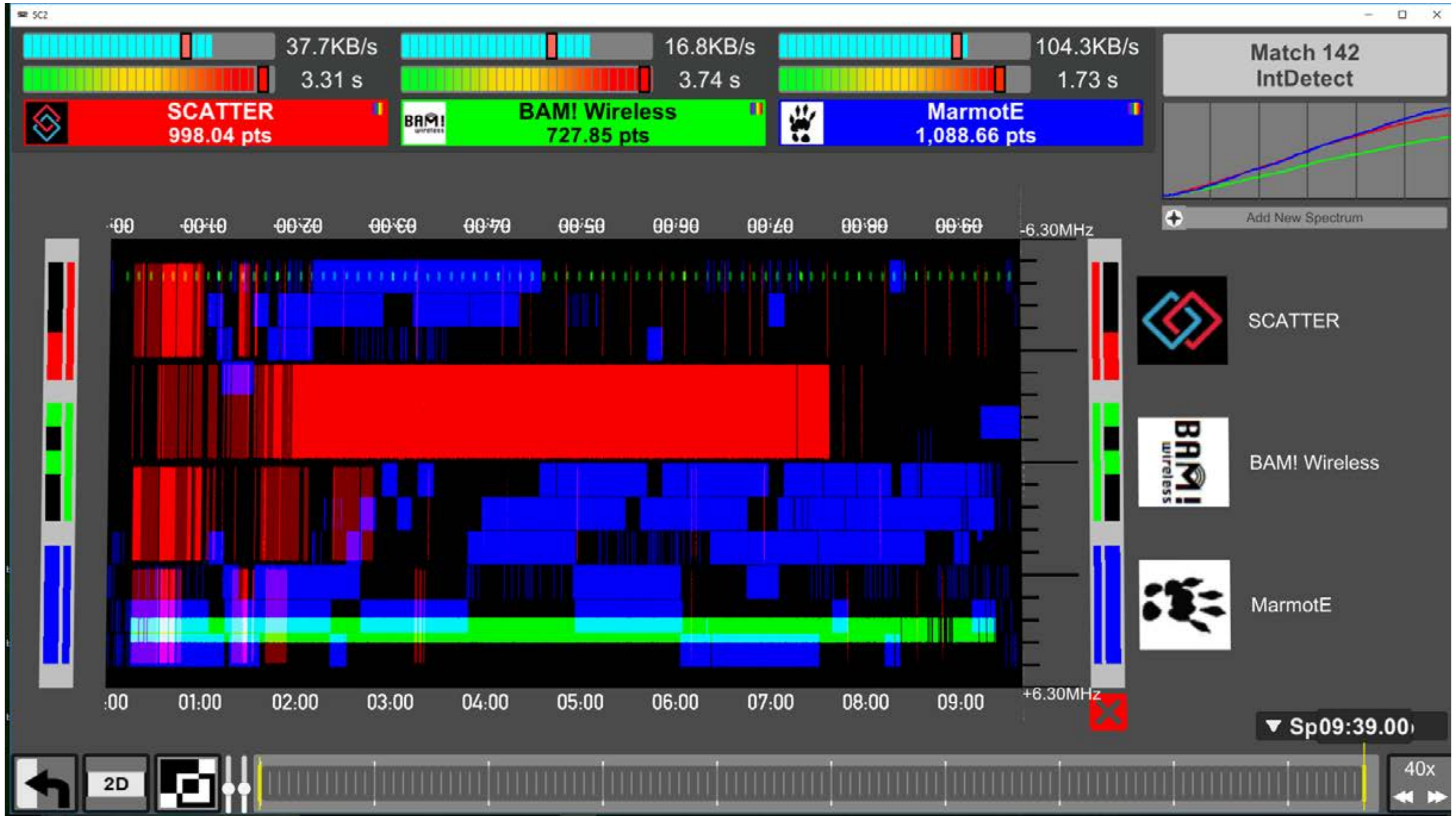
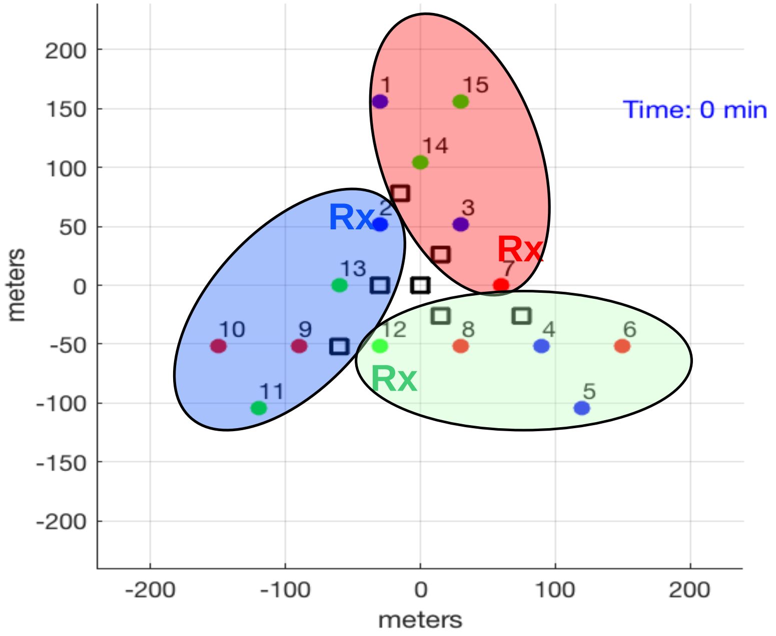
Interference Detective (Match 1)



