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The Theory of Transmit Power Control  
and Its Implementation in  
3rd Generation CDMA Systems

**Part II**

**The Theory of Transmit Power Control**

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## Outline

1. Introduction to Radio Resource Management (RRM)
2. Conventional Power Control in Fixed Cellular Broad-band Wireless Systems
3. A Common Framework for FDMA/TDMA and CDMA Systems
4. SIR-balancing and Mobile Removal Algorithms
5. Optimum Power Control
6. Centralized, Cooperative, and Distributed Algorithms
7. Discrete Constrained Power Control (DCPC)
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11. References

# 1. Introduction to Radio Resource Management

- **Cellular structure**

- reuse → co-channel interference (CCI)
  - \* interference-limited systems

- **FDMA** and **TDMA**: inter-cluster interference

**CDMA**: intracell and intercell interference  
→ interference management: crucial

- **Co-Channel Interference Mitigation**

- Rejection
  - \* antenna architectures (directional, smart)
- Cancellation
  - \* multiuser detection
- Toleration
  - \* channel coding, advanced modems
- **Regulation** (through efficient management of radio resources)
  - \* base & channel assignment (and re-assignment)
  - \* transmit power and rate control
  - \* spreading

## RRM in Multimedia Systems

- RRM → crucial in wireless multimedia services
- 1G & 2G cellular mobile systems: voice (constant bit rate) communications
  - tx power: only adjustable factor in regulating CCI  
→ RRM  $\simeq$  adaptive tx power control (PC)
  - rich literature & vast expertise on PC
- Multimedia systems
  - tx rate: another adjustable radio resource
  - QoS: a negotiable parameter  
→ joint power-modulation-coding\_level control  
→ Joint power-rate-QoS control
- Joint power-rate-QoS control: related to admission control, BS assignment, and channel assignment (DCA)
- Literature on efficient ways of joint power-rate-QoS controlling: very limited

[Yun.Messerschmitt\_94] [Sampath.Kumar.Holtzman\_95]  
[Hanly\_96] [Zander\_97] [Ramakrishna.Holtzman\_98]  
[Soleimanipour.Zhuang.Freeman\_98]  
[Chuang.Sollenberger\_98] [Yanikomeroglu.Sousa\_99]  
[Zhang.Chong\_00] [Ikeda.Sampe.Morinaga\_00]  
[Kim.Honig\_00] [Yanikomeroglu.Sousa\_00]

## Problem Formulation

$\Gamma_i$ : SIR of MS  $i$  ( $\Gamma$ )

$\gamma_i$ : minimum required SIR for MS  $i$  ( $\gamma$ )

$P_i$ : tx power of MS  $i$  ( $\mathbf{P}$ )

$p_i$ : maximum allowable tx power for MS  $i$  ( $\mathbf{p}$ )

$R_i$ : information rate of MS  $i$  ( $\mathbf{R}$ )

$r_i$ : minimum required information rate for MS  $i$  ( $\mathbf{r}$ )

- **Goal:** find  $\mathbf{P}$  and  $\mathbf{R}$  that will satisfy the QoS, power, and rate constraints

$$\Gamma_i \geq \gamma_i, \quad 0 < P_i \leq p_i, \quad R_i \geq r_i, \quad \forall i$$

- The systems is **feasible** if there exists a solution.
- If there is more than one solution, choose the best  $\mathbf{P}$  and  $\mathbf{R}$   $\rightarrow$  optimization

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$$\min_{\mathbf{R}, \mathbf{P}} \sum P_i \quad \text{or} \quad \max_{\mathbf{R}, \mathbf{P}} \sum R_i$$

$$\text{subject to} \quad \Gamma \geq \gamma, \quad 0 < \mathbf{P} \leq \mathbf{p}, \quad \mathbf{R} \geq \mathbf{r}$$

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- Base assignment and mobility can also be incorporated
- Constrained optimization problem  
 $\rightarrow$  linear/nonlinear programming, fuzzy logic, game theory [Goodman.Mandayam\_00]

## Future Wireless (Fixed and Personal) Systems

- Much broader in scope and richer in content
  - very different devices & applications
  - very different requirements and constraints (many orders of magnitude in difference)
  - very different environments (indoors, outdoors, fixed, low-, high mobility)
- Single air-interface for all such devices & applications?  
→ too limiting
- Success of the future wireless systems depends on their capability of supporting all (or most) of such a plethora of devices.

## RRM in Future Wireless Systems

- Sophisticated BSs
  - extremely flexible
  - software-configurable to support multiple air-interfaces (which may employ different multiple access techniques)
- Hierarchically overlaid cellular architecture
  - macro-, micro-, and picocells, to increase capacity/throughput, to extend radio coverage, and to accommodate different levels of mobility
- Various antenna architectures and diversity techniques

Three inter-related assignments:

- 1) assignment of carriers to macro, micro, picocells,
- 2) assignment of access method to each carrier in different cells, and
- 3) allocation of user terminals within different cells and carriers.

→ Radio resource management in future systems:

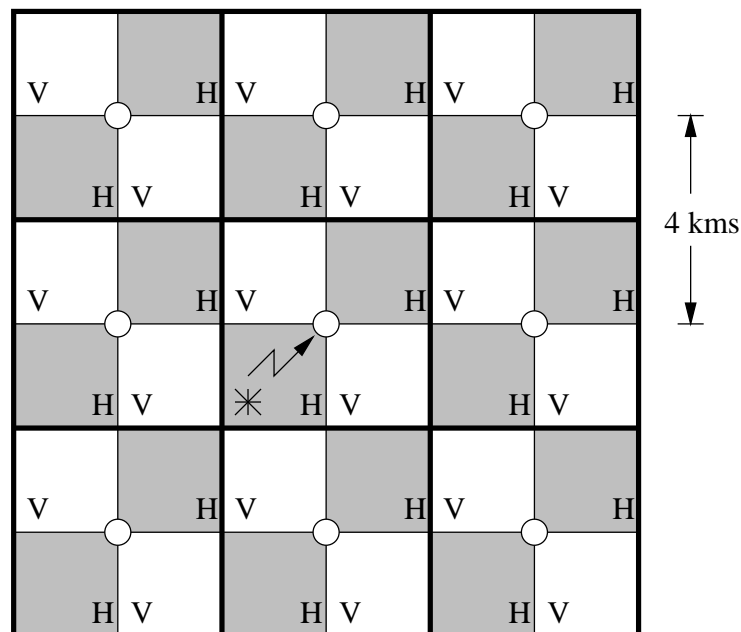
- not an easy task!
- optimal solution: very difficult to obtain
- search for efficient sub-optimal methods of managing radio resources

## 2. Conventional Power Control in

### Fixed Cellular Broadband Wireless Systems

#### LMDS (Local Multipoint Distribution System)

[Salamah.Falconer.Yanikomeroglu\_00]



