EIE3280: Networks: Technology, Economics, and Society

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Q1: What makes CDMA work for my smartphone?

(Acknowledgment to Prof. Mung Chiang for sharing the Slides)

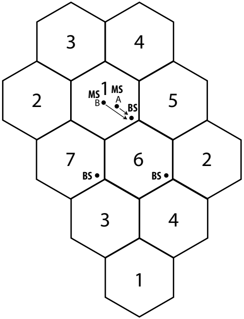
Take a Look at Your Smartphone

- Networks (wireless, Internet, web...)
- Chip, touch screen, battery, software, business model...
- Data applications: texting, emailing, web browsing, video streaming, file downloading, ...
- Networking
  - Radio air interface
  - Core and backhaul

History of Wireless

- 1940s: terrestrial wireless communications
- 1970s - now: cellular networks
  - 1G, 2G, 2.5G, 3G, 4G, 5G...
- 1990s - now: WiFi networks
- What is a cellular network?

Basic Terminologies

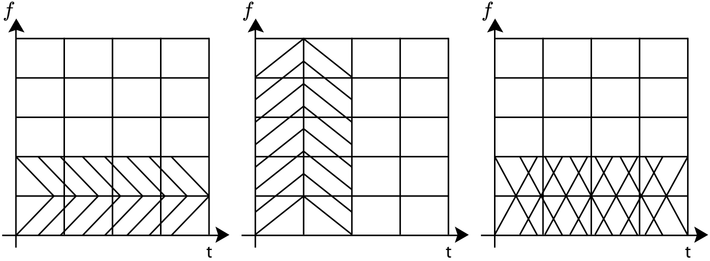


- Cells, Base Station (BS), Mobile Station (MS)
- Each BS has three directional antennas
- Signal attenuation: $\propto 1/d^2$ to $1/d^4 \Rightarrow$ Frequency reuse

The Air

- Interference among multiple transmitter-receiver pairs
- Cocktail party
  - Use different languages to separate different conversions

Orthogonal Resource Allocation



(a) (b) (c)

(a) FDMA

(b) TDMA

(c) Ideal CDMA

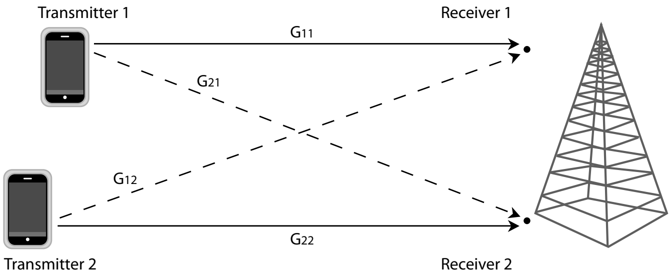
Non-orthogonal Resource Allocation

- (Practical) CDMA
- Starting in 1989, then IS-95 in 2G
- Now part of all 3G standards
- Spread spectrum technique
  - Spreading code: a sequence of 1's and -1's
  - Special design family of orthogonal spreading codes,
  - Non-orthogonal in practice due to not enough codes or imperfect synchronization
- Wikipedia: `https://en.wikipedia.org/wiki/Code-division_multiple_access`

Interference

- Our first example of **negative externality**
- Famous special case: **near-far problem**
- Simple solution by Qualcomm: feedback control
  - Transmit power control
  - Received signal power equalization
- But what if you need to achieve a target signal quality?

Uplink Interference



- G_{ij}: channel gain from transmitter j to receiver i
- G_{ii} is enhanced by CDMA spreading codes

SIR

- Signal-to-Interference-noise-Ratio (SIR):

$$\mathrm{SIR}_i = \frac{G_{ii}\ p_i}{\sum_{j \neq i} G_{ij}\ p_j + n_i}$$

  - n_i: noise at receiver i

Distributed Power Control

- An iterative, distributed algorithm
- Assume each user i has an SIR target γ_i

$$p_i[t+1] = \frac{\gamma_i}{\mathrm{SIR}_i[t]} p_i[t], \quad \text{for each } i.$$

- Achieve the target SIR with the minimum transmission power

DPC

- Simple
  - in communication
  - in computation
  - in configuration
- Intuitive
  - Equilibrium looks good
  - Convergence sounds plausible

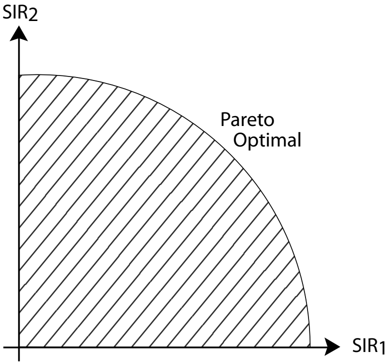
A General Theme

- Individual behaviors driven by self-interest
- Aggregate into a (hopefully fair and efficient) state across all users
- Helped by feedback signals

View 1: Optimization

- Objective: power minimization
- Constraints: achieve target SIRs for all users
- Variables: transmit powers
- Constants: channels, noise, target SIRs

Feasible Region (in SINRs)



- The shaded area is the feasible region
- maximum feasible $\mathrm{SIR}_i = G_{ii} p_i^{\max} / n_i$
- Interference relationship determines the Pareto Optimal boundary

Symbolically

- Minimize: $\sum_i p_i$
- Subject to: $\mathrm{SIR}_i(\boldsymbol{p}) \geq \gamma_i, \forall i$
- Variables: $\boldsymbol{p} = (p_i, \forall i)$

Linear Programming

- Minimize a linear function subject to linear constraints
- How to prove convergence of DPC algorithm to a solution of this optimization?

