Decentralized Cooperative Networking

PI: Leonard J. Cimini, Jr. (Univ. of Delaware)

Res. Assts.: H. Feng, Y. Xiao

Post-Doc: H. Wang

Collaborator: C.-C. Shen, Delaware

J. Walsh and S.Weber, Drexel

S. Sarkar, Penn

J. Garcia-Frias, Delaware

AFOSR Complex Networks Workshop (Nov. 29-Dec. 3, 2010, Arlington, VA)

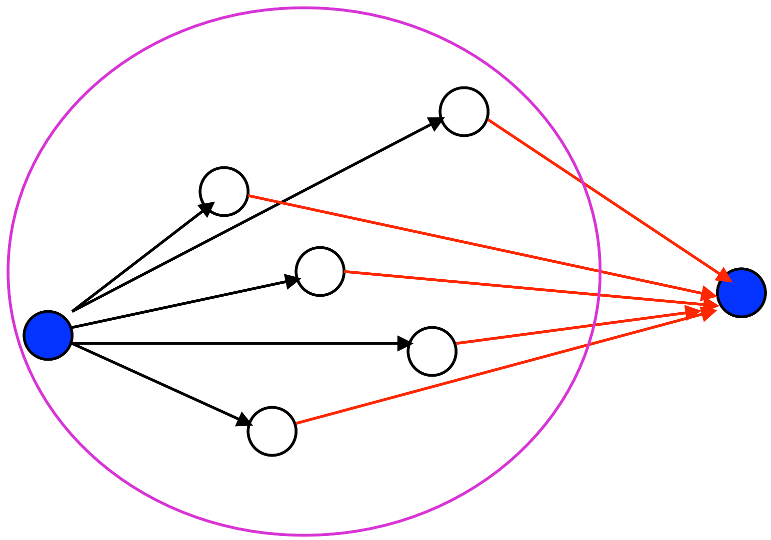
FA9550-09-1-0175

Outline

- Cooperative Networking
- Project Focus and Current Research
- Energy Efficient Distributed Resource Allocation
- Summary

Cooperative Networking

- Single-antenna nodes transmit as a virtual antenna array
- Potential advantages:
  - Increased bandwidth efficiency
  - Reduced energy consumption
  - More reliable and longer lasting network connectivity



Issues:
- Relay selection
- Transmit precoding
- Receiver processing
- Information exchange
- Synchronization, …
- Network performance

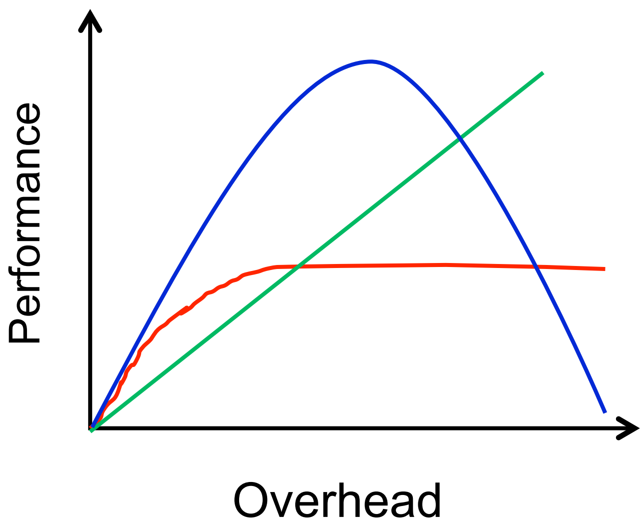
- Objective: Cooperative strategies for reliable and robust connectivity in highly dynamic, energy- and bandwidth-constrained, networks.

Project Focus and Current Research

- Focus
  - Decentralized, distributed algs. with low overhead
  - Locally obtained info. → globally “good”, robust to uncertainties
  - Realistic propagation and network scenarios (“cost”)
- Decentralized Cooperative Networking
  - Low-overhead, location-aware, cooperative routing
  - Decentralized, cooperative OFDM-based resource allocation
  - Evaluation/management of interference
- Realistic Evaluation of Coop. in a Net. Context (“Analysis”)
- Optimization with Overhead Constraints (“Synthesis”)

Overhead Considerations

Goal: Trade-off between overhead and performance when using cooperation in a multihop networking context



- How to quantify the overhead required for a given protocol?
- How to relate performance and overhead?
- What is the optimal design for a given amount of overhead and a specified performance?