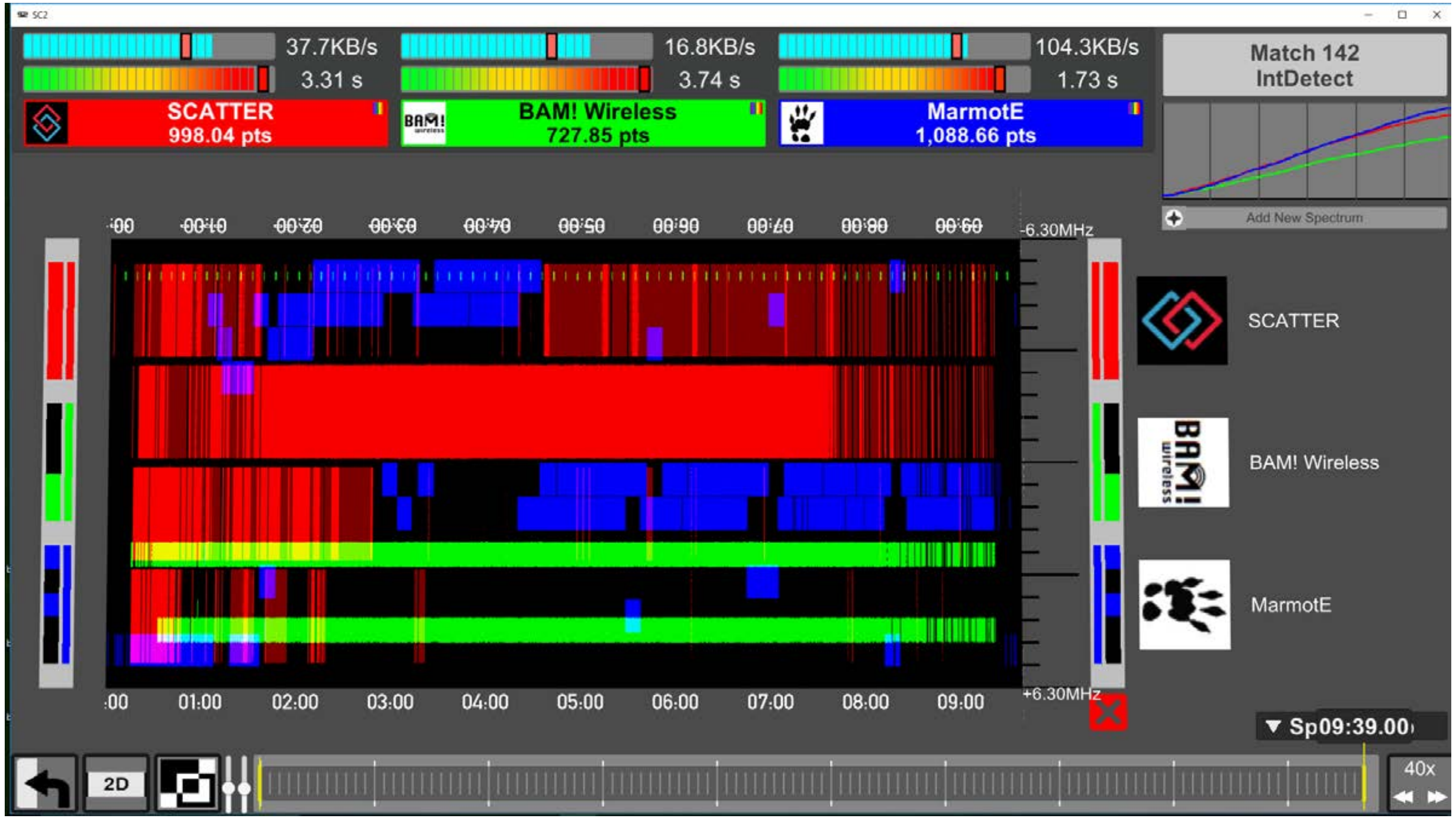
Blue Zone



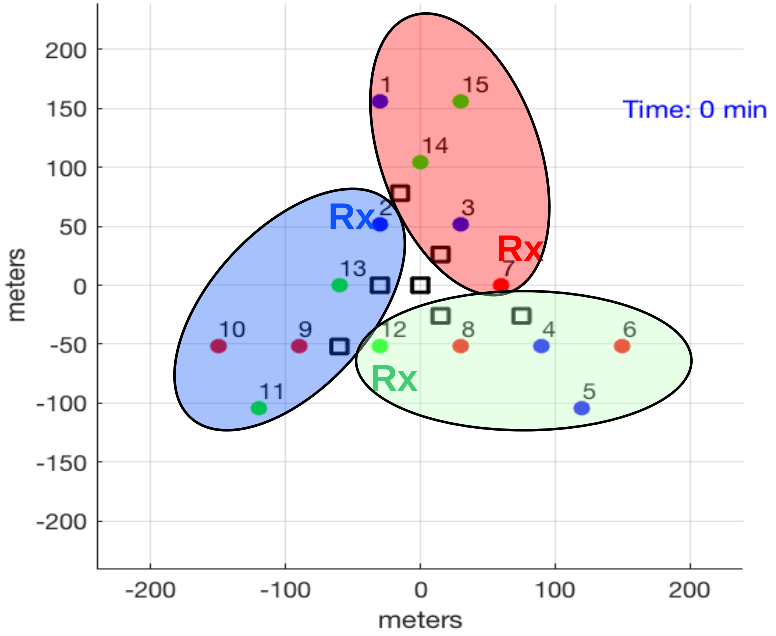
