IEEE WCNC'00

Wireless Communications and Networking
Conference 2000

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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September 23, 2000 - Chicago, USA

Outline

1. Introduction to Radio Resource Management (RRM)
2. Conventional Power Control in Fixed Cellular Broadband 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
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8. Forward-Link versus Reverse-Link Formulation
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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

    → $\boxed{\text{RRM} \simeq \text{adaptive tx power control (PC)}}$
  - ○ rich literature & vast expertise on PC
- Multimedia systems
  - ○ tx rate: another adjustable radio resource
  - ○ QoS: a negotiable parameter

    → joint power-modulation-coding_level control

    → $\boxed{\text{Joint power-rate-QoS control}}$
- 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.Sampei.Morinaga_00] [Kim.Honig_00] [Yanikomeroglu.Sousa_00]

Problem Formulation

Γ_i: SIR of MS i (Γ)
γ_i: minimum required SIR for MS i (γ)

P_i: tx power of MS i (**P**)
p_i: maximum allowable tx power for MS i (**p**)

R_i: information rate of MS i (**R**)
r_i: minimum required information rate for MS i (**r**)

- **Goal**: find **P** and **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 **P** and **R** → optimization

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

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

- Base assignment and mobility can also be incorporated
- Constrained optimization problem
  → 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:

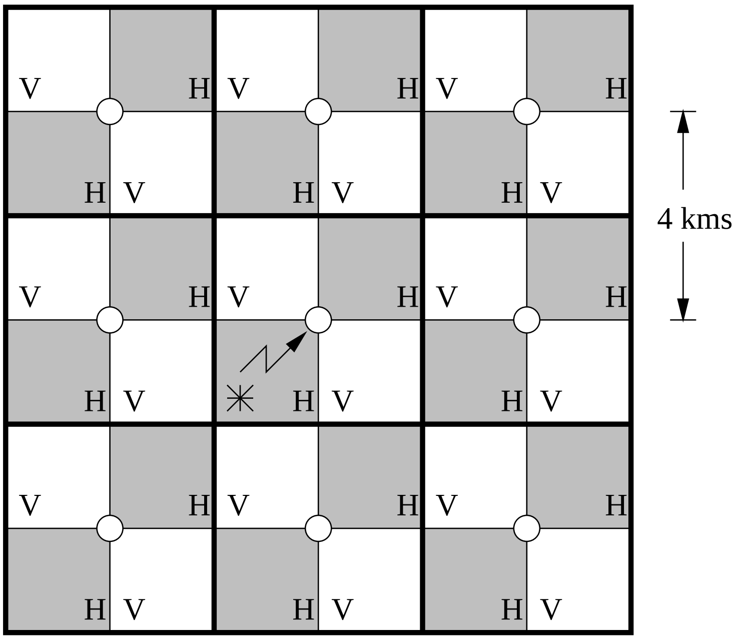
- not an easy task!
- optimal solution: very difficult to obtain
- search for efficient sub-optimal methods of managing radio resources

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^o, subcriber antenna beamwidth = 3^o

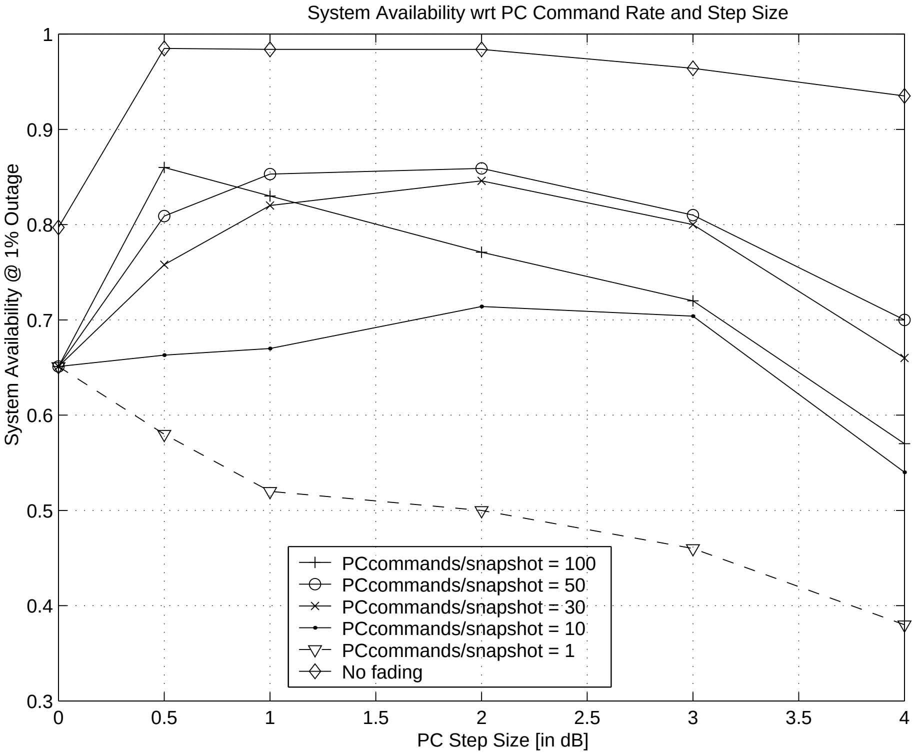
Uniform main and side lobes, antenna gain ratio = 25 dB

