Cross-layer design of wireless networks with resource-constrained nodes

Andrea Goldsmith
Stanford University
wsl.stanford.edu

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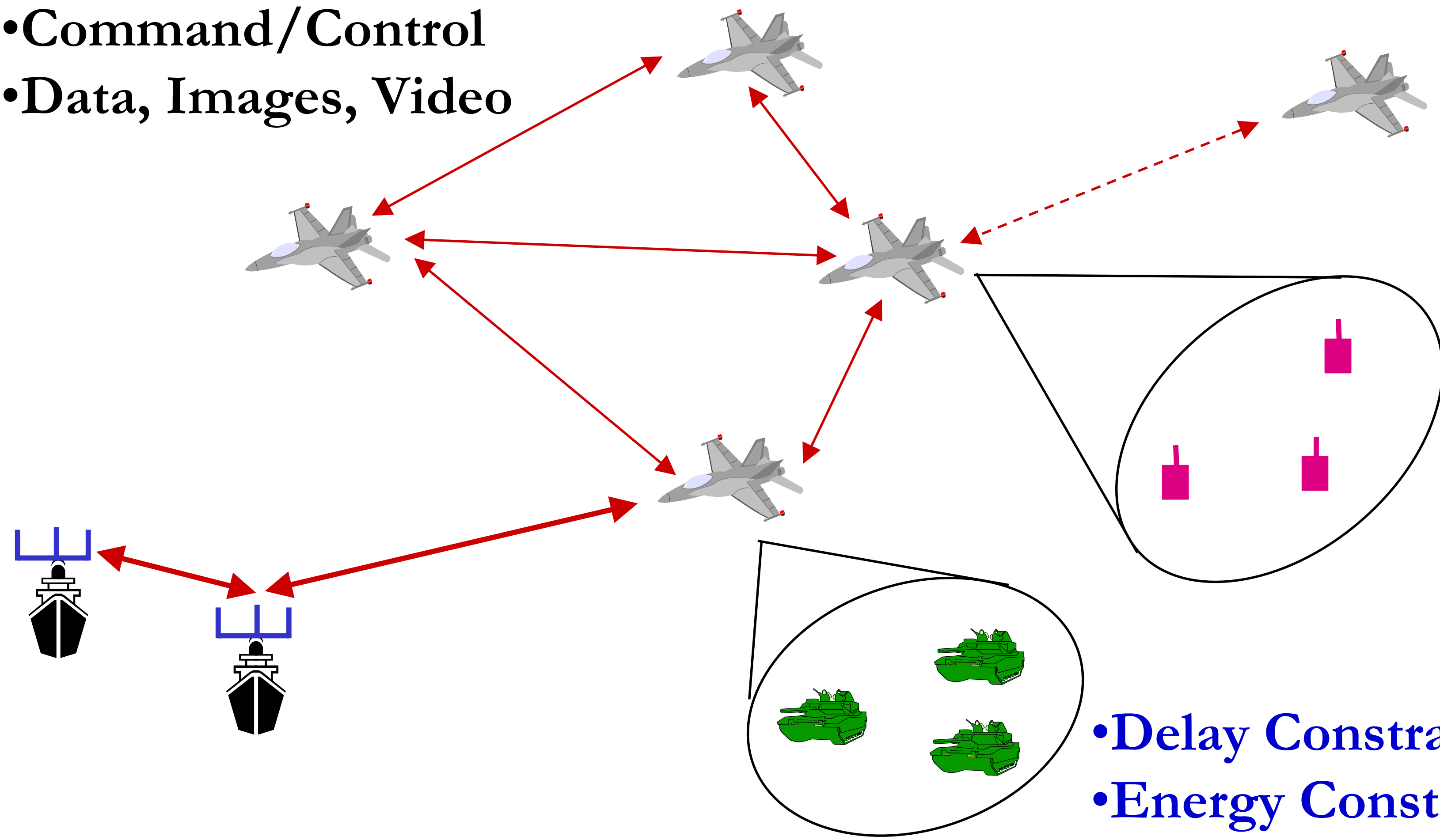
Wireless Multimedia Networks In Military Operations

- Command/Control
- Data, Images, Video



- Delay Constraints
- Energy Constraints

Challenges to meeting network performance requirements

- Wireless channels are a difficult and capacity-limited broadcast communications medium
- Hostile jammers can disrupt communication
- Traffic patterns, user locations, and network conditions are constantly changing
- No single layer in the protocol stack can guarantee QoS: cross-layer design needed

Crosslayer Design

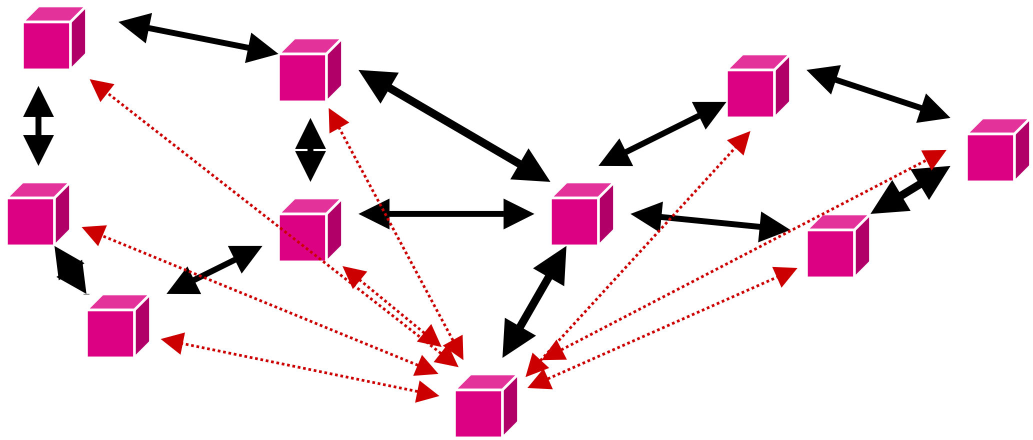
- Hardware
- Link
- Access
- Network
- Application

Delay Constraints
Rate Requirements
Energy Constraints
Complexity Constraints
Robustness

Crosslayer Techniques

- Adaptive techniques
  - Link, MAC, network, and application adaptation
- Diversity techniques
  - Link diversity (antennas, channels, etc.)
  - Access diversity
  - Route diversity
  - Application diversity
  - Content location/server diversity
- Scheduling
  - Application scheduling/data prioritization
  - Access scheduling
  - Resource reservation