Terminologies

- **Infeasible** optimization problem
- **Feasible** optimization problem
- **Global** optimal and **local** optimal solution

View 2: Game

- Power control is a competition
- Every user tries to minimize his transmission power
  - Subject to the SINR constraint
- Games are models for
  - Competition
  - Cooperation
- There is a formal (mathematical) language for games

A Game

- A set of **players**
- A **strategy space** for each player
- A **payoff** for each player

Prisoner's Dilemma

- 2-user game

	Not Confess	Confess
Not Confess	$(-1, -1)$	$(-5, 0)$
Confess	$(0, -5)$	$(-3, -3)$

Strategies

- Best response strategy

$$a^*(b) = \arg\max_{a \in \mathcal{A}} U_1(a, b)$$

  - Best response might not be unique $\Rightarrow$ Best Response correspondence

- Dominant strategy
  - A player's strategy that always leads to a payoff **no worse** than his any other strategies, **independent** of his opponents' strategies
  - **Strictly** dominant and **weakly** dominant

Equilibrium

- Equilibrium
  - Socially optimal?
  - Pareto optimal?
  - Exist?
  - Unique?

Coordination Game: Battle of Sexes

- Another 2-user game

	Action Movie	Romance Movie
Action Movie	$(2, 1)$	$(0, 0)$
Romance Movie	$(0, 0)$	$(1, 2)$

Nash Equilibrium

- Best response strategies "match"

Power Control Game

- Let's identify
  - Players
  - Strategy spaces
  - Payoff functions
- DPC is just the best response strategy!
- Monotonicity of strategy space $\rightarrow$ convergence of algorithm

Example

Receiver of Link	Transmitter of Link 1	2	3	4
1	1	0.1	0.2	0.3
2	0.2	1	0.1	0.1
3	0.2	0.1	1	0.1
4	0.1	0.1	0.1	1

- Target SNRs: 2, 2.5, 1.5, 2
- Noise level: 0.1 mW

Iteration 0

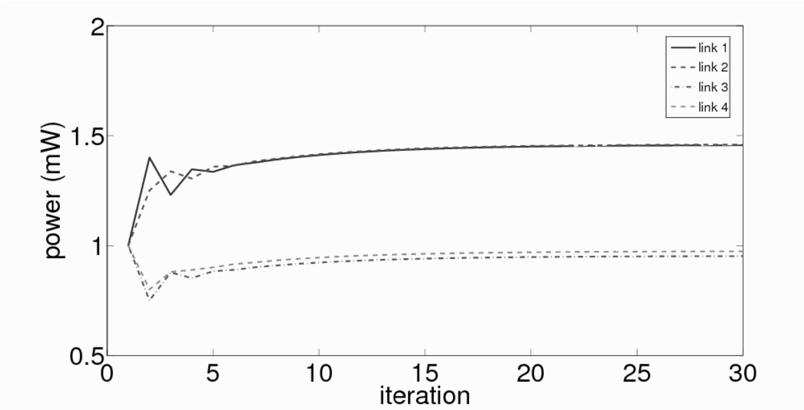
- Initialize all power levels to be 1 mW
- Let s calculate the corresponding SIRs

Iteration 1

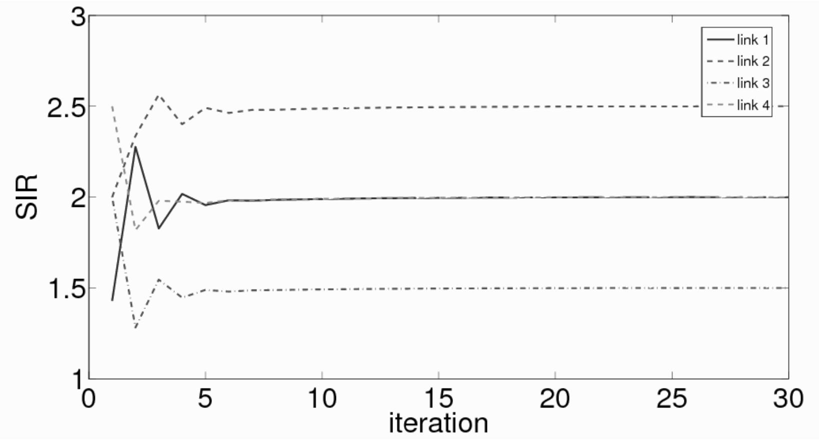
- Let's calculate power levels

- Let's calculate SIRs

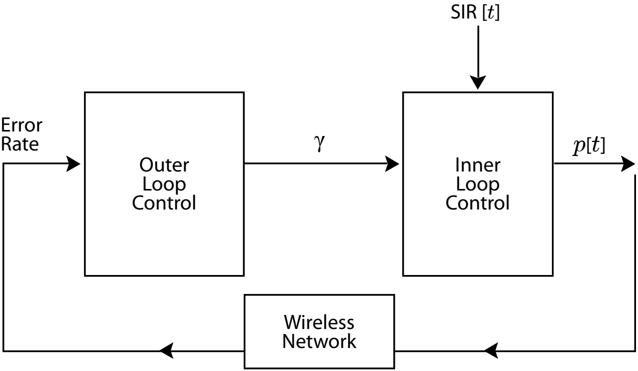
Convergence in Powers



Convergence in SNRs



Two Control Loops



In Practice

- Asynchronous and discrete
- Frequency: 800   1500
- Granularity: 0.1 dB, 0.2 dB, 0.5 dB
- Power control + handoff made all 3G standards work

Summary

- Different users' signals interfere with each other in the air
  - Feasible SIR region with a Pareto-optimal boundary
- Interference coordination in CDMA uses DPC with feedback
  - Solves an optimization problem in the form of LP
  - Or viewed as the best response updates of a non-cooperative game