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# Energy Conservation and Interference Mitigation

## --From Decoupling Property to Win-Win Strategy

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# Introduction

- Energy Conservation of mobile terminals in a multi-cell TDMA network
  - Within a cell: TDMA (no interference)
  - Across cells: overlap in time (interference)
- Two trade-offs:
  - Within a cell: transmit energies trade off against each other

$$b = xT = wT \log\left(1 + \frac{E \cdot G}{T\sigma^2}\right)$$

  - Across cells: tradeoff between energy and inter-cell interference

$$b = wT \log\left(1 + \frac{E \cdot G}{T(\sigma^2 + q)}\right)$$

- Airtime allocation within a cell and power control across cells

# Network Model

- Power Consumption
  - Transmit power: $x = w\log\left(1+\frac{p\cdot G}{\sigma^2+q}\right) \Leftrightarrow p = \left(\exp\left(\frac{x}{w}\right)-1\right)\frac{\sigma^2+q}{G}$
  - Total power consumption: $f(x) = \begin{cases} \left(\exp\left(\frac{x}{w}\right)-1\right)\frac{\sigma^2+q}{\theta G}+\alpha, & \text{if } x>0 \text{ (active)} \\ \beta, & \text{if } x=0 \text{ (idling)} \end{cases}$
- Dynamic Sessions:
  - Real-time sessions: Poisson arrival with rate $\lambda$
  - Energy-Power Equivalence:
    - minimizing the average energy consumption per session ⟺

      minimizing the average power consumption

# Key notations

- $M$ cells: $\{C(m), 1 \leq m \leq M\}$
- Each cell $C(m)$ contains a set of mobile users: $\mathcal{A}(m)$
- $\mathcal{S}$ : the set of mobile users active simultaneously, $|\mathcal{S}| \leq M$
- Total $K$ concurrent transmission sets: $\{\mathcal{S}_k, 1 \leq k \leq K\}$
- Binary coefficient: denote whether user $i(m)$ is scheduled in set $\mathcal{S}_k$

$$z_{i(m)}(k) = \begin{cases} 1, & \text{if } i(m) \in \mathcal{S}_k, \\ 0, & \text{if } i(m) \notin \mathcal{S}_k. \end{cases}$$

# Problem Formulation

- $\mathbf{x}_{\mathcal{S}_k}$ :the instantaneous rate vector of set $\mathcal{S}_k$
- Given the rate vector, the required SINR vector and the minimum power solution vector can be computed:

$$\mathbf{x}_{\mathcal{S}_k}$$

$$\Longrightarrow \gamma_{\mathcal{S}_k} = \exp\left(\frac{\mathbf{x}_{\mathcal{S}_k}}{w}\right) - 1$$

$$\Longrightarrow \mathbf{p}_{\mathcal{S}_k}(\mathbf{x}_{\mathcal{S}_k}) = \left(\mathbf{I} - \mathbf{D}\left(\exp\left(\frac{\mathbf{x}_{\mathcal{S}_k}}{w}\right) - 1\right)\mathbf{B}_{\mathcal{S}}\right)^{-1} \cdot \mathbf{D}\left(\exp\left(\frac{\mathbf{x}_{\mathcal{S}_k}}{w}\right) - 1\right)\mathbf{v}_{\mathcal{S}}$$

# Problem Formulation

- **Problem: Power Minimization in a Multi-cell Network**

$$\begin{array}{ll}
\text{minimize} & \displaystyle\sum_{k=1}^{K} t_k \left( \sum_{m=1}^{M} \left( \sum_{i(m)\in\mathcal{A}(m)} \left( (1 - z_{i(m)}(k))\beta_{i(m)} \right.\right.\right. \\
& \displaystyle \left.\left.\left. + z_{i(m)}(k) \left( \alpha_{i(m)} + \frac{p_{i(m)}(k)}{\theta} \right) \right) \right) \right) \\
\text{subject to} & \displaystyle\sum_{k=1}^{K} t_k = 1, \\
& \displaystyle\sum_{k=1}^{K} z_{i(m)}(k) \cdot x_{i(m)}(k) \cdot t_k = r_{i(m)}, \forall i(m), \forall m, \\
\text{variables} & x_{i(m)}(k) \geq 0, \quad \forall k, \forall i(m), \forall m, \\
& t_k \geq 0, \quad \forall k.
\end{array}$$

sum over all slots

sum over all cells

power consumption in idle state

power consumption in active state

system capacity constraint

rate requirement of each user

# Decomposition Method

- In general, the scheduling and power control are coupled
- One simple assumption:
  - Within each cell, the interference experienced by the base station remains constant within a time frame.
- Decomposition method:
  - Solve intra-cell average power minimization and inter-cell power control separately