Ad-Hoc Networks

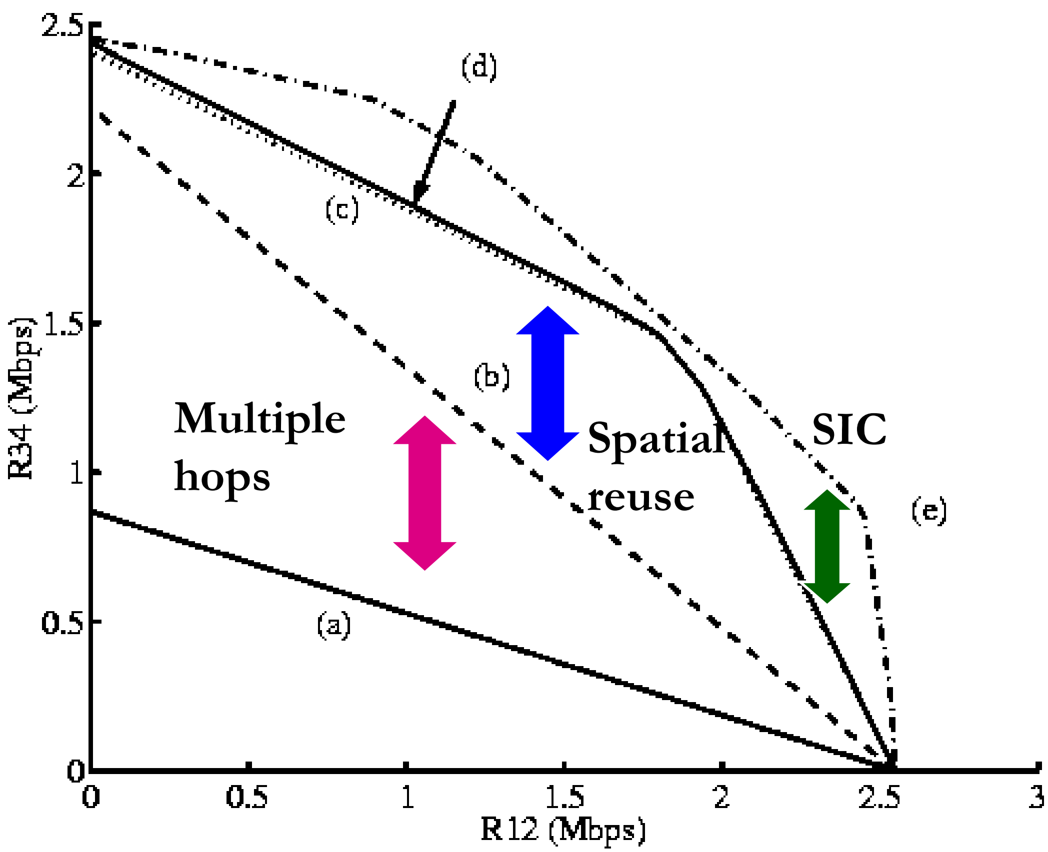


- Peer-to-peer communications.
- No backbone infrastructure.
- Routing can be multihop.
- Topology is dynamic.
- Fully connected with different link SINRs

Capacity Region Slice

Optimized link, MAC, and routing

$$\boxed{R_{ij} = 0, \quad ij \neq 12{,}34, \quad i \neq j}$$



(a): Single hop, no simultaneous transmissions.

(b): Multihop, no simultaneous transmissions.

(c): Multihop, simultaneous transmissions.

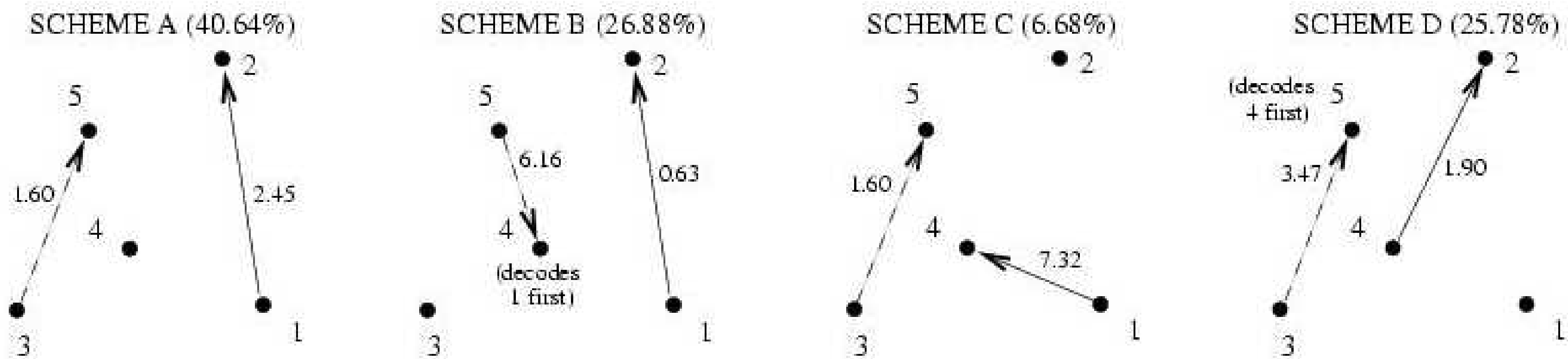
(d): Adding power control

(e): Successive interference cancellation, no power control.

Limited node and network complexity significantly limit performance

Optimal Routing

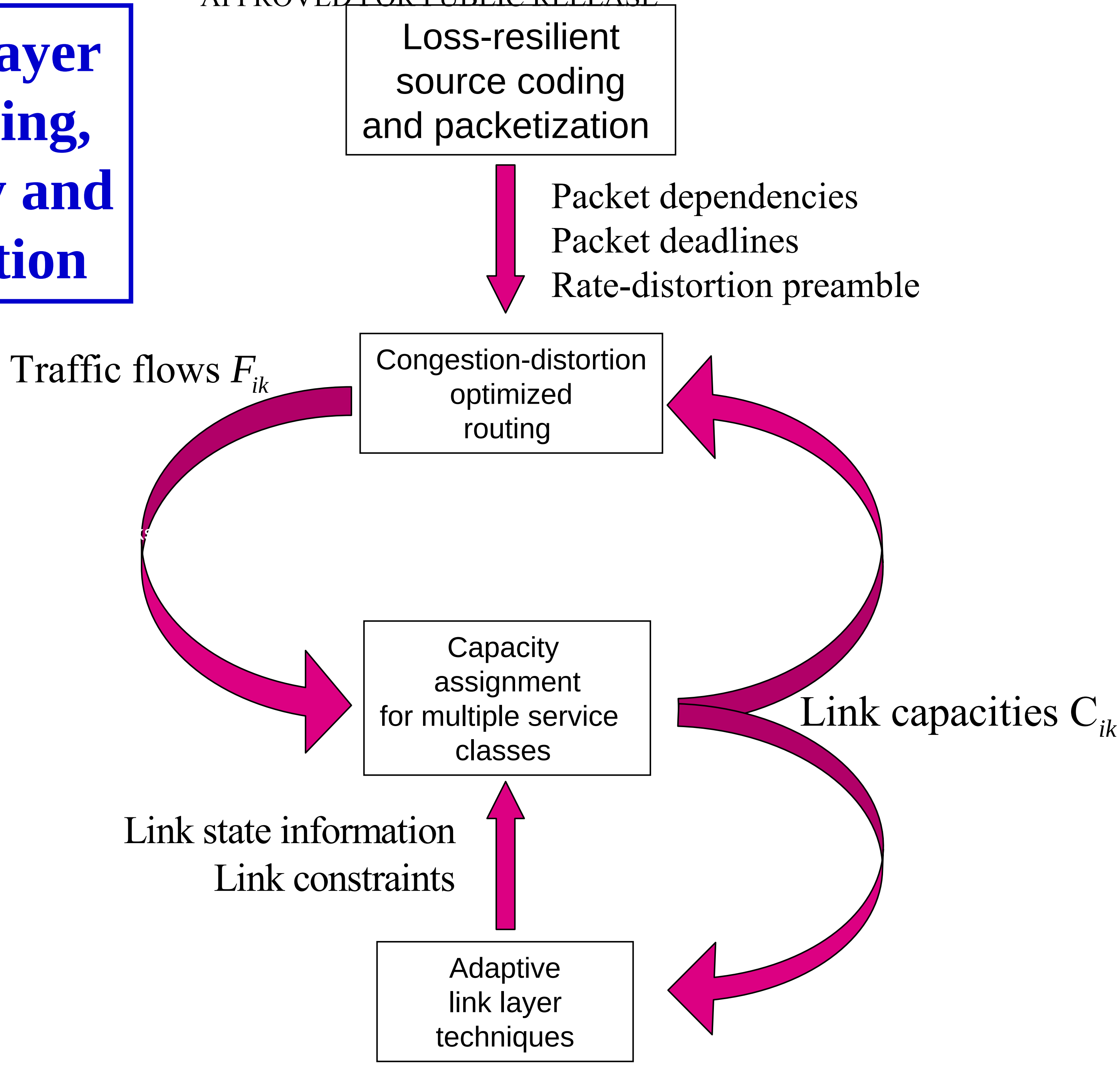
- **The point $R_{12} = R_{34} = 1.64\,Mbps$ is achieved by the following time division:**



