Information Flow in Wireless Networks

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Acknowledgements

- Andrew Thangaraj
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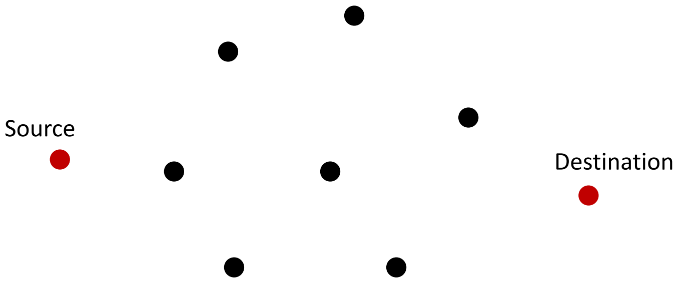
Information Flow Problem



- Wireless network of nodes
- Single source, single or multiple destinations
- Information rate maximization
- Per node power constraint

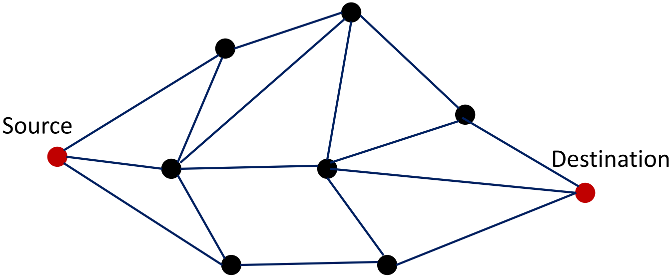
Outline

- Wired Networks
  - Max-flow min-cut theorem
  - Network coding
- Wireless Networks
  - Broadcast and interference
  - Interference Avoidance Approach
  - Information-theoretic Approach
    - ★ Cut-Set Bounds
    - ★ Flow optimization
    - ★ Approximate capacity
- Summary

Wired Networks

Single Source - Single Destination

Wired Network as a Graph



- Graph $G = (V, E)$, V: set of nodes (vertices), E: set of links (edges)
- Each edge (i, j) associated with a capacity C_{ij}

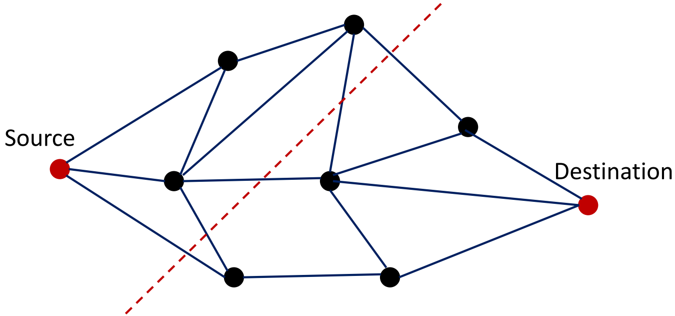
Flow

- Given G, assign $\{x_{ij}\}$ such that:
- $x_{ij} \geq 0$
- Rate constraints: $x_{ij} \leq C_{ij} \quad \forall i, j$
- Flow constraints:

$$\sum_i x_{ji} - \sum_i x_{ij} = \begin{cases} f & j = s \text{ (Source)} \\ -f & j = t \text{ (Destination)} \\ 0 & \text{else.} \end{cases} \quad \forall j$$

- f is the value of the flow from s to t
- Maximum flow can be found using linear programming

Cut and Cut Capacity



Cut with respect to s and t

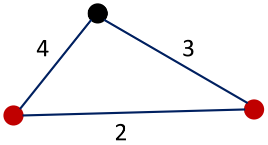
- Partitions V into S and S^c with $s \in S$, $t \in S^c$
- Cut Capacity (sum of capacities of edges from S to S^c):

$$C(S, S^c) = \sum_{i \in S, j \in S^c} C_{ij}$$

Max-Flow Min-Cut Theorem

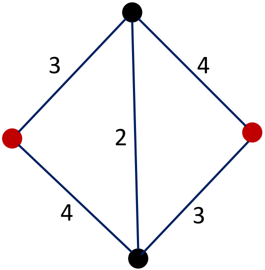
For a given G, the maximum value of flow from s to t is equal to the minimum value of the capacities of all cuts in G that separate s from t.

- Examples



Cut capacities: 6, 5

Min-cut : 5

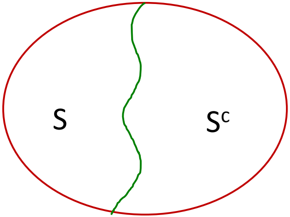


Cut capacities: 7, 7, 8, 10

Min-cut : 7

Proof Outline (Directed Graph)[1]

Part 1: Show that $f \leq C(S, S^c)$ for any cut



$$\sum_{p \in S, i \in G} x_{pi} - \sum_{i \in S, p \in G} x_{pi} = f$$

Since $$\sum_{p \in S, i \in S} x_{pi} - \sum_{i \in S, p \in S} x_{pi} = 0, \sum_{p \in S, i \in S^c} x_{pi} - \sum_{i \in S, p \in S^c} x_{pi} = f$$

$$\Rightarrow f \leq \sum_{p \in S, i \in S^c} x_{pi} \leq \sum_{p \in S, i \in S^c} C_{pi} = C(S, S^c)$$

[1] N. Deo, Graph Theory with Applications to Engineering and Computer Science, Prentice Hall India, 1974.
An undirected graph can be converted into a directed graph by replacing each undirected edge by two directed edges.