Frequency reuse factor = 4

9 cells, 17 interferers

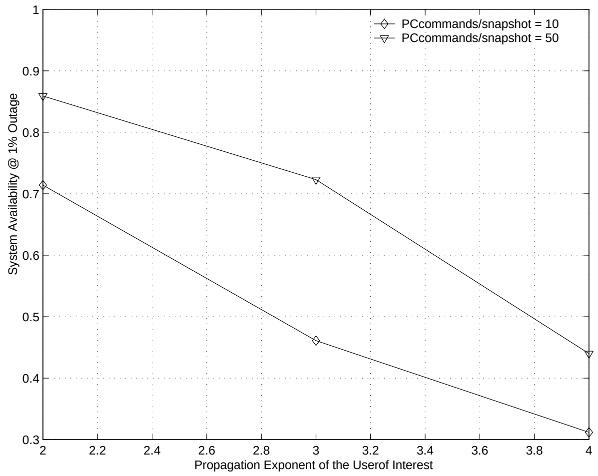
Maximum transmit power = 100 milliwatts

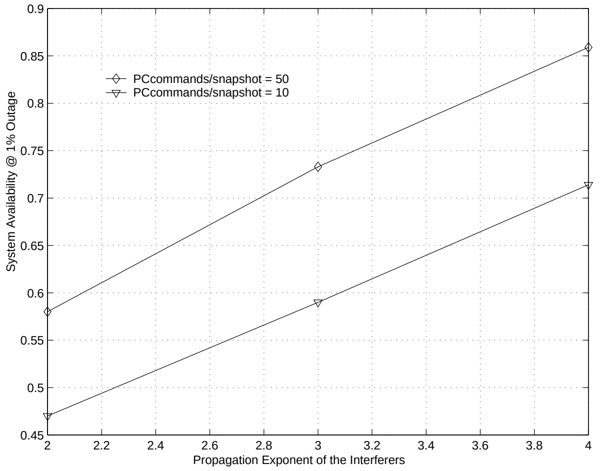
- Simulation Parameters
  - ∘ target SINR = 10 dB
  - ∘ propagation exp
    user of interest and the main interferer = 2
    other interferers = 4
  - ∘ Rician K factor
    user of interest and the main interferer = 10
    other interferers = 4
  - ∘ shadowing standard deviation = 10 dB (all users)
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

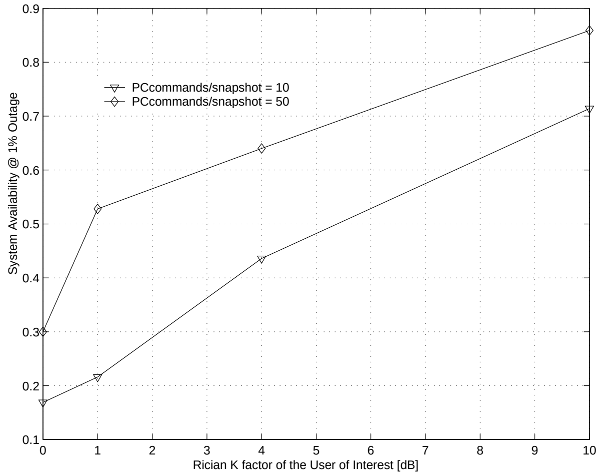


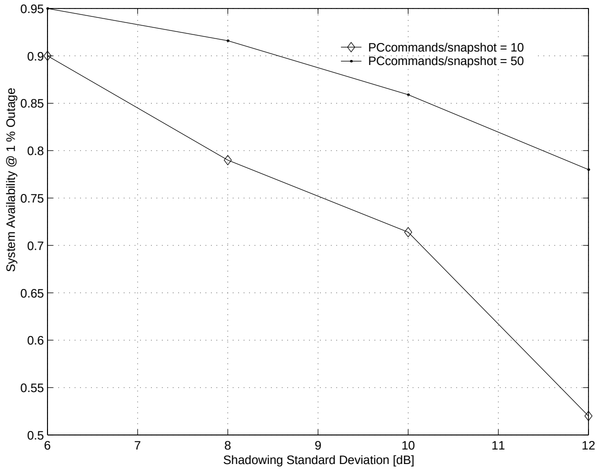
- System availability =
percentage of locations for which $P(\gamma < 10 \text{ dB}) < 1\%$

System Availability wrt Propogation Environment





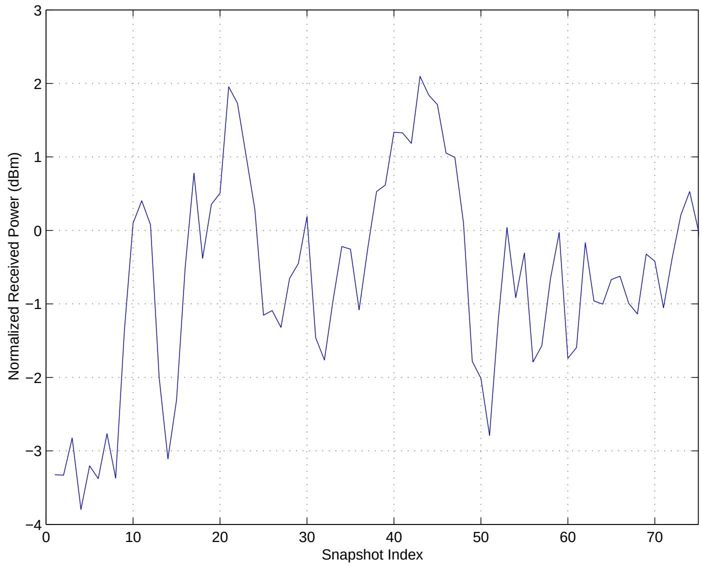




→ Power control enhances coverage

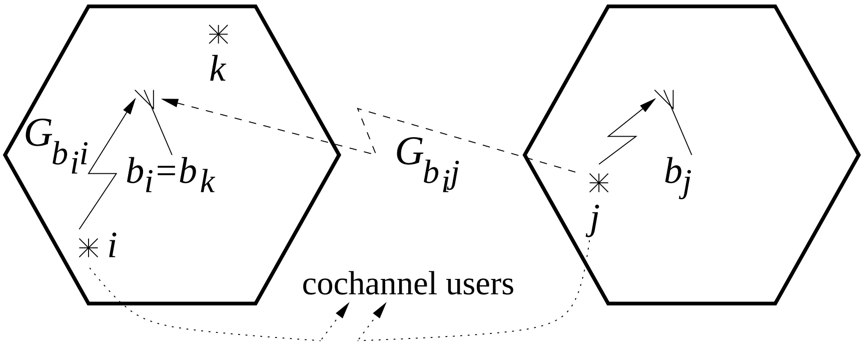
- Measured received power with time ([Naz.Falconer_00])

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



→ 1 snapshot $\simeq$ 1/15 seconds
→ ~ 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 $\mathcal{C}$

- $G_{b_i j}$: 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 $\mathcal{C}$