Interference Detective (Match 1)



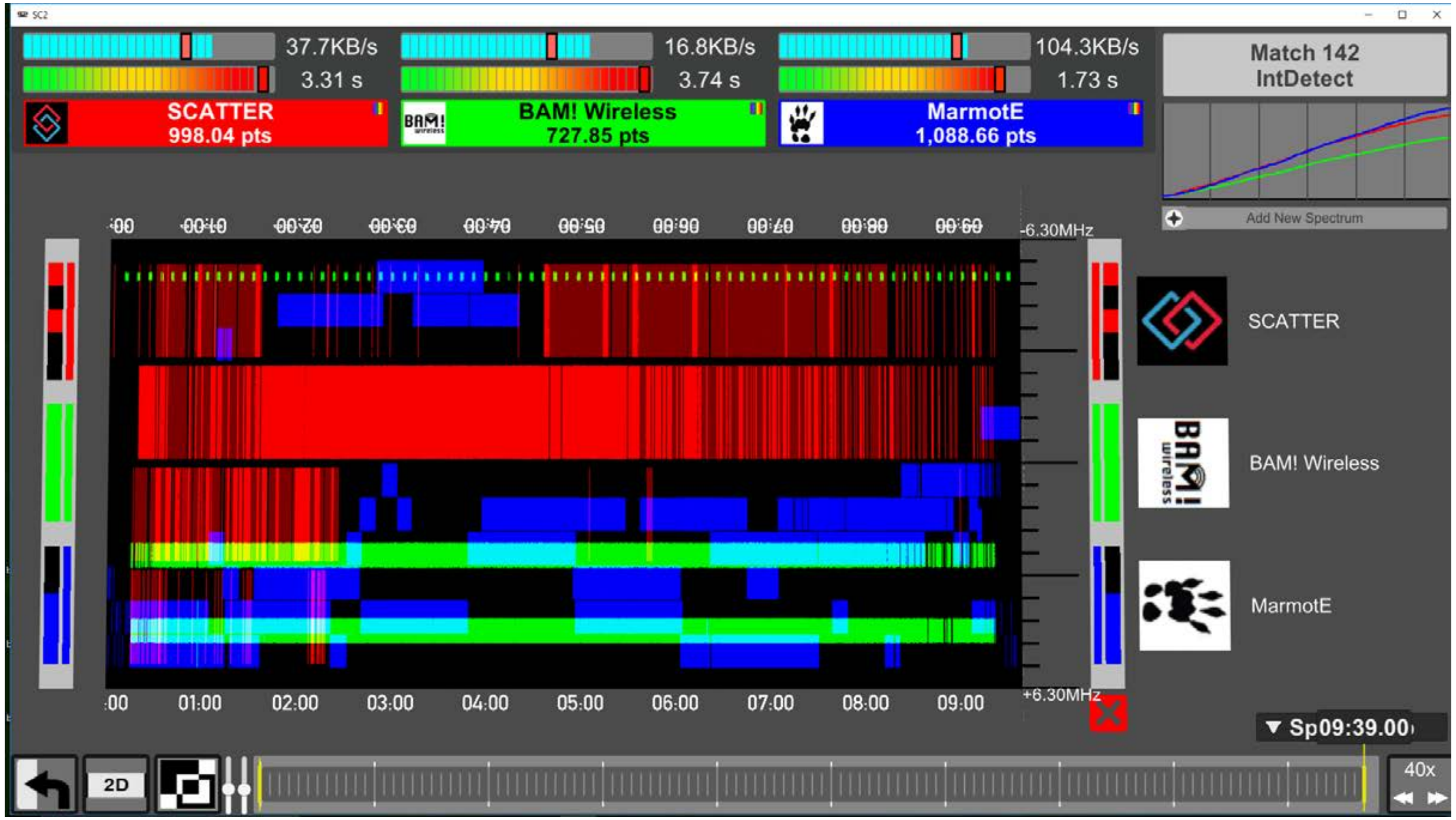
Red Zone



Interference Detective (Match 1)