Proof Outline

Part 2: There exists a flow $f_0 = C(S_0, S_0^c)$ for some cut

- Step 1: Consider flow pattern corresponding to maximum flow
- Step 2: Define S_0 as:
  - $s \in S_0$
  - If $i \in S_0$ and either $x_{ij} < C_{ji}$ or $x_{ji} > 0$, then $j \in S_0$.
- Step 3: Show $t \in S_0^c$
- Step 4: Show $f_0 = C(S_0, S_0^c)$

Wired Networks

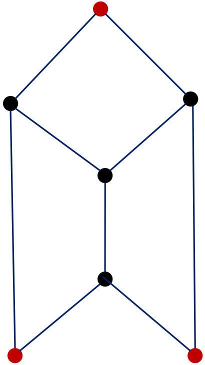
Single Source - Multiple Destinations

Multicast and Network Coding[2]

- Source s, L destinations $t_1, \; t_2, \; \cdots, \; t_L$
- All destinations want the same information
- Let f_k denote the maximum flow possible from s to t_k
- Maximum multicast rate

$$f = \min_k f_k$$

- Routing is not enough, network coding is required



[2] R. Ahlswede, N. Cai, S-Y. R. Li, R. W. Yeung, "Network Information Flow," IEEE Transactions on Information Theory, vol. 46, no. 4, pp. 1204-1216, July 2000.

Multicast Flow Optimization

$$\max_{\{x_{ij}^{(k)}\}} f$$

- Flow constraints:

$$\sum_i x_{ji}^{(k)} - \sum_i x_{ij}^{(k)} = \begin{cases} f & j = s \text{ (Source)} \\ -f & j = t \text{ (Destination)} \\ 0 & \text{else.} \end{cases} \quad \forall k, j$$

- Rate constraints:

$$x_{ij}^{(k)} \leq C_{ij} \quad \forall k, i, j$$

- $x_{ij}^{(k)}$: Flow in (i, j) towards destination t_k

Network Codes

- Random $\alpha-$codes[3]
- Linear codes[4]
- Random linear network codes[5]
- Network codes exist for every feasible flow solution[6]

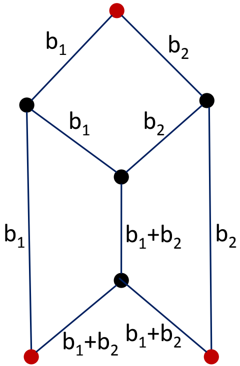
[3] R. Ahlswede, N. Cai, S-Y. R. Li, R. W. Yeung, "Network Information Flow," IEEE Transactions on Information Theory, vol. 46, no. 4, pp. 1204-1216, July 2000.

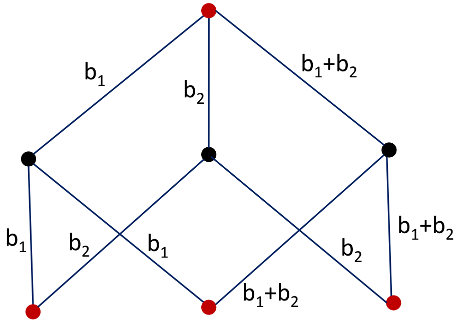
[4] S-Y. Li, R. Yeung, N. Cai, "Linear Network Coding," IEEE Transactions on Information Theory, vol. 49, no. 2, pp. 371-381, 2003.

[5] T. Ho, M. Medard, R. Koetter, D. R. Karger, M. Effros, J. Shi, B. Leong "A Random Linear Network Coding Approach to Multicast," IEEE Transactions on Information Theory, vol. 52, no. 10, pp. 4413-4430, 2006.

[6] D. S. Lun, N. Ratnakar, M. Medard, R. Koetter, D. R. Karger, T. Ho, E. Ahmed, "Minimum-cost multicast over coded packet networks," IEEE Transactions on Information Theory, vol. 52, no. 6, pp. 2608-2623, 2006.

Examples



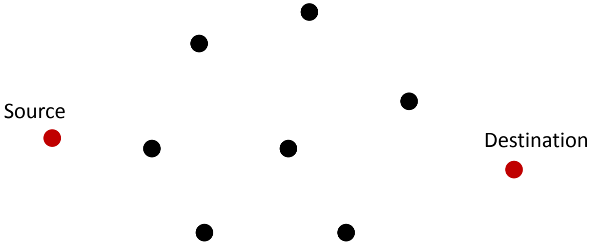


- Links with unit capacity

Wireless Networks

Single Source - Single/Multiple Destinations

Wireline Networks vs. Wireless Networks

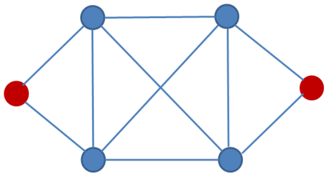


- Wireline networks
  - Links are independent
  - Graph model natural
- Wireless networks
  - Single shared resource → Broadcast nature, Interference
  - Links are dependent → Cross-layer optimization

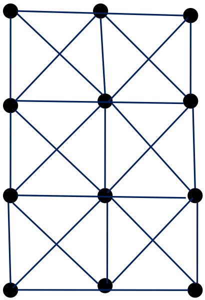
Wireless Network as a Graph

Many possibilities

- Complete graph: All nodes connected to all others
- Finite transmission range model



Two-stage relay network

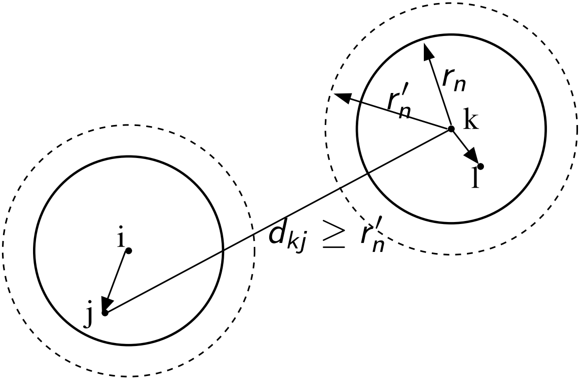


Wireless Networks

Interference Avoidance Approach

Interference Avoidance Model for Links

- Protocol model to avoid interference between links[7]
  - Check transmission range: $d_{ij} \leq r_n$, $d_{kl} \leq r_n$
  - Check interference range: $d_{kj} \geq r'_n$, $d_{il} \geq r'_n$

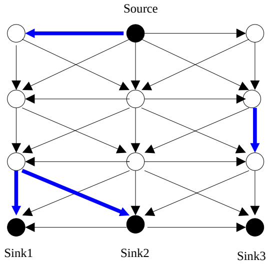


- Link activation constraints can be extended for broadcast hyperarcs [8]

