Wireless Network Coding- The Next Revolution

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June 8, 2005

Traditional Networking View

- One “Flow” for Each Source-Destination Pair
- Packets are “Inviolate”
- Intermediate Nodes Decode and Re-encode Every Packet of Each Flow
- “Integrity” is Respected and Preserved

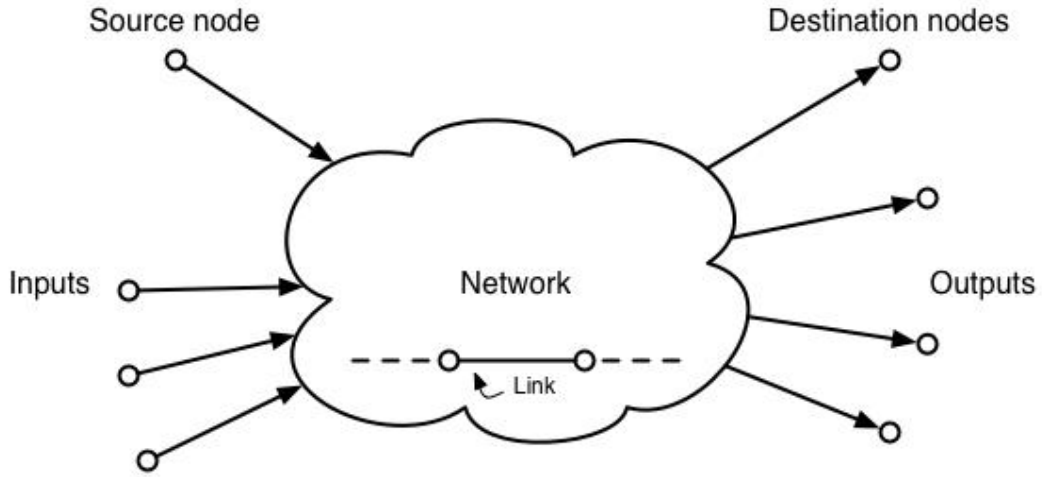
This is the Cornerstone of the IP Architecture

A Paradigm Shift

- **Packets are NOT Indivisible Units**
- **Packets Consist of BITS**

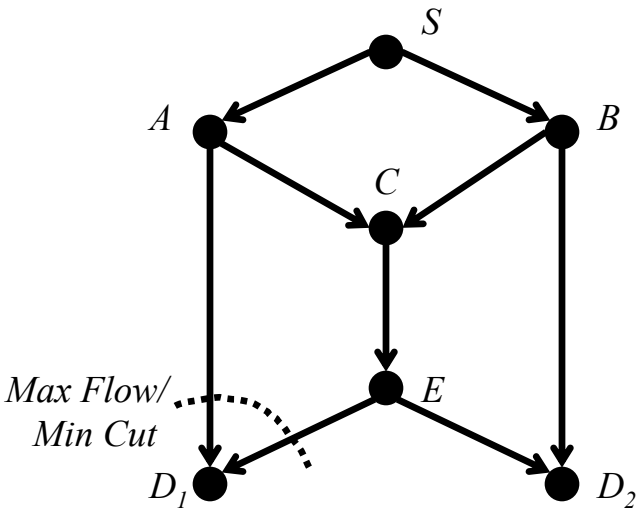
  (Or Symbols over a Finite Field and are thus Subject to Operations in that Field)
- **For Information and Communication Theorists This is an Elementary Concept**
- **Is There a Reason to Perform Such Operations?**

A Concept Familiar to "Physical-Layer" Views



- **A MIMO System!**
- **Correlated Inputs Should Be Combined ("Merged")**
- **Effects of Channel on Any Link are Similar for Different Packets (And Thus Create Correlation)**
- **More Importantly: Bottlenecks Can Be "Finessed"!**

