Motivation for the Spectrum Collaboration Challenge
The “Spectrum Crunch”

Increasing Spectrum Demand

Dwindling Supply

US Spectrum Auction Pricing

- 2005: $23M / MHz
- 2006: $152M / MHz
- 2008: $306M / MHz
- 2015: $636M / MHz

http://wireless.fcc.gov/auctions/default.htm?job=auctions_all

Email questions to sc2@darpa.mil
Distribution A. Approved for public release
America’s Cup and the beginning of frequency isolation

September 1899
Marconi provides up-to-the-minute reports on America’s cup via spark telegraphy.

October 1899
Marconi equips USN Massachusetts and New York. Interference results from simultaneous ship and shore communication.

April 1900
Marconi’s famous 7777 patent enables frequency tuning on transmit and receive.

https://en.wikipedia.org/wiki/1899_America
http://www.marconicalling.com/

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The Wireless World Today:
A patchwork of planned isolation
Today – Evolving access, but still isolation

Evolution of spectrum access strategies

1920’s

Network A

Licensed

1960’s / 1980’s

Network B

Unlicensed

2010’s

Network C, D, E

Dynamic Spectrum Access

Static Isolation
Systems never operate at the same time, place, channel

Blind “Sharing”
Systems operate without information from others

Coarse Dynamic Isolation
Spectrum is coarsely (re)allocated

Inefficient

Scarce $ / MHz

Vulnerable

20%* utilization unscalable avoidance

Constrainted and well-known operating freqs

New approach needed to realize truly shared and optimized spectrum access


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Vehicle-to-Vehicle Collaboration
AI adapting to changing road conditions, not as a single vehicle, but as an ensemble

http://www.extremetech.com/wp-content/uploads/2014/02/dot-v2v-program_100349712_m.jpg
Only the radios themselves know their interference conditions, so they should be the ones making interference mitigation decisions.

100-1000x increase in efficiency

Autonomous collaboration for efficient spectrum sharing
Radio Network Autonomy Requires Learning

- Autonomy: radio network self-optimizes to changing operating conditions
- Autonomy requires a radio network to repeatedly decide its:
  - frequency
  - waveform
  - antenna direction, hop pattern, time slot, …
- Each decision depends in complex ways on the current situation
  - number and location of devices
  - propagation channel between each device pair
  - other network types and operating characteristics
  - current spectrum use by other networks
- Complex dependencies create combinatorial decision space growth
  - Hard-coded algorithms can only achieve limited autonomy
- Broaden scope of autonomy through *learning*
Learning and Collaboration Are Synergistic

• Learning benefits from information sharing
  • The environment includes other radio networks
  • Accurate information about their needs, outcomes, and plans reduces the combinatorial space
  • If interference occurs, accurate information about why it happened accelerates discovery of successful strategies

• Collaboration benefits from learning
  • Networks seek to optimize others’ performance in addition to their own
  • Much faster combinatorial explosion
  • Hard-coded algorithms are even less effective for collaboration than for single-network autonomy
  • Full state-space isn’t known at design time
An open competition

To develop radio networks

Which can thrive in the spectrum without allocations

Which learn how to adapt across multiple degrees of freedom

Which collaboratively optimize the total spectrum capacity, moment-to-moment
Each team develops a Collaborative Intelligent Radio Network (CIRN)

Winning design is the one that best shares spectrum
- ... with any network(s)
- ... in any environment
- ... without prior knowledge

CIRNs are evaluated in a collaborative, tournament-style competition
SC2 Competition Structure

- SC2 Competition events are “round-robin” tournament style
  - Each match will pair up to 5 competitor teams together (i.e., ensemble)
  - Teams must demonstrate the ability to work with numerous ensembles
  - Overall score determined as a composite across the entire tournament

- Ensuring Fairness of the Competition
  - Ability to create identical RF conditions across matches
  - Play in ensembles with all other eligible radio networks

- Scrimmaging to prepare for tournaments
  - Monthly scrimmages will be established within small “divisions”
Match Overview

One node per network serves as a gateway

Collaboration takes place over internet-like infrastructure connected to the gateway (models realistic internets)

Each node is given IP traffic
Sources and destinations are contained in the same network
Traffic will emulate multiple canonical types