[7] P. Gupta *et al.*, The Capacity of Wireless Networks, IEEE Transactions on Information Theory, Mar. 2000

[8] Park *et al.*, Performance of network coding in adhoc networks, in Proc. of IEEE MILCOM 2006

Interference Avoidance (IA) with Broadcast Hyperarcs

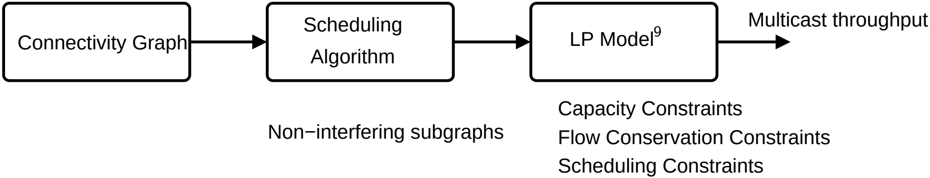


A non-interfering subgraph

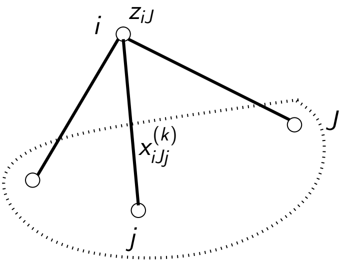
- A collection of non-interfering hyperarcs forms a non-interfering subgraph
- All non-interfering subgraphs can be generated using:
  - Conflict graph scheduling[a]

[a] Jain *et al* "Impact of interference on multihop wireless networks," Mobicom 2003

Optimization Model



- $\mathcal{A}$: Set of hyperarcs
- (i, J): Broadcast hyperarc
- $x_{iJj}^{(k)}$: Flow from i to $j \in J$ using hyperarc (i, J) towards sink t_k
- z_{iJ}: Average rate at which packets are injected by i in (i, J)



[9] Lun *et al*, Performance of network coding in adhoc networks, MILCOM 2006

Flow Optimization Model: Wireless Networks

$$\max_{\{\lambda_m\},\{z_{iJ}\},\{x_{iJj}^{(k)}\}} f$$

- Scheduling constraints: $\sum_m \lambda_m \leq 1$
- Rate constraints:

$$\sum_{j \in J} x_{iJj}^{(k)} \leq z_{iJ} \quad \forall (i, J) \in \mathcal{A}, k$$

$$z_{iJ} \leq \sum_m \lambda_m C_m(i, J)$$

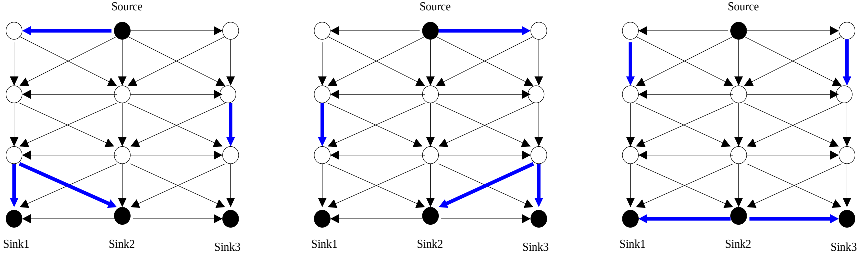
- Flow constraints:

$$\sum_{(i,J) \in \mathcal{A}} \sum_{j \in J} x_{iJj}^{(k)} - \sum_{(j,I) \in \mathcal{A}} \sum_{i \in I} x_{jIi}^{(k)} = \begin{cases} f & i = s \text{ (Source)} \\ -f & i = t \text{ (Destination)} \\ 0 & \text{else.} \end{cases} \quad \forall k, i$$

- $\lambda_m \geq 0$, $x_{iJj}^{(k)} \geq 0$, $z_{iJ} \geq 0$

IA Solution for 4 x 3 Grid Network

$\lambda_1 = 1/3$ $\lambda_2 = 1/3$ $\lambda_3 = 1/3$



- $f = 2/3$ packets per time unit

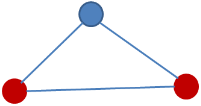
Wireless Networks

Information-theoretic Approach

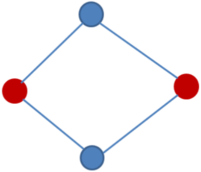
Wireless Relay Networks: What is known/unknown?

Single source-destination pair Gaussian relay networks

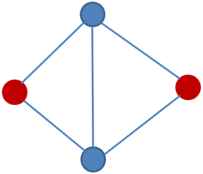
- Capacity unknown for arbitrary topology
- Cut-set upper bound
- Achievable rates for specific protocols and topologies
- Appproximate capacity



Three terminal network



Diamond Channel



Diamond Channel
with Interfering Relays

Wireless Relaying: Assumptions and Results

Duplex	SNR	Cooperation	Topology
Full	Large	MIMO	Arbitrary, Directed
Half	All	Limited	Restricted
		No MIMO	Arbitrary

- Both, Large SNR, MIMO, Arbitrary directed[10]
  - Constant gap to capacity
- Both, Large SNR, MIMO, Arbitrary[11]
  - Diversity-multiplexing trade-off
- Half duplex, All SNR, Limited, Restricted[12]
  - Rates close to capacity
- Half duplex, All SNR, No MIMO, Restricted[13]
  - Constant gap to capacity

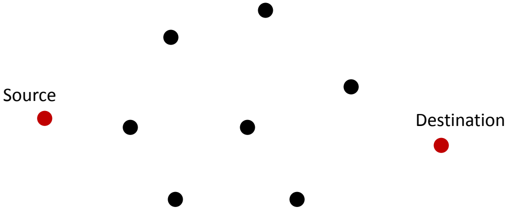
[10] A. S. Avestimehr, S. N. Diggavi, and D. N. C. Tse, Wireless network information flow: A deterministic approach, IEEE Transactions on Information Theory, vol. 57, no. 4, pp. 1872 1905, April 2011.

[11] K. Sreeram, P. S. Birenjith, P. V. Kumar, "DMT of multi-hop cooperative networks," IEEE ITW, Cairo, Egypt, Jan. 2010.