Network Coding

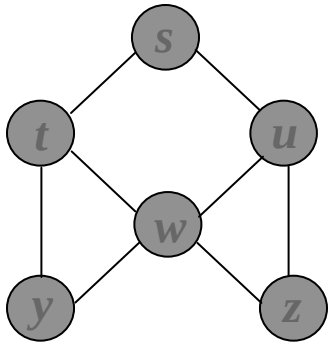


Routing: Slot 1: S → A (P_1)
S → B (P_2)
Slot 2: A → C,D_1 (P_1)
B → C,D_2 (P_2)
Slot 3: C → E (P_1)
Slot 4: E → D_2 (P_1)
C → E (P_2)
Slot 5: E → D_1 (P_2)

- Fundamental Premise of Preserving Packet Integrity is Flawed
- Combining Packets along the way achieves MaxFlow/MinCut Rate Bounds

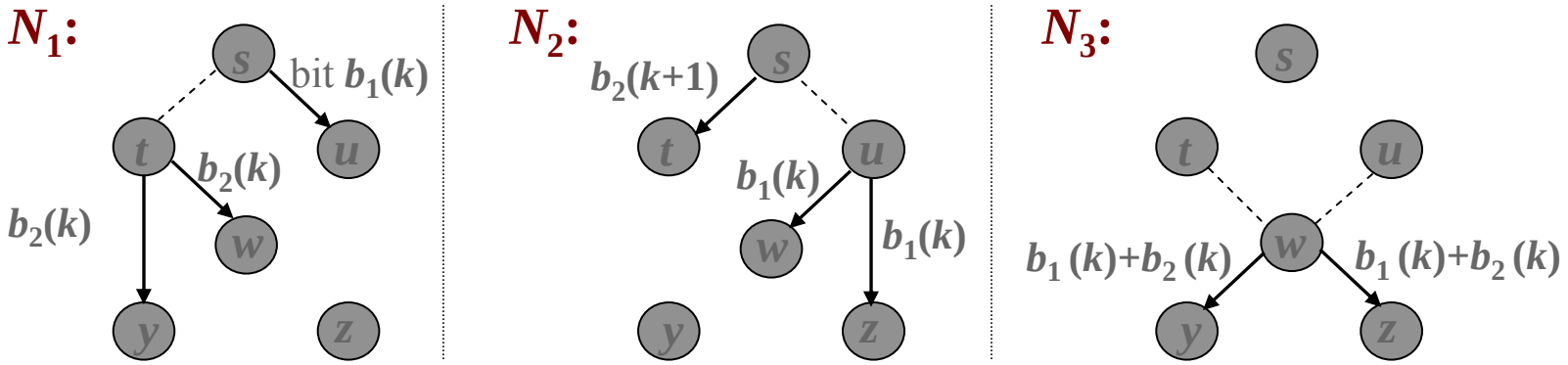
Network Coding: Slot 1: S → A (P_1)
S → B (P_2)
Slot 2: A → C,D_1 (P_1)
B → C,D_2 (P_2)
Slot 3: C → E (P_1+P_2)
Slot 4: E → D_1,D_2 (P_1+P_2)

Example of Wireless Network Coding



- Source ***s*** wishes to transmit packets of one bit to destinations ***y*** and ***z***.
- Assume **classical collision channel model**:
  - Channel Outcomes: Success, Idle, or Collision
  - Limited transmission/reception ranges with **sharp** boundaries

- Conflict-free **network realizations** $\{N_m\}_{m=1}^{M}$ **are periodically activated with link sets** $\{E_m\}_{m=1}^{M}$ **over** disjoint **time intervals (in a predetermined order) as follows:**

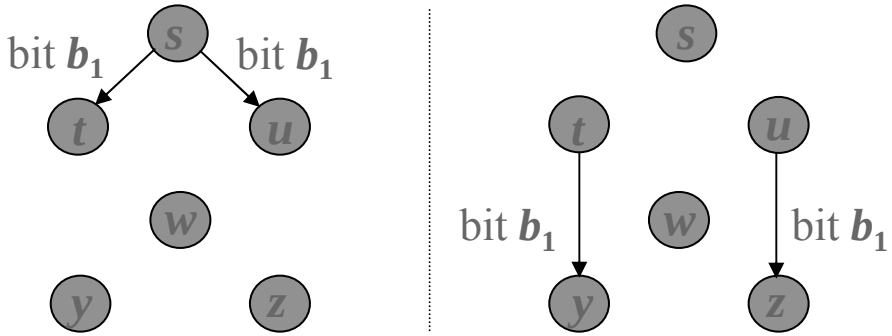


Encoding : ***w*** performs $b_1 + b_2$

Decoding : 1. ***z*** performs $b_1 + (b_1 + b_2)$ to recover b_2
2. ***y*** performs $b_2 + (b_1 + b_2)$ to recover b_1