Radio environment emulated in real-time:
- Large-scale path loss
- Multipath & Doppler
- Channel correlation
- Motion

Ensemble of up to 5 teams placed in arena

Incumbent

Arena may also contain other Non-Collaborative Radios (NCR):
- Incumbents
- "Jammers"
Note: Times shown are exemplary. Match durations and change event frequency may be different than shown.
Teams work together to conquer obstacles and find effective communication strategies.
What does a match look like… $T_n$
Just one example of obstacles that may be presented during a match
Scoring

**Match Score** = \( f(\text{performance score, collaboration score}) \)

- A function of:
  - Goodput
  - Prioritization
  - Fairness
  - Quality of Service

- A function of:
  - Other networks’ performance scores
  - Interference to incumbents

**Tournament Score** = weighted sum of match scores

- Scoring formula & mechanisms are under development
- Specifications will be finalized approximately 2 months prior to competition event
Collaboration Protocol

Information exchange between networks

• Important byproduct of SC2
• No such protocol exists today

• What is it?
  • An extensible protocol
  • Large majority of fields are *optional*

• Who is designing it?
  • Everybody
  • Living, growing protocol, to experimentally add to
  • DARPA will periodically merge all the versions in the wild to create a new baseline
Reconfigurable radio

- Adaptability along dimensions of time, frequency, space, code, waveform, MAC scheme, network, etc.

Intelligent radio characteristics

- **Understanding**: Understand and characterize signals to infer the conditions of the local RF environment through noisy observations

- **Reasoning**: Reason about how to take sequential actions to result in successful communication, taking into account the effect the action may have on others using the same spectrum

- **Contextualization**: Contextualize what the system has already learned to be able to rapidly overcome changes and new challenges by leveraging and transferring previous knowledge to these new problems

- **Collaboration**: Learn how to collaborate with previously unknown radio systems by discovering what information is valuable to them to optimize the overall joint outcome while minimizing the cost of collaboration
The ability to interact with and accommodate the needs of other radio systems is predicated on a CIR’s ability to flexibly adapt to the changing scenarios it finds itself in. Strong CIR designs will implement a reconfigurable communications system, exposing their decision-making engines to a wide variety of tunable radio parameters to be able to operate under these scenarios. Proposers will need to consider which tunable parameters are of most value to their CIR’s and the extent to which their radios are able to freely select among them. Tunable frequency, bandwidth, modulation, coding, medium access, spatial directivity, and networking along with the plethora of options available to radio designer under each of these disciplines should be considered. Proposals should discuss the adaptation envelope and justify design decisions.
In order to inform decision making, the proposed systems must understand the composition and characteristics of the RF environment around them. This potentially includes: understanding large and small-scale wireless channel propagation conditions; the ability to train the CIR network to identify non-collaborative wireless systems, including those that may need to be protected; the ability to learn online how to identify (classify) other CIR and non-collaborative radio (NCR) networks without prior knowledge; the ability to create stateful characterizations of other CIR states; and any other information which the CIR may infer about environment which is useful in their decision-making process.

Proposers should address what level of understanding their CIR network will ultimately have, what algorithms the system will use, and what information feeds those algorithms.
A CIR must leverage its current understanding of the RF environment to make the best decision about any changes it may make to its communications strategy. Unlike traditional decision making systems, a CIR is a small piece of a much larger ensemble. For example, changing the type of waveform used by one pair of CIRs may have a ripple effect through the broader collective. As such, a CIR’s decision making process must broadly consider the ramifications of how a particular action may affect the overall ensemble and find the best strategy, not solely for a single CIR, or CIR network, but for the entire collective. Proposers should address how their CIRs will make decisions based on information provided by the understanding process. Proposers should also discuss their approaches for making optimal joint decisions with previously unknown CIRs.
CIR networks comprising the ensemble are expected to rapidly learn (<5 min.) how to respond to changes in a scenario in order to remain an effective radio system (see the SC2 Rules Document for examples). In order to do this effectively, radio systems must contextualize knowledge they have already acquired (both a-priori and online-learned) and determine how to transfer the relevant information to the current scenario. Classically, contextualization has been achieved through leveraging prior knowledge of both the source and target task in order to build an explicit mapping between them ahead of time.