[12] W. Chang, S. Chung, and Y. Lee, Capacity bounds for alternating twopath relay channels, in Proc. of the Allerton Conference on Communi- cations, Control and Computing, Monticello, Illinois, USA, Sep. 2007, pp. 11491155.

[13] H. Bagheri, A. Motahari, and A. Khandani, On the capacity of the halfduplex diamond channel, in Proc. of IEEE International Symposium on Information Theory, Austin, USA, June 2010, pp. 649 653.

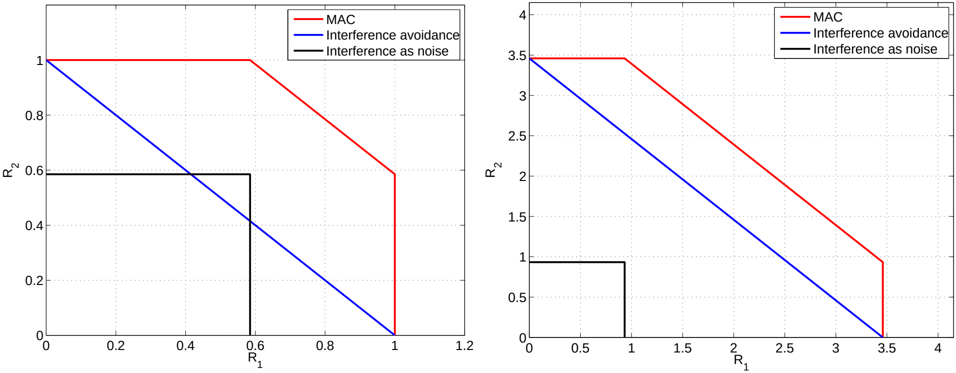
Relay Networks



- Interference processing/decoding
  - Decode strong interference and cancel
  - Joint decoding of interfering signals
- Processing at the relays
  - More general than decode and forward and network coding
  - Relay can transmit any encoded function of received signal

Interference Processing

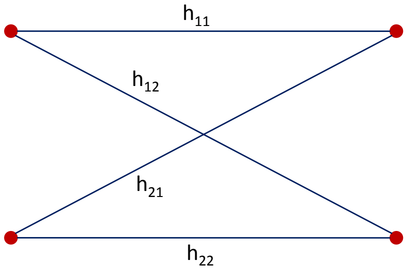
- Gaussian Multiple Access Channel



$P_1 = 0$ dB, $P_2 = 0$ dB

$P_1 = 10$ dB, $P_2 = 10$ dB

Interference Channel

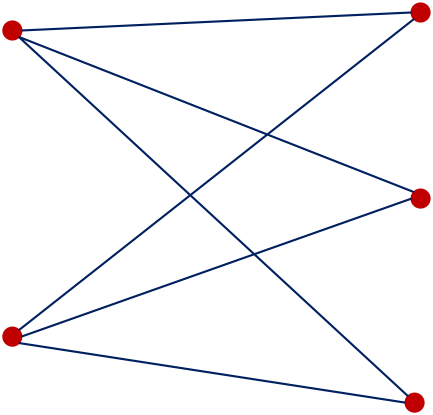


- Two transmit-receive pairs
- Strong interference: Decode interference and cancel[14]
- Weak interference: Treat interference as noise[15]

[14] A. B. Carleial, A case where interference does not reduce capacity, IEEE Trans. Inform. Theory, vol. IT-21, pp. 569-570, Sept. 1975.

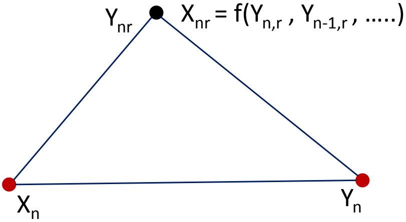
[15] V. Annapureddy and V. Veeravalli, Gaussian interference networks: Sum capacity in the low-interference regime and new outer bounds on the capacity region, IEEE Transactions on Information Theory, vol. 55, no. 7, pp. 3032 3050, July 2009.

Interference Networks



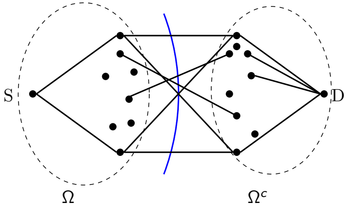
2 x 3 Interference Network

Processing at the Relays



- Transmit signal $= f$(past received signals)
- Link model with an associated rate
  - Decode-and-forward (DF) + Network coding
- Other general models
  - Amplify-and-forward (AF)
  - Compress-and-forward (CF)
  - Quantize-map-and-forward
  - ...

Cut-Set Bound



- Full Duplex Network[16]

$$R \leq \min_{\Omega} I(X^{\Omega}; Y^{\Omega^c} | X^{\Omega^c}) \text{ for some } p(x_1, x_2, \cdots, x_N)$$

- Half Duplex Network [17]

$$R \leq \sup_{\lambda_k} \min_{\Omega} \sum_{k=1}^{\mathscr{M}} \lambda_k I(X^{\Omega}_{(k)}; Y^{\Omega^c}_{(k)} | X^{\Omega^c}_{(k)}) \text{ for some } p(x_1, x_2, \cdots, x_N | k)$$

[16] T. M. Cover, J. A. Thomas, Elements of Information Theory, John Wiley, 2004.

[17] M. Khojestepour,A. Sabharwal, B. Aazhang, "Bounds on achievable rates for general multiterminal networks with practical constraints", IPSN, pp. 146-161, 2003

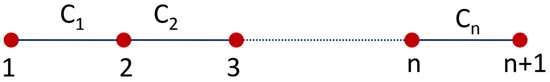
Cut Capacity Bounds: Gaussian Relay Networks[18]

- Based on MIMO capacity
  - Maximize
    $$\log\det\left(\mathbf{I} + \mathbf{H}K_X\mathbf{H}^H\right)$$
    subject to $\mathrm{tr}(K_X) \leq N_t P$
  - MIMO capacity – Water-filling
  - Easy to compute MIMO capacity bound
    $$\log\det\left(\mathbf{I} + PN_t\mathbf{H}\mathbf{H}^H\right)$$
  - Per antenna power constraint
  - Same input distribution for a state for all cuts

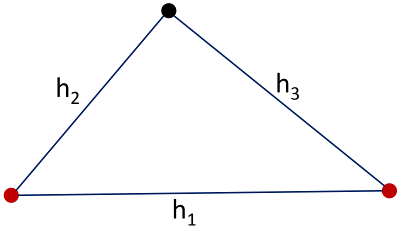
[18] M. Bama, "Cut-set Bound for Gaussian Relay Networks," Available at http://www.ee.iitm.ac.in/∼skrishna/TechRepCUB.pdf.

