Cross-Layer Optimizations for Intersession Network Coding on Practical 2-Hop Relay Networks

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joint work with Ness B. Shroff (The OSU) and Abdallah Khreishah (Purdue)

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- Many promised advantages:
  - Throughput,
  - Energy and power savings, [Cui *et al.* 08], [Goseling *et al.* 09], etc.
  - Security (cryptography) [Bhattad *et al.* 06], [Ngai *et al.* 09], etc.
  - Error correction [Ahlswede *et al.* 09], [Silva *et al.* 08], etc.
  - Network tomography [Sattari *et al.* 09], [Gjoka *et al.* 08],etc.
  - Speed up computation of the min-cuts and min-cut values [Wu *et al.* 06] [Wang *et al.* 09].
  - Storage [Wu 09], P2P [M. Wang *et al.* 07], etc.
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- Nonetheless, commercial adaptation of network coding for WMNs remains in its early stage.
- For comparison: the capacity-achieving turbo and LDPC codes are commercialized in the span of 5 years.

The goal of this paper

- Several practical schemes, e.g. COPE and MORE, demonstrate improvement in certain scenarios.
- Different competing techniques: 1-hop intersession NC (COPE), spatial-diversity-based opportunistic routing (MORE), cross-layer optimizations.
- Question: How much gain can we expect from coding? How does coding fare when combined with other techniques?
  - The capacity region of COPE is still unknown (let alone with cross-layer optimizations).
  - Many difficulties when combining COPE and MORE.
- We will try to answer these questions analytically for a somewhat restricted, but quite practical scenario.

Outline

- Existing results on multi-hop wireline networks:
  - Cross-layer, Intersession NC, the achievability results.
  - Modeling wireless channels: From wireline to wireless?
- A more practical setting on 2-hop relay networks:
  - Packet erasure channels (PECs) and the freq. of feedback.
- Capacity results of
  - Broadcast PECs with side information.
  - Intersession NC on 2-hop relay networks.
  - LP-based solutions with cross-layer optimization
- Simulation results that compare the gains of cross-layer optimization, opportunistic routing, intersession NC.

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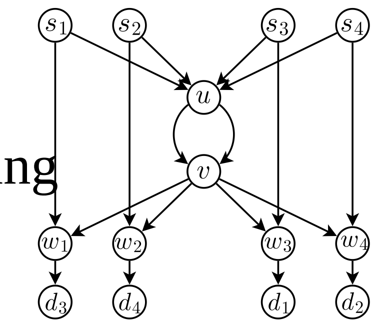
Achievable rates for general topology:

- Superposition of butterflies by linear programming (LP) [Traskov *et al.* 06], etc.



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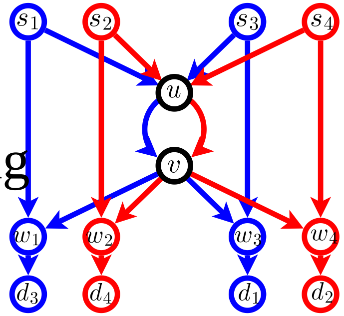

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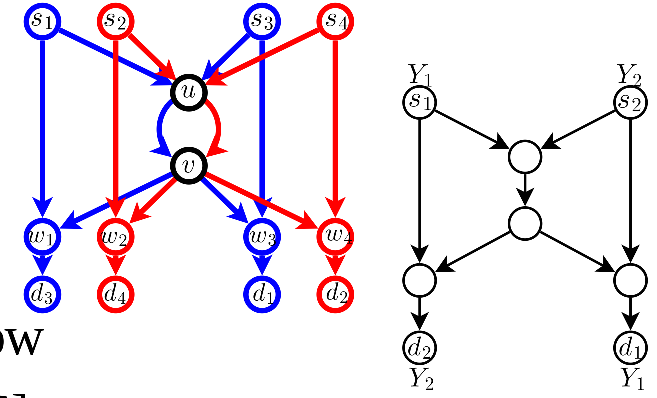

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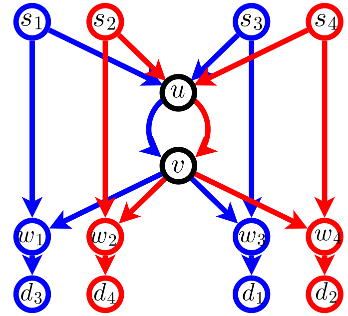

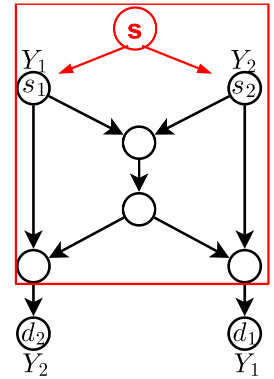

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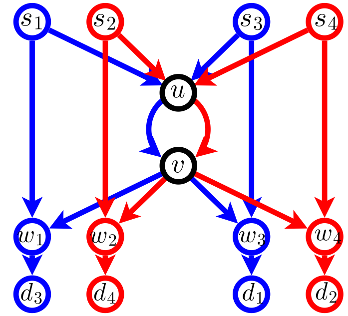
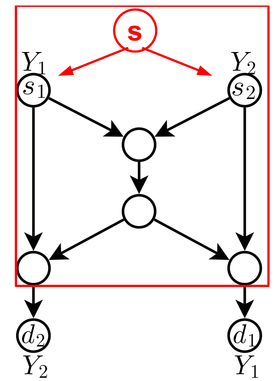
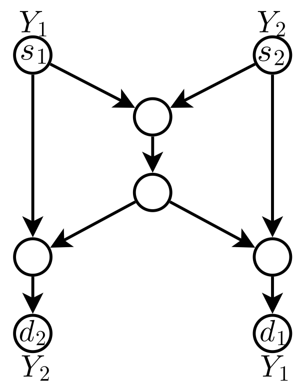
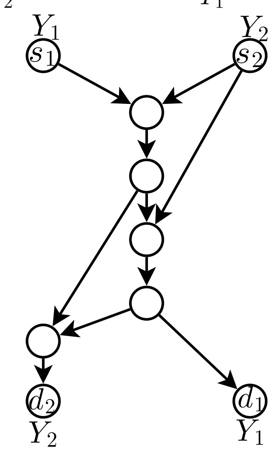
- When limiting to two multicast symbols, the graph-theoretic capacity characterization is known [Wang *et al.* 07]. + LP superposition.

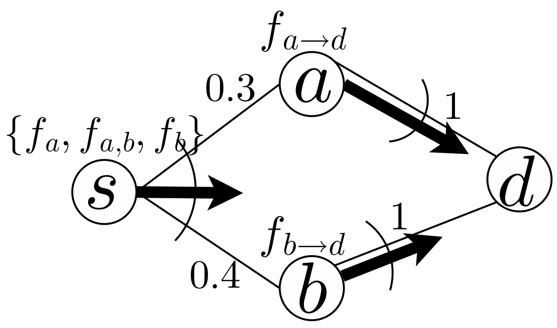








From Wireline to Wireless



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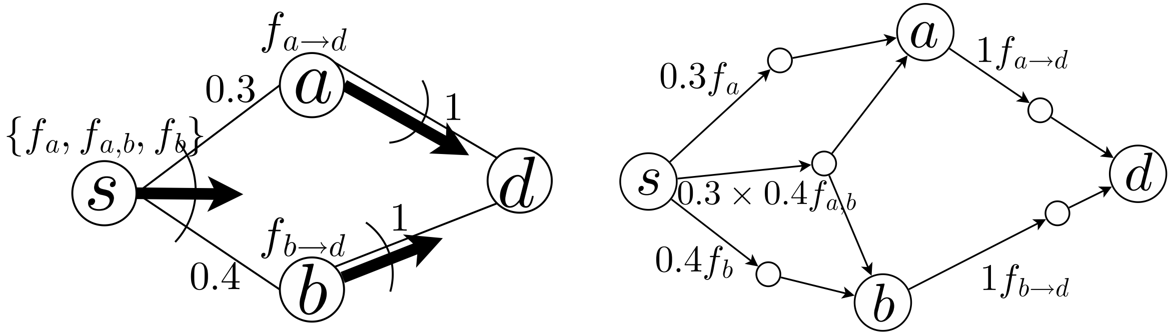

