Cross-layer scheduling of end-to-end flows using a spectrum server

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Talk Outline

- Introduction – Cognitive Radio & Spectrum Server
- Scheduling of variable rate links
- End-to-end scheduling of flows using spectrum server
- Fairness and Max-Min Fair Flows
- Conclusion

The Spectrum Debate

- **What everyone agrees on:**
  - Spectrum use is inefficient
  - FCC licensing has yielded false scarcity
- **Proposed Solutions**
  - Spectrum Property Rights
    - The triumph of economics
  - Open Access (Commons)
    - The triumph of technology

Open Access

- **A Technology Panacea**
  - Agile wideband radios will dynamically share a commons
  - Minor technical rules (power spreading) for transceivers
- **Systems of end-user devices**
  - Spread spectrum, UWB, MIMO, OFDM
  - Short range communications
  - Ad hoc multi-hop mesh networks
- **Evidence: (perceived) success of 802.11 vs. 3G**

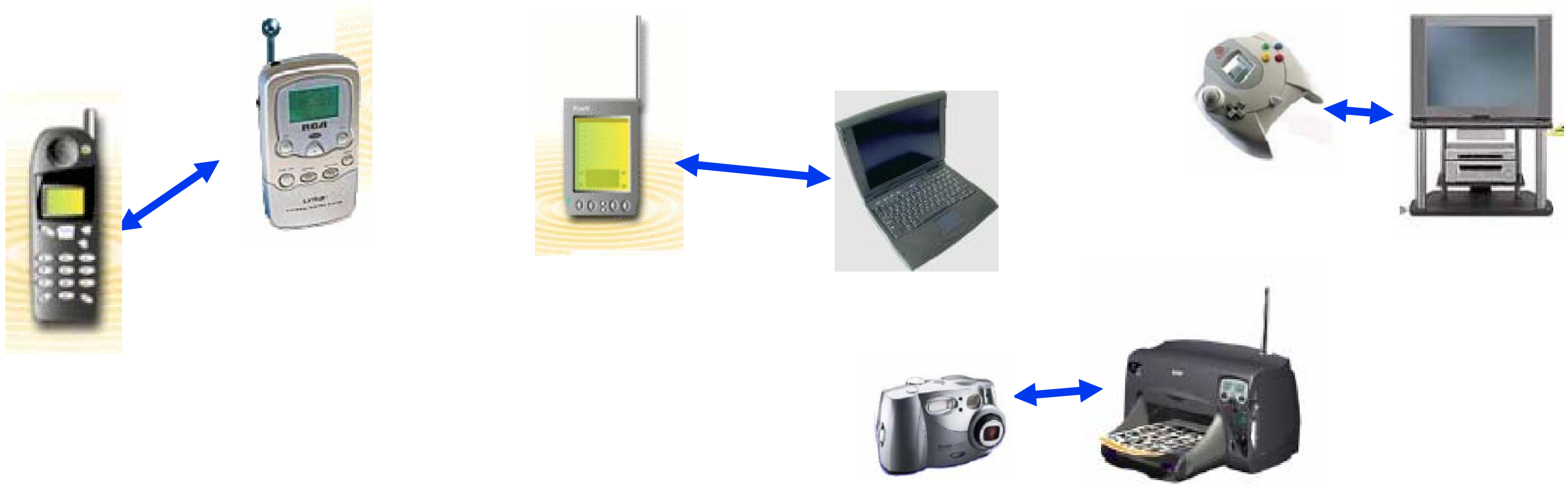
Open Access Needs Radio Agility

- Require radios that can :
  - Discover
  - Cooperate
  - Self-Organize into hierarchical networks
- Agility needed at every protocol layer
- But cannot predict environments/applications

The Answer? "Cognitive Radios"

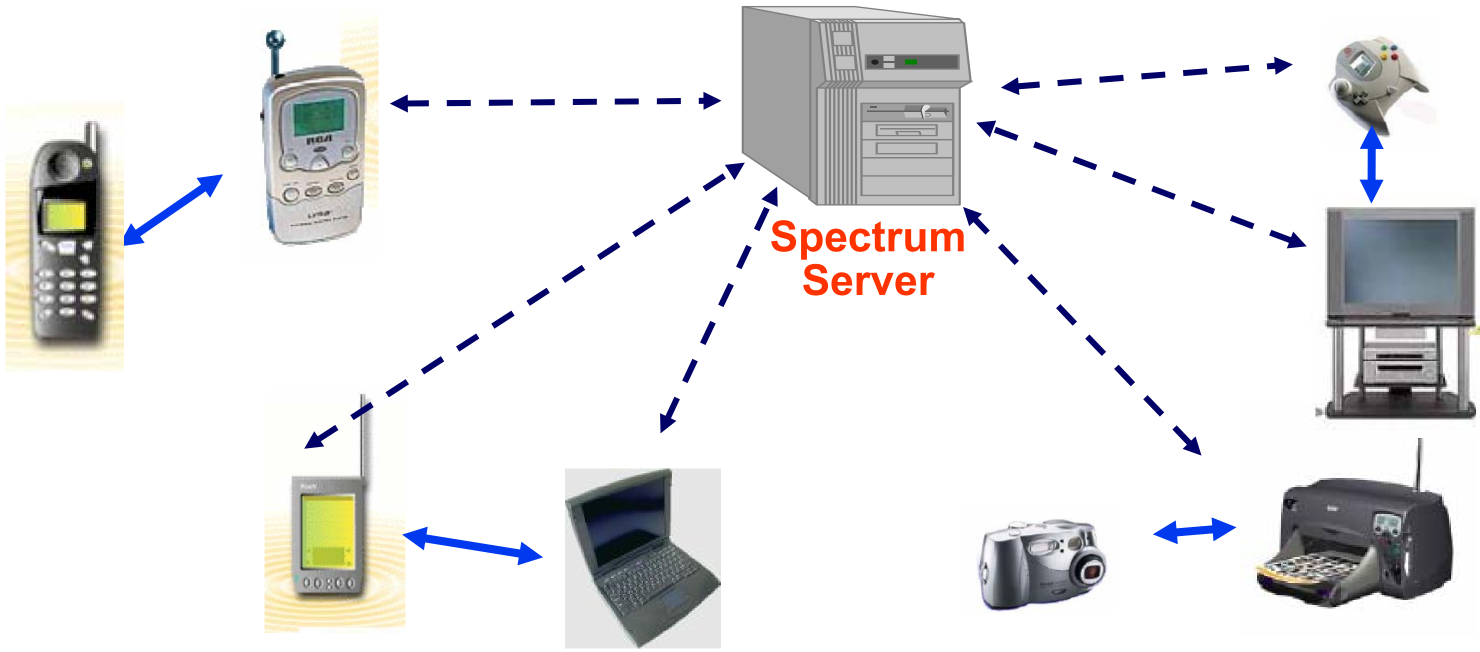
- Optimization Perspective:
  - Enlarging the space of feasible solutions
    $\Rightarrow$ improved performance