Network Coding vs. Routing

- **Network realizations for optimal routing solution:**



- **Performance Measures:**
  - r : average number of packets (bits) delivered to each destination per unit time
  - e_{avg} : average transmission **energy** consumed to deliver a packet to any destination
  - d_{avg} : average **delay** per packet (in terms of time slots)

	r	e_{avg}	d_{avg}
Routing	0.5 bits/slot	1.5 energy units/bit/dest.	2 slots
Network Coding	2/3 bits/slot	1.25 energy units/bit/dest.	3.25 slots

dest.	y	z
b_1	2	3 slots
b_2	3	5 slots

  - Performance objectives can possibly **conflict** depending on topology and traffic.

Joint Scheduling and Network Coding Solution

Step 1: Predetermine **conflict-free** wireless network realizations $\{N_m\}_{m=1}^{M}$, and assign minimum power $P_i^{(m)}$ to each node i for any realization N_m.

Step 1 determines the flows $z_{i,j}^{(m)}$ on link (i, j) for network realization N_m.

Step 2: Assign time fractions τ_m to each network realization N_m , and determine flows $x_{i,j}^{(m)}(d)$ addressed to each destination d through network coding in order to either

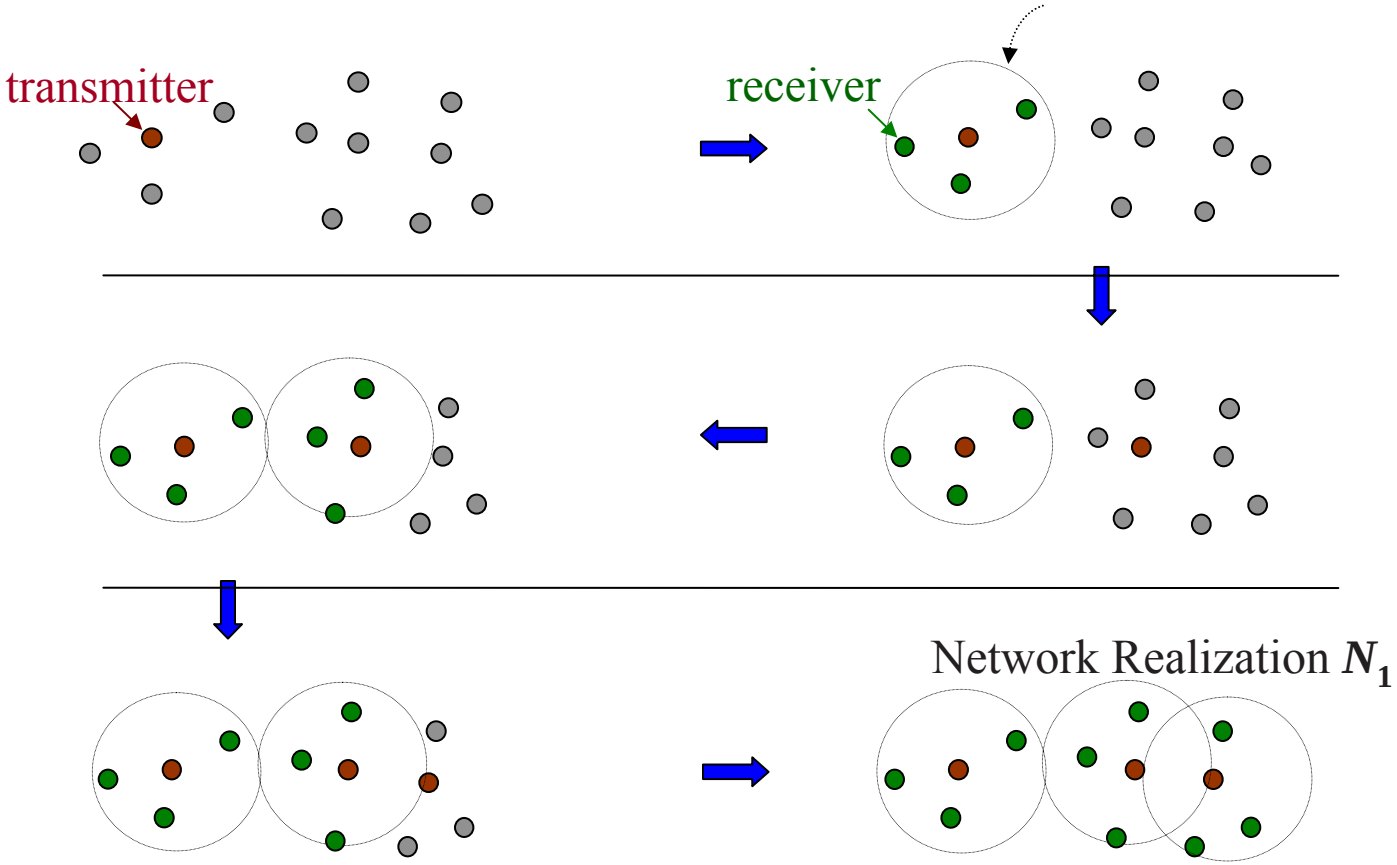
(i) maximize throughput r **, or**

(ii) minimize average cost $a = \sum_{m=1}^{M} \tau_m a_m$ **for given** r**, where** $a_m = \sum_{i \in V} P_i^{(m)}$ **, or**

(iii) minimize $\frac{a}{r}$ **.**

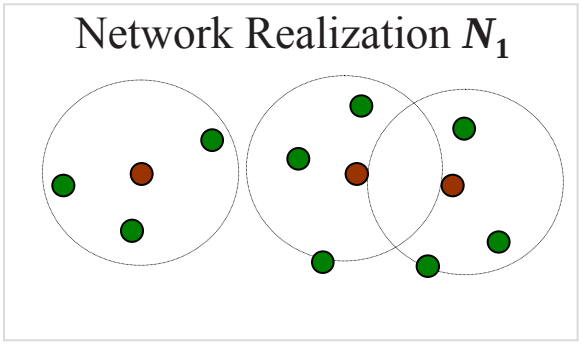
Step 1: Construction of Network Realizations

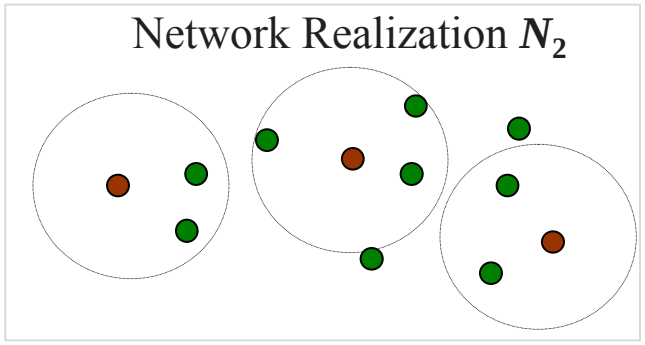
- **A simple heuristic to construct wireless network realizations:**
  - Assume **classical collision channel** model and **sharp** circular transmission/reception ranges.

