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Dynamic Power Allocation and Routing for Time-Varying Wireless Networks

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OUTLINE

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- Problem formulation
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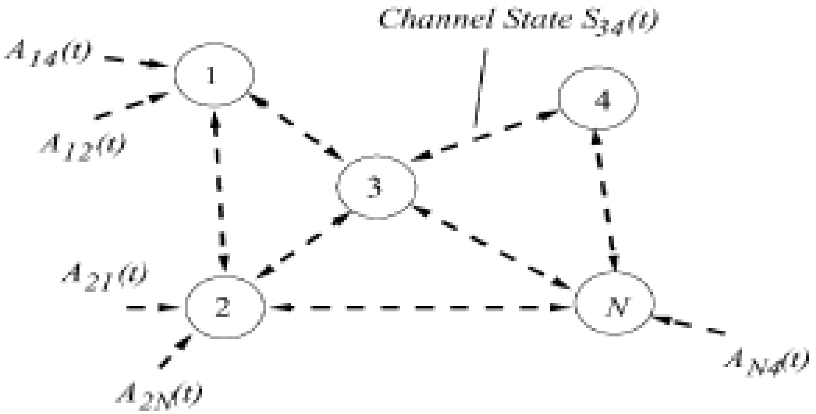
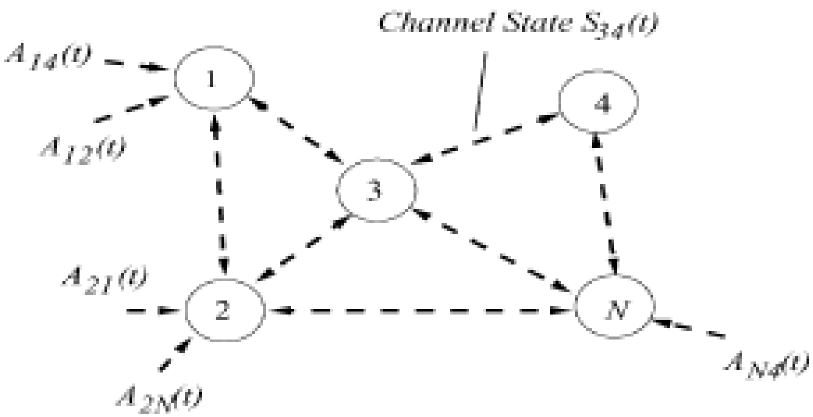
- Delay and Stability Analysis
- Distributed DRPC
- Simulation Results
- Multi Commodity Flows and Convex Duality
- Conclusion

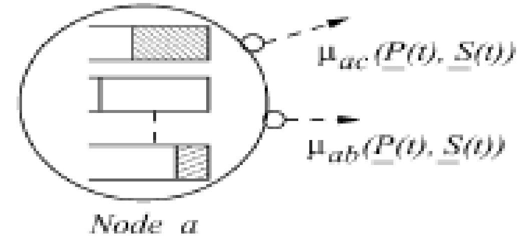
MOTIVATION

- In a wireless network, the nodes have limited power allocation.
- Essential to achieve maximum network capacity to support high speed voice and data services, under the power constraints present.
- Emerging microprocessor technologies help provide processing powers needed to implement adaptive coding techniques and to make intelligent routing decisions.
- Need for efficient network control algorithms.



SYSTEM MODEL





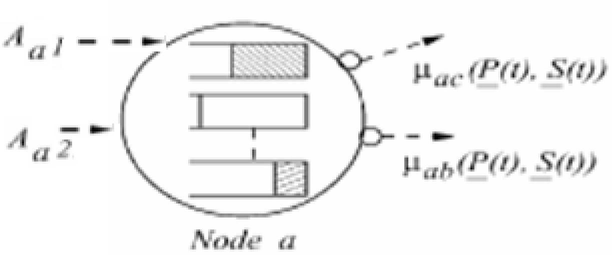
Power Constraint for Node a:

$$\sum_k P_{ak}(t) \leq P_a^{tot}$$

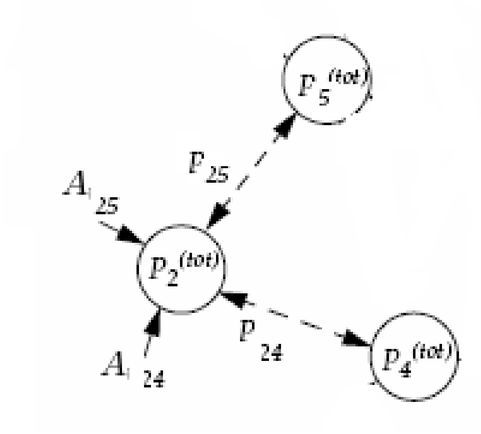
SYSTEM MODEL

- N number of nodes are considered in the topology
- Time is slotted, with slot length T
- Random Traffic (Markov Modulated, bursty, etc.)
- Incoming traffic to the network is defined by the rate matrices λ_{ij}, which can be stably supported by the system.
- Channel conditions $S_{ij}(t)$ of a link (i,j) change randomly every time slot, due to factors like fading, user mobility, time varying weather conditions.
- Each channel holds its state for the duration of time slot.
- Transmission rates for a each link determined by P(t) and S(t) according to a rate-power curve $\mu_{ij}(P(t), S(t))$.

- Data can be split continuously, so that in each time slot the transmission rate $\mu_{ab}(.)$ determines the number of bits that can be transferred over the wireless link (a,b).
- Each node contains N-1 internal queues for storing data according to its destination.
- $A_{ij}(t)$ represents the process of packets arriving to node *i* destined for node *j.*



- Nodes can transmit data over multiple links simultaneously by assigning power to the link for each node according to a power matrix $P(t)=(P_{ab}(t))$, subject to a total power constraint at each node.
- Assigned power to a link for each node pair (a,b) is $P_{ab}(t)$.

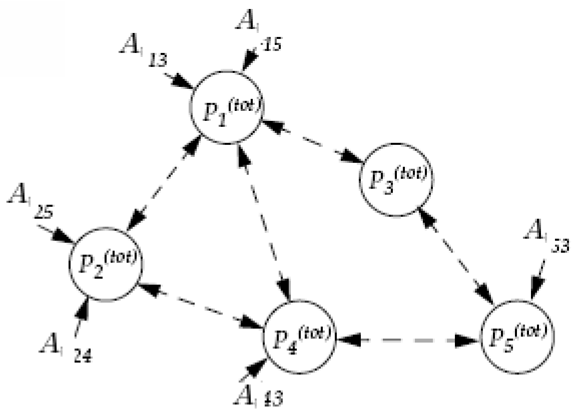


Power Constraint at node 2:

$P_{25}(t)+P_{24}(t) \leq P_2^{total}(t)$

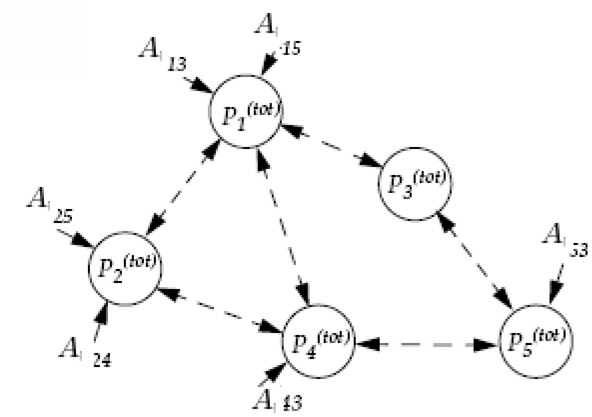
DYNAMIC CONTROL STRATEGY

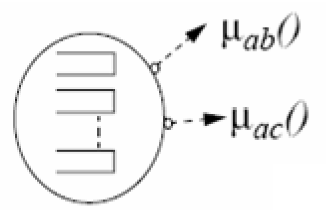
- Network controller provides the following functions in each time slot
  - Dynamic power allocation
  - Routing
  - Scheduling



- Goals:
  - Achieve system capacity with low delay
  - Maintain low backlog at output queues at each node and thereby provide system stability, given the rate matrix λ_{ic}, is within the network capacity region

- Network controller observes every time slot
  - U(t), amount of unfinished work matrix (at the queues)
  - S(t), channel state matrix