Reverse-link, TDMA, carrier = 28GHz, 2 MHz channels

H: horizontal polarization V: vertical polarization

Hub antenna beamwidth =  $90^\circ$ , subscriber antenna beamwidth =  $3^\circ$

Uniform main and side lobes, antenna gain ratio = 25 dB

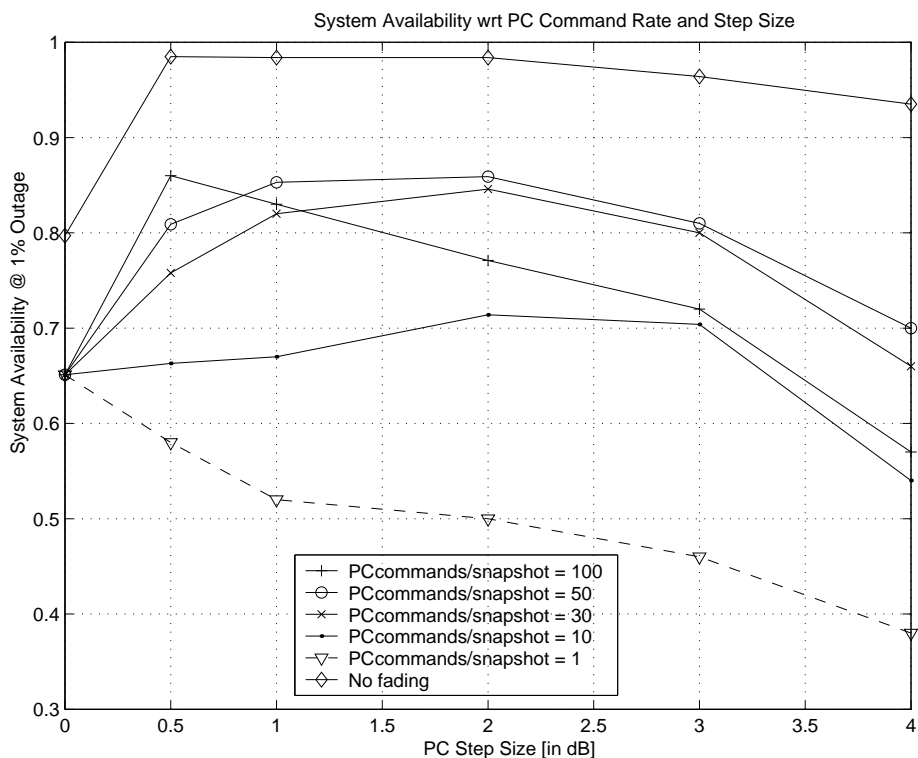
Frequency reuse factor = 4

9 cells, 17 interferers

Maximum transmit power = 100 milliwatts

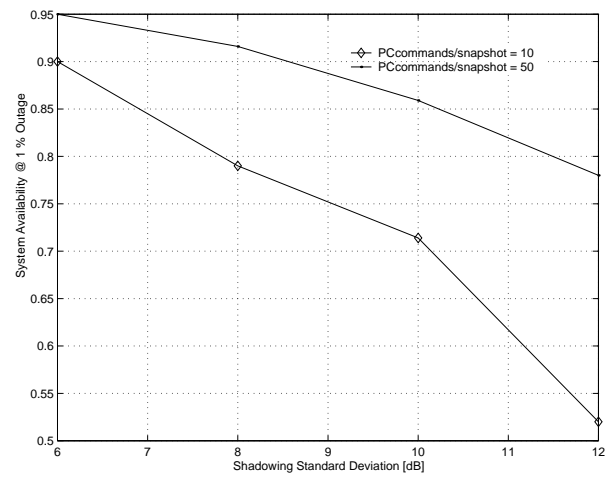
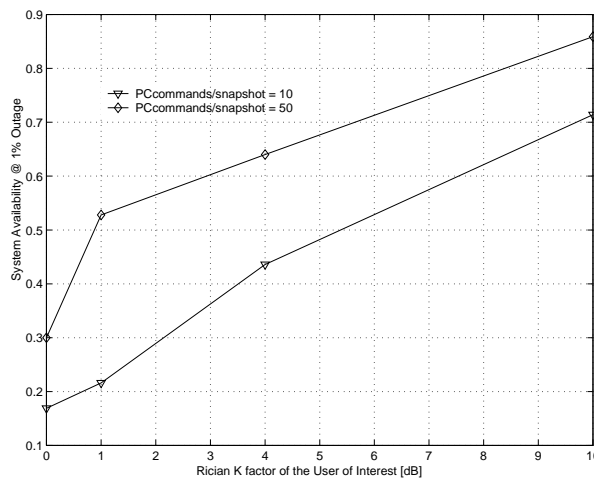
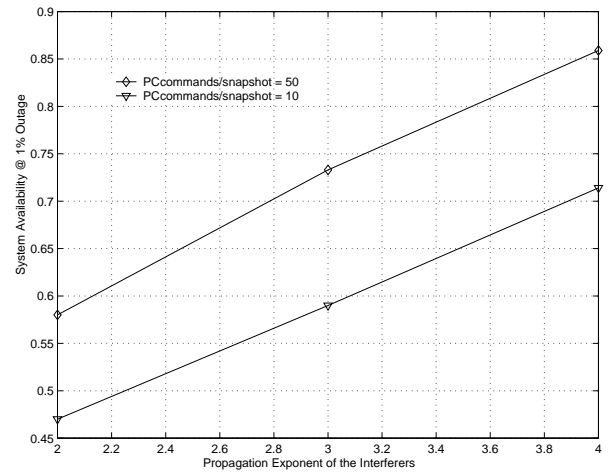
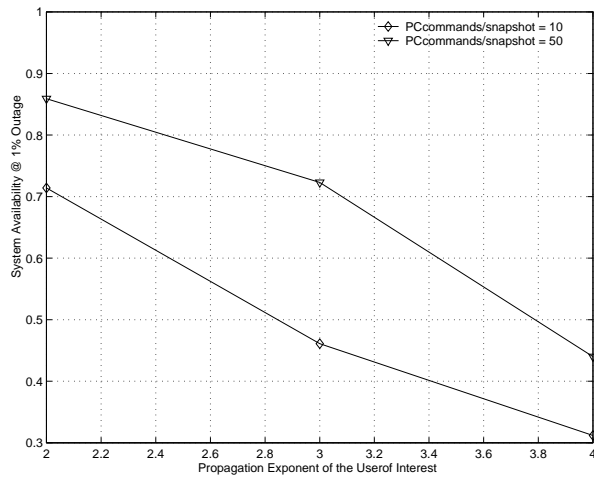
- Simulation Parameters

- target SINR = 10 dB
- propagation exp
  - user of interest and the main interferer = 2
  - other interferers = 4
- Rician  $K$  factor
  - user of interest and the main interferer = 10
  - other interferers = 4
- shadowing standard deviation = 10 dB (all users)
- Correlated Rician fading from snapshot to snapshot



- System availability = percentage of locations for which  $P(\gamma < 10 \text{ dB}) < 1\%$

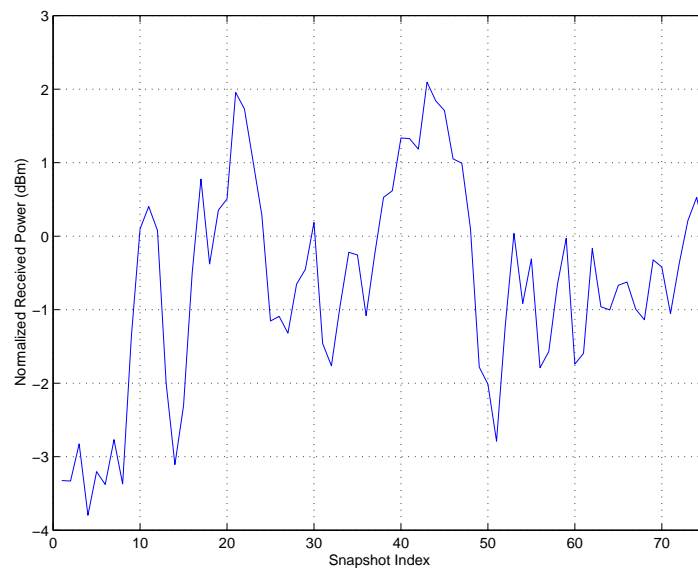
# System Availability wrt Propogation Environment



→ Power control enhances coverage

- Measured received power with time ([Naz.Falconer\_00])

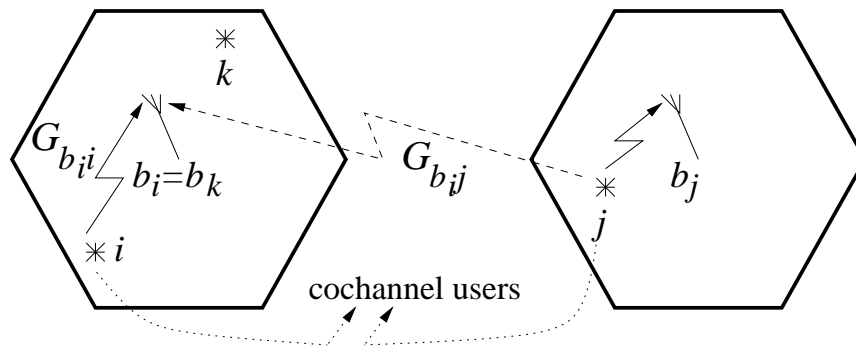
- Simulated channel (Rician,  $K=10$ , correlated in time)



- 1 snapshot  $\simeq$  1/15 seconds
- $\sim$  450 PC commands/sec tracks multipath fading

### 3. A Common Framework for

### FDMA/TDMA and CDMA Systems



- $b_i$ : BS that user  $i$  is communicating with
- $\mathcal{C}_i$ : cochannel set for user  $i$
- $P_i$ : transmit power of user  $i$
- $\mathbf{P} = [P_i]$ : tx power vector for users in the same  $\mathcal{C}$
- $G_{b_{ij}}$ : radio link gain, between BS that user  $i$  is communicating with, and user  $j$  ( $G_{ij}$ : simplified notation)
- $\mathbf{G} = [G_{ij}]$ : link gain matrix for users in the same  $\mathcal{C}$
- $\gamma_i$ : SIR for user  $i$
- $\mathbf{\Gamma} = [\gamma_i]$ : SIR vector for users in the same  $\mathcal{C}$