Energy Efficient Dist. Res. Allocation

Collaborators: John Walsh and Steven Weber, Drexel
Saswati Sarkar, Drexel
Javier Garcia-Frias, Delaware

Objective: Design an allocation algorithm for a network of nodes that maximizes performance while meeting QoS demand

Problem:

– Observations (e.g., channel gains, queue lengths), y, are distributed at different nodes throughout network
– Control policies, x(y) (resource allocations) chosen as

$$x^*(y) \in \arg\max \max_{x \mid P[x \in C(y,h)] \geq 1-\varepsilon} E[J(x,y,h) \mid y]$$

where

C(h) = network constraints
h = hidden, unobserved variables
ε = small failure probability

Energy Efficient Dist. Res. Allocation

Focus: self-organizing, efficient OFDMA ad hoc networks

- Maximize energy efficiency while providing QoS to network apps
- Nodes select: Tx powers, subcarriers, the connection the subcarriers are assigned to, and the subcarrier modulation and coding rates
- Control variables depend on:
  - channel coefficients
  - which connections are requested and QoS requirements
- Assume this information is not available collectively at any node

For a given amount of collaboration overhead, what is the performance gap from what an omniscient centralized controller could achieve?

How can a distributed, low-complexity, scheduler be built to approach the efficiency of the centralized scheduler's design?

How much information do nodes need to exchange in order to achieve a target energy efficiency and QoS?

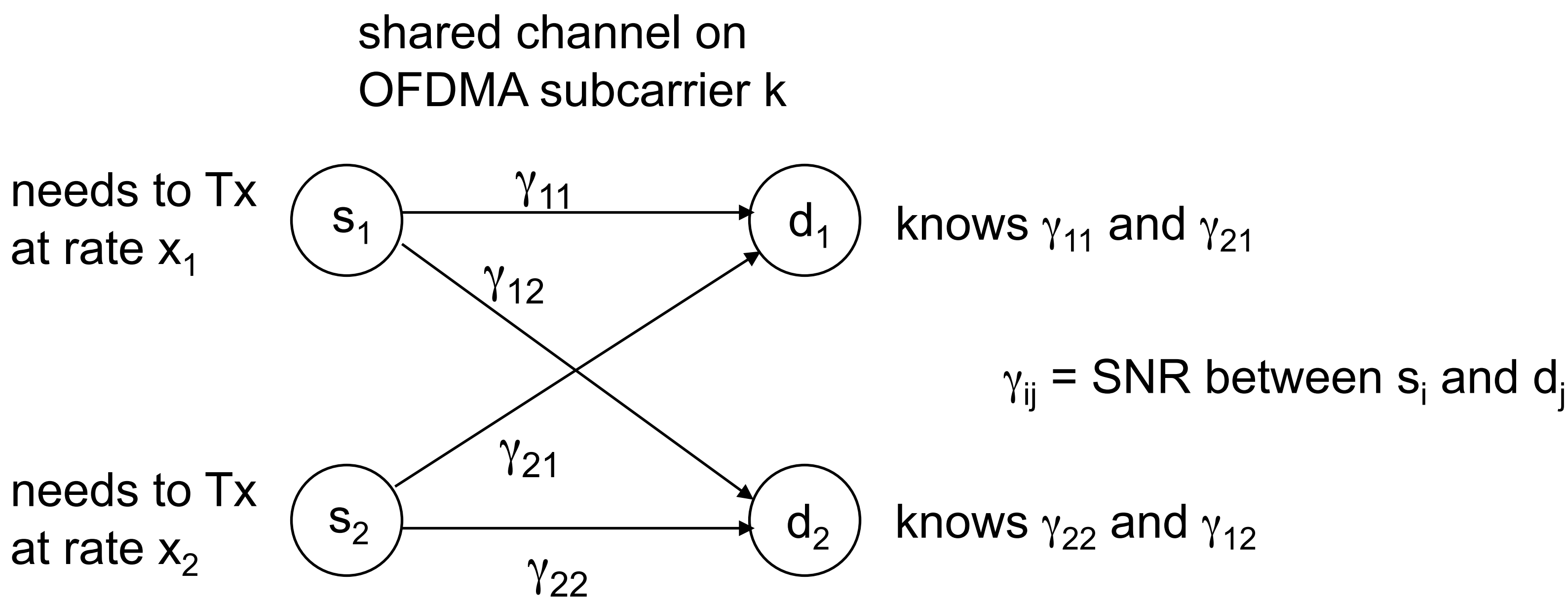
Energy Efficient Dist. Res. Allocation
Distributed Source Coding

- Use multiterminal rate distortion theory:
  - Think of information exchange and algorithm that leads to resource allocations as a lossy (rate distortion) code itself.
  - Sum rate of code = amount of overhead information exchanged in making the resource decisions
  - Distortion = energy efficiency and QoS
- The key idea is to consider x*(y) itself as a random variable, and measure the amount of collaboration necessary to reach a certain gap from the optimal performance. For example, consider the metric

$$\boxed{d(x^*, \hat{x}) = E[J(x^*, y, h) - J(\hat{x}, y, h)]}$$

- Objectives
  - Quantify tradeoffs between overhead and performance
  - Evaluate existing algorithms against fundamental bounds
  - Design new algorithms for specified levels of overhead and perf.

