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Joint Routing, Scheduling and Power-control in Multihop Wireless Networks With Multiple Antennas

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Outline of the Presentation

- ✓ **Basic Introduction to the network & the problem**
- General Problem formulation & application to MIMO
- Solution procedure – A *Heuristic* algorithm.
- Simulations with P2P transmission model.
- New transmission models to improve the performance and simulation results.
- Conclusions

Multihop Wireless Networks

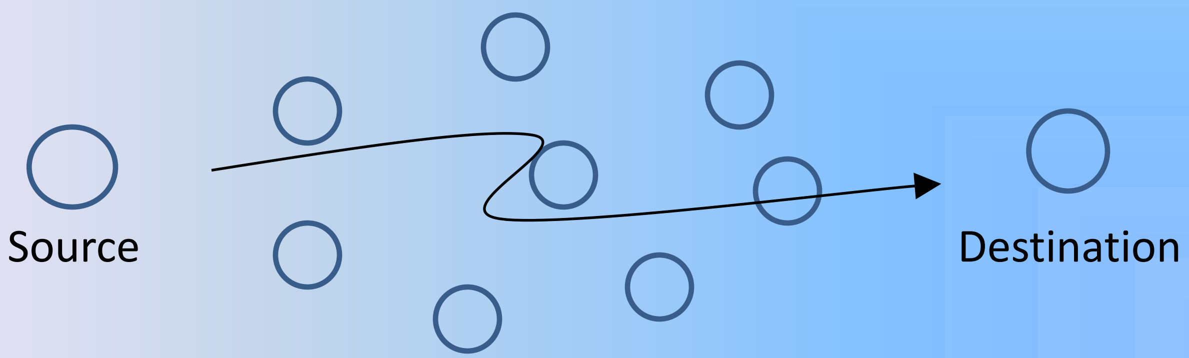
- Multihop Wireless Networks (MHWN) are essential for ubiquitous computation and communication.
- Many experimental theoretical setups around the world.
- A MHWN fundamentally increases the coverage area for communication.
- E.g.: Ad hoc Wireless Networks, Cellular networks, Sensor networks.

A Simple Illustration of MHWN

Single-hop *Communication*

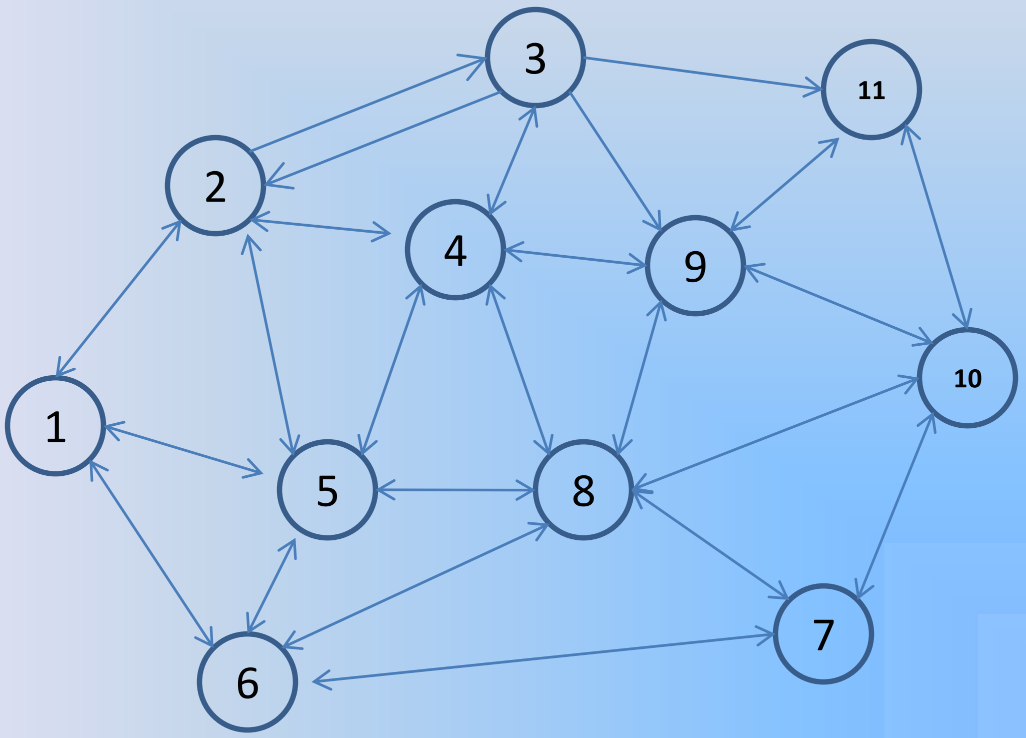
The ‘*Destination’* must be in the coverage area of the ‘*Source’*

Multiple Hops Enabled



The *‘Destination’* need not necessarily be in the coverage area of ‘*Source*’

A Multihop Wireless Network (MHWN)



A Graph $\mathcal{G}(\mathcal{N}, \mathcal{L})$ representation of MHWN

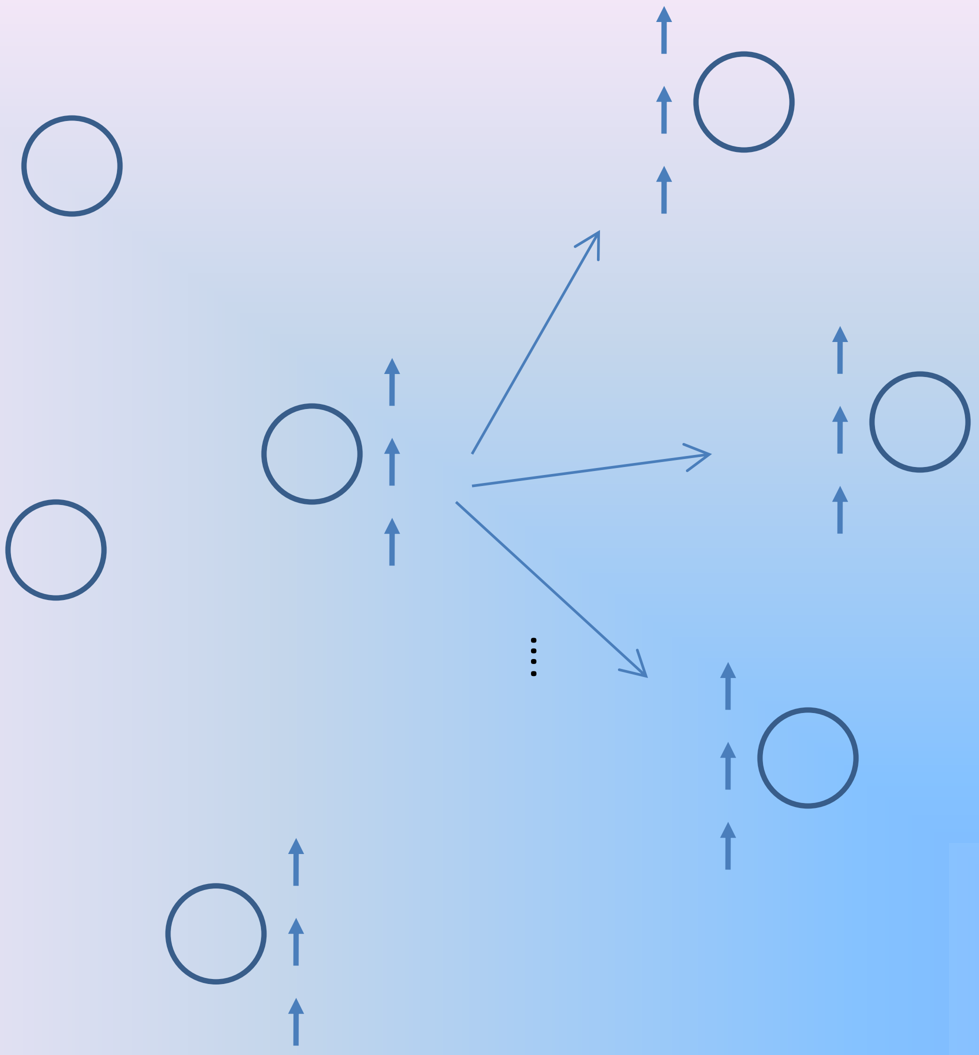
A MHWN, *…contd]*

- A Multihop wireless network is now represented as,
  - A di-graph : $\mathcal{G}(\mathcal{N},\mathcal{L})$ Fully connected and no self-loops.
  - Here, $\mathcal{L}$: The set of indexed links {1,2,…,L} and

    $\mathcal{N}$: is the set of indexed nodes {1,2,…, N}.
- All nodes are *half-duplex*.
- Nodes have *multiple antennas* being used both for transmission and reception.
- Every node which is active as a transmitter, *interferes* at all receiving nodes in the network. (Irrespective of the presence of a link)

The Joint Routing Scheduling and Power-control (JRSP) Problem in MHWN

- Routing VS Scheduling VS Power-control
  given that a set of source nodes want to transmit to destinations.
- All are interrelated problems in MHWN. In OSI model terms, it's a cross-layer optimization problem.
- Many authors have attempted to propose joint procedures to perform all the three simultaneously but most of the significant effort is for *<u>single</u>* antenna networks only.
- The network is not tractable to JRSP problem beyond a very limited number of nodes, with single antennas itself.
- `MIMO' in the network is not obvious, making the complexity manifold, though one can *<u>expect</u>* a good improvement in network performance.
- MIMO poses new challenges such as a feasible transmission model, capacity calculations and so on.



More degrees of freedom for transmission to each node, making the transmission model of the whole network non-obvious.

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The Notations and Terminology

- A number of nodes acquire data, act as data *sources* and want to transmit to their own choice of *destinations*.
- The problem is to simply provide a *fair* rate of transmission to all the sources towards their destination.
- All the respective (source, destination) ordered pairs will be called as *flows*, $f \in \mathcal{F}$, $\mathcal{F} = \{1,2,\ldots,F\}$.
- Transmission models chosen in our work are *P2P*, *MAC only*, *BC only* and *MAC+BC*. Many others models can be proposed. It inspires from a traditional *multi-commodity flow* problem setup and adds new constraints.
- Time is slotted and power-allocation is discrete and chosen from a set of finite number of power-levels.

The routing, scheduling and power-control

- Each of Routing, Scheduling and Power-control can be modeled as constraints in an optimization problem.
- Routing implies choosing paths and conservation of data along those path. (i.e. in-flow = out-flow for all intermediate nodes)
- *Scheduling* provides how each of the links should act in each time slot.
- *Power control* says, the amount of power spent on a node should not exceed the average availability of power at any point of time.
- It turns out that, by defining entities called "*modes*", all of them are achieved *simultaneously* by simply deciding a specific set of modes and activating them in sequence in the system.

A Mode

- A mode is defined as an entity that tells what each link in the set $\mathcal{L}$ should do at an instant. i.e., it needs to tell us,

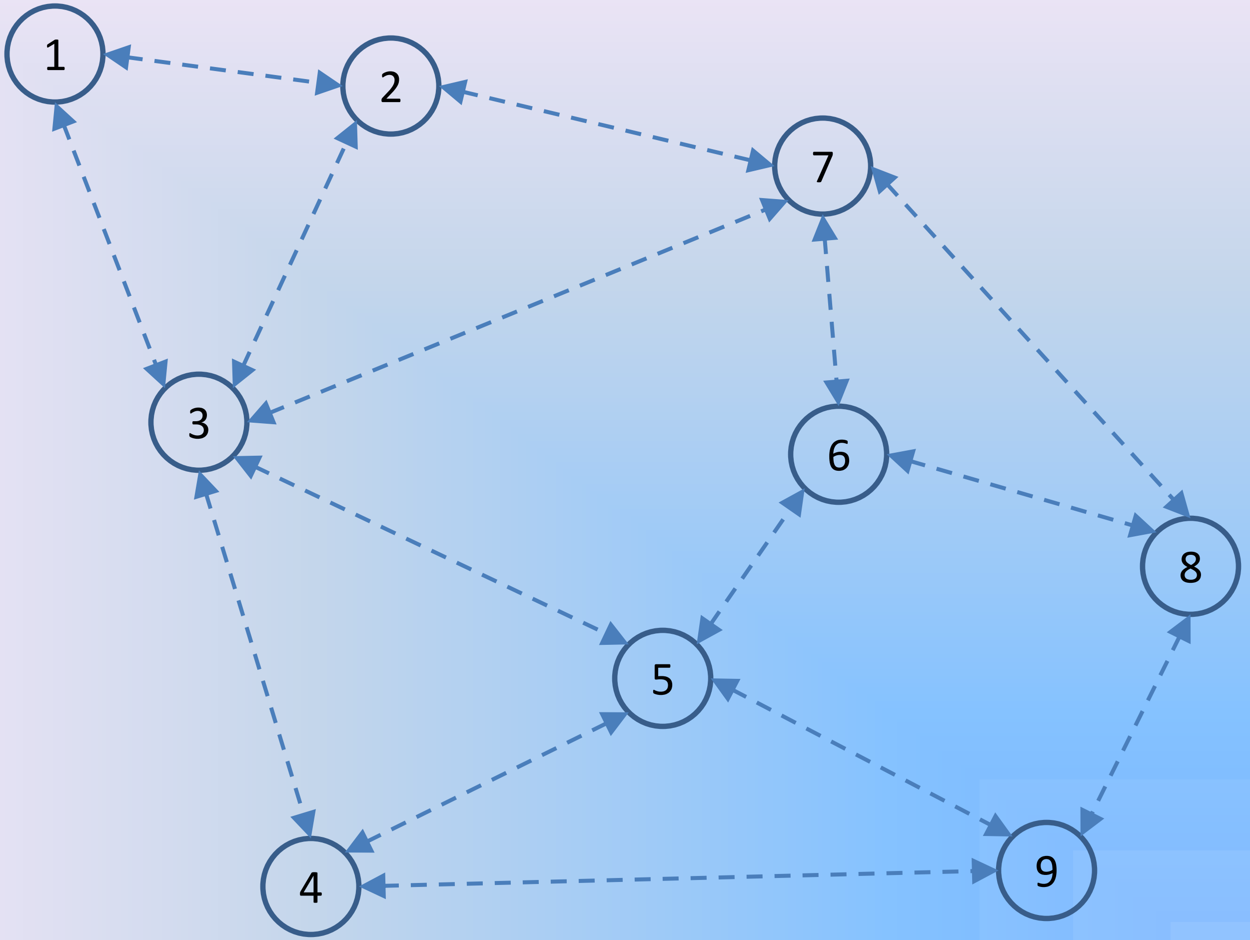
  "what subset of links should be active and how should they be active?"