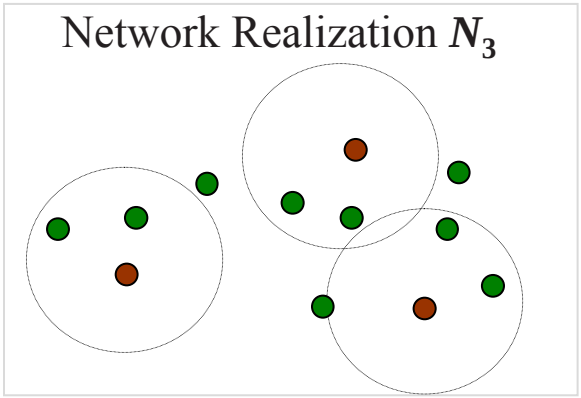


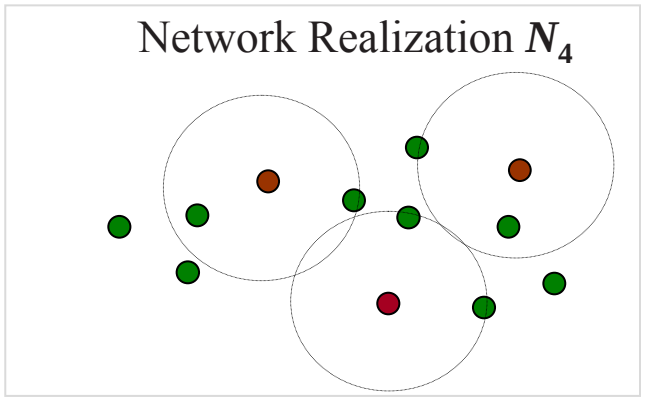
Complete Set of Network Realizations

- **Activate each node (except source node) as a transmitter and receiver at least** one **time over all network realizations.**





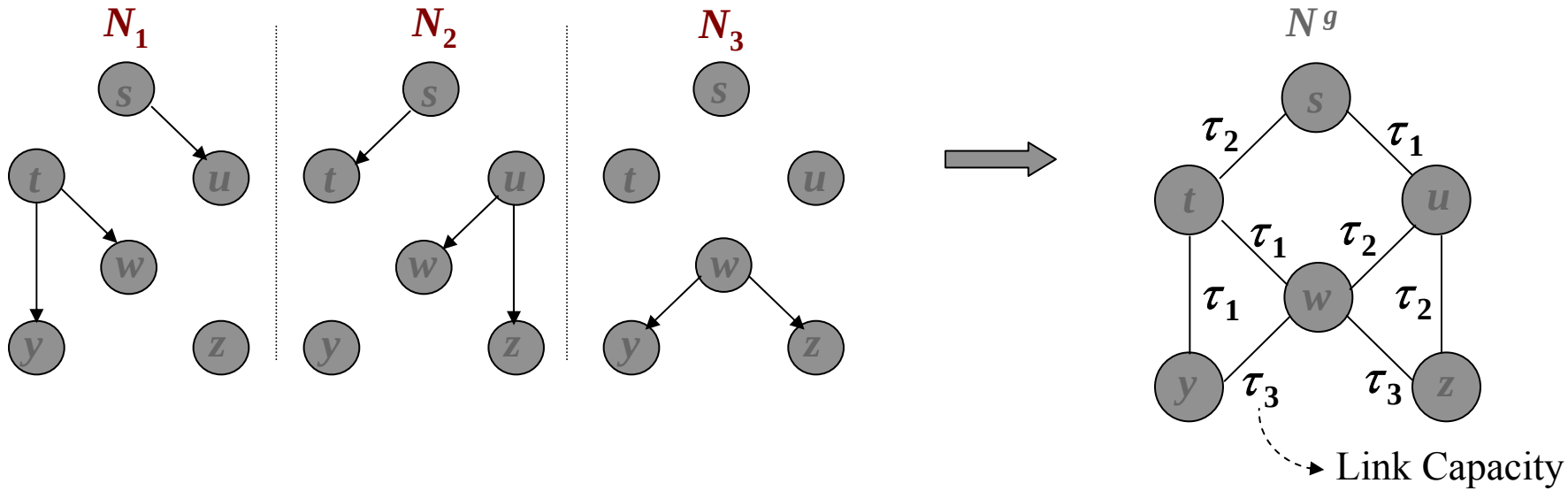




- **For the SINR-based** physical model**, we can use a similar scheduling heuristic based on** power control **to determine conflict-free network realizations.**