Maximum Spectral Efficiency Res. Allocation



- Destinations d_1 and d_2 know the SNRs on their own channels.
- Sources s_1 and s_2 must determine which subcarriers to use and the rates (modulation and coding) to maximize the spectral efficiency.
- No interference cancellation → treat signal from other transmitter as noise
- Omniscient controller simply selects weights as simple function of all SNRs
- Sources do not know all SNRs → d_1 and d_2 must communicate with s_1 and s_2 over a feedback channel to come up with estimates for rates.

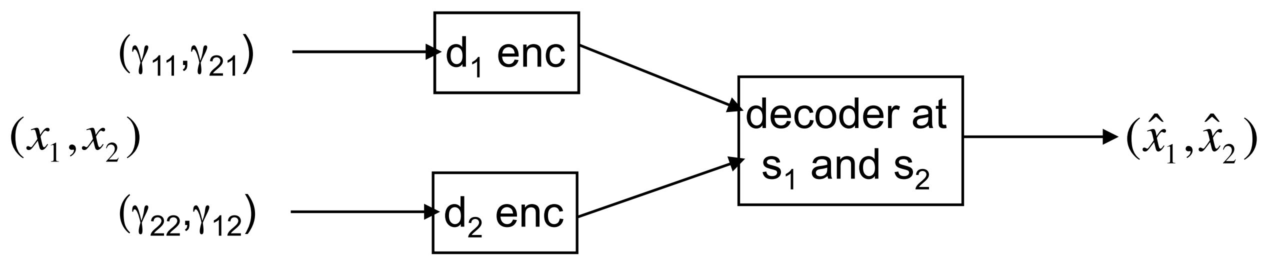
Maximum Spectral Efficiency Res. Allocation

CEO Problem

- Determine the number of overhead bits per carrier broadcasted from the destination nodes as a function of the gap to the optimal efficiency.

- Each node encodes its local observations into a series of finite rate messages sent to the other nodes.
- The rate distortion problem is to study the region of rates which allow a gap to centralized optimality not greater than D.

- This can be reorganized as the CEO problem, and solved using tools from multiterminal source coding theory.



Maximum Spectral Efficiency Res. Allocation

Omniscient Resource Controller

- Use spectral efficiency, η, as measure of performance.
- Allocate rates, blocks of subcarriers, and transmit powers.
- x_i^k = Tx rate on subcarrier k that maximizes total spectral efficiency (under successful transmission constraint)

$$\eta = \frac{1}{K}\sum_{k=1}^{K}\left(x_1^k + x_2^k\right)$$

$$x_1^k = \begin{cases} \log_2(1+\gamma_{11}^k), & \gamma_{11}^k > \max\{\gamma_{22}^k, \gamma_c^k\} \\ \log_2\left(1+\dfrac{\gamma_{11}^k}{1+\gamma_{21}^k}\right), & \gamma_c^k \geq \max\{\gamma_{11}^k, \gamma_{22}^k\} \\ 0, & \gamma_{22}^k > \max\{\gamma_{11}^k, \gamma_c^k\} \end{cases} \quad \gamma_c^k = \left(1+\frac{\gamma_{11}^k}{1+\gamma_{21}^k}\right)\left(1+\frac{\gamma_{22}^k}{1+\gamma_{12}^k}\right)-1$$

#1 transmits on subcarrier k or #2 transmits on subcarrier k or both transmit

Maximum Spectral Efficiency Res. Allocation

Imperfect Allocation

- s_1 and s_2 only have the messages sent from d_1 and d_2, and not the SNRs themselves → they may not perfectly calculate x_1 and x_2.
- So, the spectral efficiency will be

$$\eta = \frac{1}{K}\sum_{k=1}^{K} g\left(\hat{x}_1^k, \hat{x}_2^k\right)$$

$$g\left(\hat{x}_1^k, \hat{x}_2^k\right) = \hat{x}_1^k 1\left[\left\{\hat{x}_2^k = 0 \cap \hat{x}_1^k \le \log_2\left(1+\gamma_{11}^k\right)\right\} \cup \left\{\hat{x}_2^k \neq 0 \cap \hat{x}_1^k \le \log_2\left(1+\frac{\gamma_{11}^k}{1+\gamma_{21}^k}\right)\right\}\right]$$

$$+ \hat{x}_2^k 1\left[\left\{\hat{x}_1^k = 0 \cap \hat{x}_2^k \le \log_2\left(1+\gamma_{22}^k\right)\right\} \cup \left\{\hat{x}_1^k \neq 0 \cap \hat{x}_2^k \le \log_2\left(1+\frac{\gamma_{22}^k}{1+\gamma_{12}^k}\right)\right\}\right]$$

- Treat the reduction in efficiency as a distortion metric

$$d(\mathbf{x}, \hat{\mathbf{x}}) = x_1 + x_2 - g(\hat{x}_1, \hat{x}_2)$$

We can quantify the relationship between overhead and efficiency by applying the Berger-Tung bounds for the CEO problem.