- A *mode* is denoted as a vector of power values spent on each link. Hence, its an Lx1 vector, irrespective of number of antennas.
- An immediate question that arises is

  "What is the set of all possible modes in the network?"

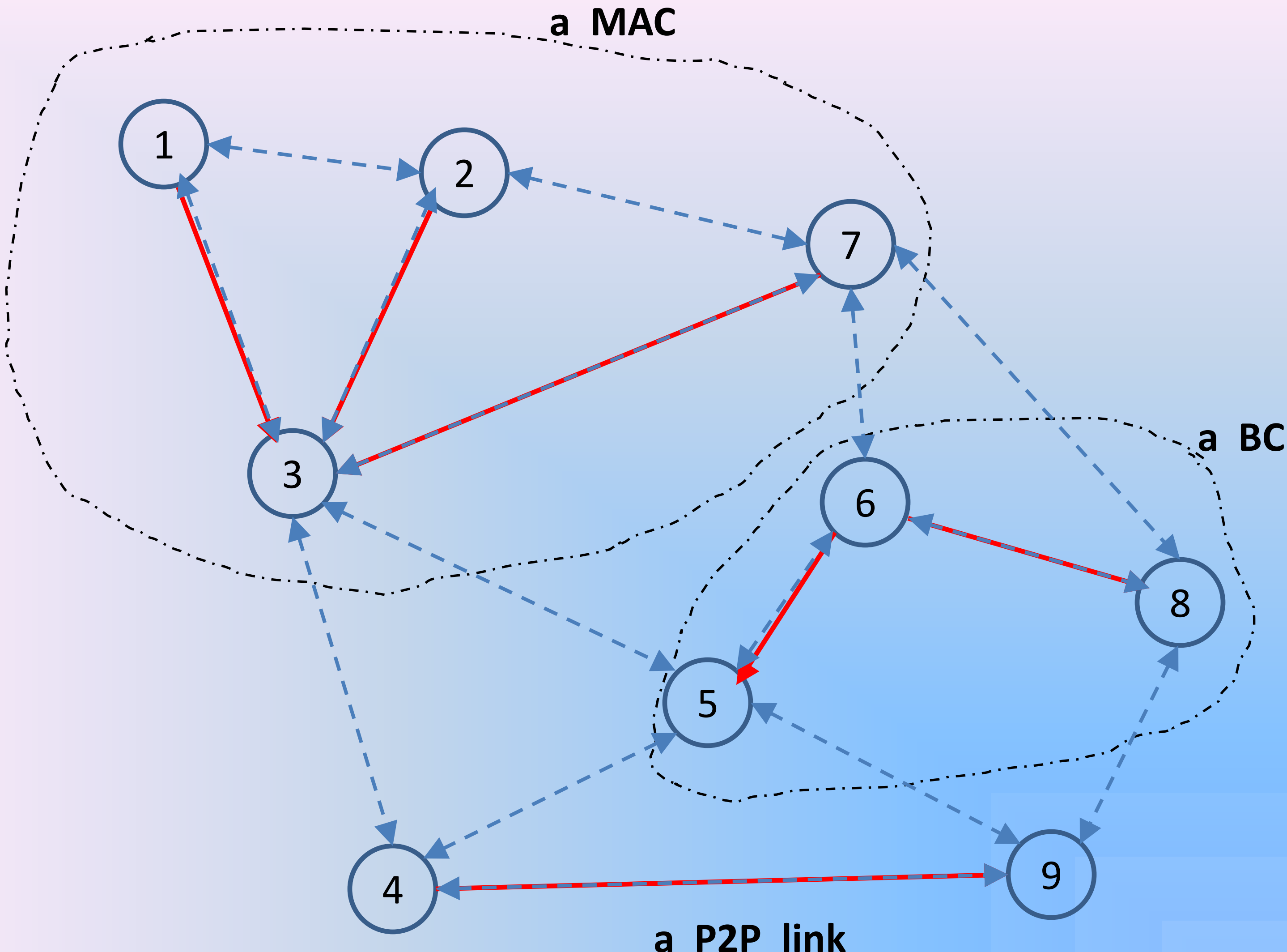
  so that, we can choose some modes and schedule them.

- Given the half-duplex and transmission model constraints, not all subsets but a sub-set of them can be considered as *modes*.
- For now, we assume that such a set is given to us. And call it $\mathcal{M} = \{ 1, 2, \dots, M \}$. Computational aspects of this set computation are discussed later.



Given a network as a graph

$\mathcal{G}(\mathcal{N},\mathcal{L})$



An example to a *mode* of the Graph $\mathcal{G}(\mathcal{N},\mathcal{L})$

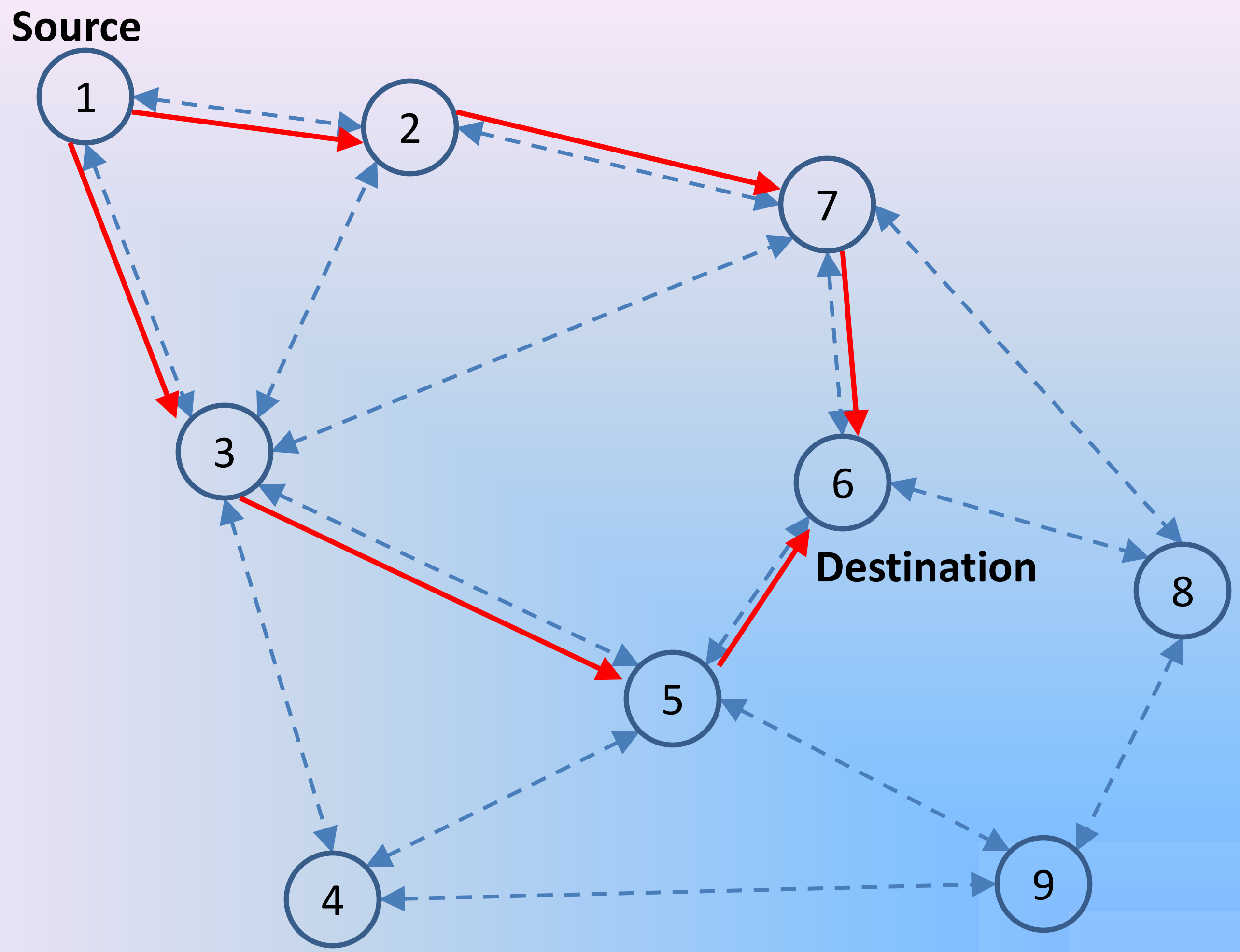


Illustration of functioning of *modes* in the network.

Scheduling using *modes*

- Given the total set of modes $\mathcal{M}$, just choose a scheduling vector $\underline{\alpha}$ representing the time fractions of each mode, so that the desired, *fair* rate of transmission is achieved from all sources to their respective destinations.
- Where, vector $\underline{\alpha}$ satisfies,

$$\underline{1}^T \underline{\alpha} = 1$$

Fairness

- If we decide user rates $\{r_1, r_2, \ldots, r_F\}$ based on the system analysis, while their demands are $\{d_1, d_2, \ldots, d_F\}$, we define *fairness* as

$$\lambda \triangleq \min_i \{\frac{r_i}{d_i}\}$$

- Our final objective is:

$$\max \ \lambda$$

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MATHEMATICAL FORMULATION

The problem in compact matrix notation

$$\max \left(\lambda \triangleq \min_i \left\{ \frac{r_i}{d_i} \right\} \right)$$

subject to:

$$AX = \mathbf{r} \,,$$ **Flow Conservation**

$$X \underline{1} \le C \underline{\alpha} \,,$$ **Capacity Constraints**

$$P \underline{\alpha} \le \underline{P}^{avg},$$ **Power Constraints**

$$\underline{\alpha} \cdot \underline{1} = 1 \,,$$ **Time consistency of Scheduling**

$$X_{lf} \ge 0, \ \forall f \in \mathcal{F}, \ \forall l \in \mathcal{L}$$

$$P_{nm} \ge 0, \alpha_m \ge 0, \ \forall n \in \mathcal{N}, \forall m \in \mathcal{M}$$

$$X = \begin{bmatrix} \underline{X}^1 & \underline{X}^2 & \cdots & \underline{X}^f & \cdots & \underline{X}^F \end{bmatrix} = \begin{pmatrix} X_{11} & X_{12} & \cdots & X_{1f} & \cdots & X_{1F} \\ X_{21} & X_{22} & \cdots & X_{2f} & \cdots & X_{2F} \\ \vdots & \vdots & & \vdots & & \vdots \\ X_{L1} & X_{L2} & \cdots & X_{Lf} & \cdots & X_{LF} \end{pmatrix}$$

$$C = \begin{bmatrix} \underline{C}^1 & \underline{C}^2 & \cdots & \underline{C}^m & \cdots & \underline{C}^M \end{bmatrix} = \begin{pmatrix} C_{11} & C_{12} & \cdots & C_{1m} & \cdots & C_{1M} \\ C_{21} & C_{22} & \cdots & C_{2m} & \cdots & C_{2M} \\ \vdots & \vdots & & \vdots & & \vdots \\ C_{L1} & C_{L2} & \cdots & C_{Lm} & \cdots & C_{LM} \end{pmatrix}$$

A is the node versus link incidence matrix representation of the graph

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r is a constant NxF matrix with values $\boldsymbol{r_{ij}}$ of *surplus* data-rate at a node -i for flow -j.

i.e. $\boldsymbol{r_{ij}}$ is ***positive*** if node-i is a source to flow-j, ***negative*** if node-i is a destination to flow-j and **zero** if node-i is an intermediate node to flow-j.

