EE360: Lecture 9 Outline
Resource Allocation in Ad Hoc Nets

- Announcements
  - Paper summaries due next Wednesday
- Overview of resource allocation in ad-hoc networks
- Cross-layer adaptation
- Distributed power control
- Joint scheduling and power control for wireless ad hoc networks (Haleh Tabrizi)
- Adaptation and interference (wideband CDMA)
- Adaptation via game theory (Manas Deb)
Adaptive Techniques for Wireless Ad-Hoc Networks

- Network is dynamic (links change, nodes move around)
- Adaptive techniques can adjust to and exploit variations
- Adaptivity can take place at all levels of the protocol stack
- Negative interactions between layer adaptation can occur
What to adapt, and to what?

- **QoS**
  - Adapts to application needs, network/link conditions, energy/power constraints, …

- **Routing**
  - Adapts to topology changes, link changes, user demands, congestion, …

- **Transmission scheme (power, rate, coding, …)**
  - Adapts to channel, interference, application requirements, throughput/delay constraints, …

Adapting requires information exchange across layers and should happen on different time scales.
Bottom-Up View: Link Layer Impact

- “Connectivity” determines everything (MAC, routing, etc.)
  - Link SINR and the transmit/receive strategy determine connectivity
  - Can change connectivity via link adaptation

- Link layer techniques (MUD, SIC, smart antennas) can improve MAC and overall capacity by reducing interference

- Link layer techniques enable new throughput/delay tradeoffs
  - Hierarchical coding removes the effect of burstiness on throughput
  - Power control can be used to meet delay constraints
Each node generates independent data.

Source-destination pairs are chosen at random.

Topology is dynamic (link gain $G_{ij}$s time-varying)

Different link SIRs based on channel gains $G_{ij}$

Power control used to maintain a target $R_i$ value

$$R_i = \frac{G_{ii}P_i}{\eta_i + \sum_{i \neq j} G_{ij}P_j}$$
Power Control for Fixed Channels

- Seminal work by Foschini/Miljanic [1993]

- Assume each node has an SIR constraint

\[
R_i = \frac{G_{ii}P_i}{\eta_i + \sum_{i\neq j} G_{ij}P_j} \geq \gamma_i \quad (I - F)P + u \geq 0, \quad P \geq 0
\]

- Write the set of constraints in matrix form

\[
F_{ij} = \begin{cases} 0, & i = j \\ \frac{\gamma_i G_{ij}}{G_{ii}}, & i \neq j \end{cases}
\]

\[
u = \begin{bmatrix} \gamma_1 \eta_1/G_{11}, & \cdots, & \gamma_N \eta_N/G_{NN} \end{bmatrix}^T
\]

Scaled Interferer Gain

Scaled Noise
Optimality and Stability

• Then if $\rho_F < 1$ then $\exists$ a unique solution to

$$P^* = (I - F)^{-1} u$$

• $P^*$ is the global optimal solution

• Iterative power control algorithms

  Centralized:  $P(k+1) = FP(k) + u$

  Distributed:  $P_i(k+1) = \frac{\gamma_i}{R_i(k)} P_i(k)$
What if the Channel is Random?

- Can define performance based on distribution of $R_i$:
  - Average SIR
  - Outage Probability
  - Average BER

- The standard F-M algorithm overshoots on average

\[ E[\log R_i] = \log \gamma_i \Rightarrow ER_i \geq \gamma_i \]

- How to define optimality if network is time-varying?
Can Consider A New SIR Constraint

\[ R_i = \frac{G_{ii}P_i}{\eta_i + \sum_{i \neq j} G_{ij}P_j} \geq \gamma_i \quad \Leftarrow \text{Original constraint} \]

\[
E \left[ G_{ii}P - \gamma_i \left( \eta_i + \sum_{i \neq j} G_{ij}P_j \right) \right] \geq 0
\]

\[
(I - \overline{F})\overline{P} + \overline{u} \geq 0
\quad \Leftarrow \text{Multiply out and take expectations} \]

\[
\overline{F}_{ij} = \begin{cases} 
0, & i = j \\
\frac{\gamma_i E[G_{ij}]}{E[G_{ii}]}, & i \neq j 
\end{cases} \quad \overline{u} = \left[ \frac{\gamma_1 \eta_1}{E[G_{11}]}, \ldots, \frac{\gamma_N \eta_N}{E[G_{NN}]} \right]^T
\]