Green Zone



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

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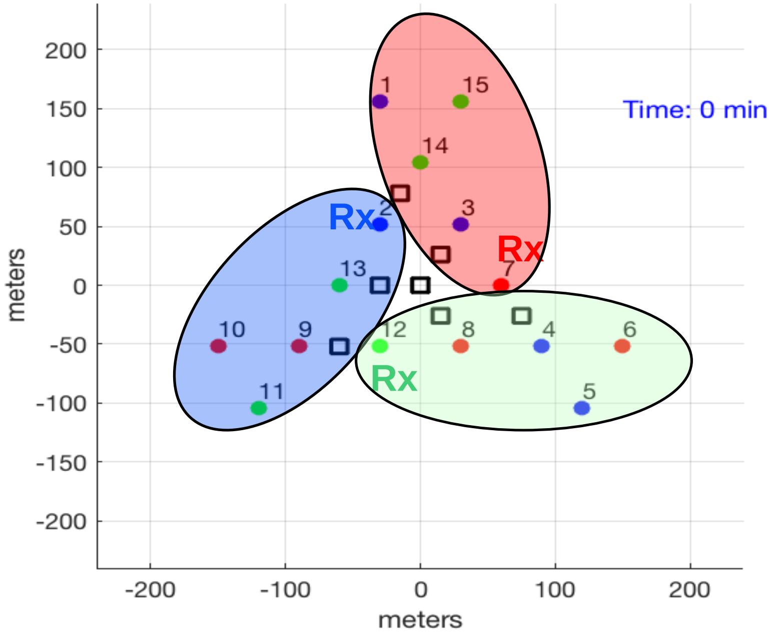
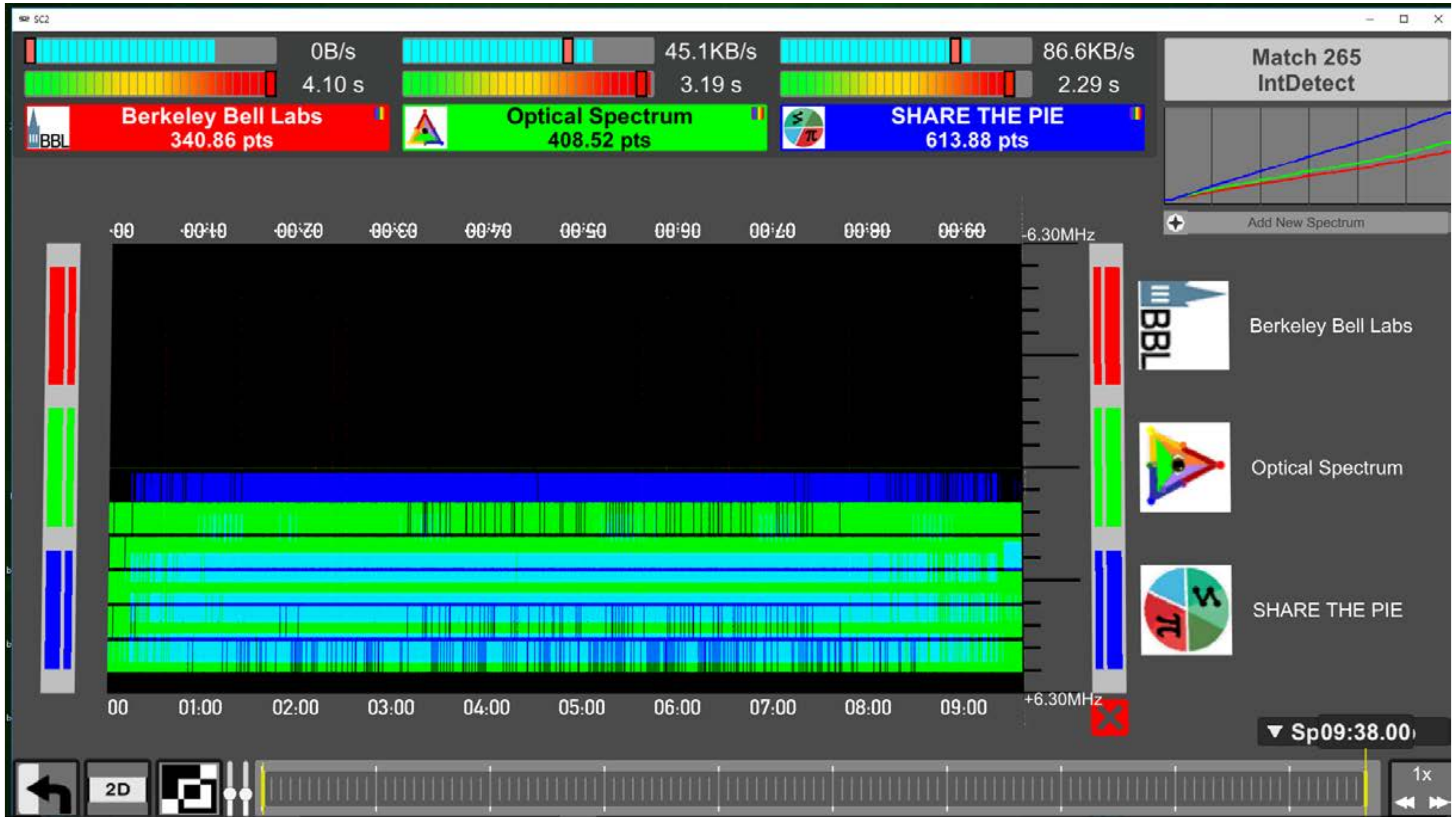
Interference Detective (Match 2)