Comments on the problem statement

- Variables are X, $\underline{\alpha}$ and **r** (contains r_i' s)
- A, P, C are constants(matrices), once the set of all modes $\mathcal{M}$ is fixed.

- The problem finally chooses the best set of *modes* from $\mathcal{M}$ and *schedules* them obeying the power constraints and other sanity constraints, maximizing the *fairness*
- *It's a pure Linear Programming Problem (LPP).*

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The Problem Statement for MIMO

$$\max \lambda \triangleq \left(\min_i \left\{ \frac{r_i}{d_i} \right\} \right)$$

subject to:

$$AX = \mathbf{r} \ ,$$

$$X \cdot \underline{1} \leq C \cdot \underline{\alpha} \ ,$$

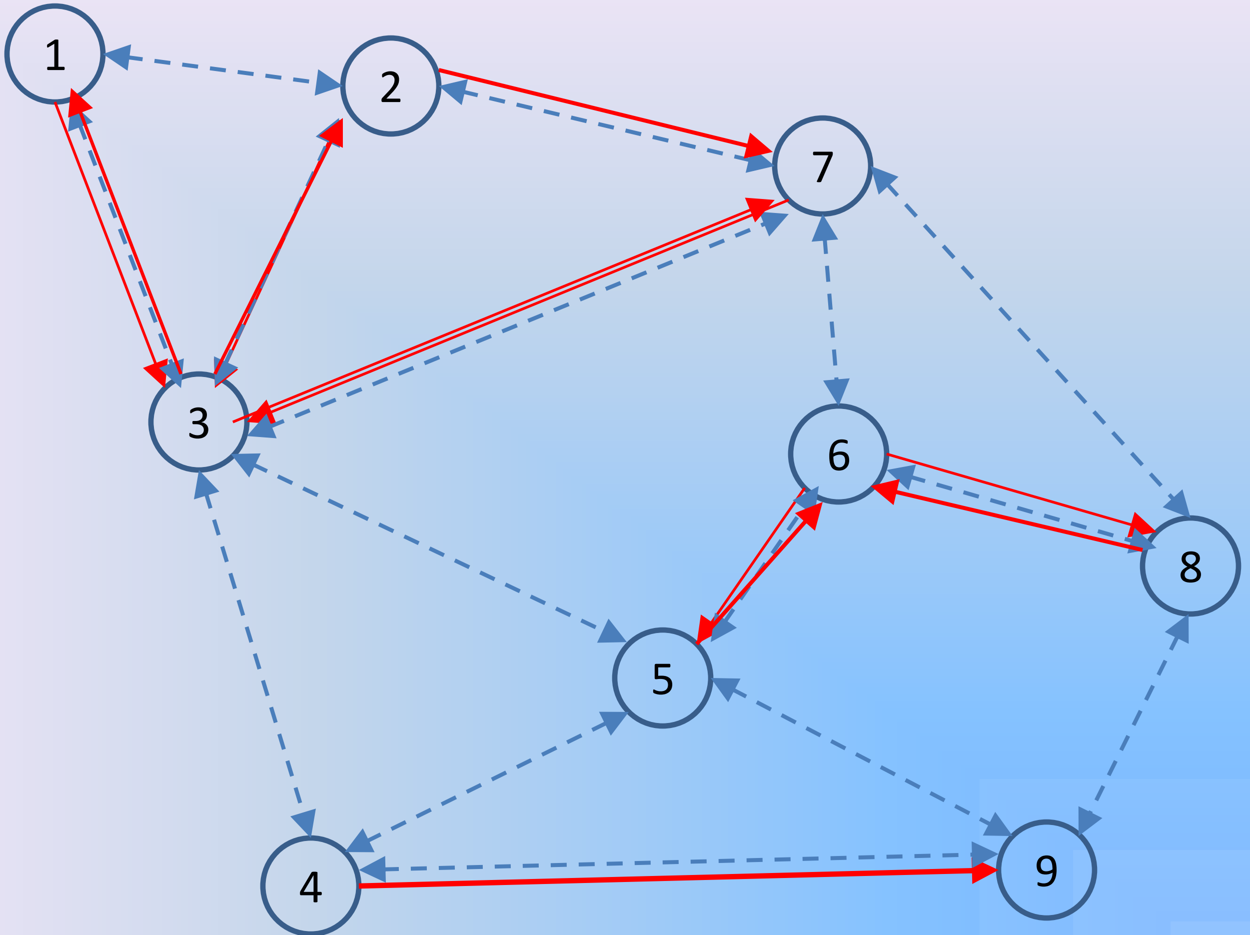
$$P \cdot \underline{\alpha} \leq \underline{P}^{avg} ,$$

$$\underline{\alpha} \cdot \underline{1} = 1 \ , \quad \textit{all} \text{ variables} \geq 0$$

- The problem statement is perfectly valid, but we need to define the set of *modes*, which is implied by the Transmission-Model.
- Feasibility of capacity calculations is a primary concern.

Transmission models

- We propose three possible models for transmission:
  - Point to Point – One node involves in one link only.
  - MAC only – A transmitter should transmit to only one node but a receiver can receive from multiple dedicated transmitters.
  - BC only – A transmitter may transmit to any number of its neighbors. But a node cannot receive from more than one node.
  - MAC+BC – Any node can transmit to or receive from multiple other nodes. But isolation is maintained between modules(MAC or BC). (no sharing of nodes between two modules)
- The sum-capacity calculations for such independent modules are available in literature. We make use of them.

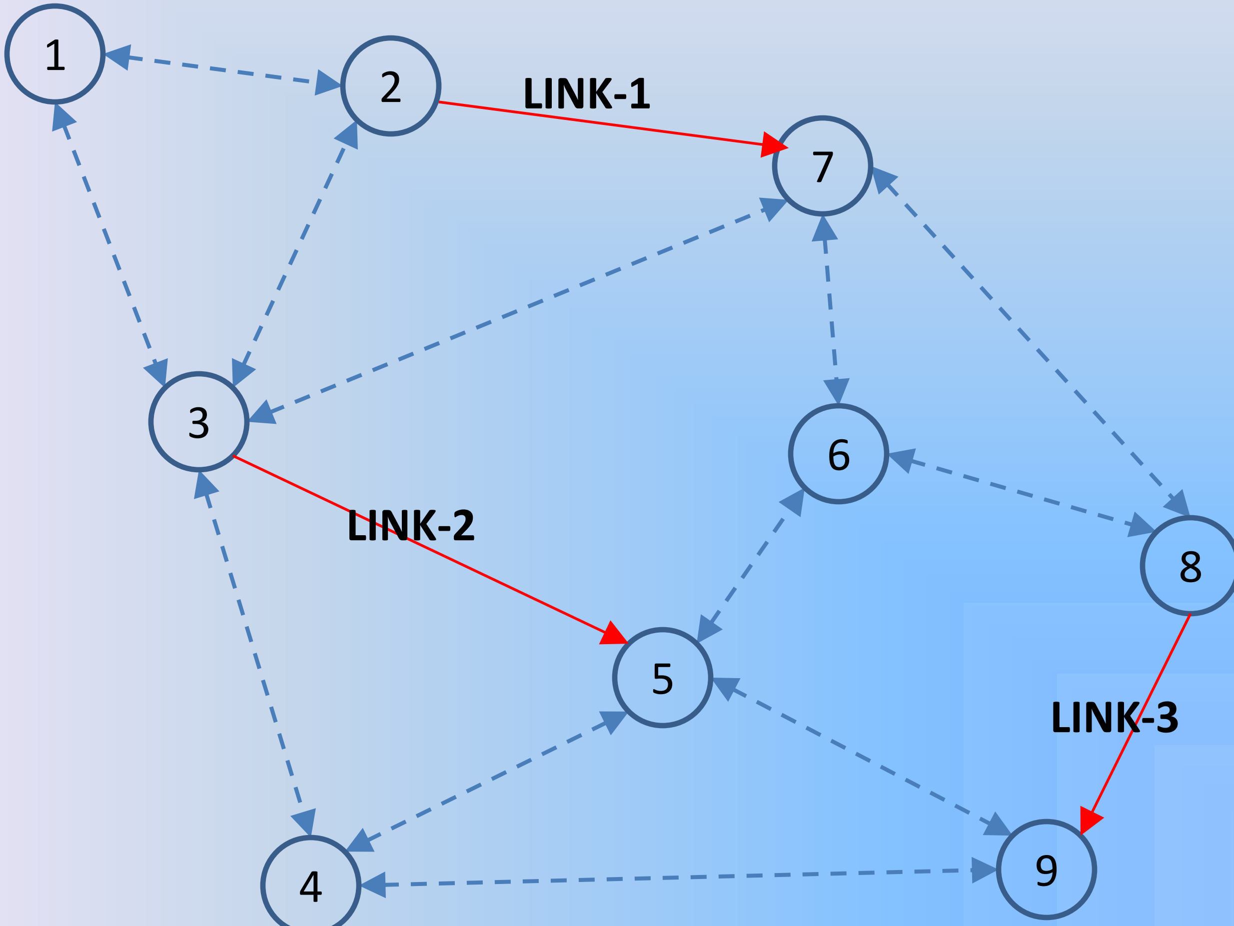


Illustrating Different Transmission Models

P2P Model

- We use SINR model for Capacity calculation of a link.
- We define the modes and their representation
- We give an iterative water-filling way to capacity calculation of a *mode*.
- Solve the problem for any number of antennas
- Demonstrate the linear gain in the throughput with number of antennas

Illustrating a link's capacity calculation under interference



How to find all link capacities simultaneously?

- Clearly, any link's capacity computation needs the knowledge of all other links.
- Let $f(\,.\,)$ denote rate function of all user co- variances(Capacity under fixed statistics). Hence maximizing it over all covariance matrices under trace constraint is water filling. It gives two outputs, namely covariance matrix and capacity.

$$[K_{x_1}^{opt}, C_1] = \max_{K_{x_1}} f_1(K_{x_1}, K_{x_2}, \ldots, K_{x_m})$$

$$[K_{x_2}^{opt}, C_2] = \max_{K_{x_2}} f_2(K_{x_1}, K_{x_2}, \ldots, K_{x_m})$$

$$\vdots$$

$$[K_{x_m}^{opt}, C_m] = \max_{K_{x_m}} f_m(K_{x_1}, K_{x_2}, \ldots, K_{x_m})$$

- It's a joint optimization problem, unknown overall objective.

An iterative algorithm to obtain capacities of links in a P2P mode

Algorithm 1 Iterative Waterfilling algorithm for finding link-capacities in a

initialize $sumrate \leftarrow -\infty$; $C_i = 0; K_i = (P_i/a) * I; \forall i = \{1, 2, \ldots, m\}$