Same form as SIR constraint in F-M for fixed channels
New Criterion for Optimality

- If $\rho_F < 1$, then exists a global optimal solution
  \[ \overline{P}^* = (I - \overline{F})^{-1} \overline{u} \]

- For the SIR constraint
  \[ \frac{E[G_{ii}P_i]}{E[\eta_i + \sum_{j \neq i} G_{ij}P_j]} = \gamma_i \]

- Can find $P^*$ in a distributed manner using stochastic approximation (Robbins-Monro)
Robbins-Monro algorithm

\[ P(k+1) = P(k) - a_k g(P(k)) + a_k \varepsilon_k \]

Where \( \varepsilon_k \) is a noise term

\[ \varepsilon_k = \left( \bar{F} - F(k) \right) P(k) + \left( \bar{u} - u(k) \right) \]

Step size: \( a_k \to 0 \quad \sum_{n=1}^{k} a_k \to \infty \quad \sum_{n=1}^{k} a_k^2 < \infty \)

Under appropriate conditions on \( \varepsilon_k \)

\[ P(k) \to \bar{P}^* \]
Admission Control

- What happens when a new user powers up?
  - More interference added to the system
  - The optimal power vector will move
  - System may become infeasible

- Admission control objectives
  - Protect current user’s with a “protection margin”
  - Reject the new user if the system is unstable
  - Maintain distributed nature of the algorithm
Fixed Step Size Algorithm Properties

- Have non-stationary equilibria
  - So cannot allow $a_k \to 0$

  Step size: $a_k = a \sum_{n=1}^{k} a_k \to \infty \quad \sum_{n=1}^{k} a_k^2 = \infty$

- A fixed step size algorithm will not converge to the optimal power allocation

  \[ P(k) \Rightarrow \tilde{P} \quad \text{where} \quad E[\| P^* - \tilde{P} \|] = O(a) \]

- This error is cost of tracking a moving target
Example: i.i.d. Fading Channel

- Suppose the network consists of 3 nodes
- Each link in the network is an independent exponential random variable

\[
E[G] = \begin{pmatrix} 1 & 0.0375 & 0.02 \\ 0.0375 & 1 & 0.04 \\ 0.02 & 0.04 & 1 \end{pmatrix}
\]

\[\gamma_i = 5 \quad \eta_i = 1 \quad \forall i\]

- Note that \(\rho_F = 0.33\) so we should expect this network to be fairly stable
Fig 1: Transmit Powers for the Standard Foschini–Miljanic Algorithm and the Two Proposed Stochastic Approximation Algorithms

- Fixed Step Size Stochastic Approximation
- Decreasing Step Size Stochastic Approximation
- Foschini–Miljanic Power Control
Fig. 3 Comparison of the Stand and Modified Stochastic Approximations Algorithms: Transmit Powers with an Admission Event at Time 2000

- **User 1 Fixed Step Size Algorithm**
- **User 4 Fixed Step Size Algorithm**
- **User 1 Decreasing Step Size Algorithm**
- **User 4 Decreasing Step Size Algorithm**

Entry Time of User 4
Power Control + …

- Power control impacts multiple layers of the protocol stack
- Power control affects interference/SINR, which other users react to
- Useful to combine power control with other adaptive protocols
  - Adaptive routing and/or scheduling (Haleh)
  - Adaptive modulation and coding
  - Adaptive retransmissions
  - End-to-end QoS
  - …
Multiuser Adaptation

Channel interference is responsive to the cross-layer adaptation of each user
Multiuser Problem Formulation

- Optimize cross-layer adaptation in a multi-user setting

- Users interact through interference
  - Creates a “Chicken and Egg” control problem
  - Want an optimal and stable equilibrium state and adaptation for the system of users

- The key is to find a tractable stochastic process to describe the interference
Linear Multi-User Receiver

- Assume each of K mobiles is assigned a N-length random spreading sequence

\[ S_i = \frac{1}{\sqrt{N}} \{ V_{i1}, \ldots, V_{iN} \} \]

\[ SIR_K (i, t) = \frac{(c_i^T S_i)^2 a_i(t) z_i(t)}{(c_i^T c_i) \sigma^2 + \sum_{j \neq i} (c_i^T S_j)^2 a_j(t) z_j(t)} \]