Cognitive Radio: Modeling Issues



- **Heterogeneous PHYs:**
  - OFDM, UWB, FH, CDMA
- **Is there a control channel?**
- **What are control actions?**

A Simple Spectrum Server



- Spectrum Server tells radios to turn OFF/ON
- Radios use best rate given signal & interference

Simple System Model

- **Users share a common frequency band**
  - Orthogonal signal dimensions = time slots
  - Time domain scheduling is used for channelization

- **Wireless network of *L* directed links**

- **Links follow ON-OFF transmission schedule over time slots**
  - Use constant transmission power in the ON state

- **Links employ interference-adaptive modulation/coding**
  - Link rate in each time slot depends on interference from other active links

- **Interference depends on the transmission mode**
  - **mode =** subset of links that are ON simultaneously

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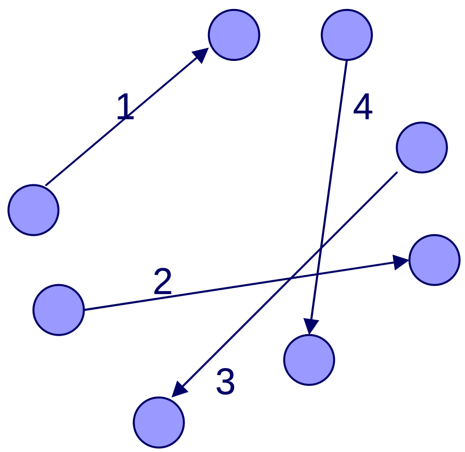
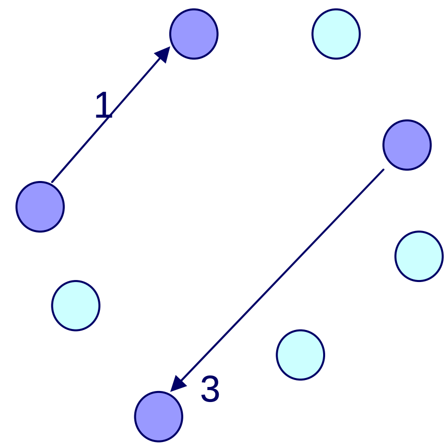
Transmission modes



Network with L = 4 links



Transmission mode [1 0 1 0]

(one of 2^4 possible modes)

Transmission mode matrix ***T:***

[0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1]

[0 0 0 0 1 1 1 1 0 0 0 0 1 1 1 1]

[0 0 1 1 0 0 1 1 0 0 1 1 0 0 1 1]

[0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1]

t_{li} *= 1, if active link l is in mode i*

= 0, otherwise.

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Transmission Mode ⇒ Data Rate

- **Example: Gaussian Interference, Single User Decoding**
  - Each receiver measures its own SIR γ_{li} in every mode *i* :

$$\gamma_{li} = \frac{t_{li} G_{ll} P_l}{\sum_{k \in \mathcal{E}, k \neq l} t_{ki} G_{lk} P_k + \sigma_l^2}$$

G_{lk} = link gain from Tx *k* to Rx *l*

  - Achievable rate at link *l* in mode *i* is

$$c_{li} = \log(1 + \gamma_{li})$$

- ***L* × *2*^{L} matrix *C*: column *i* = rates in mode *i***

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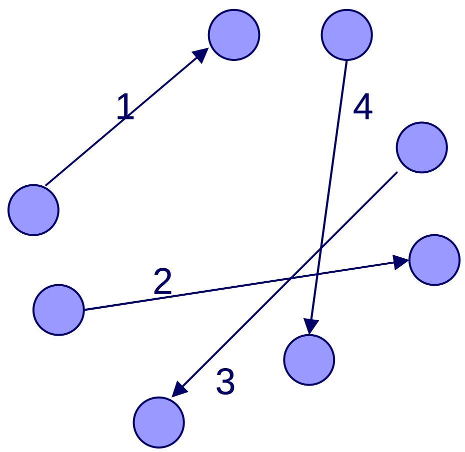
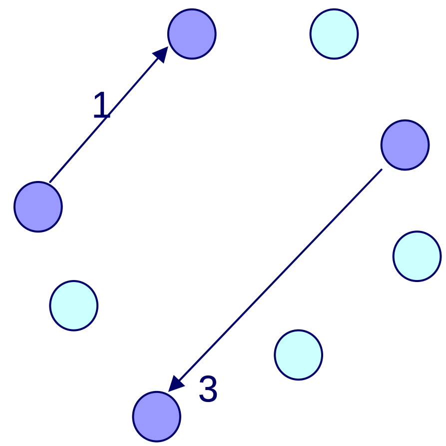
Mode Matrix ⇒ Rate Matrix





network with 4 links

Transmission mode [1 0 1 0]

Rate matrix *C* =

[6.6	0	0.01	0	0.56	0	0.01	0	2.05	0	0.01	0	0.49	0	0.01]
[0	6.6	0.06	0	0	1.86	0.06	0	0	0.97	0.06	0	0	0.77	0.06]
[0	0	0	6.6	1.0	1.86	0.83	0	0	0	0	0.04	0.04	0.04	0.04]
[0	0	0	0	0	0	0	6.65	0.32	0.05	0.04	0.40	0.19	0.05	0.04]

Spectrum Server = Mode Scheduler

- **Spectrum server specifies**
  x_i **= fraction of time mode *i* is ON**

- **Schedule = Stationary Distribution on Modes**

- **Average rate in link *l* is** $r_l = \sum_i c_{li}\, x_i$

- **In vector form,** $r = Cx$

- **Spectrum server specifies *schedule* *x* to:**
  - Maximum sum rate of the network
  - Maximize the common rate on the links
  - Satisfy session flow requests
  - Fair scheduling

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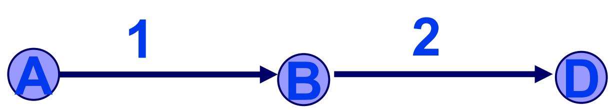
Comments on the Model

- **Average link data rates $r = Cx$**
- **Any ergodic dynamic spectrum access policy $\Rightarrow$**
  schedule x
  average link rates $r = Cx$
  - Centralized scheduling upperbounds distributed/dynamic solutions
- **Tx/Rx technology assumptions are embedded in C**