Maximum Spectral Efficiency Res. Allocation

Upper Bound (Berger-Tung Inner Bound)

Using the rate-distortion formulation, the # of collaboration bits per carrier for a given gap to the optimum is upper bounded by the solution to

$$\min I((\gamma_{11},\gamma_{22},\gamma_{21},\gamma_{12});(U_1,U_2))$$

where I is the mutual information between the SNRs and the auxiliary random variables U_1 (represents message from d_1) and U_2 (from d_2)

under the distortion constraint

$$E\left\{d\left[\begin{pmatrix}x_1\\x_2\end{pmatrix},\begin{pmatrix}\hat{x}_1\\\hat{x}_2\end{pmatrix}\right]\right\}\le D$$

Reflect info. available to encoders to form their messages

and the Markov chain constraints

$$x_1,x_2,\gamma_{11},\gamma_{22},\gamma_{12},\gamma_{21}\leftrightarrow U_1,U_2\leftrightarrow \hat{x}_1,\hat{x}_2$$

$$U_2,x_1,x_2,\gamma_{22},\gamma_{12}\leftrightarrow \gamma_{11},\gamma_{21}\leftrightarrow U_1$$

$$U_1,x_1,x_2,\gamma_{11},\gamma_{21}\leftrightarrow \gamma_{22},\gamma_{12}\leftrightarrow U_2$$

U_1 can only depend on $(\gamma_{12},\gamma_{22},x_1,x_2)$ through these observations

d_1 can only encode its local observations $(\gamma_{11},\gamma_{21})$ to get U_1

Maximum Spectral Efficiency Res. Allocation

Lower Bound (Berger-Tung Outer Bound)

- Same distortion constraint, but with alternate Markov constraints

$$x_1, x_2, \gamma_{11}, \gamma_{22}, \gamma_{12}, \gamma_{21} \leftrightarrow U_1, U_2 \leftrightarrow \hat{x}_1, \hat{x}_2$$
$$x_1, x_2, \gamma_{22}, \gamma_{12} \leftrightarrow \gamma_{11}, \gamma_{21} \leftrightarrow U_1$$
$$x_1, x_2, \gamma_{11}, \gamma_{21} \leftrightarrow \gamma_{22}, \gamma_{12} \leftrightarrow U_2$$

- More difficult to prove → Obtain simpler (looser) bound
  - Assume destination nodes know each others SNRs
  - Using the rate distortion function

$$\min I((\gamma_{11}, \gamma_{22}, \gamma_{21}, \gamma_{12}); (\hat{x}_1, \hat{x}_2))$$

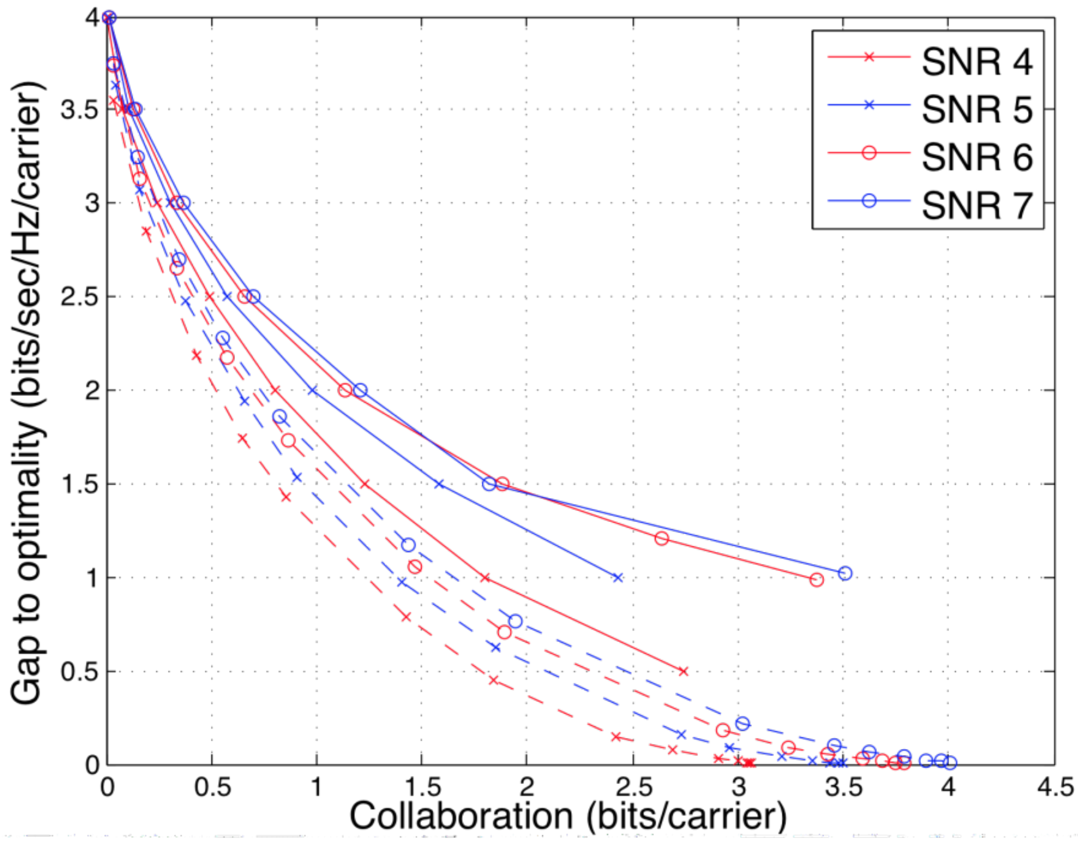
  - Under the same distortion constraint with the Markov constraint