- γ_i: SIR for user i

○ $\Gamma = [\gamma_i]$: SIR vector for users in the same $\mathcal{C}$

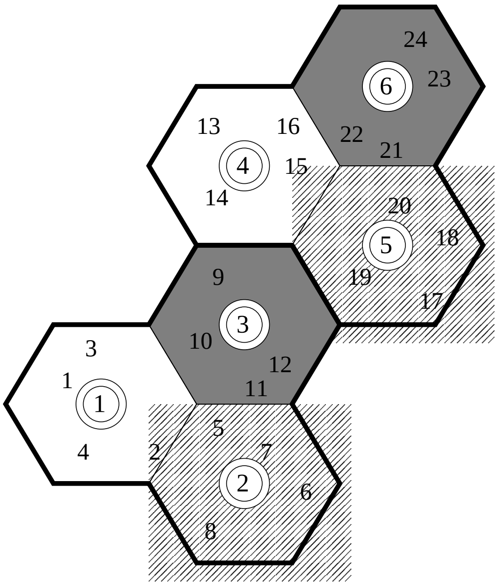
$$\gamma_i = \frac{G_{b_i i} P_i}{\sum_{j \in \mathcal{C}_i, j \neq i} G_{b_i j} P_j}$$

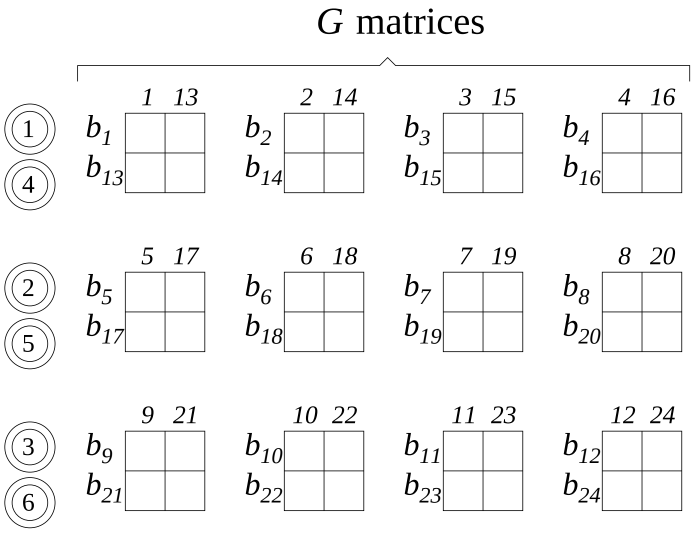
TDMA/FDMA Systems

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

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

$\rightarrow$ 12 parallel power control processes





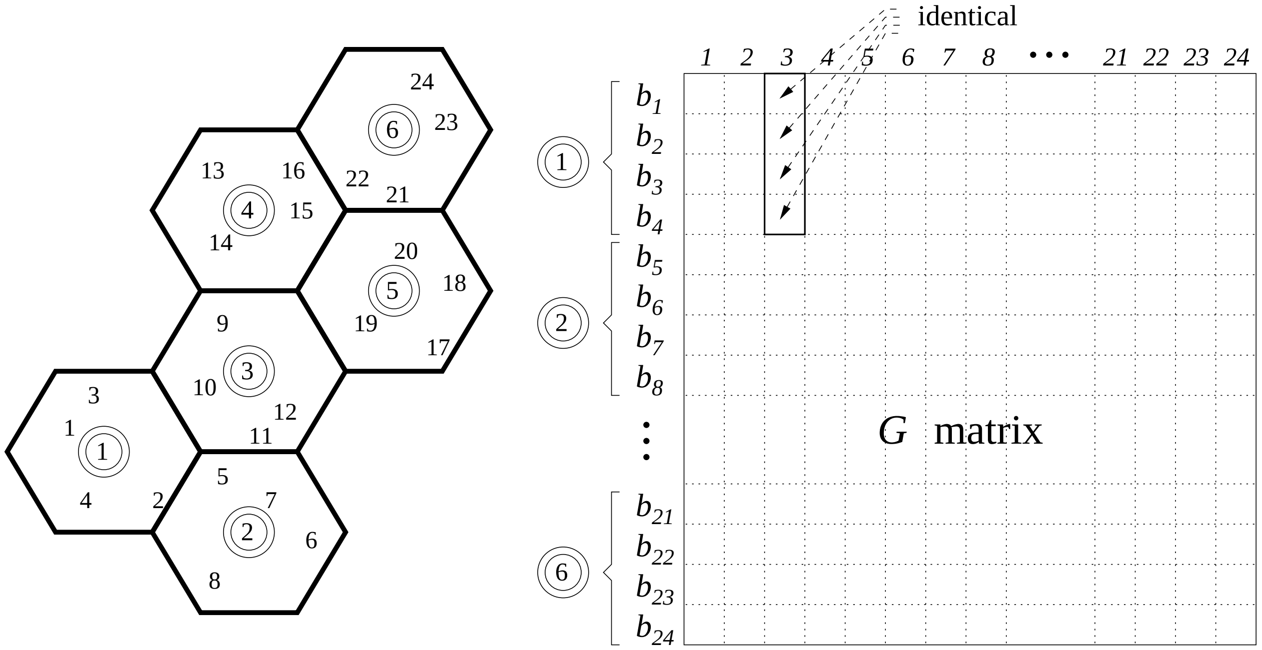
$$\gamma_i = \frac{G_{b_i i} P_i}{\displaystyle\sum_{j \in \mathcal{C}_i, j \neq i} G_{b_i j} P_j}$$

CDMA Systems

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

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

→ 1 parallel power control process



M: size of the cochannel set

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

Some Results from Linear Algebra

- **Eigenvalue and Eigenvector**

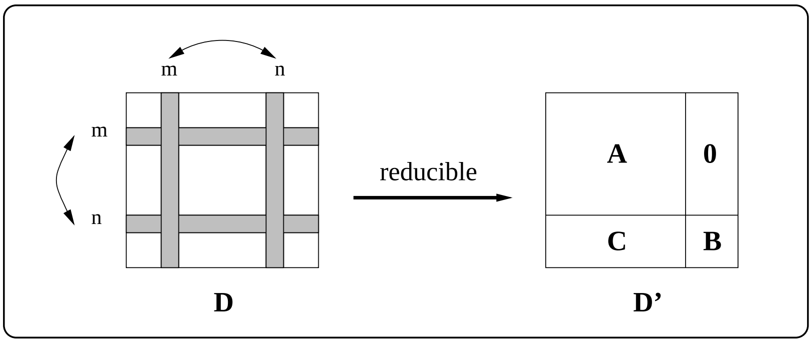
  $*$ Let $\mathbf{Z}_{(L)}$ be an $L \times L$ square matrix.