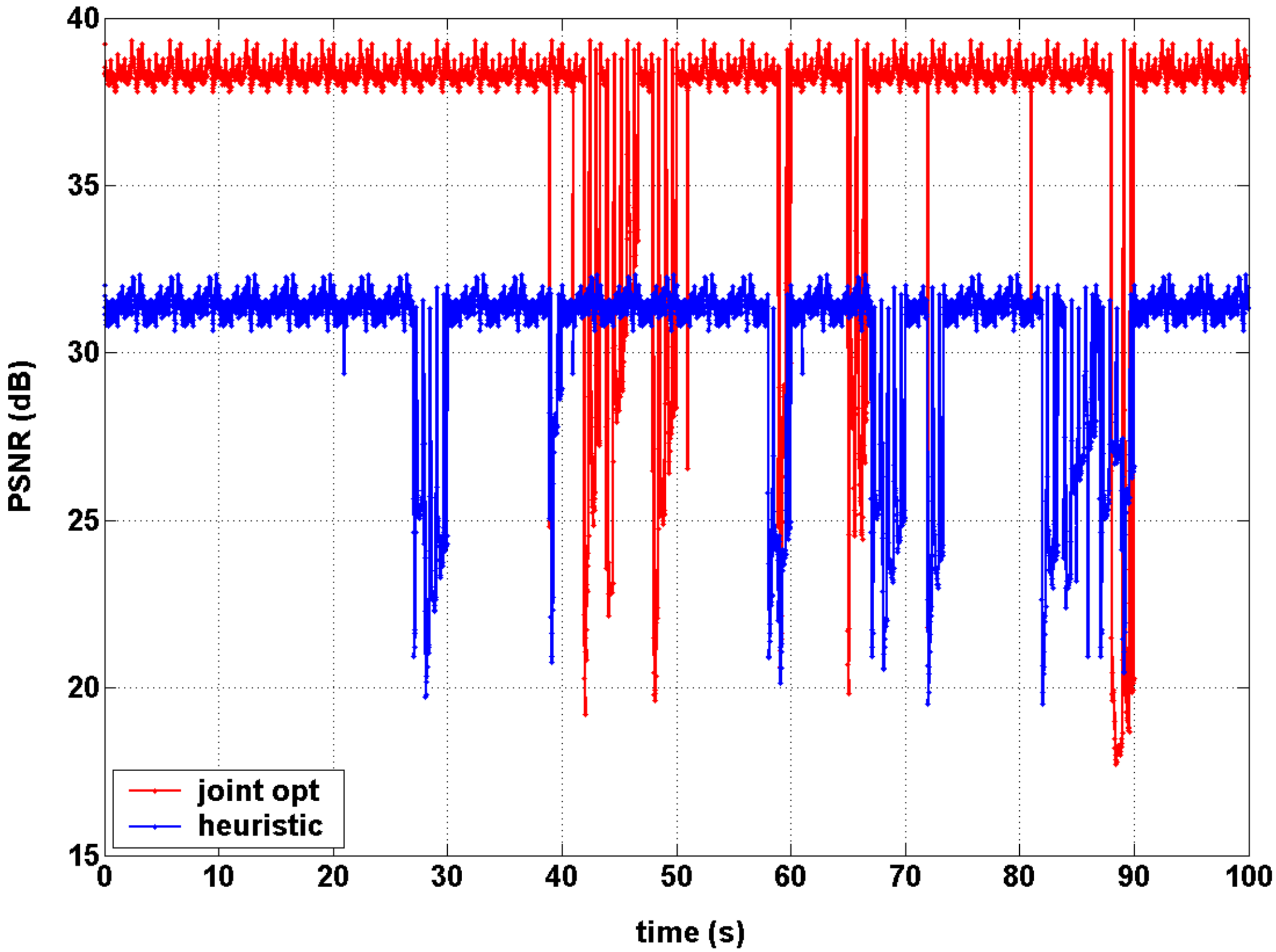
Route Diversity

Increases capacity and provides robustness

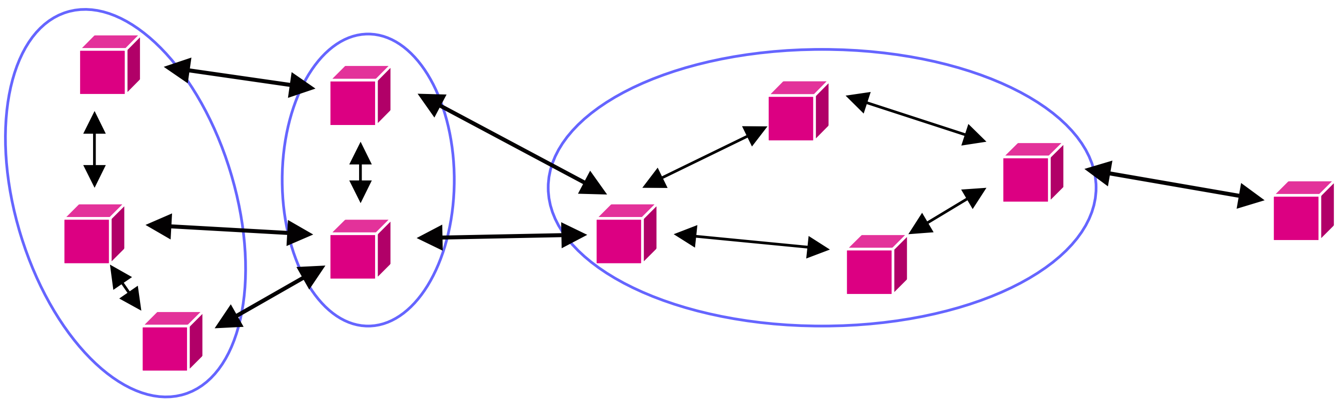
Cross-Layer Scheduling, Diversity and Adaptation