Examples: Full-duplex Cut-Set Bound

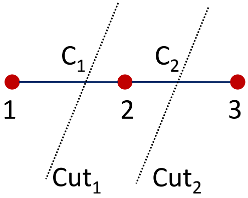
- Linear network (n hops/stages, $n+1$ nodes)
  - 2^{n-1} cuts, $C_{FD} = \min_n C_n$



- 3-node relay network
  - 2 cuts, $C_{FD} = \min\{C((h_1^2 + h_2^2)P), C((h_1 + h_3)^2 P)\}$



Examples: Half-Duplex Cut-Set Bound



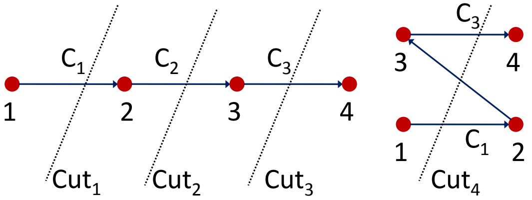
State	Cut_1	Cut_2
S_0 (00)	0	0
S_1 (01)	0	C_2
S_2 (10)	C_1	0
S_3 (11)	0	C_2

- Enough to consider S_1 and S_2 $(\lambda_1 + \lambda_2 = 1)$

$$C_{HD} = \max_{\lambda_1, \lambda_2} \min(\lambda_2 C_1, \lambda_1 C_2)$$

- $\lambda_1 C_2 = \lambda_2 C_1$
  $$\Rightarrow C_{HD} = \frac{C_1 C_2}{C_1 + C_2}$$
- $C_{FD} = \min(C_1, C_2)$

Examples: Half-Duplex Cut-Set Bound



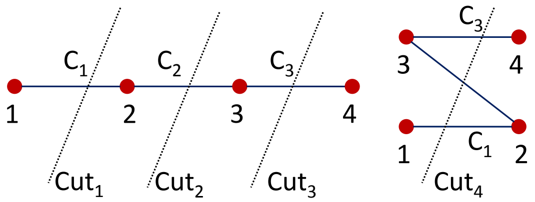
State	Cut_1	Cut_2	Cut_3	Cut_4
S_0 (000)	0	0	0	0
S_1 (001)	0	0	C_3	C_3
S_2 (010)	0	C_2	0	0
S_3 (011)	0	0	C_3	C_3
S_4 (100)	C_1	0	0	C_1
S_5 (101)	C_1	0	C_3	$C_1 + C_3$
S_6 (110)	0	C_2	0	0
S_7 (111)	0	0	C_3	C_3

- Enough to consider S_2 and S_5 $(\lambda_2 + \lambda_5 = 1)$

$$\max_{\lambda_2,\lambda_5} \min(\lambda_2 C_2, \lambda_5 C_1, \lambda_5 C_3)$$

- $C_{HD} = \min_n \frac{C_{n-1} C_n}{C_{n-1} + C_n}$
- $C_{FD} = \min_n C_n$

Undirected network with more than 2 stages/hops



State	Cut_1	Cut_2	Cut_3	Cut_4
S_0 (000)	0	0	0	0
S_1 (001)	0	0	C_3	C_3
S_2 (010)	0	C_2	0	0
S_3 (011)	0	0	C_3	C_3
S_4 (100)	C_1	0	0	C_1
S_5 (101)	C_1	0	C_3	$C_1 + C_3$
S_6 (110)	0	C_2	0	0
S_7 (111)	0	0	C_3	C_3

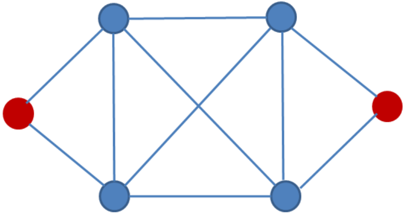
- Interference from node 3 to node 2
- Dirty paper coding (DPC) if interference is known non-causally
- Knowing interference not always possible

Wireless Networks

Information-theoretic Approach and Flow Optimization

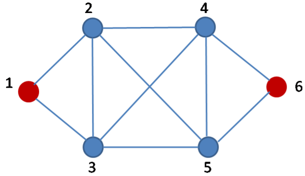
Our Focus

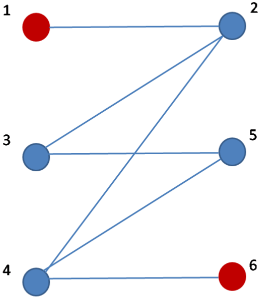
- Half-duplex
- All SNR
- No MIMO/Limited cooperation
- Restricted, arbitrary
- Decode-and-Forward



Two-stage relay network

States of a Half-Duplex Network





- Each node: Transmit, Receive, or Idle
- Each state is an interference network

Relaying Scheme

- Two components: Scheduling and Coding
- Scheduling of states
  - Which states help in information flow?
  - What is the best time-sharing of these states?
- Coding for a given state
  - Which encoding and decoding scheme should be used?
  - Choice of operating point in capacity region

Scheduling: Choice of States

All States

- Complexity

Interference Avoidance

- Only one node can transmit at any time

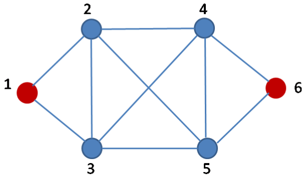
Interference Processing

- Source should be in transmit mode
- Destination should be in receive mode
- Relays should be in both transmit and receive modes
  - Required for information flow
- Atleast two node-disjoint paths required for source to be transmitting in all chosen states