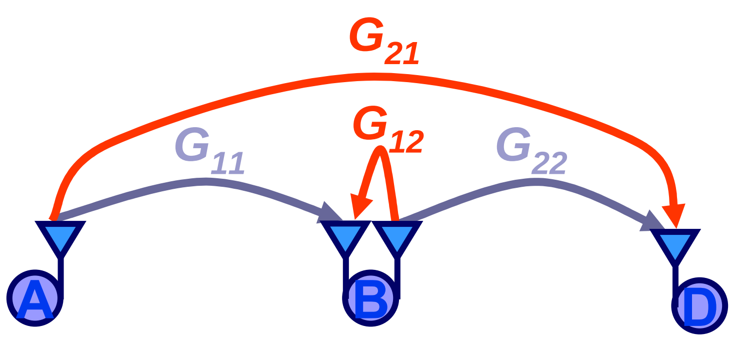
Technology Modeling Example
Duplexing

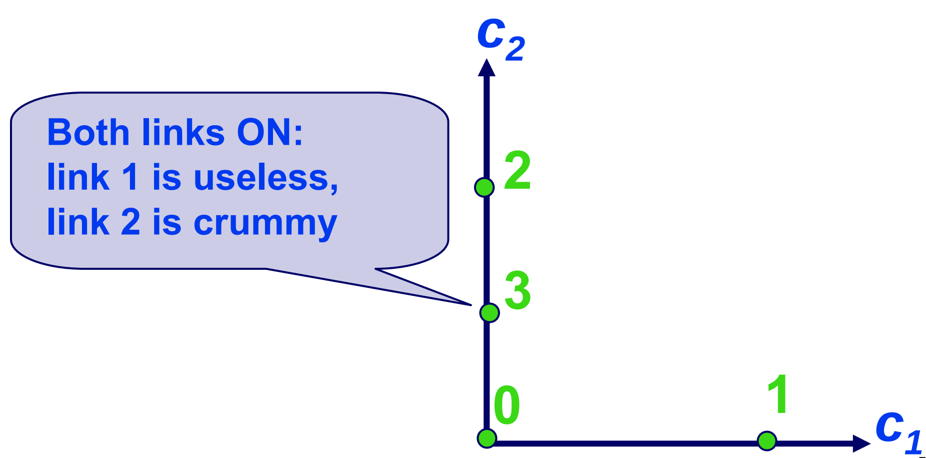
- **Duplex constraints in the rate matrix *C***
  - Node B: Link 1 RX, Link 2 TX
  - $G_{12} = \infty$
  - In mode [1 1], link 1 gets rate $\varepsilon_0 \approx 0,\ c_0 < 1$



$$C = \begin{bmatrix} 0 & 1 & 0 & \varepsilon_0 \\ 0 & 0 & 1 & c_0 \end{bmatrix}$$

Modes 0 1 2 3





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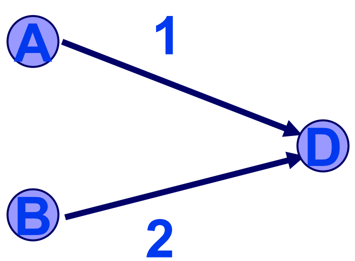
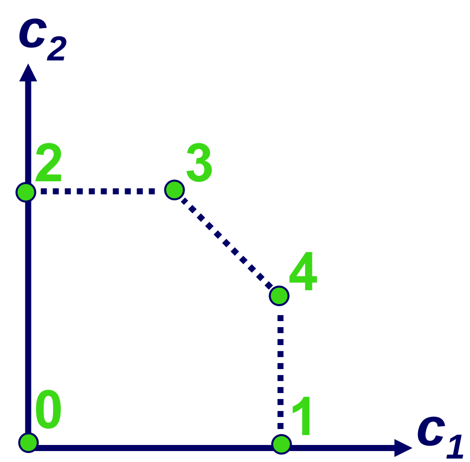
Technology Modeling Example
IT Multiaccess

- **Nodes A and B send to D**
- **D employs joint decoding**
  - Mode induced by sender code rates & successive decoding order at D



$$C = \begin{bmatrix} 0 & 1 & 0 & 0.5 & 1 \\ 0 & 0 & 1 & 1 & 0.5 \end{bmatrix}$$

Modes 0 1 2 3 4



System model for end-to-end flows

- Wireless network with N nodes and L links
- K end-to-end sessions – a session described by an origin-destination (OD) pair
- Set of R routes in the network
- End-to-end route incidence matrix for each flow k:

  $[A_k]_{lr} = 1$, *if link* l *is part of route* r

  $= 0$, *otherwise*
- Vector f_k – session k flows in the R routes

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System model for end-to-end flows

- **Aggregate rates through links** $\quad r = \sum_k A_k f_k$
- **Maximum Sum Utility of the flows:**

$$
\begin{array}{ll}
\text{max} & \sum_k U_k(y_k) \\
\text{subject to} & y_k = \mathbf{1}^T \mathbf{f}_k, \quad k = 1, \ldots, K, \\
 & \mathbf{r} = \mathbf{C}\mathbf{x}, \\
 & \mathbf{r} \geq \sum_k \mathbf{A}_k \mathbf{f}_k, \\
 & \mathbf{x} \geq \mathbf{0}, \ \ \mathbf{1}^T \mathbf{x} = 1, \\
 & \mathbf{f}_k \geq 0, \quad k = 1, \ldots, K.
\end{array}
$$

Session flows feasible given link rates

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Cross Layer Optimization??

- PHY: Link rates c_{li} for each mode i
- MAC: Schedule $x \Rightarrow$ Link rates $r = Cx$
- Network: Routes A_k
- Transport: Flows f_k

PHY
MAC

$$r = Cx \geq \Sigma_k A_k f_k$$

Network
Transport

- Issues
  - Dual decomposition methods don't yield distributed solutions.
  - x_i is not controlled locally by entity i
- [Bonald & Proutiere, WP-01]: Flow allocation f drives schedule x