End-to-end distortion



Sensor Networks

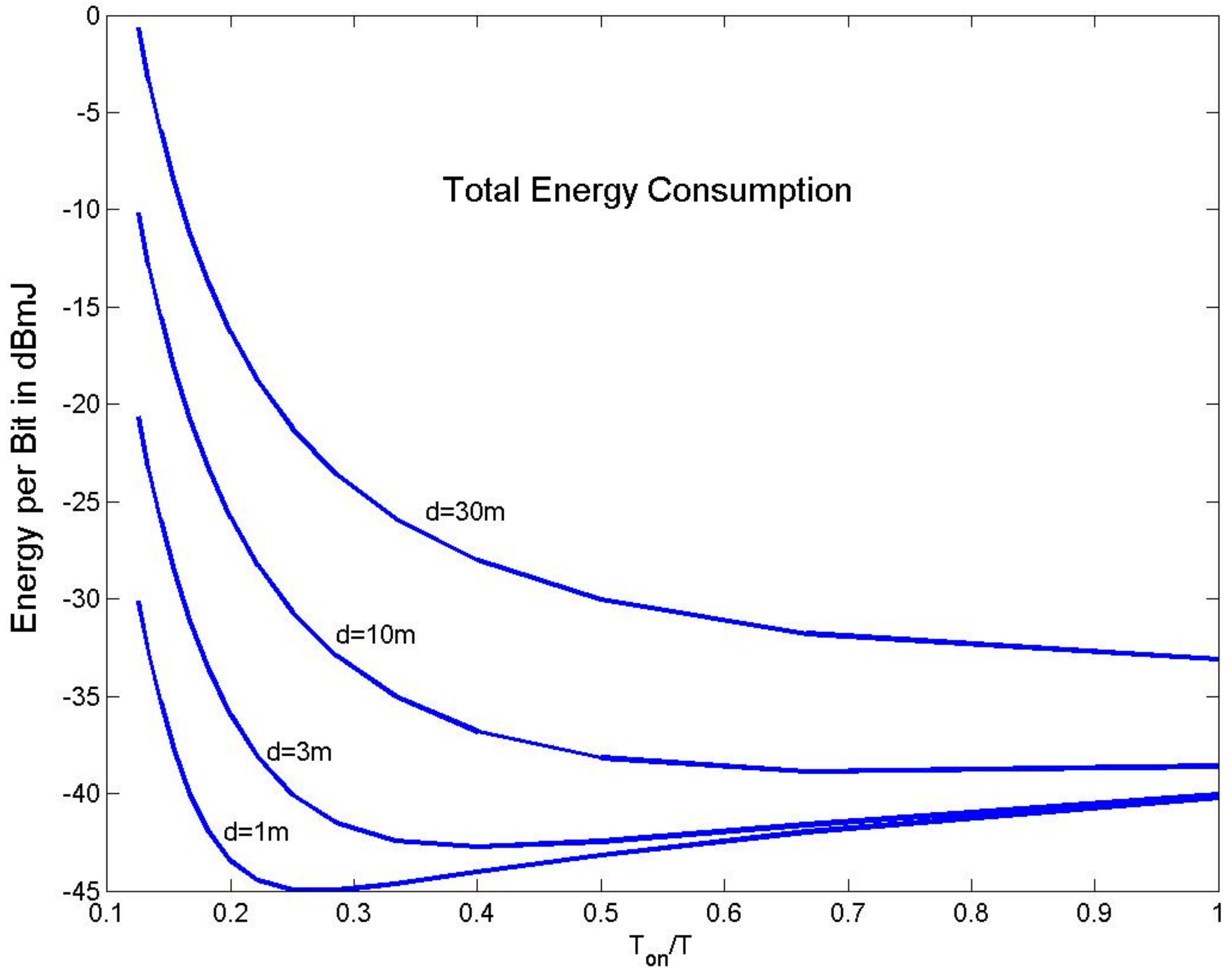


- Energy a driving constraint
- Data flows to centralized location.
- Low per-node rates but 10s to 1000s of nodes
- Data highly correlated in time and space.
- Nodes can cooperate in transmission, reception, and compression.

