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

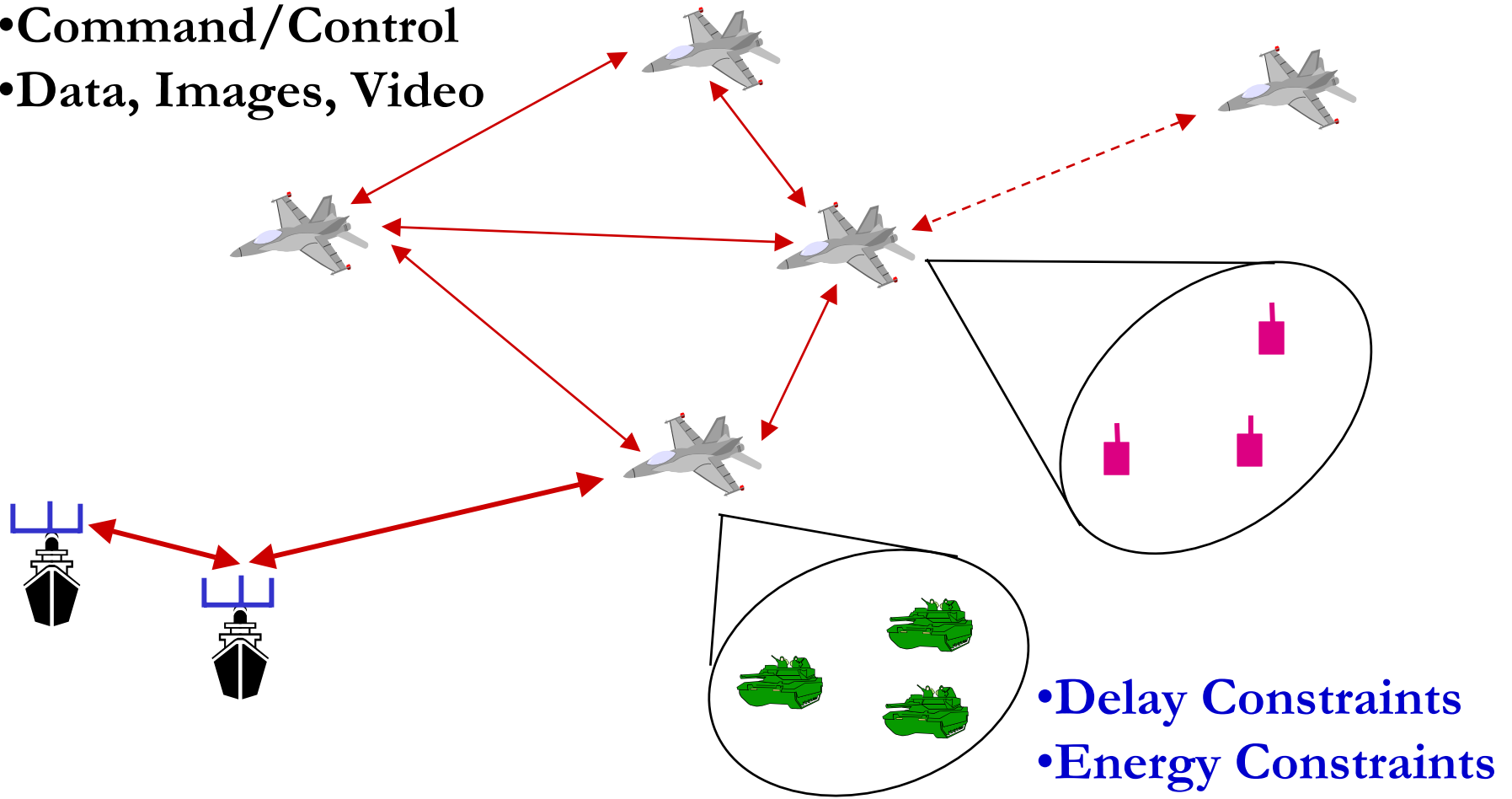
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Wireless Multimedia Networks In Military Operations

- Command/Control
- Data, Images, Video

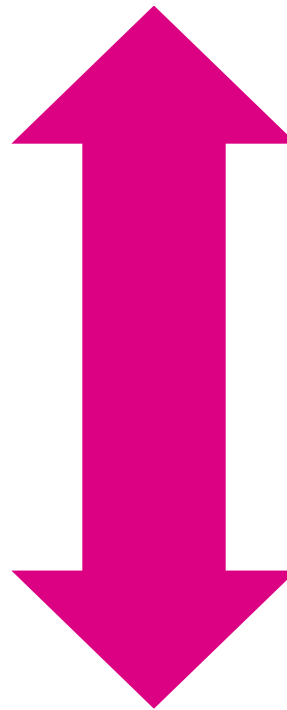


Challenges to meeting network performance requirements

- 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

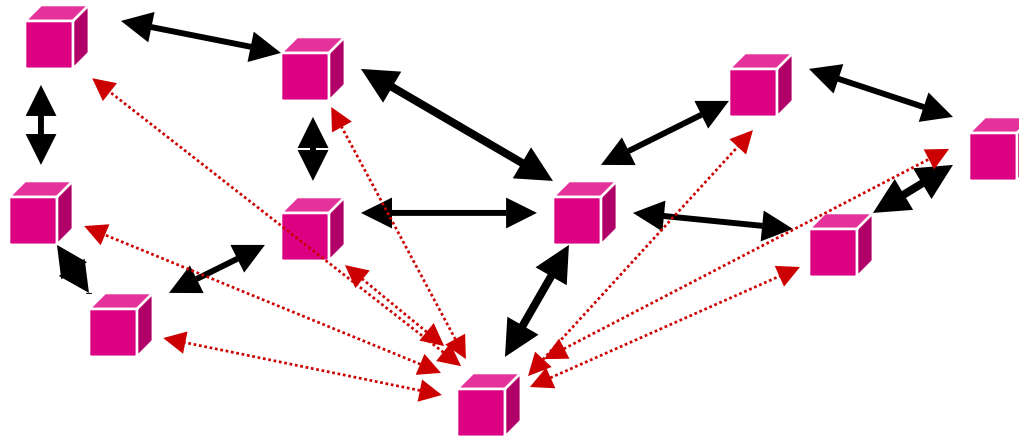


Delay Constraints
Rate Requirements
Energy Constraints
Complexity Constraints
Robustness