- The receiver \( c_i \) takes different values for different structures (MMSE, de-correlator, etc.)
Interference Models

- Jointly model the state space of every mobile in the system
  - Problem: State space grows exponentially

- Assume unresponsive interference
  - Avoids the “Chicken and Egg” control issue
  - Problem: Unresponsive interference models provide misleading results

- Approximations use mean-field approach
  - Model aggregate behavior as an average
  - Can prove this is optimal in some cases
CDMA Wideband Limit

- Let $K, N \rightarrow \infty$ and $\frac{K}{N} \rightarrow \alpha$ the “system load”

- Previous research has proved convergence of the SIR in the wideband limit [Tse and Hanly 1999, 2001]

- Can apply a wideband approximation to the stochastic process describing a CDMA system and the corresponding optimal control problem
Optimization in the Wideband Limit

- Want to find optimal multi-user cross-layer adaptation for a given performance metric, subject to QoS constraints
- Approximate the network dynamics with wideband limit
- Optimize the control in the wideband limit
- Check convergence and uniqueness to ensure the solution is a good approximation to a finite bandwidth system

**Special case of using mean field theorems**
Equilibrium in the Wideband Limit

- For any $K$, $N$, the system state vector $\Pi_k(t)$ is the fraction of users in each state.

- Define $P(\Pi_k(t), g)$ as the single user transition matrix.

- In the wideband limit we have deterministic non-linear dynamics for the system state:

  \[ \pi(t) = \lim_{K,N \to \infty} \Pi_k(t) \quad \text{and} \quad \pi(t+1) = \pi(t)P(\pi(t), g) \]

- Furthermore $\pi = \pi P(\pi, g)$ has a unique fixed point.
Wideband Optimal Control Problem

\[
\min_g \quad \pi(g)r(g)^T
\]

subject to:

\[
\pi(g)P(g,\pi(g)) = \pi(g), \quad \sum \pi(g) = 1, \quad f(\pi) \leq \alpha
\]

- Very similar to the single user optimization

- The non-linear constraint can introduce significant theoretical and computational complications

- The non-linear program is not convex
  - Can show that it can be solved by a sequence of linear programs
Example: Power Adaptation With Deadline Constrained Traffic

- Assume deadline sensitive data (100ms)
- 50 km/h Microcell (same channel as before)
- Minimize average transmission power subject to a deadline constraint
- Assume we have a matched filter receiver
- What happens as system load increases?
  - Let “number of users per Hz” vary between 0 and 1
Power vs. System Load
vs. Deadline Constraint
Crosslayer Design in Ad-Hoc Wireless Networks

- Application
- Network
- Access
- Link
- Hardware

Substantial gains in throughput, efficiency, and end-to-end performance from cross-layer design
Crosslayer Design

- Hardware
- Link
- Access
- Network
- Application

Delay Constraints
Rate Requirements
Energy Constraints
Mobility

Optimize and adapt across design layers
Provide robustness to uncertainty
Crosslayer Adaptation

- **Application Layer**
  - Design optimization criterion
  - Data prioritization
  - Adaptive QoS

- **Network Layer**
  - Adaptive routing

- **MAC Layer**
  - Access control
  - MUD/interference cancellation/smart antennas

- **Link Layer**
  - Adaptive rate, coding, power, framing, etc.
  - Adaptive retransmission/hierarchical coding

*Link, MAC, and network have the most obvious synergies, but the application layer dictates the optimization criterion*
Why a crosslayer design?

- The technical challenges of future mobile networks cannot be met with a layered design approach.
- QoS cannot be provided unless it is supported across all layers of the network.
  - The application must adapt to the underlying channel and network characteristics.
  - The network and link must adapt to the application requirements
- Interactions across network layers must be understood and exploited.
Adaptive Routing

- Routing establishes the mechanism by which a packet traverses the network
- As the network changes, the routes should be updated to reflect network dynamics
- Updating the route can entail significant overhead.
Route dissemination

- **Route computed at centralized node**
  - Most efficient route computation.
  - Can’t adapt to fast topology changes.
  - BW required to collect and disseminate information

- **Distributed route computation**
  - Nodes send connectivity information to local nodes.
  - Nodes determine routes based on this local information.
  - Adapts locally but not globally.