  $*$ $\{\lambda_i\}_{i=1}^{L}$: 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

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

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

4. SIR-Balancing and Mobile Removal Algorithms

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

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

$$\text{PC Algorithm} \begin{cases} \text{a) Try to achieve } (\mathbf{P}^*, \gamma^*), \\ \text{b) Develop a strategy for the case} \\ \quad \gamma^* < \gamma_o \,\text{(threshold)} \end{cases}$$

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!

  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: $\gamma^* = \frac{1}{\lambda^* - 1}, \ \mathbf{P}^*$

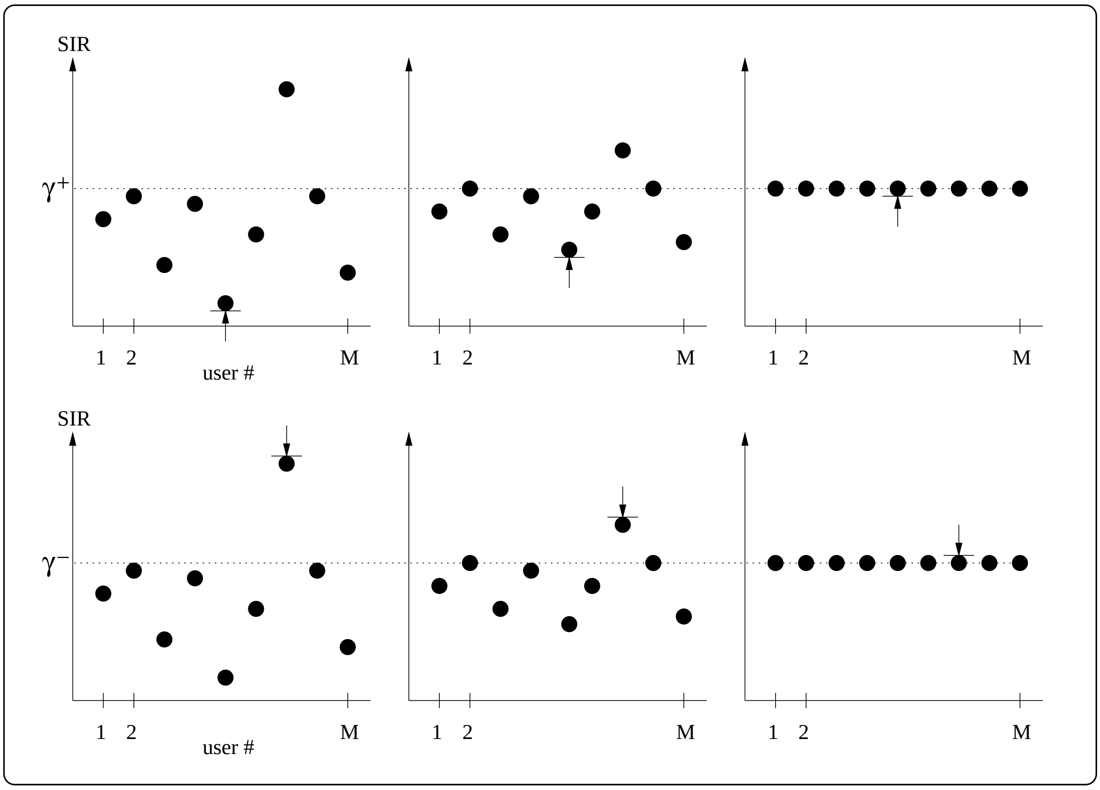
5. Optimum Power Control

- Can an unbalanced case yield a higher γ ?

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

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

[Grandhi.Vijayan.Goodman.Zander_93]



- SIR-balanced system yields the largest achievable γ.

- Remark: largest achievable SIR is related to the spectral properties of **Z**.

$$\text{PC Algorithm} \begin{cases} \text{a) Try to achieve } (\mathbf{P}^*, \gamma^*), \\ \text{b) Develop a strategy for the case} \\ \quad \gamma^* < \gamma_o \end{cases}$$

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 $\mathbf{P}^* \rightarrow \gamma^* < \gamma_o$.

  Form $\bar{\mathbf{P}}^* : \begin{cases} \bar{P}_i^* = P_i^*, & i \neq k \\ \bar{P}_k^* = 0 \end{cases}$, i.e., turn off MS k.

  $\bar{\gamma}_k = 0$

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

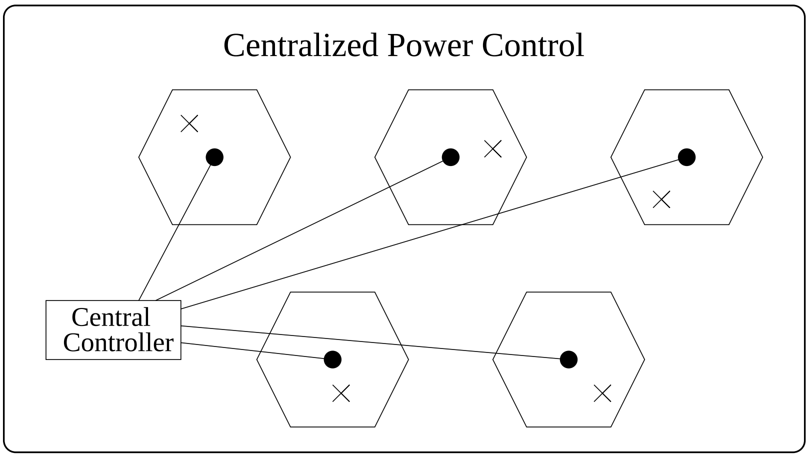
- Remark: the above system is not balanced (by balancing it even a higher SIR level can be achieved for all MSs).

- Turn off MS kth $\equiv$ form $\bar{\mathbf{Z}}$ by removing the kth row and column of **Z**. Then, SIR balance $\rightarrow \bar{\gamma}^* > \gamma^*$.

