Hierarchical Control for Resource Management in Wireless Data Networks

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Summary: Optimal SIR Control Algorithms are proposed for CDMA systems using the theory of hierarchical control. Implementation issues are also discussed.

Presentation outline

- CDMA control structure — inner-loop and outer-loop
- System architecture and hardware implementation
- Introduction to hierarchical control
- Hierarchical algorithm for SIR control
- Simulation results
- Conclusion and future work

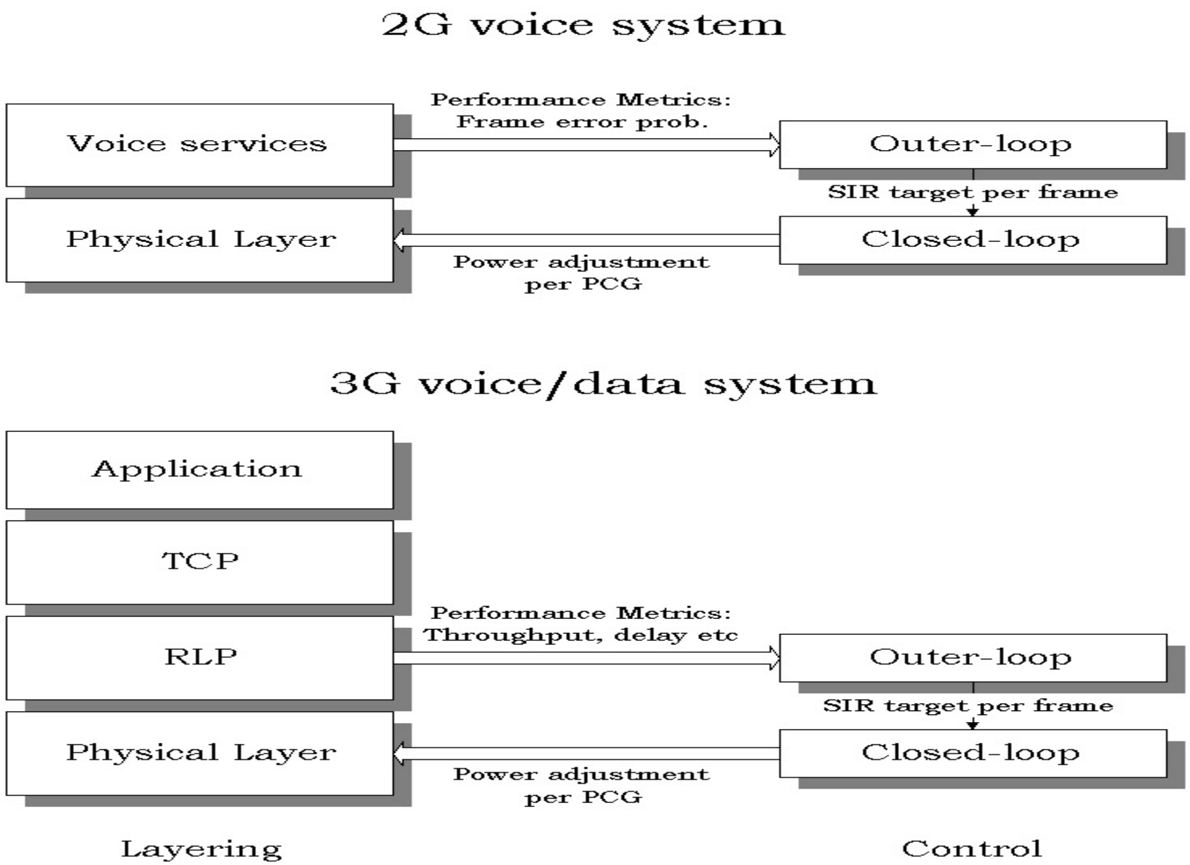
CDMA Control

- Fading channel $\Rightarrow$ Control power to meet a SIR target
  - Closed-loop (inner-loop) power control
  - Similar algorithms for 2nd generation (2G) systems and 3rd generation (3G) systems
- Resource sharing $\Rightarrow$ Control SIR target to optimize performance
  - Outer-loop SIR control
  - 2G based on target FER
  - New challenge in 3G

