USC Viterbi School of Engineering

Ming Hsieh Department of Electrical Engineering

Forschungszentrum Telekommunikation Wien - FTW
10th anniversary

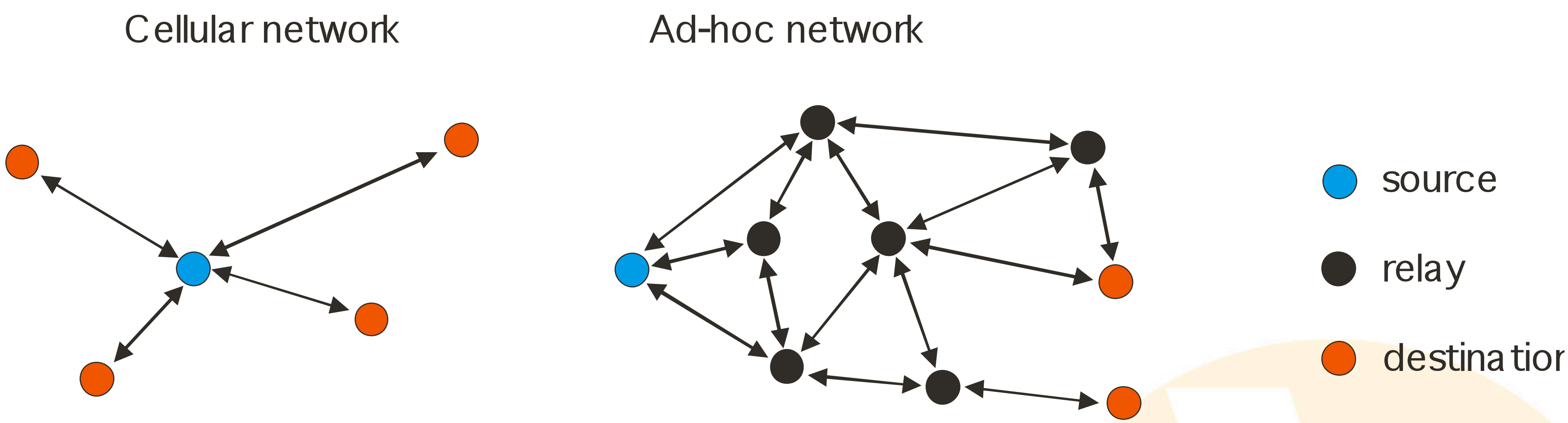
Cross-layer Design in Collaborative Wireless Ad-hoc Networks

Andreas F. Molisch

Wireless Devices and Systems (WiDeS) Group
University of Southern California (USC)

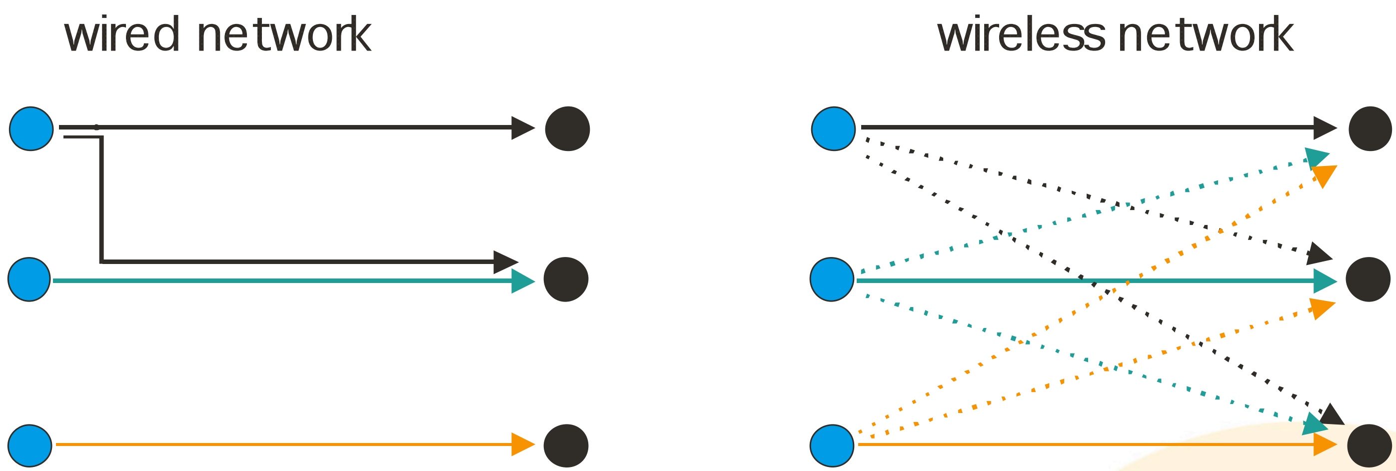
USC

Cellular vs. ad-hoc network



- Advantages of ad-hoc networks:
  - no infrastructure needed (lower cost)
  - higher reliability
  - higher flexibility