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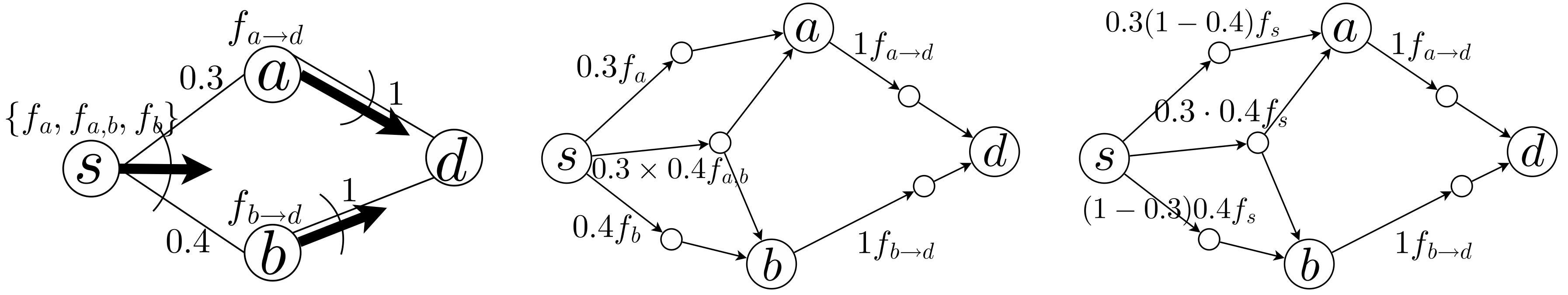

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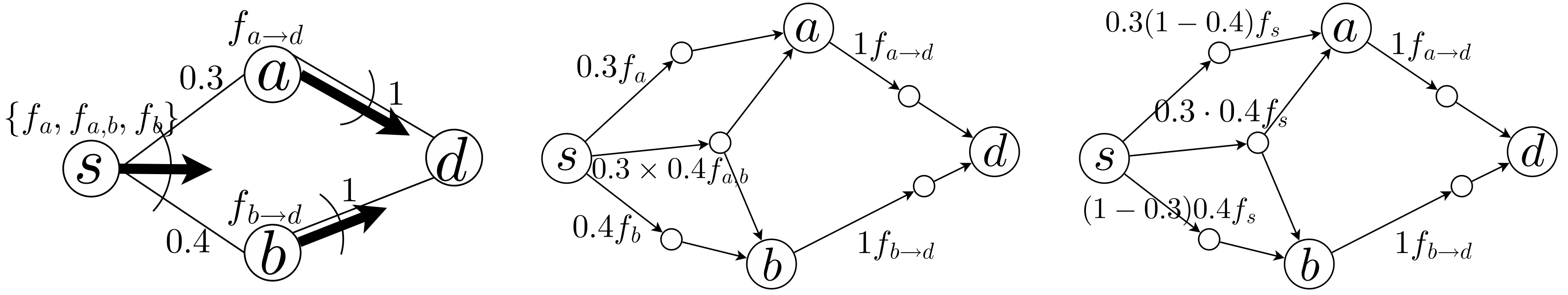

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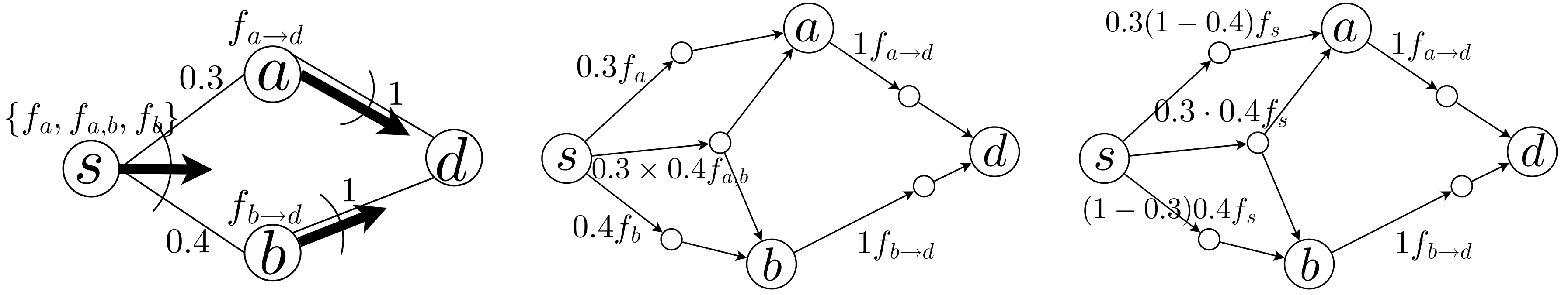

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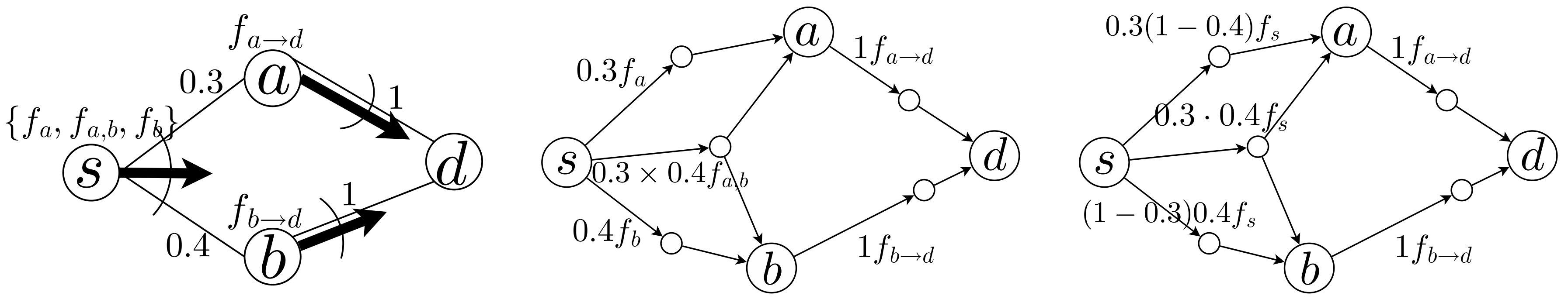

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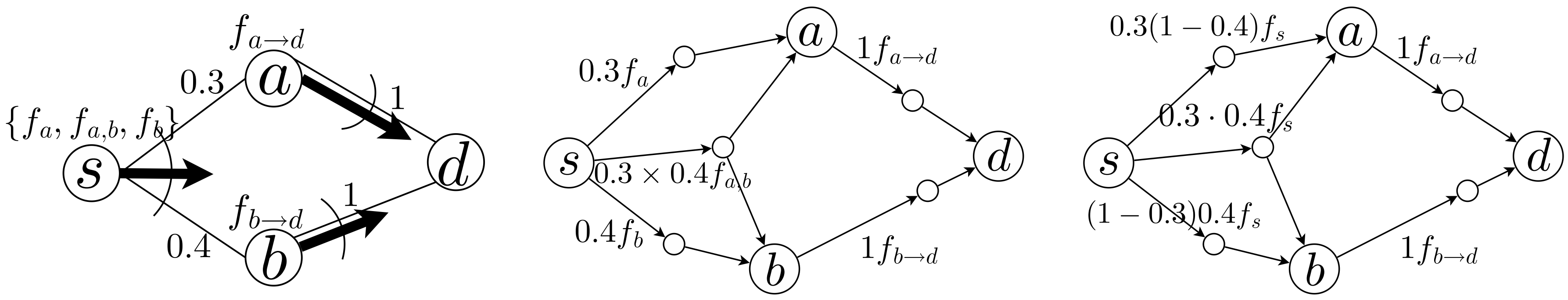

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- To closely model the scenario, we consider the packet erasure channels for 2-hop, single-relay networks.