Step 2: Time Allocation to Network Realizations

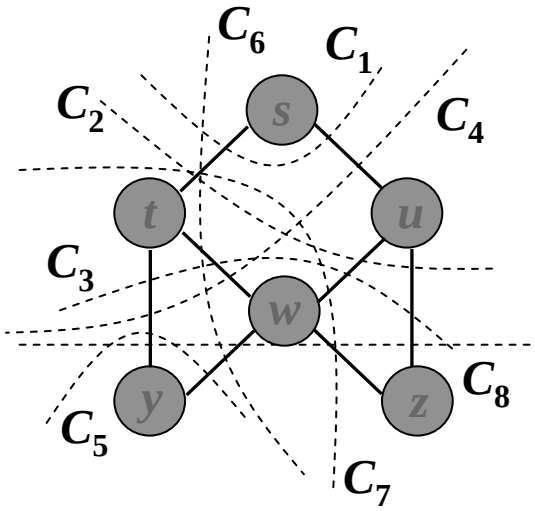
- Next Problem: **Find time fraction τ_m allocated to each network realization N_m.**
- **Construct a** hypothetical wired **network graph N^g from the given wireless network realizations $\{N_m\}_{m=1}^M$ with time allocation $\{\tau_m\}_{m=1}^M$ as follows:**



  - The capacity of any link on the graph N^g is equal to the time-average number of successful transmissions on that link over all wireless network realizations $\{N_m\}_{m=1}^M$.

Wireless Formulation of Cuts and Flows

- **Define** $c_i(s, y)$: the sum of capacities of links crossed by the cut C_i that separates source s from destination y



- Omnidirectional **transmissions require that the contribution of a node to any cut is limited to the value of at most** <u>one</u> **per unit time.**

$$c_1(s,y) = \tau_1 + \tau_2\,, \quad c_2(s,y) = 2\,\tau_2\,, \quad c_3(s,y) = \tau_1 + \tau_2\,, \quad c_4(s,y) = 2\,\tau_1\,,$$
$$c_5(s,y) = \tau_1 + \tau_3\,, \quad c_6(s,y) = \tau_2 + \tau_3\,, \quad c_7(s,y) = 2\,\tau_2\,, \quad c_8(s,y) = \tau_2 + \tau_2 + \tau_3\,, \ \ldots$$

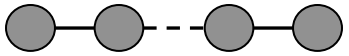
- Choose $\{\tau_m\}_{m=1}^{M}$ in order to maximize $r = \min_{d \in D} \min_i c_i(s, d)$

  or minimize average cost $a = \sum_{m=1}^{M} \tau_m a_m$ for given r, or minimize $\frac{a}{r}$.

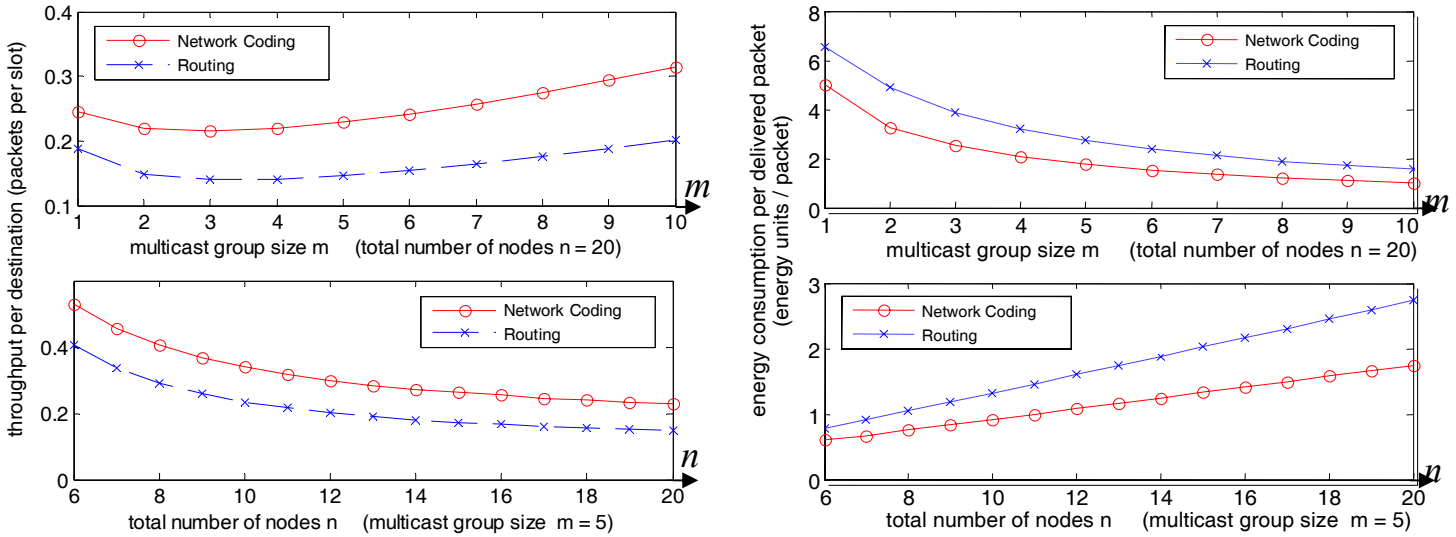
  – $\tau_1 = \tau_2 = \tau_3 = 1/3$ maximizes r to **2/3** (achievable **only** by network coding).