Difference to wired network problems

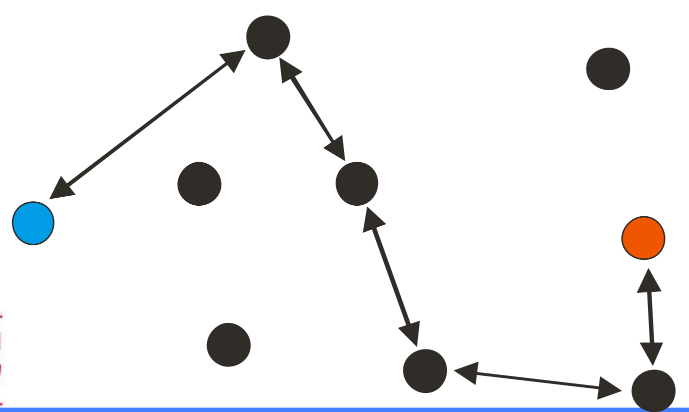


- Wireless transmission is inherently a broadcast transmission; affects all other links
  - \+ Broadcast advantage
  - \- Interference
- Time-variation of links
  - – Congestion due to traffic flow and link breakdown

Traditional ad-hoc networks: multi-hop

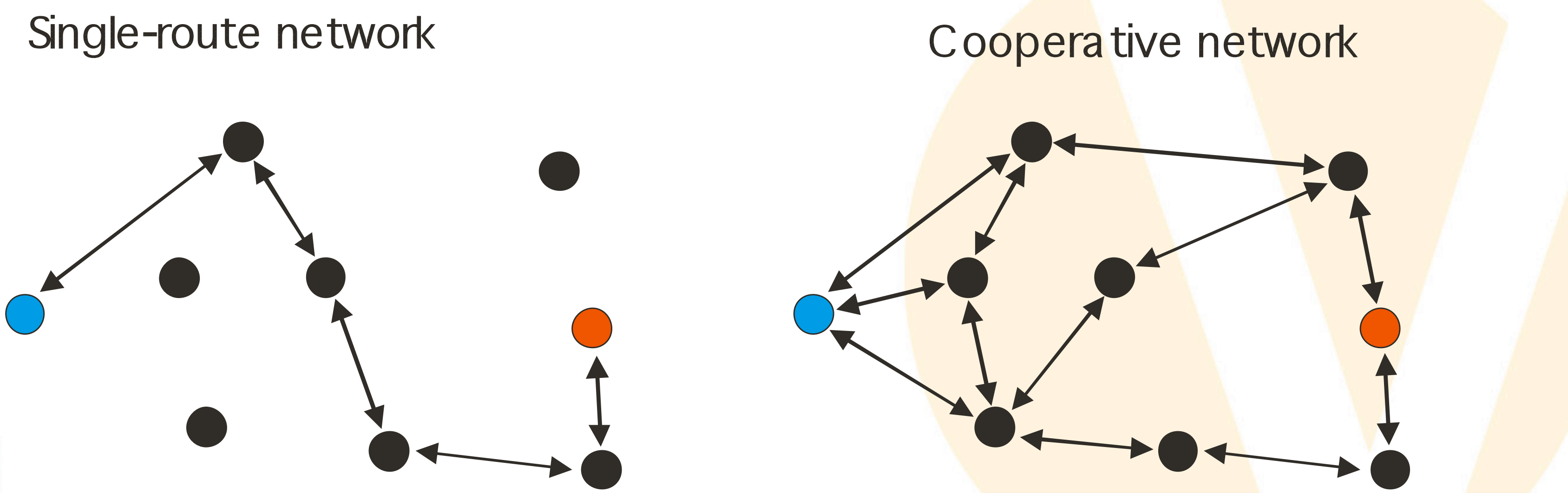
- Forwarding packet to node that is “in range”
- Transmit power per node can be dramatically reduced
- Finding shortest path in network is well-researched problem
- Route changes, mobility, unreliable channel information are still challenging
- Resource allocation e.g. through convex optimization