Our setting

Memoryless packet erasure broadcast channels: Example: A 1-to-2 PEC is governed by the success probabilities $p_{s;12}, p_{s;12^c}, p_{s;1^c2}, p_{s;1^c2^c}$.

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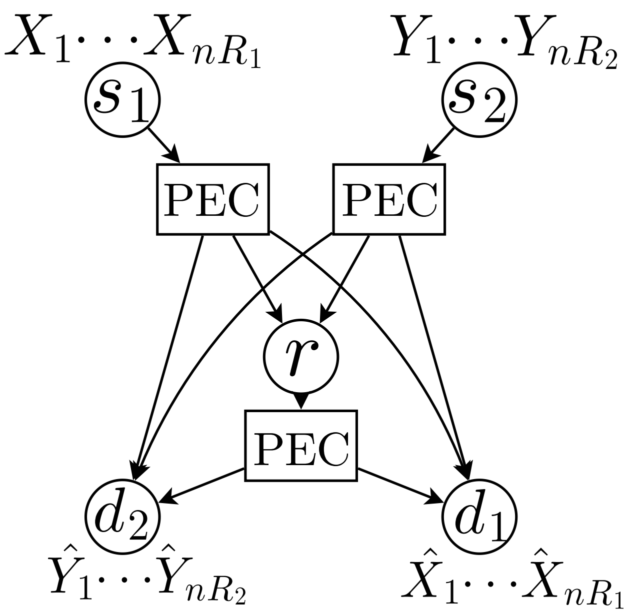

- Sequentially, s_1, s_2, and r each can send n packets.
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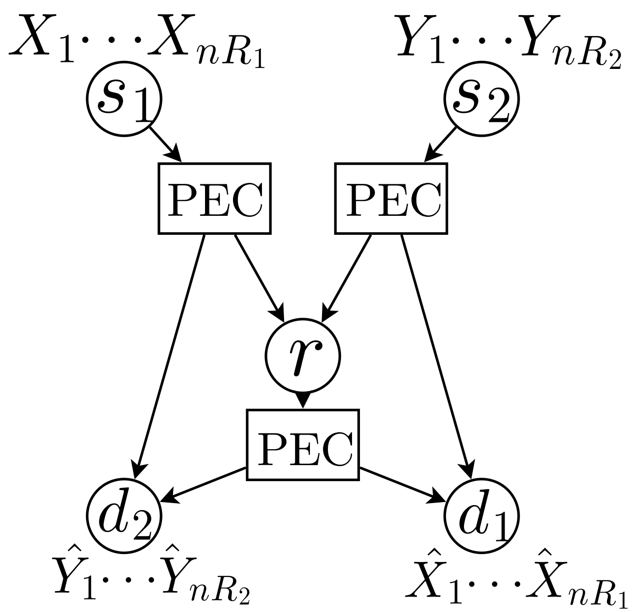

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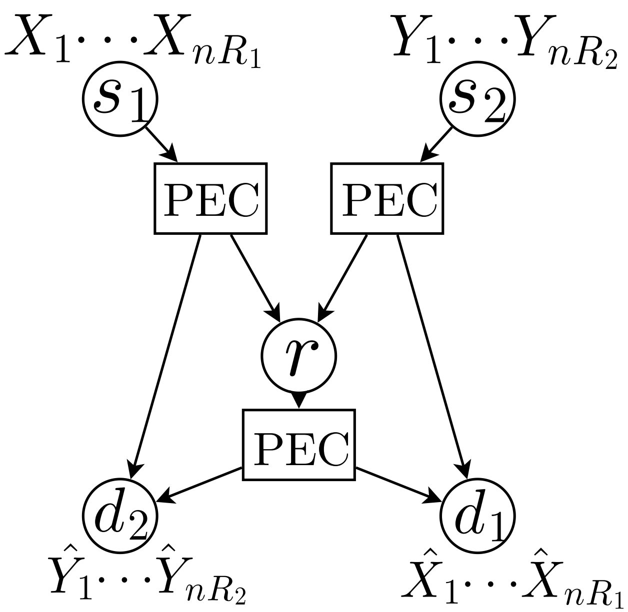

PEC parameters:

$p_{s_1;2r}, p_{s_1;2r^c}, p_{s_1;2^cr}, p_{s_1;2^cr^c}$;

$p_{s_2;1r}, p_{s_2;1r^c}, p_{s_2;1^cr}, p_{s_2;1^cr^c}$;

$p_{r;12}, p_{r;12^c}, p_{r;1^c2}, p_{r;1^c2^c}$.

$$p_{r;1} \triangleq p_{r;12} + p_{r;12^c}, \quad p_{r;1^c} \triangleq p_{r;1^c2} + p_{r;1^c2^c};$$

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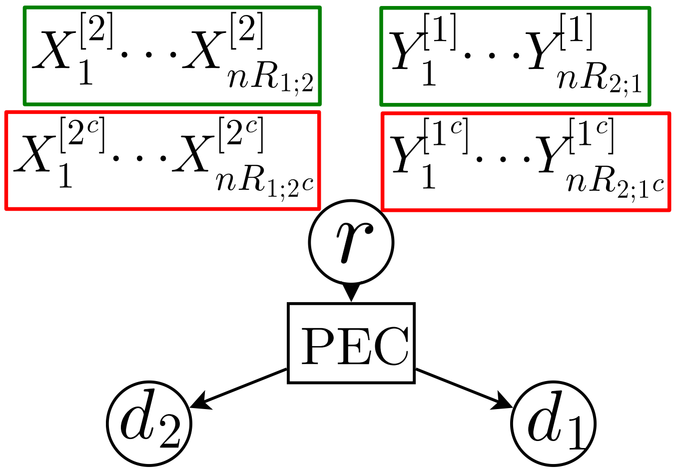

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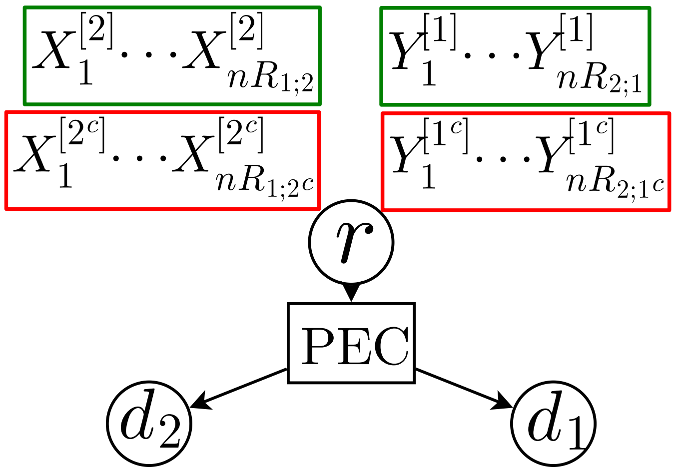

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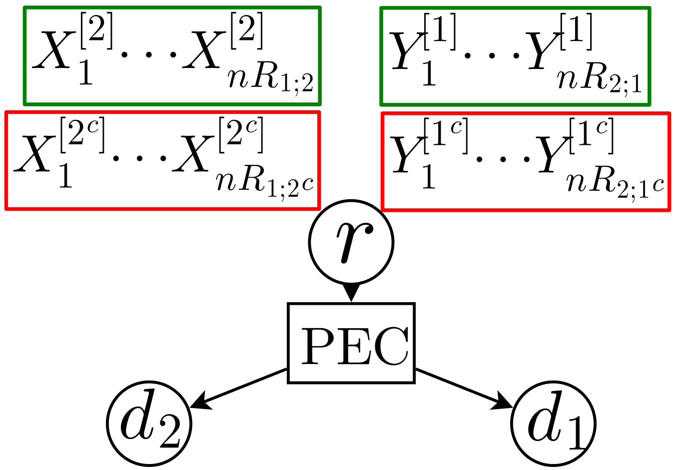