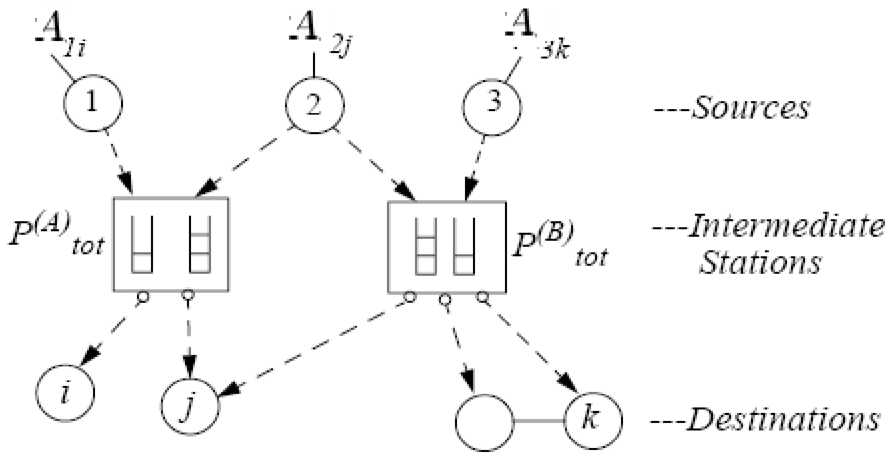




- Network controller decides
  - Power Allocation: Choose P(t) such that $P(t) \in \Pi$, where Π is the set of acceptable power levels
  - Routing/Scheduling: Choose $\mu^{(c)}_{ab}(t)$ such that $\Sigma\, \mu^{(c)}_{ab}(t) \leq \mu_{ab}(t) = \mu_{ab}(P(t), S(t))$
- The current backlog of bits at node *i* destined for node *c*, $U^{(c)}_{i}(t)$ must evolve according to the following queuing dynamics

$$U_i^{(c)}(t+1) \leq \max\left[U_i^{(c)}(t) - \sum_b \mu_{ib}^{(c)}(t), 0\right] + \sum_a \mu_{ai}^{(c)}(t) + A_i^{(c)}(t).$$

EXAMPLE



- Information known at slot t:
  - Channel State $S(t)=(S_{ai}(t), S_{aj}(t), S_{bj}(t), S_{bk}(t), S_{bz}(t))$
  - Unfinished work backlog $U(t)=(U_{ai}(t), U_{aj}(t), U_{bj}(t), U_{bk}(t), U_{bz}(t))$
- Routing: From which stations do we put packets from source 2?
- Power Allocation: For all time we are power constrained such that

$P_{ai}(t)+P_{aj}(t) < P_{tot}^{(a)}, \quad P_{bj}(t)+P_{bk}(t)+P_{bz}(t) < P_{tot}^{(b)}.$

- What is the capacity region of the network?

RATE-POWER CURVE

- Link Rates are determined by a corresponding rate-power curve $\mu(P(t), S(t)) = (\mu_{ab}(P(t), S(t)))$.
- Transmission rate over a link (a,b) of the network depends on the full matrix of power allocation decisions.
- Achievable data rates could be approximated using signal-to-interference ratio (SIR) over link (a,b).

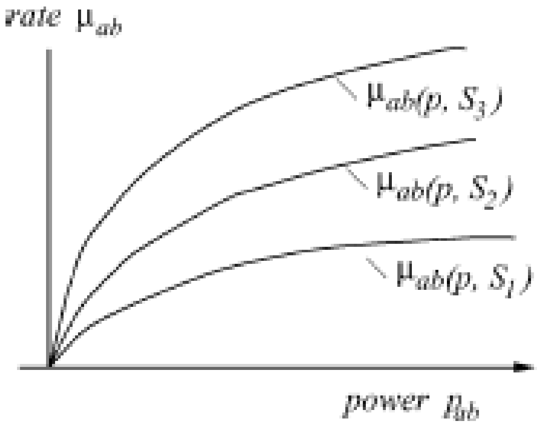
- Example:

$$\mu_{ab}(\underline{P}, \underline{S}) \triangleq \log\left(1 + \frac{\alpha_{ab} P_{ab}}{N_b + \alpha_{ab} \sum_{j \neq b} P_{aj} + \sum_{i \neq a} \alpha_{ib} \sum_j P_{ij}}\right)$$