Single-route network

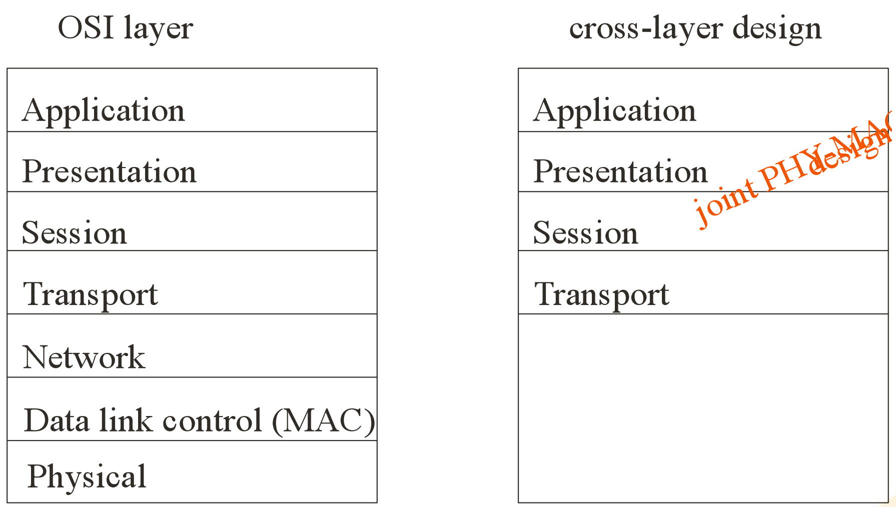


Single-route vs. cooperative transmission

- Key idea of cooperative communication: send data over multiple routes *in parallel*.
  - Nodes help each other in transmission
  - Increased diversity: unlikely that multiple paths are in fading dip simultaneously
  - Dynamically invest more power into paths with smaller attenuation



Layered design versus cross-layer design



- OSI model: 7 layers, each optimized separately

+ Modular approach, different modules can be easily combined

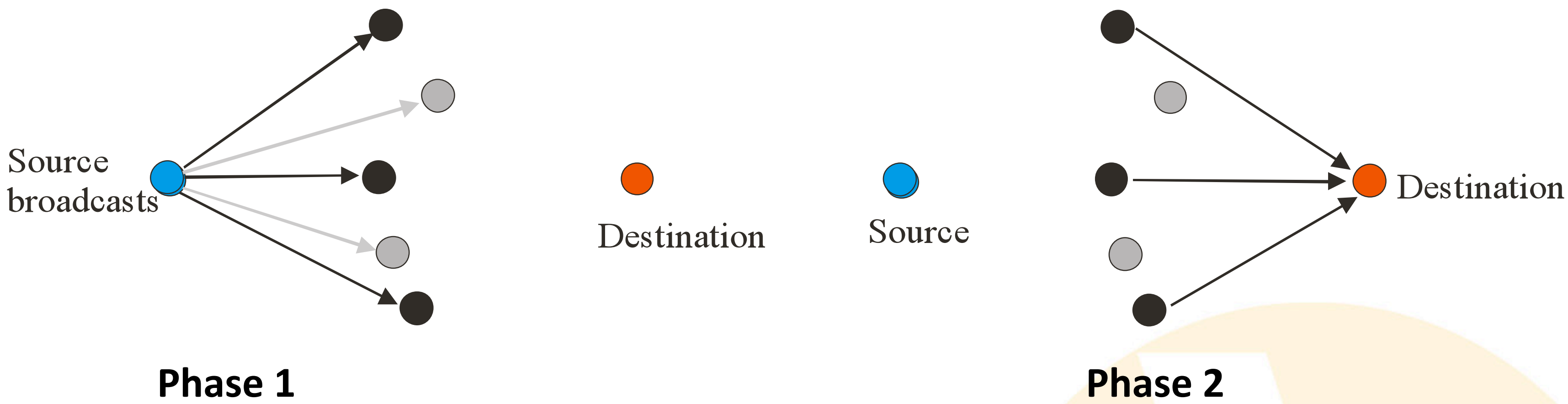
- Suboptimum results. Lower performance than optimized cross-layer design, especially for wireless ad-hoc networks

Cross-layer design

- PHY, MAC, NET layers all depend on each other
- Example: finding optimum route in the presence of interference
  - PHY layer design (coding, modulation, type of diversity combining) design determines how sensitive each link is to interference
  - MAC-layer design (scheduling, multiple-access format) determines how much interference is present for a given route
  - NET-layer finds best route given those constraints
  - Optimized design looks for best combination of PHY, MAC, and NET layer