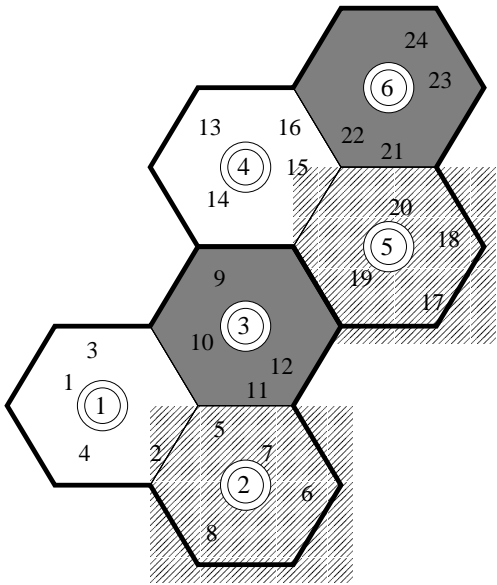
$$\gamma_i = \frac{G_{b_{ii}} P_i}{\sum_{j \in \mathcal{C}_i, j \neq i} G_{b_{ij}} P_j}$$

# TDMA/FDMA Systems

**Ex:** 6-cell system, 2 clusters, 4 users/cell

→ 12 cochannel sets:  $\mathcal{C}_1 = \{1, 13\}, \dots, \mathcal{C}_{12} = \{12, 24\}$

→ 12 parallel power control processes



*G* matrices

Ⓚ	1 13	2 14	3 15	4 16
Ⓚ	$b_1$ <input type="checkbox"/>	$b_2$ <input type="checkbox"/>	$b_3$ <input type="checkbox"/>	$b_4$ <input type="checkbox"/>
Ⓚ	$b_{13}$ <input type="checkbox"/>	$b_{14}$ <input type="checkbox"/>	$b_{15}$ <input type="checkbox"/>	$b_{16}$ <input type="checkbox"/>
Ⓚ	5 17	6 18	7 19	8 20
Ⓚ	$b_5$ <input type="checkbox"/>	$b_6$ <input type="checkbox"/>	$b_7$ <input type="checkbox"/>	$b_8$ <input type="checkbox"/>
Ⓚ	$b_{17}$ <input type="checkbox"/>	$b_{18}$ <input type="checkbox"/>	$b_{19}$ <input type="checkbox"/>	$b_{20}$ <input type="checkbox"/>
Ⓚ	9 21	10 22	11 23	12 24
Ⓚ	$b_9$ <input type="checkbox"/>	$b_{10}$ <input type="checkbox"/>	$b_{11}$ <input type="checkbox"/>	$b_{12}$ <input type="checkbox"/>
Ⓚ	$b_{21}$ <input type="checkbox"/>	$b_{22}$ <input type="checkbox"/>	$b_{23}$ <input type="checkbox"/>	$b_{24}$ <input type="checkbox"/>

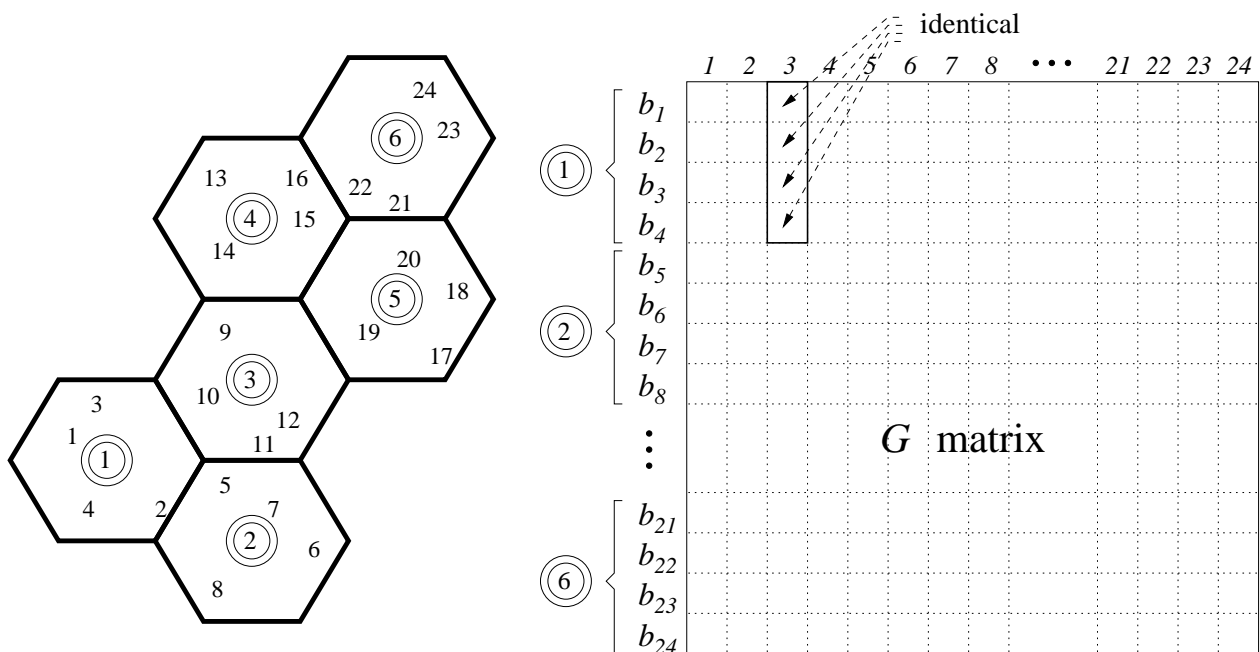
$$\gamma_i = \frac{G_{b,i} P_i}{\sum_{j \in \mathcal{C}_i, j \neq i} G_{b,j} P_j}$$

## CDMA Systems

**Ex:** 6-cell system, 6 clusters, 4 users/cell

→ 1 cochannel set:  $\mathcal{C} = \{1, 2, 3, \dots, 23, 24\}$

→ 1 parallel power control process



$M$ : size of the cochannel set

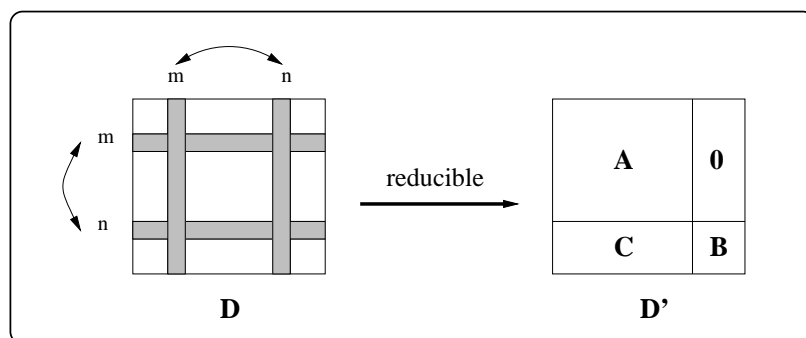
$$\gamma_i = \frac{G_{b_i} P_i}{\sum_{j:j \neq i} G_{b_j} P_j} = \frac{G_{ii} P_i}{\left( \sum_{j=1}^M G_{ij} P_j \right) - G_{ii} P_i}$$

## Some Results from Linear Algebra

### • Eigenvalue and Eigenvector

- \* Let  $\mathbf{Z}_{(L)}$  be an  $L \times L$  square matrix.
- \*  $\{\lambda_i\}_{i=1}^L$ : eigenvalues of  $\mathbf{Z}$  are the roots of the characteristic equation  $|\lambda\mathbf{I} - \mathbf{Z}| = 0$ .
- \*  $\{\mathbf{P}_i\}_{i=1}^L$ : eigenvectors of  $\mathbf{Z}$  are the  $L \times 1$  vectors that satisfy  $\lambda_i \mathbf{P}_i = \mathbf{Z}\mathbf{P}_i$ .
- \* An eigenvector can arbitrarily be scaled.