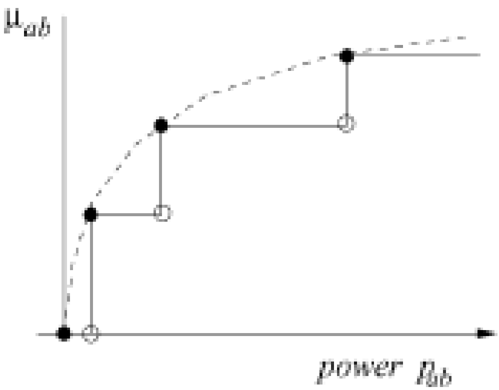
,where N_b and α_{ab} represent noise and fading coefficients associated with the particular channel state S.

- Rate-power curve for this example is a continuous curve.
- Rate-power curves could also represent rates for specific set of coding schemes.
- For such finite code sets, the rate-power curve is restricted to a finite set of feasible operating points, and hence are piece wise constant

RATE CURVES



(a)



(b)

CAPACITY REGION

- Capacity Region Λ is the closure of the set of all rate matrices λ_{ic} that can be stably supported over the network.
- Can also be defined as the set of input rate matrices (λ_{ic}) for which there exists Multi Commodity flow variables $\{f_{ab}^{(c)}\}$ satisfying

$$f_{ab}^{(c)} \geq 0, \quad f_{aa}^{(c)} = f_{ab}^{(a)} = 0 \quad \forall a, b, c$$

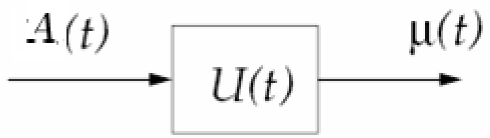
$$\lambda_{ic} \leq \sum_{b} f_{ib}^{(c)} - \sum_{a} f_{ai}^{(c)} \quad \forall i, c \quad \text{where } i \neq c$$

$$\sum_{c} f_{ab}^{(c)} \leq R_{ab} \quad \forall a, b, \quad \text{and for some } (R_{ab}) \in \Gamma.$$

- Rate constraint R_{ab} , is the long term transmission rates that the network can be configured to support on the single-hop wireless links connecting node pairs (a,b).
- The network is necessarily unstable if $\lambda_{ic} \notin \Lambda$.
- The network can be stabilized if λ_{ic} belongs to capacity region.

STABILITY

- Consider a queue with input process A(t) and a time varying server process μ(t).



  - A(t)=amount of bits that arrived in [0,t]
  - μ(t)=instantaneous processing rate
  - U(t)=Unfinished work in queue at time t
- Overflow function g(V) is given as

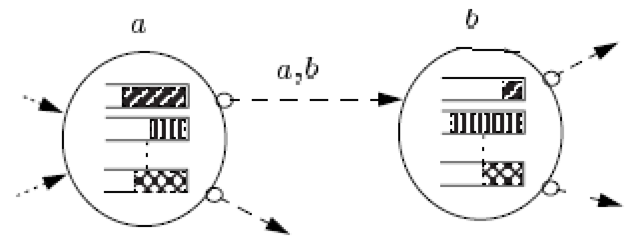
$$g(V) \triangleq \lim_{t\to\infty} \frac{1}{t}\sum_{\tau=0}^{t-1} \Pr[U(\tau) > V]$$

- A single server queuing system is stable if g(V)->0 as V->∞ A network of queues are stable if all individual queues are stable.