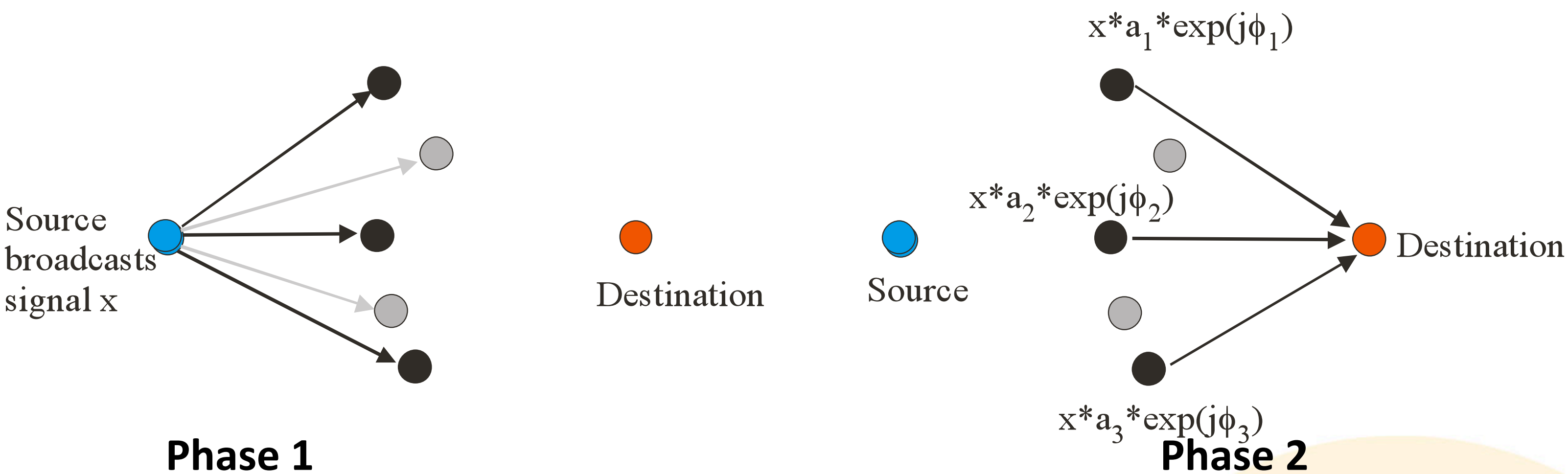
Building blocks for CC

- Parallel multi-relay channel



- Impact of channel state information (CSI)
  - Phase 1: always same transmission scheme: broadcast.
    - Power depends on amount of CSI (instantaneous power or average power)
  - Phase 2: relaying *scheme* depends on amount of CSI

Full CSI: virtual beamforming



- In phase 2, relay nodes adjust transmit weights so that signals add up coherently at destination (maximum-ratio transmission)
- Requires *full CSI* at the relays
- Include costs for acquiring and communicating CSI

Instantaneous magnitude CSI

- In phase 1, transmission to the “best” relay
- Phase 2: forwarding of the information to the destination
- Provides selection diversity gain, but no beamforming gain
- Requires to estimate magnitude CSI; but fewer bits for communicating (only index of best relay)

