iPack: in-Network Packet Mixing for High Throughput Wireless Mesh Networks

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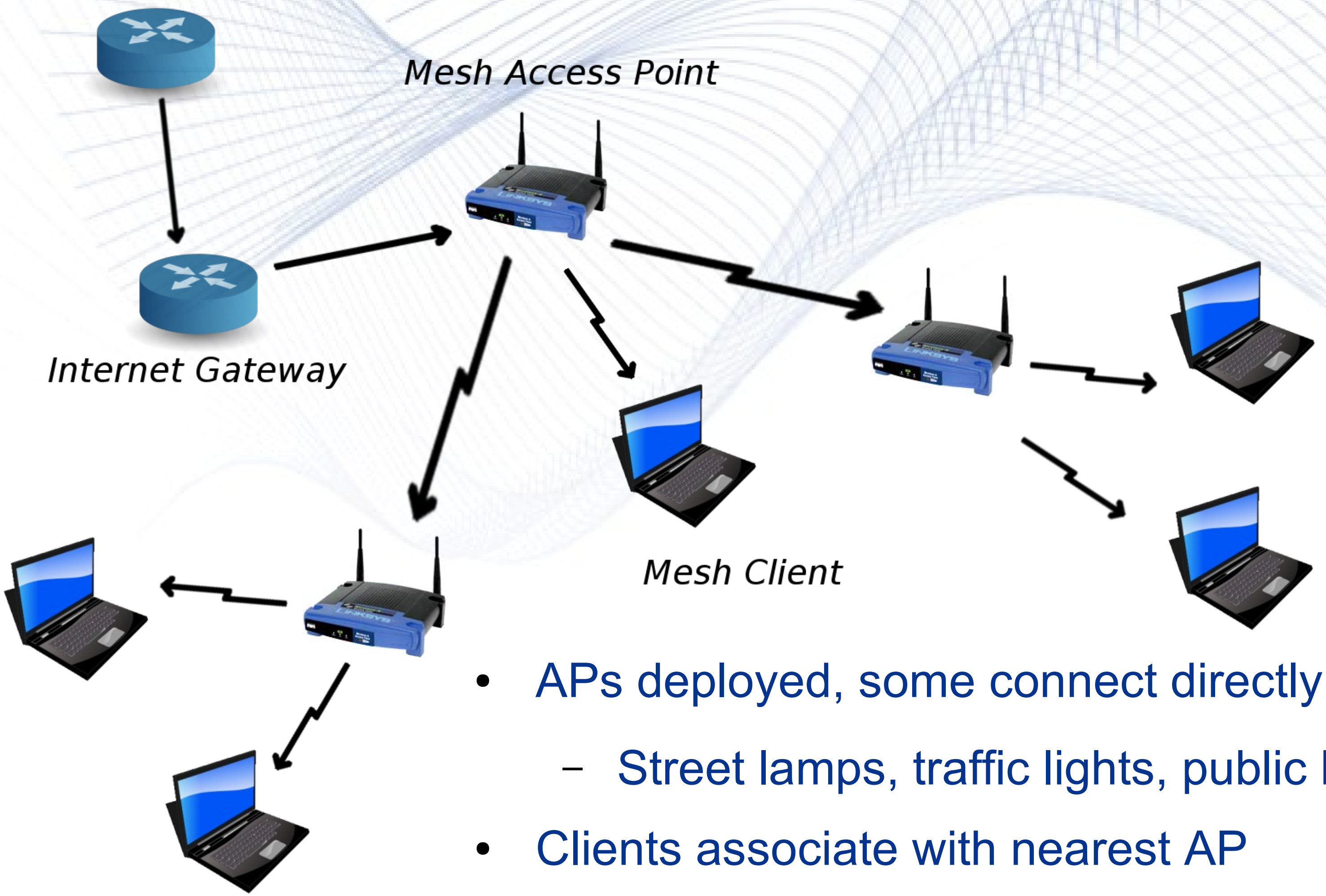
Wireless Mesh Networks

- City- and community-wide mesh networks widely used
  - New approach to the "last mile" of Internet service
  - In United States alone [muniwireless.com, Jan 16, 2007]:
    - 188 deployed
    - 148 in-progress or planned

Mesh Network Structure



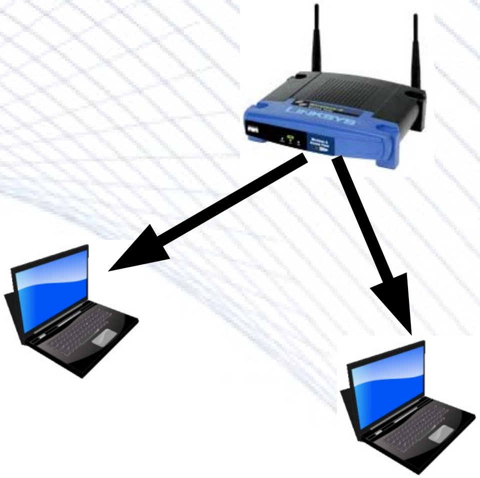
- APs deployed, some connect directly to Internet
  - Street lamps, traffic lights, public buildings
- Clients associate with nearest AP
- Traffic routed to/from Internet via APs (possibly multi-hop)

Limited Capacity of Mesh Networks

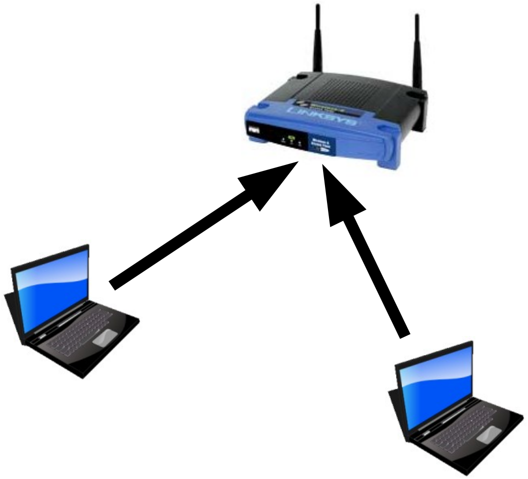
- Current mesh networks have limited capacity
  [Li *et al.* 2001, dailywireless.org 2004]
- Increased usage will only worsen congestion
  - More devices
  - Larger downloads, P2P, video streaming
  - Limited spectrum
- Network-wide transport capacity does not scale
  [Gupta and Kumar 2001]
- Must bypass traditional constraints

Current Coding Techniques

- Transmitter-side
  - Downlink superposition coding
    [Cover 1972, Bergmans and Cover 1974]
  - XOR-style network coding
    [Katti *et al.* 2006]

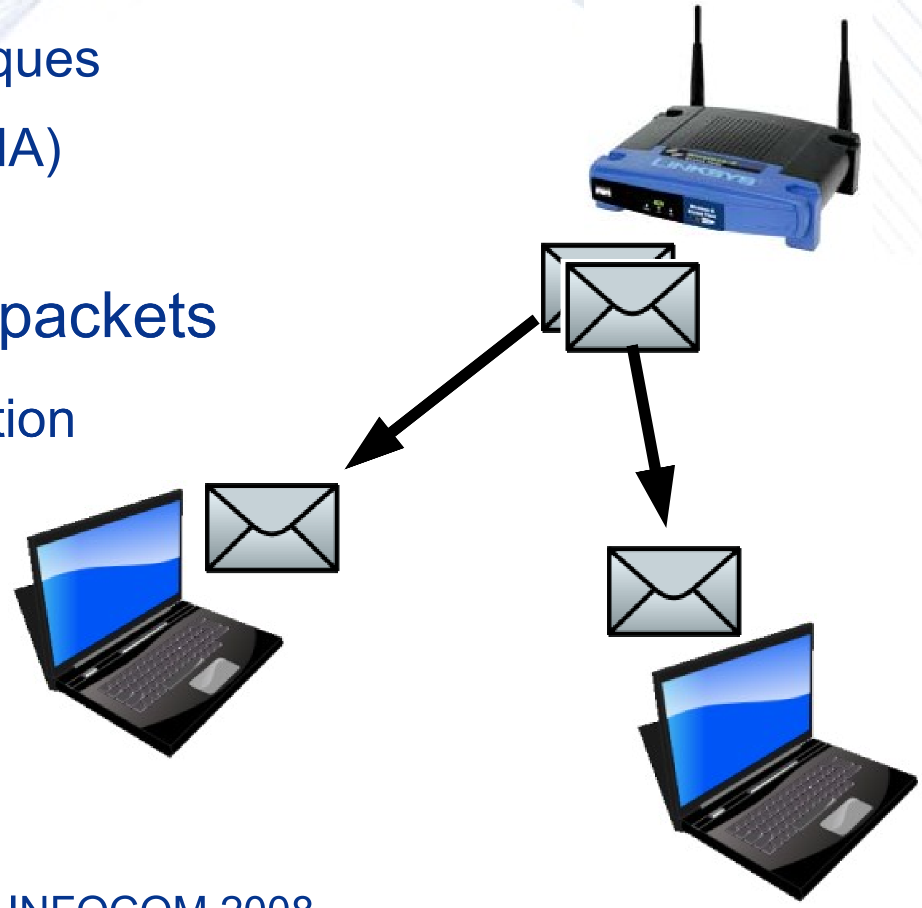


- Receiver-side
  - Uplink superposition coding
  - Analog [Katti *et al.* 2007] and physical-layer [Zhang *et al.* 2006] network coding