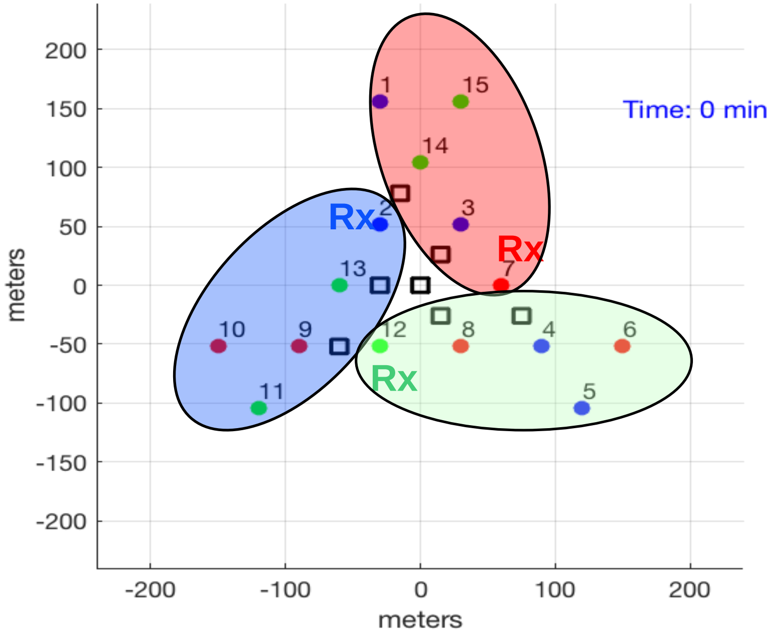


Composite Spectrum Overlay

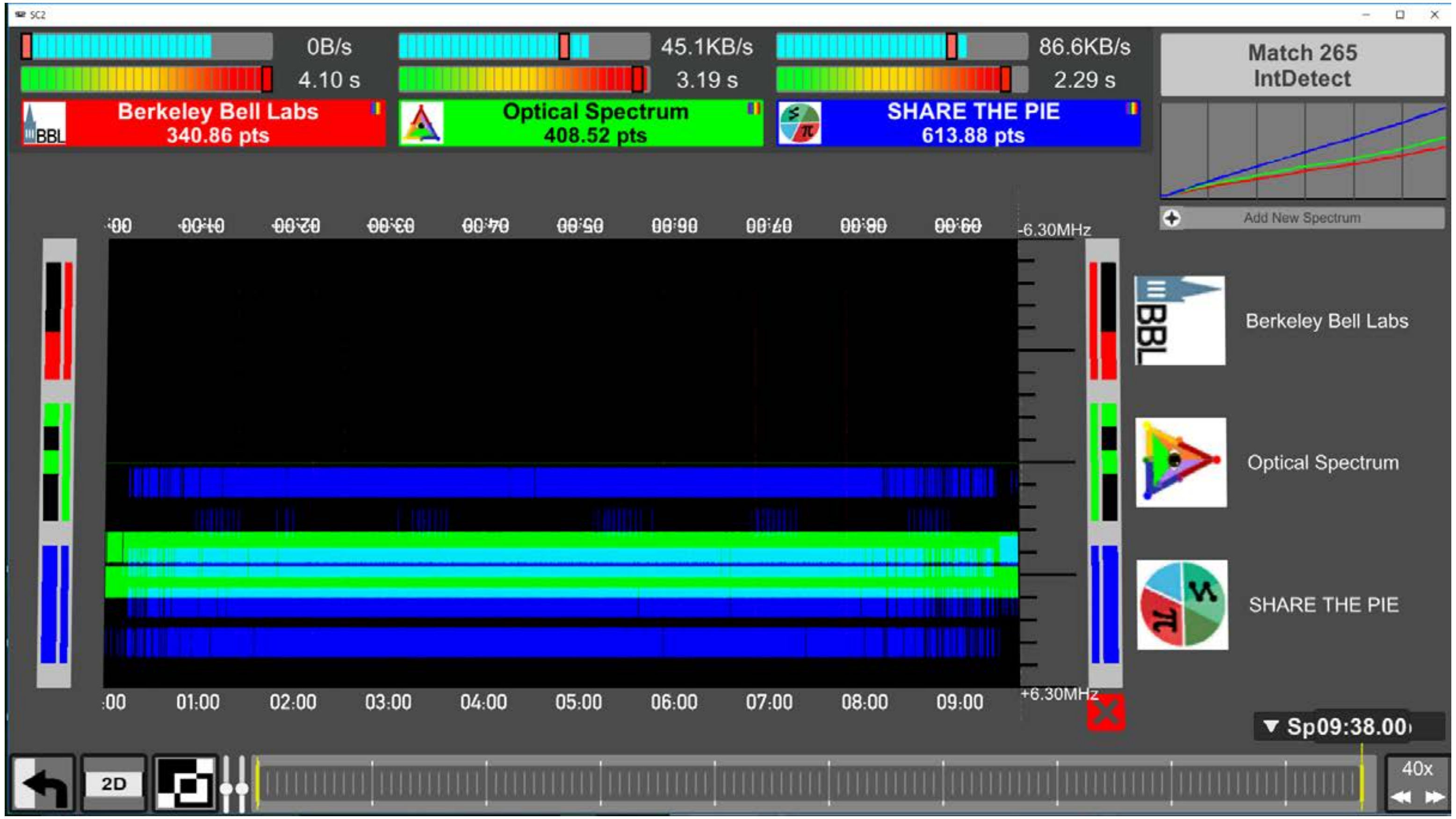