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

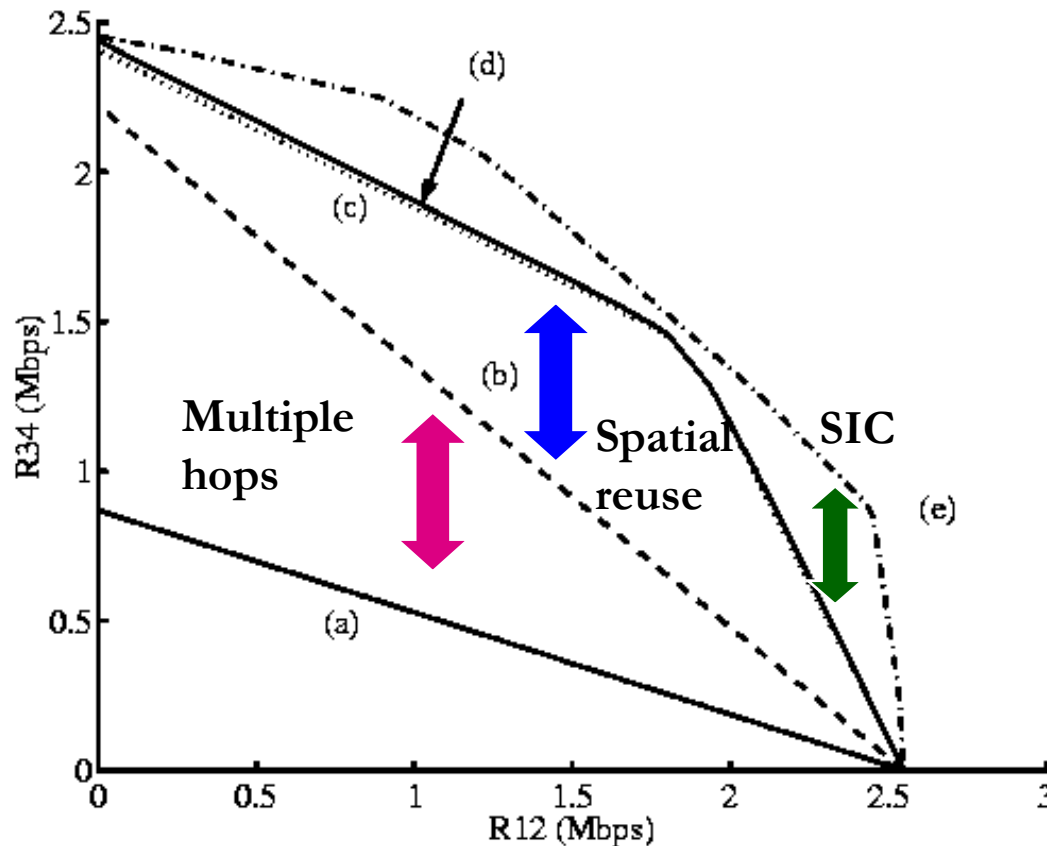


- Peer-to-peer communications.
- No backbone infrastructure.
- Routing can be multihop.
- Topology is dynamic.
- Fully connected with different link SINRs

Capacity Region Slice

Optimized link, MAC, and routing

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

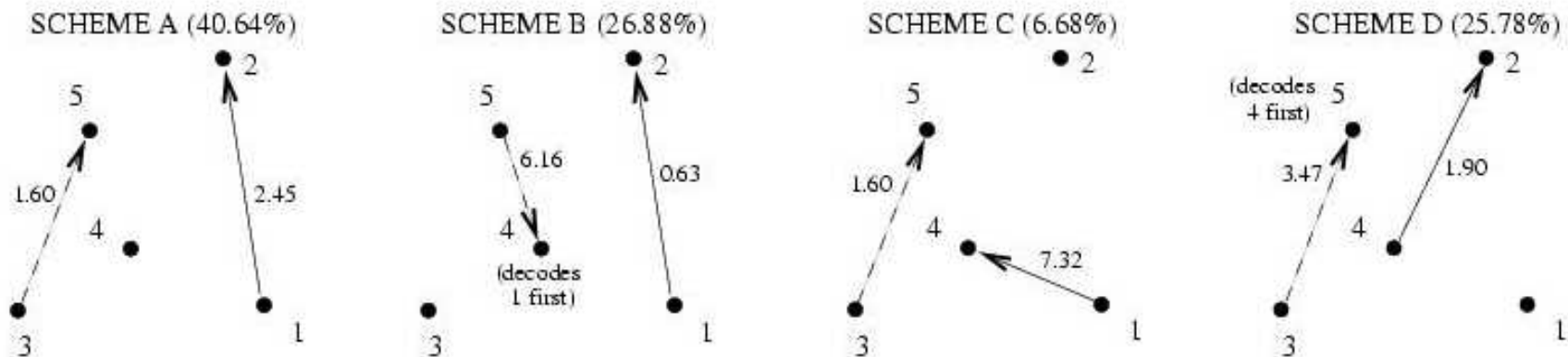


- (a): Single hop, no simultaneous transmissions.
- (b): Multihop, no simultaneous transmissions.
- (c): Multihop, simultaneous transmissions.
- (d): Adding power control
- (e): Successive interference cancellation, no power control.