### • Frobenius-Perron Theorem



- \* Let  $\mathbf{Z}_{(L)}$  be an irreducible, nonnegative matrix with  $\{\lambda_i\}_{i=1}^L$ , then

$$\exists \lambda^* = \max_i \{|\lambda_i|\} \text{ (with multiplicity 1) : } \mathbf{P}^* > \mathbf{0}$$

$$* \text{ Also, } \min_i \sum_j Z_{ij} \leq \lambda^* \leq \max_i \sum_j Z_{ij}$$

## 4. SIR-Balancing and Mobile Removal Algorithms

$\gamma$  : achievable  $\mid \exists \mathbf{P} > \mathbf{0} : \gamma_i \geq \gamma, \forall i$

$$\gamma^* = \max_{\mathbf{P} > \mathbf{0}} \{\gamma\}$$

PC Algorithm  $\left\{ \begin{array}{l} \text{a) Try to achieve } (\mathbf{P}^*, \gamma^*), \\ \text{b) Develop a strategy for the case} \\ \quad \gamma^* < \gamma_0 \text{ (threshold)} \end{array} \right.$

### a) Obtaining $\mathbf{P}^*, \gamma^*$ [Aein\_73]

Normalized link gain matrix  $\mathbf{Z}_{(M)} = [Z_{ij}]_{M \times M}$ , where  $Z_{ij} = G_{ij}/G_{ii}$ . Then,

$$\gamma_i = \frac{G_{ii}P_i}{\left( \sum_{j=1}^M G_{ij}P_j \right) - G_{ii}P_i} = \frac{P_i}{\sum_{j=1}^M Z_{ij}P_j - P_i}$$

$$\rightarrow \frac{1 + \gamma_i}{\gamma_i} P_i = \sum_{j=1}^M Z_{ij}P_j$$

- SIR-balancing: set  $\gamma_i = \gamma, \forall i$

$$\lambda \mathbf{P} = \mathbf{Z} \mathbf{P}, \text{ where } \lambda = \frac{1+\gamma}{\gamma}$$

Eigenvalue problem  $\rightarrow \begin{cases} \lambda : \text{an eigenvalue of } \mathbf{Z} \\ \mathbf{P} : \text{corresponding eigenvector} \end{cases}$

- Remark: not all solutions are physically realizable!

$$\text{Constraints: } \lambda > 1 \left( \gamma = \frac{1}{\lambda-1} > 0 \right), \mathbf{P} > \mathbf{0}$$

- $\mathbf{Z}_{(M)}$ : irreducible, nonnegative

Frobenius-Perron Theorem  $\rightarrow$

$$\exists \lambda^* = \max_i \{|\lambda_i|\} \text{ (with multiplicity 1) : } \mathbf{P}^* > \mathbf{0}$$

$$Z_{ii} = 1 \rightarrow \lambda^* > 1 \rightarrow \gamma^* = \frac{1}{\lambda^* - 1} > 0$$

- SIR-balancing guarantees a solution to the PC problem:  $\gamma^* = \frac{1}{\lambda^* - 1}, \mathbf{P}^*$

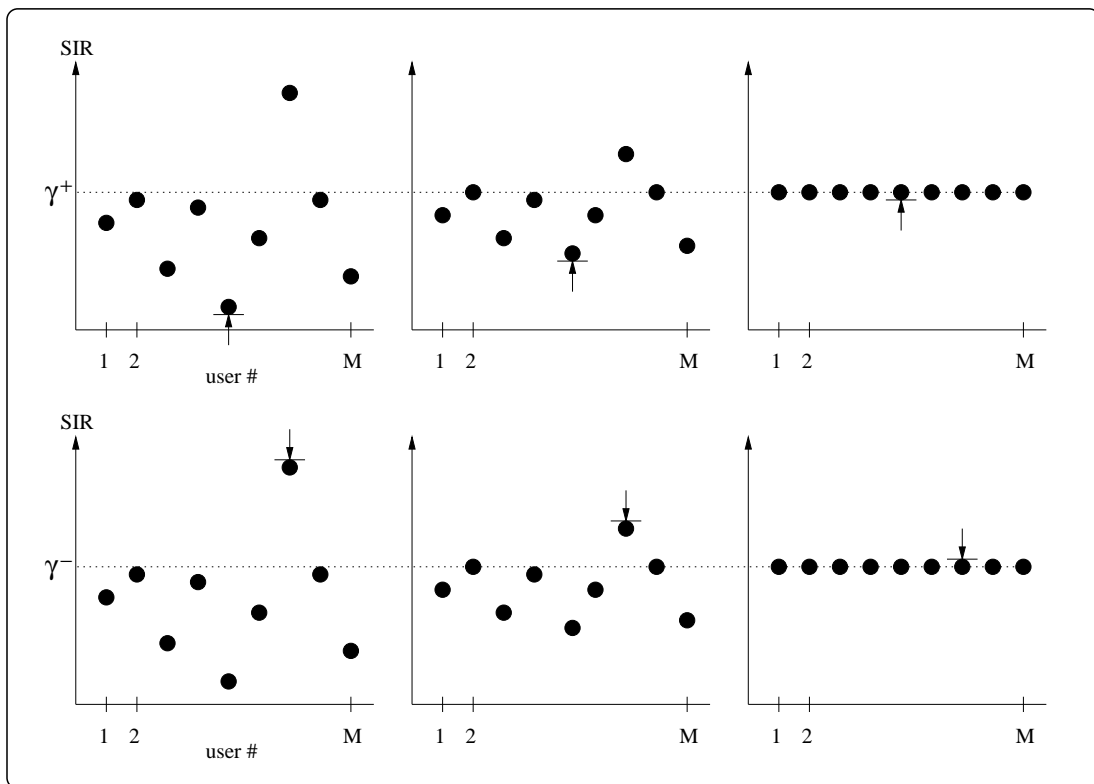
## 5. Optimum Power Control

- Can an unbalanced case yield a higher  $\gamma$  ?

Define:  $\gamma^+ = \max_{P>0} \min_{1 \leq i \leq M} \{\gamma_i\}$ ,  $\gamma^- = \min_{P>0} \max_{1 \leq i \leq M} \{\gamma_i\}$

Then,  $\gamma^+ = \gamma^- = \gamma^* = \frac{1}{\lambda^* - 1}$

[Grandhi.Vijayan.Goodman.Zander\_93]



- SIR-balanced system yields the largest achievable  $\gamma$ .
- Remark: largest achievable SIR is related to the spectral properties of  $\mathbf{Z}$ .

PC Algorithm  $\left\{ \begin{array}{l} \text{a) Try to achieve } (\mathbf{P}^*, \gamma^*), \\ \text{b) Develop a strategy for the case} \\ \gamma^* < \gamma_0 \end{array} \right.$

## b) Mobile (MS) Removal [Zander\_92a]

- Removal: handoff, channel reassignment (DCA), blocking, dropping.
- Straightforward SIR-balancing, without MS removal, may cause all links drop below the SIR threshold.
- Suppose  $\mathbf{P}^* \rightarrow \gamma^* < \gamma_0$ .

Form  $\bar{\mathbf{P}}^* : \left\{ \begin{array}{l} \bar{P}_i^* = P_i^*, \quad i \neq k \\ \bar{P}_k^* = 0 \end{array} \right.$ , i.e., turn off MS  $k$ .

$$\bar{\gamma}_k = 0$$

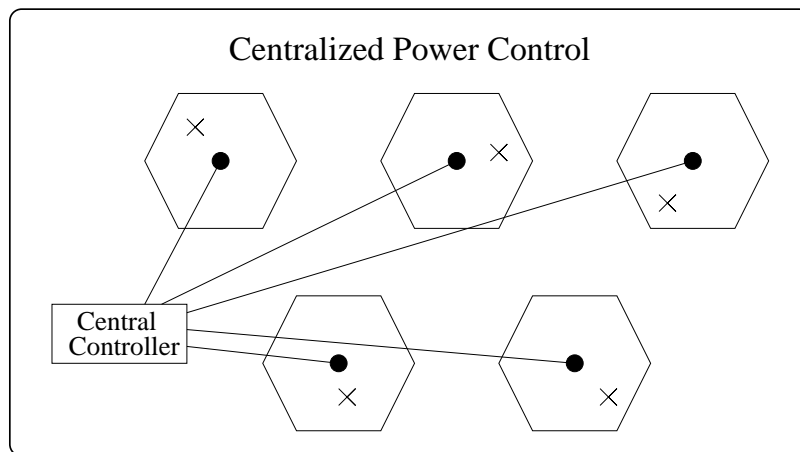
$$\bar{\gamma}_i = \frac{\bar{P}_i}{\sum_{j=1}^M \bar{P}_j Z_{ij} - \bar{P}_i} = \frac{P_i^*}{\sum_{j=1}^M P_j^* Z_{ij} - P_i^* - P_k^* Z_{ik}} > \gamma^*, \quad i \neq k$$

- Remark: the above system is not balanced (by balancing it even a higher SIR level can be achieved for all MSs).
- Turn off MS  $k$ th  $\equiv$  form  $\bar{\mathbf{Z}}$  by removing the  $k$ th row and column of  $\mathbf{Z}$ . Then, SIR balance  $\rightarrow \bar{\gamma}^* > \gamma^*$ .