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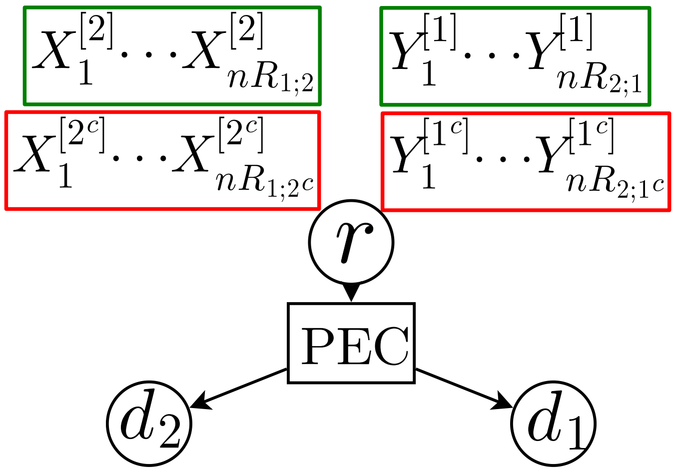

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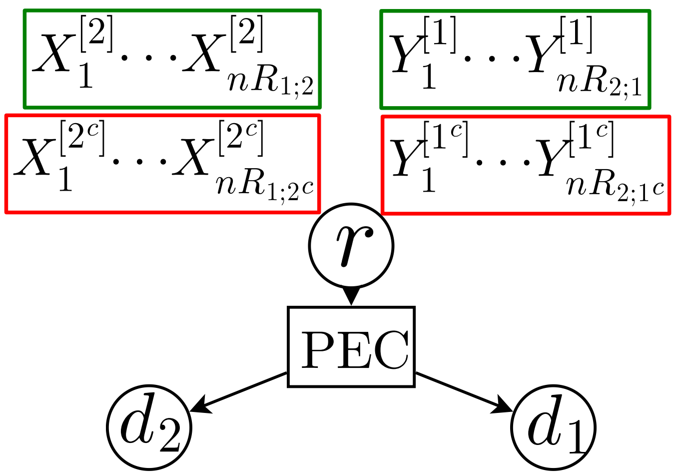

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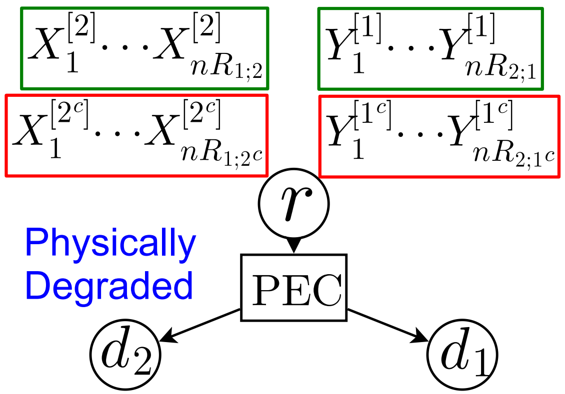
- Cap. of 3-user PEC BC w. SI., & 3-session 2-hop relay networks.

An Intuitive Argument



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$\Leftrightarrow r \longrightarrow d_2$ is a physically degraded channel.

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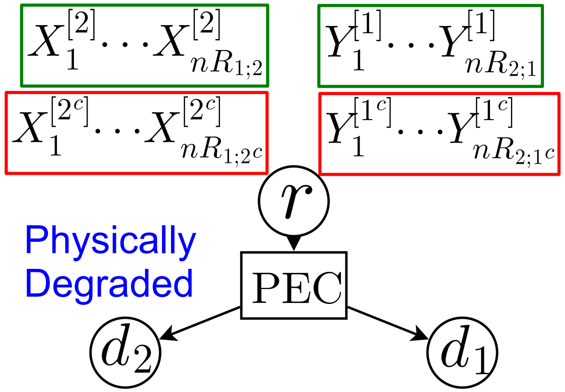

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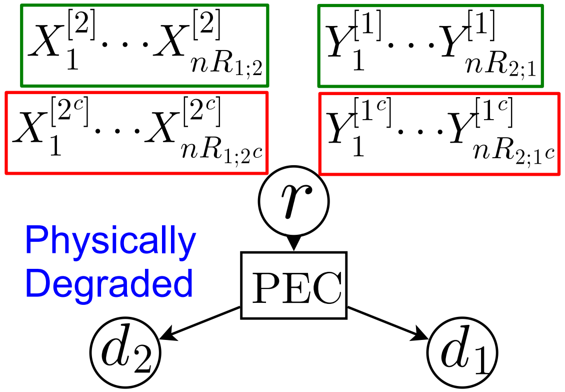

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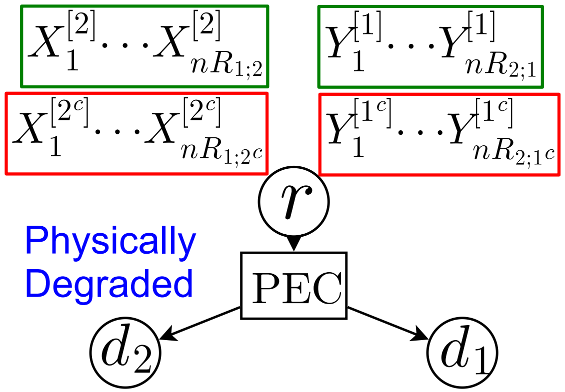

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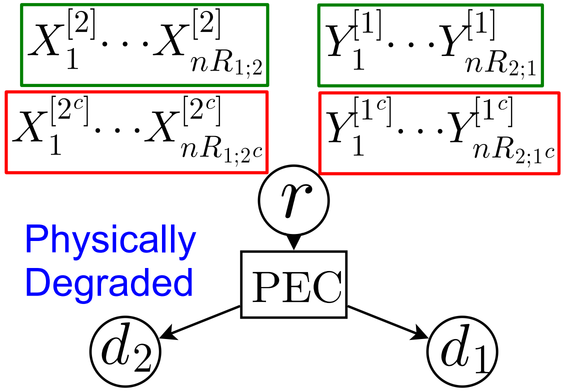

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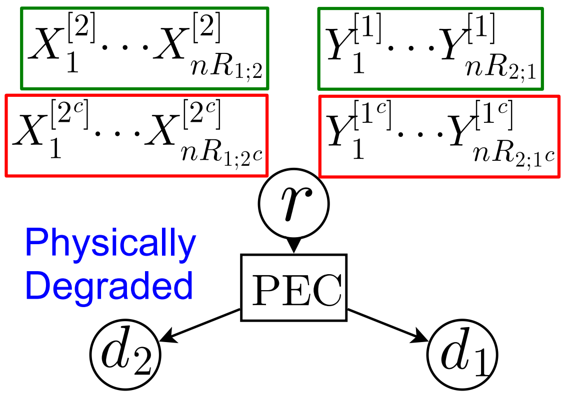

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- Observation 3.2*: Then among the $nR_{1;2^c}$ basis vectors received by d_1, they will contribute at least $\frac{p_{r;2}}{p_{r;1}} nR_{1;2^c}$ interfering basis vectors at d_2.

Cap. 2-user PEC BS w. SI

The cap. outer bound:

$$d_1\text{'s perspective:}\quad nR_{1;2} + nR_{1;2^c} + nR_{2;1^c} \leq np_{r;1}$$

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The achievability: A 2-stepped coding scheme.

- Step 1: Randomly mix the packets from $nR_{1;2}$, $nR_{2;1^c}$, and $nR_{2;1}$ and send

  $$\max\left(\frac{nR_{1;2} + nR_{2;1^c}}{p_{r;1}}, \frac{nR_{2;1^c} + nR_{2;1}}{p_{r;2}}\right) \quad \text{such randomly gen. pkts.}$$

Cap. 2-user PEC BS w. SI

The cap. outer bound:

$$d_1\text{'s perspective:}\quad nR_{1;2} + nR_{1;2^c} + nR_{2;1^c} \leq np_{r;1}$$

$$d_2\text{'s perspective:}\quad nR_{2;1} + nR_{2;1^c} + \frac{p_{r;2}}{p_{r;1}} nR_{1;2^c} \leq np_{r;2}.$$

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- Step 2: Randomly mix the packets from $nR_{1;2^c}$ and send

  $$\frac{nR_{1;2^c}}{p_{r;1}}$$ such randomly gen. pkts.