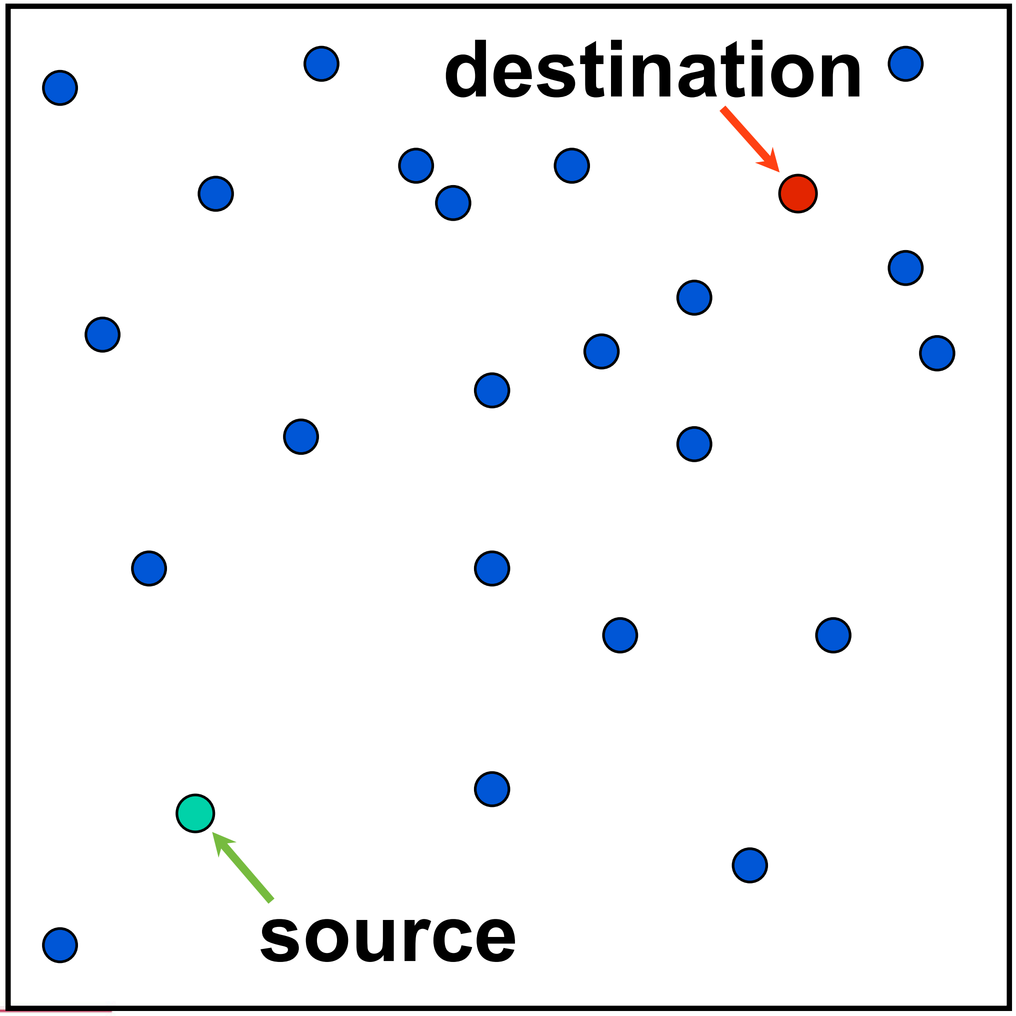
Average CSI

- Average CSI: TX diversity; power of each TX depends on
  - Average channel state
  - Outage criterion
  - Type of receiver (energy accumulation, mutual-information accumulation)
- No CSI: like average CSI, but no adaptation of power to CSI state

Case study: ad-hoc networks with Fountain codes

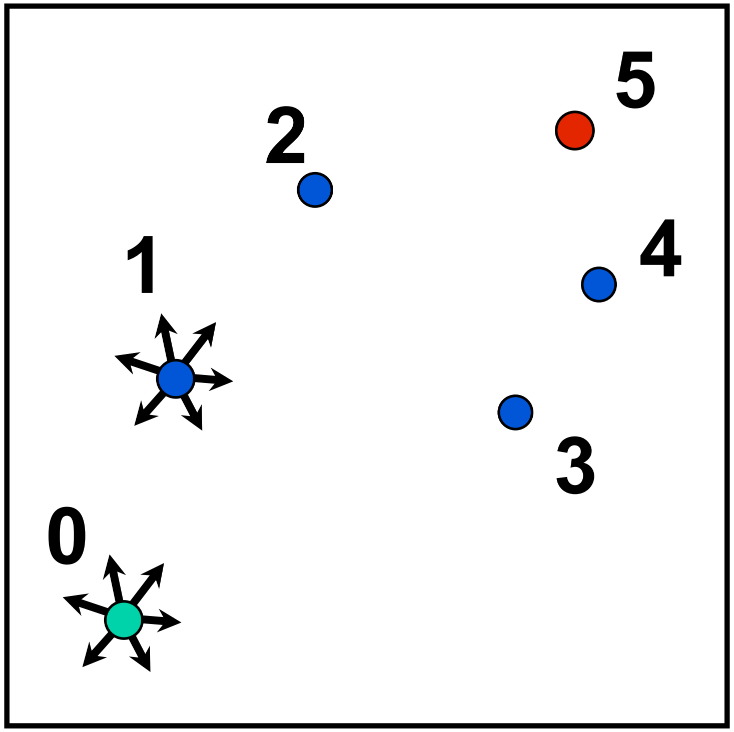
- Rateless codes (e.g., Fountain codes):
  - Convert a finite-length source word into an infinitely long bitstream
  - Transmission of bitstream is terminated when received mutual information reaches the entropy of the source word
  - Receiver only needs to send single-bit feedback
- Fountain codes perform mutual-inform. accumulation
  - Every received bit contributes to received mutual information
  - If destination receives data streams from N nodes, it adds up *mutual information* from those nodes (fountain codes for different nodes are different
- Use in relay networks:
  - require only single-bit feedback and no other CSI
  - In relays forwarding to destination help relays still receiving from source [Molisch et al., IEEE Trans. Wireless Comm., 2007]