while $|\sum_i C_i - sumrate| \geq \varepsilon$ **do**

$sumrate = \sum_i C_i$

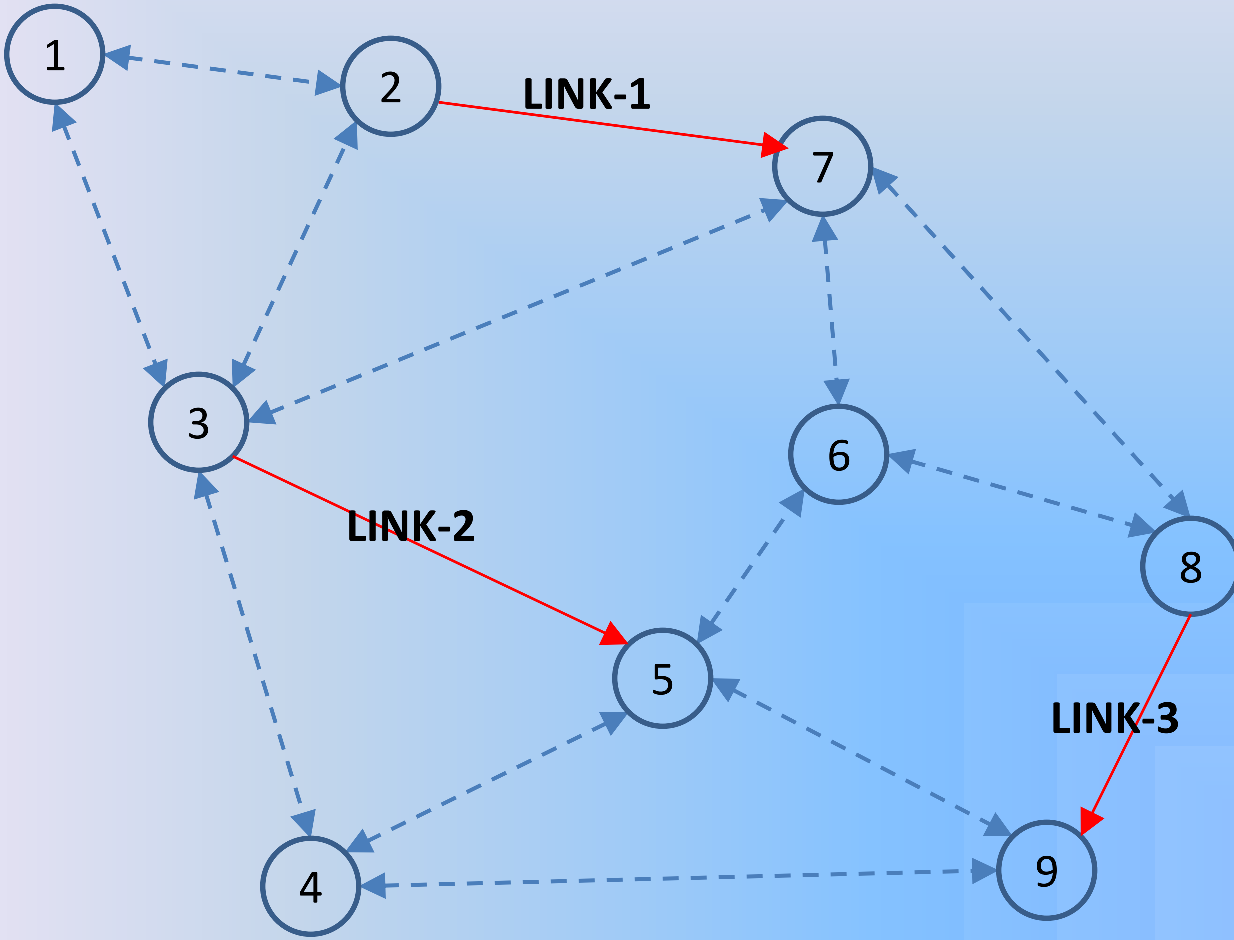
for $i = 1$ **to** m **do**

$[K_i, C_i] = \text{waterfill}(i; \sigma^2; \{K_j, H_{ji} \forall j\})$

end for

end while

Illustrating iterative capacity calculation of a P2P mode.



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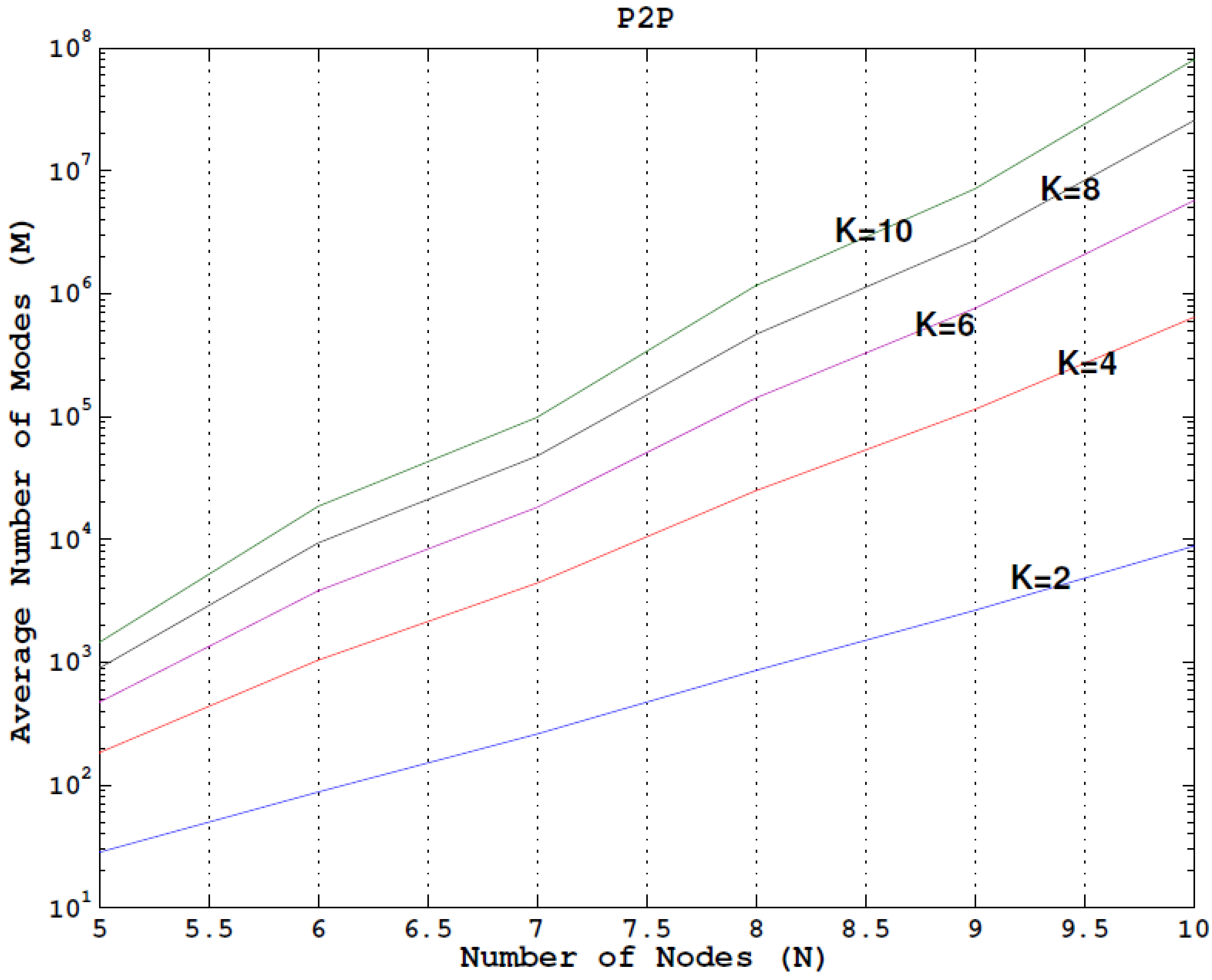
Complexity issue

- Number of constraints in the problem
  $= N(F+1) + L + 1$
  Number of variables in the problem
  $= (L+1)F + M$
- Here, N – number of nodes, L – number of Links
  F – number of flows, M – number of modes.
- The number of constraints is of $O(N^2)$, hence is not a bottle neck to go towards reasonably higher dimensional networks.
- The number of variables is limited by the number of modes M, where M is seen to be exponential in N. This forms the bottleneck in larger networks. (Typically M > 1million for N=11, and 4 power-levels).



P2P
Average Number of Modes (M)
Number of Nodes (N)
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
10
K=10
K=8
K=6
K=4
K=2

Issues with the JRSP problem

- The problem is a large-scale LPP, and not feasible to be solved for more than roughly 10 nodes.
- It is essential to have alternate techniques.
- Fortunately, this kind of problems exist in literature and are not completely new.
  E.g. Cutting stock problem.
- A popularly used technique for solving large scale LPPs is '*column generation*'. We attempt to use this.

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Column Generation

- A technique for used for a simplex problem with unusually fat coefficient matrix, that is not even storable.
  But it needs a useful structure among the variables.
- It’s a variant of revised-simplex procedure itself. i.e. It divides the problem into Master Problem and Sub-problem and solves at each iteration.
- But the sub-problem is the stage, where it gets modified as column-generation.

The Column Generation

Master Problem:

$$\max \lambda \triangleq \left(\min_i \left\{ \frac{r_i}{d_i} \right\} \right)$$

subject to:

$$AX = \mathbf{r} \ ,$$

$$X \cdot \underline{1} \ \le \ C'\underline{\alpha}' \ ,$$

$$P'.\underline{\alpha}' \ \le \ \underline{P}^{avg} ,$$

$$\underline{\alpha}'.\underline{1} = 1 \ , \ All\, are\, non-neg,$$

$$(except \ \ few \ of \ those\, in \ A)$$

Number of Variables equal to N+L+1 only. (Due to random subset $\mathcal{M}'$ replaces actual $\mathcal{M}$)

Sub Problem:
(Entering mode index)

$$j = \max_{i \in \mathcal{M} \setminus \mathcal{M}'} (\theta \triangleq \underline{u}^T C_i - \underline{v}^T \underline{m}_i - \beta \,)$$

$$subject\, to:$$

$$\theta \ge 0$$

m_i is the Lx1 mode vector and C_i is the capacity vector of i^{th} mode. Rest are dual variables

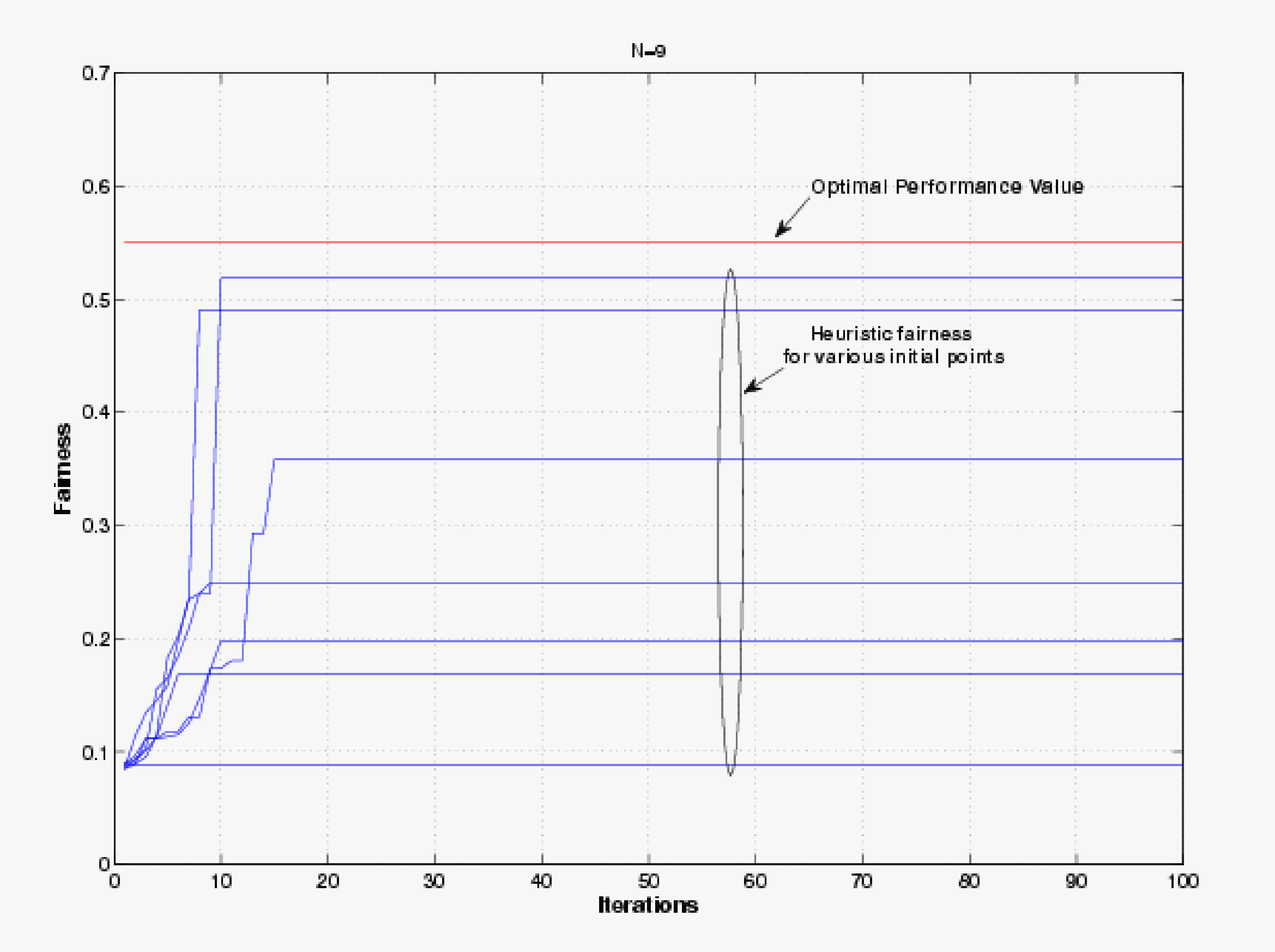
The Column Generation *…contd]*

- Unfortunately even the sub-problem needs an exhaustive search. Any structure among the set of 'modes' will help us in this case.
- Our JRSP has a sub-problem which cannot be converted into any simpler form using the structure among all the *modes*.
- A greedy *Heuristic* proposed by earlier works comes to our help in this case. We now call it as "Heuristic Column Generation".
- It is a simple greedy transition strategy, which starts from zero mode vector and gets to a non-zero mode vector in steps till the sub-problem's objective converges.