Packet Mixing for Increased Capacity

- Multiple packets transmitted simultaneously
  - Same timeslot
  - Cross-layer coding techniques
  - No spreading (unlike CDMA)
- Receiver(s) decode own packets
  - Possibly use side-information



Packet Mixing in Mesh Networks

- Objective
  - Scheduling algorithms to take advantage of mixing
  - Construct a mixed packet with
    - Maximum effective throughput
    - Sufficiently-high decoding probability at receivers
    - Mixture of coding techniques

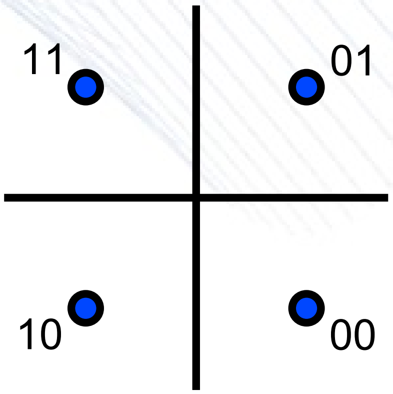
- Currently consider two techniques
  - Downlink superposition coding *(denoted by SC)*
  - XOR-style network coding *(denoted by NC)*

Talk Outline

- ***Basic concepts***
  - ***Downlink superposition coding***
  - ***XOR-style network coding***
- Mixed packet construction
  - Algorithms
  - Evaluations
- GNU Radio implementation
- Conclusions and future work

Physical Layer Signal Modulation

- Signal has two components: I and Q
- Represented on complex plane



- Sender
  - Map bits to symbol (*constellation point*)
- Receiver
  - Determine closest symbol and emit bits

Downlink Superposition Coding (SC)

- Basic idea
  - Different message queued for each receiver
  - Transmit messages simultaneously
  - Exploit client channel diversity
- Example

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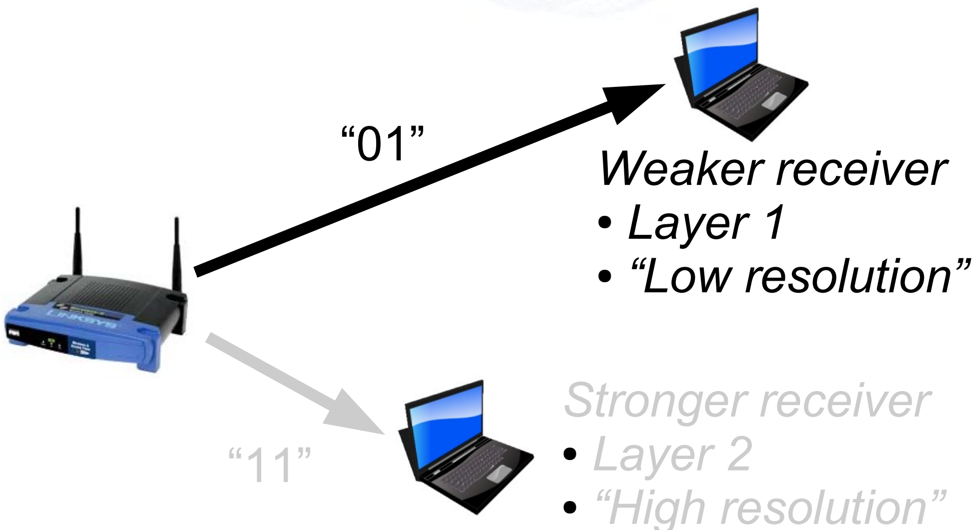