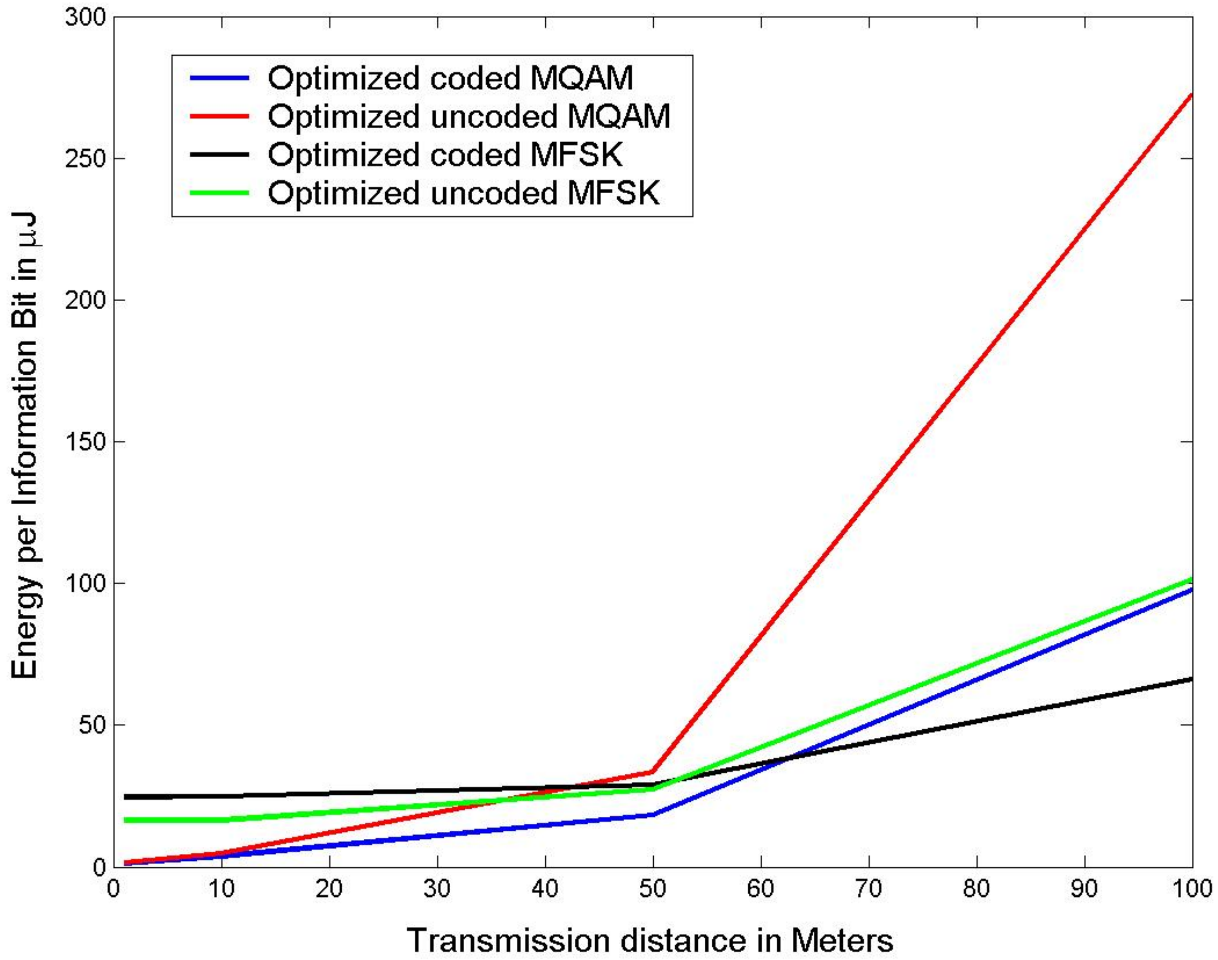
Energy-Constrained Nodes

- Each node can only send a finite number of bits.
  - Transmit energy minimized by maximizing bit duration.
  - Introduces a delay versus energy tradeoff for each bit.
- Short-range networks must consider transmit, circuit, and processing energy.
  - Sophisticated techniques not necessarily energy-efficient.
  - Circuit energy maximized by maximizing bit duration.
  - Sleep modes save energy but complicate networking.
- Changes everything about the network design:
  - Bit allocation must be optimized across all protocols.
  - Delay vs. throughput vs. node/network lifetime tradeoffs.
  - Optimization of node cooperation.

Total Energy (MQAM)

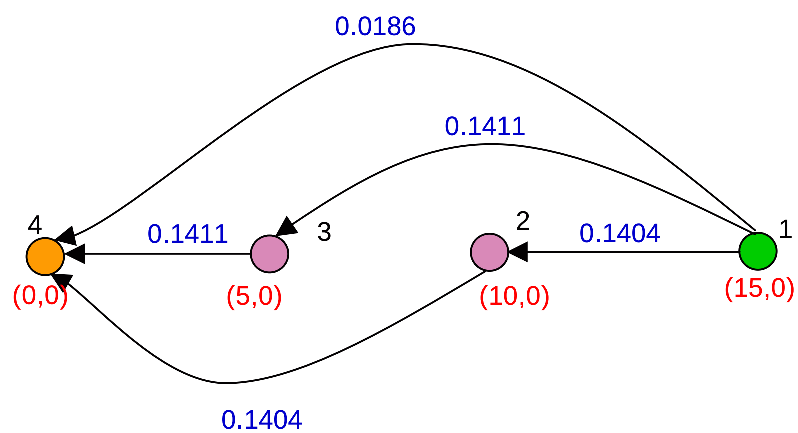


Benefits of Coding



Routing to Minimize Total Energy

- Intermediate nodes act as relays



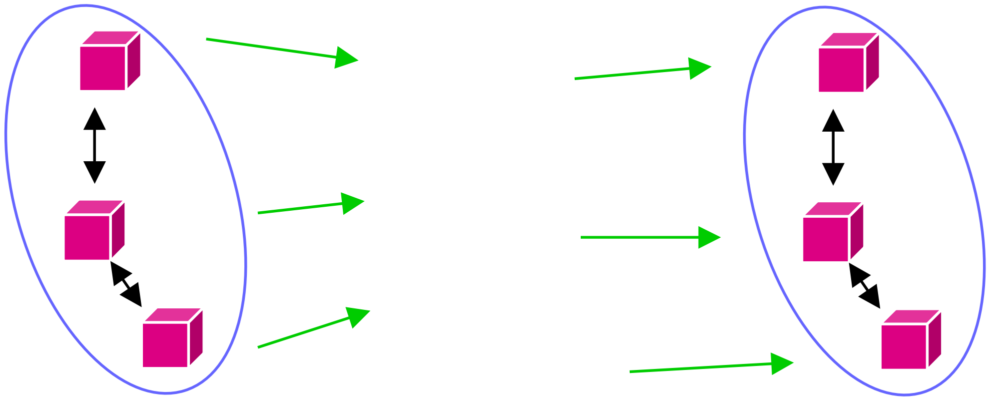
Orange: hub node
Pink: relay only
Green: relay/source