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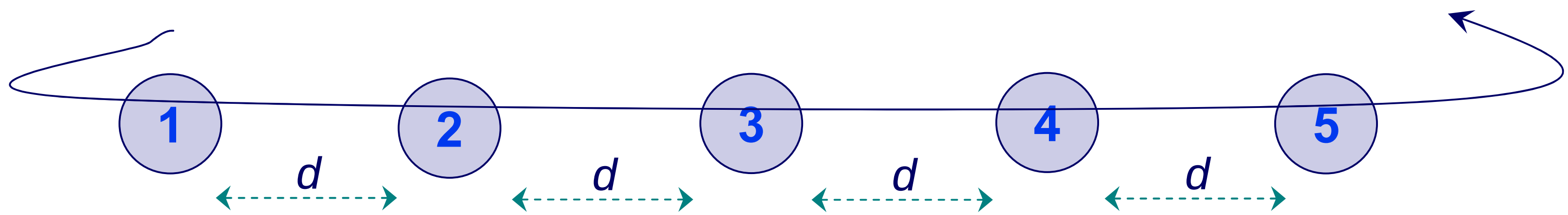
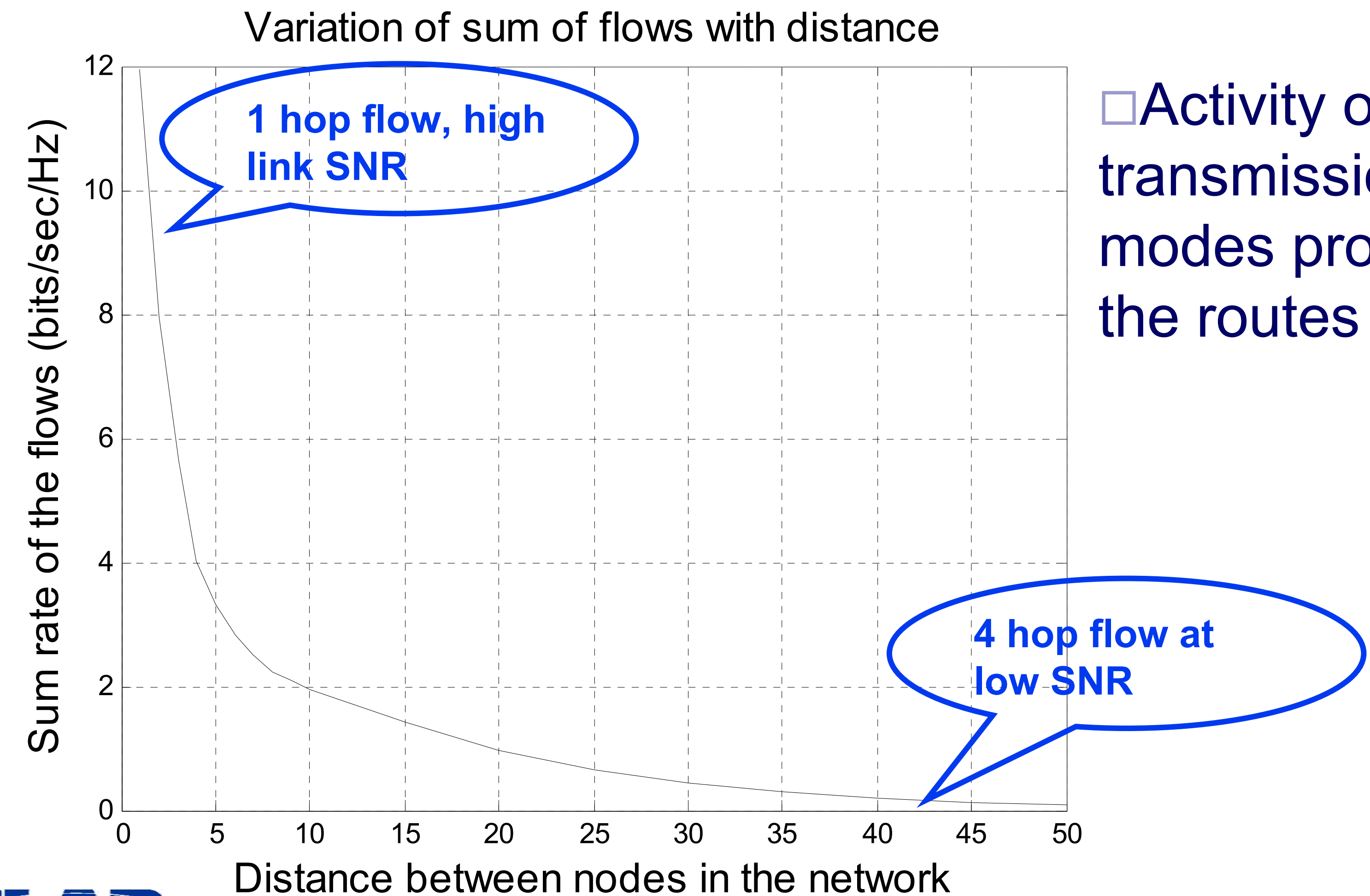
Example 1: Max Flow scheduling on a linear network



- **One flow, linear network, 5 nodes equally spaced**
  - 10 directional links: (*1,2*), (*1,3*) … (*4,5*)
  - 25 useful (half-duplex) transmission modes
  - 8 paths in the network
  - Routes are chosen to maximize the end-to-end flow

Example 1: Max Flow



- Activity of transmission modes provides the routes

Special Case: Session Flows = Link Rates

- Each flow traverses one link.
- Each link carries one flow.
- $A_k = I$, $f_k = r_k e_k$,
- (Session flow) $y_k = r_k$ (link rate)

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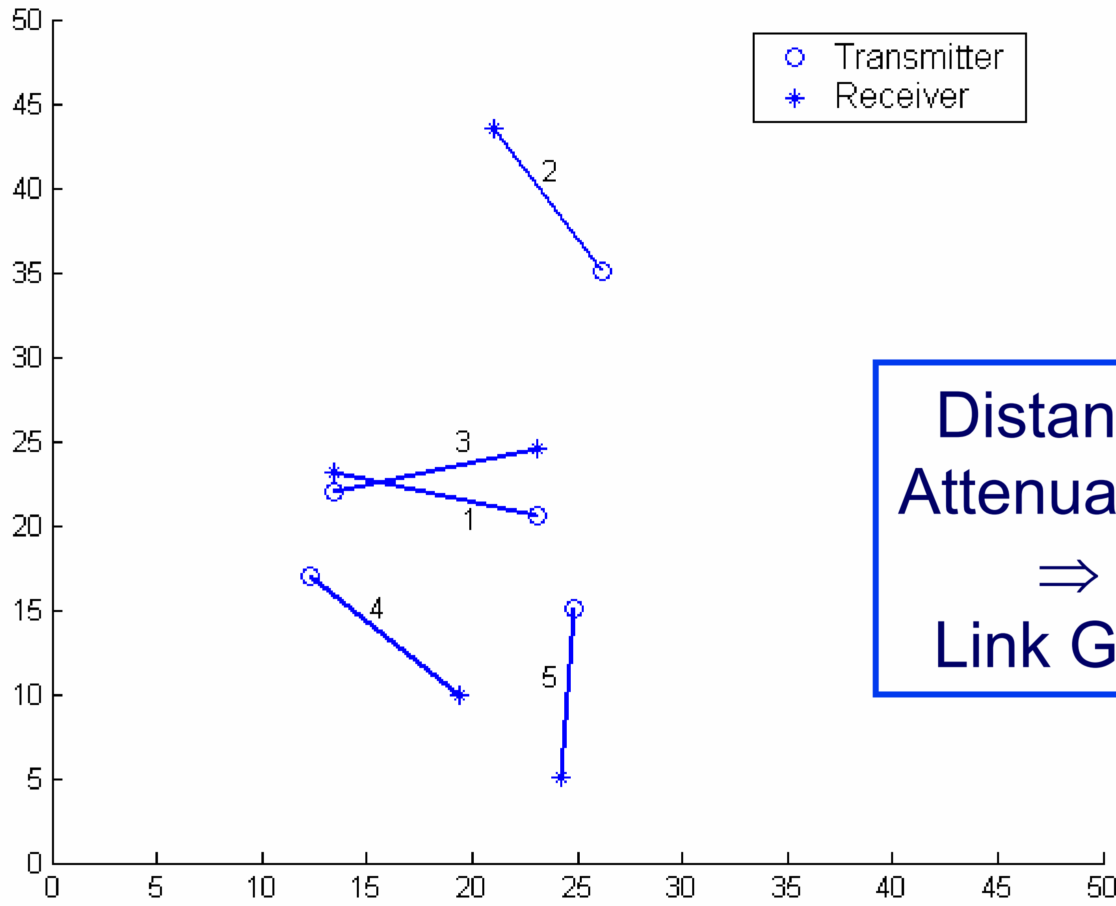
Max sum link-rate scheduling