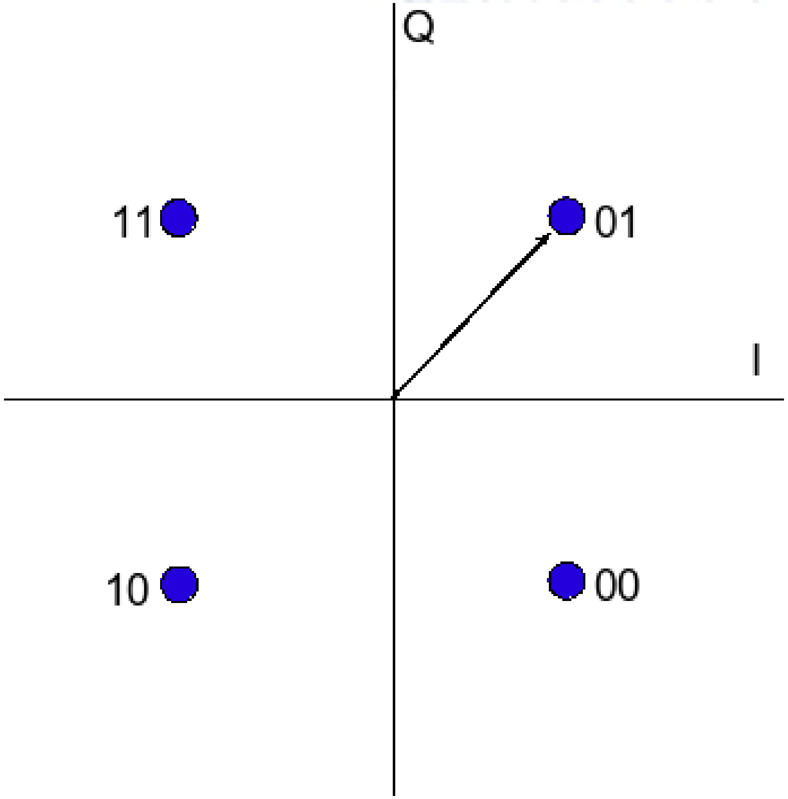

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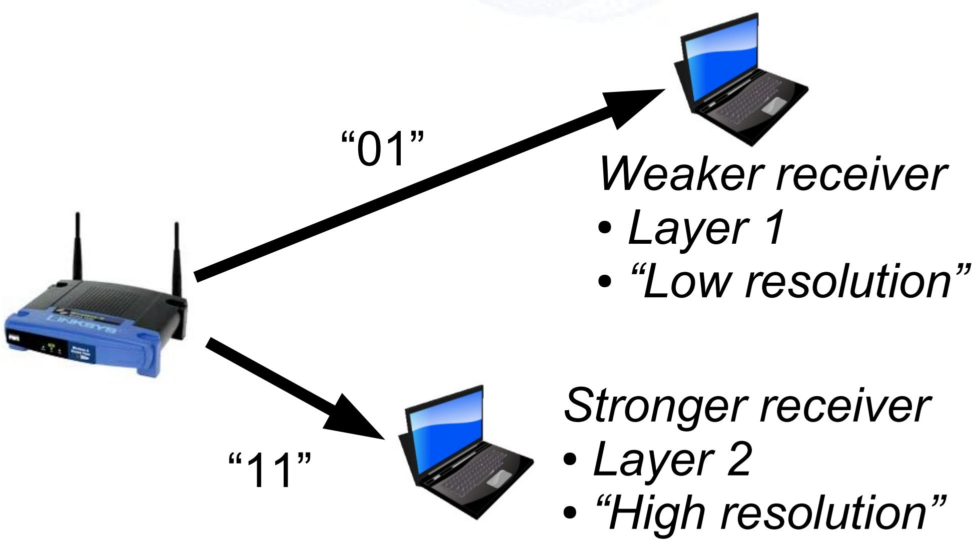
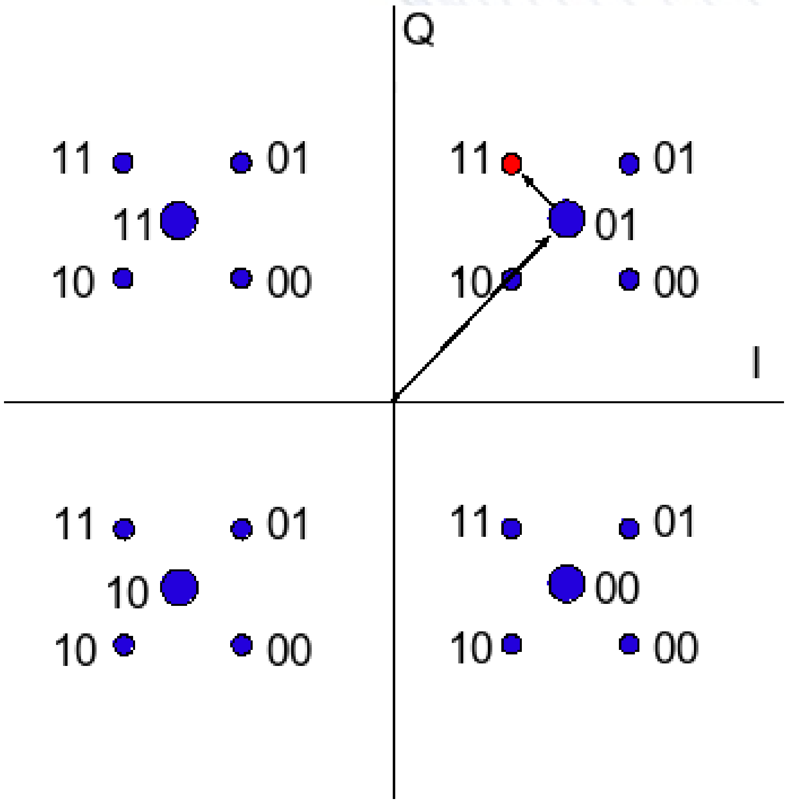
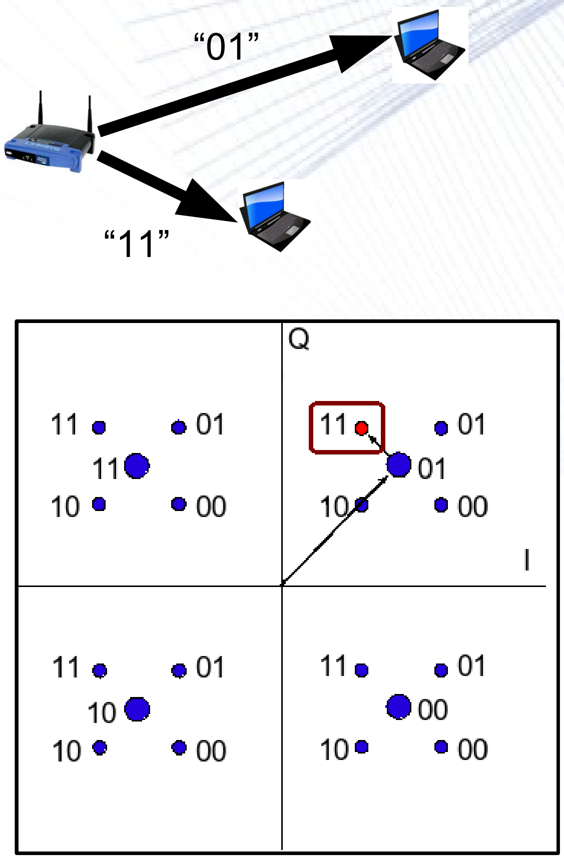
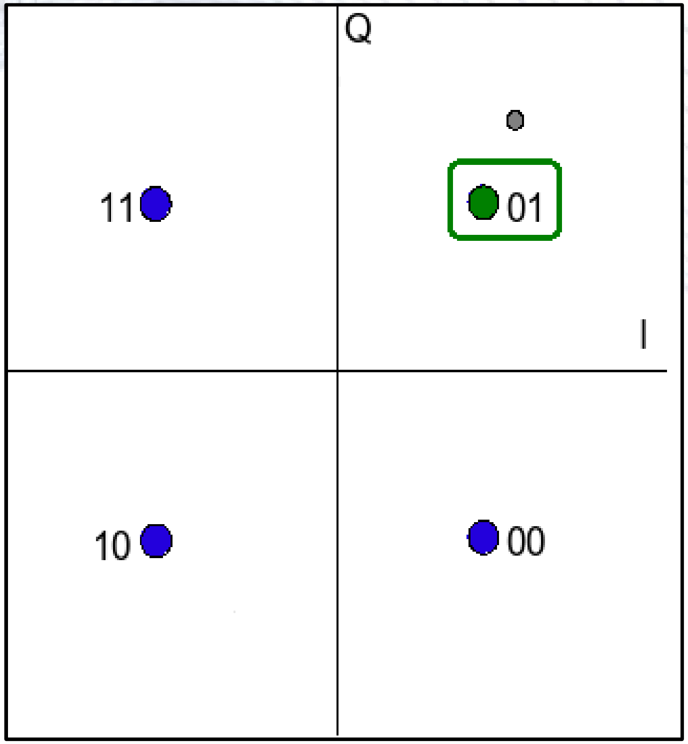