Coding for a State

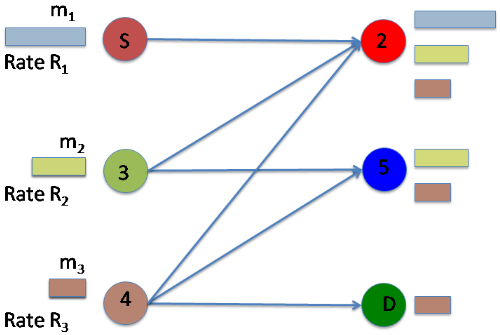
- $M \times N$ interference network [Carleial1978]
- Possible message from each transmitter to each subset of receivers
  - $M(2^N - 1)$ possible rates
- $M-$user Interference channel
  - M possible messages (M rates)
- Achievable rate regions based on
  - Superposition
  - Successive interference cancellation
  - Dirty paper coding

Two-Path Two-State Schedule



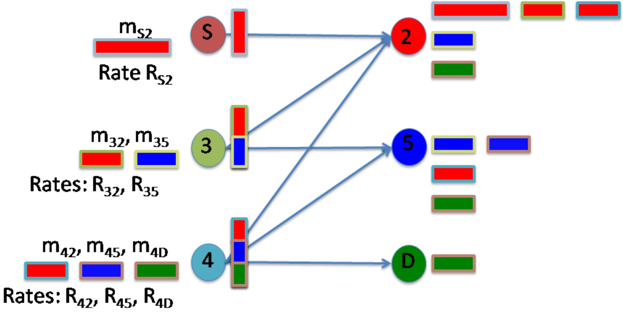
- Shortest (three-hop) paths connecting S and D
  - Path P1: S $\rightarrow$ 2 $\rightarrow$ 4 $\rightarrow$ D
  - Path P2: S $\rightarrow$ 3 $\rightarrow$ 5 $\rightarrow$ D
  - Path P3: S $\rightarrow$ 2 $\rightarrow$ 5 $\rightarrow$ D
  - Path P4: S $\rightarrow$ 3 $\rightarrow$ 4 $\rightarrow$ D.
- Only two pairs of node-disjoint paths: (P1, P2) and (P3, P4).
- States from (P1, P2):
  - State S1: Nodes S, 3, 4 transmit, Nodes 2, 5, D receive
  - State S2: Nodes S, 2, 5 transmit, Nodes 3, 4, D receive

Common Broadcast (CB)



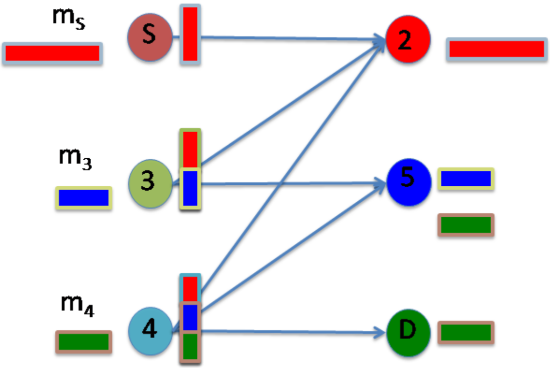
- Rate limited by weakest link
- Receivers employ SIC/MAC decoding

Superposition Coding (SC)



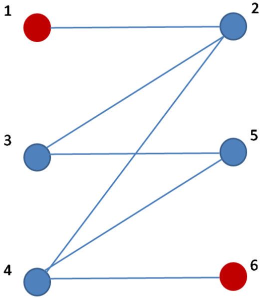
- Transmitters send superposed codewords
- Constraints involve power allocation parameters (non-linear)
- Larger rate region than CB

Dirty paper coding (DPC) at the source



- Source: origin for all messages; knows m_3 and m_4
- Source does DPC to eliminate interference at receiver 2
- Can be combined with CB or SC at other transmitters

Coding for the Two-Stage Relay Example



DPC-SC

- State S1: Nodes S (1), 3, 4 transmit, Nodes 2, 5, D (6) receive
- Node S: Transmit to Node 2 using DPC
- Node 3: Transmit to Node 5
- Node 4: Transmit to Nodes 5 and D using SC

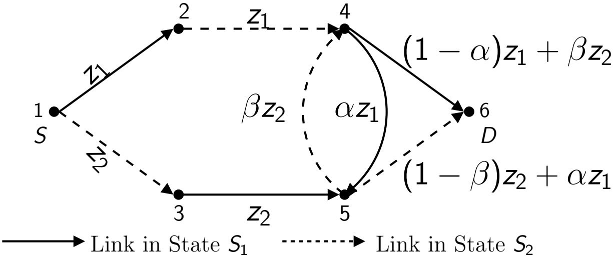
Flow Optimization

- Joint optimization problem

maximize Rate
subject to

- Scheduling constraints
  - State k is ON for λ_k units of time
  - Total transmission time is one unit
- Rate region constraints
  - appropriate rate region depending on the coding scheme
- Flow constraints
  - Total flow in a link $(i, j) = \sum_k$ flow in link (i, j) in state k
  - Outgoing flow from Node i - Incoming flow to Node i = Rate, if i = S,
    -Rate, if i = D,
    0, otherwise.

Two-Stage Relay Flow optimization: DPC-SC



Two-Stage Relay Flow optimization

$$\max_{0 \leq \lambda_1, \lambda_2, \alpha, \beta \leq 1} R = z_1 + z_2,$$

subject to rate constraints

- Flow in each link less than average rate

$$z_1 \leq \lambda_1 R_{S2}, \quad z_1 \leq \lambda_2 R_{24}, \quad z_2 \leq \lambda_2 R_{S3}, \quad z_2 \leq \lambda_1 R_{35},$$
$$(1-\alpha) z_1 + \beta z_2 \leq \lambda_1 R_{4D}, \quad (1-\beta) z_2 + \alpha z_2 \leq \lambda_2 R_{5D},$$
$$\alpha z_1 \leq \lambda_1 R_{45}, \quad \beta z_2 \leq \lambda_2 R_{54},$$