$$x_1, x_2 \leftrightarrow \gamma_{11}, \gamma_{22}, \gamma_{21}, \gamma_{12} \leftrightarrow \hat{x}_1, \hat{x}_2$$

  - Can be computed using the alternating minimization of the Blahut-Arimoto algorithm.

Collaboration-Efficiency Tradeoff

Sensitivity to "Quantization"



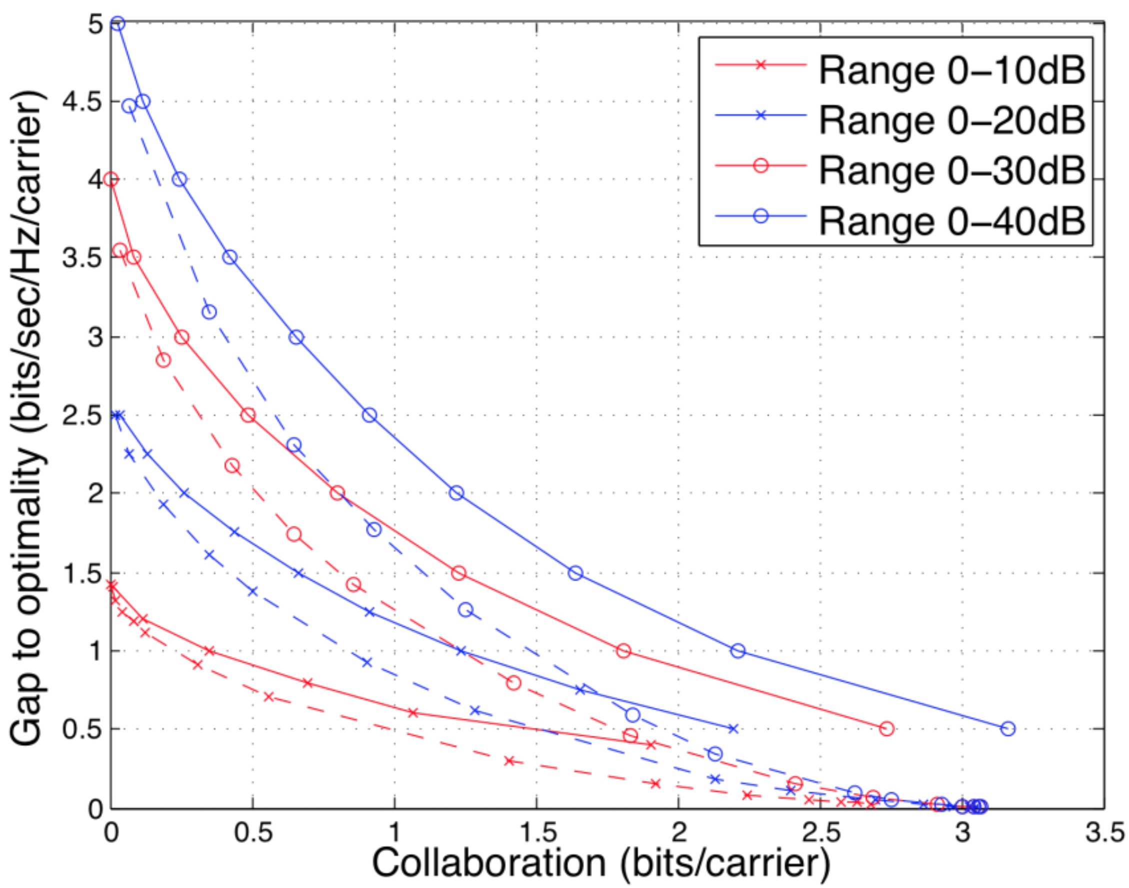
SNR
- N linearly spaced points (dB)
- uniform over range (0-30 dB)