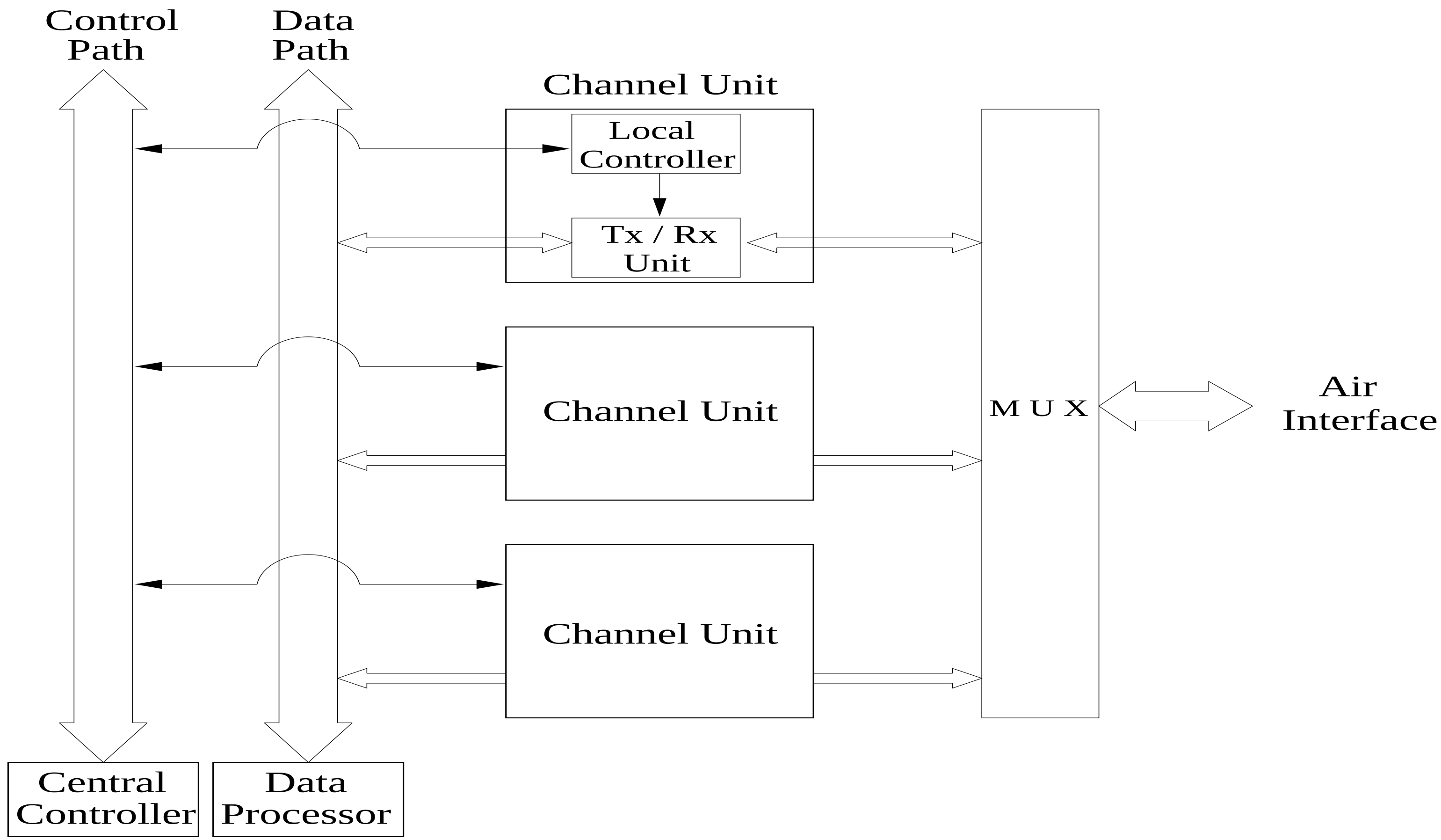
Control schemes

- Closed-loop: to maintain a SIR target
  - $SIR^{\text{meas}} < SIR^{\text{tar}} \Rightarrow$ MS power $\uparrow$ ΔdB
  - Otherwise $\Rightarrow$ MS power $\downarrow$ ΔdB
- 2G Outer-loop: to maintain a constant FER
  - A frame error $\Rightarrow$ SIR target $\uparrow$ Δ
  - Otherwise $\Rightarrow$ SIR target $\downarrow$ $\Delta \cdot FER^{\text{tar}}$
- 3G Outer-loop: to optimize voice/data performance
  - Voice users: the same as 2G
  - Data users: focus of our work

System architecture



Current base station architecture



Current base station architecture

- Data path and control signaling path
- Each user is handled by a channel unit
- A central controller and many local controllers
- Need a **simple distributed** algorithm requiring **minimum information exchange**

Introduction to hierarchical control

- Formulation:

$$\min_{\underline{\gamma}} \sum_{i=1}^{N} f_i(\gamma_i) \quad \text{subject to} \quad \sum_{i=1}^{N} g_i(\gamma_i) = 0$$

- Approach: solving the dual problem using a hierarchical algorithm

What is the dual problem?