- Each flow traverses one link. Each link carries one flow.
- Objective: To maximize the sum rate in the network with minimum rate constraints on each link
- Optimization problem can be posed as a linear program

$$\begin{array}{ll} \max & \mathbf{1}^T \mathbf{r} \\ \text{subject to} & \mathbf{r} = \mathbf{C}\mathbf{x}, \\ & \mathbf{r} \geq \mathbf{r}_{\min}, \\ & \mathbf{1}^T \mathbf{x} = 1, \\ & \mathbf{x} \geq \mathbf{0}. \end{array}$$

Example 2



Distance Attenuation
⇒
Link Gain

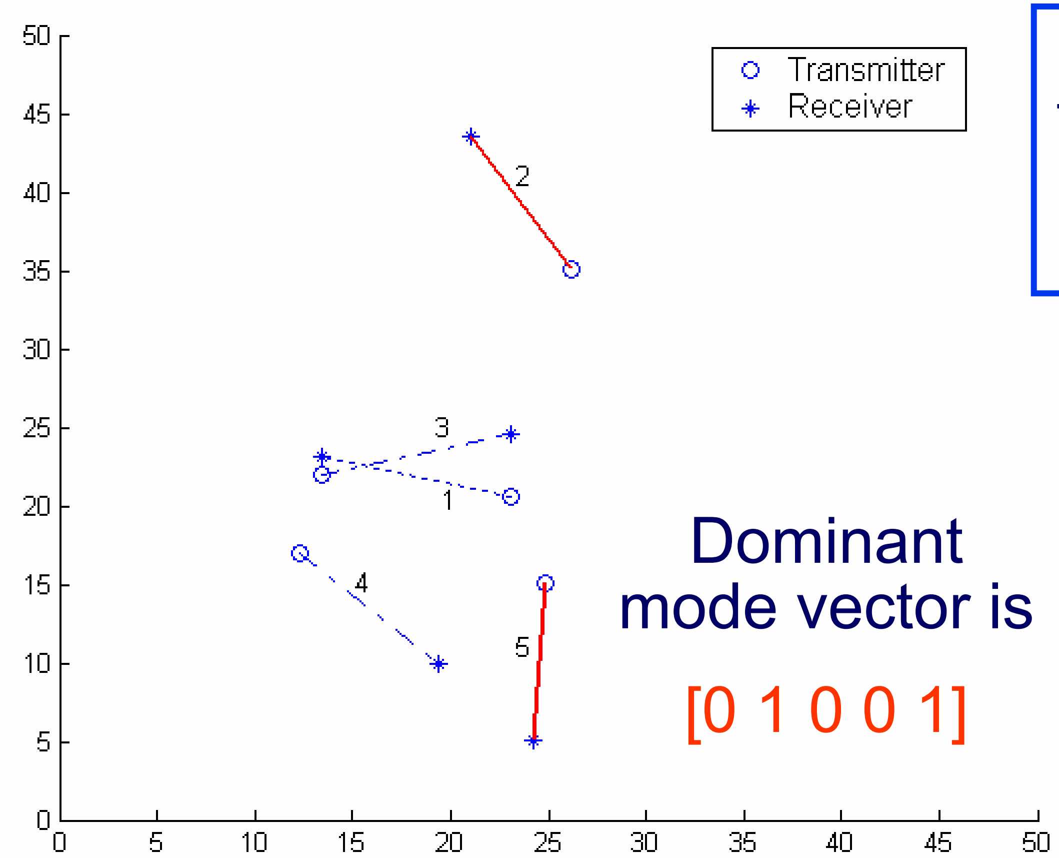
Maximum sum rate solution

- **When $r_{min} = 0$, the *dominant mode* is always scheduled**

- **Dominant mode – the mode corresponding to the maximum column sum in *C***

- **Leads to inherent unfairness in the schedule**
  - links not active in the dominant mode are never scheduled

Example 2: Dominant mode



Dominant mode: the mode that has maximum sum rate

Dominant mode vector is

[0 1 0 0 1]

Maximum Sum rate - solution

- When each component $r_{min} > 0$, more than one mode is used
- The disadvantaged links are operated for just enough time to satisfy their rate requirement
- Most transmission modes are unused