6. Centralized, Cooperative, and Distributed Algos

PC Algorithm Types			
Structure	Centralized	Cooperative	Distributed
Link Info	extensive	limited	very limited

Centralized algorithm: instantaneously controls the entire vector **P**.



- BSs report radio link information to a central controller. The controller then distributes the power control decisions throughout the network.

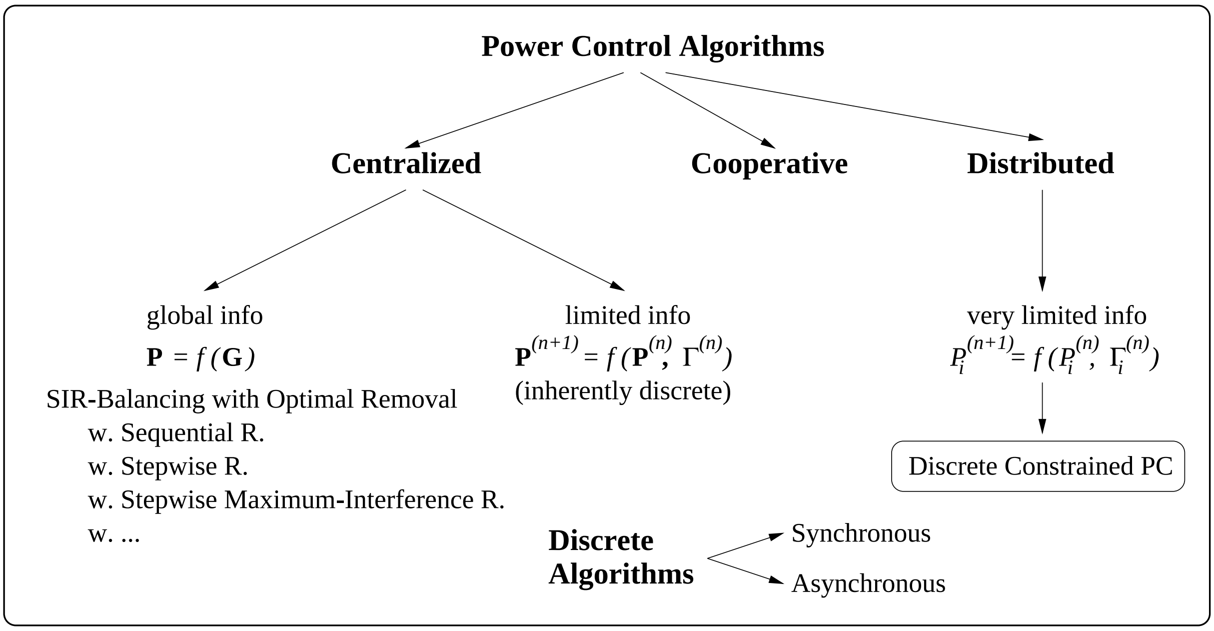
- global radio link information: instantaneous access to the entire link gain matrix **G** (→ optimum algorithm possible)
  - $*$ a central controller required
  - $*$ significant control signal exchange
  - $*$ delay introduced

  - ∗ 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 **G**.



Power Control Algorithms

Centralized **Cooperative** **Distributed**

global info
$\mathbf{P} = f(\mathbf{G})$
SIR-Balancing with Optimal Removal
w. Sequential R.
w. Stepwise R.
w. Stepwise Maximum-Interference R.
w. ...

limited info
$\mathbf{P}^{(n+1)} = f(\mathbf{P}^{(n)}, \Gamma^{(n)})$
(inherently discrete)

very limited info
$P_i^{(n+1)} = f(P_i^{(n)}, \Gamma_i^{(n)})$

Discrete Constrained PC

Discrete Algorithms → Synchronous, Asynchronous

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

Centralized PC Algorithms

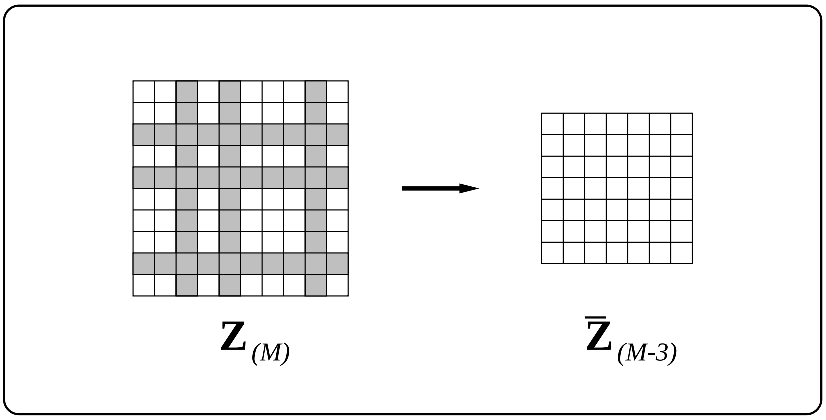
Optimum MS Removal Strategy: Find the largest square submatrix of $\mathbf{Z}$, denoted by $\bar{\mathbf{Z}}$, for which γ_o is achievable, by removing as few MSs as possible (NP-complete).

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 → no interference left → algorithm works.

- Construct smaller and smaller balanced systems by removing MSs. Find the largest square submatrix of **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:

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

→ exponential complexity

Sequential Removal Algorithm: Remove one MS at a time until γ_o is achieved.

- The number of eigenvalue computations in the worst case:

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

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 $\surd$

• The SRA seeks to maximize the lower bound for γ^*

• 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 $m = m + 1$.