SC Decoding: Successive Interference Cancellation

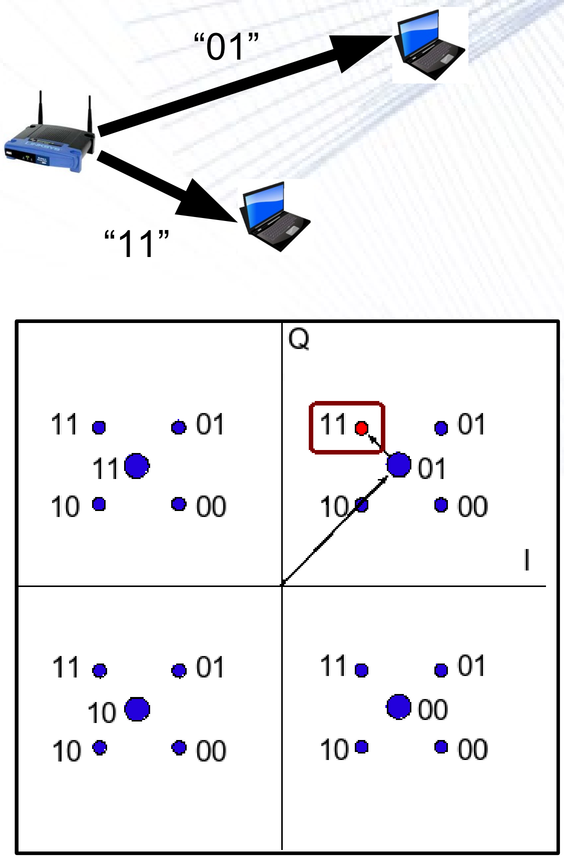


Weaker Receiver

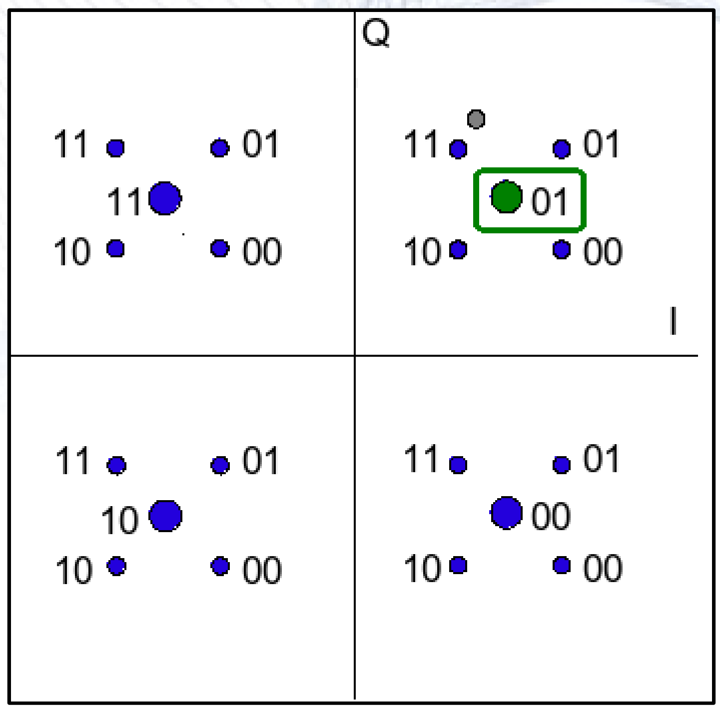


Decode Layer 1

SC Decoding: Successive Interference Cancellation

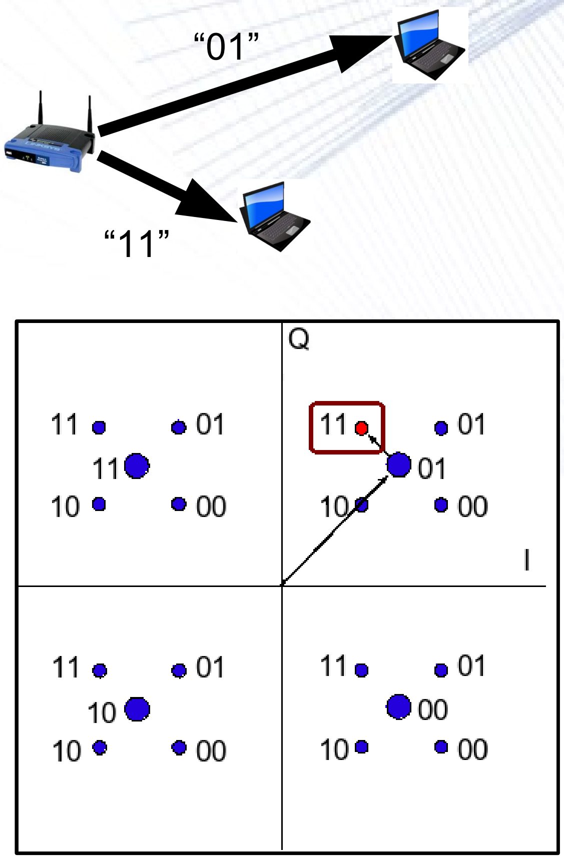


Stronger Receiver



(1) Decode Layer 1

SC Decoding: Successive Interference Cancellation



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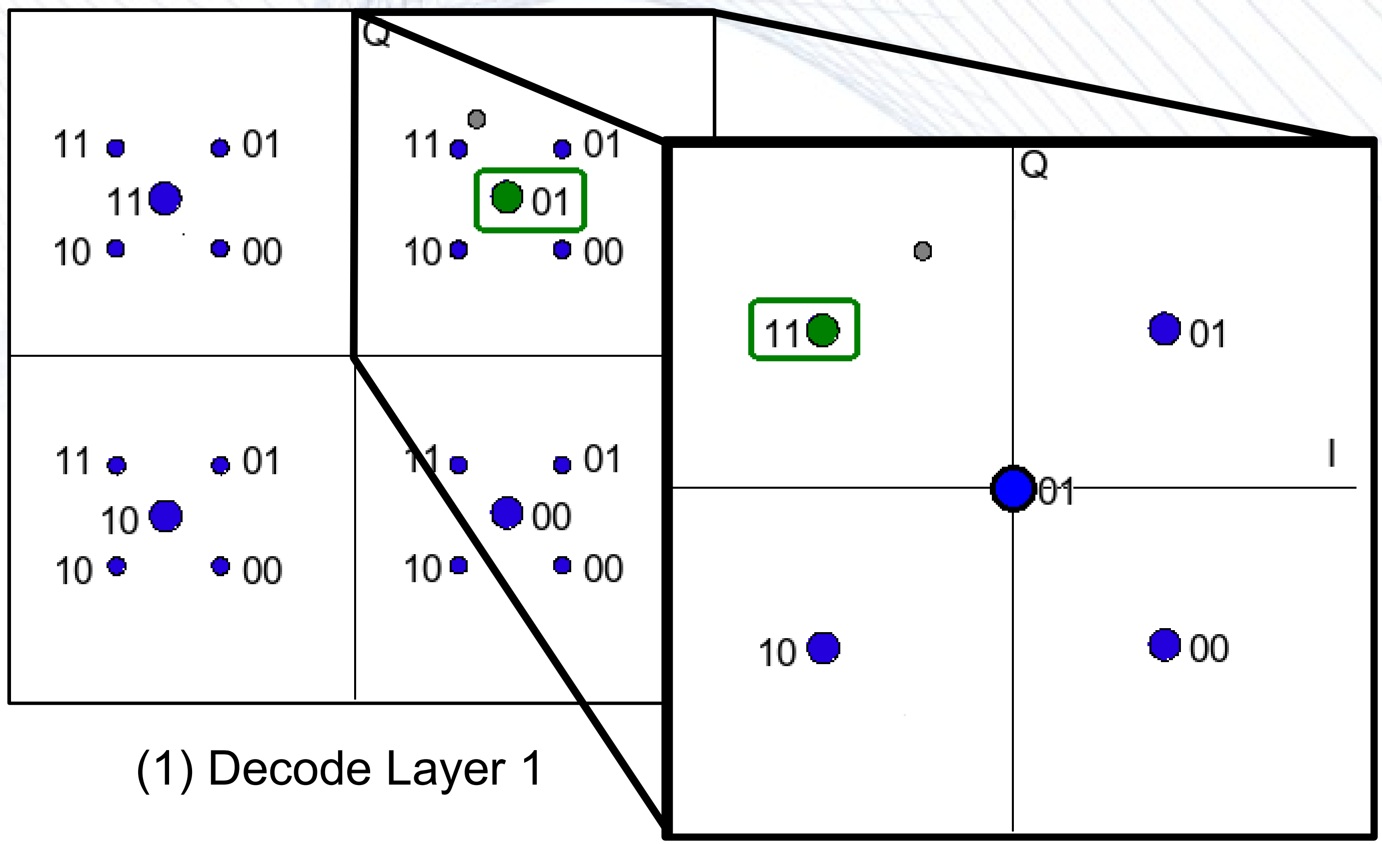
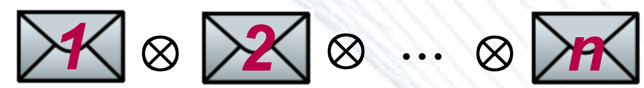


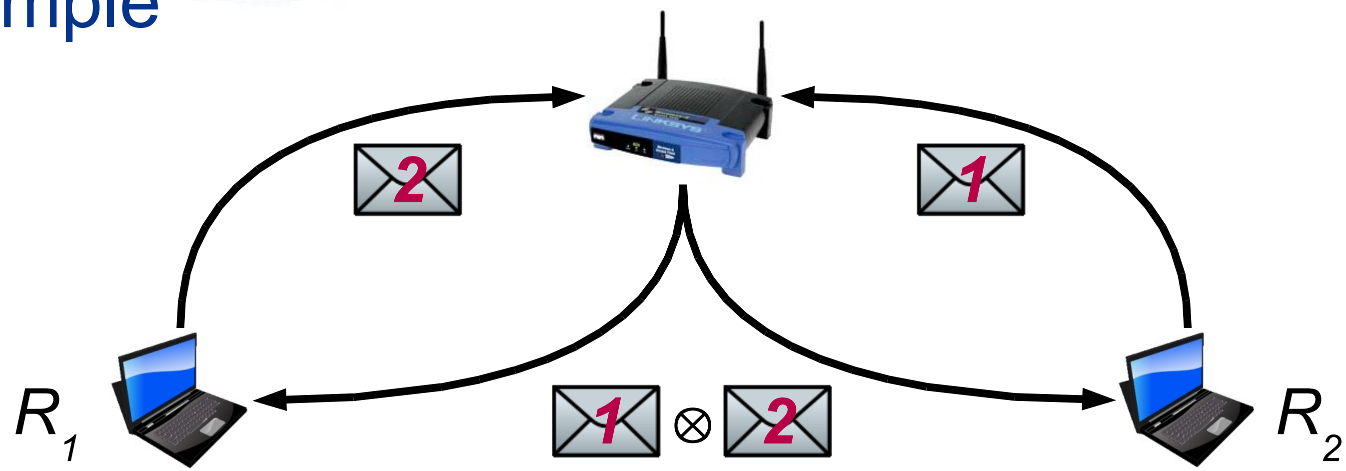
(1) Decode Layer 1

(2) Subtract and decode Layer 2

XOR-style Network Coding

- Basic idea
  - Nodes remember overheard and sent messages
  - Transmit bitwise XOR of packets: 