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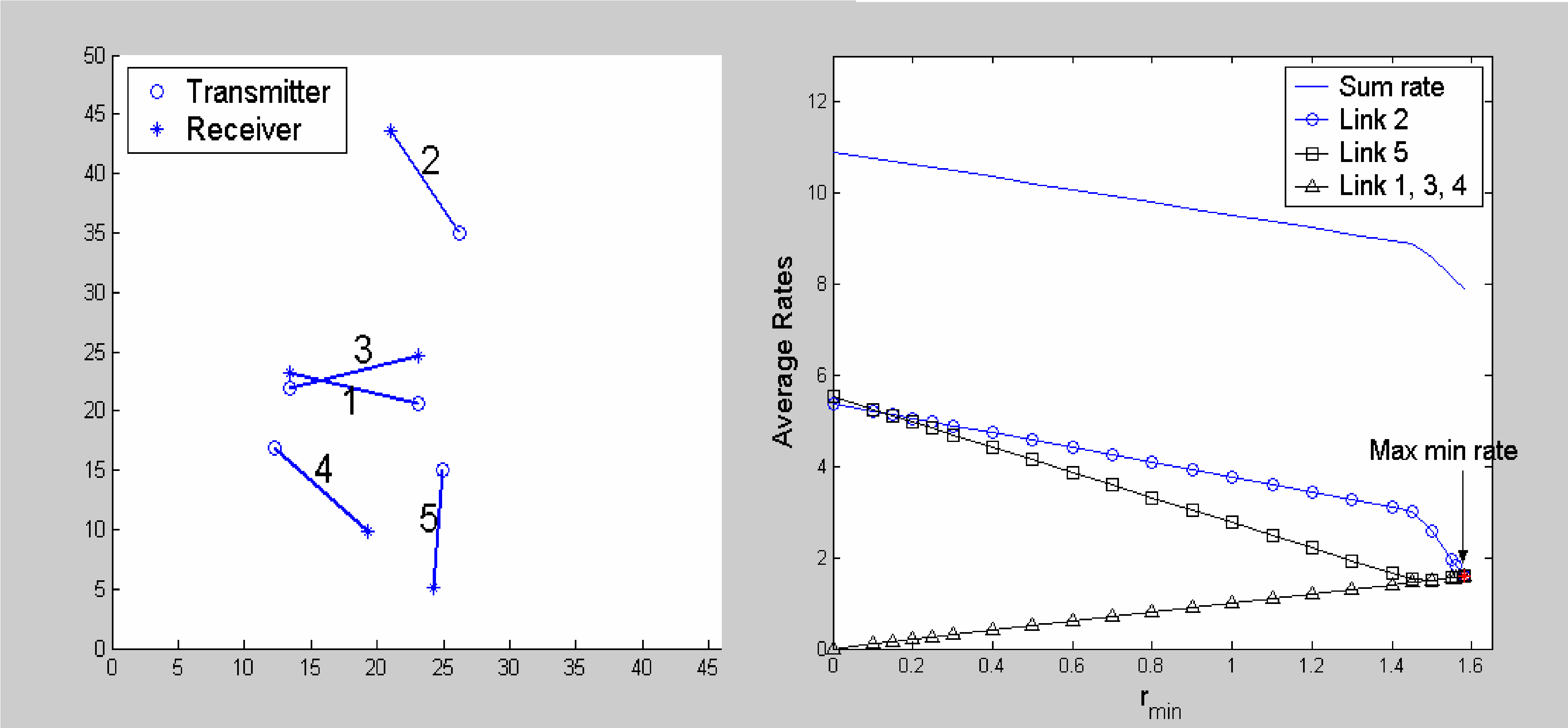

- **Example 2: As common r_{min} increases,**
  - the sum rate decreases
  - Rates of dominant mode links decrease
  - Rates of disadvantaged links increase

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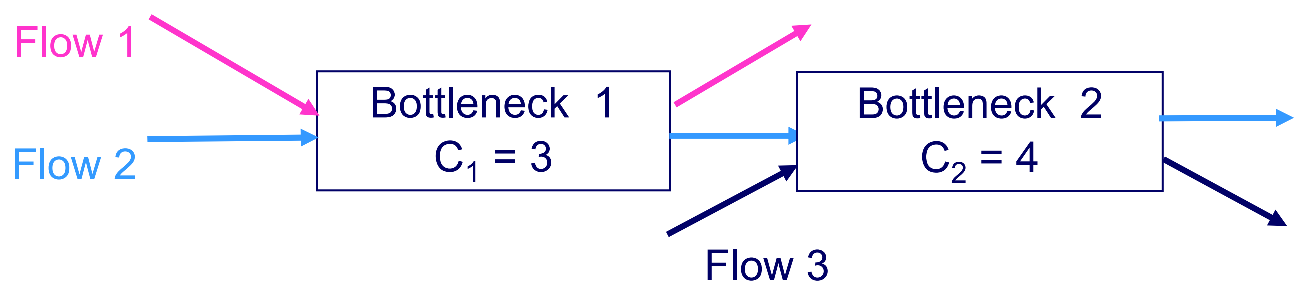
Max-min fairness

- **Flow vector f is max-min fair if f_l cannot be increased while maintaining feasibility without decreasing $f_{l'}$ for some l' such that $f_{l'} \leq f_l$**

- **Example from data networks:**



MMF Rates:

Flow 1 = 1.5, Flow 2 = 1.5, Flow 3 = 2.5

Max-min flow schedule

- **What is the max-min fair flow schedule in our model?**

- **Step 1: Maximize the minimum flow *y* using the LP**

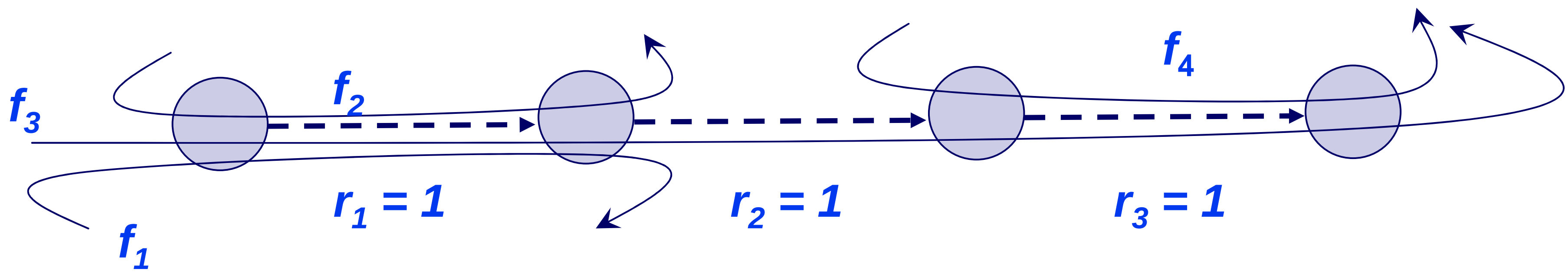
$$
\begin{array}{ll}
\text{max} & y \\
\text{subject to} & y \leq \mathbf{1}^T \mathbf{f}_k, \quad k = 1, \ldots, K, \\
& \mathbf{r} = \mathbf{C}\mathbf{x}, \\
& \mathbf{r} \geq \sum_k \mathbf{A}_k \mathbf{f}_k, \\
& \mathbf{x} \geq 0, \mathbf{1}^T \mathbf{x} \leq 1, \\
& \mathbf{f}_k \geq 0, \quad k = 1, \ldots, K.
\end{array}
$$

Max-min fair schedule

- ***Theorem***: **Non-zero link gains $\Rightarrow$ equal rate flows are max-min fair**