Comparison of Network Coding and Routing

- **Consider a** tandem **network with classical collision channels:**



  - There are total of ***n*** nodes randomly distributed on the network.
  - **5 source** nodes are randomly chosen out of ***n*** nodes.
  - Each source node independently chooses its multicast group of size ***m***.



- Network coding improves routing, if a **relay node** combines traffic incoming from both neighbors.
- Improvement is **not** possible for the cases with **single** source or **directional** transmissions.

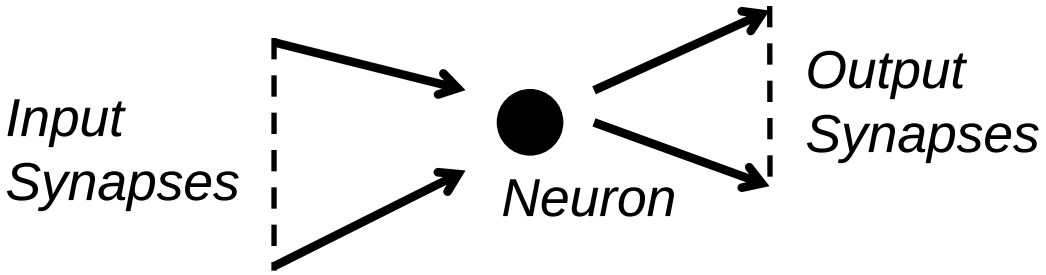
Potential Impact

- **Elusive Connection between Information Theory and Networking**
- **A New Architecture for Networking to Replace IP**

  (We have been wrong all along in building networks!)
- **Re-emergence and Dominance of the Physical Layer**
- **There's More!**

Connection to Broader Network Science

- **Biological Neural Nets**



- **Output Action Potential is a Function of the SUM of the Input Action Potentials**
- **Neurons DO Add Their Inputs!**

(Cont.)

- **Furthermore:**
  - The Firing of a Neuron Can Inhibit the Firing of Adjacent Neurons

    (-Scheduling-)

- **Biosystems Offer Useful Design Guidance**
  - Energy Efficiency
  - Robust with respect to Failures

Where Next?

- **Numerous Specific Technical Questions**
  - What if the MAC is Contention Based?
  - What if the Flows are not Analytical?
  - What are the Optimal Trade-Offs in Wireless?
  - How can the Physical Layer Issues be connected to Networking Issues?
- **Can all this translate to a New Architecture?**
- **Are there "Deeper" connections to biology?**

(Cont.)

- **What are the Energy Implications in Wireless Systems?**
- **A New View of <u>Scheduling</u>**
  - Combinatorial Component of Optimization
  - Possible to Consider a "Continuous" Optimization Framework
    (In each slot every line is assigned a transmission power ≥ 0)
  - Power Control Framework "Waterfilling"
  - How do we then decide on number of slots?
    (Percentages of Time)

Conclusions

- **Network Coding is a Potentially Revolutionary Development**
- **Leads to a Truly Cross-Layer View of Networking**
- **Shows Similarities to Biological Processing**

  (For Whatever This is Worth)
- **May Lead to New Networking Architecture**

It Does Improve Performance

(Bottomline)