## 6. Centralized, Cooperative, and Distributed Algos

PC Algorithm Types			
<b>Structure</b>	Centralized	Cooperative	Distributed
<b>Link Info</b>	extensive	limited	very limited

**Centralized algorithm:** instantaneously controls the entire vector  $\mathbf{P}$ .

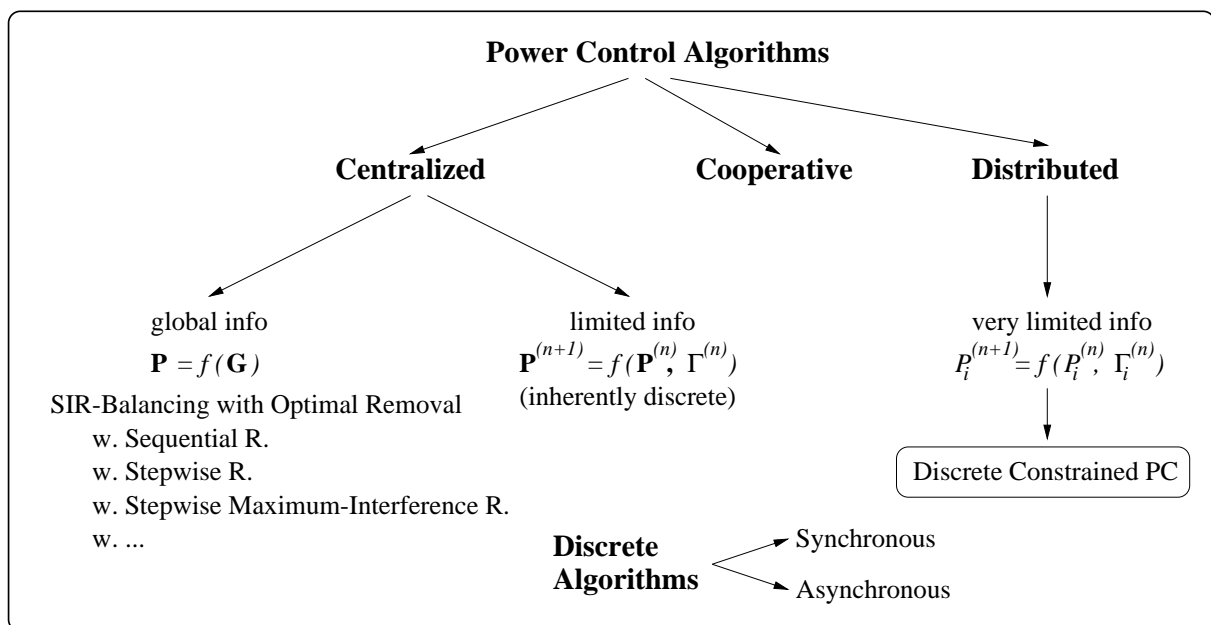


- BSs report radio link information to a central controller. The controller then distributes the power control decisions throughout the network.
- global radio link information: instantaneous access to the entire link gain matrix  $\mathbf{G}$  ( $\rightarrow$  optimum algorithm possible)
  - \* a central controller required
  - \* significant control signal exchange
  - \* delay introduced

- \* high complexity
  - sets the performance upper bound but, difficult to implement
- limited radio link information
  - discrete PC algorithms
  - power evolution (adaptation)

**Cooperative algorithm:** limited data exchange (information flow) among BSs.

**Distributed algorithm:** each MS (or BS) controls its own tx power based on only limited knowledge about  $\mathbf{G}$ .



$$\text{Perf}(\text{best centralized algo}) \geq \text{Perf}(\text{best cooperative algo}) \geq \text{Perf}(\text{best distributed algo})$$

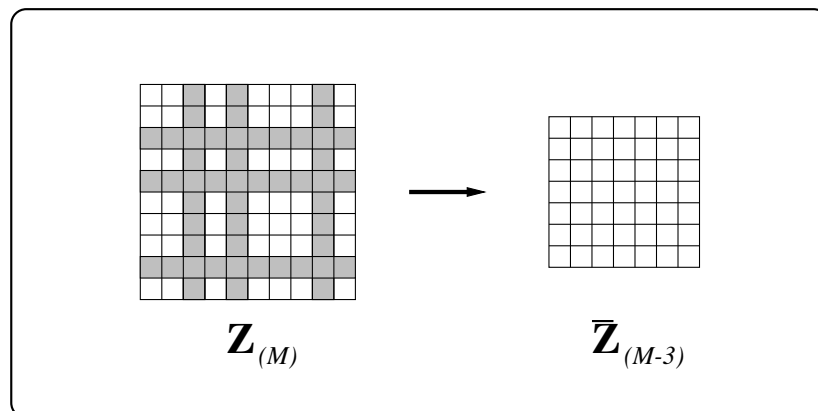
## Centralized PC Algorithms

**Optimum MS Removal Strategy:** Find the largest square submatrix of  $\mathbf{Z}$ , denoted by  $\bar{\mathbf{Z}}$ , for which  $\gamma_o$  is achievable, by removing as few MSs as possible (NP-complete).

**Optimum PC Algorithm** (Brute-Force Implementation) [Zander\_92a]

1. SIR-balance the system  $\mathbf{Z}_{(M)}$ .  
If  $\gamma_{(M)}^* \geq \gamma_o$ , then use  $\mathbf{P}_{(M)}^*$  and stop; otherwise,
2. Set  $m = 1$ .  
While  $m < M$ ,

Find the submatrix  $\bar{\mathbf{Z}}_{(M-m)}$  that will yield the highest achievable SIR:  $\bar{\gamma}_{(M-m)}^*$ .  
If  $\bar{\gamma}_{(M-m)}^* \geq \gamma_o$ , then use  $\bar{\mathbf{P}}_{(M-m)}^*$  and stop; otherwise set  $m = m + 1$ .



- Eventually,  $M-1$  MSs will be removed  $\rightarrow$  no interference left  $\rightarrow$  algorithm works.
- Construct smaller and smaller balanced systems by removing MSs. Find the largest square submatrix of  $\mathbf{Z}$  with an eigenvalue

$$\lambda^* < \lambda_o = \frac{1 + \gamma_o}{\gamma_o}$$

- Straightforward but tedious method (NP-complete)
- The number of eigenvalue computations in the worst case:

$$\binom{M}{1} + \binom{M}{2} + \dots + \binom{M}{M-2} \simeq 2^M$$

$\rightarrow$  exponential complexity

**Sequential Removal Algorithm:** Remove one MS at a time until  $\gamma_o$  is achieved.

- The number of eigenvalue computations in the worst case:

$$M + (M-1) + \dots + 2 \simeq \frac{M^2}{2}$$

## Stepwise Removal Algorithm (SRA): [Zander\_92a]

Remove MS  $k$  for which the max of the row and column sums is maximized.

1. SIR-balance the system  $\mathbf{Z}_{(M)}$ .  
If  $\gamma_{(M)}^* \geq \gamma_o$ , then use  $\mathbf{P}_{(M)}^*$  and stop; otherwise,

2. Set  $m = 0$  and  $\bar{\mathbf{Z}}_{(M)} = \mathbf{Z}_{(M)}$ .  
While  $m < M$ ,

form submatrix  $\bar{\mathbf{Z}}_{(M-m-1)}$  from  $\bar{\mathbf{Z}}_{(M-m)}$  by removing MS  $k$  for which

$$\max\{r_k = \sum_{j=1}^{M-m} \bar{Z}_{kj}, r_k^T = \sum_{j=1}^{M-m} \bar{Z}_{jk}\} \geq \max\{r_i, r_i^T\},$$

$\forall i$ . If  $\bar{\gamma}_{(M-m-1)}^* \geq \gamma_o$ , then use  $\bar{\mathbf{P}}_{(M-m-1)}^*$  and stop; otherwise set  $m = m + 1$ .