The Heuristic and its sub-optimality

- The Heuristic Column Generation starts by choosing a random set of modes as initial set and goes on improving over the solution. The convergence point is the final solution.
- The final performance given by the algorithm highly depends upon the initial point we start with.
- It is seen via simulations in the networks which can be solved directly for optimal solution, that the heuristic solution can be very close to the optimal.

N=9



Variation in final solution, when we choose different initial points, relative to the optimal solution

Modification to Heuristic Column Generation

- We propose to solve the problem for multiple initial points and choose the best solution.
- We use this method through out this report and call this as “Heuristic Column Gen”.

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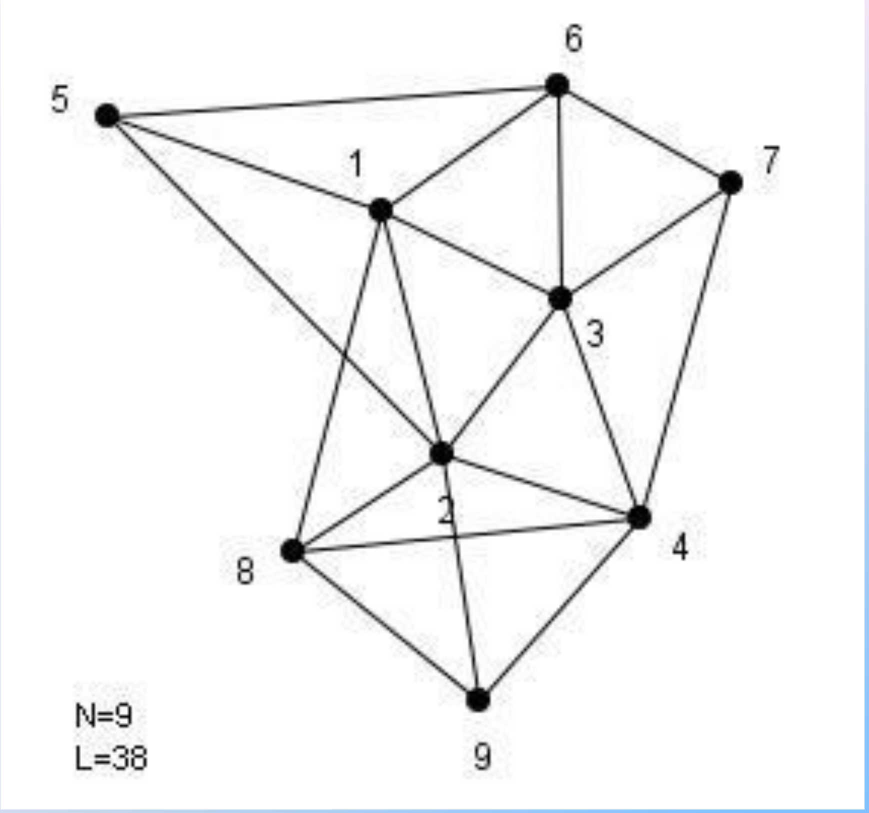
Solution to the problem with MIMO

- For less nodes, we solve the problem in both optimally and using our heuristic. This shows the validity of the algorithm
- For higher nodes, we solve just using *heuristic column generation* algorithm.
- We finally demonstrate the MIMO gain in performance both optimally and in heuristic performance terms.



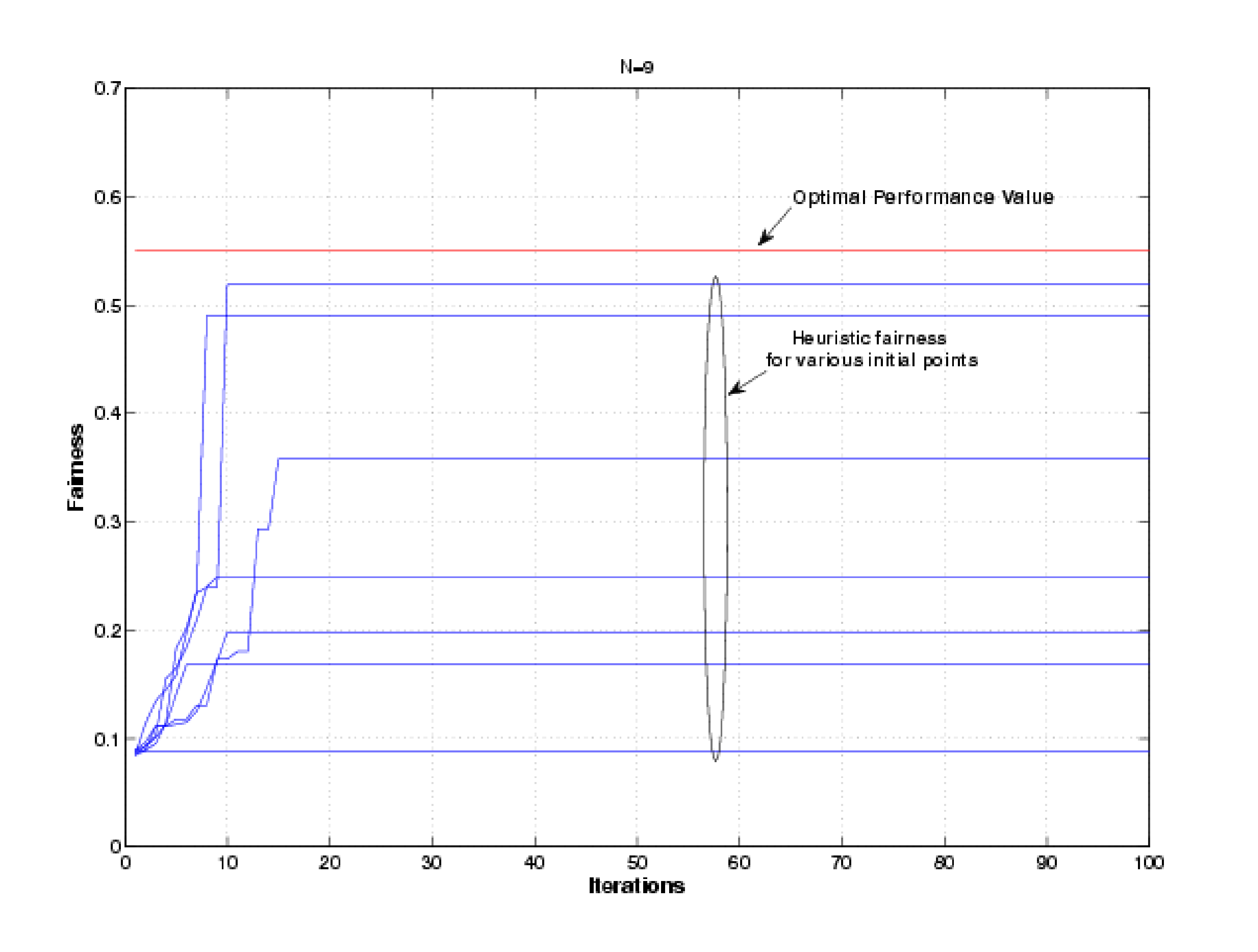
Number of antennas = 4

The average power constraints are : uniform power availability = 30mW.

The source-destination pairs are : (7,9),(1,4)

The desired rates for the pairs are: [10,40]bits/s/Hz

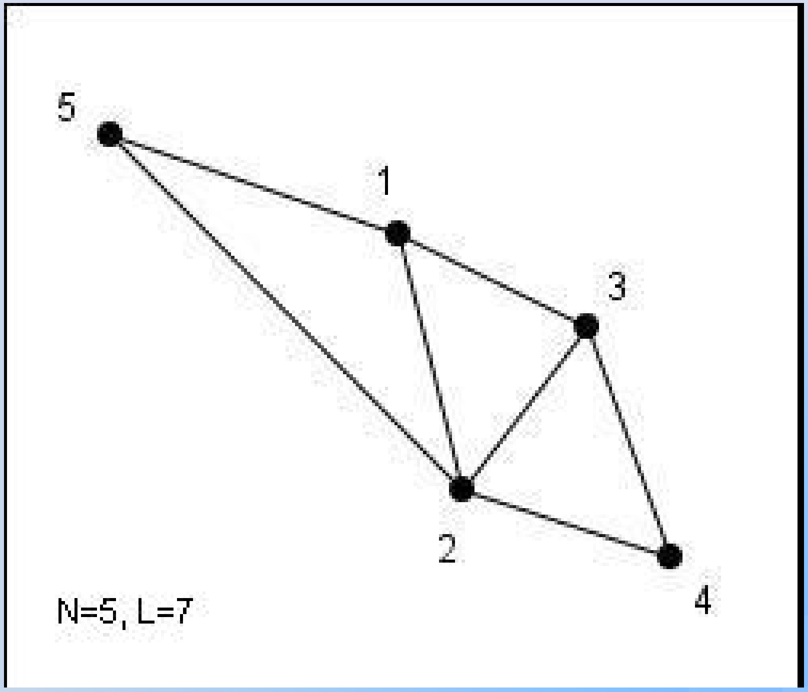
Solution to a network of 9 nodes



The MIMO gain

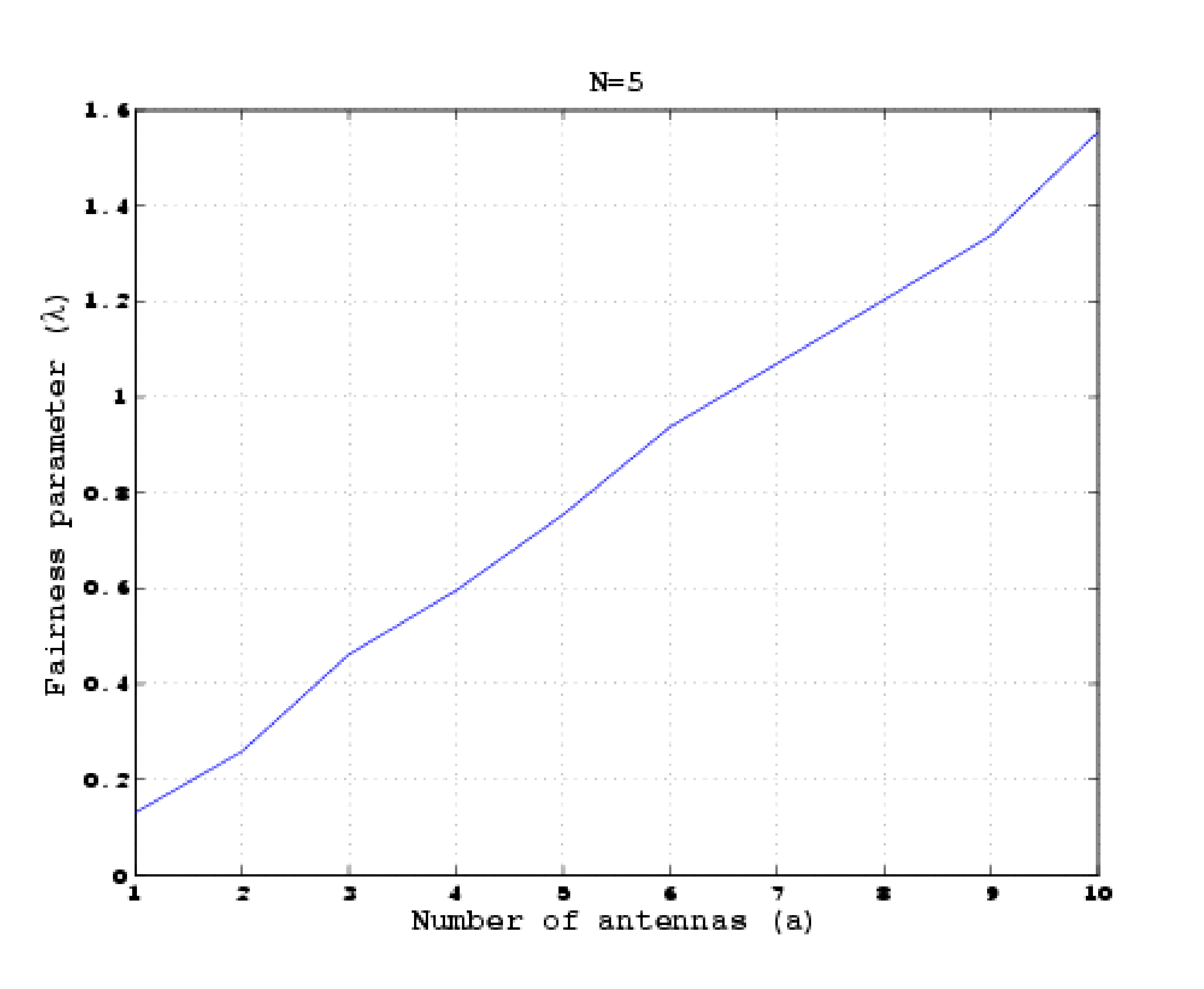
- We take two graphs of 5 and 8 nodes respectively.
- We fix the network parameters except the number of antennas (a) .
- We vary ‘a’ and observe the performance variation.