Limited node and network complexity significantly limit performance

Optimal Routing

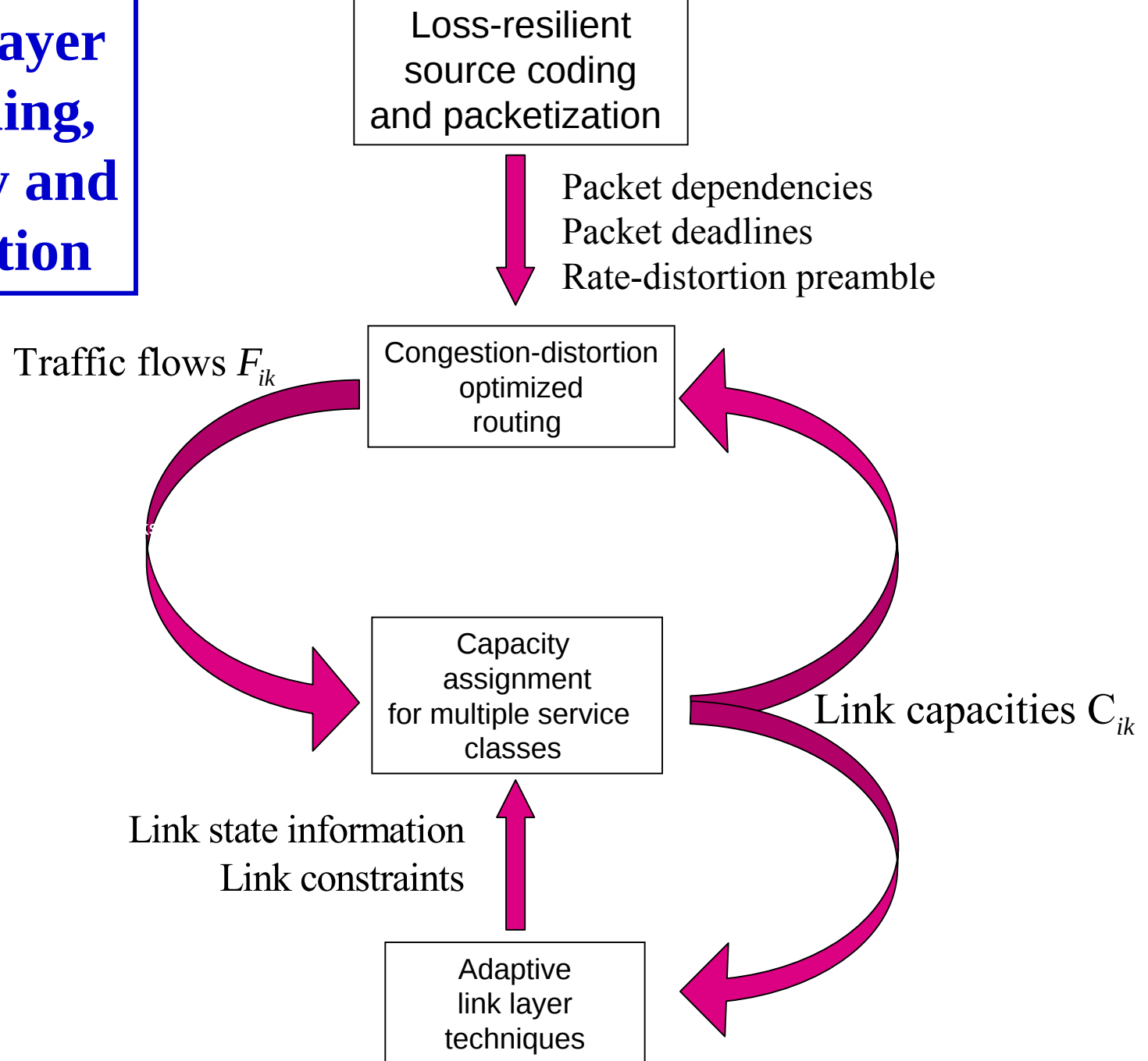
- The point $R_{12} = R_{34} = 1.64 \text{ Mbps}$ is achieved by the following time division:



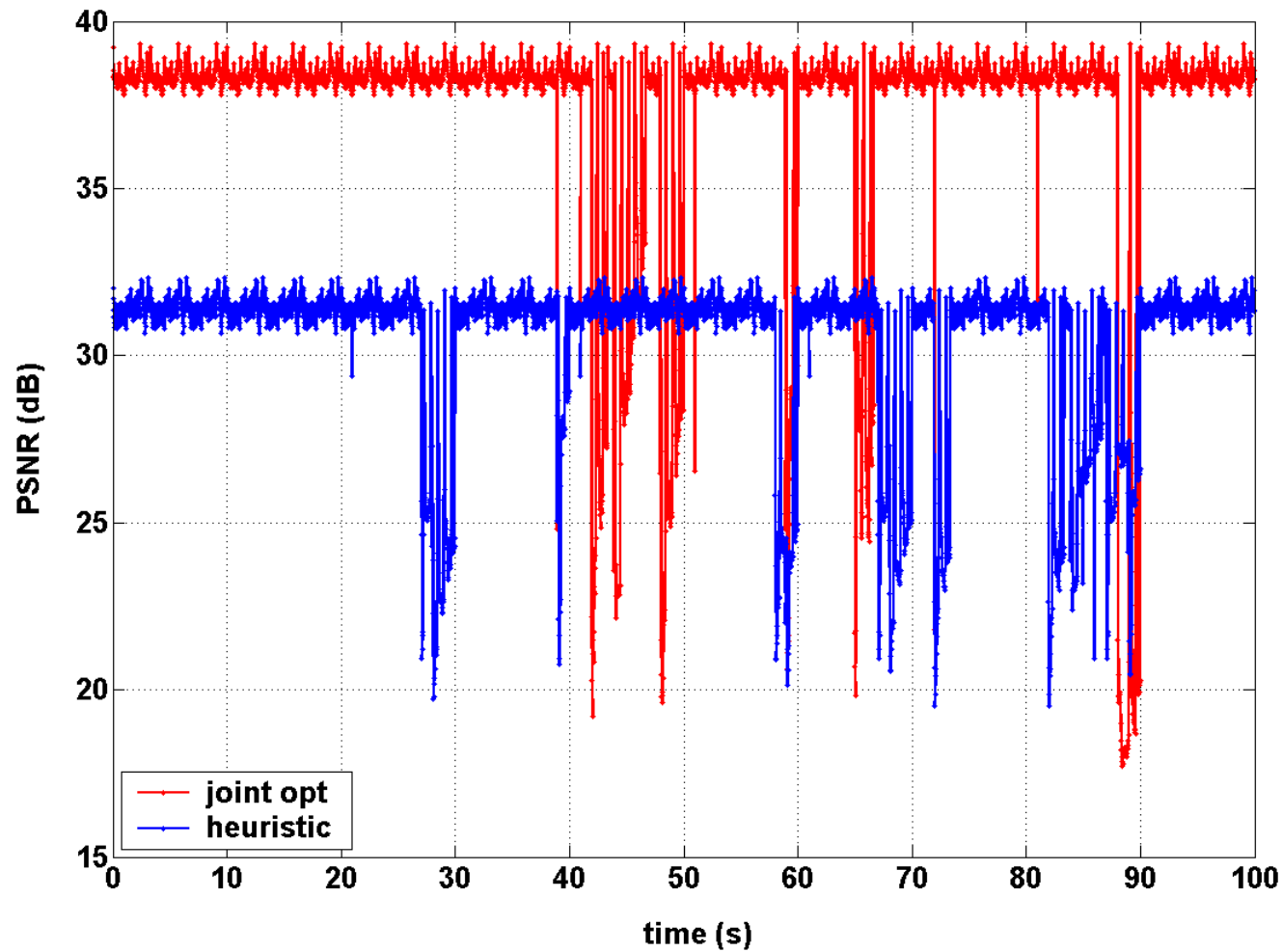
Route Diversity

Increases capacity and provides robustness

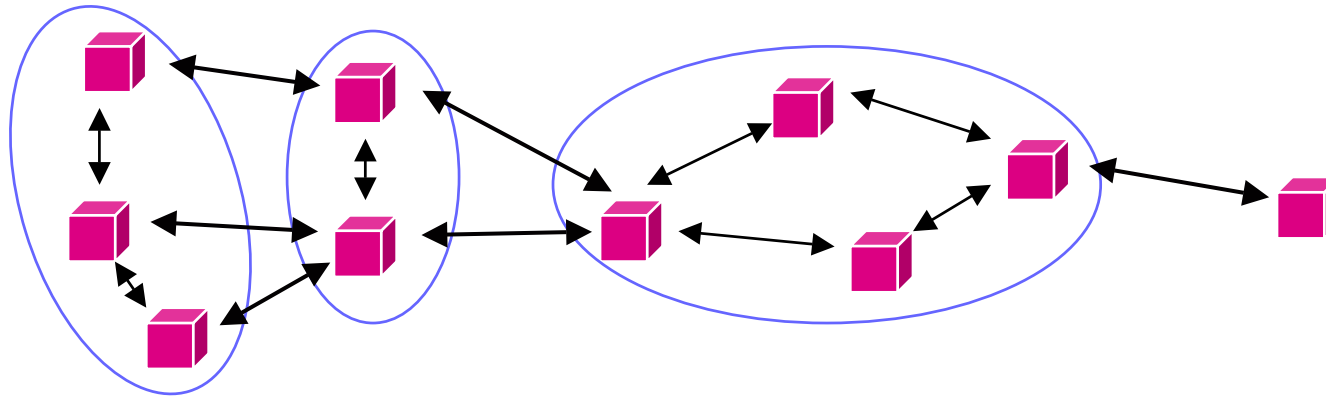
Cross-Layer Scheduling, Diversity and Adaptation



End-to-end distortion



Sensor Networks

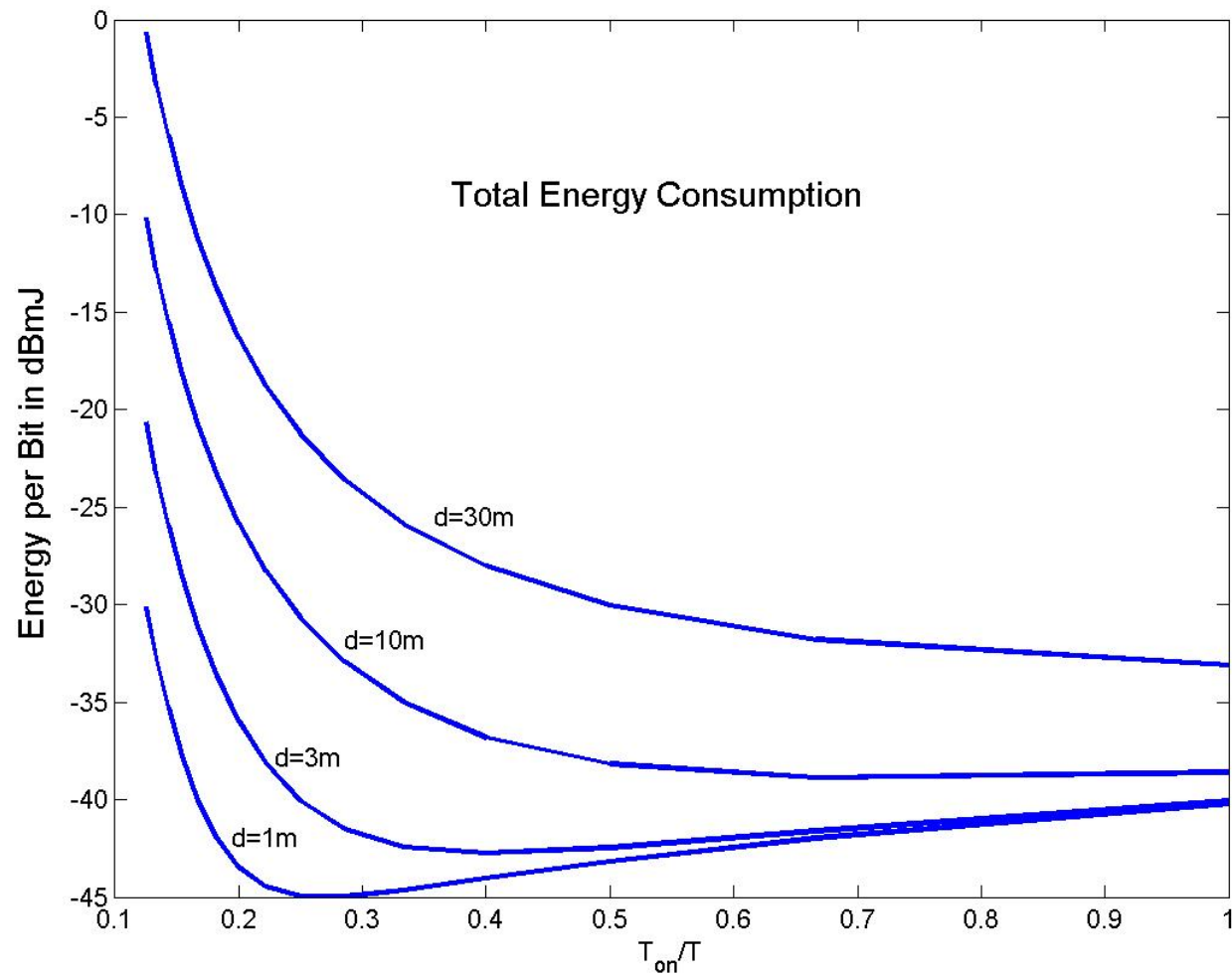


- Energy a driving constraint
- Data flows to centralized location.
- Low per-node rates but 10s to 1000s of nodes
- Data highly correlated in time and space.
- Nodes can cooperate in transmission, reception, and compression.