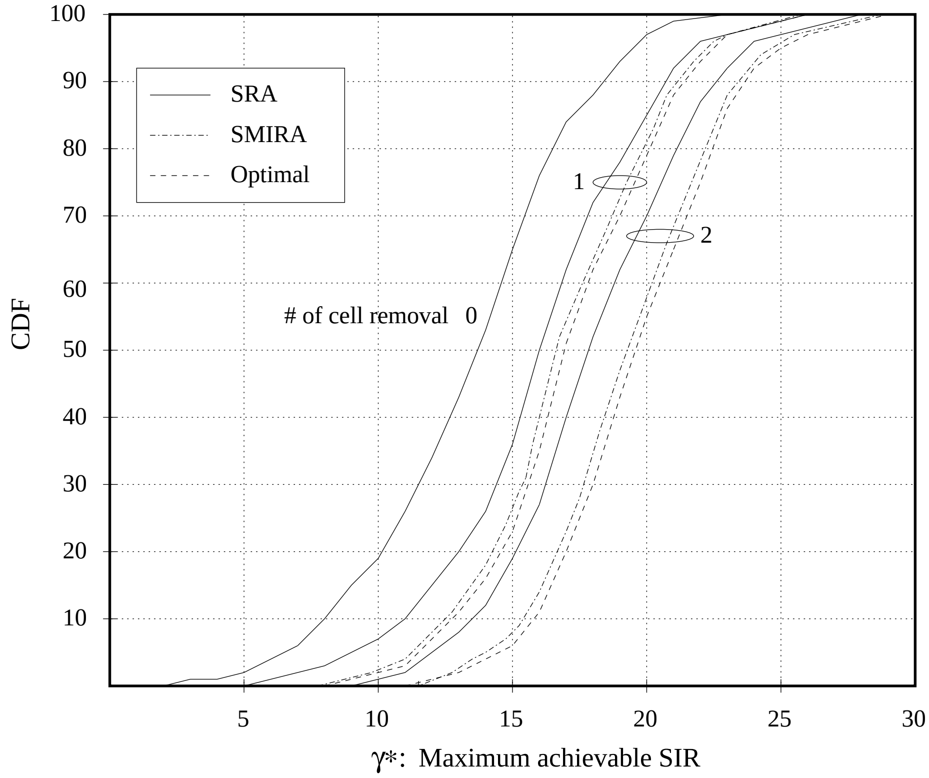
Other One-By-One Removal Algorithms

[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 γ^*

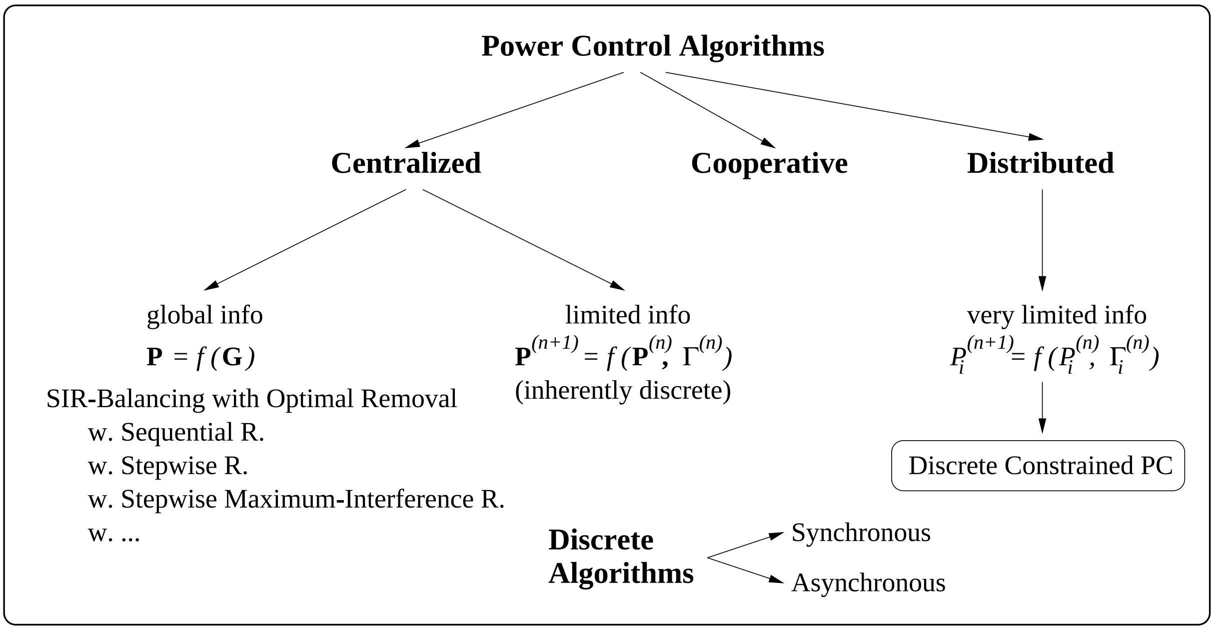
# of MSs rmvd	Optimal	SMIRA	SRA
1	17.29	17.02	16.16
2	19.91	19.58	18.24

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]



Power Control Algorithms

Centralized

global info

$\mathbf{P} = f(\mathbf{G})$

SIR-Balancing with Optimal Removal
  w. Sequential R.
  w. Stepwise R.
  w. Stepwise Maximum-Interference R.
  w. ...

limited info

$\mathbf{P}^{(n+1)} = f(\mathbf{P}^{(n)}, \Gamma^{(n)})$

(inherently discrete)

Cooperative

Distributed

very limited info

$P_i^{(n+1)} = f(P_i^{(n)}, \Gamma_i^{(n)})$

Discrete Constrained PC

Discrete Algorithms

Synchronous

Asynchronous

- 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

  ∘ γ_i^t: target SIR for user i (SIR-balancing to different values → multimedia applications)