Optimal Performance Gain with MIMO N=5

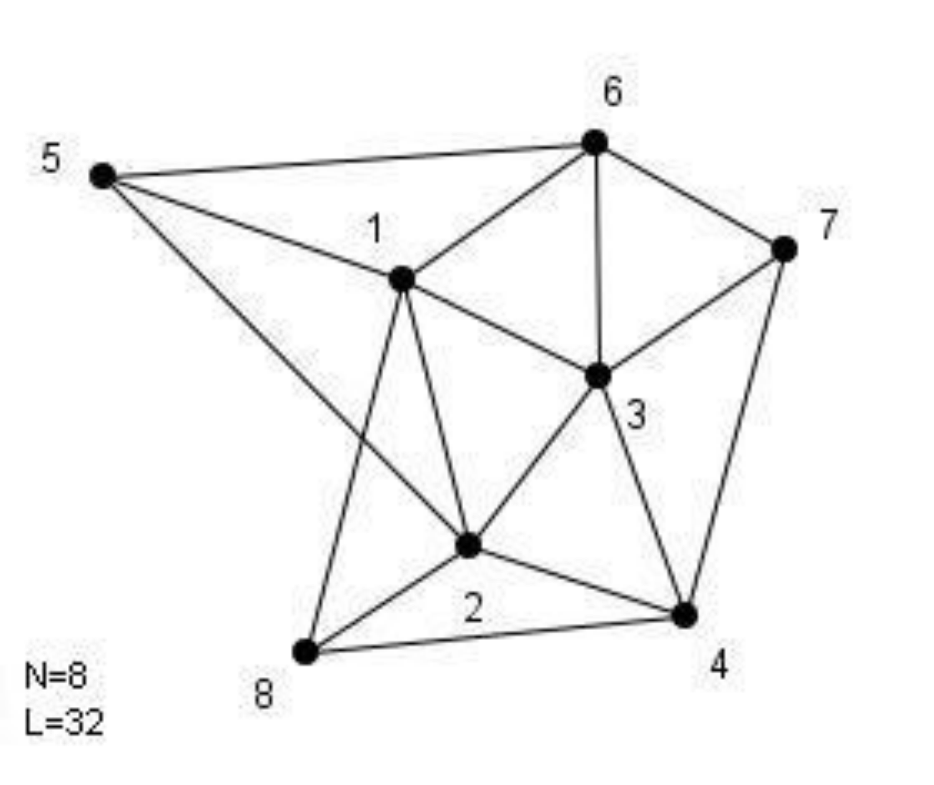


The average power constraints are : uniform power availability = 30units.
The source-destination pairs are : (3,5), (4,5)
The desired rates for the pairs are: [10,40] units

The MIMO gain for N=5

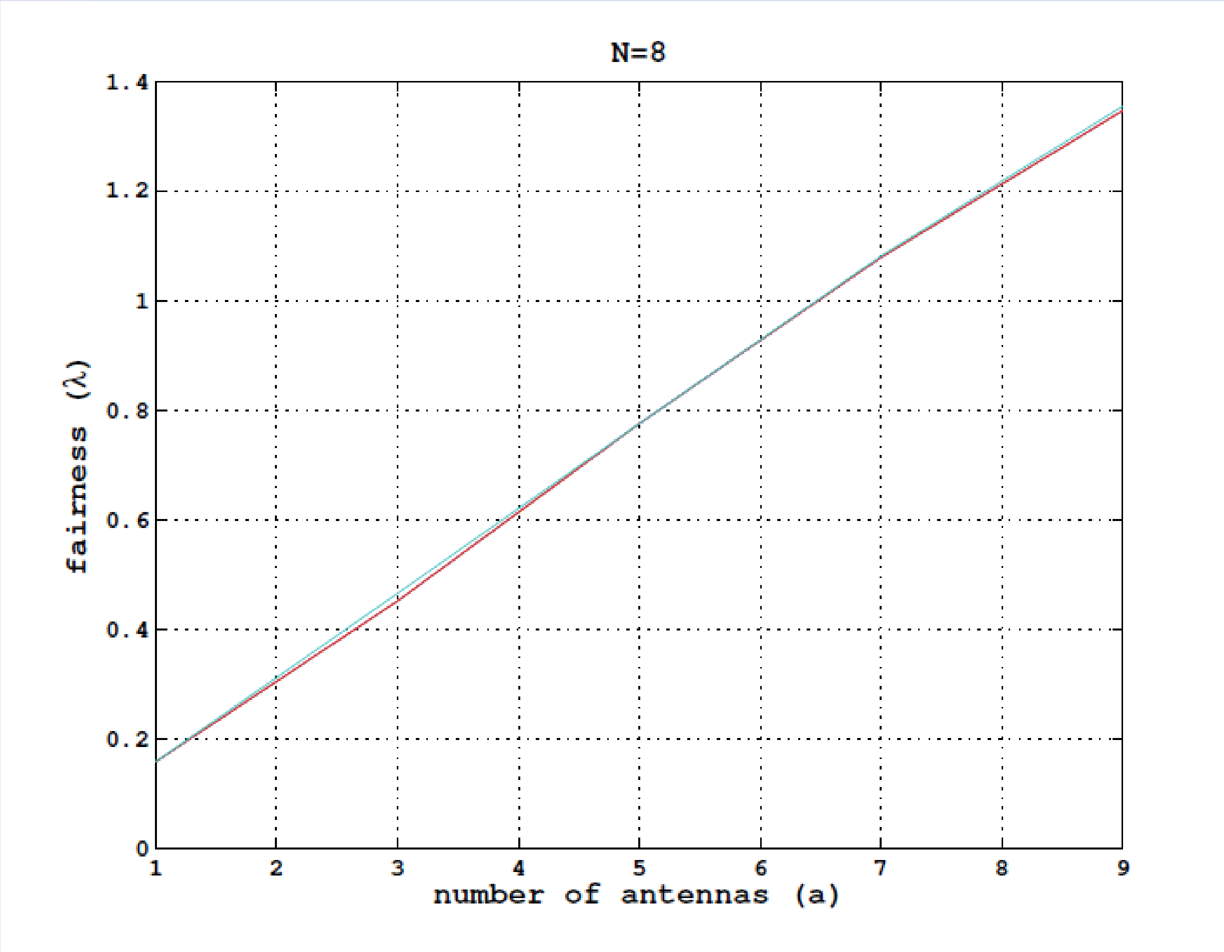


N=8

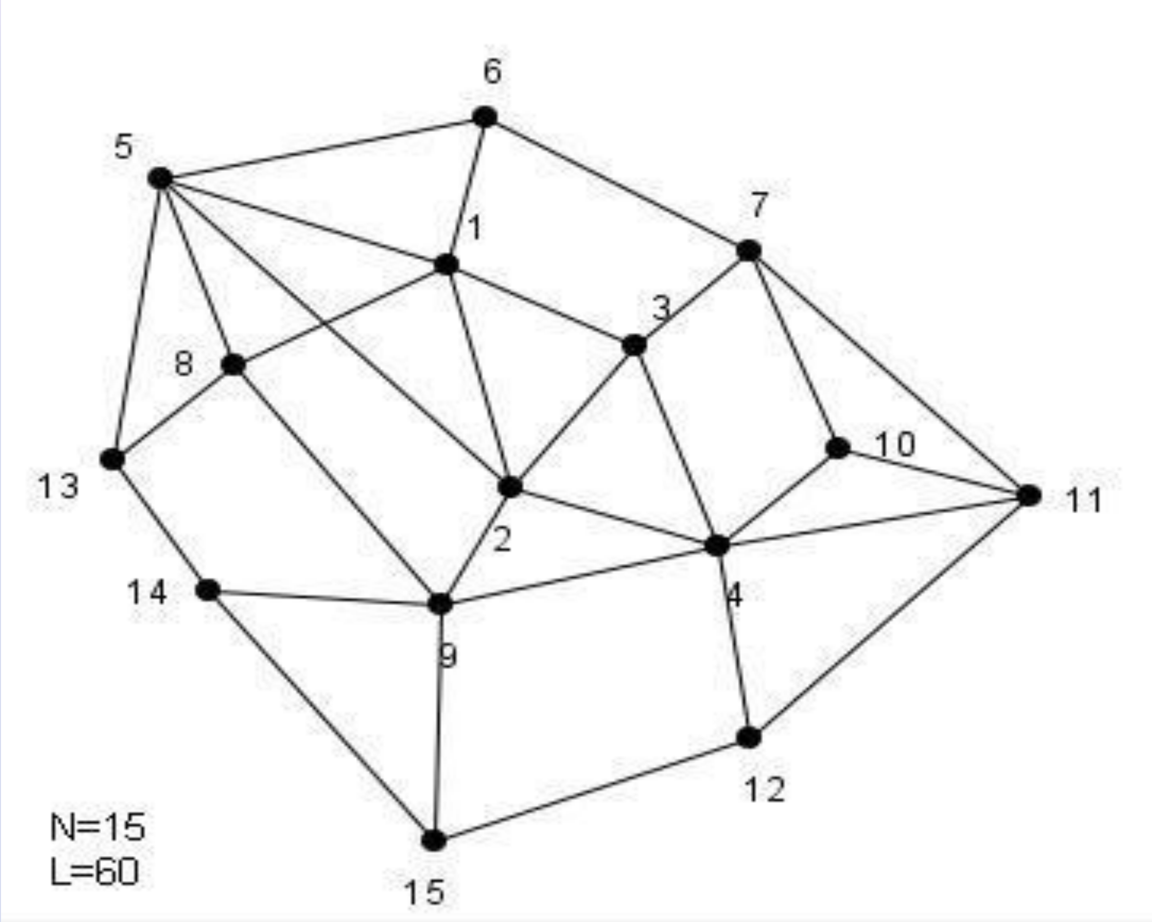


The average power constraints are : uniform power availability = 30 units.
The source-destination pairs are : (5,3), (8,7)
The desired rates for the pairs are: [10,40] units.