Upper bound (solid): Each destination knows only its SNR's (γ_{1i},γ_{2i}) for the transmitters → CEO problem

Lower bound (dash): Each destination node knows all SNRs → rate distortion problem

Collaboration-Efficiency Tradeoff

Sensitivity to Range



SNR

- 4 linearly spaced points (dB)
- uniform over range (0-X dB)

Maximum Queue Stability Region Resource Scheduling

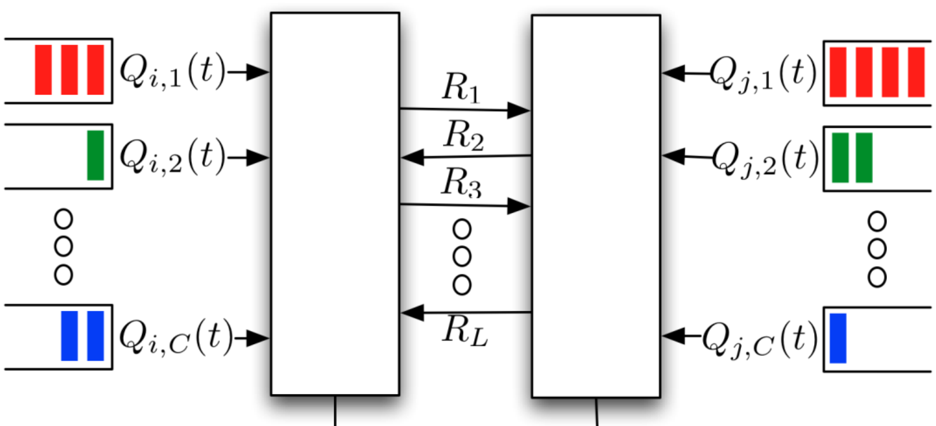
- Design control policies that achieve the stability region of the network, where

  Stability region = set of all packet arrival rate vectors such that there exists a network control that supports that vector (i.e., keeps the queue length finite)

- Classic result: Tassiulas and Ephremides (1992) - optimal centralized alg. schedules transmissions according to a maximum weight independent set (MWIS) in each time slot ("backpressure")
  - Set of feasible concurrent transmissions with associated rates dependent upon prevailing channel conditions
  - Weights on edge reflect the maximum queue length differential (Tx length - Rx queue length) for any commodity traversing that edge

Max. Queue Stability Region Res. Scheduling

- In practice, balance allocation between
  - Users that need most urgently (large queue diff.)
  - Users in channels with high capacities
- Example:
  - Two-node subset of a network with one Tx s and one potential Rx d.
  - Scheduling algorithm must decide which commodity c (s-d pair route traversing this link) it should transmit
  - The control signal must be determined at both s and d through an info. exchange between s and d
- Quantify the collaboration-efficiency tradeoffs via rate distortion theory