  - Receivers decode if they already know *n-1* packets
- Example



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  - ***Algorithms***
  - ***Evaluations***
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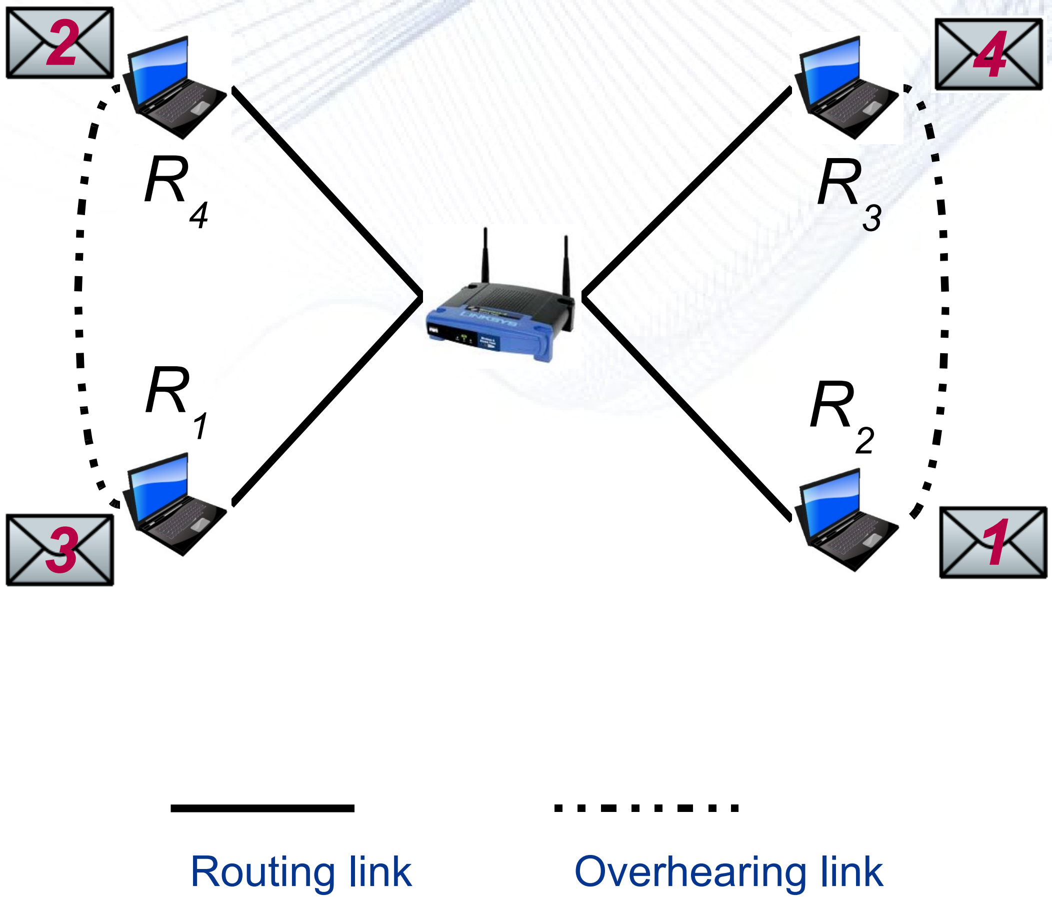
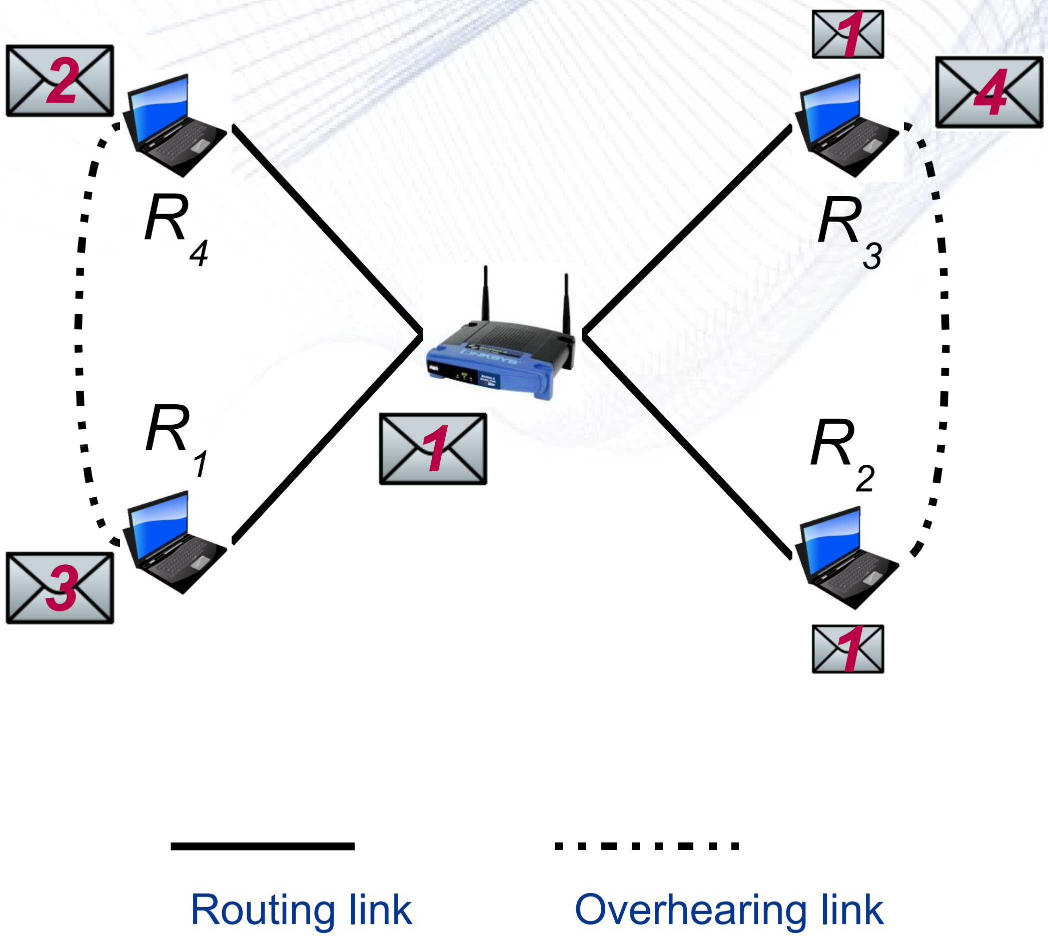
Packet Mixing Example



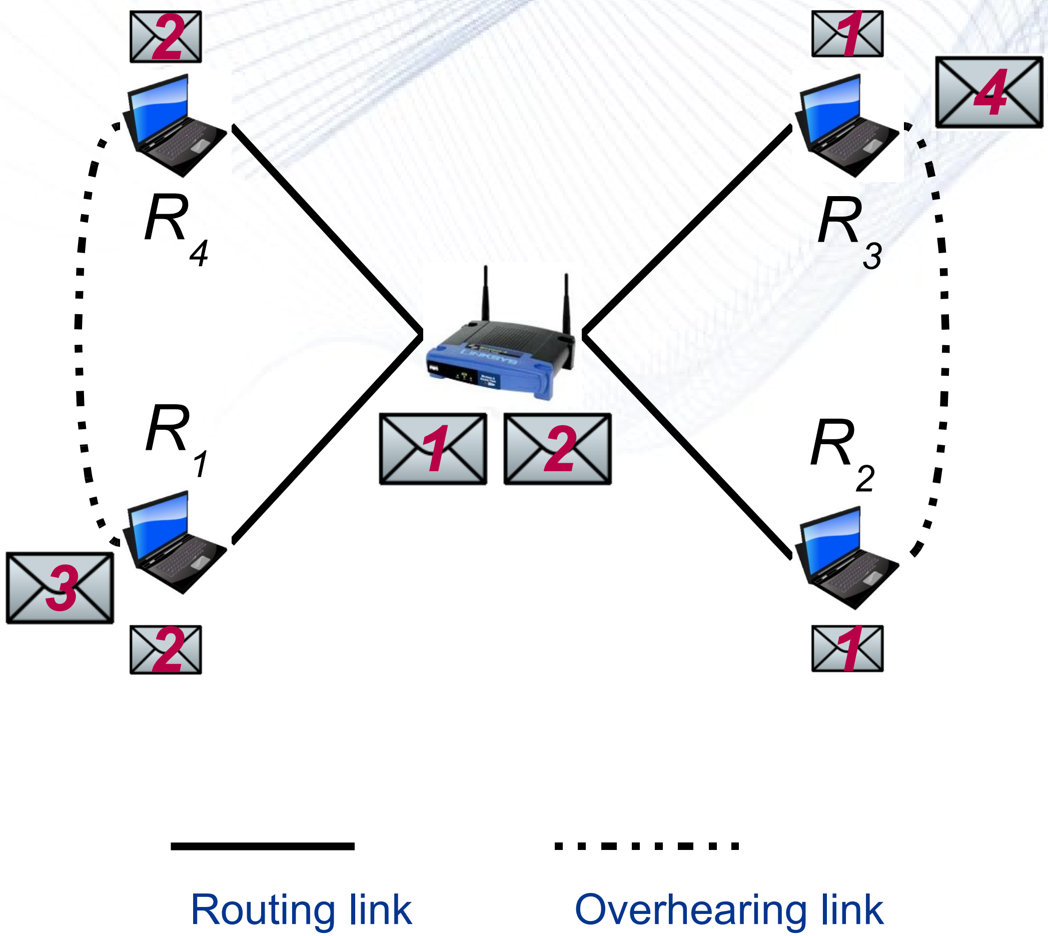
- 4 Flows
  - Packet *d* has dest R_d
- Without packet mixing
  - 8 transmissions required
- With packet mixing
  - 5 transmissions required