- The Lagrangian: $L(\underline{\gamma}, \lambda) = \sum_{i=1}^{N} f_i(\gamma_i) + \lambda g_i(\gamma_i) = \sum_{i=1}^{N} L_i$

- The dual function is a function of λ:

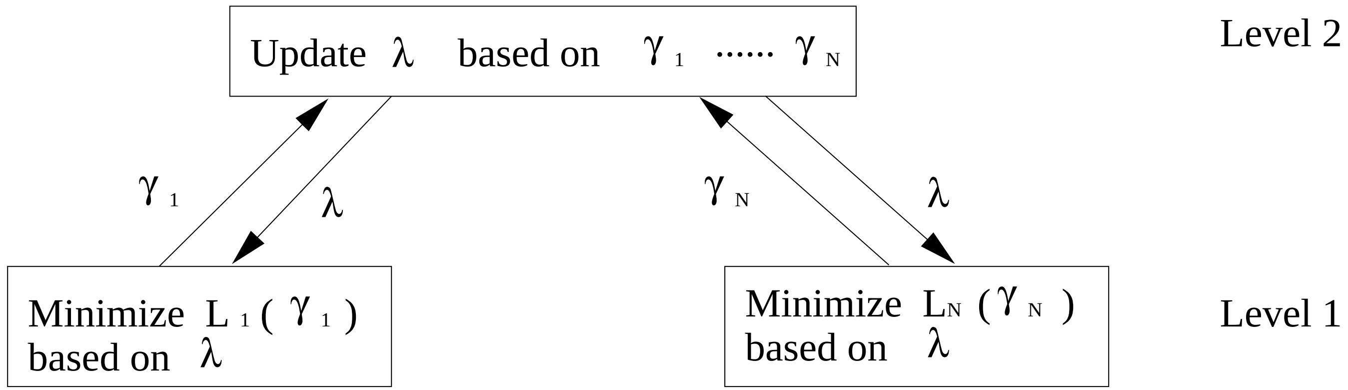
$$\phi(\lambda) = \min_{\underline{\gamma}} L(\underline{\gamma}, \lambda)$$

- Dual Problem is to optimize the dual function over λ:

$$\max_{\lambda} \phi(\lambda)$$

Hierarchical solution

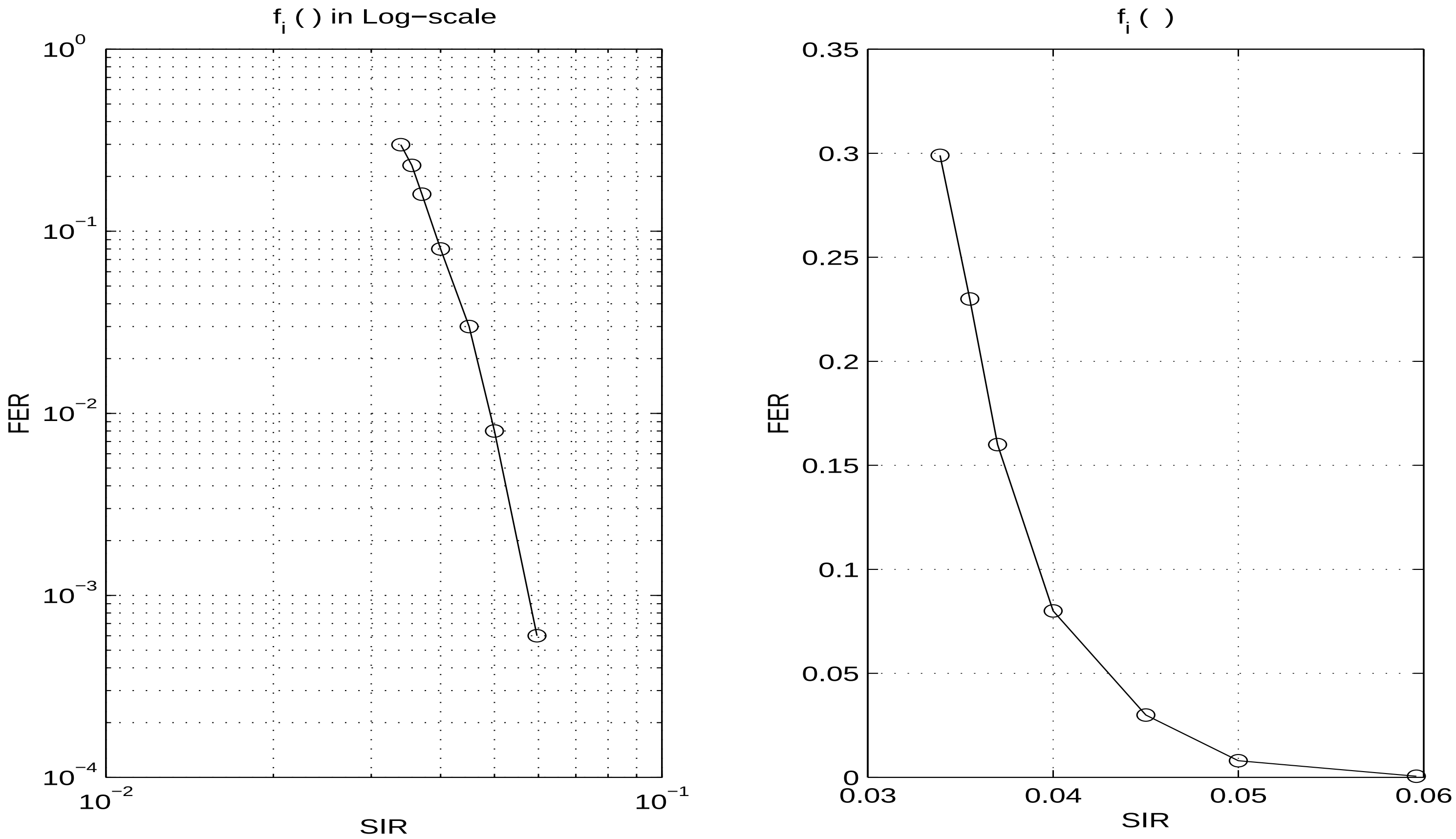
- Use a two-level algorithm solving the dual problem
- Lower level uses λ to optimize $L_i \Rightarrow$ calculates γ_i
- Upper level uses $\{\gamma_i, ..., \gamma_N\}$ to optimize $\phi(\lambda) \Rightarrow$ updates λ