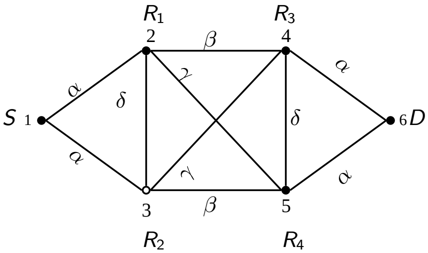
- Scheduling constraint: $0 \leq \lambda_1 + \lambda_2 \leq 1$
- Rates chosen according to rate region of interference network

$$(R_{S2}, R_{35}, R_{45}, R_{4D}) \in \mathcal{R}_1, (R_{S3}, R_{24}, R_{54}, R_{5D}) \in \mathcal{R}_2.$$

Numerical Results

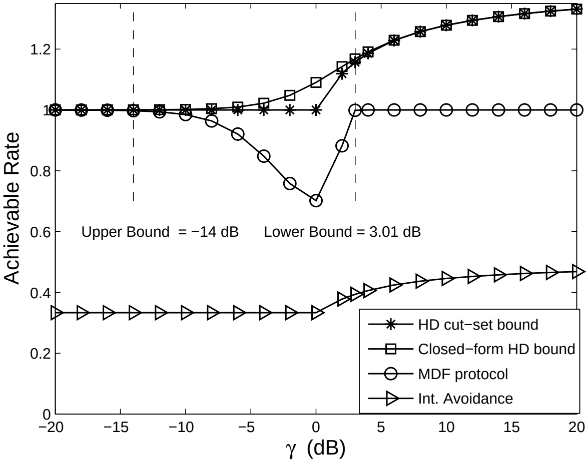
Parameters:

- Tx power, $P = 3$ units
- Noise variance, $\sigma^2 = 1$
- Variable channel gains



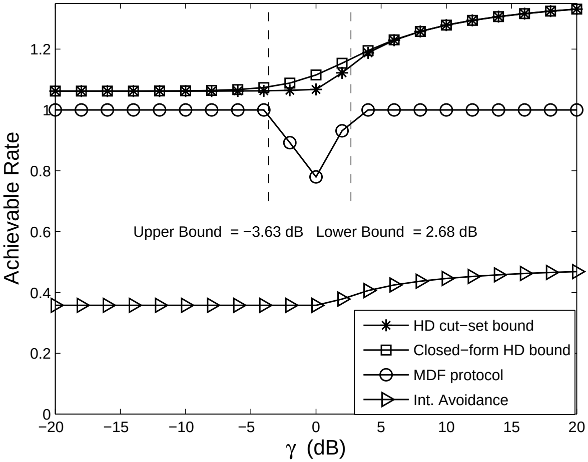
- Case 1: $\alpha = \beta = 1$, $\gamma = \delta$
- Case 2: $\alpha = \beta = 1.25$, $\gamma = \delta$

Numerical Results: Case 1



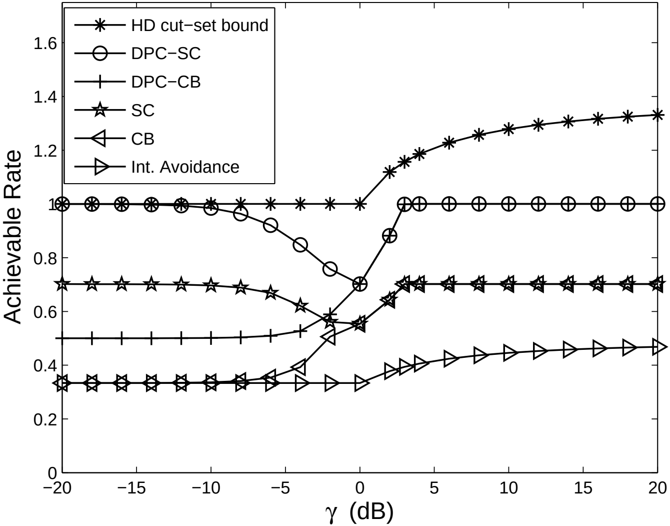
- Achieves cut-set bound in weak interference regime
- Gap from cut-set bound in strong interference regime ≤ 0.33 bits

Numerical Results: Case 2



- Gap from cut-set bound in weak interference regime ≤ 0.06 bits
- Gap from cut-set bound in strong interference regime ≤ 0.33 bits

Comparison of All Schemes: Case 1



Numerical Results: Multicast

Parameters:

- Tx power, $P = 3$ units
- Noise variance, $\sigma^2 = 1$
- Variable channel gains

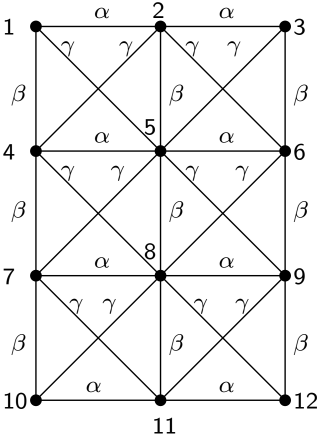
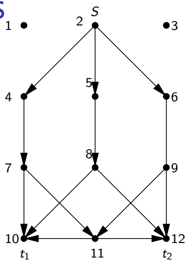
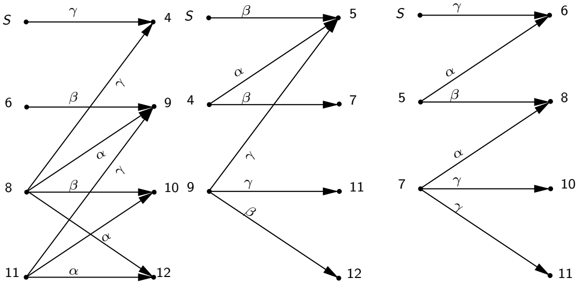


Figure: 4×3 Grid Network.