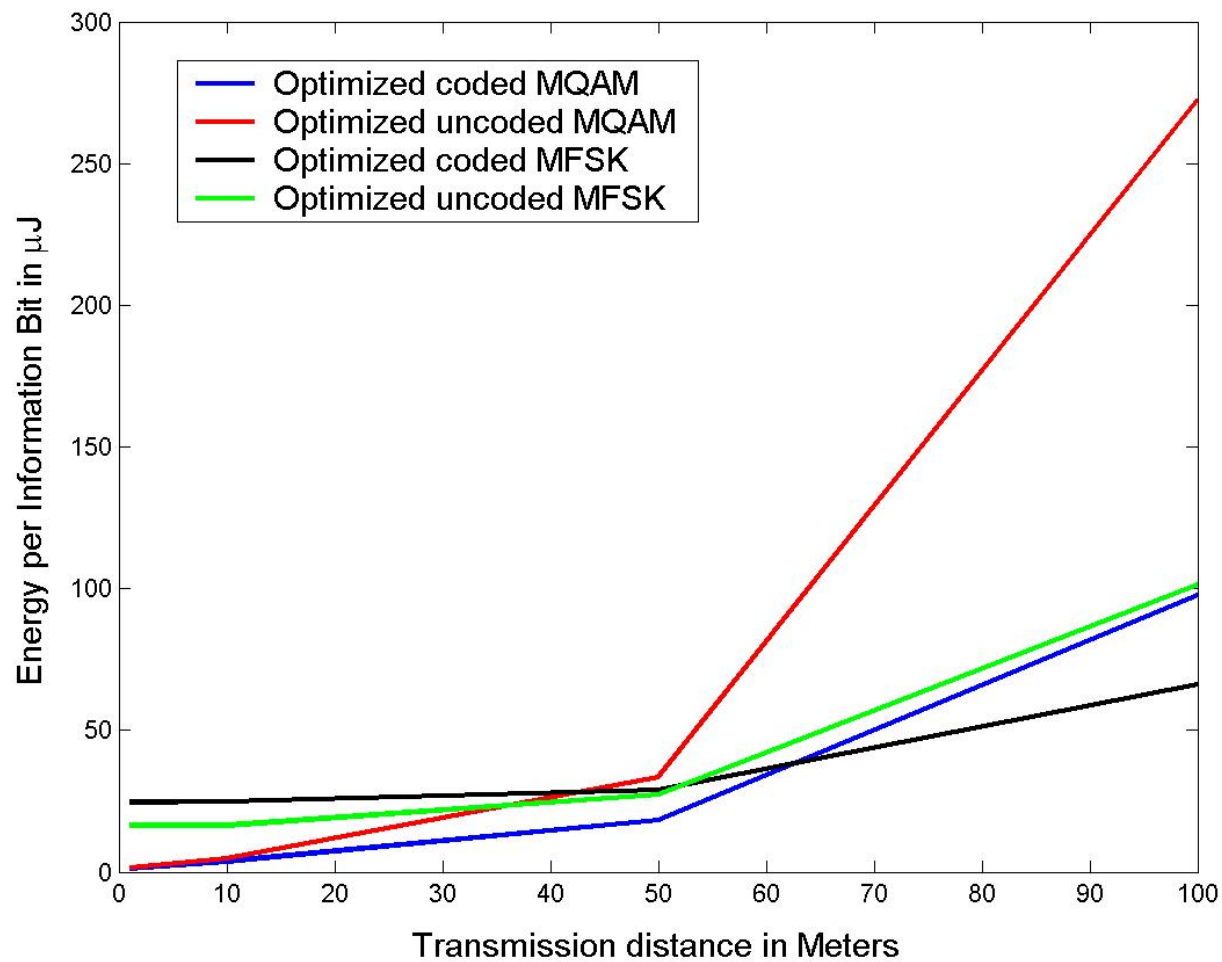
Energy-Constrained Nodes

- 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)