SIR control

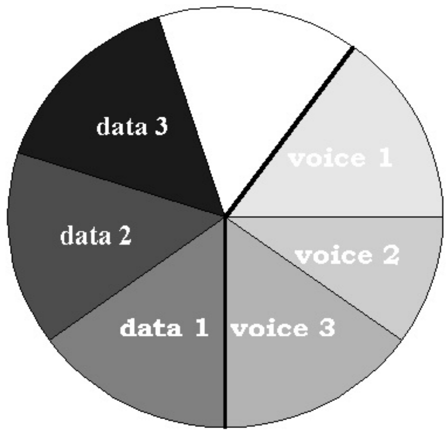
- Objective is to maximize total throughput
- Radio link protocol (RLP) is the persistent RLP $\Rightarrow$ throughput is $1 - f_i(\gamma_i)$
- Given a SIR target γ_i, the FER function $f_i(\gamma_i)$ can be estimated
- $f_i(\gamma_i)$: analytic, monotonically decreasing and convex for $\gamma_i \in [\gamma_{min}, \gamma_{max}]$
- Constraint is the total loading limit, i.e., $\sum \gamma_i \leq C$.

Convex assumption of FER function



System loading

- SIR: $\gamma_i = \frac{\alpha_i P_i^r}{\sum \alpha_j P_j^r + \sigma^2}$
- Loading $= \sum \gamma_i = \frac{\sum \alpha_i P_i^r}{\sum \alpha_j P_j^r + \sigma^2} = \frac{1}{1 + \frac{\text{Noise}}{\text{Total Rx Pwr}}}$
- Loading $\uparrow \Rightarrow$ Total received power $\uparrow$. Load sharing between voice & data as:



Problem formulation

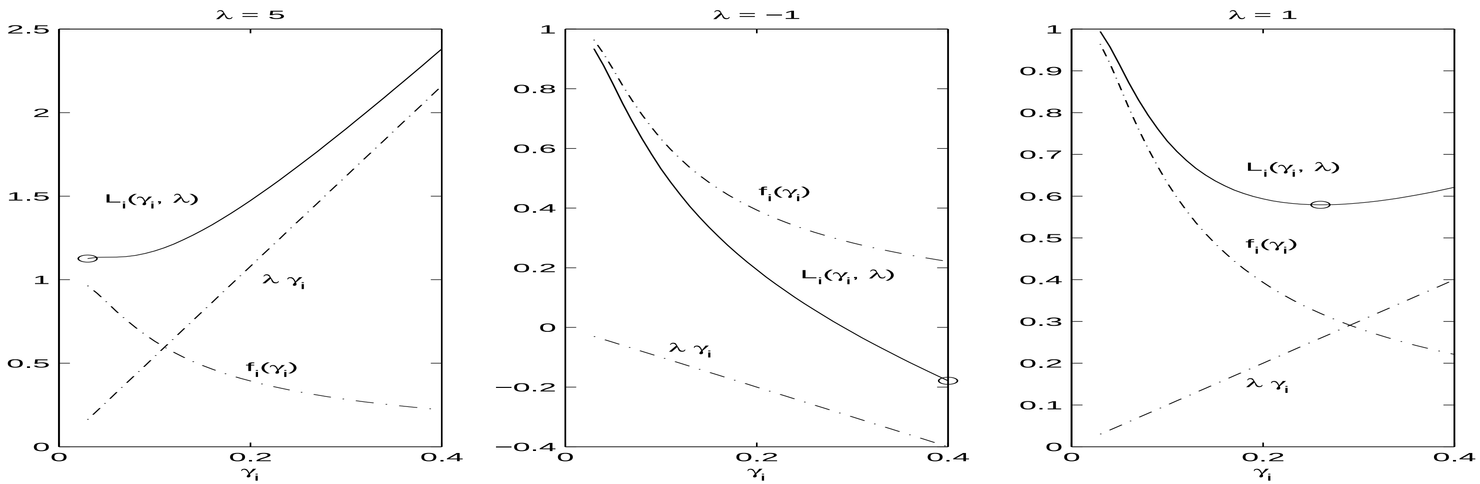
- Original optimization problem: choose $\underline{\gamma} = [\gamma_1 \ \gamma_2 \ ... \ \gamma_{N_d}]$:

$$\min_{\underline{\gamma}} \ \sum_{i=1}^{N_d} f_i(\gamma_i) \ \text{ subject to} \sum_{i=1}^{N_d} \gamma_i \leq C.$$

- Dual problem: $L_i = f_i(\gamma_i) + \lambda\gamma_i$

$$\max_{\lambda} \phi(\lambda) = \max_{\lambda} \ \{\min_{\underline{\gamma}} \sum_{i=1}^{N_d} L_i - \lambda C\}$$

Level 1: local controllers: Given $\lambda(k)$, choosing $\gamma_i(k)$ to minimize L_i



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$$\gamma_i^*(k) = \gamma_{min} \qquad \gamma_i^*(k) = \gamma_{max} \qquad \gamma_i^*(k) = \frac{df_i}{d\gamma_i}^{-1}(-\lambda(k))$$

Level 2: Central controller: given $\underline{\gamma}^*(k)$, update $\lambda(k+1)$

Can use gradient procedure: $\lambda(k+1) = \lambda(k) + a \cdot b(k)$

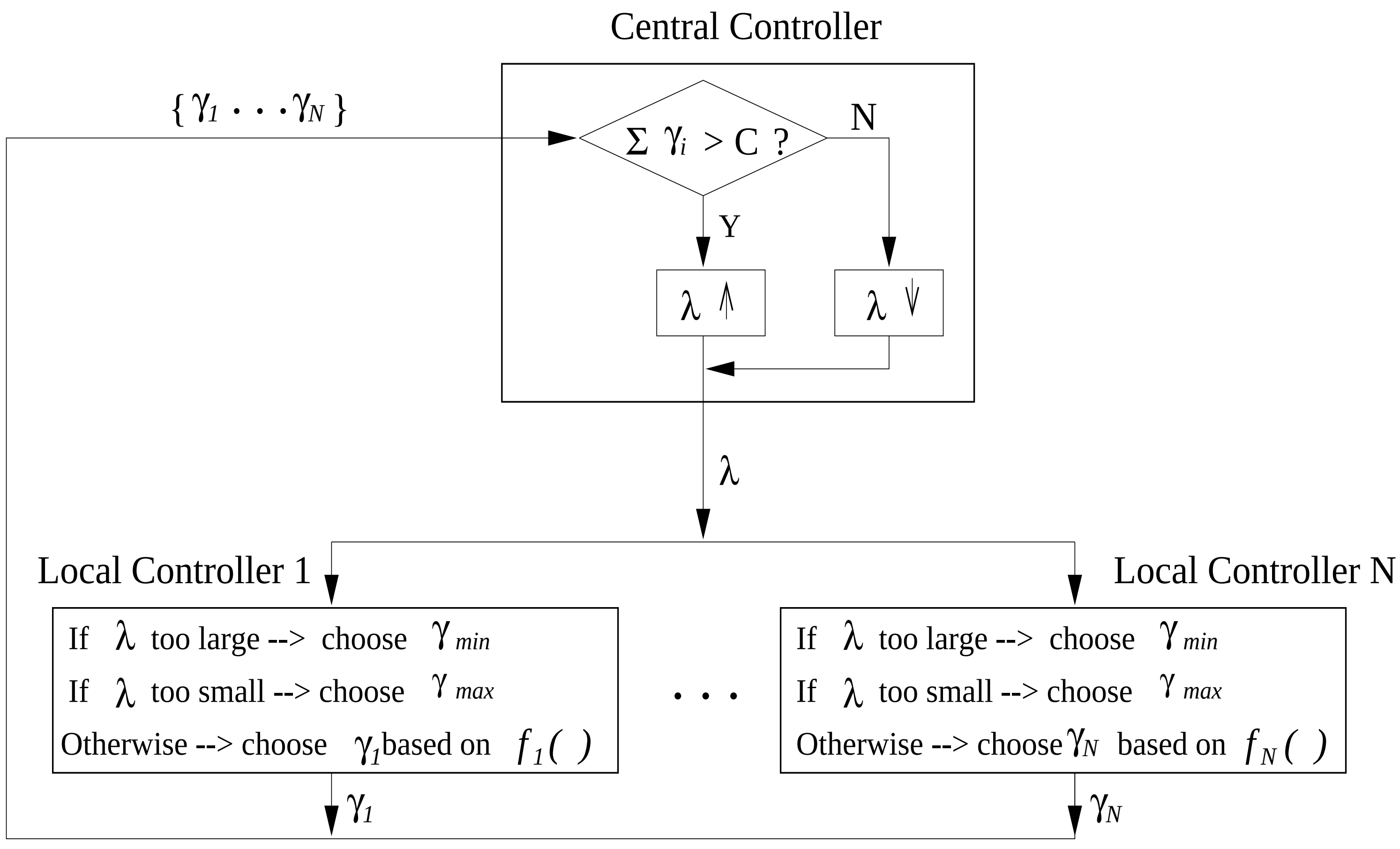
- $b(k)$ is the search direction

- $e(k) = \phi'(\lambda(k)) = C - \sum_{i=1}^{N_d} \gamma_i^*(k)$

- The steepest descent method: $b(k) = e(k)$

- The conjugate gradient method: $b(k) = e(k) + \frac{e^2(k)}{e^2(k-1)} b(k-1)$

Algorithm implementation



Proof of convergence

- f_i convex $\Rightarrow$ local optimization gives the single minimum $\Rightarrow$ $\phi(\ )$ is well defined

- Strong Lagrange Duality Theory $\Rightarrow$ no duality gap $\Rightarrow$ Solving original problem $=$ solving dual problem

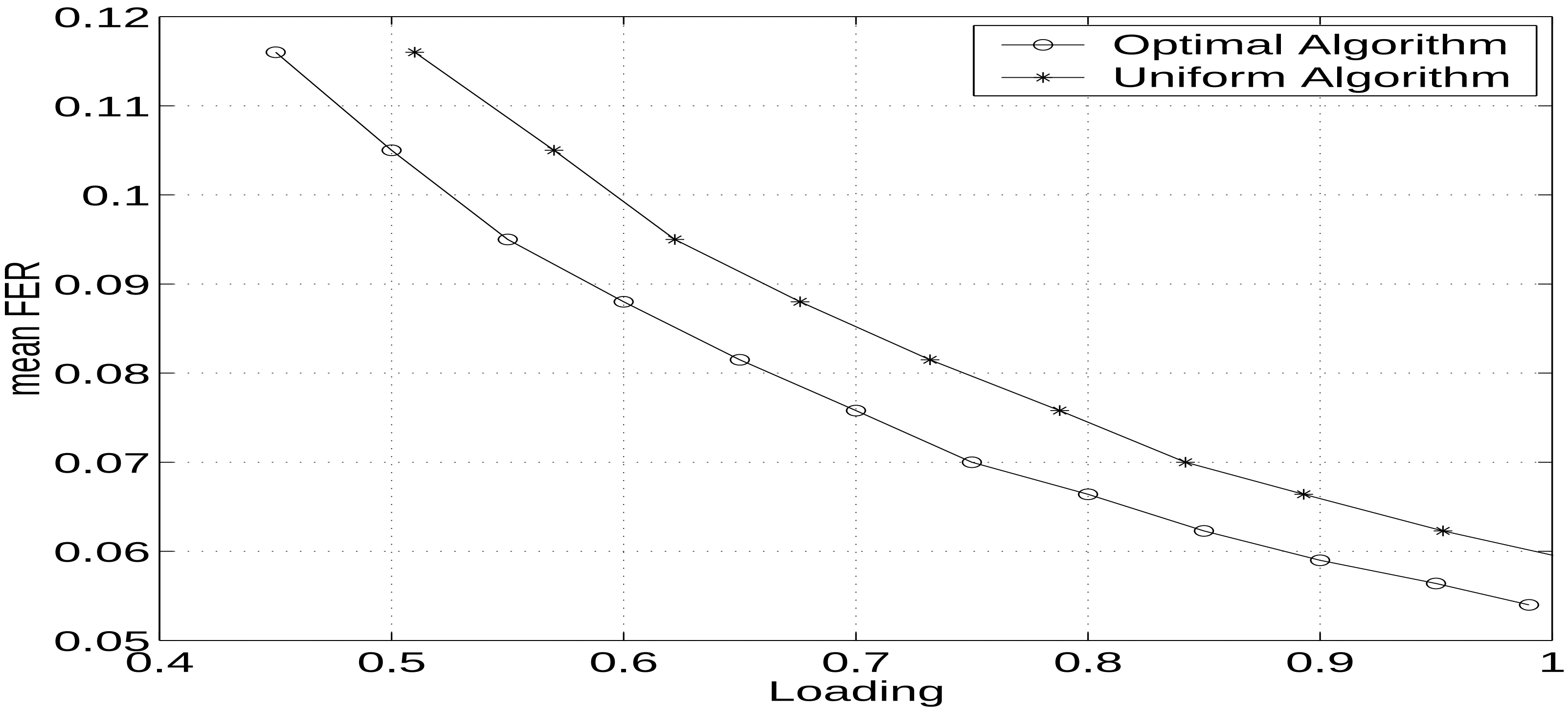
- $\phi(\ )$ can be shown to be concave $\Rightarrow$ upper level converges