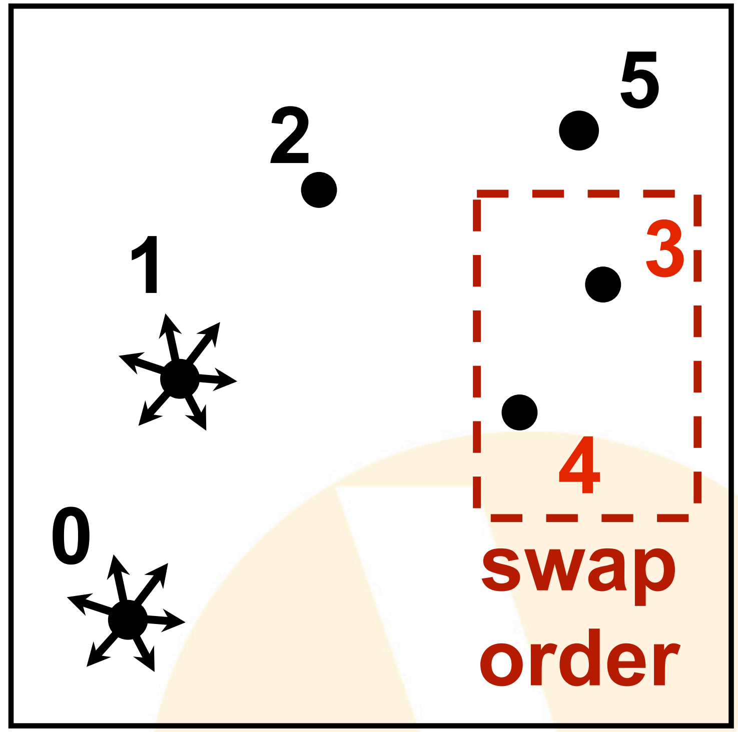
Routing in large networks



- Objective:
  - minimize delay
- Constraints:
  - energy
  - BW
- Challenges are:
  - who transmits?
  - when & for how long?
  - over what bandwidth?
  - because use MI accumul, can't solve for route using DP