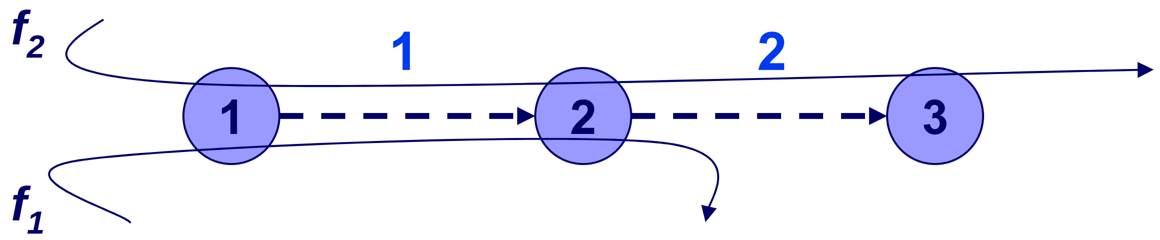
- **Scheduler timeshares between bottlenecks to equalize the user flow rates**
- **The shared bandwidth is the bottleneck**

Example 3 – Fair scheduling



- **Linear network of four nodes, equal link distances**
- **Fixed Schedule (Equal link rates)**
  - MMF rates are (f_1, f_2, f_3, f_4) = (1/3, 1/3, 1/3, 2/3)
- **Mode scheduling of links $\Rightarrow$ equal flows**
  - MMF rates are (f_1, f_2, f_3, f_4) = (0.37, 0.37, 0.37, 0.37)

Example 4: Max-min fair flows (Fixed Mode Schedule)



Spectrum Server Schedule:

Link Rates $r_1 = 10$, $r_2 = 4$

$$f_1 + f_2 \le r_1$$
$$f_2 \le r_2$$

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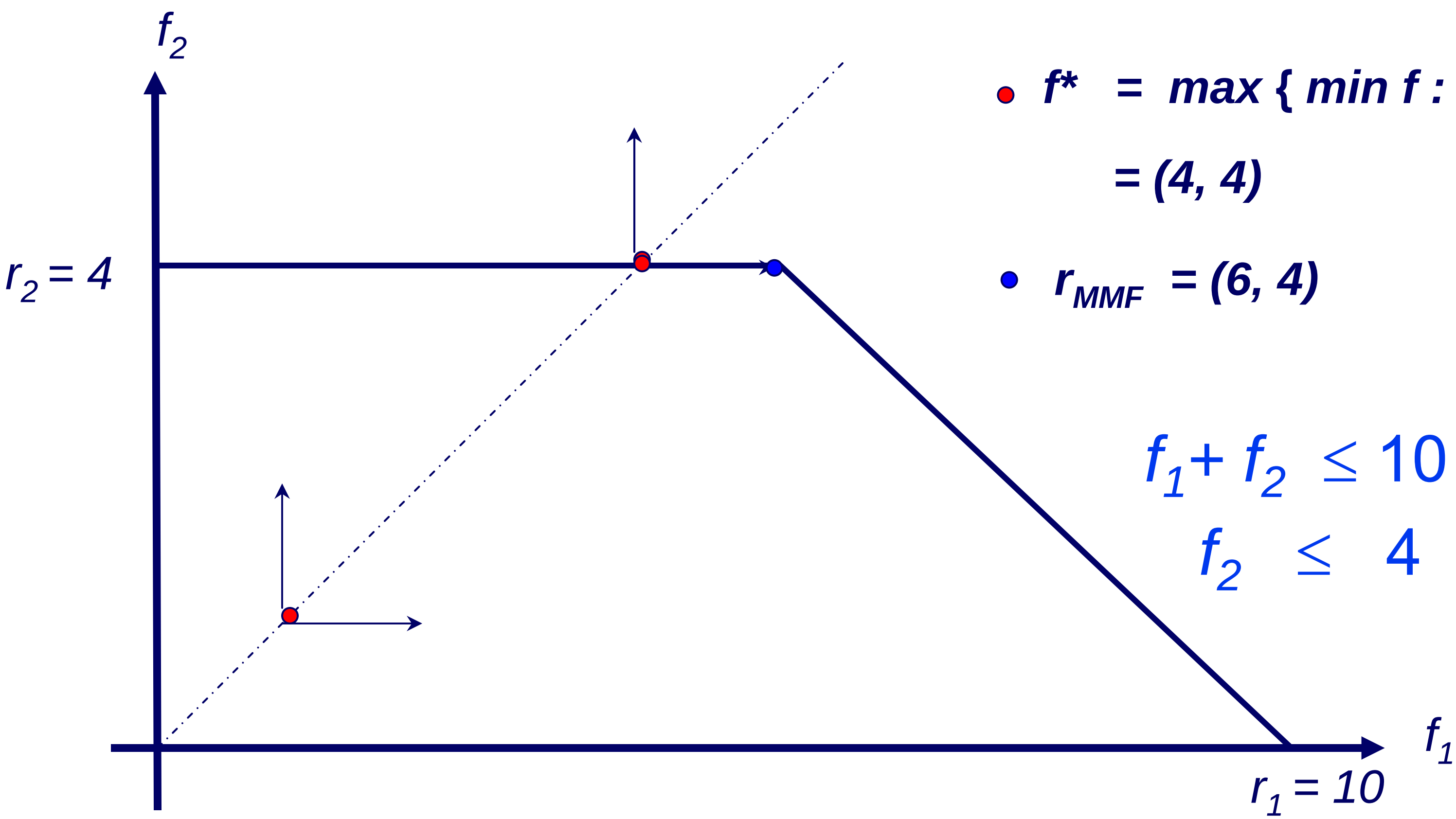
Max-min fair rates (Example)



- $f^* = \max\{\min f : f_1 \geq f, f_2 \geq f\}$
  $= (4, 4)$
- $r_{MMF} = (6, 4)$