$$R_1 = 6000bps$$

$$R_2 = R_3 = 0$$

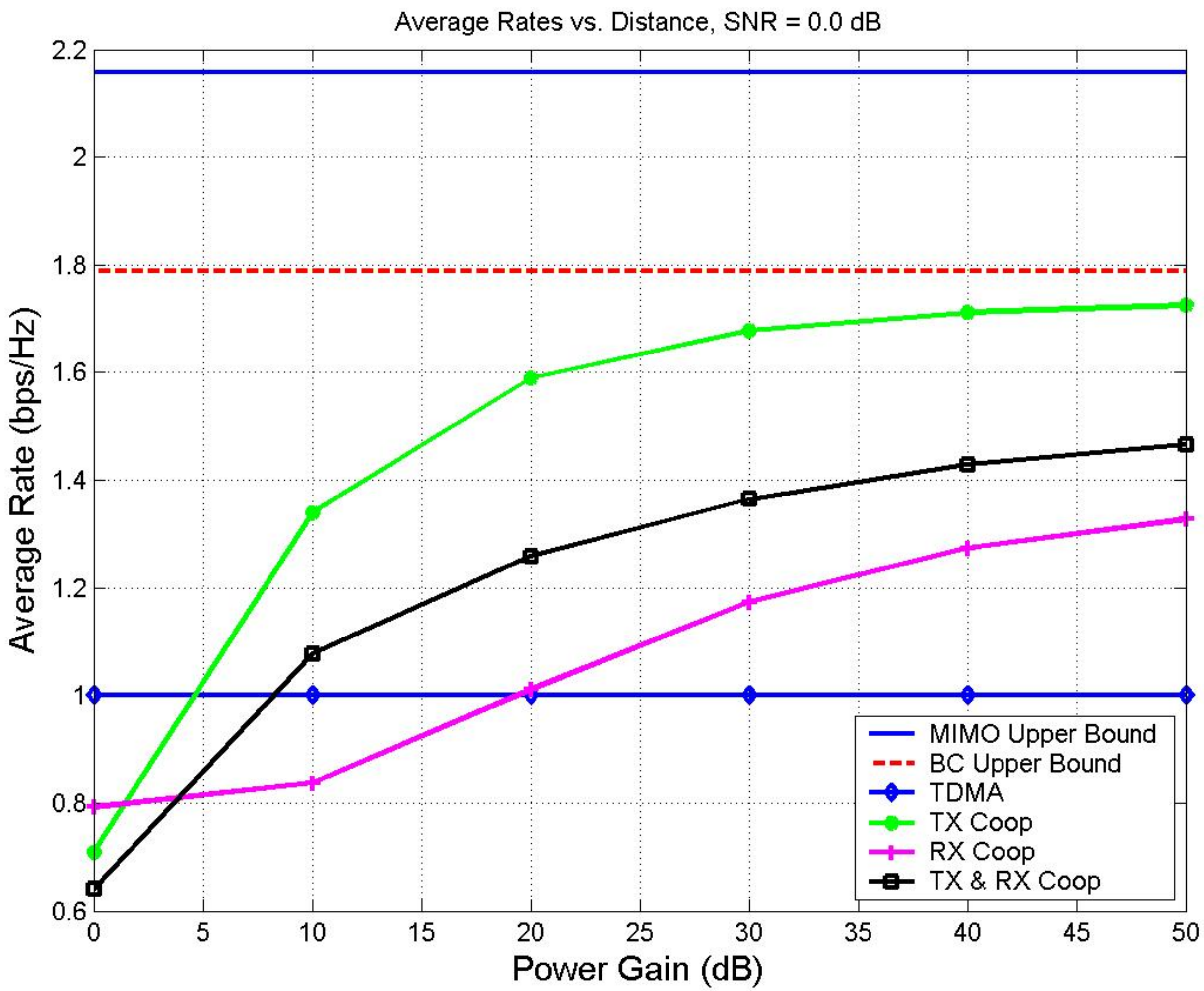
Multi-hop may not be optimal when circuit energy consumption is concerned

Cooperative MIMO

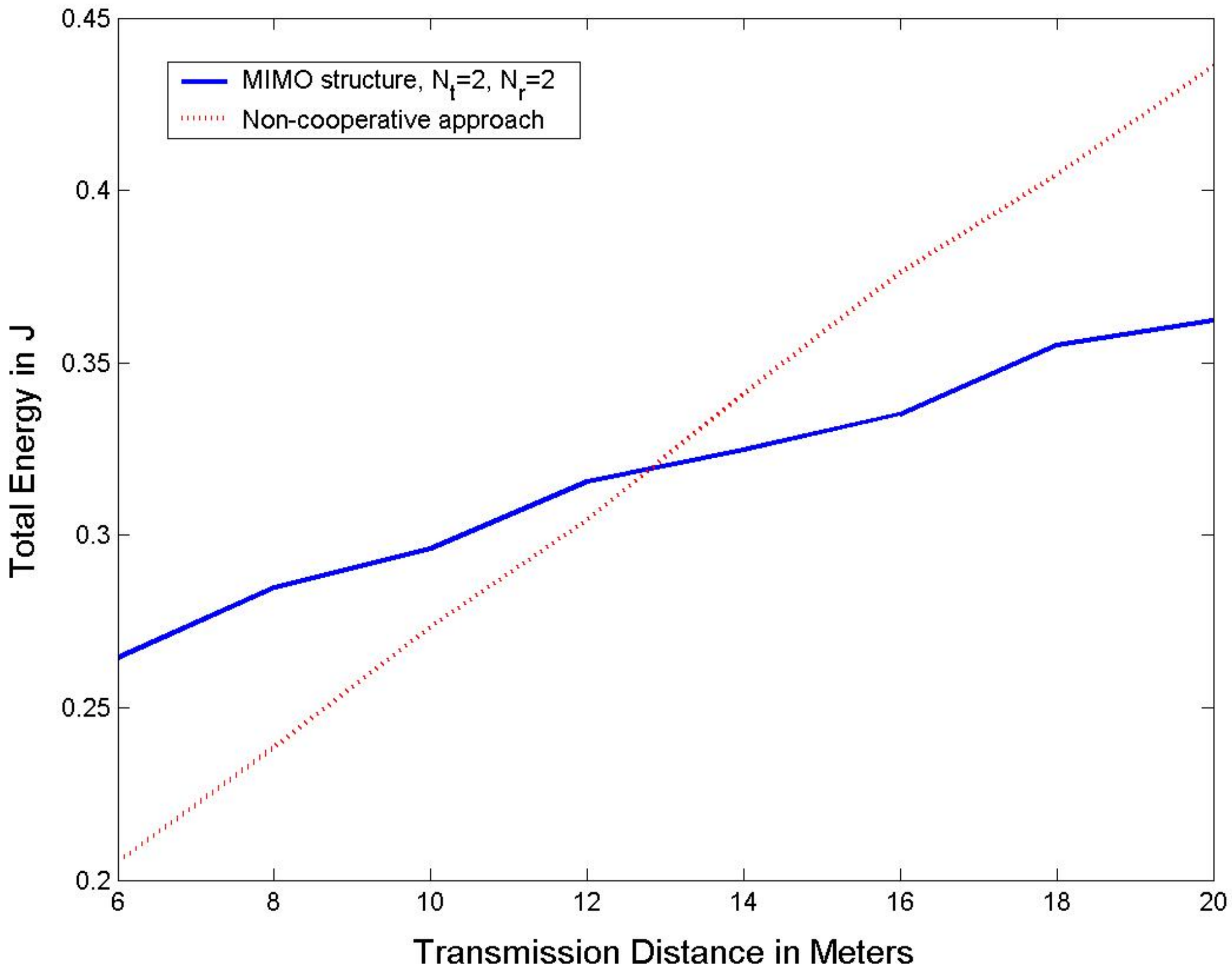


- Nodes close together can cooperatively transmit
  - Form a multiple-antenna transmitter (MIMO Broadcast)
- Nodes close together can cooperatively receive
  - Form a multiple-antenna receiver (MIMO MAC)
- MIMO introduces capacity vs. diversity tradeoffs
  - The communication cost of cooperation must be considered in studying performance gains.