Some matches showed room for improvement in inter-network coordination.

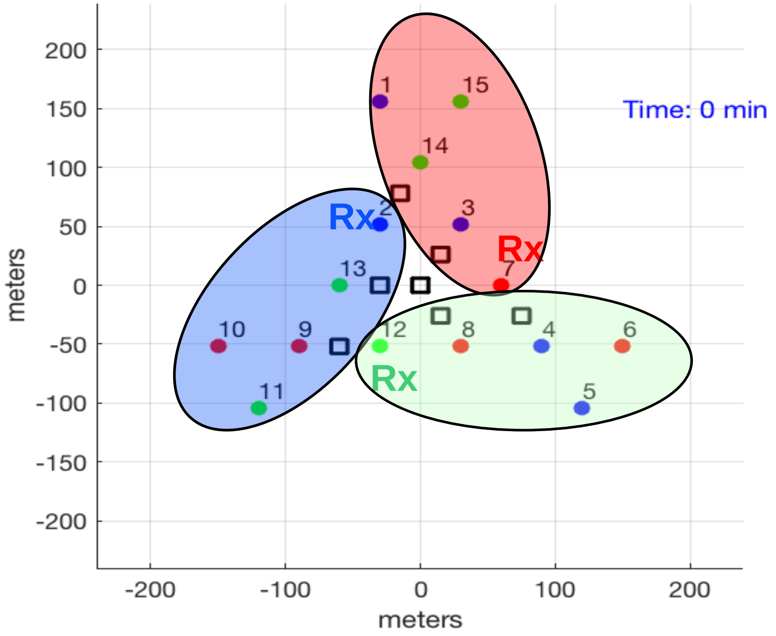
Interference Detective (Match 2)