# Intra-Cell Average Power Minimization

**Problem: Intra-Cell Average Power Minimization:**

$$\begin{aligned}
\text{minimize} \quad & \sum_{i(m)\in\mathcal{A}(m)} \frac{r_{i(m)}}{x_{i(m)}} \left( \frac{\exp\left(\frac{x_{i(m)}}{w}\right)-1}{\theta G_{i(m)i(m)}} \left(\sigma^2+q(m)\right) + \alpha_{i(m)} + \sum_{j(m)\in\mathcal{A}(m)\backslash\{i(m)\}} \beta_{j(m)} \right) \\
& + \left(1 - \sum_{i\in\mathcal{A}(m)} \frac{r_{i(m)}}{x_{i(m)}}\right) \sum_{i\in\mathcal{A}(m)} \beta_{i(m)} \\
\text{subject to} \quad & \sum_{i(m)\in\mathcal{A}(m)} \frac{r_{i(m)}}{x_{i(m)}} \leq 1 \\
\text{variables} \quad & x_{i(m)} \geq 0, \forall i(m) \in \mathcal{A}(m).
\end{aligned}$$

sum over all users in a cell

power consumption in active airtime

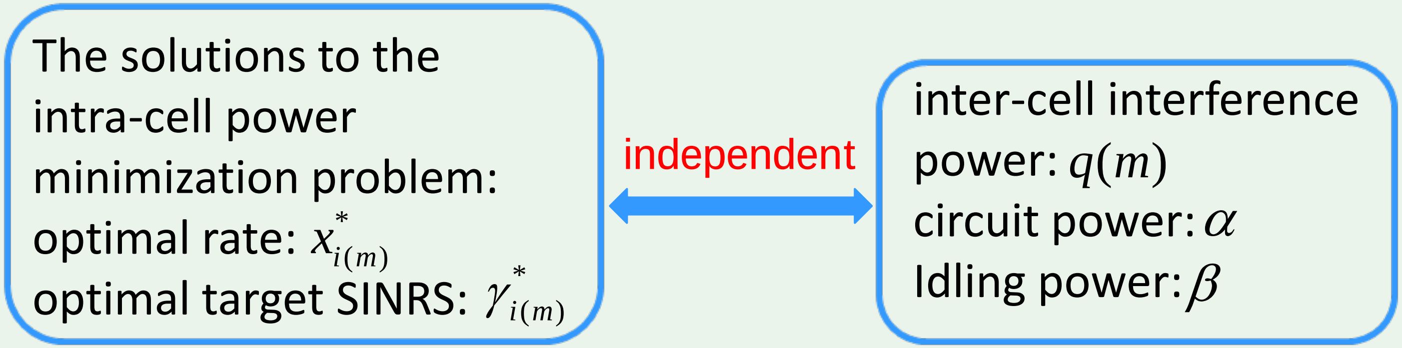
power consumption in idle airtime

- Convex optimization
- Lagrangian method
- In general, optimal solution depends on the inter-cell $q(m)$ interference

# Decoupling Property

- When idling power $\geq$ circuit power

**Theorem 1:**



The solutions to the intra-cell power minimization problem:
optimal rate: $x_{i(m)}^{*}$
optimal target SINRS: $\gamma_{i(m)}^{*}$

independent

inter-cell interference power: $q(m)$
circuit power: $\alpha$
Idling power: $\beta$

# DSP Algorithm when idling power $\geq$ circuit power

- DSP: Decoupling Scheduling and Power control
- when idling power $\geq$ circuit power: totally decoupled

Solve the convex intra-cell power minimization problem using Lagrangian method:

1) Compute the optimal Lagrangian multiplier $\varphi^*$ with Newton method
2) Calculate the optimal rate: $x_{i(m)}{}^* = \left( W\left( \frac{\varphi^* G_{i(m)i(m)} - 1}{e} \right) + 1 \right) w$
3) Calculate the optimal target SINR: $\gamma_{i(m)}{}^* = \exp\left( \frac{x_{i(m)}{}^*}{w} \right) - 1$