Dynamic Routing and Power Control (DRPC) policy

- For every time slot and for each link (a,b), find the commodity $C_{ab}(t)$, which has the highest differential backlog $U_a^{(c)}(t) - U_b^{(c)}(t)$

$$c_{ab}^*(t) = \arg \max_{c \in \{1,\dots,N\}} \left\{ U_a^{(c)}(t) - U_b^{(c)}(t) \right\}$$



- Define $W_{ab}^*(t) = \max \left[U_a^{(c_{ab}^*(t))}(t) - U_b^{(c_{ab}^*(t))}(t), 0 \right]$

- Route this commodity from a to b using the power allocation P(t), determined by

$$\text{maximize:} \quad \sum_{a,b} \mu(\underline{P}, \underline{S}(t)) \left[U_a^{c_{ab}^{**}}(t) - U_b^{c_{ab}^{**}}(t) \right]$$

$$\text{subject to:} \quad \sum_{b} P_{a,b} \leq P_a^{tot}$$

- Choose matrix P(t) such that

$$\underline{P}(t) = \arg\max_{\underline{P}\in\Pi} \sum_{a,b} \mu_{ab}(\underline{P}, \underline{S}(t)) W^*_{ab}(t)$$

- Define transmission rates as follows:

$$\mu_{ab}^{(c)}(t) = \begin{cases} \mu_{ab}(\underline{P}(t), \underline{S}(t)), & \text{if } c = c^*_{ab}(t) \quad \text{and } W^*_{ab}(t) > 0 \\ 0, & \text{otherwise} \end{cases}$$

- If any node does not have enough bits of a particular commodity to send over all its outgoing links requesting that commodity, null bits are delivered.
- Policy uses backpressure in an effort to equalize differential backlog.

STABILITY AND DELAY PERFORMANCE

- The DRPC algorithm stabilizes the system, given input arrival rates(λ_{ic}) are within the network capacity region, without requiring knowledge of the arrival processes or channel state.
- For a N node wireless network, DRPC policy stabilizes the system and guarantees bounded average congestion satisfying

$$\sum_{i,c} \overline{U_i^{(c)\mathrm{DRPC}}} \leq \frac{KBN}{\epsilon} + \frac{(K-1)\tilde{B}N}{\epsilon}$$

,where K is the convergence interval satisfying

$$\left| \lambda_{ic} - \frac{1}{K} \sum_{\tau=t_0}^{t_0+K-1} \mathbb{E}\left\{ A_i^{(c)}(\tau) \,|\, H(t_0) \right\} \right| \leq \delta$$

- B is given by

$$B \triangleq (A_{\max} + \mu_{\max}^{\mathrm{in}})^2 + (\mu_{\max}^{\mathrm{out}})^2$$
$$\tilde{B} \triangleq 2\max\left[\mu_{\max}^{\mathrm{out}}, \mu_{\max}^{\mathrm{in}}\right] (\mu_{\max}^{\mathrm{out}} + \mu_{\max}^{\mathrm{in}} + A_{\max})$$

- μ_{MAX}^{OUT} and μ_{MAX}^{IN}, are the maximum transmission rates out of any node and into any node, respectively.
- And, $$\overline{\sum_{i,c} U_i^{(c)}} \triangleq \limsup_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \left[\sum_{i,c} \mathbb{E}\left\{ U_i^{(c)}(\tau) \right\} \right]$$
- DRPC algorithm ensures delay guarantees, with bound given as $$\overline{D}_{\text{bit}} \leq \frac{KBN + (K-1)\tilde{B}N}{\epsilon N \lambda} = \frac{KBN + (K-1)\tilde{B}N}{\rho(1-\rho)R^2}$$
- Effective loading, ρ = λ/ R, λ is the input rate, R= λ+N∈
- The stability and the delay characteristics of the DRPC algorithm is proved using the Lyapunov Drift Analysis.

ENHANCED DRPC ALGORITHM

- The DRPC algorithm could give significant delay values for large systems when the network is lightly loaded.(ρ is small)
- Under light load conditions, very little information is contained in the differential backlog values, which could lead to packets taking false turns.
- Performance is improved by introducing a bias into the DRPC algorithm.
- Bias is introduced by defining $\tilde{W}_{ab}^{(c)} \triangleq \theta_a^c(U_a^c(t) + V_a^c) - \theta_b^c(U_b^c(t) + V_b^c)$
- In low loading conditions, the nodes are inclined to route the packets in the direction of their destinations.
- Power allocation and routing is done as in DRPC.