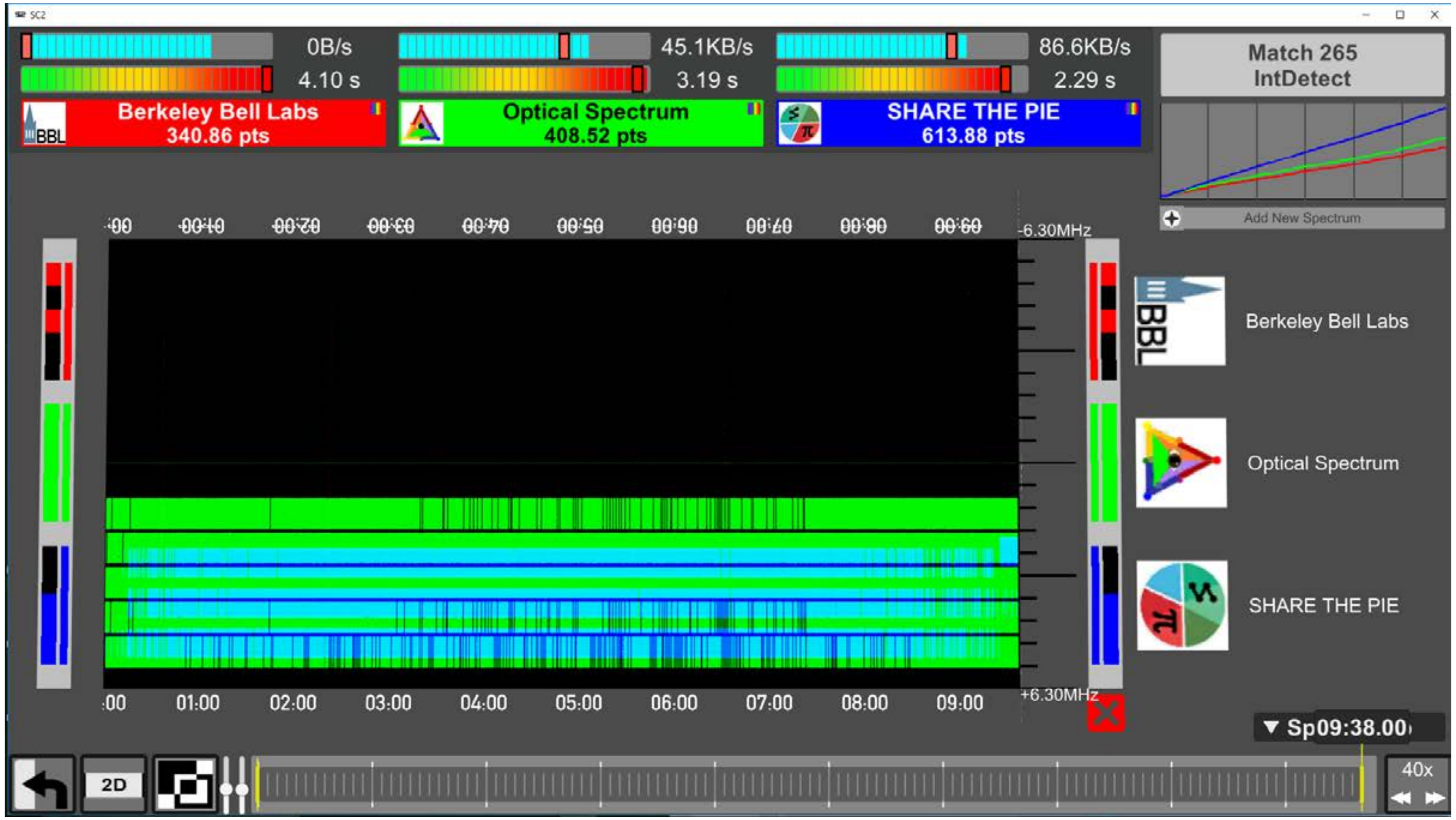
Blue Zone



Interference Detective (Match 2)