$$f_1 + f_2 \leq 10$$
$$f_2 \leq 4$$

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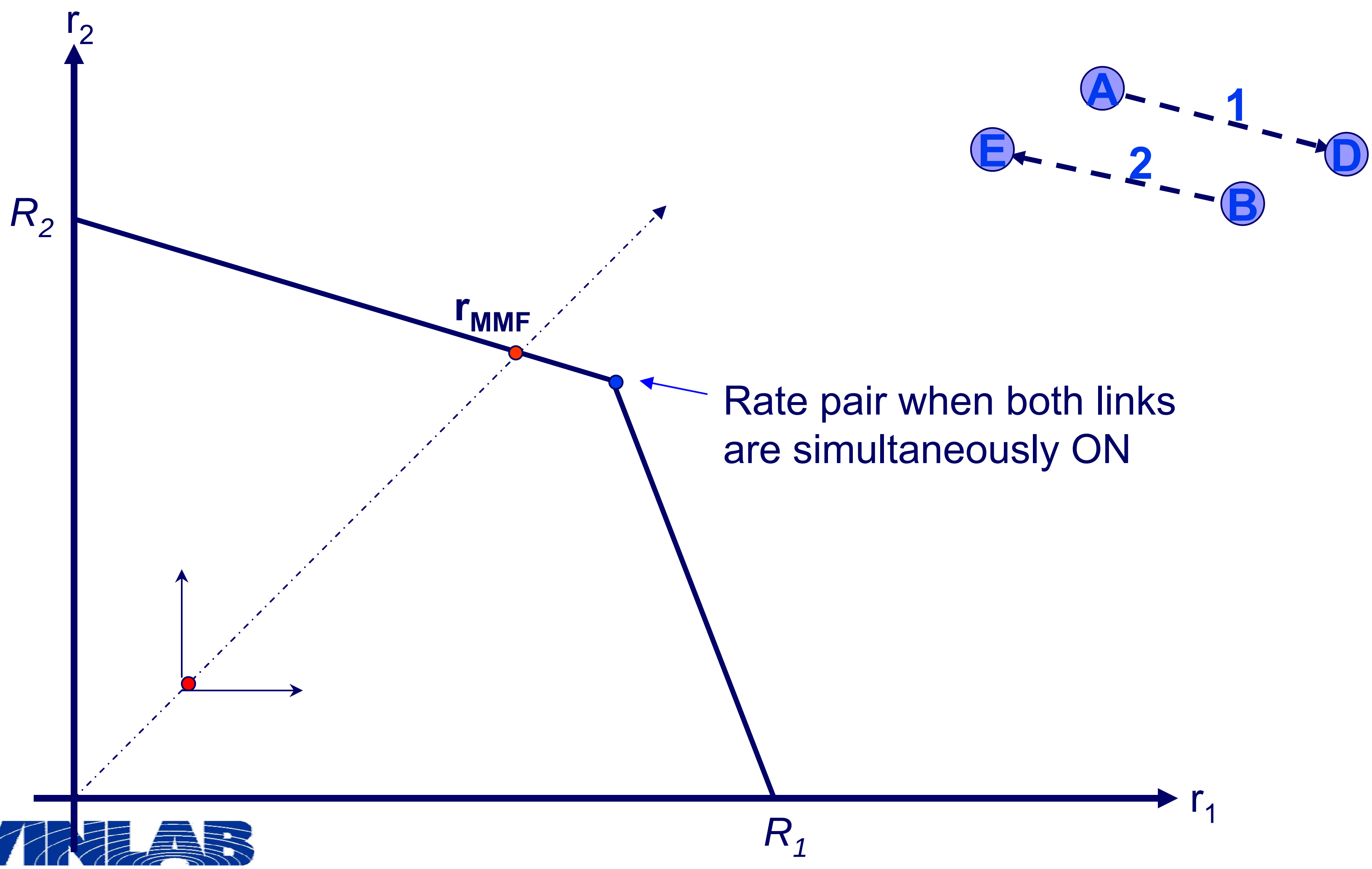
MMF rates for the interference model



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Max-min fair schedules

- **"Equal rates are max-min fair" is a property of**
  - flexible (centralized) link scheduling
  - Gaussian interference model

- **[Radunovic & Le Boudec, Infocom 04]**
  - ***Solidarity Property:*** Decrease in flow *i* enables **strict** increase of flow *j*
  - ***Solidarity*** $\Rightarrow$ equality of max-min fair rates

- **Solidarity holds for the Gaussian interference model.**

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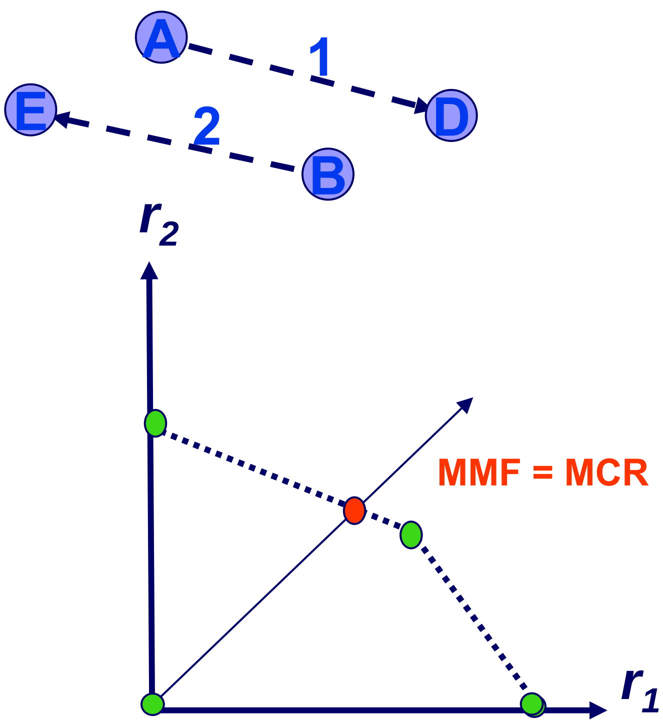
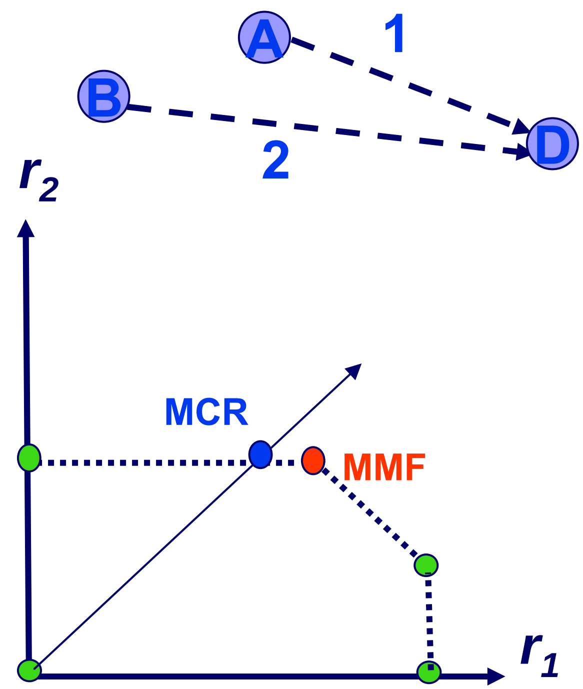
Solidarity and the *C* matrix

- **Solidarity depends on the PHY layer (*C* matrix)**
  - In general, Max Common Rate (MCR) ≠ Max Min Fair (MMF) Rate



Interference Model



IT MAC Model

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Concluding remarks

- **Spectrum server computes schedule – time sharing of transmission modes of the network**
- **Maximizing common rate over flows gives the max-min fair flows for the interference model**
- **Centralized scheduler needs to know a lot of information**
  - granularity and timeliness of measurements required by the Spectrum Server will be important
- **Distributed solutions for finding good PHY layer modes?**