DISTRIBUTED APPROACH

- Users attempt to maximize weighted sum of data rates by exchanging information with their neighbors.
- For networks with independent channels, transmission rate on any link (a,b), depends only on local parameters

$$\mu_{ab}(\underline{P}, \underline{S}) = \mu_{ab}(P_{ab}, S_{ab})$$

- Such independent channels are possible when all links use orthogonal coding schemes, links are spatially separated.
- Each node makes independent power control and routing decisions based on their local information.
- Each node maximizes $\sum_b W^*_{nb}(t)\mu_{nb}(P_{nb}, S_{nb}(t))$ subject to constraints $\sum_{b \in \Omega_n(t)} P_{nb} \leq P^{\text{tot}}_n$

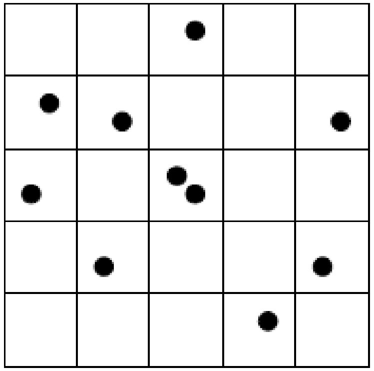
DISTRIBUTED APPROACH(2)

- For networks with interfering channels, a simple decentralized approach is used in which each node transmits with either zero power or total available power.
- Each node can only transmit to a single receiver.
- At beginning of each timeslot, each node randomly decides to transmit with probability q (at full power P_{tot}) or remain idle.
- A control signal of power γP_{tot} is transmitted.
- Each node measures its total interference $\gamma I_b \triangleq \gamma \sum_{i \in Q} \alpha_{ib} P_{\text{tot}}$, where Q is the set of all transmitting nodes
- Each node sends γI_b over a control channel to all its neighbors
- Using knowledge of the interference, attenuation, and queue backlogs of neighbors, user *a* transmits with full power to user *b* who maximizes the function.

$$W_{ab}^* \log\left(1 + \frac{\alpha_{ab} P_{\text{tot}}}{N_b + I_b - \alpha_{ab} P_{\text{tot}}}\right)$$

SIMULATION OF CENTRALISED AND DISTRIBUTED DRPC

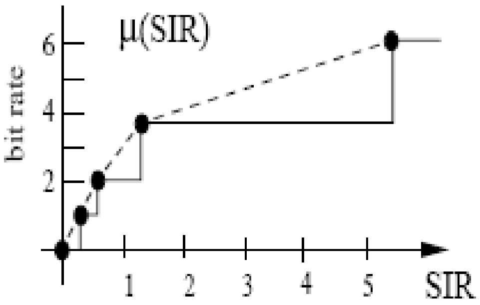
- For simulation of Distributed DRPC, a square network with 10 mobile users, with user locations distributed across 5 *5 grid, was used.
- Channel Model S(t): Each time slot, users stay in there location with a probability ½ and move to a adjacent cell with ½ probability.
- Attenuation model used was



$$\alpha_{ab} = \begin{cases} 1/[((x_a - x_b)^2 + (y_a - y_b)^2)^2 + 1], & \text{if } a \neq b \\ \infty, & \text{if } a = b \end{cases}$$

$$\mu_{ab}(\underline{P}, \underline{\alpha}) = f(\mathrm{SIR}_{ab}(\underline{P}, \underline{\alpha}))$$

modulation	bits/symbol	power/symbol
2 PAM	1	$0.25\Delta^2$
4 QAM	2	$0.5\Delta^2$
16 QAM	4	$1.25\Delta^2$
64 QAM	6	$5.25\Delta^2$