Optimal Performance Gain with MIMO N=8

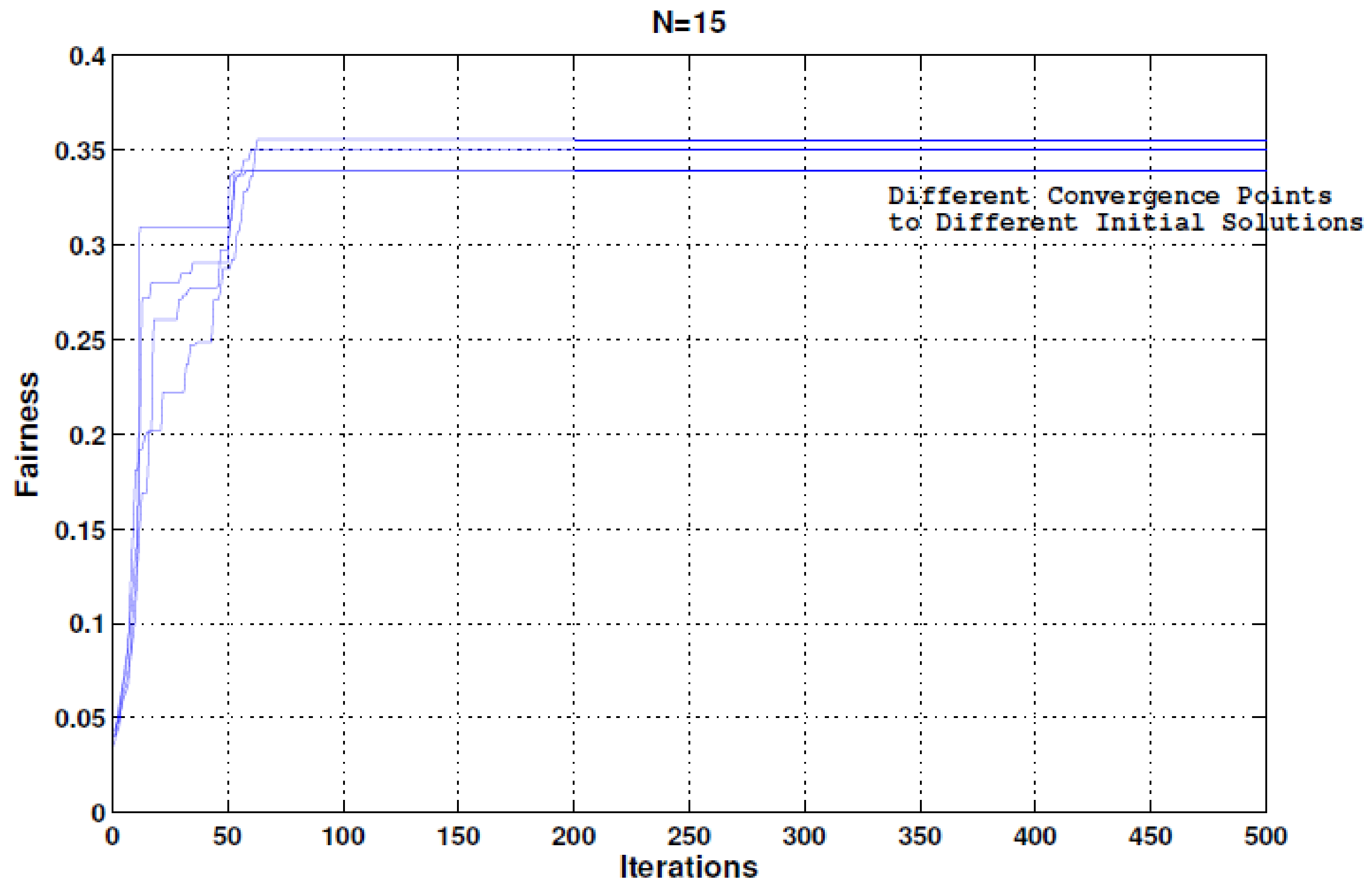


N=15

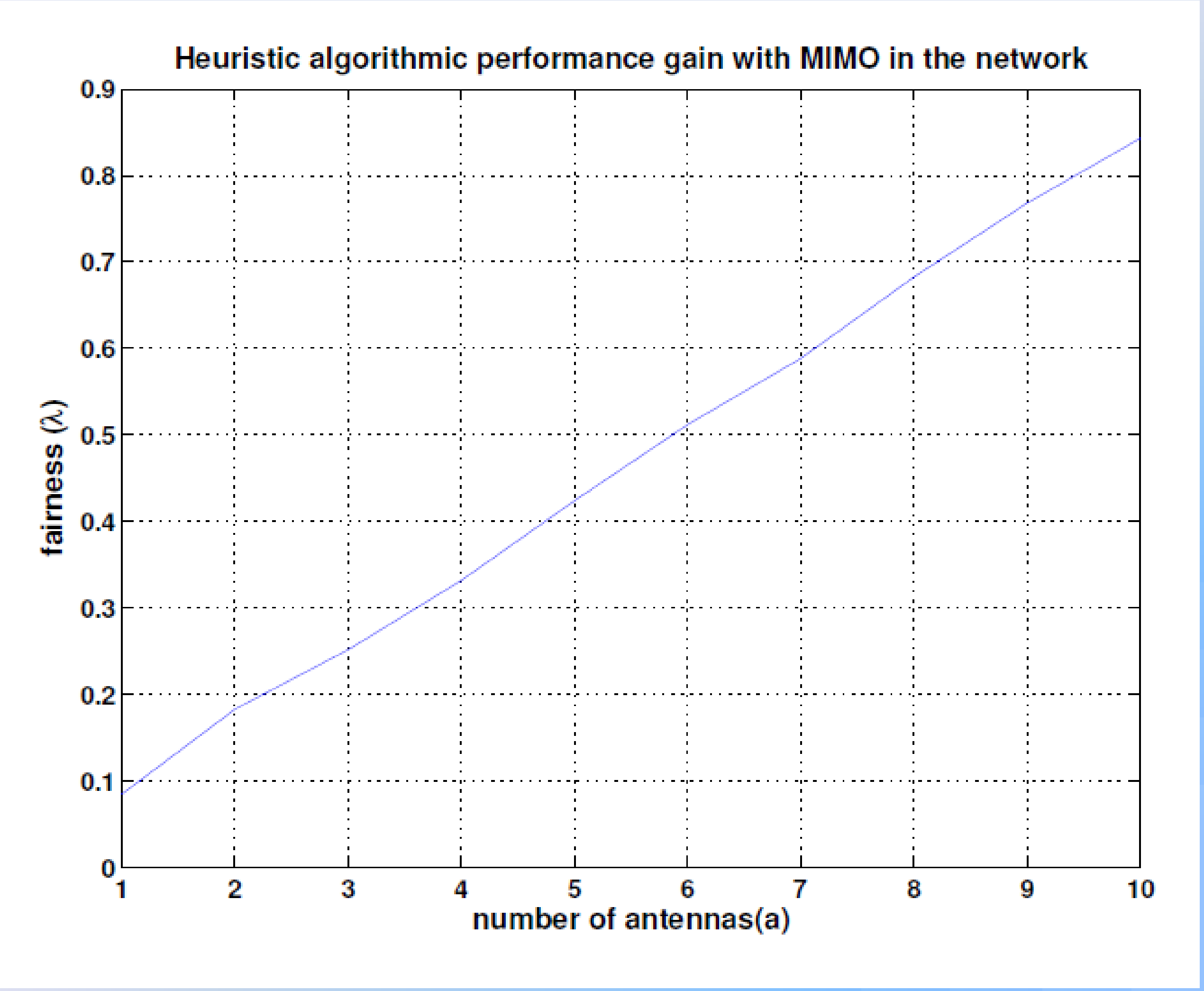


The parameters are :
Average powers: each node has uniform power availability = 3 units.
Source-destination pairs: (7,13), (10,5), (11,8), (12,6), (4,14)
Desired rates: [10,15,20,20,10] units

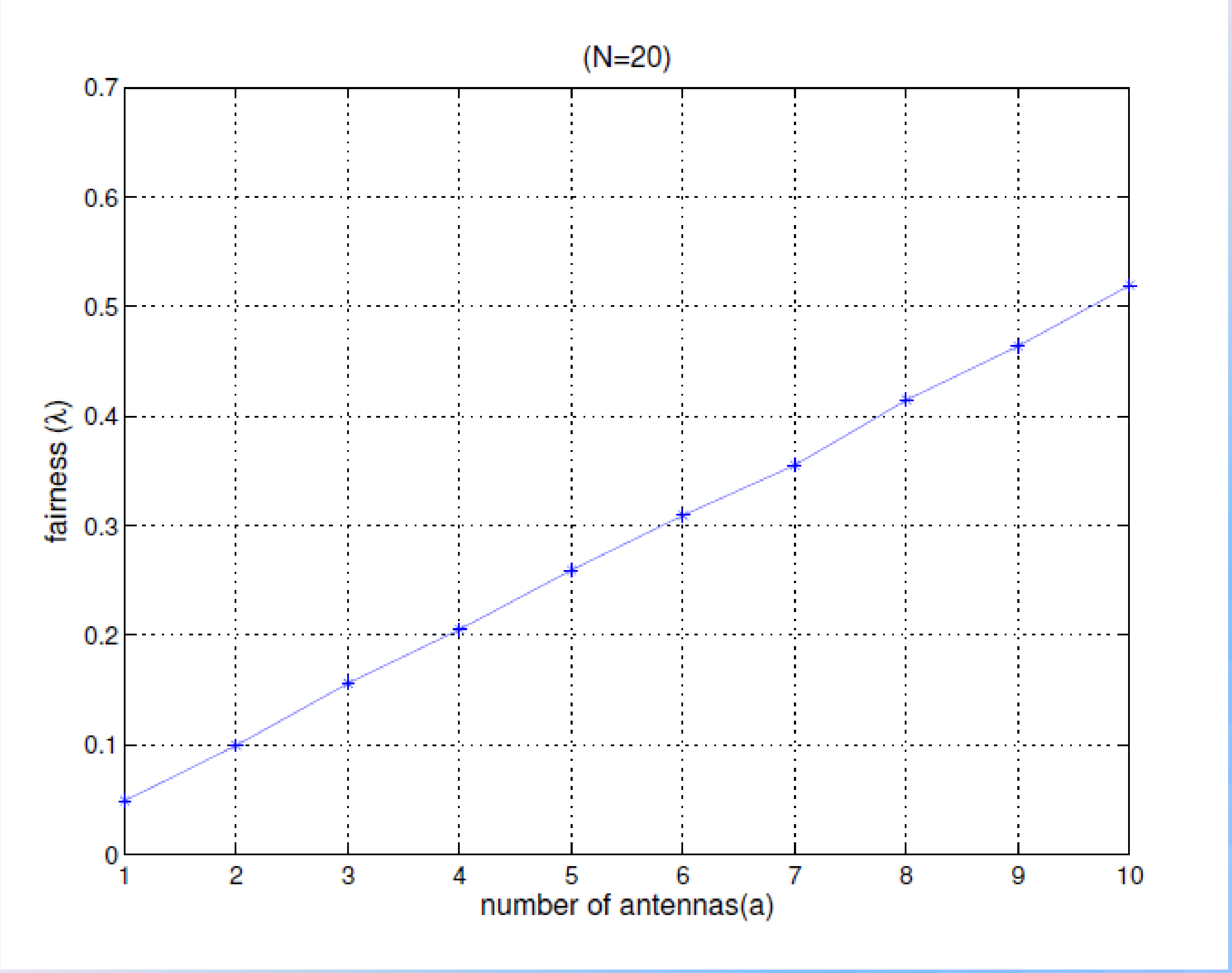
Heuristic Performance for N=15



Heuristic Performance Gain with MIMO N=15



N=20



(N=20)
fairness (λ)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10
number of antennas(a)

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Issues with MAC and BC in the system

- Total set of modes further increases.
- Apart, we don't know the capacity expressions of a MAC and BC in the interference environment.
- While a MAC's capacity region is well known, a vector-BC capacity region is still an open problem, under the simplest system model itself.
- But sum capacities of both these are known and simple iterative schemes are developed.
- We try to utilize the available iterative schemes under SINR model of capacity calculations.

Sum Capacity of a vector-MAC Iterative Water filling

Algorithm 2 Iterative Waterfilling algorithm for a vector Gaussian MAC

initialize $sumrate \leftarrow -\infty$; $C_i = 0; K_i = (P_i/a) * I$; $\forall i = \{1, 2, \ldots, n\}$

while $|\sum_i C_i - sumrate| \geq \varepsilon$ **do**

  for $i = 1$ **to** n **do**

    $N_{eff} = Z + \sum_{j \neq i} H_j * K_j * H_j^*$

    $[K_i, C_i] = \text{waterfill}(N_{eff}; H_i; K_i)$

  end for

  $sumrate = \sum_i C_i$

end while

Sum Capacity of a vector-BC Iterative Water filling, using Duality.

Algorithm 3 Iterative Waterfilling algorithm for a dual-MAC of a vector Gaussian BC

initialize $sumrate \leftarrow -\infty; \quad C_i = 0, M_i = (P_i/a) * I \quad \forall i = \{1, 2 \dots n\}$

while $|\sum_i C_i - sumrate| \geq \varepsilon$ **do**

  $sumrate = \sum_i C_i$

  for $i = 1$ **to** n **do**

    $H_i' = H_i Z^{-1/2}$

  end for

  for $i = 1$ **to** n **do**

    Generate effective channels $H_i^{eff} = H_i'(I + \sum_{j \neq i} H_j'^{*} K_j H_j')^{-1/2}$

  end for

  $S = \text{blockdiag}\{H_j^{eff}, j = 1, 2 \dots, n\}$

  $[T, C_{tot}] = \text{waterfill}(I; S; P_{BC})$, here $T \equiv \text{blockdiag}(\{T_i, i = 1, 2, \dots, n\})$.

  for $i = 1$ **to** n **do**

    $M_i \leftarrow \frac{(n-1)}{n} M_i + \frac{1}{n} T_i$ (The dual-MAC user covariances)

