EE360 Discussion Session

(A sparse sampling of ) Broad topics covered in the course so far

January 23, 2014
Disclaimer

These slides are designed primarily to stimulate ideas/discussions!

So in particular

- I will try to keep the details out, and will only go into details if there is interest
- I will look forward to your comments/questions to make the slides more relevant
- You can send in your comments via email or Piazza if you are not able to come in
Outline

1. Topics

2. Centralized systems

3. Distributed systems
Outline

1 Topics

2 Centralized systems

3 Distributed systems
Main difference from single user systems

**Difference**

Instead of a single transmitter (Tx) and receiver (Rx) pair, one has multiple Tx or Rx
Pertinent issues in multiuser systems

Issues

- Physical (PHY) layer issues (transmit power, coding (?), decoder, MIMO)
- Medium access control (MAC) layer issues (how to share, access channel)
- Transport layer issues (how to route, single-hop versus multi-hop)
- …
- Cross layer issues (PHY layer parameters depend on MAC layer parameters)

The above MAC is not the same as the MAC (multiple access channel) that we will come back to later!
Pertinent issues in multiuser systems

Issues

- Physical (PHY) layer issues (transmit power, coding (?), decoder, MIMO)
- Medium access control (MAC) layer issues (how to share, access channel)
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Note

PHY layer design problems would be similar to single user systems (EE359)
Different paradigms of managing multiuser systems

Two main paradigms (MAC layer)

- Centralized (e.g. cellular)
- Decentralized (e.g. Wifi, sensor networks)

Many systems are often a hybrid of the two
Outline

1. Topics
2. Centralized systems
3. Distributed systems
Basic premise

Idea
Someone has a global view of the entire multiuser system

Pros
- Channel state information (or link quality or ... ) between every possible pair of Tx,Rx
- Requirements of each Tx,Rx
- ...

Cons
- Getting a global picture takes time (causing imperfect CSI, pilot overhead)

Let’s assume perfect global picture. What can be done now?
Enter Information Theory (IT)

Idea
Probabilistic model of channel states extracted from global knowledge

Goal
Compute best rates for the multiuser system, for infinite delay

Hope
Information theoretic achievable schemes can give good design insights for practical systems

Reality
Suggests sophisticated PHY and some MAC layer techniques, but MAC layer often needs delay constraints (not well understood)
IT multiuser channel models (2 users for simplicity)

\[ y_1 = h_{11}x_1 + h_{12}x_2 + n_1 \]
\[ y_2 = h_{21}x_1 + h_{22}x_2 + n_2 \]

Interference channel (as general as it can get)
IT multiuser channel models (2 users for simplicity)

\[ y_1 = h_1 x_1 + h_1 x_2 + n_1 \]
\[ y_2 = h_2 x_1 + h_2 x_2 + n_2 \]

BC (broadcast channel or downlink)
IT multiuser channel models (2 users for simplicity)

\[ y = h_1 x_1 + h_2 x_2 + n \]

MAC (multiple access channel or uplink)
IT multiuser channel models (2 users for simplicity)
Some metrics in multiuser IT

Capacity region $\mathcal{C}$ (for $M$ users)

Rate tuples $\mathbf{R} = (R_1, R_2, \ldots, R_M)$ which can be achieved using asymptotically long codes with vanishing error probability

Sum throughput (or weighted sum or \ldots)

Maximum sum $\sum_{i=1}^{M} \omega_i R_i$ for some $\omega_i > 0$

Scaling law with large $M$

- Computing metrics for $M$ finite may be difficult
- Asymptotic characterization of the same metrics may be useful enough to give good insights
Some metrics *not* in (traditional) multiuser IT

**Delay**
- Not quite addressed in IT
- Queueing theory is much more explicit about delay

**General utility functions**
- Usually capacity region is the holy grail from which everything else is defined
- What if rate is not most relevant (pricing models of carrier data plans)?
Some achievable strategies suggested by characterization of capacity regions

**MAC Layer Techniques**
- Time-sharing/frequency sharing/any orthogonal resource sharing
- Superposition coding (simultaneous transmission)

**PHY layer techniques**
- Transmitting from multiuser/single user codebooks
- Decoding everything together (joint decoding, multiuser detection, ...), or separately
On capacity regions and achievable strategies

Setting
Two users ($M = 2$), what is the best rate region?