Packet Mixing Example



(1) R_2 sends Pkt 1 to AP

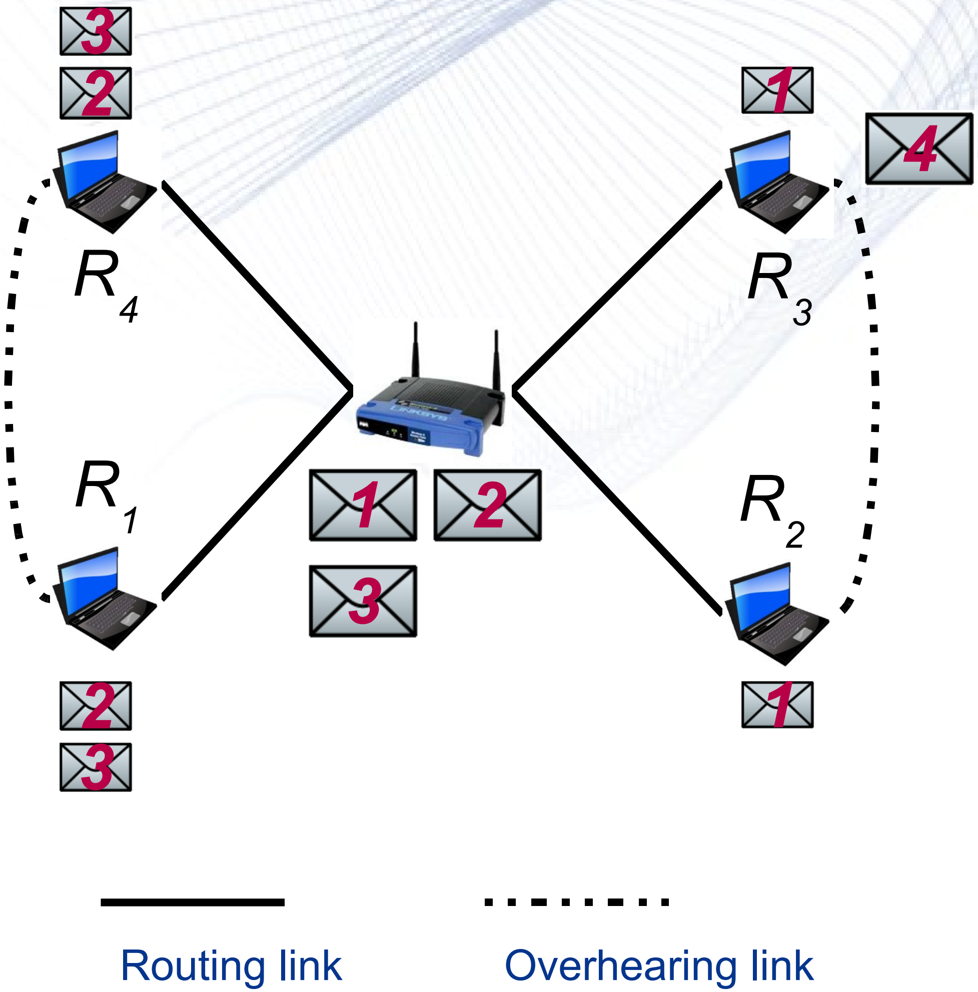
Packet Mixing Example



(1) R_2 sends Pkt 1 to AP

(2) R_4 sends Pkt 2 to AP

Packet Mixing Example

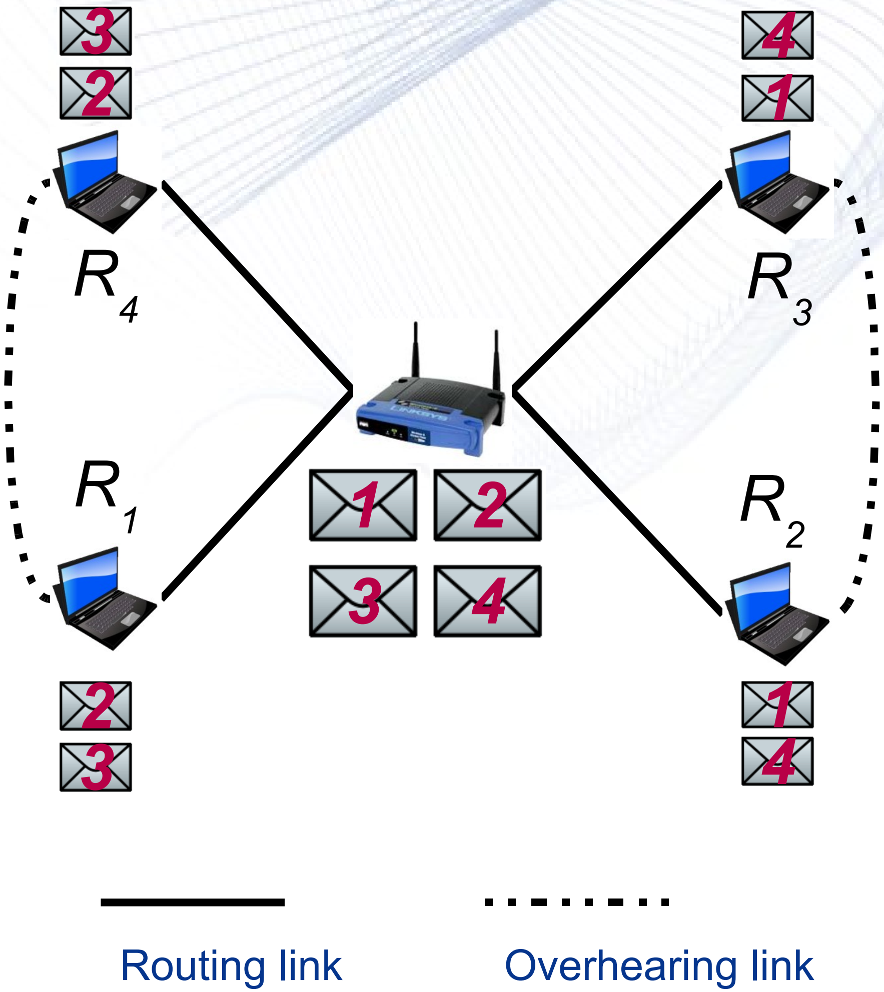


(1) R_2 sends Pkt 1 to AP

(2) R_4 sends Pkt 2 to AP

(3) R_1 sends Pkt 3 to AP

Packet Mixing Example



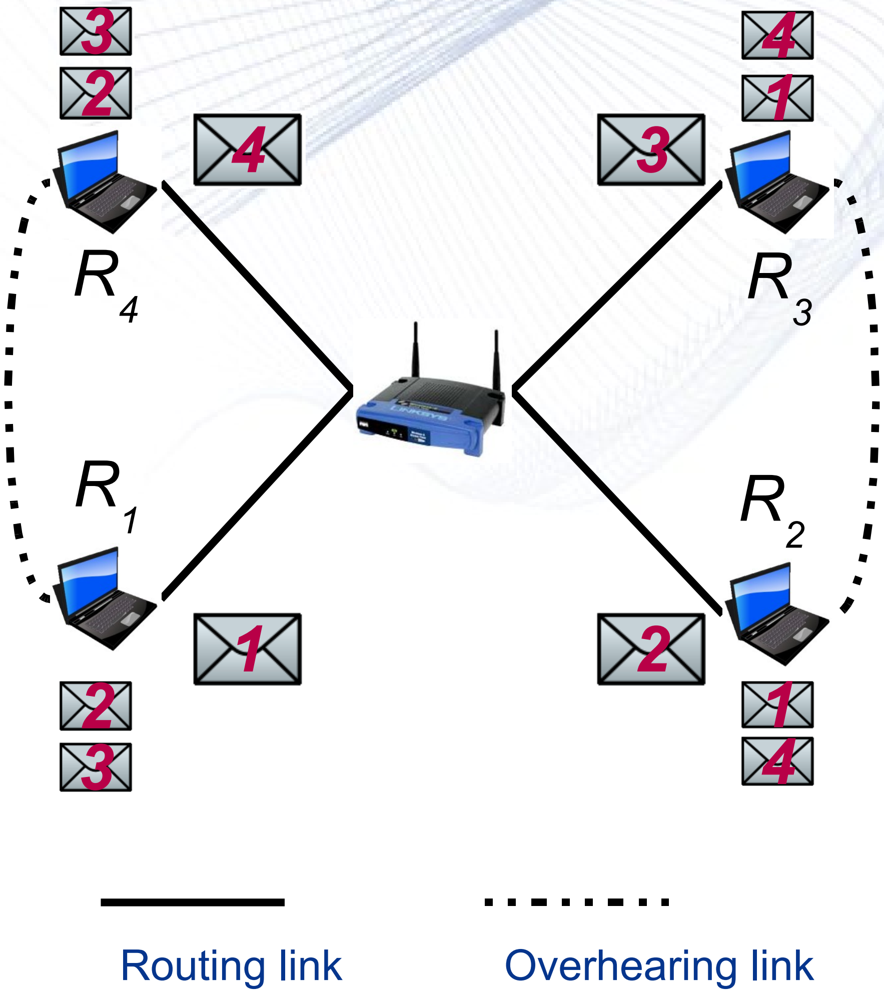
(1) R_2 sends Pkt 1 to AP

(2) R_4 sends Pkt 2 to AP

(3) R_1 sends Pkt 3 to AP

(4) R_3 sends Pkt 4 to AP

Packet Mixing Example



(1) R_2 sends Pkt 1 to AP

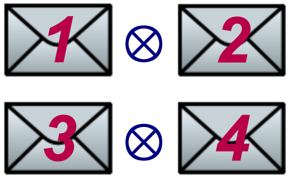
(2) R_4 sends Pkt 2 to AP

(3) R_1 sends Pkt 3 to AP

(4) R_3 sends Pkt 4 to AP

(5) AP sends mixed packet using SC:

(a) Layer 1: ***(b) Layer 2:***



Scheduling under Packet Mixing

- Per-neighbor FIFO packet queues
  - Q_d is queue for neighbor *d* – first denoted by *head*(Q_d)
- Total order on packets in all queues
  - Ordered by arrival time – first denoted by *head(Q)*
- Rule: always transmit *head(Q)*
  - Prevents starvation

SC Scheduler: G_{opp}

- Prior work: mesh network scheduling with SC [Li *et al.* 2007]
- Overview
  - SC Layer 1: Select *head(Q)* with dest d_1 at rate r_1
  - SC Layer 2: Select $floor(r_2 / r_1)$ packets for dest $d_2 \neq d_1$ at rate r_2
  - Allows different rates for each layer
    - Selects best rates given current channels
    - Ensures sufficient decoding probabilities

Layer 1	*head(Q_2)*	Destination 2, rate 12 Mbps