    $C_i \leftarrow \log |I + H_i^{eff*} N_i H_i^{eff}|$ (individual user rates in BC or dual-MAC)

  end for

end while

Conversion between co-variances of dual-MAC and BC

Algorithm 4 Transformation from covariance matrices of dual-MAC $\{M_i\}_i$ to its original BC $\{K_i\}_i$

for $i = 1$ **to** n **do**

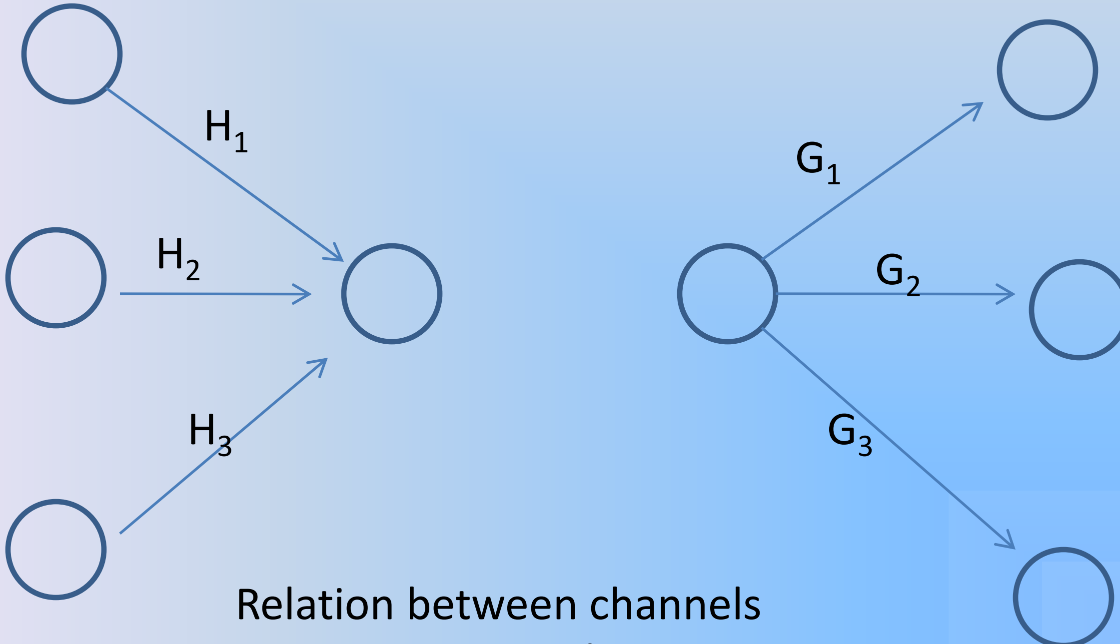
$A_i \triangleq \left(I + H_i \left(\sum_{j=1}^{i-1} K_j\right) H_i^*\right)$ *with* $A_1 \triangleq I$ and

$B_i \triangleq \left(I + \sum_{j=i+1}^{n} H_j^* M_j H_j\right)$ *with* $B_n \triangleq I$

$K_i = B_i^{-1/2} \overline{A_i^{1/2} M_i A_i^{1/2}} B_i^{-1/2}$

end for

Duality between a BC and a MAC



Relation between channels

$H_i = G_i^*$,

$n \sim \mathcal{N}(0,1)$, on each channel.

Total power used is same at transmission side of both modules

Algorithm 5 Iterative Waterfilling algorithm for finding link-capacities in a general m

Initialize $\mathscr{T}' = \mathscr{T}$. Initialize $sumrate \leftarrow -\inf$; $C_l = 0; K_i = (P_i/a) * I$; $\forall l \in \mathscr{L}$

while $|\sum_l C_l - sumrate| \geq \varepsilon$ **do**

  $sumrate = \sum_i C_i$

  for *each* $i \in T'$ **do**

    if $\mathrm{R}(i) = 1$ **then**

      Find the link $l \in \mathscr{L}$, and the receiver node $j \in \mathscr{N}$ attached to node-i.

      if $\mathrm{T}(j) = 1$ **then**

        Find effective noise+interference covariance at receiver node j,

        $K_{z_i} = \sigma^2 I + \sum_{t \in \mathscr{T}, t \neq i} H_{ti}^* K_t H_{ti}$

        $[C_l, K_i] = \text{waterfill}(K_{z_i}; H_{kj}; K_i)$

        $\mathscr{T}' = \mathscr{T}' \setminus \{i\}$

      else if $\mathrm{T}(j) > 1$ **then**

        Find all the transmitting nodes and links in the MAC to node j,

        call them $\mathscr{N}_{MAC} \subseteq \mathscr{N}$, $\mathscr{L}_{MAC} \subseteq \mathscr{L}$

        Find effective noise+interference covariance at node i,

        $K_{z_i} = \sigma^2 I + \sum_{t \in \mathscr{T} \setminus \mathscr{N}_{MAC}} H_{ti}^* K_i H_{ti}$

        $[\{K_n, n \in \mathscr{N}_{MAC}\}, \{C_l, l \in \mathscr{L}_{MAC}\}] =$

          $\text{MACSumCapacity}(K_{z_i}; \{H_{it}, t \in \mathscr{N}_{MAC}\}; \{m_t, t \in \mathscr{N}_{MAC}\})$

        set $\mathscr{T}' = \mathscr{T}' \setminus \mathscr{N}_{MAC}$

      end if

    else if $\mathrm{R}(i) > 1$ **then**

      Find all the receiver nodes and links in the BC from node-i,

      call them $\mathscr{N}_{BC} \subseteq \mathscr{N}$, $\mathscr{L}_{BC} \subseteq \mathscr{L}$

      Find effective noise+interference covariance,

      $K_{z_t} = \sigma^2 I + \sum_{w \in \mathscr{T}, n \neq i} H_{wt}^* K_i H_{wt}$, at each receiver $t \in \mathscr{N}_{BC}$

      $[\{K_{it}, t \in \mathscr{N}_{BC}\}, \{C_l, l \in \mathscr{L}_{BC}\}] =$

        $\text{BCSumCapacity}(K_{z_i}; \{H_{it}, t \in \mathscr{N}_{BC}\}; m_i)$

(user covariance

      Finally, $K_i = \sum_{t \in \mathscr{N}_{BC}} K_{it}$

(effective covariance matrix of tr

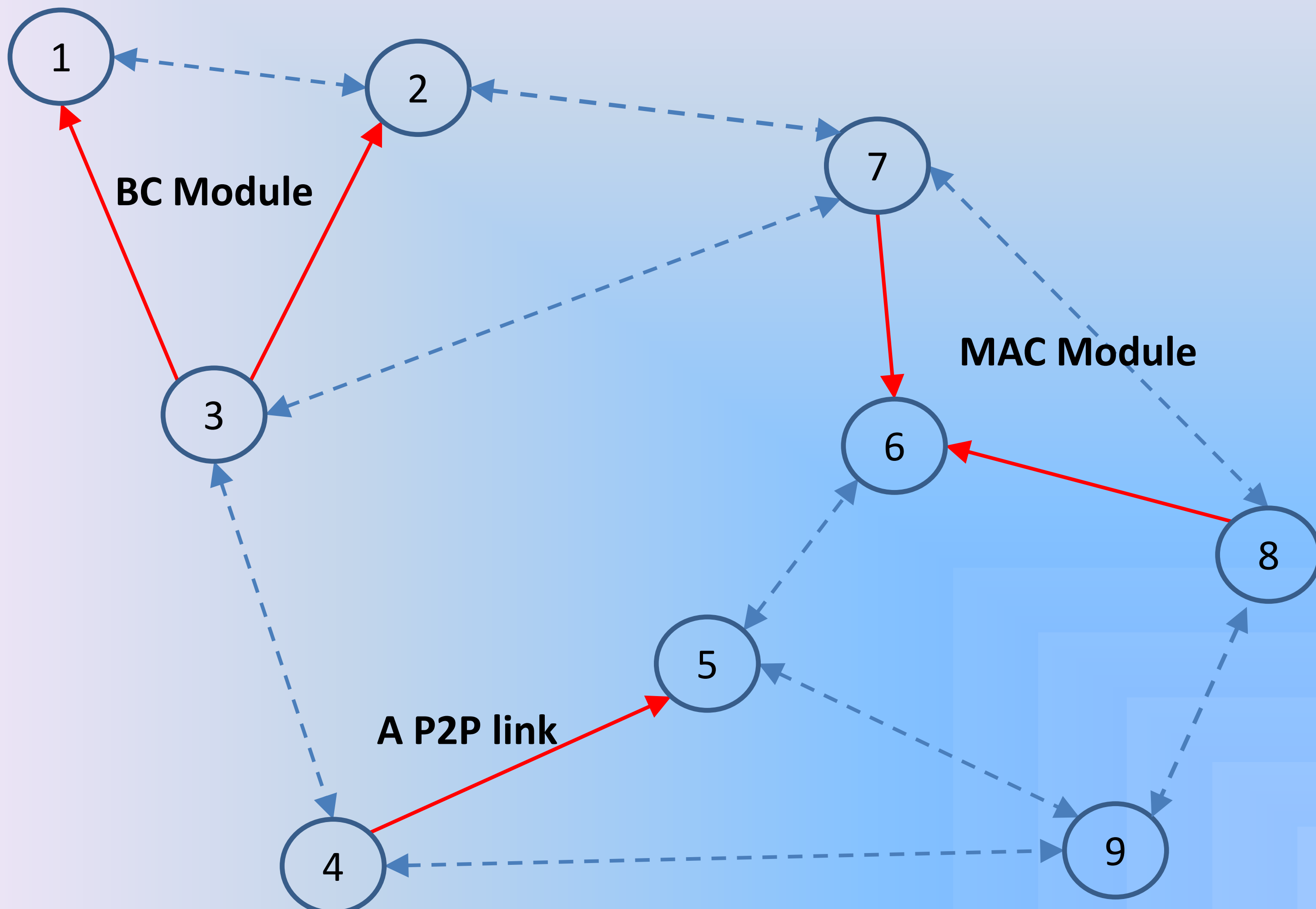
      set $\mathscr{T}' = \mathscr{T}' \setminus \{i\}$

    end if

  end for

end while

Illustration of capacity calculation of a mode with MAC & BC



Performance of MAC, BC transmission models

- Using the definitions of Mode and its capacity as shown, similar to p2p,
  - Smaller Networks: solved both optimally as well as heuristically.
  - Larger Networks: solved using Heuristic algorithm.
- Taking P2P model as a base-line, we try to see the performance improvement by using new transmission models, in both Heuristic and optimal sense.

Optimal Performance improvement in various Transmission models

No. of Nodes	P2P	MAC-only	% Gain over P2P	BC-only	%Gain over P2P	MAC+BC	%Gain over P2P
N=5	0.745	0.752	0.91%	0.746	0.00%	0.904	21.26%
	1.07	1.070	0.00%	1.075	0.48%	1.498	39.99%
N=6	0.772	0.810	4.87%	0.772	0.00%	1.139	47.45%
	1.083	1.090	0.62%	1.084	0.02%	1.584	46.16%
N=7	0.480	0.486	1.25%	0.480	0.00%	0.637	32.69%
	1.110	1.115	0.42%	1.115	0.41%	1.599	43.97%
N=8	0.735	0.723	-1.67%	0.736	0.00%	0.981	33.31%
	1.061	1.062	0.00%	1.065	0.29%	1.564	47.27%
N=9	0.550	0.577	4.80%	0.583	5.77%	1.108	101.18%
	1.123	1.124	0.00%	1.137	1.19%	1.581	40.68%

Heuristic Algorithmic Performance improvement in various Transmission models

No. of Nodes	P2P	MAC-only	% Gain over P2P	BC-only	%Gain over P2P	MAC+BC	%Gain over P2P
N=5	0.974	1.137	16.70%	1.137	16.70%	1.419	45.68%
	0.742	0.752	1.40%	0.742	0.00%	0.798	7.54%
N=6	0.575	0.575	0.00%	0.574	0.00%	0.745	29.75%
	1.013	1.009	-0.42%	1.014	0.00%	1.184	16.82%
N=8	0.523	0.574	9.56%	0.587	12.20%	0.703	34.38%
	1.057	1.081	2.20%	1.058	0.00%	1.210	14.40%
N=9	0.394	0.433	10.02%	0.483	22.48%	0.712	80.57%
	1.132	1.158	2.29%	1.132	0.00%	1.246	10.05%
N=10	0.418	0.401	-4.00%	0.418	0.00%	0.540	29.21%
	0.181	0.180	-0.44%	0.181	0.00%	0.317	75.65%
N=15	0.356	0.364	2.36%	0.354	-0.56%	0.509	42.96%
	0.166	0.153	-8.05%	0.166	0.00%	0.327	96.39%
N=20	0.221	0.228	2.99%	0.2199	-0.50%	0.277	25.11%
	0.166	0.149	-10.01%	0.1527	-7.96%	0.222	33.94%

Outline of the Presentation

- ✓ Basic Introduction to the network
- ✓ Introduction to the problem
- ✓ General Problem formulation & application to MIMO
- ✓ Solution procedure – A *Heuristic* Column Generation algorithm.
- ✓ Simulations with P2P transmission model.
- ✓ New transmission models to improve the performance and simulation results.
- ✓ **Conclusions**

Conclusions

- In a MHWN with JRSP and with MIMO:
  - We have a feasible formulation for JRSP problem in MHWN with MIMO.
  - We have a feasible capacity computation in a mode.
  - We have extended a feasible heuristic algorithm for finding the solution (which works only with single antenna networks) to a network with MIMO.
  - We have proposed new transmission models to improve the performance.
  - We have demonstrated the MIMO gains in the system in all Transmission models.
  - We have demonstrated the improvement in throughput by using new transmission models.
  - We have seen that, MAC,BC alone give a marginal gain in throughput while both together give substantial gains.

Thank you