→ linear complexity in eigenvalue computation ✓

- The SRA seeks to maximize the lower bound for  $\gamma^*$
- Remark: SRA uses full knowledge of the link gain matrix in order to calculate its eigenvalues
- Outage(SRA with cluster size = 3) > Outage(Fix tx power with cluster size = 13) → capacity gain of 4

## Stepwise Maximum-Interference Removal Algorithm (SMIRA)

[Lee.Lin.Su\_95]

Tx power is also taken into account in removal process.

1. SIR-balance the system  $\mathbf{Z}_{(M)}$ .  
If  $\gamma_{(M)}^* \geq \gamma_o$ , then use  $\mathbf{P}_{(M)}^*$  and stop; otherwise,
2. Set  $m = 0$ ,  $\bar{\mathbf{Z}}_{(M)} = \mathbf{Z}_{(M)}$ , and  $\bar{\mathbf{P}}_{(M)} = \mathbf{P}_{(M)}$ .  
While  $m < M$ ,

form submatrix  $\bar{\mathbf{Z}}_{(M-m-1)}$  from  $\bar{\mathbf{Z}}_{(M-m)}$  by removing MS  $l$  for which

$$\max\{r_l = \sum_{j=1}^{M-m} \bar{P}_j \bar{Z}_{lj}, r_l^T = \sum_{j=1}^{M-m} \bar{P}_l \bar{Z}_{jl}\} \geq \max\{r_i, r_i^T\},$$

$\forall i$ . If  $\bar{\gamma}_{(M-m-1)}^* \geq \gamma_o$ , then use  $\bar{\mathbf{P}}_{(M-m-1)}^*$  and stop; otherwise set  $m = m + 1$ .

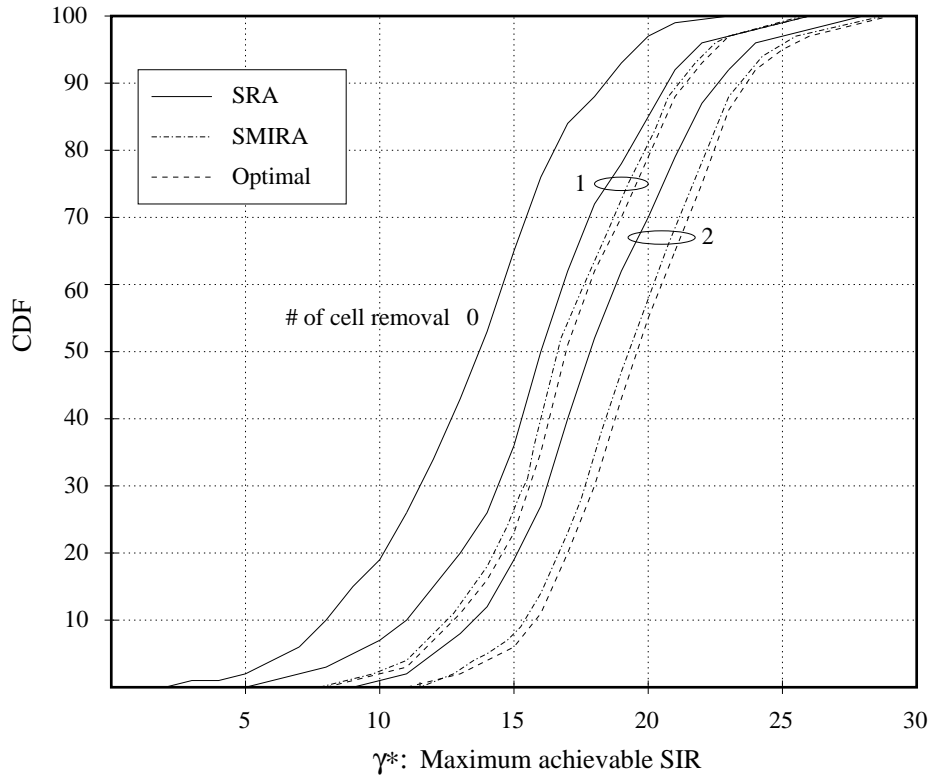
## Other One-By-One Removal Algorithms

[Andersin.Rosberg.Zander\_96]

- outage performance: very close to optimal removal

## Performance Comparison

[Lee.Lin.Su\_95]: 19 cochannel cells with 7-cell cluster



Ensemble mean of  $\gamma^*$

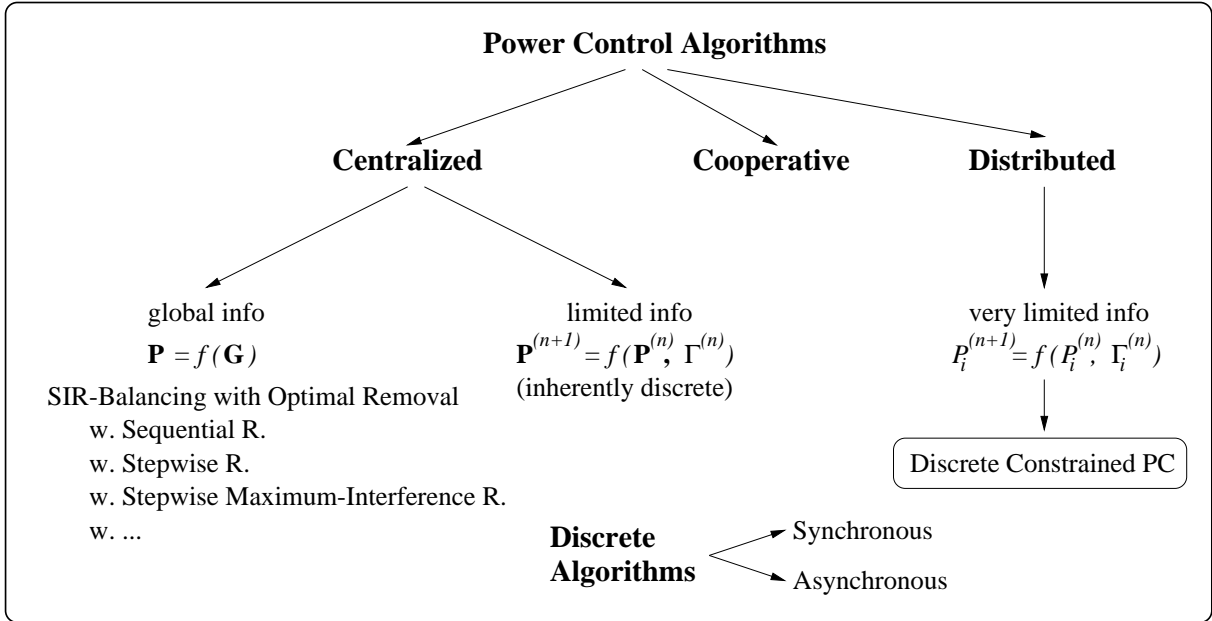
# of MSs rmvd	Optimal	SMIRA	SRA
1	17.29	17.02	16.16
2	19.91	19.58	18.24

Percentage of optimum removals

# of MSs rmvd	Optimal	SMIRA	SRA
1	100	64.8	44
2	100	48.8	22.2

# Distributed PC Algorithms

[Zander\_92b] [Grandhi.Vijayan.Goodman\_92] [Lee.Lin.Su\_95]  
 [Grandhi.Zander.Yates\_95] [Andersin.Rosberg.Zander\_96]



- SIR-balancing can be implemented in a distributed manner
  - $\gamma_i = P_i / \sum_{j:j \neq i} Z_{ij} P_j$ : SIR for user  $i$
  - $I_i = \sum_{j:j \neq i} Z_{ij} P_j$ : total interference experienced by user  $i$
  - $\gamma_i^t$ : target SIR for user  $i$  (SIR-balancing to different values  $\rightarrow$  multimedia applications)

- **Discrete (Iterative) Power Control**

$$\mathbf{P}^{(0)} = \mathbf{P}_o, \quad \mathbf{0} < \mathbf{P}_o$$

$$P_i^{(n+1)} = \frac{\gamma_i^t P_i^{(n)}}{\gamma_i^{(n)}} = \gamma_i^t I_i^{(n)}$$

<b>7. Discrete Constrained Power Control (DCPC)</b>
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- $P_{i,max}$ : maximum tx power for user  $i$

$$\mathbf{P}^{(0)} = \mathbf{P}_o, \quad \mathbf{0} < \mathbf{P}_o \leq \mathbf{P}_{max}$$

$$P_i^{(n+1)} = \min(\gamma_i^t I_i^{(n)}, P_{i,max})$$

- DCPC: always converges to a unique (stable) power vector (fixed point problem), for both synchronous and asynchronous updates.