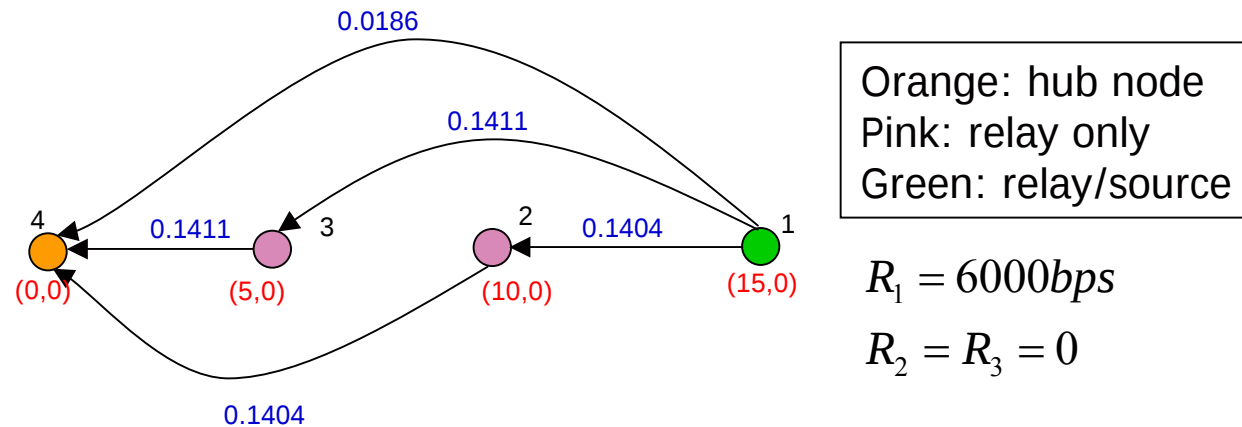


Benefits of Coding



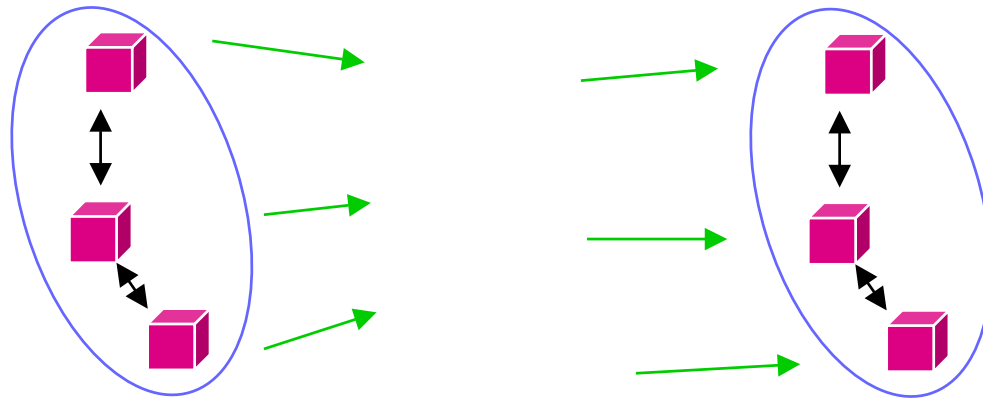
Routing to Minimize Total Energy

- Intermediate nodes act as relays



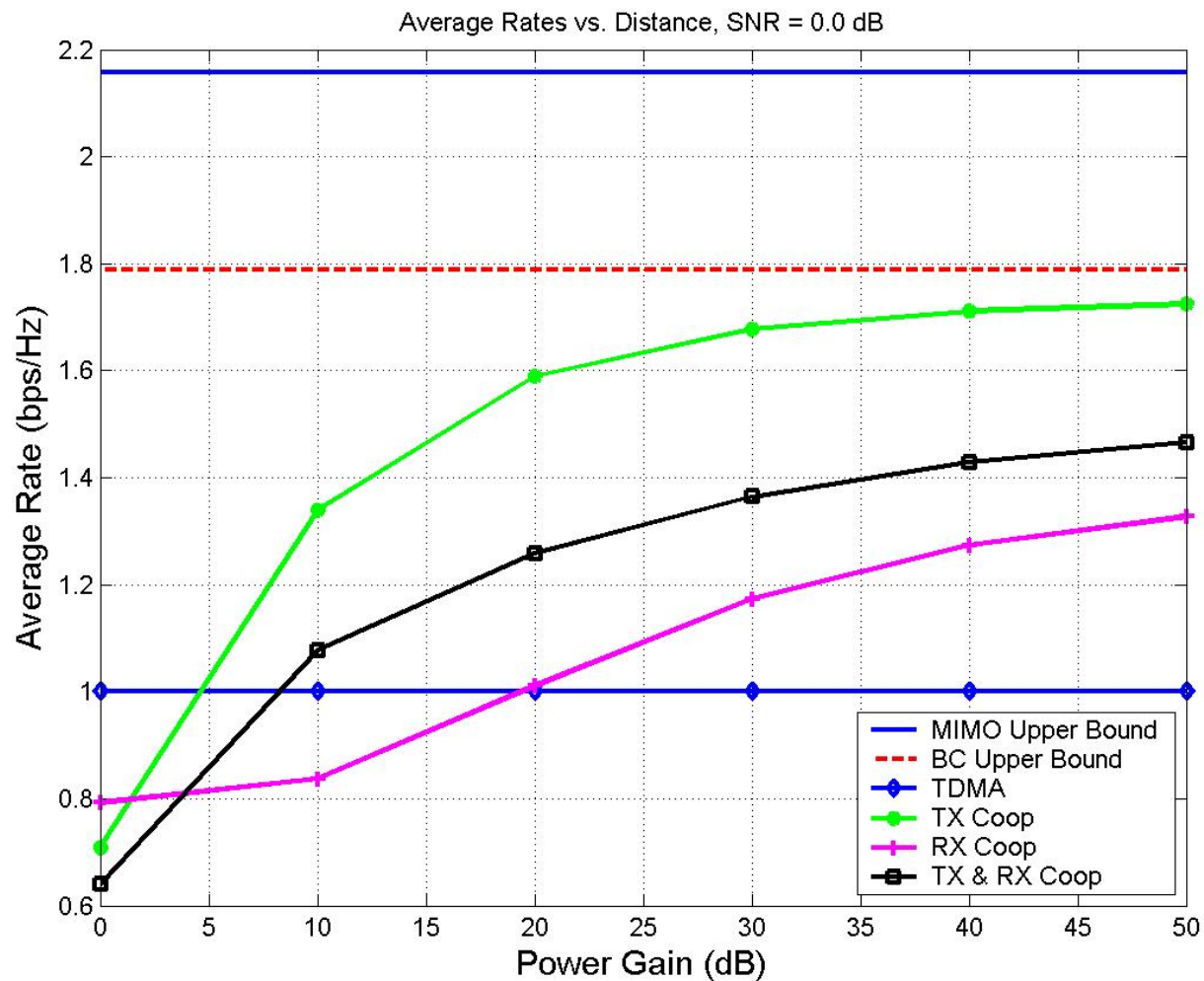
Multi-hop may not be optimal when circuit energy consumption is concerned

Cooperative MIMO

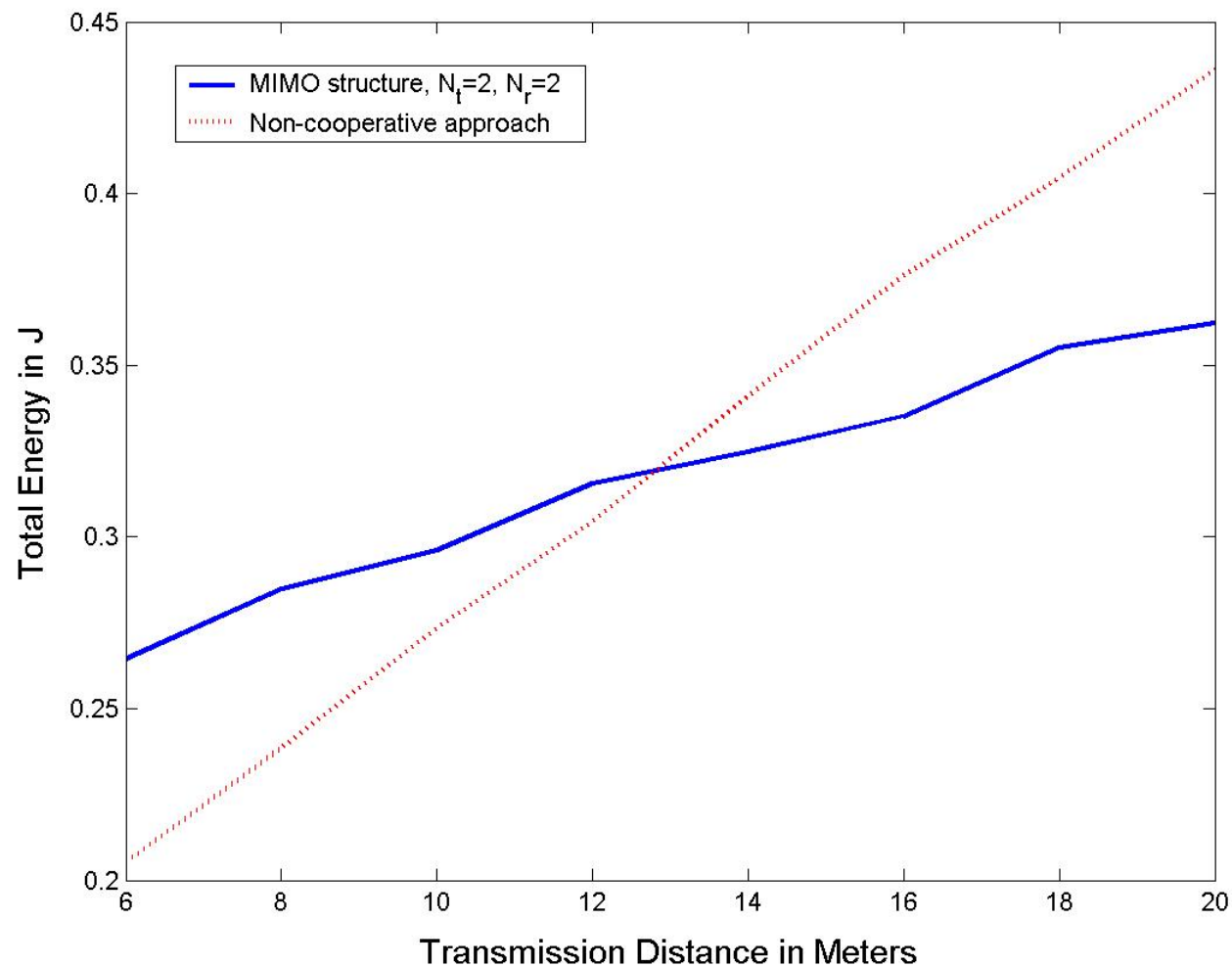


- **Nodes close together can cooperatively transmit**
 - Form a multiple-antenna transmitter (MIMO Broadcast)
- **Nodes close together can cooperatively receive**
 - Form a multiple-antenna receiver (MIMO MAC)
- **MIMO introduces capacity vs. diversity tradeoffs**
 - The communication cost of cooperation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