Answer
Not known in general! Known e.g. if

\[ \text{inner bound} = \text{outer bound} \]

Some examples of known capacity regions
- MAC channels
- Degraded broadcast channels
- Interference channels with very strong or very weak interference
On capacity regions and achievable strategies

**Setting**

Two users \((M = 2)\), what is the best rate region?

**Answer**

Not known in general! Known e.g. if

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**Some examples of known capacity regions**

- MAC channels
- Degraded broadcast channels
- Interference channels with very strong or very weak interference
Example: Gaussian MAC channels

Model

\[ y = x_1 + x_2 + n, \]

where \( y \) is at the receiver, \( x_1 \) is user 1’s signal (power \( P_1 \)) and \( x_2 \) is user 2’s signal (power \( P_2 \)) and \( n \) is the noise (power \( \sigma^2 \))

Goal

What pair of rates \((R_1, R_2)\) can be supported?

Approach

- Try an inner bound (or achievable scheme)
- Try an outer bound (any suggestions?)
- See if they match
Example: Gaussian MAC channels

Achievable strategies (Inner bound)

- One user stays silent, other transmits. Gives
  \[ R_1 \leq \log(1 + P_1/\sigma^2); \ R_2 \leq \log(1 + P_2/\sigma^2). \]

- The receiver decodes user j first treating user i as noise, subtracts user j’s signal and decodes user i, gives
  \[ R_j \leq \log(1 + P_j/(P_i + \sigma^2)); \ R_i \leq \log(1 + P_i/\sigma^2). \]

Outer bounds

- Consider 2 users are a single superuser, so sum rate can only be better. Thus
  \[ R_1 + R_2 \leq \log(1 + (P_1 + P_2)/\sigma^2). \]

- We have the bounds \( R_i \leq \log(1 + P_i/\sigma^2) \)
Example: Gaussian MAC channels

An observation

Outer bound equals inner bound! (Please verify!)

We know the capacity region of Gaussian MAC 😊
Some general techniques in capacity region analysis

- **Time-sharing**: If $R$ and $\tilde{R}$ are achievable, $\alpha R + (1 - \alpha)\tilde{R}$ also achievable (so capacity regions are convex)
- **Decode interference**: Capacity achieving for many settings (BC, MAC, 2 user IC with strong interference)
- **Treat interference as noise**: Capacity achieving for e.g. 2 user IC with weak interference, BC (order of decoding is important)
- **Duality**: Obtain capacity regions based on some kind of equivalence in the mathematical description (e.g. BC-MAC duality)
- ...
Manifestations in practical systems (carrier networks)

IT capacity achieving techniques are computationally demanding. Yet, in practice, they influence design.

Some ideas implemented in practice
- Cellular: Orthogonalize into spatial “cells”
- Channel access methods: TDMA, FDMA, CDMA (orthogonalization in 'code' space)

General evolution of cellular standards is towards joint transmission and processing (better performance) over orthogonalization and simple processing (lower complexity)
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Basic premise

Idea
There is no central authority with a global knowledge of the channel

Pros
- Less need for complex infrastructure
- No overhead in channel estimation

Cons
- Lots of overhead in MAC layer
- Essentially interference limited (complex cross layer interactions)

Example
802.11 (Wifi), 802.3 (Ethernet), 802.15 standard protocols (includes bluetooth)
### Issues

#### PHY layer
- Increasing transmit power increases interference level to others so may not be good
- What decoding technique to use (joint decoding or single user decoding)?

#### MAC layer
- When to transmit (e.g. when channel is quiet (ALOHA, CSMA), based on some schedule (slotted ALOHA))?
- How much global information can be inferred from local info?

#### Transport layer
- Routing: Single hop or multi hop routing?
- Redundancy versus effective data rate (feedback needed or not)

Cross-layer design issues are more interesting here