Layer 2	*3 packets from Q_4*	Destination 4, rate 36 Mbps

Rate:	*12 Mbps*
Packets:	*4*
Throughput:	*48 Mbps*

Multirate NC: *mnetcode*

- SC requires multirate for better gains, so extend NC as well
- Algorithm
  - Run single-rate COPE algorithm *snetcode(r)* for each rate *r* and select best
    - Skip rate if not supported by neighbor
    - Only consider $head(Q_d)$ for each neighbor *d*
    - N packets XOR'd at rate *r*
    - Effective throughput is $N \cdot r$

Simple Cross-layer Mixing: *SC1*

- Utilize physical- and network-layer coding
- Algorithm
  - SC Layer 1: Select NC packet with *mnetcode*
    - Must include *head(Q)*
  - SC Layer 2: Select packet with G_{opp}

Layer 1	$head(Q_1) \otimes head(Q_2)$
Layer 2	*3 packets from* Q_4

- Problems
  - No NC used in Layer 2 packets
  - Limited rate combinations

Joint Algorithm: *SCJ*

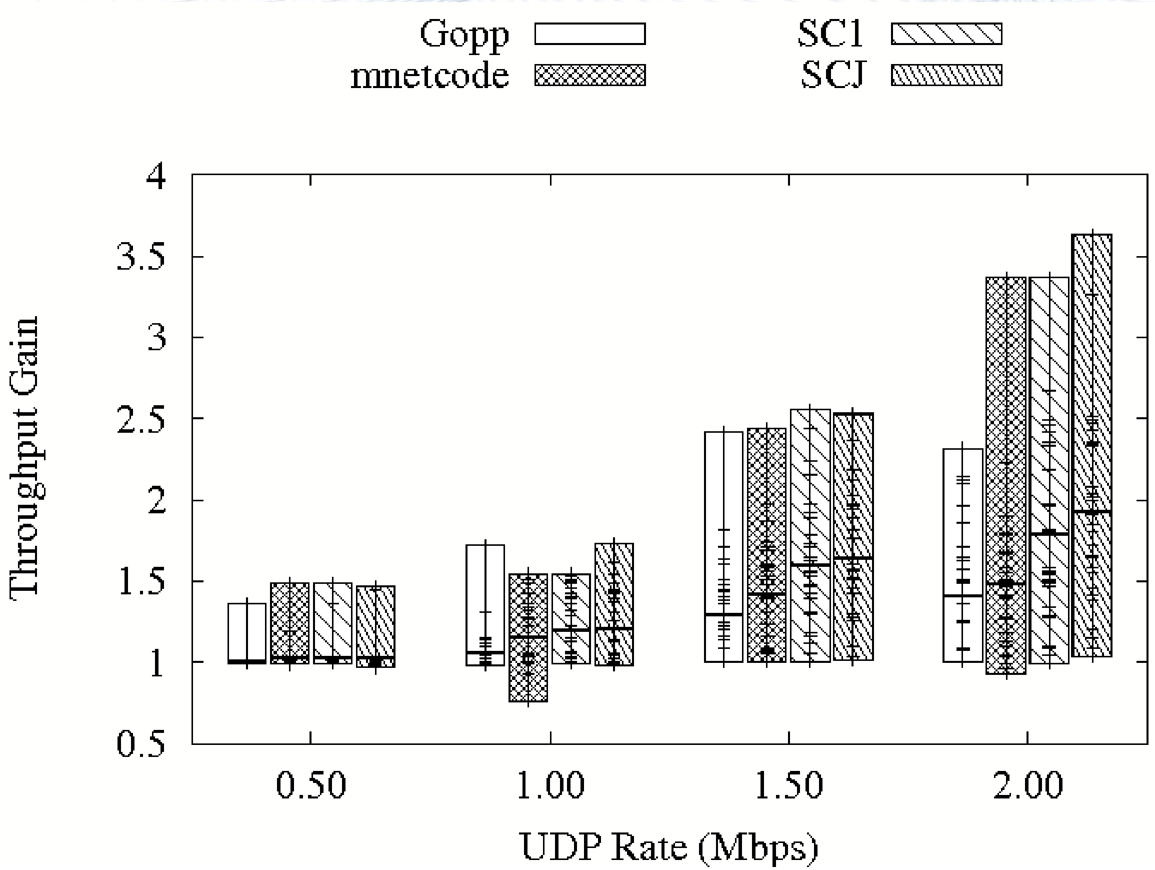
- Improved utilization of physical- and network-layer coding
- Algorithm
  - Iterate over discrete rates for each layer, r_1 and r_2
    - SC Layer 1: *snetcode*(r_1) selects packet, N_1 packets encoded
    - SC Layer 2: *snetcode*(r_2) selects *floor*(r_2 / r_1), N_2 packets encoded
      - Only consider neighbors that support r_2 in second layer
    - Effective throughput is $r_1 \cdot (N_1 + N_2)$

Layer 1	$head(Q_1) \otimes head(Q_2)$
Layer 2	$head(Q_3) \otimes head(Q_4)$, $head(Q_5) \otimes head(Q_6)$, $head(Q_7) \otimes head(Q_8)$