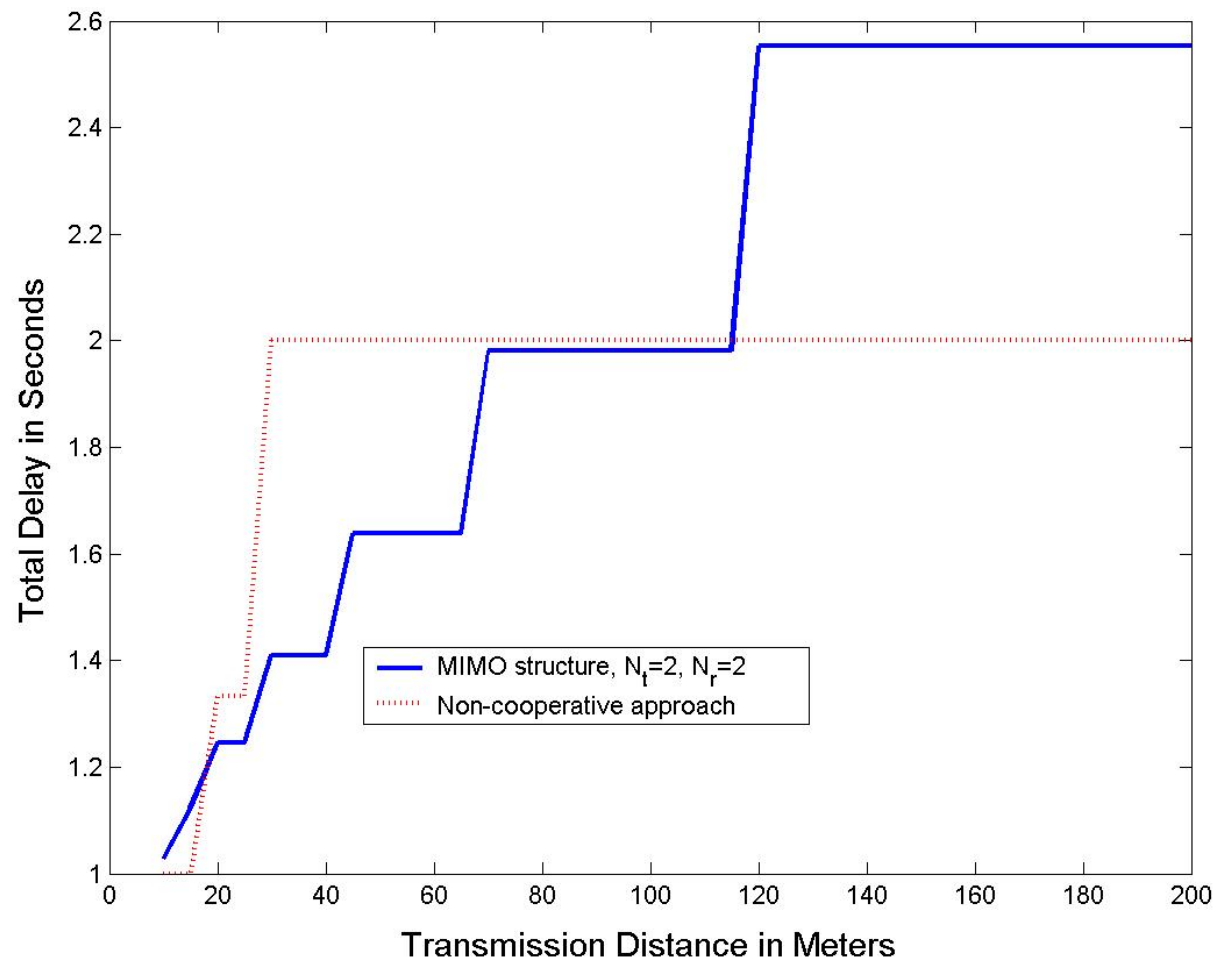
Cooperative MIMO Capacity



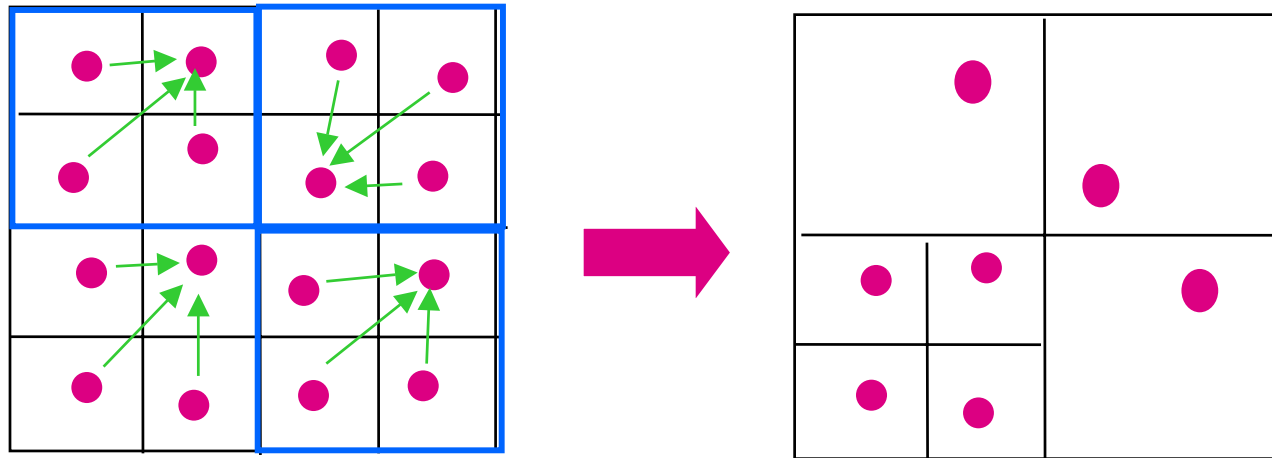
Energy Consumption



Delay



Cooperative Compression



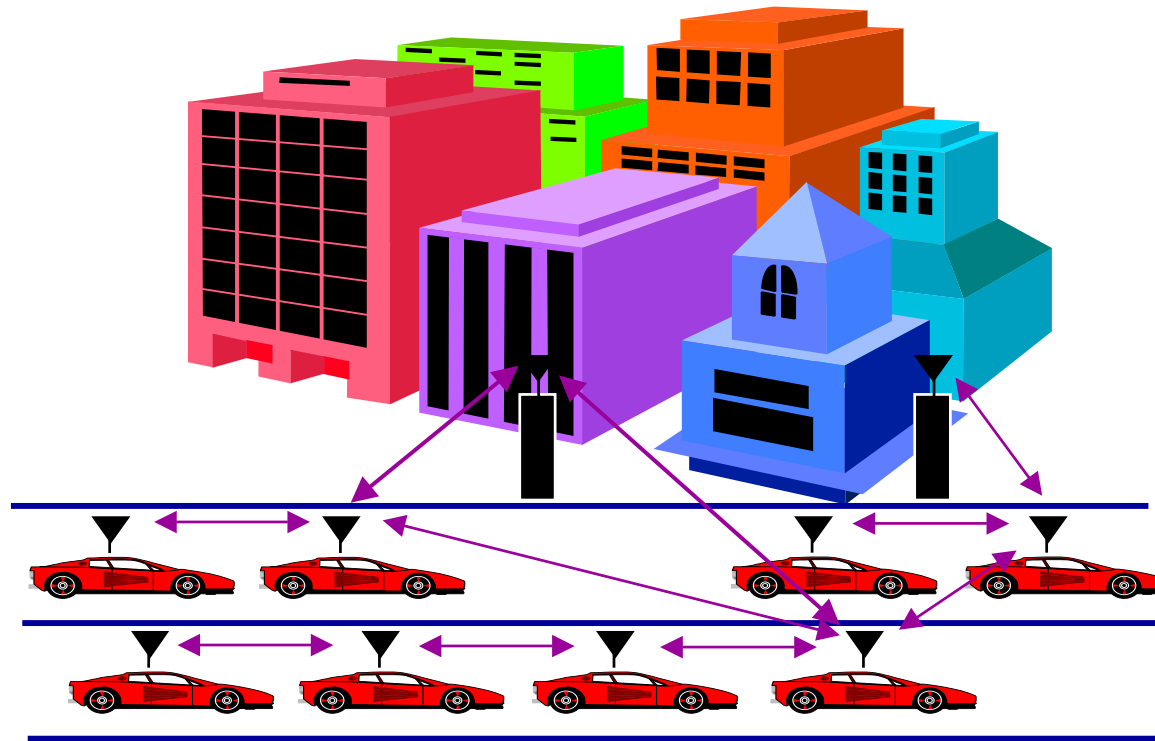
- Intelligent local processing can save power and improve centralized processing
- Local processing also affects MAC and routing protocols

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**