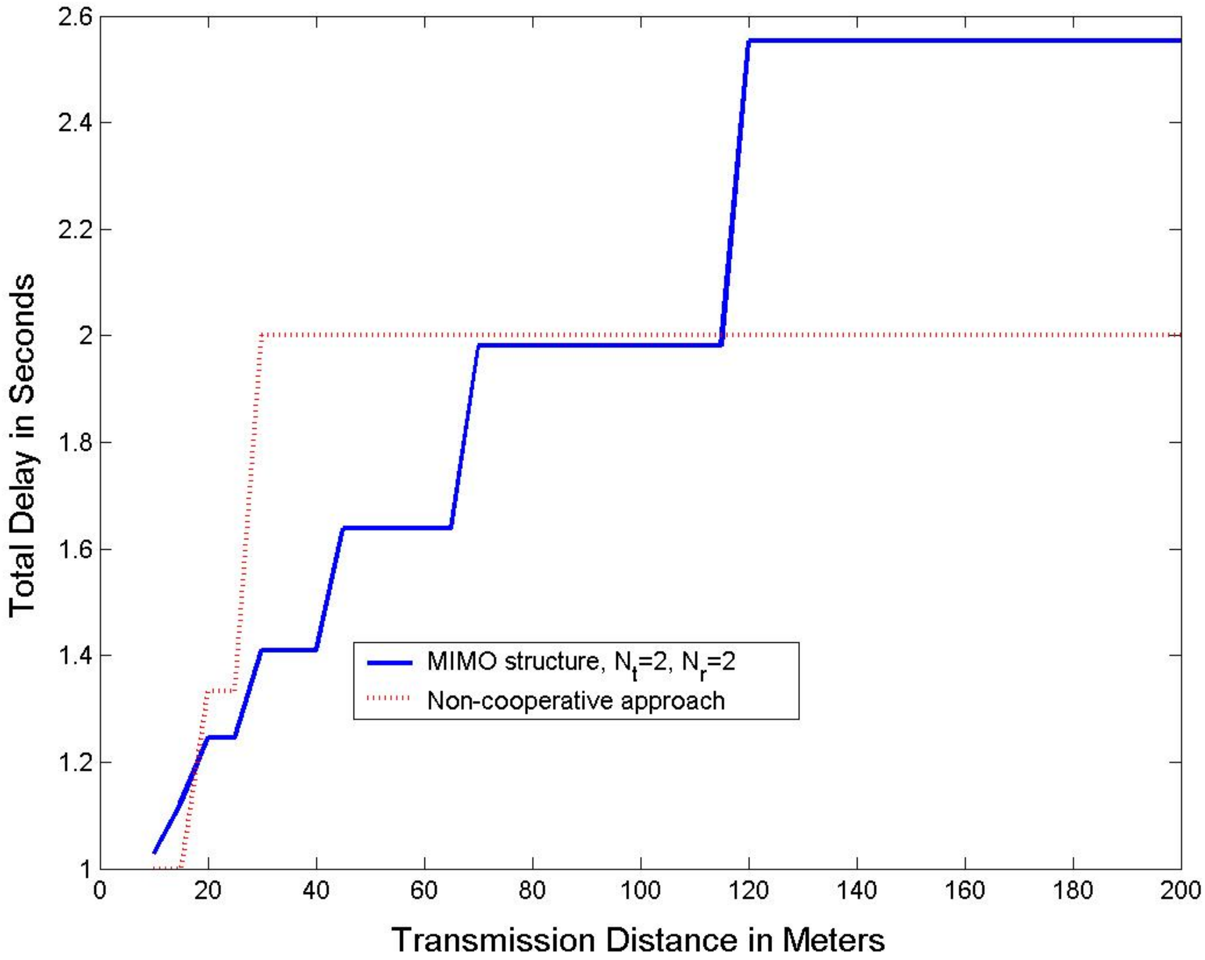
Cooperative MIMO Capacity



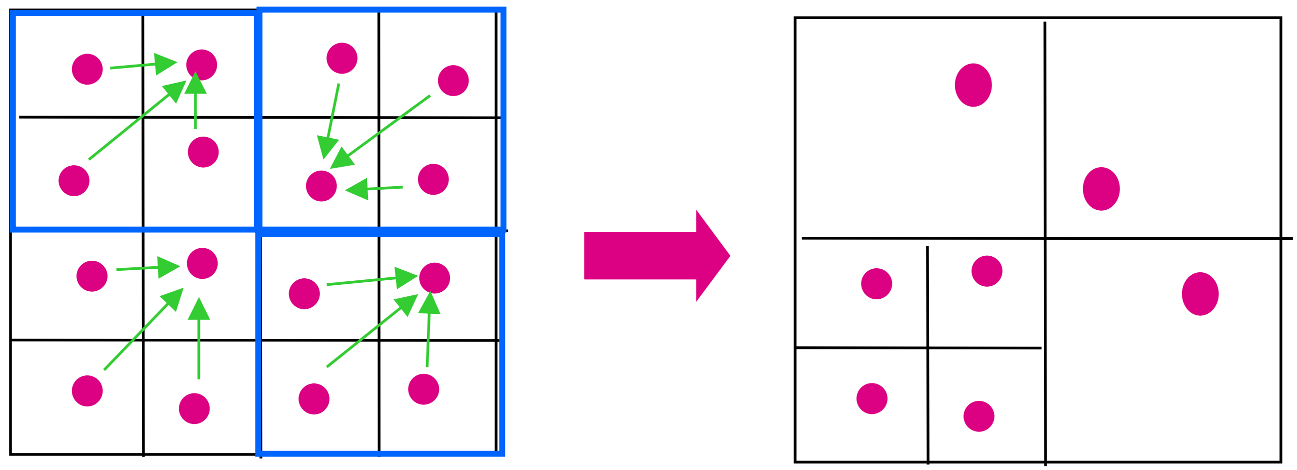
Energy Consumption



Delay


Total Delay in Seconds
Transmission Distance in Meters
MIMO structure, N_t=2, N_r=2
Non-cooperative approach
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0
20
40
60
80
100
120
140
160
180
200

Cooperative Compression



- Intelligent local processing can save power and improve centralized processing
- Local processing also affects MAC and routing protocols

Key Message

Ad-hoc networks impose tradeoffs between rate, power/energy, and delay

The tradeoff implications for sensor networks and distributed control is poorly understood