Combine it with $s_i \longrightarrow r$ coding

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Given that $R_1 = R_{1;2} + R_{1;2^c}$, maximizing R_2 is equivalent to allocating the smallest R_1 to $R_{1;2^c}$.

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- By s_1 performing random linear NC, we max. the overhearing

$$nR_{1;2^c} = (nR_1 - np_{s_1;2})^+$$

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- Therefore:

$$R_1 \leq p_{r;1} - (R_2 - p_{s_2;1})^+$$

$$R_2 \leq p_{r;2} - \frac{p_{r;2}}{p_{r;1}}(R_1 - p_{s_1;2})^+$$

The Capacity Regions (Cont'd)

$$R_1 \leq p_{r;1} - (R_2 - p_{s_2;1})^+$$

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- Final Results:

$$R_1 \le \min\left(p_{s_1;r}, p_{r;1} - (R_2 - p_{s_2;1})^+\right)$$

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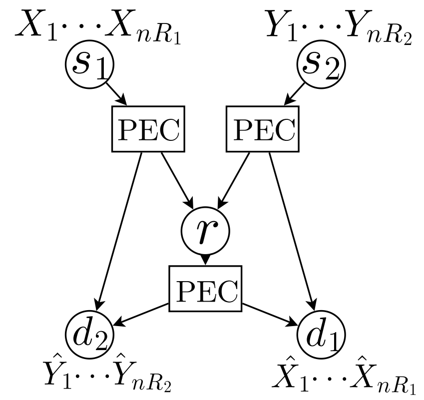

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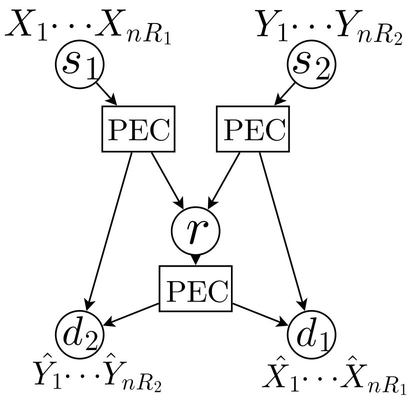
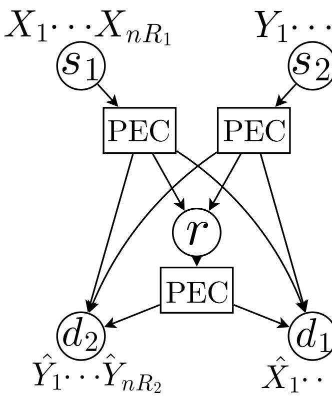


- With opp. routing (jump over 2 hops):

$$R_1 \le \min\left(p_{s_1;1\cup r}, p_{s_1;1} + p_{r;1} - (R_2 - p_{s_2;1\cup 2})^+\right)$$

$$R_2 \le \min\left(p_{s_2;2\cup r}, p_{s_2;2} + p_{r;2} - \frac{p_{r;2}}{p_{r;1}}(R_1 - p_{s_1;1\cup 2})^+\right)$$



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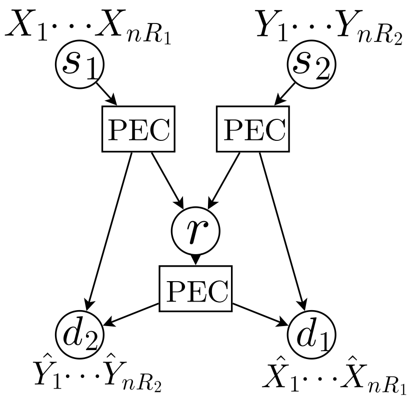

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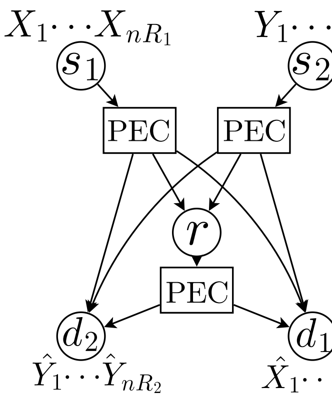

- Each round of $3n$ packets $\Rightarrow$ variable scheduling t_{s_1}, t_{s_2}, t_r.

The Capacity Regions (Cont'd)

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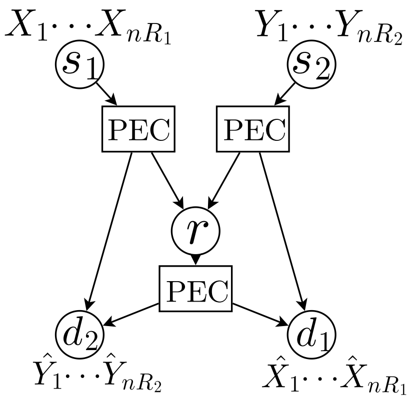

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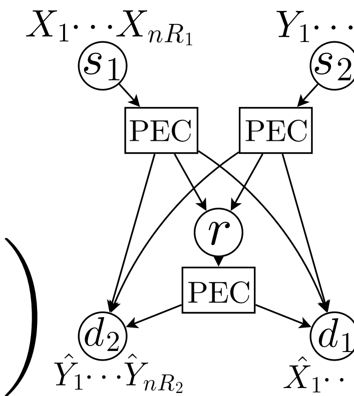


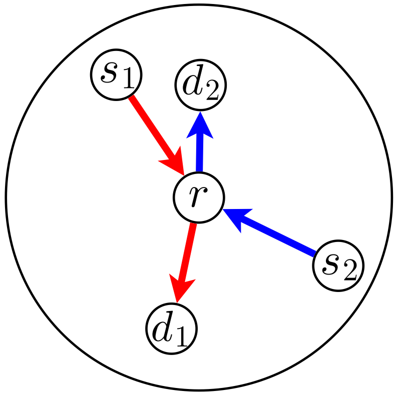
- Each round of $3n$ packets $\Rightarrow$ variable scheduling t_{s_1}, t_{s_2}, t_r.

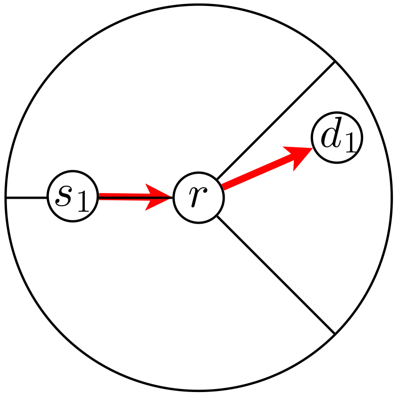
Results

- Our linear formulation contains three orthogonal components.
  - Intersession NC (INC): Whether to use the new cap. region.
  - Opp. Routing (OpR): Randomly vs. pre-planned 2-hop tx.
  - Cross-layer (CL): Fixed schedule 1/3, 1/3, 1/3 vs. t_{s_1}, t_{s_2}, t_r.
- Mixed & match: (INC, OpR, $\times$CL), (INC, $\times$OpR, CL), ...
  - The baseline scheme: Preplanned multipath routing with fixed schedules ($\times$INC, $\times$OpR, $\times$CL).
- The capacity region has been generalized to $N = 3$ sessions, and empirically tight upper and lower bounds for $N > 3$.

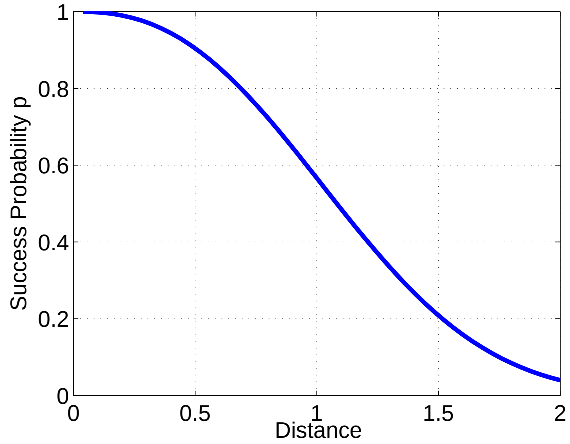
Simulation Settings

- The 2-hop random networks.