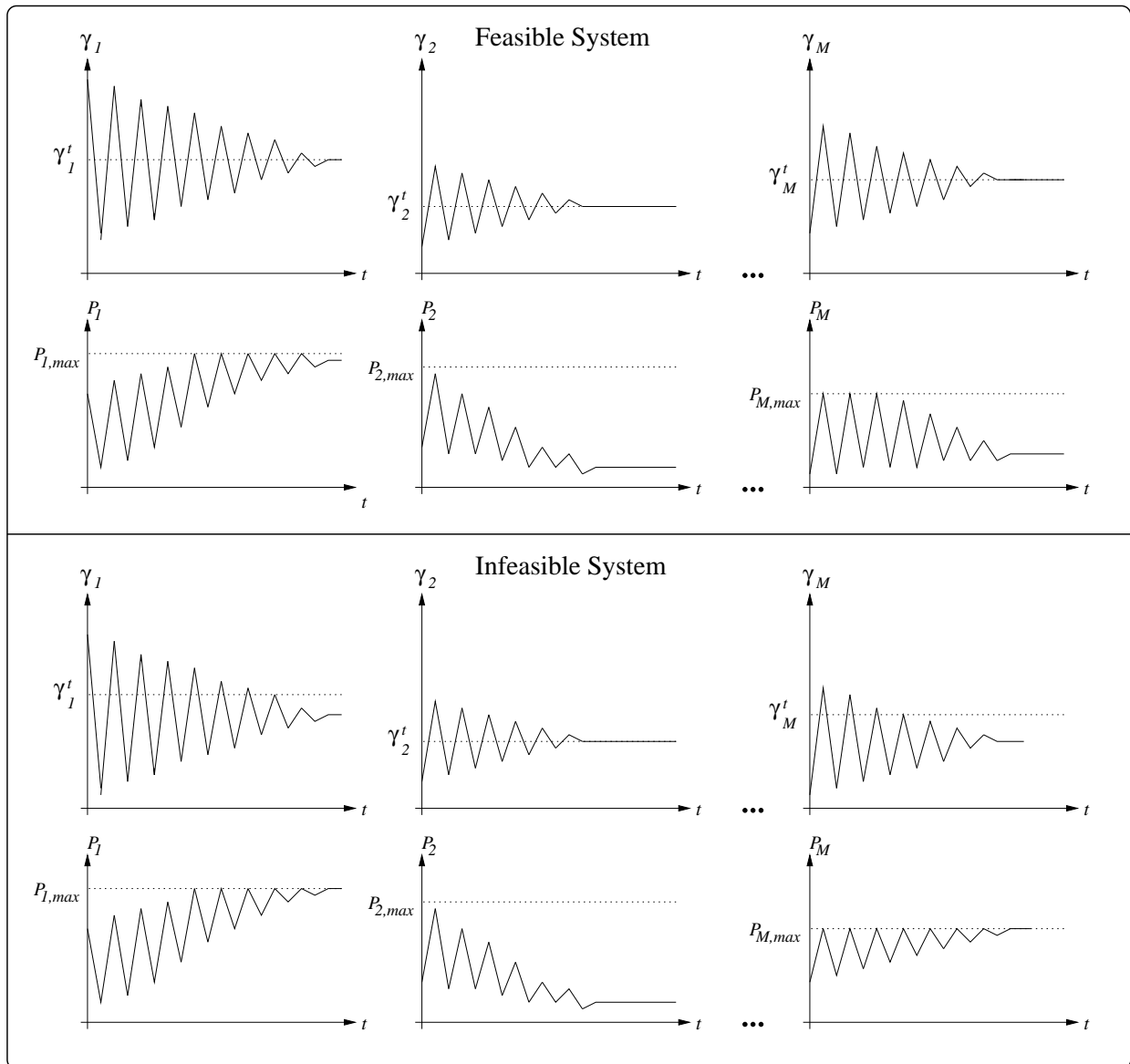
- **Removal Strategies:**

(a) Remove at the stable point

- one-by-one removal (SMIRA, ...)
- multiple removals

(b) PC and removal combined (remove before the stable point reached)

## DCPC in Feasible and Infeasible Systems

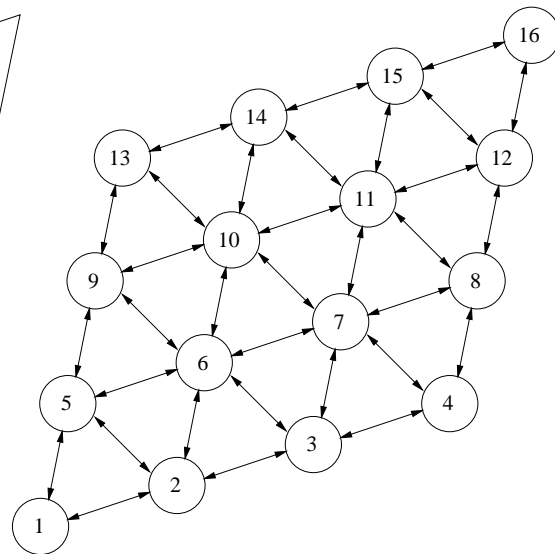
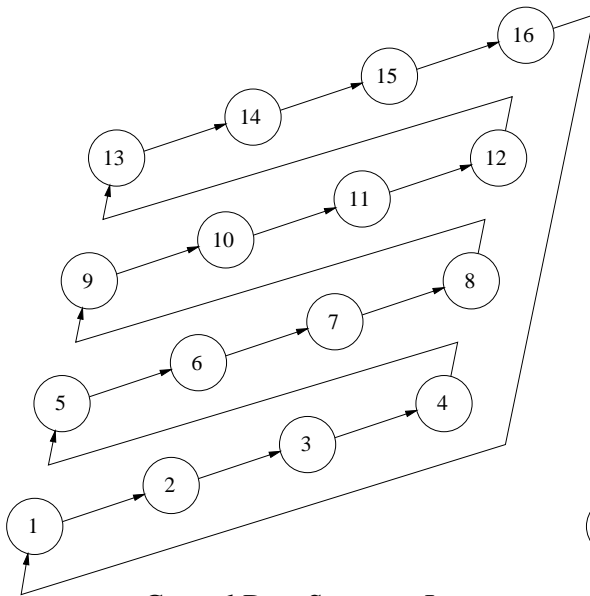
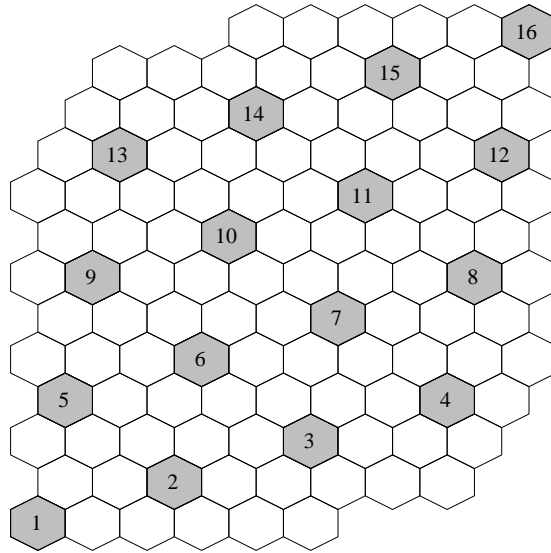


## Example: DCPC with One-by-One Removal

1. Set  $P = 1$ . If  $\gamma_i^{(0)} > \gamma_o, \forall i$ , stop; else,
  2. Operate PCPC algorithm for at most  $N$  steps. If for  $n < N, \gamma_i^{(n)} > \gamma_o, \forall i$ , stop; else,
  3. Remove MS  $i$  according to a meaningful rule (eg: the user with the smallest  $\gamma_i^{(0)}$ ). Go to step 1.
- Uses the SIR measurements of the wanted links
  - Removal procedure requires the collection of data from the BSs in order to compare the SIR values in the different cells.
    - straightforward procedure in a global network control scheme.
  - Rather insensitive to SIR estimation errors

# Cooperative PC Algorithms

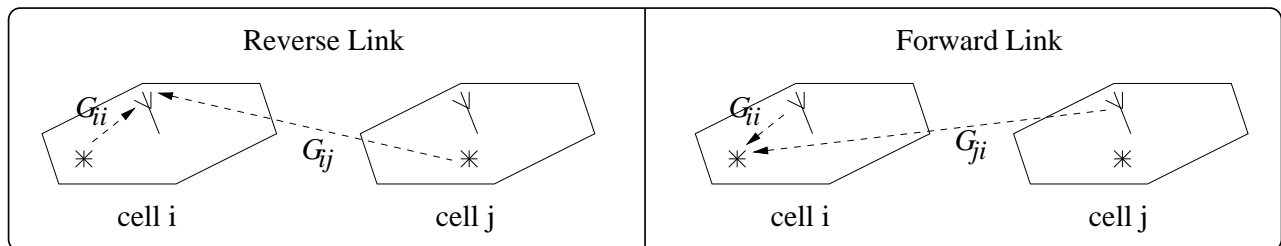
[Sung.Wong\_99]



