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

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**Abstract**

See also ADM002082., The original document contains color images.
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*

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

(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

- Capacity assignment for multiple service classes
- Congestion-distortion optimized routing
- Link capacities \( C_{ik} \)
- Link state information
- Link constraints
- Adaptive link layer techniques
- Packet dependencies
- Packet deadlines
- Rate-distortion preamble
- Traffic flows \( F_{ik} \)
- Loss-resilient source coding and packetization
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

![Graph showing energy per information bit vs. transmission distance]

- Optimized coded MQAM
- Optimized uncoded MQAM
- Optimized coded MFSK
- Optimized uncoded MFSK
Routing to Minimize Total Energy

- Intermediate nodes act as relays

### Diagram:

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

### Mathematical Expressions:

\[ R_1 = 6000 \text{ bps} \]
\[ R_2 = R_3 = 0 \]

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

Average Rates vs. Distance, SNR = 0.0 dB

- MIMO Upper Bound
- BC Upper Bound
- TDMA
- TX Coop
- RX Coop
- TX & RX Coop
Energy Consumption

![Graph showing energy consumption versus transmission distance. The graph compares MIMO structure (N_t=2, N_r=2) with a non-cooperative approach.]
Delay

![Graph showing total delay in seconds versus transmission distance in meters. The graph compares MIMO structure with $N_f=2$, $N_r=2$ to a non-cooperative approach.]
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

Performance Comparison

- Perfect Communication
- Hard Decoding with Optimal Data Rate
- Soft Decoding

$H_2$ Norm vs. Sample Period (msec)
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