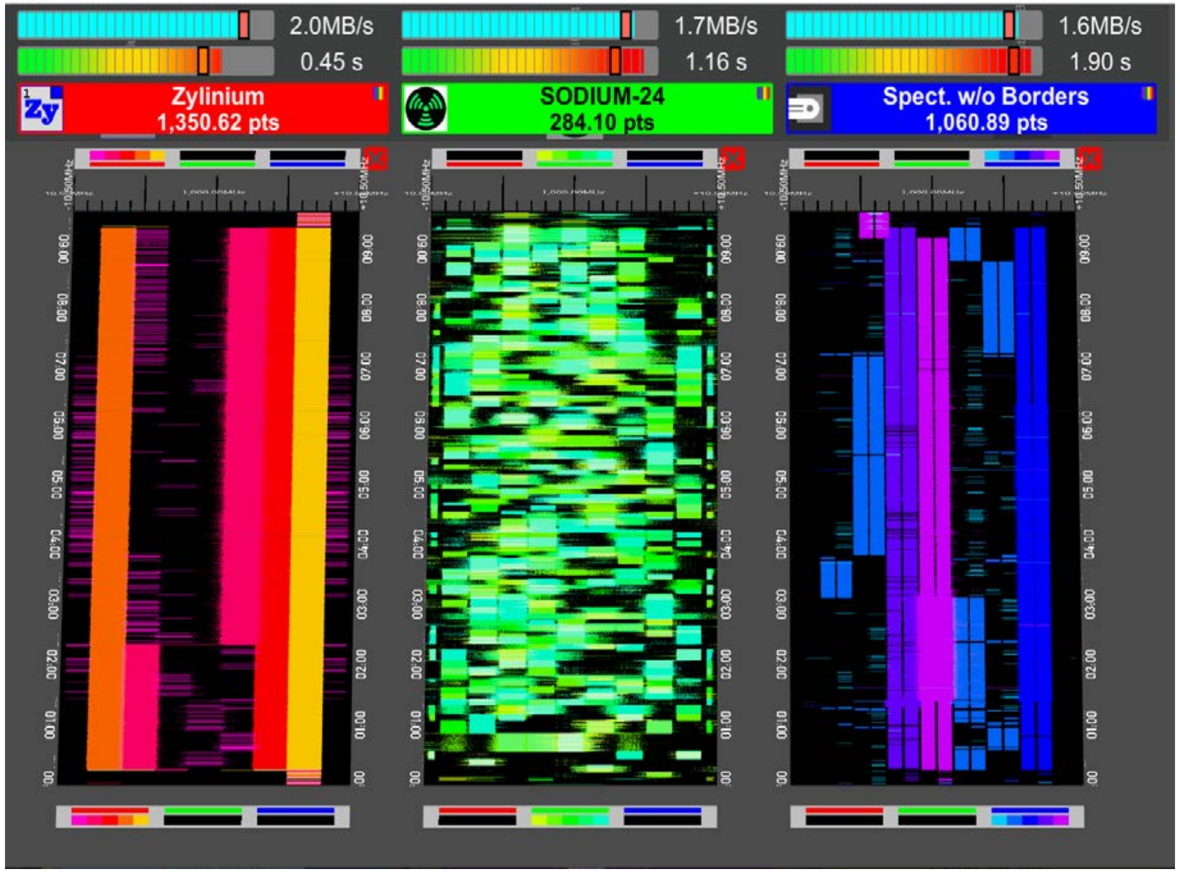


Green Zone

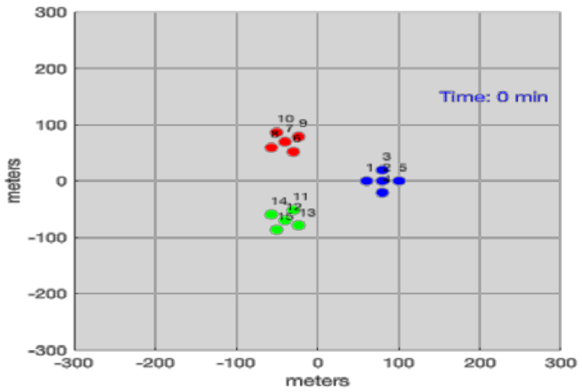


N-Corners

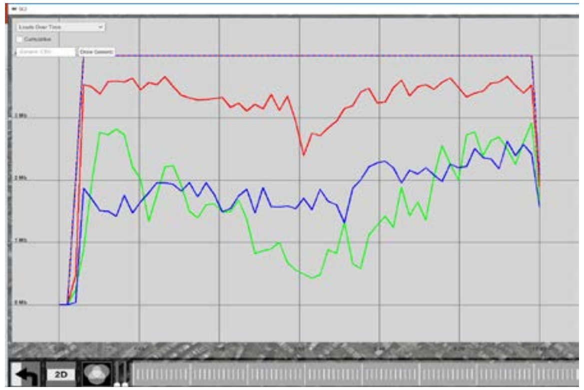
Spectrum Access Waterfall



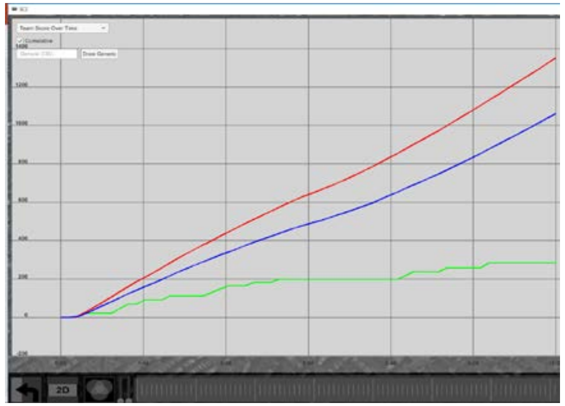
Scenario Map



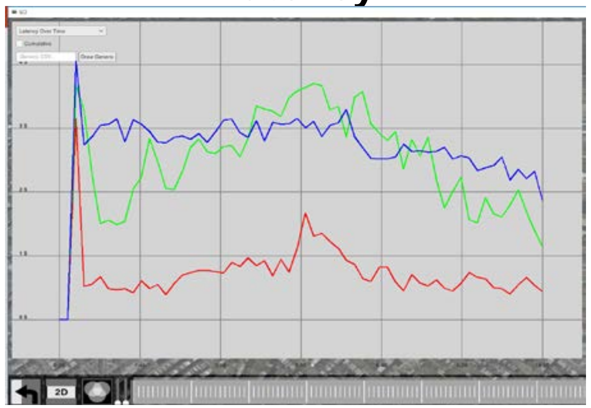
Throughput



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*