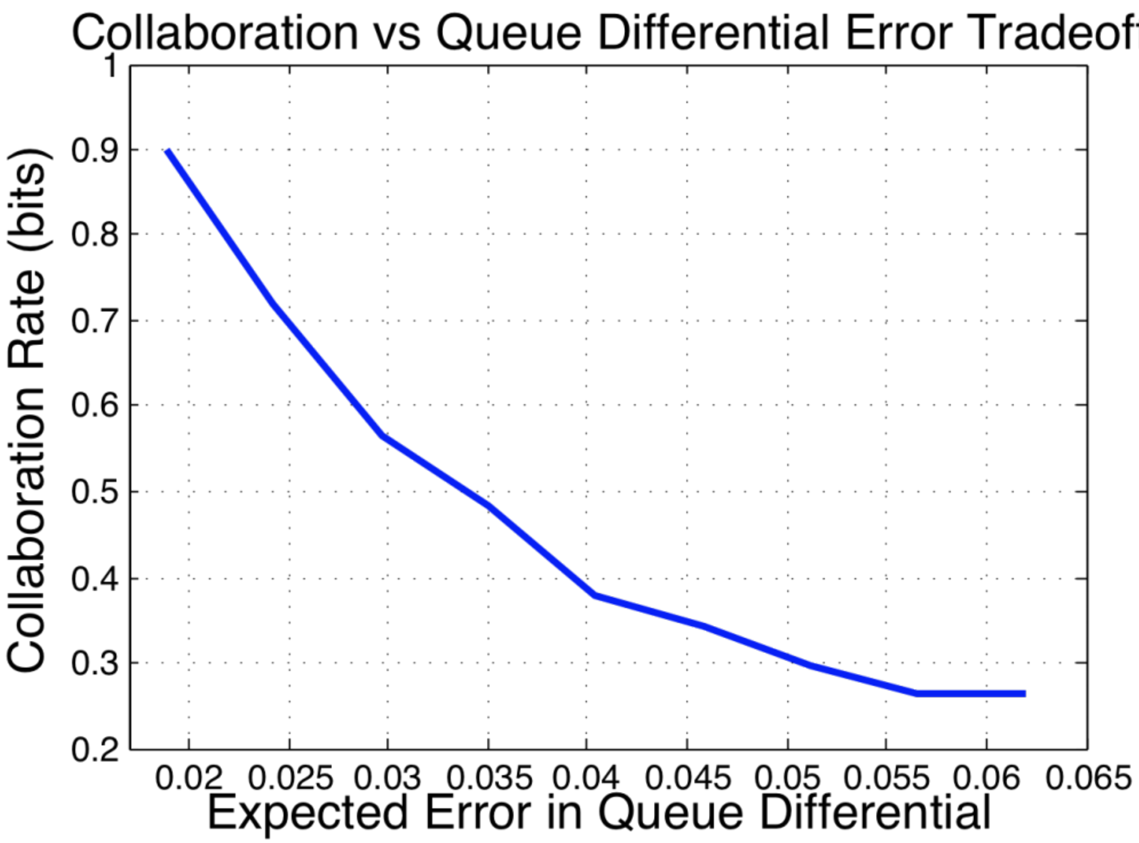
$$c^*(t) = \arg\max_c \left(Q_{i,c}(t) - Q_{j,c}(t)\right)^+$$

"interactive rate distortion problem"

Max. Queue Stability Region Res. Scheduling

Collaboration-Queue Differential Error Tradeoff

- Distortion = gap between largest queue differential and one selected
- Apply Berger-Tung inner bound



Single round of message exchange

Uniform binary queue lengths

Summary

- Use multiterminal distributed coding theory to study the tradeoffs between overhead and efficiency/QoS
- We can simultaneously study
  – Cost and benefits of collaboration
  – Performance of naïve schemes, or uncoordinated schemes
  – Amount of communication required to have the distributed controller perform as well as the centralized controller
- Next steps
  – Expand distortion metrics
  – Scaling behavior of bounds as a function of network parameters
  – More general models, e.g., allowing for some interaction (iteration) -- “interactive function computation”
  – Compare to existing algorithms for distributed resource controllers
  – Synthesize practical allocation algorithms using recent approaches to practical distributed source code design (to approach bounds)
  – Testbed

THANK YOU

Decentralized Cooperative Networking (Cimini)

FA9550-09-1-0175

Objective:

Develop a suite of cooperative strategies which can provide robust connectivity in highly dynamic, energy- and bandwidth-constrained, complex networks.

Technical Approach:

- Focus on decentralized, distributed, and robust algorithms with low overhead.
- Consider realistic propagation environments and network scenarios.
- Evaluate cooperation in a network context and extend to multihop networks.
- Investigate the dynamics and stability of decentralized control for cooperative networks.

DoD Benefit:

Future tactical networks will be complex and highly dynamic, with severe constraints on energy and bandwidth. This is precisely where cooperative networking will have the most impact. Through cooperation, the energy used in the network can be significantly reduced, and the reliability and connectivity can be dramatically increased.

Budget:

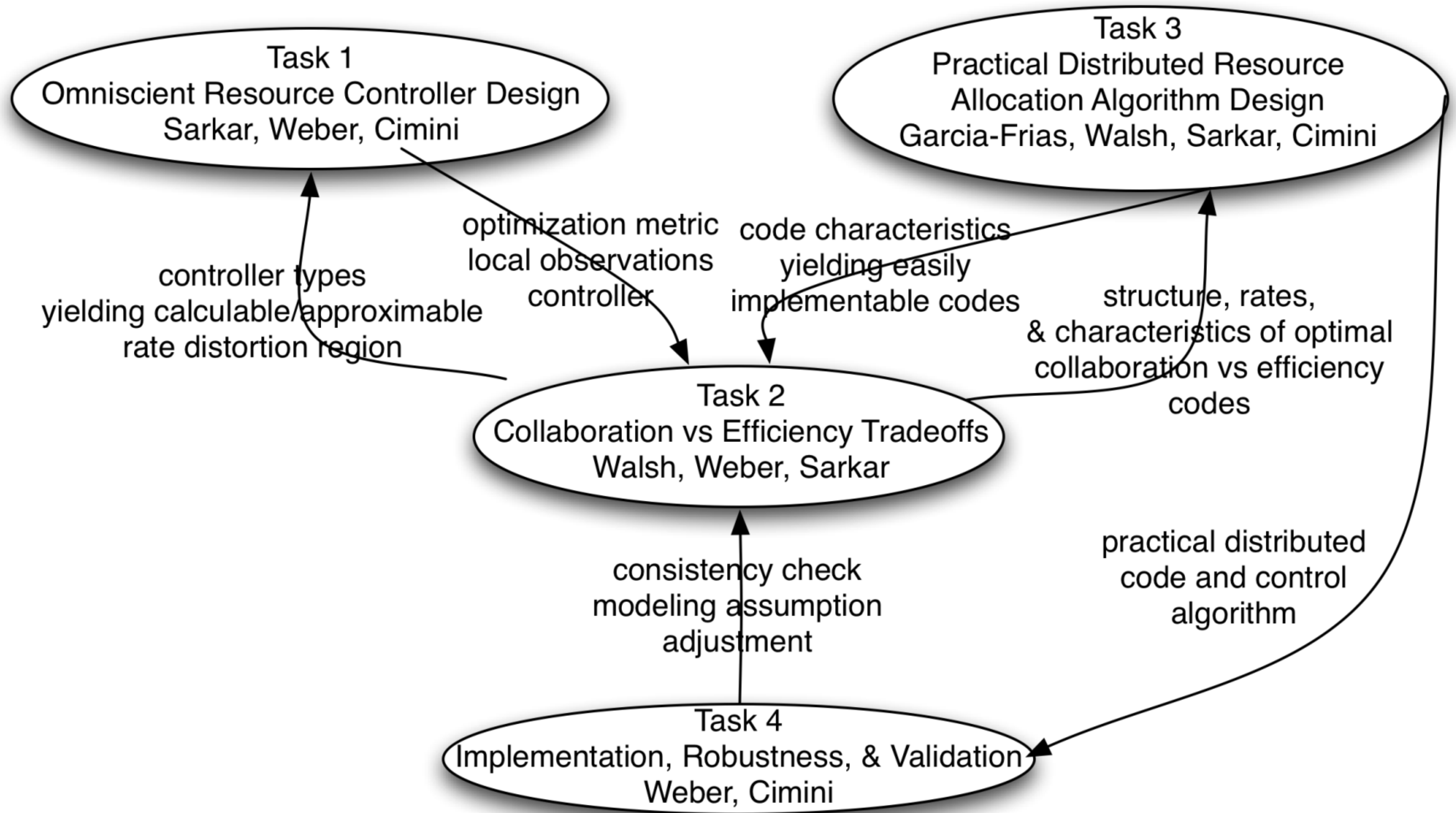
2009	2010	2011
$131.5K	$145.8K	$140.5K

Annual Progress Reports Submitted? Yes

Project End Date: November 30, 2011

<u>List of Publications Attributed to the Grant</u>

- Dai, Chen, Cimini, and Letaief, “Fairness improves throughput in energy-constrained cooperative ad-hoc networks,” *IEEE Trans. On Wireless Commun*., pp. 3679-3691, July 2009.
- Gui, Dai, and Cimini, "Routing strategies in multihop cooperative networks," *IEEE Trans. on Wireless Commun., pp. 843-855, Feb. 2009.*
- Zhang and Cimini, "Efficient power allocation for decentralized distributed space-time block coding," *IEEE Trans. on Wireless Commun.*, pp. 1102-1106, March 2009.
- Yackoski, Zhang, Gui, Shen, and Cimini, “Networking with cooperative communications: Holistic design and realistic evaluation,” *IEEE Comm. Mag.,* pp. 113-119, Aug. 2009.
- Xiao, Guan, Chen, Shen, and Cimini, “Location-aware cooperative routing in multihop wireless networks,” submitted to *WCNC 2011*.
- Guan, Xiao, Shen, and Cimini, “CSR: Cooperative source routing using virtual MISO in wireless ad hoc networks,” submitted to *WCNC 2011*.


Task 1
Omniscient Resource Controller Design
Sarkar, Weber, Cimini
Task 3
Practical Distributed Resource
Allocation Algorithm Design
Garcia-Frias, Walsh, Sarkar, Cimini
optimization metric
local observations
controller
code characteristics
yielding easily
implementable codes
controller types
yielding calculable/approximable
rate distortion region
structure, rates,
& characteristics of optimal
collaboration vs efficiency
codes
Task 2
Collaboration vs Efficiency Tradeoffs
Walsh, Weber, Sarkar
practical distributed
code and control
algorithm
consistency check
modeling assumption
adjustment
Task 4
Implementation, Robustness, & Validation
Weber, Cimini