It’s unrealistic to believe that one could give a CIR full knowledge of every scenario it might encounter in the real world. Proposers should describe how their CIRs learn to transfer knowledge from scenario to scenario, enabling the radio system to quickly adapt without extended disruption to their quality of service. A CIR which must "unlearn" previous and inapplicable knowledge and then "relearn" the new scenario will ultimately react too slowly to be a viable radio system. Proposers should describe the basis for their transfer learning strategies.
Collaboration takes place on two fronts: between like CIRs within the same network, and between CIRs of different networks using the collaboration channel. While any two networks will be able to collaborate over a wired channel, the information to be shared, and the resulting decisions, must be distributed throughout the networks wirelessly. This overhead implies a cost to collaboration. Sending all information, to every CIR, all the time, is neither a tenable nor scalable approach to collaborating. A CIR should judiciously find the optimal information sharing strategy, such that throughput is maximized and collaboration excess is minimized. Intra-network collaboration can be optimized as part of the design, however in the inter-network case it can’t be known a-priori what information, under what context, will be useful to other networks. The specific instantiation of the inter-network protocol will be determined by a Government-led working group consisting of all participants prior to PE1.
DARPA seeking innovative approaches for a new breed of radio network

- Collaborative
- Intelligent
- Practical

Incremental evolution of existing approaches are not sought

- Open loop only (e.g., non-collaborative) approaches
- “Whitespace hunting”
- Approaches which rely on hardware other than the SRNs provided

Paradigm shifting – approaches do not have to be constrained by traditional comms architectures (military and commercial)
Program Structure
Program Participation Options

Competitors
Radio Network Development

Open Track
Unfunded

Proposal Track
Funded

• Testbed Access
• Scrimmages
• Tournaments

Prize Awards

Architecture Development
• Scoring Methodology
• Scenario Development
• Integrity Development

SC2 Rules Doc
DARPA-BAA-16-47

DARPA-BAA-16-48
Proposal vs Open Track Funding and Prize Awards

PE1/2: Preliminary Events
SCE: SC2 Championship Event
New team registration and hurdles process also available at start of Phase 2 and 3
Characteristics of the two tracks:

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Proposal Track</th>
<th>Open Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respond to this BAA (DARPA-BAA-16-47)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Contract funding</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Submit Application Form</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Complete Entrance Hurdles</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Cash prizes at PE1, PE2 and SCE</td>
<td>SCE only</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- Proposal Track teams receiving an award through DARPA-BAA-16-47 may not simultaneously participate in the Open Track. However, a team whose proposal is not selected for DARPA funding under the Proposal Track may opt to register under the Open Track.

- Proposal Track teams are treated identically to Open Track teams during the competitive events and have the potential to compete with each other in the Preliminary and Championship events.
  - SC2 Rules Document
  - SC2 System Specification Document
  - Access to SC2 Testbed, Standard Radio Node (SRN), Scrimmages, etc.
Program Tournaments

• Each team independently develops Collaborative Intelligent Radio (CIR) networks
  • Teams may develop protocols, waveforms, ML algorithms and backchannel collaboration using the Standard Radio Node (SRN)
  • DARPA testing and evaluation performed on the Colosseum testbed

• The number of radios and network size used in tournaments increase with each program phase
  • Scenario complexity will become more challenging

• Preliminary Event tournaments are held at the end of Phase 1 and 2. Top finishers are automatically qualified to enter the next phase
  • Scrimmages are planned throughout each phase

<table>
<thead>
<tr>
<th></th>
<th>Phase 1 PE1</th>
<th>Phase 2 PE2</th>
<th>Phase 3 SCE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of radios in a network</strong></td>
<td>5</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td><strong>Number of networks (teams) per match</strong></td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
Teams are encouraged to disseminate and publish their work
  - No prior review or restriction by DARPA (except for proposal track groups that are
    not conducting fundamental research)

SC2 anti-collusion rules apply
  - Teams must not disseminate information that would affect competition fairness
  - PRIOR to the end of Phase N:
    - Information about Phase N algorithms or design is presumed to affect fairness
    - unless it clearly does not disclose behavioral details of the team’s CIRN
  - AFTER the end of Phase N:
    - Information about the Phase N algorithms or design is presumed NOT to affect fairness

- Use of an unprotected online collaboration tool (such as code repository or
  discussion board) is considered dissemination

Teams violating the anti-collusion rules may be disqualified from the
competition