Break into two sub-problems





A) for fixed "decoding order" resource allocation is a LP

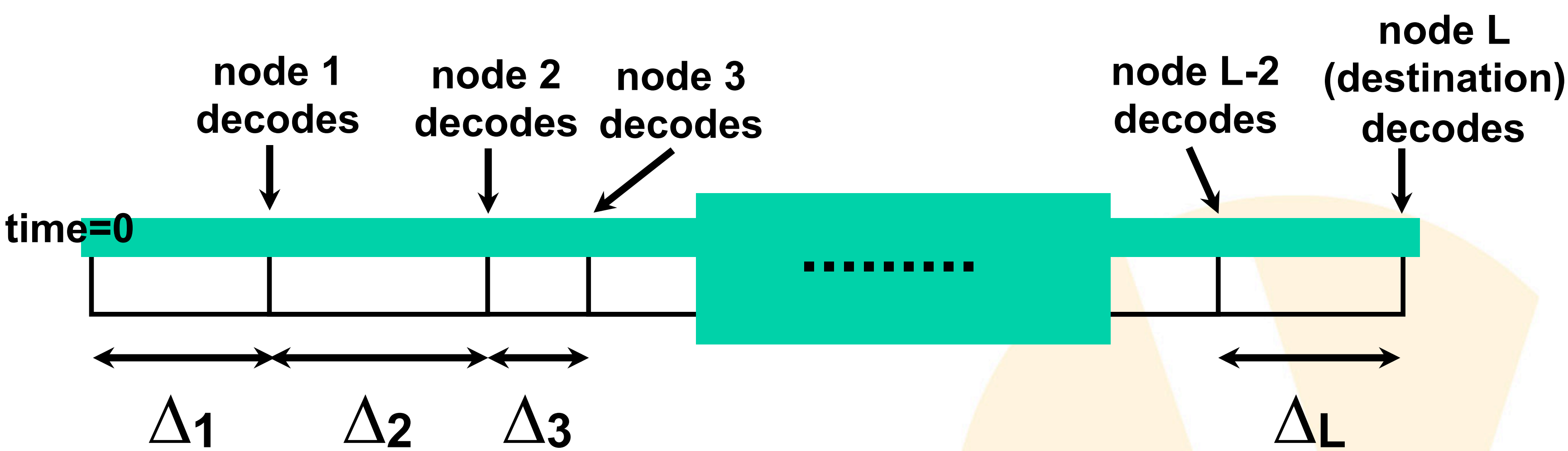
computationally quick

B) revise decoding order based on LP optimum

- for 50 nodes 10^{63} orderings

Parameterization: inter-node delays

- Inter-node decoding delay (node i-1 to i) = Δ_i



Minimize delay = min $\sum_{i=1}^{L} \Delta_i$

Decoding order induces linear constraints

Pairwise rate (flat fading, fixed transmit PSDs):

$$C_{i,j} = \log_2\left[1 + \frac{h_{i,j} P_i W_i}{N_0 W_i}\right] = \log_2\left[1 + \frac{h_{i,j} P_i}{N_0}\right] \text{ bits/s/Hz},$$

Decoding constr. (MI accumulation, orthogonal Tx):

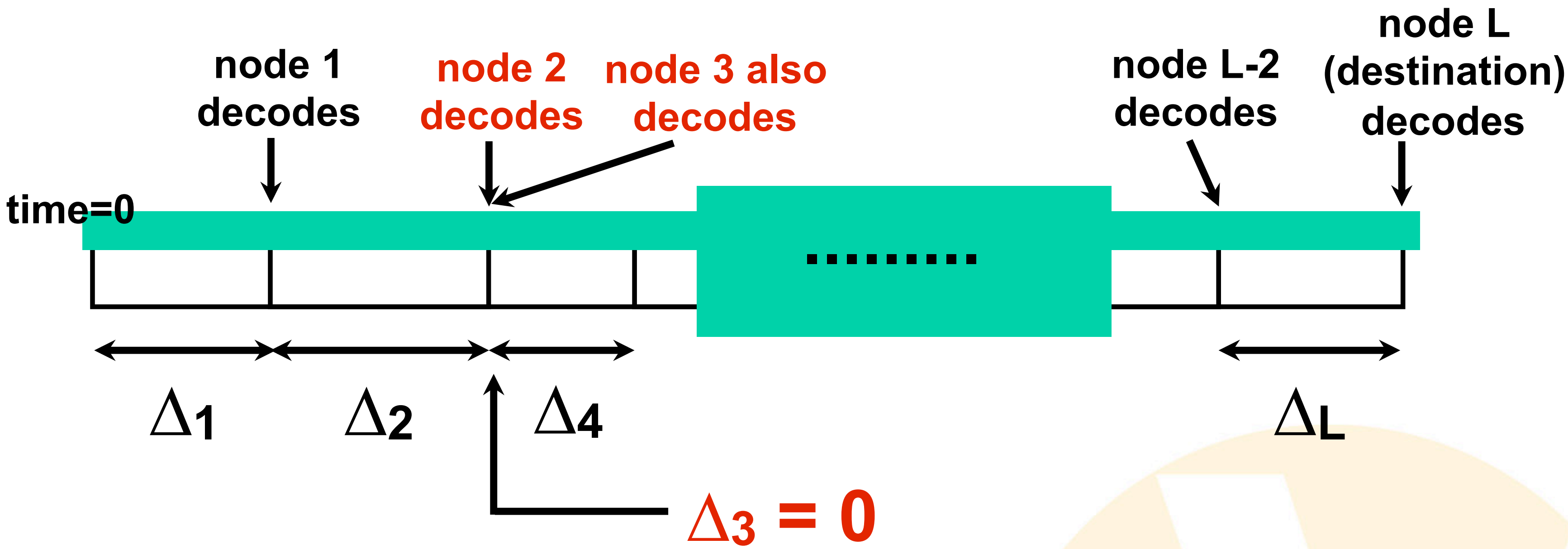
$$\sum_{i=0}^{k-1} \sum_{j=i+1}^{k} A_{i,j} C_{i,k} \geq B \quad \text{for all} \quad k \in \{1, 2, \ldots, L\}$$

$$A_{i,j} \geq 0 \quad \text{for all} \quad \begin{array}{l} i \in \{0, 1, \ldots L-1\} \\ j \in \{1, 2, \ldots, L\} \end{array}$$