- The algorithm converges to the optimal point, i.e., the resulting SIR target set maximizes the throughput

Simulation

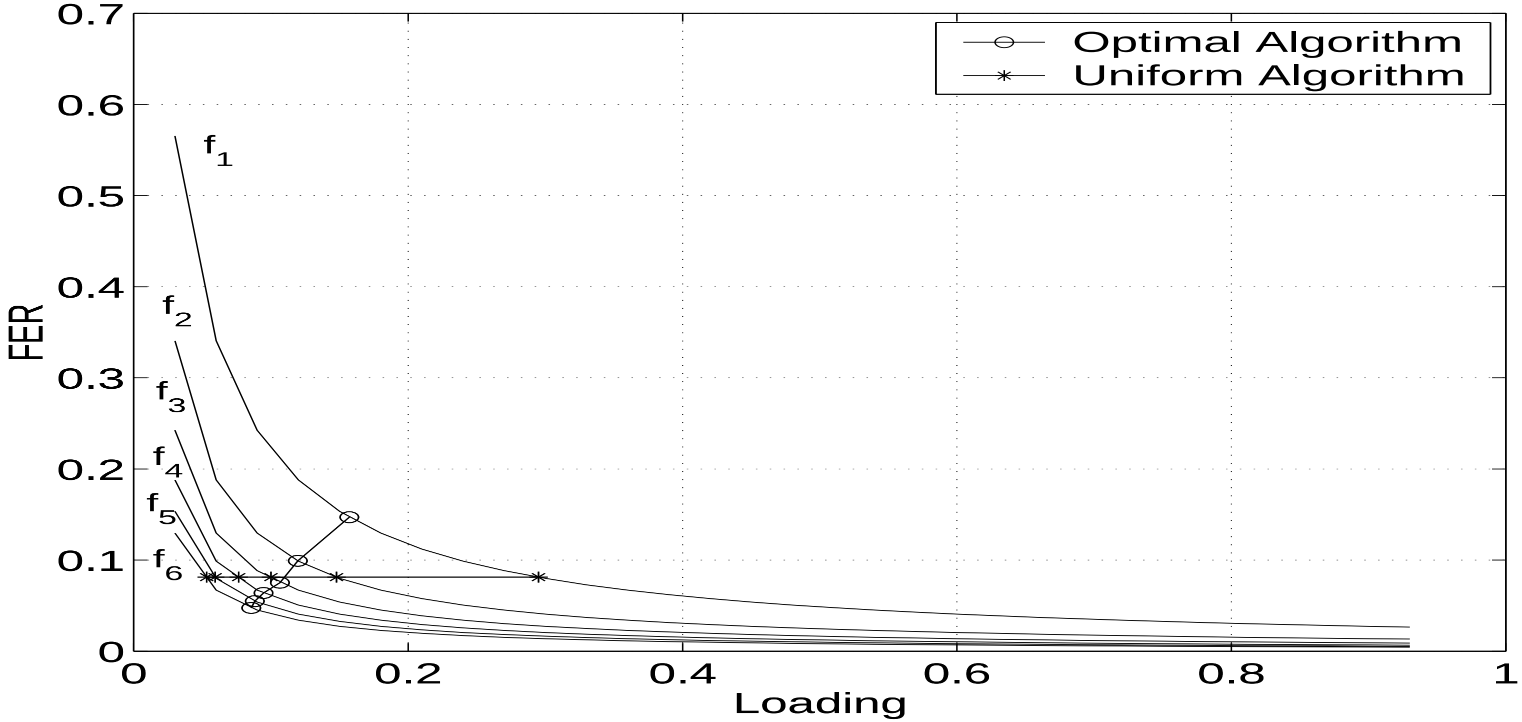
- FER functions: $f_i(\gamma_i) = 1 - e^{-\frac{1}{F_i}}$
- F_i is the parameter representing the fade margin. $F_i = \beta_i \gamma_i W$, where
  - γ_i is the SIR, W is the spreading gain, $W = 240$ in simulation
  - β_i is the parameter reflecting the power control efficiency. $\beta_i = \frac{i}{6}$ for $i = 1, 2, ..., 6$.
- Reference scheme is the one used in current 2G systems $\Rightarrow$ same SIR target
- Assume only the SIR can be controlled