Evaluations: Setup

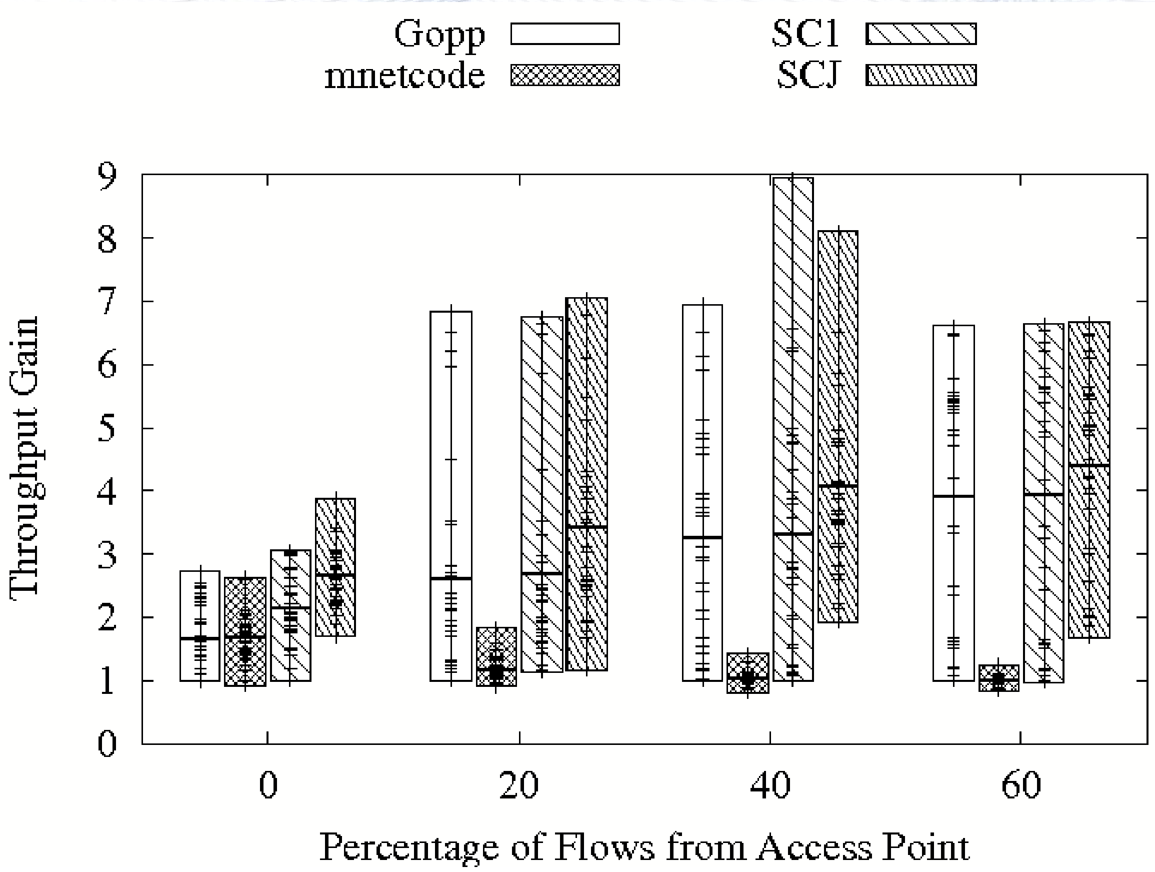
- Algorithms implemented in *ns*-2 version 2.31
- Careful attention to physical layer model
  - Standard *ns*-2 physical layer model does not suffice
  - Use packet error rate curves from actual 802.11a measurements [Doo *et al.* 2004]
  - Packet error rates used for physical layer decoding and rate calculations
- Realistic simulation parameters
  - Parameters produce similar transmission ranges as Cisco Aironet 802.11g card in outdoor environment

Evaluations: Network Demand



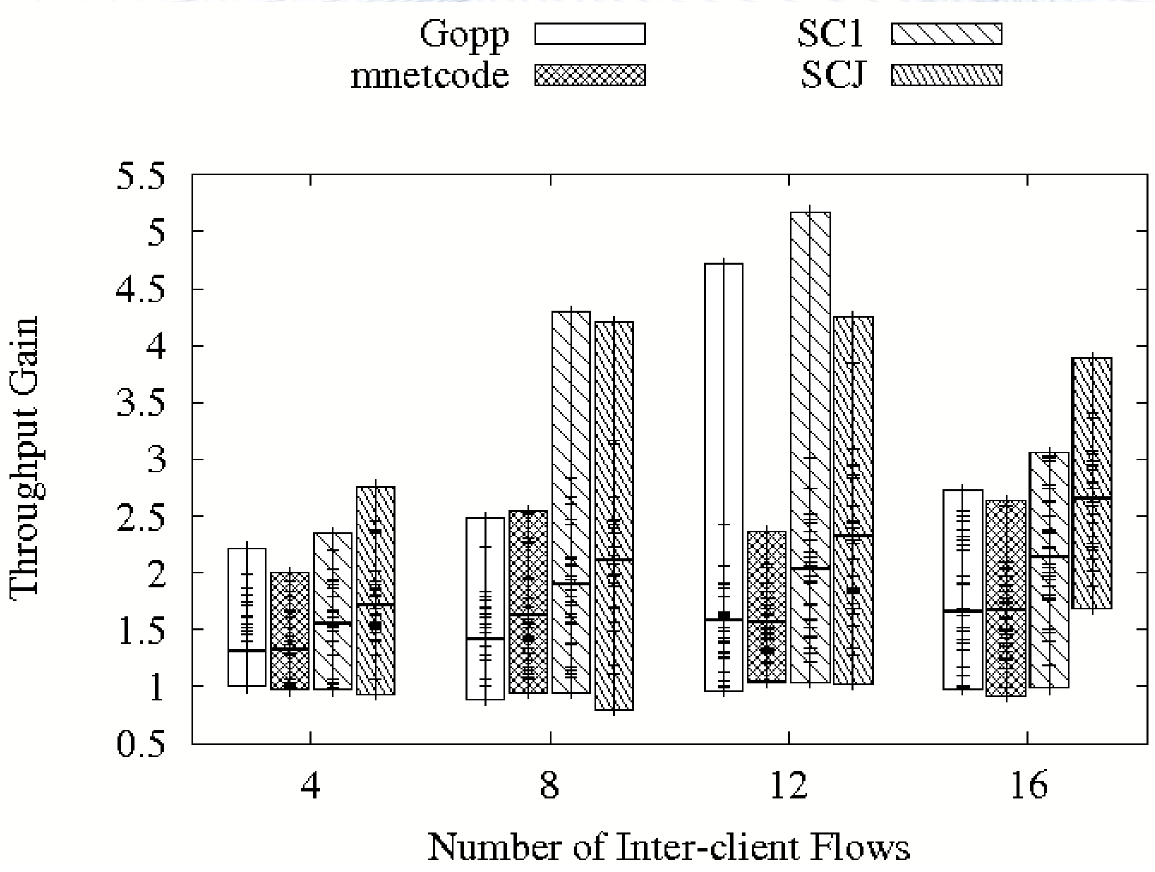
- Setup
  - 1 AP
  - 10 clients
  - 8 flows
  - Vary client sending rate
- Packet mixing gains are sensitive to network demand
- Queues are usually empty with low demand
  - Few mixing opportunites
- NC shows ~3% gain with TCP [Katti *et al.* 2006]

Evaluations: Internet → Client Flows



- Setup
  - 1 AP
  - 20 clients
  - 16 flows
  - Backlogged flows
  - Vary % of flows originating at AP
- SC mixing superior when Internet → client flows are common
- Throughput gains as high as 4.24

Evaluations: Client → Client Flows



- Setup
  - 1 AP
  - 20 clients
  - Backlogged flows
  - Vary # of flows
- Both SC and NC mixing alone improve with # of flows
  - More opportunities
- Gains each SC and NC exploited successfully by *SC1* and *SCJ* schedulers

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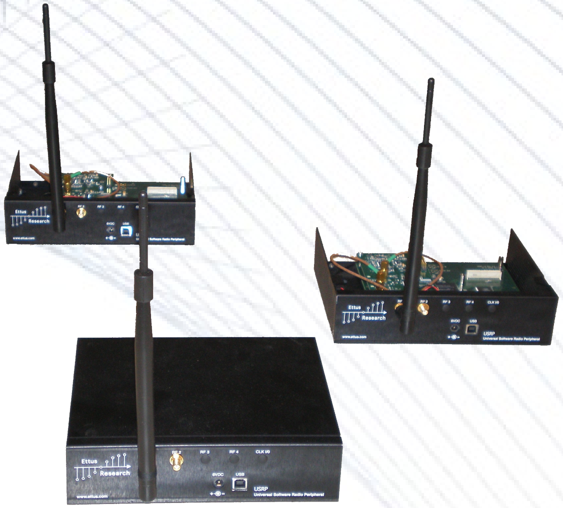
GNU Radio Implementation



- Open Source software radio
  - RF frontend hardware (USRP)
  - Signal processing in software
- Components
  - Implementation of SC in GNU Radio environment
  - 802.11 MAC implemented with NC support
- Measurement Results

Scheme	Norm. exp. trans. time	Gain ratio
No Coding	3.92	1
Superposition	2.88	1.4
Network coding	2.30	1.7
iPack	2.07	2.0

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Conclusions and Future Work

- Packet mixing increases throughput
  - Exploit packet mixing at network and physical layers
  - Cross-layer coding techniques can significantly improve throughput
- Ongoing and Future Work
  - Expand and improve implementation testbed
  - Improve TCP gains
  - Simultaneous ACKs
  - Generalize packet-mixing framework

Thanks!