System bandwidth constraint

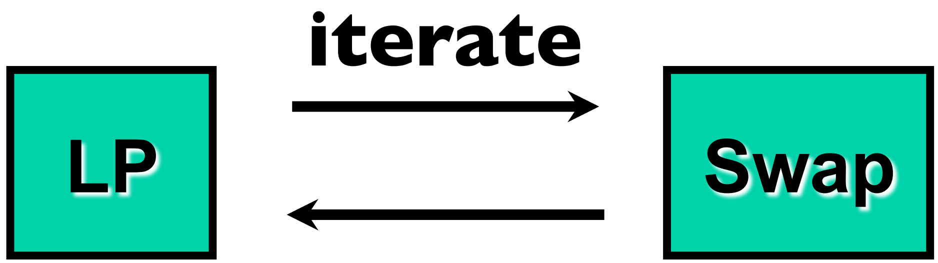
Sum Energy constraint

LP solution suggests a revised order



- If $\Delta_3 = 0$ then "swap" ordering of nodes 2 & 3
- Old solution is feasible for new order
- Re-run LP, delay can only get better or stay same
- If swap nodes L-1 & L (destination), "drop" L-1 from order

Iterative algorithm



until LP solution satisfies

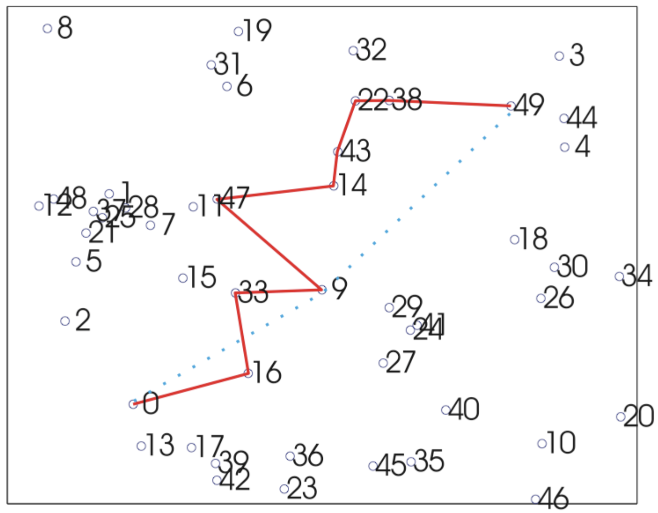
$\Delta_i \geq 0$ for all i

- Only necessarily local optimum. For small networks (8-10 nodes) optimum often global
- Problem when multiple $\Delta_i = 0$; which swaps to make?
- Start from minimum delay “flooding” order and sequentially tighten energy constraint

Key insights

- Only one node active at a time
- Energy gains because of MI accumulation
- Due to use of MI, optimum route is different from shortest-path route
- Minimum delay solution equals minimum energy solution for system-wide bandwidth constraints
- Tradeoff between energy and delay for per-node bandwidth constraint
- Distributed algorithms are possible (though suboptimum)

Results: 50 nodes, sum BW constraint



$$h_{i,j} = (d_{i,j})^{-2}$$

- Node numbering arbitrary, path-loss
- At min energy cooperative Tx follows red line
- Compare with Dijkstra (dotted), 21.4 sec vs. 13.1 sec., 50% gain from MI accumulation, 50% from routing

Summary and Conclusions

- Wireless ad-hoc networks can save energy, eliminate costs for infrastructure, and increase reliability
- Difference from wired problems, because of the broadcast nature of wireless channel
- Cross-layer optimization is indispensable
- Cooperative networks use parallel relays as basic building block
- Optimum collaboration strategy depend on CSI
- Case study of mutual-information accumulation
  - Can use fountain codes to achieve practical information accumulation
  - Relay nodes that already have information can help other nodes that are still acquiring
  - Routing is more challenging with collaborative routing

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Contact information

Andreas F. Molisch

Ph.D., FIEEE, FIET
Head, Wireless Devices and Systems (WiDeS) Group
Communications Sciences Institute,
Dpt. Of Electrical Engineering
Viterbi School of Engineering
University of Southern California (USC)
Los Angeles, CA, USA

Email: Andreas.Molisch@ieee.org
Website: wides.usc.edu