- **Discrete (Iterative) Power Control**

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

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

7. Discrete Constrained Power Control (DCPC)

- $P_{i,max}$: maximum tx power for user i

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

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

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

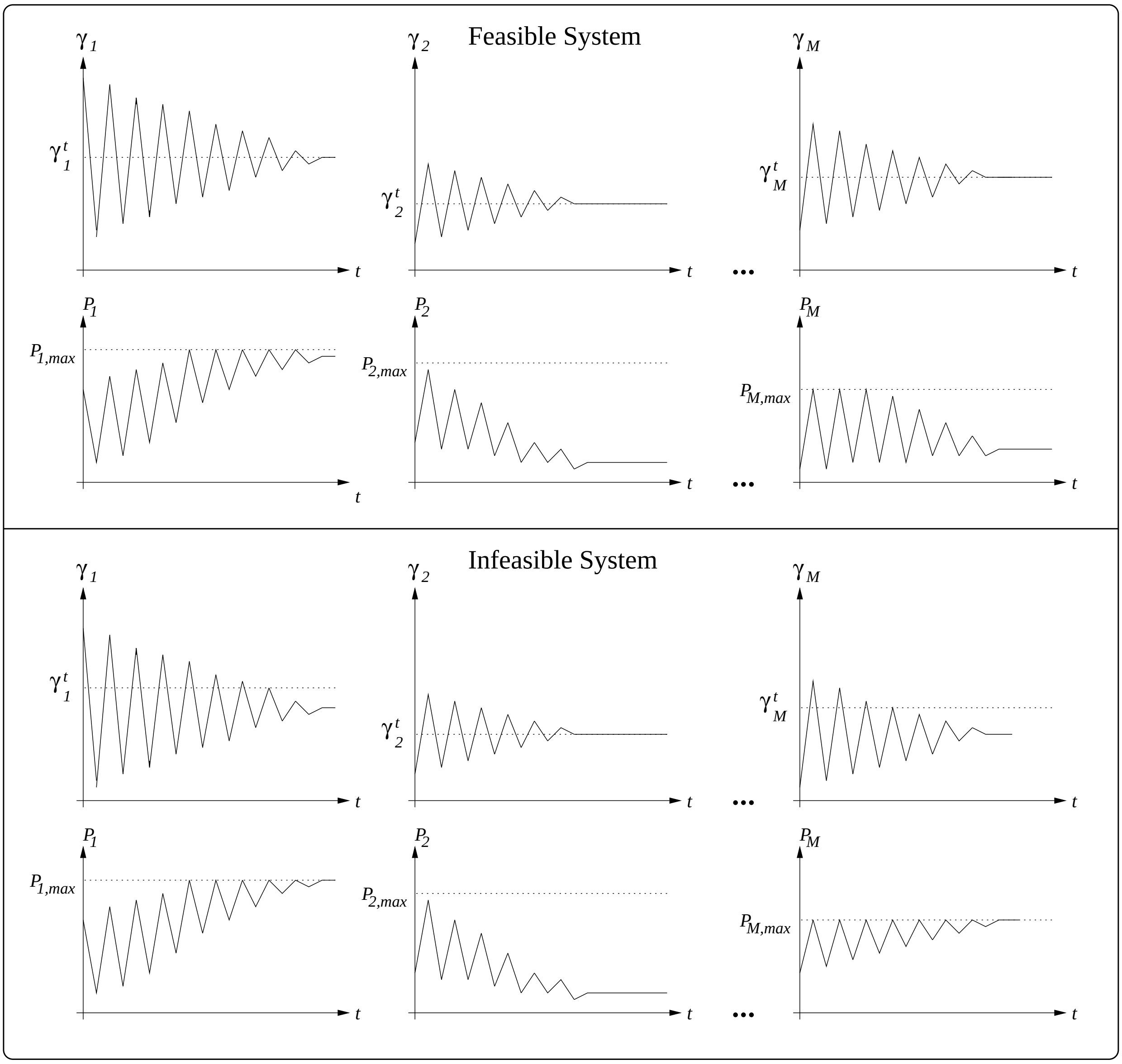
- **Removal Strategies**:

(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 $\mathbf{P} = 1$. 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.

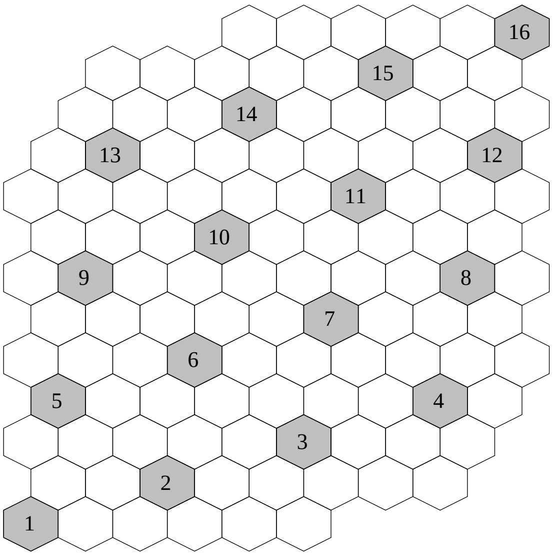
- Uses the SIR measurements of the wanted links

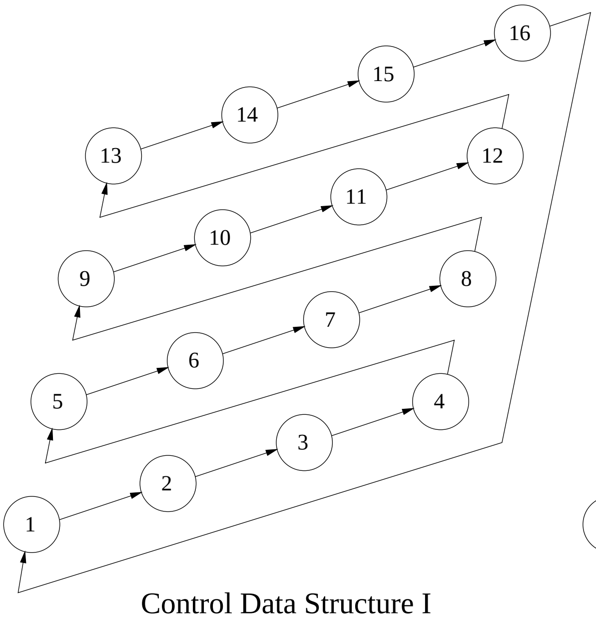
- Removal procedure requires the collection of data from the BSs in order to compare the SIR values in the different cells.
  → straightforward procedure in a global network control scheme.