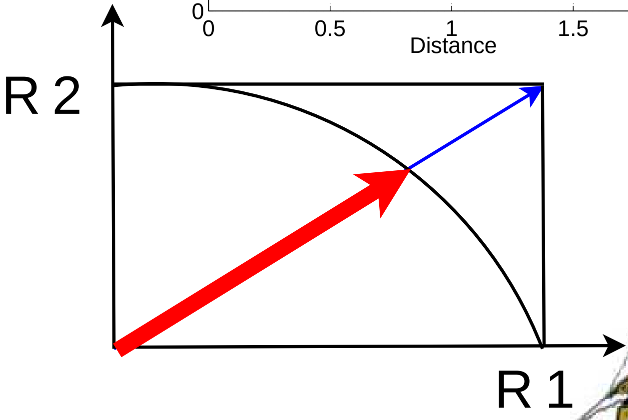




- The success probability versus distance (By Rayleigh fading channels w. $\alpha = 2.5$):

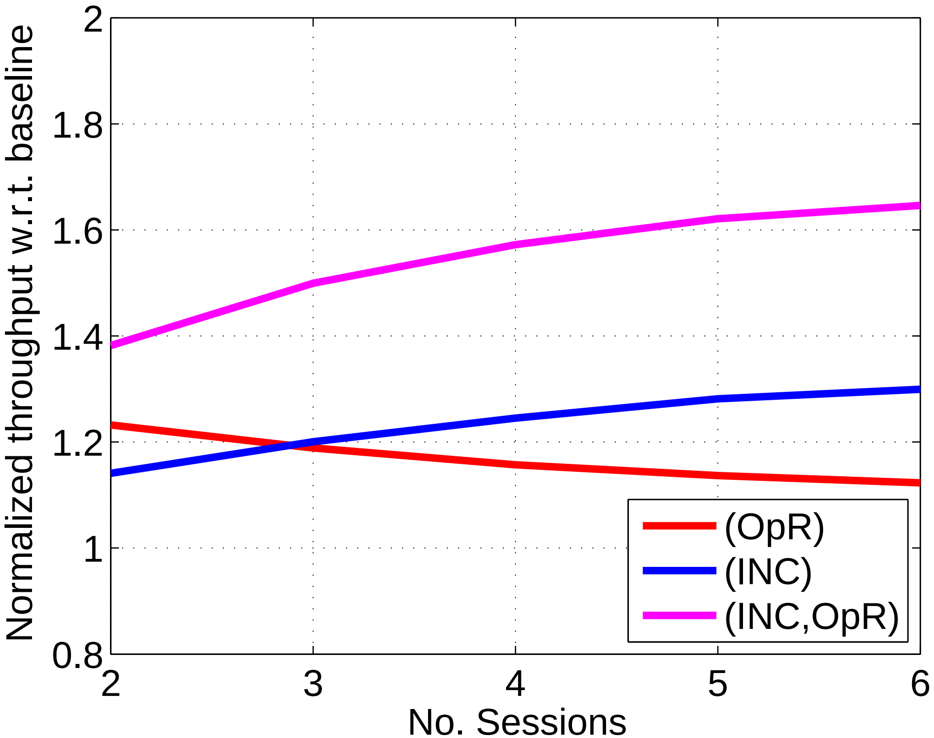


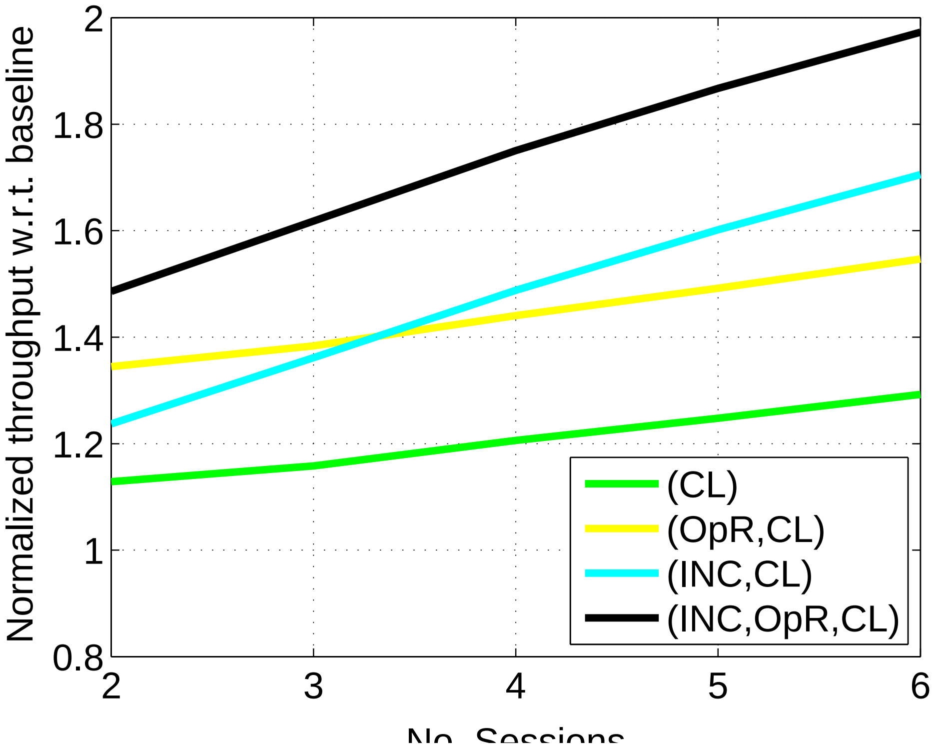
- Objective function: Achieving the percentage of the unicast capacities.



- Baseline scheme: ($\times$INC, $\times$OpR, $\times$CL)
- 2000 random topologies