## 8. Relation Between Forward and Reverse Link

### PC Formulations in FDMA/TDMA Systems

[Nettleton.Alavi\_83], [Zander.Frodigh\_94], [Wu\_99]



$$\gamma_{i,RL} = \frac{G_{ii}P_i}{\sum_{j=1}^M G_{ij}P_j - G_{ii}P_i} = \frac{P_i}{\sum_{j=1}^M \frac{G_{ij}}{G_{ii}}P_j - P_i},$$

$$\gamma_{i,FL} = \frac{G_{ii}P_i}{\sum_{j=1}^M G_{ji}P_j - G_{ii}P_i} = \frac{P_i}{\sum_{j=1}^M \frac{G_{ji}}{G_{ii}}P_j - P_i},$$

$$\text{with } Z_{ij} = \frac{G_{ij}}{G_{ii}} \text{ and } W_{ij} = \frac{G_{ji}}{G_{ii}}.$$

$$\text{Since, } Z_{ji} = \frac{G_{ji}}{G_{jj}} \rightarrow W_{ij} = Z_{ji} \frac{G_{jj}}{G_{ii}}.$$

- Therefore,  $\mathbf{W} \neq \mathbf{Z}^T$ , but they are related; indeed,

$$|\mathbf{Z} - \lambda\mathbf{I}| = |\mathbf{W} - \mu\mathbf{I}|$$

→  $\mathbf{Z}$  and  $\mathbf{W}$  have the same characteristic equations and thus identical eigenvalues:  $\lambda_i = \mu_i, \forall i \rightarrow \lambda^* = \mu^*$ .

→ The maximum achievable SIR in the forward and reverse links are identical, i.e.,  $\gamma_{\text{reverse}}^* = \gamma_{\text{forward}}^*$ .

Remark: the corresponding eigenvectors (the tx powers) will in general be different.

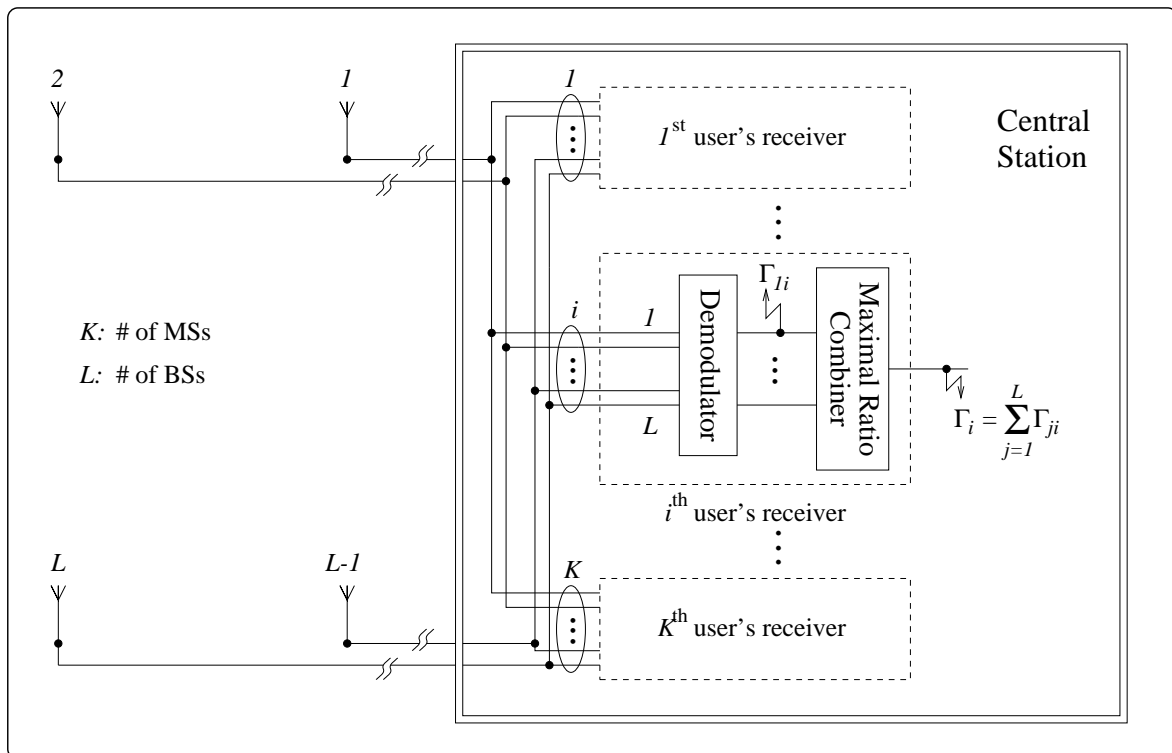
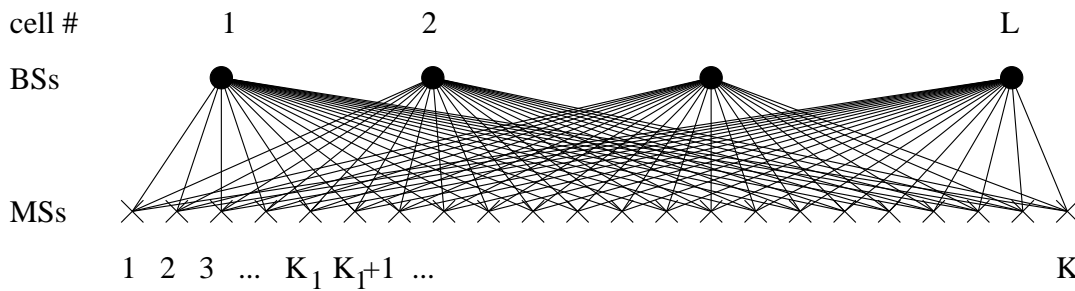
- Whenever a certain SIR level is achieved in one direction, the tx power in the other direction can always be adjusted to achieve at least the same SIR value.

- For a given  $\gamma_o$ , the optimal removal set of the forward and reverse links are always the same when the optimal removal algorithm is executed independently on either direction.

→ The optimal removal action performed in one direction can always be directly performed on the other direction to achieve the optimum performance in both directions.

## 9. PC in CDMA Macrodiversity Systems

- Logical limit of macrodiversity (MD):  
all MSs communicate with all BSs  
→ not a cellular structure
- single index for MSs:  $1 \rightarrow K$



- $\gamma_{ji}$ : SIR at the  $j$ th finger of the combiner for MS  $i$ , that is, the SIR contribution from BS  $j$

$$\gamma_{i,\text{MD}} = \sum_{j=1}^L \gamma_{ji} = \sum_{j=1}^L \frac{G_{ji}P_i}{\left(\sum_{k=1}^K G_{jk}P_k\right) - G_{ji}P_i}, \quad \forall i$$

- Obtain  $\gamma^*$  and  $\mathbf{P}^*$

### SIR-Balancing in Macrodiversity Systems

$$\gamma_{i,\text{MD}} = \sum_{j=1}^L \frac{G_{ji}P_i}{\left(\sum_{k=1}^K G_{jk}P_k\right) - G_{ji}P_i} = \gamma, \quad \forall i$$

- nonlinear set of equations
  - eigenvalue method does not apply
  - no closed-form solution exists
  - solve iteratively [Yanikomeroglu.Sousa\_98]

## 10. Future Research Directions in PC and RRM

- Joint power-rate-QoS-handoff-... control in advanced wireless system architectures
  - very rich, multi-dimensional, challenging problem
  - potentially remarkable returns
- PC in 1-3G mobile systems
  - strategy: simple
  - implementation: complex
- More powerful PC strategies ?
  - may be possible for not-too-fast changing channels (fixed or low-mobile terminals)
  - computationally efficient and fast-converging optimal or suboptimal algorithms
    - \* distributed and cooperative (limited information) constrained PC algorithm
- PC: closely related to other systems issues
  - smart antennas
  - handoff
  - dynamic channel assignment
  - base assignment
  - medium access control (MAC)
  - ...
- PC in ad hoc networks

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