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

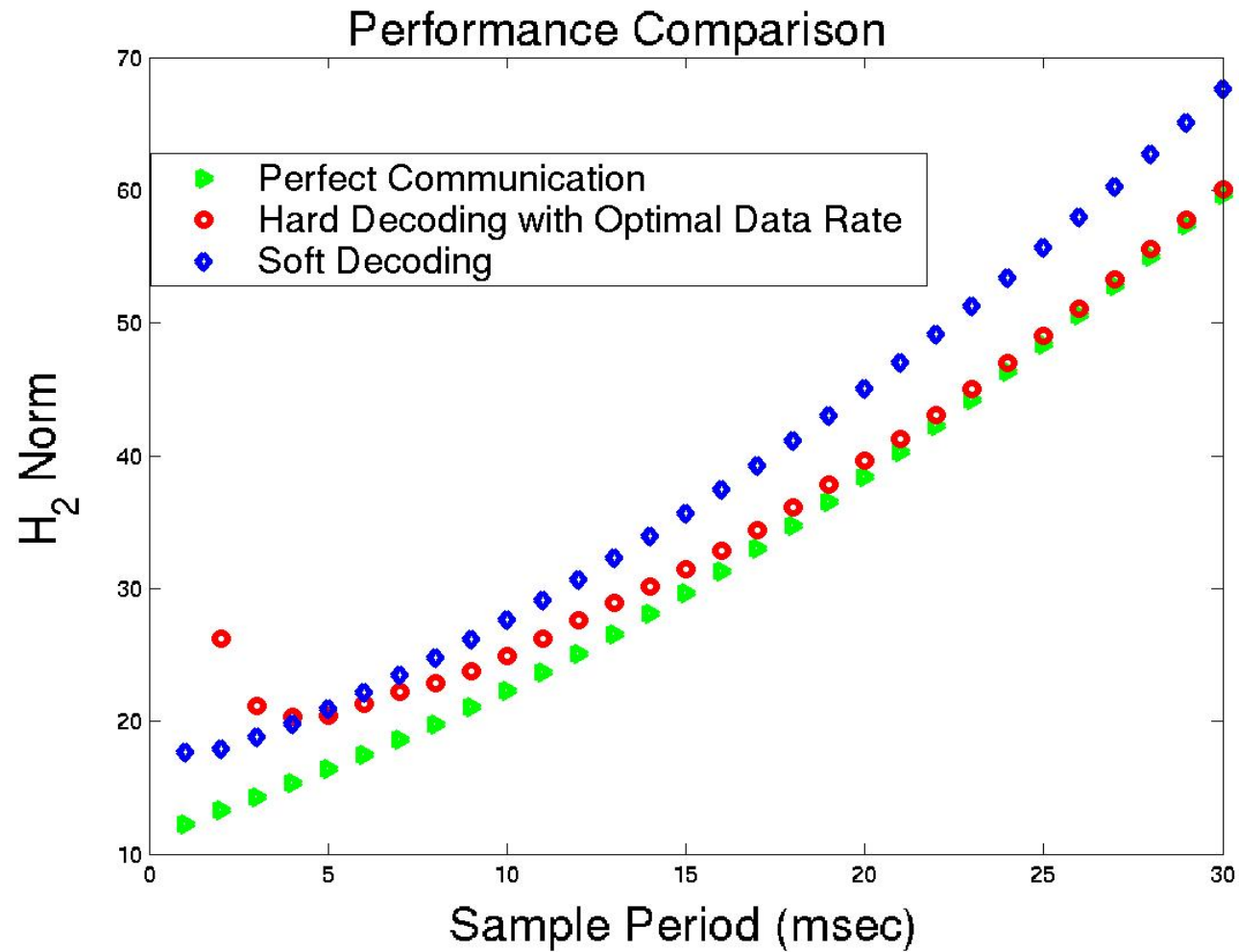
- There is no methodology to incorporate random delays or packet losses into control system designs.
- The best rate/delay tradeoff for a communication system in distributed control cannot be determined.
- Current autonomous vehicle platoon controllers are not string stable with *any* communication delay



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