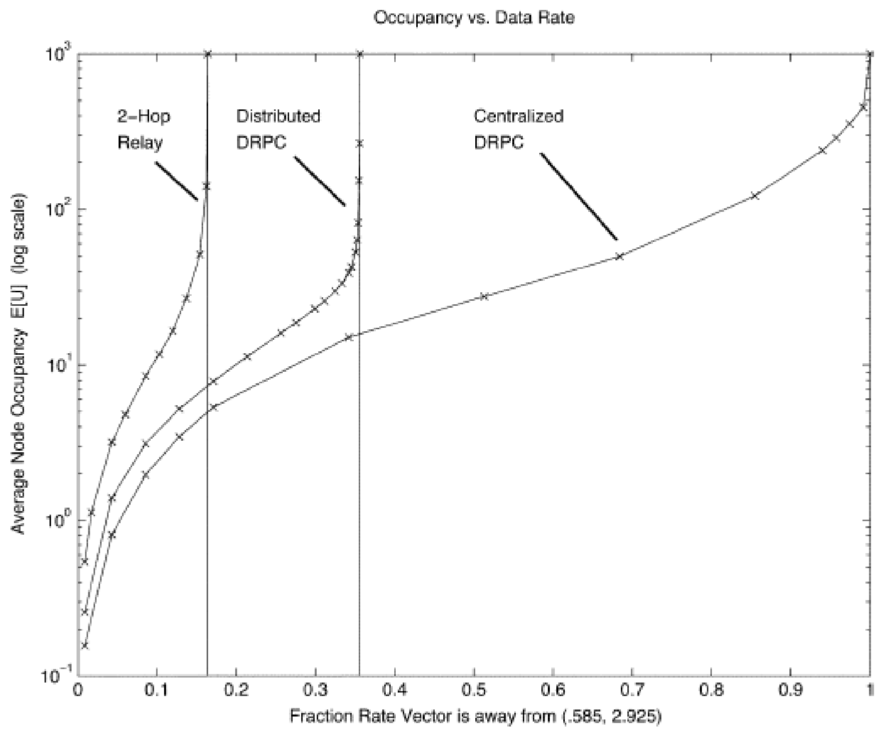
- For centralized implementation, the optimization problem

$$\text{maximize:} \quad \sum_{a,b} \mu(\underline{P}, \underline{S}(t)) \left[U_a^{C_{ab}}(t) - U_b^{C_{ab}}(t) \right]$$

$$\text{subject to:} \quad \sum_{b} P_{a,b} \le P_a^{tot}$$

is implemented using the bit rate vs. SIR plot

- Average network delay when rates (λ_1, λ_2) are linearly scaled to the values (0.585,2.925) are plotted.
- Centralized DRPC provides Stability and delays at more than four times the data rates of two-hop relay algorithm, and more than twice the data rate of decentralized DRPC algorithm



MULTI COMMODITY FLOWS AND CONVEX DUALITY

- A relationship between static method for computing a multi-commodity flow and dynamic DRPC policy that achieves network capacity is obtained through the unifying framework of convex duality.
- For the problem of finding a Multi Commodity flow, corresponding optimization problem is

Maximize: 1

Subject to:

$$\lambda_{ic} + \sum_a f_{ai}^{(c)} \leq \sum_b f_{ib}^{(c)} \quad \forall i, c, \quad \text{such that } i \neq c$$

$$\left(\left\{f_{ab}^{(c)}\right\}, \{\mu_{ab}\}\right) \in \Theta.$$

where Θ is the set of all variables $(\{f_{ab}^{(c)}\}, \{\mu_{ab}\})$ such that

$$f_{ab}^{(c)} \geq 0, \quad \text{for all } a, b, c \in \{1, \dots, N\}$$

$$f_{aa}^{(c)} = f_{ab}^{(a)} = 0, \quad \text{for all } a, b, c \in \{1, \dots, N\}$$

$$\left(\sum_c f_{ab}^{(c)}\right) \leq (\mu_{ab}), \quad \text{for some } (\mu_{ab}) \in \Gamma.$$

- For the given problem, a dual problem is developed, which is given as

$$\text{Minimize:} \quad L\left(\left\{U_i^{(c)}\right\}\right)$$
$$\text{Subject to:} \quad U_i^{(c)} \geq 0, \quad \text{for all } i, c \in \{1, \ldots, N\}.$$

- By making modifications to the dual problem, it is shown that it could solve the same optimization problems as a dynamic DRPC algorithm would do.
- It follows that the DRPC algorithm can be viewed as an dynamic implementation of a subgradient search method for computing the solution to an optimization problem using convex duality.

CONCLUSIONS

- A general power allocation problem for a multi node wireless network with time varying channels and adaptive transmission rates was developed.
- Concept of network capacity region was established, and a DRPC algorithm, using both Centralized and Decentralized approach was developed.
- DRPC algorithm was shown to be providing stability and bounded delays to the network.
- Performance of the two DRPC approaches were compared.