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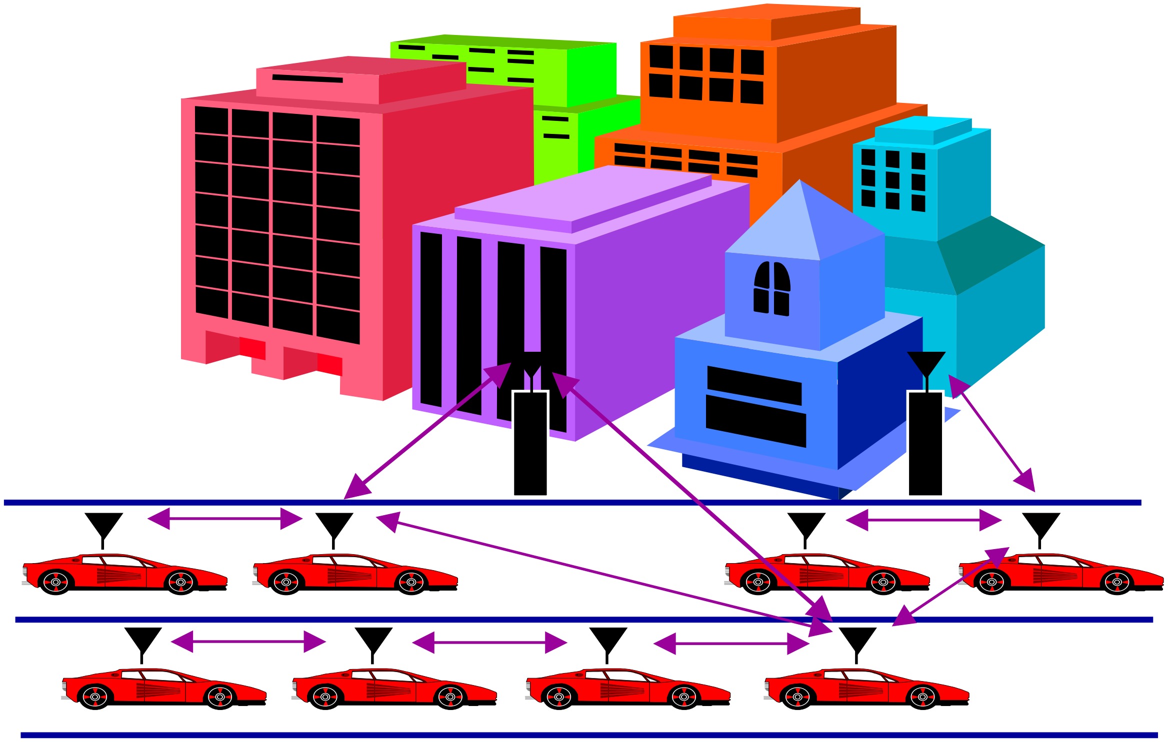
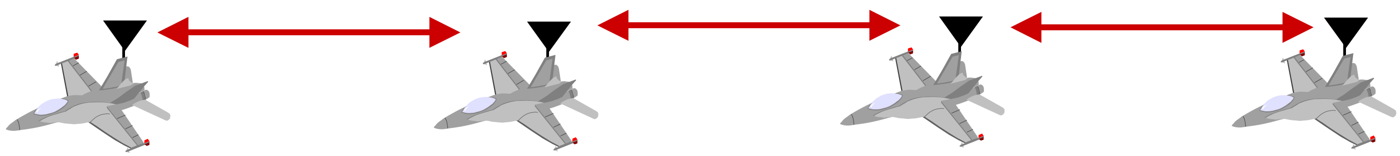
Distributed Control over Wireless Links



- Packet loss and/or delays impacts controller performance.
- Controller design should be robust to network faults.
- Joint application and communication network design.

Joint Design Challenges

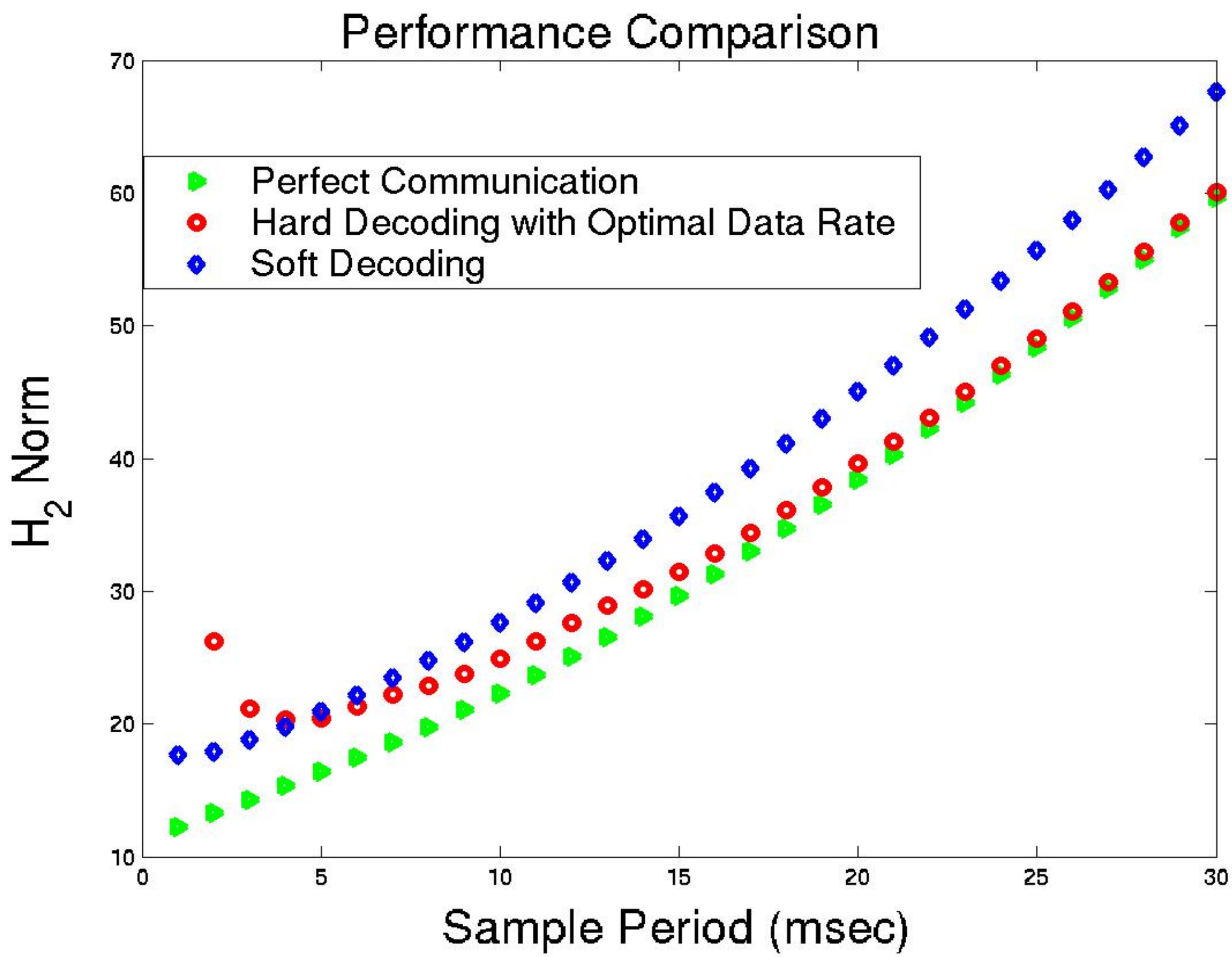
- There is no methodology to incorporate random delays or packet losses into control system designs.
- The best rate/delay tradeoff for a communication system in distributed control cannot be determined.
- Current autonomous vehicle platoon controllers are not string stable with *any* communication delay



Can we make distributed control robust to the network?

Yes, by a radical redesign of the controller and the network.

Controller Performance



Summary

- Crosslayer design needed to meet the military's wireless communication needs
- Key synergies in crosslayer design must be identified
- The design must be tailored to the application
- Crosslayer design should include adaptivity, scheduling and diversity across protocol layers
- Energy can be a precious resource that must be shared by different protocol layers
- Node cooperation in communication and compression can provide significant performance gains