The throughput improvement w.r.t. N





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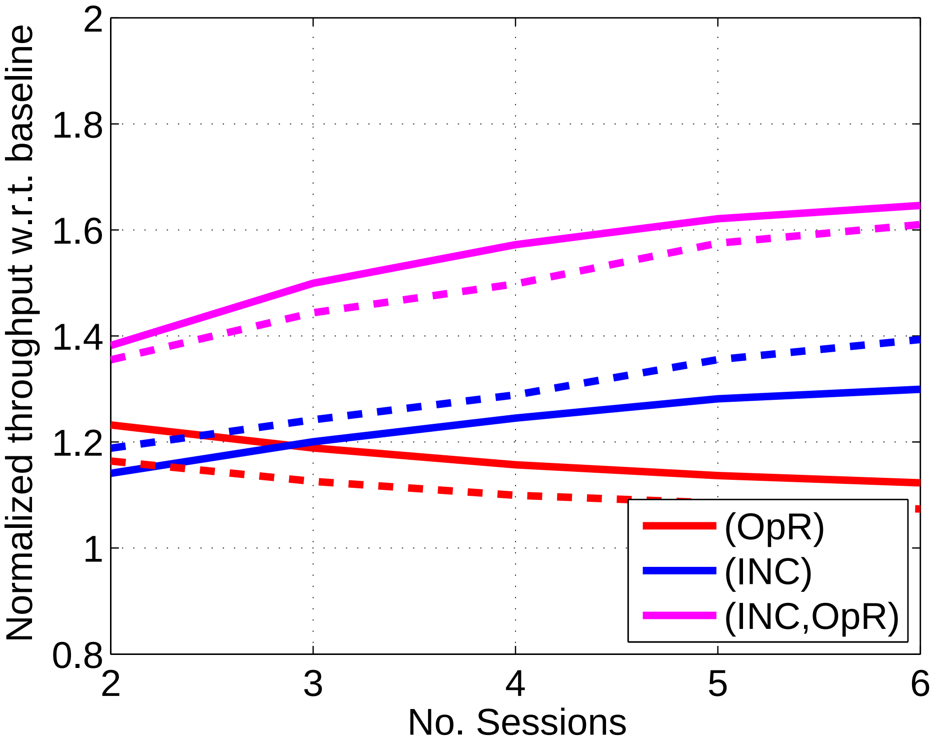
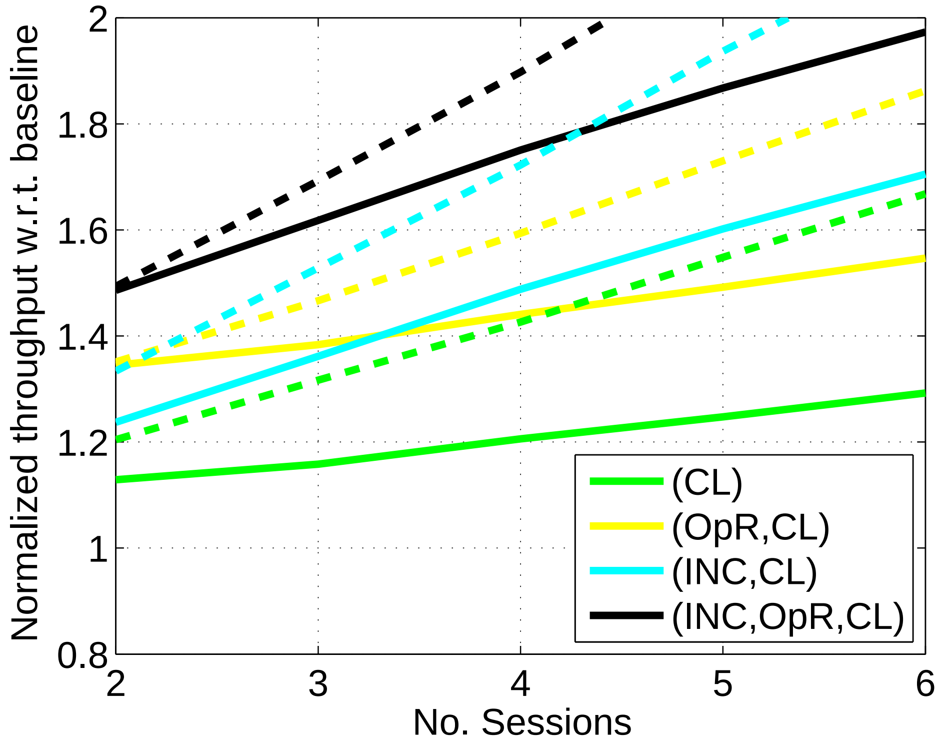
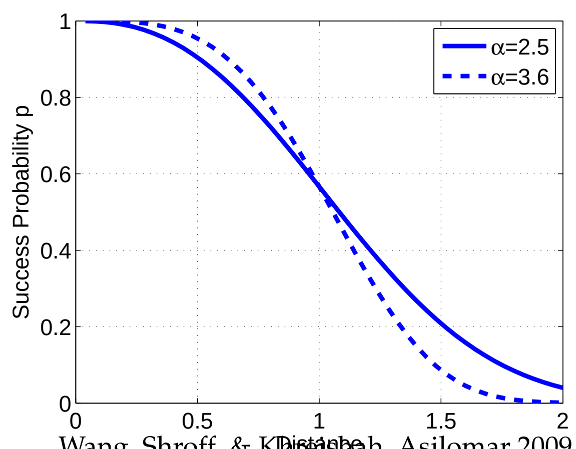


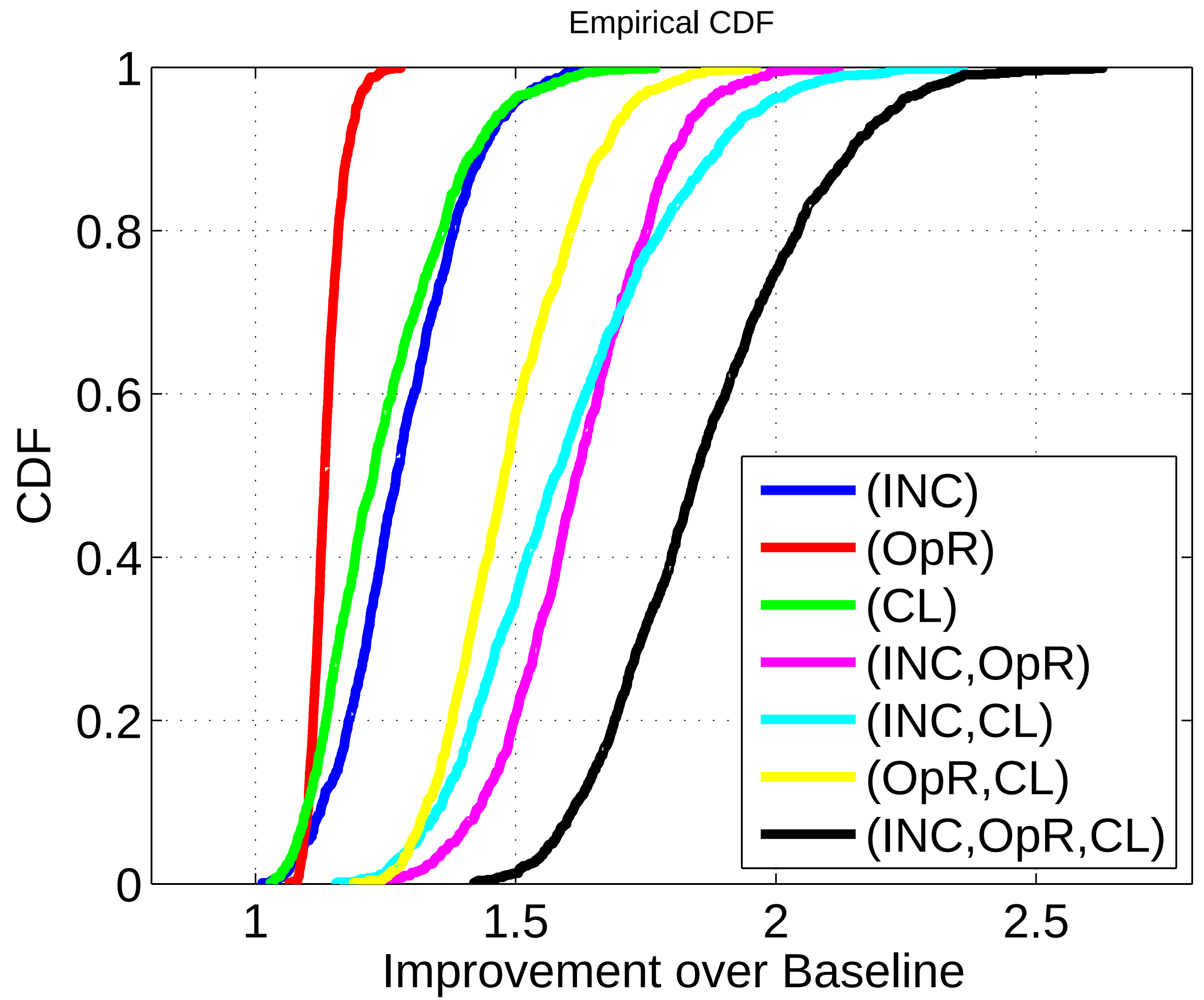


For different channel conditions: $\alpha = 3.6$.