Simulation



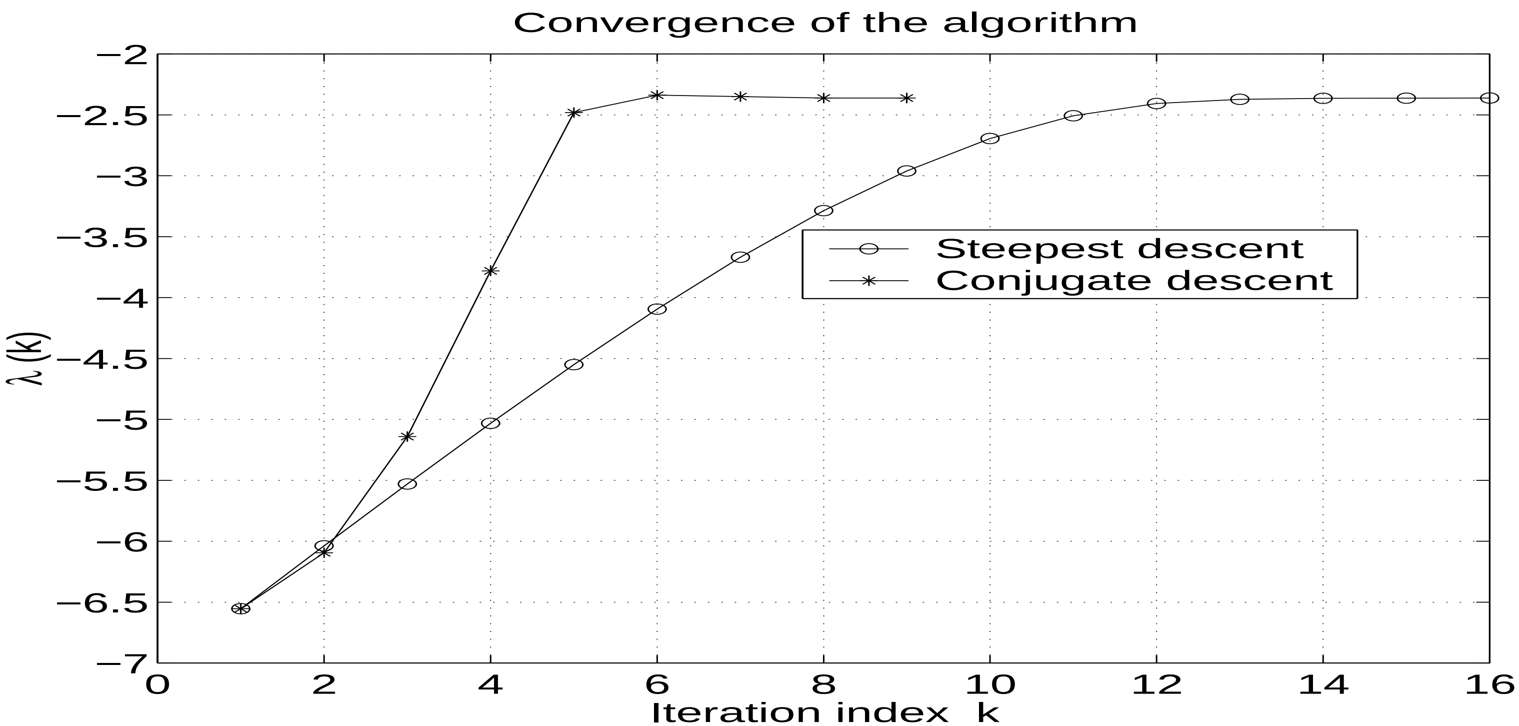
Loading vs FER for the hierarchical algorithm and the uniform algorithm

Simulation



SIR targets for the hierarchical algorithm and the uniform algorithm with 90%loading)

Simulation



Convergence of λ for the hierarchical algorithm and the uniform algorithm

Conclusions

- Proposed SIR control algorithm that maximizes throughput
- Proved convergence based on Strong Duality Theory
- Implemented via a decentrallized hierarchical structure
- Fully compatible with the current hardware architecture
- Simple computation and limited signaling between the controllers

Future work

- Optimal SIR and rate control algorithm
- Optimal algorithm for other data protocol — mapping higher layer (e.g., TCP) to RLP layer performance
- Consider other metrics, such as delay and queue length — dynamic hierarchical algorithms
- Optimal algorithm for high speed data — optimal hierarchical scheduling