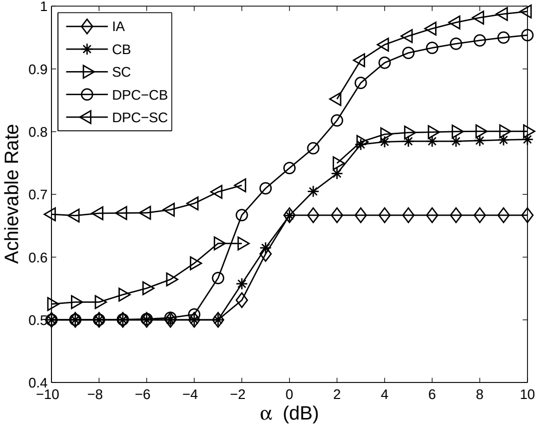
Information Flow Paths



- Three IP states



Performance in Grid Network, $\beta = 1, \gamma = 1$, vary α



- Six IA states, three IP states

Summary of Optimization Formulation

- Flow optimization with more general physical layer
- States of a half-duplex relay network as interference networks
- Scheduling + Coding components
- Scheduling of states using path heuristic
- Interference processing receivers at the relays
- Strong and weak interference conditions on channel gains
  - Close to cut-set bound

Wireless Networks

Information-theoretic Approach: Approximate Capacity

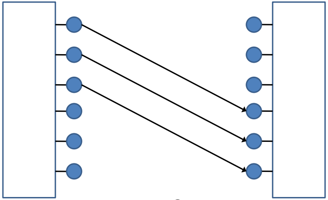
Relay Networks and Approximate Capacity[19]

- Achieve rates within a constant gap of cut-set bound
- Gap independent of channel parameters
- Gap not significant at high rate/high SNR

- Deterministic model (approximation)
- Capacity of a deterministic relay network
- Approximate schemes for Gaussian relay networks

[19] A. S. Avestimehr, S. N. Diggavi, and D. N. C. Tse, Wireless network information flow: A deterministic approach, IEEE Transactions on Information Theory, vol. 57, no. 4, pp. 1872 1905, April 2011.

Deterministic Model: Point-to-Point



- Signal strength model

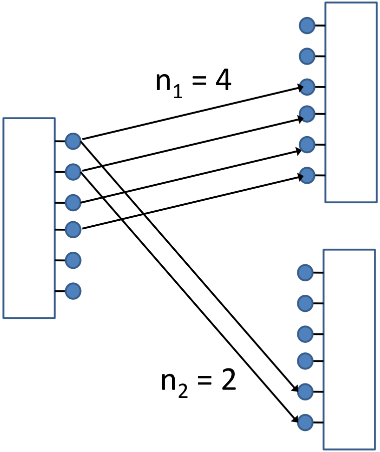
$$y = \sqrt{\mathsf{SNR}} x + z, \quad z \sim N(0,1), \quad E[x^2] \leq 1$$

$$y \approx 2^n \sum_{i=1}^{n} x(i) 2^{-i} + \sum_{i=1}^{\infty} (x(i+n) + z(i)) 2^{-i}$$

where $n = \lceil 0.5 \log \mathsf{SNR} \rceil^+$

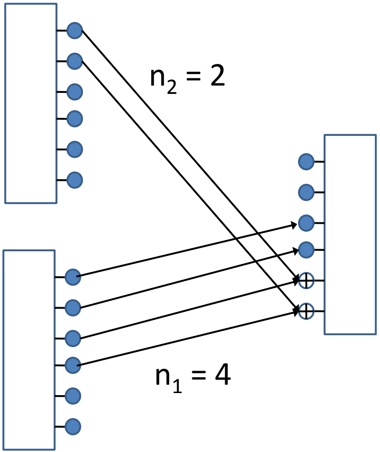
- Most significant n bits received as destination

Deterministic Model: Broadcast



- $R_2 \leq n_2$
- $R_1 + R_2 \leq n_1$

Deterministic Model: Multiple Access



- $R_2 \leq n_2$
- $R_1 + R_2 \leq n_1$

Deterministic Model: Summary

- Component-wise within one bit gap for BC and MAC
- Not a finite gap for MIMO
- Models link from transmitter to receiver

- Deterministic model for relay network
- Quantize-map-and-forward strategy
- Finite gap from cut-set bound

Related Results

- Abstract flow model for deterministic relay networks
- Simpler computable schemes (instead of random coding)[20] [21]

[20] M. X. Goemans, S. Iwata, and R. Zenklusen, An algorithmic framework for wireless information flow, in Proceedings of Allerton Conference on Communications, Control, and Computing, Sep. 2009.

[21] S. M. S. Yazdi and S. A. Savari, A combinatorial study of linear deterministic relay networks, in Proceedings of Allerton Conference on Communications, Control, and Com- puting, Sep. 2009.

Other Constant Gap Achieving Schemes

- Noisy Network Coding[22]
  - Vector-quantization of received signal in blocks
- Compress-and-forward[23]
  - Analog of algebraic flow results in deterministic networks for Gaussian networks

[22] S. H. Lim; Y. -H. Kim; A.. El Gamal, and S. -Y. Chung. Noisy Network Coding. IEEE Trans. Inform. Theory, vol. 57, no. 5, pp.31323152, May 2011.

[23] A. Raja and P. Viswanath. Compress-and-Forward Scheme for a Relay Network: Approximate Optimality and Connection to Algebraic Flows Proc. of IEEE ISIT, Aug. 2011.

Multiple Unicast and Polymatroidal Networks[24] [25]

- Wireless network as an undirected polymatroidal network
- Use results on polymatroidal networks
- Polymatroidal Networks
  - Edge capacity constraints
  - Joint capacity constraints on set of edges that meet a vertex

[24] S. Kannan and P. Viswanath. Multiple-Unicast in Fading Wireless Networks: A Separation Scheme is Approximately Optimal. Proc. of IEEE ISIT, Aug. 2011.

[25] S. Kannan, A. Raja and P. Viswanath. Local Phy + Global Flow: A Layering Principle for Wireless Networks. Proc. of IEEE ISIT , Aug. 2011.

Summary

Summary

- Wired Networks
  - Unicast: Max-flow min-cut theorem
  - Multicast: Network coding
- Wireless Networks
  - Interference management
  - Interference Avoidance Approach
  - Interference processing
  - Flow optimization + Interference processing
  - Approximate capacity + deterministic models
- Issues
  - Centralized scheduling + rate selection
  - Limited topology and channel information