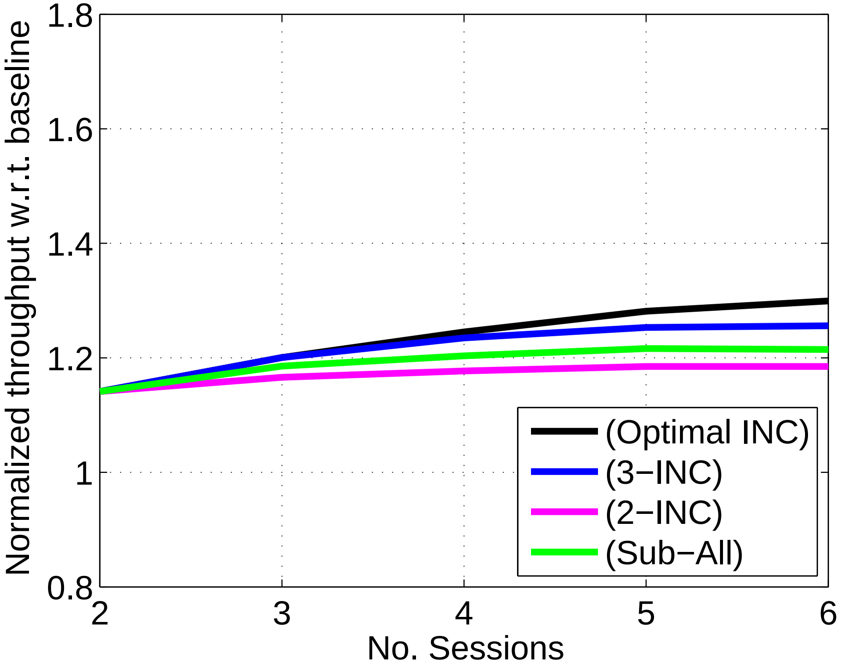
The throughput improvement w.r.t. N

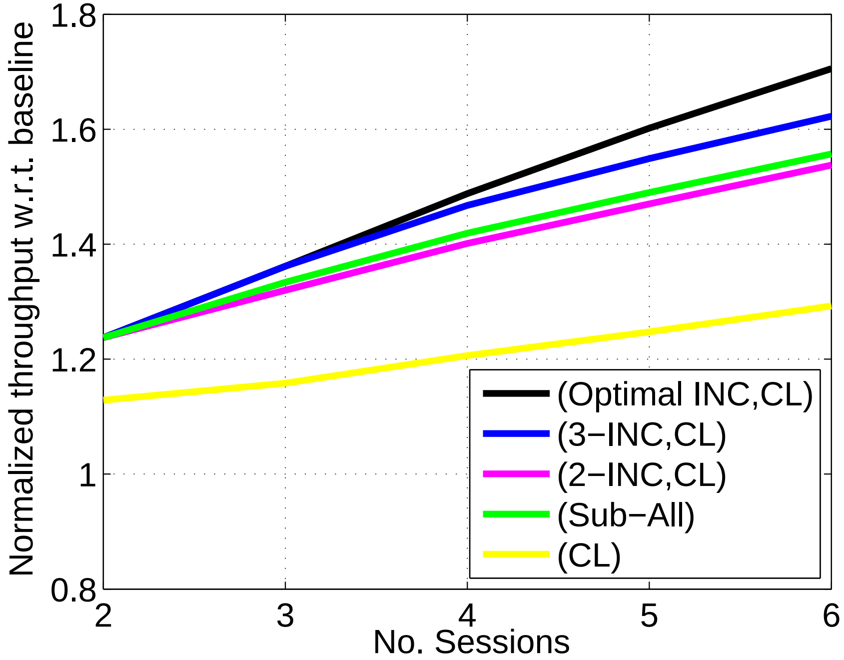
The cdf of the percentage gain when $N = 5$.



The Practical Schemes

- Optimal INC scheme is complicated (Optimal). All w. $\times$OpR.
- Optimal INC on Limited # of coded sessions + optimal time multiplexing: 2-session INC (2-INC), and 3-session INC (3-INC)
- Suboptimal INC on all coded sessions + optimal time multiplexing: (Sub-All). The importance of good INC schemes.





The Practical Schemes (cont'd)

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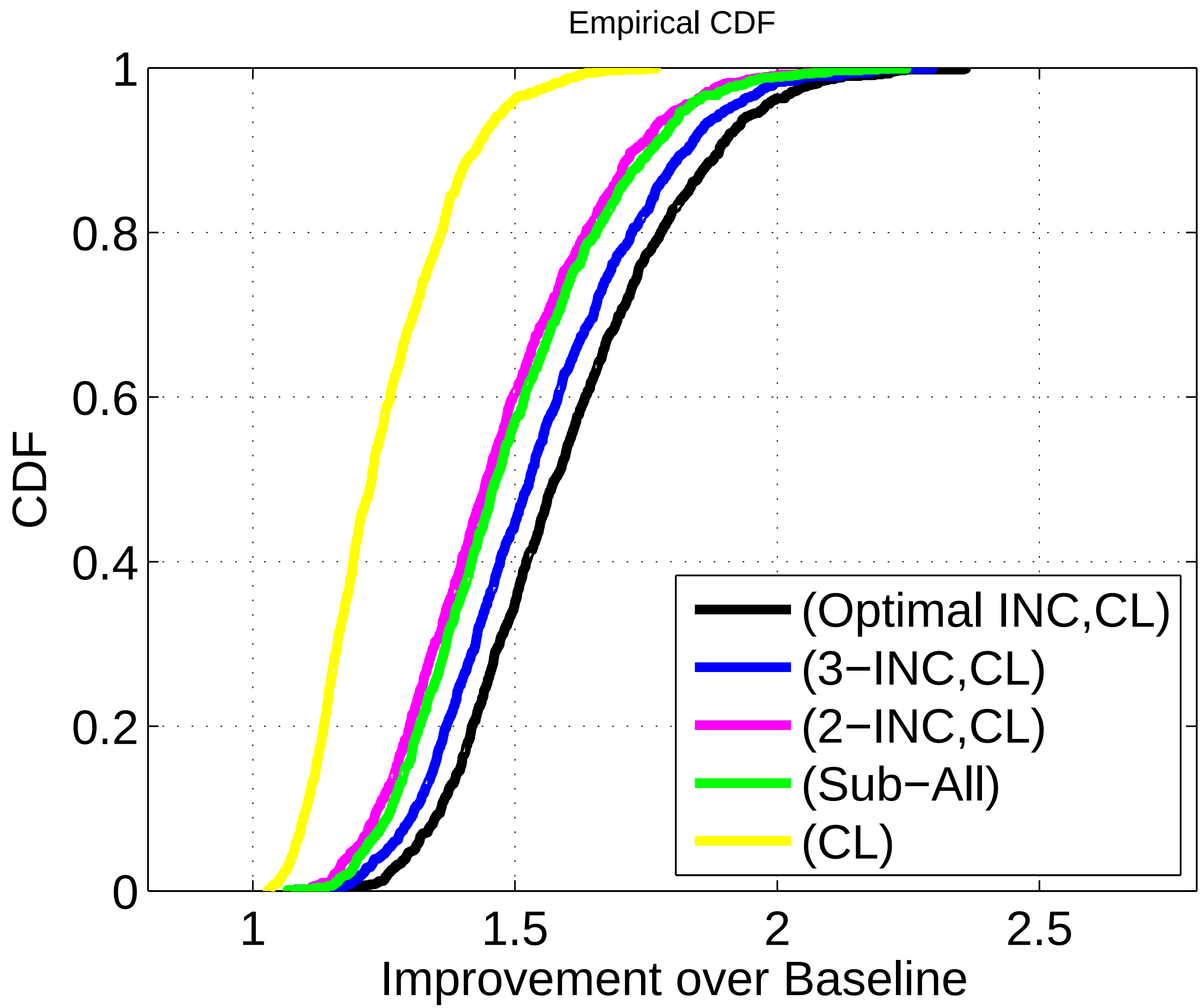

Conclusion

- Multi-hop-based vs. 2-hop-based Intersession Network Coding
  - Wireless-to-wireline conversion: 15-20% throughput improvement over non-coded solution.
  - The settings may not be practical.
- Practical 2-hop relay network capacity.
  - PEC, round-based tx, and infrequent reception report feedback.
  - Examine the performance gain of three orthogonal techniques: Intersession NC, Opp. Routing, & Cross layer.
  - An optimal scheme has 100-120% net improvement over feedback-free multi-path routing
  - Cross-layer is powerful, but is a global optimization. Both OpR and INC in this paper are local single-hop computation.
  - NC is a promising technique.