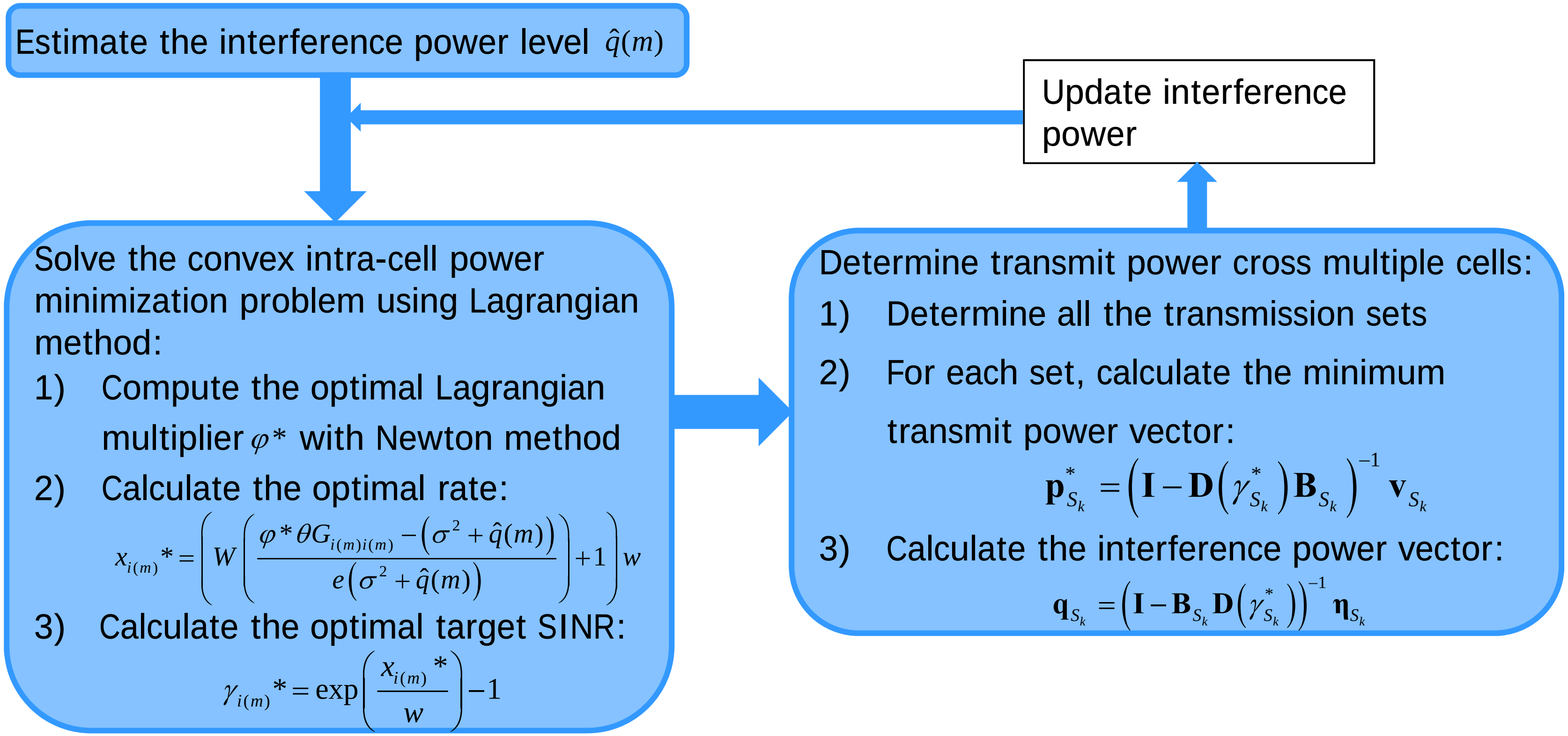
Determine transmit power cross multiple cells:

1) Determine all the concurrent transmission sets
2) For each set, calculate the minimum transmit power vector:

$$\mathbf{p}_{S_k}^* = \left( \mathbf{I} - \mathbf{D}\left( \gamma_{S_k}^* \right) \mathbf{B}_{S_k} \right)^{-1} \mathbf{v}_{S_k}$$

# DSP Algorithm when idling power < circuit power

- The intra-cell solutions depend on interference power level
- iterative method: update the interference power $\hat{q}(m)$ in each iteration
- Terminate when the total power consumption can not be further improved



Estimate the interference power level $\hat{q}(m)$

Update interference power

Solve the convex intra-cell power minimization problem using Lagrangian method:

1) Compute the optimal Lagrangian multiplier $\varphi*$ with Newton method
2) Calculate the optimal rate:

$$x_{i(m)}{}^* = \left( W\left( \frac{\varphi^* \theta G_{i(m)i(m)} - \left(\sigma^2 + \hat{q}(m)\right)}{e\left(\sigma^2 + \hat{q}(m)\right)} \right) + 1 \right) w$$

3) Calculate the optimal target SINR:

$$\gamma_{i(m)}{}^* = \exp\left( \frac{x_{i(m)}{}^*}{w} \right) - 1$$

Determine transmit power cross multiple cells:

1) Determine all the transmission sets
2) For each set, calculate the minimum transmit power vector:

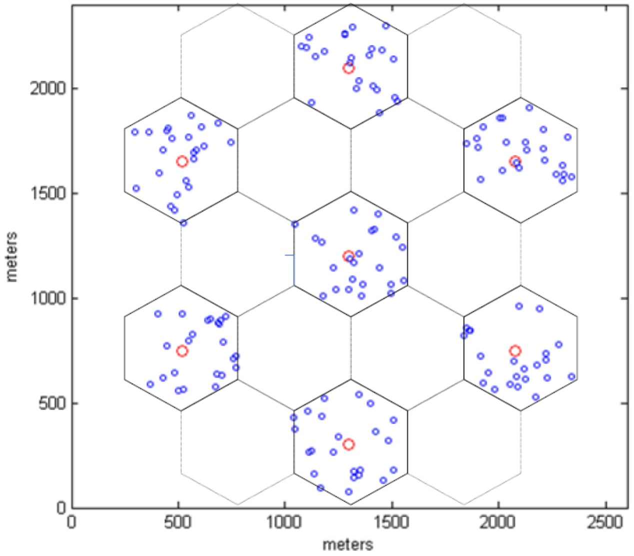
$$\mathbf{p}^*_{S_k} = \left(\mathbf{I} - \mathbf{D}\left(\gamma^*_{S_k}\right)\mathbf{B}_{S_k}\right)^{-1} \mathbf{v}_{S_k}$$

3) Calculate the interference power vector:

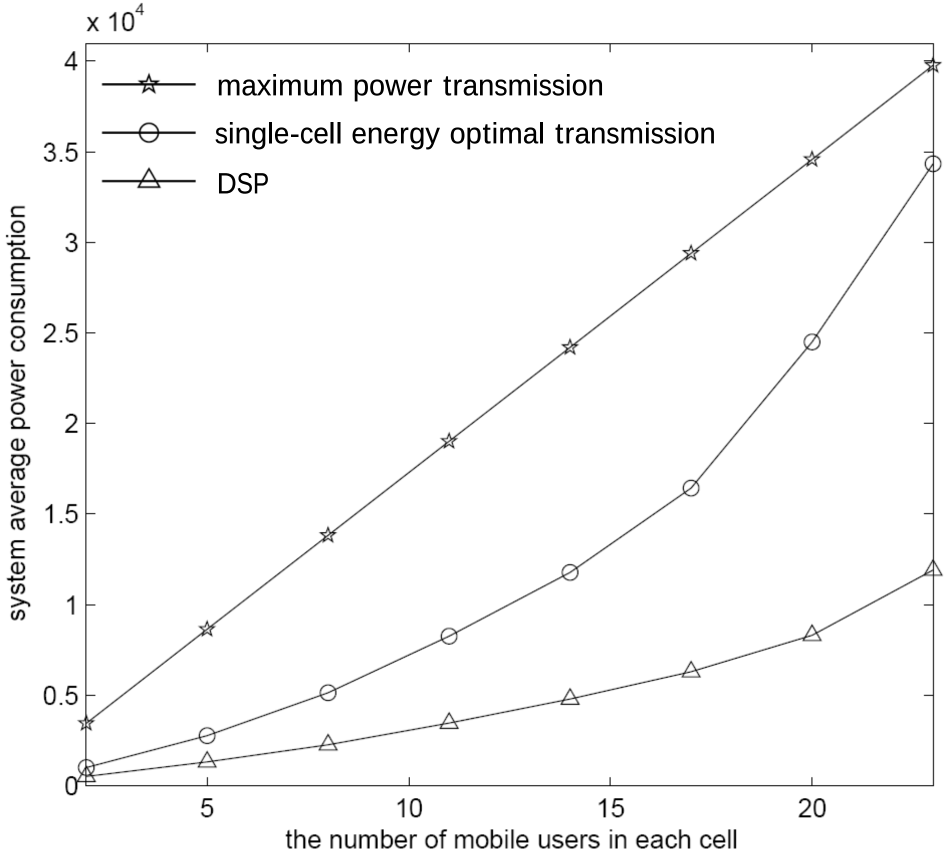
$$\mathbf{q}_{S_k} = \left(\mathbf{I} - \mathbf{B}_{S_k}\mathbf{D}\left(\gamma^*_{S_k}\right)\right)^{-1} \boldsymbol{\eta}_{S_k}$$

# Simulation Results

7-cell network with frequency-reuse factor of 3:



Each cell contains 23 mobile users



# Conclusion

- Consider the energy saving of mobile users in a multi-cell TDMA networks
- Propose a decomposition method (DSP):
  - decouples into intra-cell energy optimization and inter-cell power control
- Finds a good feasible solution, albeit not an optimal one
- Win-win: reduce energy consumption and inter-cell interference.

**Thanks!**