- Rather insensitive to SIR estimation errors

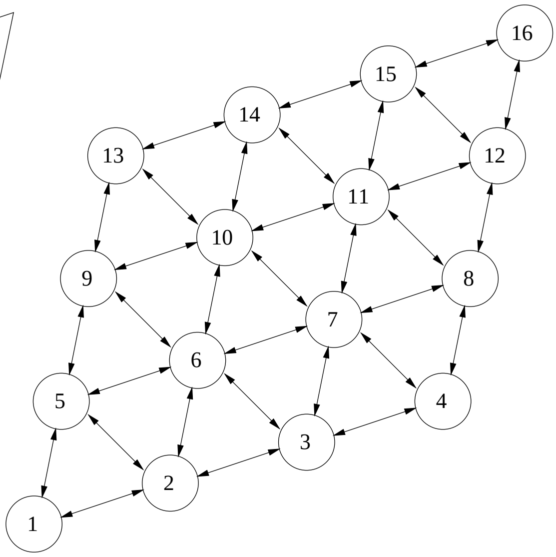
Cooperative PC Algorithms

[Sung.Wong_99]





Control Data Structure I

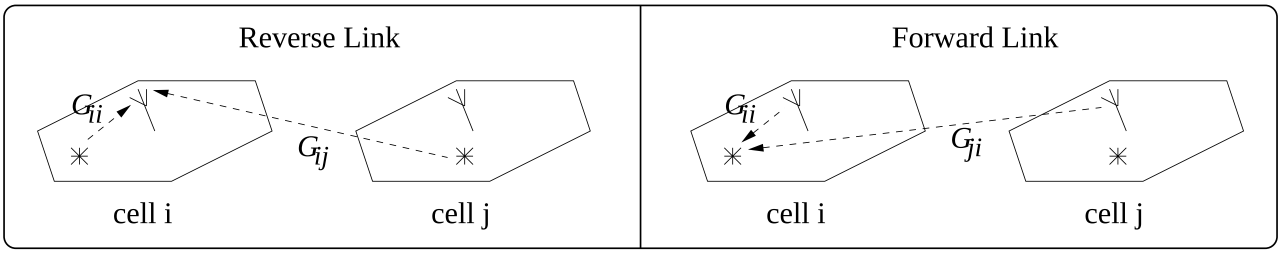


Control Data Structure II

8. Relation Between Forward and Reverse Link

PC FormulationIs in FDMA/TDMA Systems

[Nettleton.Alavi_83], [Zander.Frodigh_94], [Wu_99]



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

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

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

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,

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

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

→ 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.

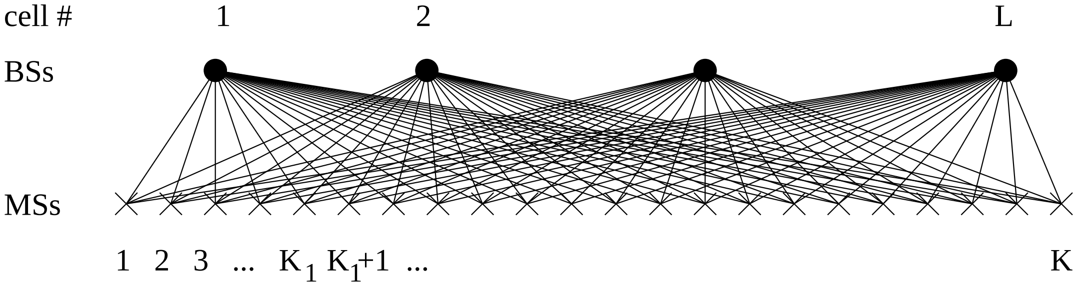
- Whenever a certain SIR level is achieved in one direction, the tx power in the other direction can always be adjusted to achieve at least the same SIR value.

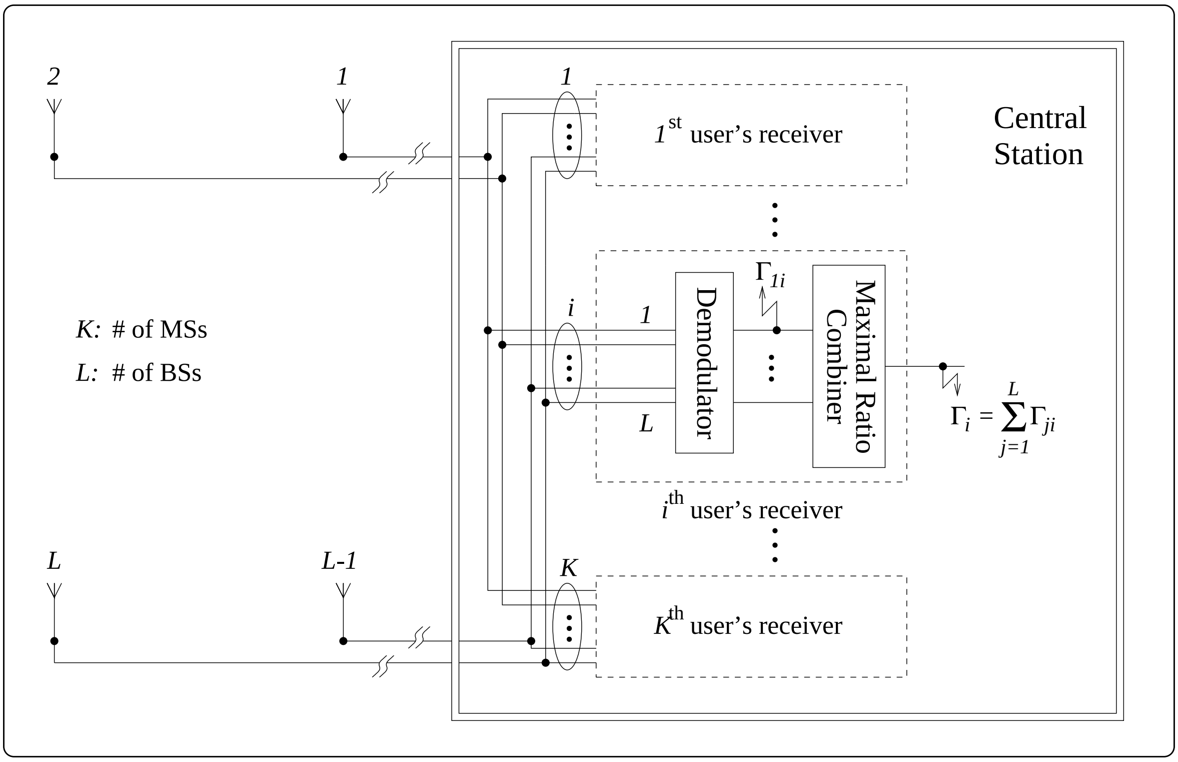
- For a given γ_o, the optimal removal set of the forward and reverse links are always the same when the optimal removal algorithm is executed independently on either direction.

→ 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: $1 \rightarrow K$





- γ_{ji}: SIR at the jth 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 γ^* 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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