- **Nodes exchange local routing tables**
  - Node determines next hop based on some metric.
  - Deals well with connectivity dynamics.
  - Routing loops common.
Reliability

- Packet acknowledgements needed
  - May be lost on reverse link
  - Should negative ACKs be used.

- Combined ARQ and coding
  - Retransmissions cause delay
  - Coding may reduce data rate
  - Balance may be adaptive

- Hop-by-hop acknowledgements
  - Explicit acknowledgements
  - Echo acknowledgements
    - Transmitter listens for forwarded packet
    - More likely to experience collisions than a short acknowledgement.
  - Hop-by-hop or end-to-end or both.
MIMO in Ad-Hoc Networks

- Antennas can be used for multiplexing, diversity, or interference cancellation
  - Cancel M-1 interferers with M antennas
- What metric should be optimized?

Cross-Layer Design
How to use Feedback in Wireless Networks

- Output feedback
- CSI
- Acknowledgements
- Network/traffic information
- Something else

Noisy/Compressed
Diversity-Multiplexing-Delay Tradeoffs for MIMO Multihop Networks with ARQ

- MIMO used to increase data rate or robustness
- Multihop relays used for coverage extension
- ARQ protocol:
  - Can be viewed as 1 bit feedback, or time diversity,
  - Retransmission causes delay (can design ARQ to control delay)
- Diversity multiplexing (delay) tradeoff - DMT/DMDT
  - Tradeoff between robustness, throughput, and delay
Multihop ARQ Protocols

- **Fixed ARQ**: fixed window size
  - Maximum allowed ARQ round for ith hop $L_i$ satisfies $\sum_{i=1}^{N} L_i \leq L$

- **Adaptive ARQ**: adaptive window size
  - **Fixed Block Length (FBL)** (block-based feedback, easy synchronization)
  - **Variable Block Length (VBL)** (real time feedback)

```
Block 1
  ARQ round 1

Block 1
  ARQ round 2

Block 1
  ARQ round 3

Block 2
  ARQ round 1

Block 2
  ARQ round 2

Block 1
  round 3

Block 2
  ARQ round 1

Block 2
  ARQ round 2

Receiver has enough Information to decode
```

```
Block 1
  ARQ round 1

Block 1
  ARQ round 2

Block 1
  round 3

Block 2
  ARQ round 1

Block 2
  ARQ round 2

Receiver has enough Information to decode
```
Asymptotic DMDT Optimality

- Theorem: VBL ARQ achieves optimal DMDT in MIMO multihop relay networks in long-term and short-term static channels.

- Proved by cut-set bound

- An intuitive explanation by stopping times: VBL ARQ has the smaller outage regions among multihop ARQ protocols
Multiple routes through the network can be used for multiplexing or reduced delay/loss.

Application can use single-description or multiple description codes.

Can optimize optimal operating point for these tradeoffs to minimize distortion.
Cross-layer protocol design for real-time media

- Loss-resilient source coding and packetization
- Congestion-distortion optimized scheduling
- Congestion-distortion optimized routing
- Capacity assignment for multiple service classes
- Adaptive link layer techniques

Traffic flows
Link state information
Link capacities
Rate-distortion preamble

Application layer
Transport layer
Network layer
MAC layer
Link layer

Joint with T. Yoo, E. Setton, X. Zhu, and B. Girod
Video streaming performance

3-fold increase

5 dB
Approaches to Cross-Layer Resource Allocation*

*Much prior work is for wired/static networks
Network Utility Maximization

- Maximizes a network utility function

\[
\max \sum_k U_k(r_k)
\]

s.t. \( Ar \leq R \)

- Assumes
  - Steady state
  - Reliable links
  - Fixed link capacities

- Dynamics are only in the queues
Wireless NUM

- Extends NUM to random environments
- Network operation as stochastic optimization algorithm

\[
\begin{align*}
\text{max} & \quad E[\sum U(r_m(G))] \\
\text{st} & \quad E[r(G)] \leq E[R(S(G), G)] \\
& \quad E[S(G)] \leq \bar{S}
\end{align*}
\]
WNUM Policies

- Control network resources

- Inputs:
  - Random network channel information $G^k$
  - Network parameters
  - Other policies

- Outputs:
  - Control parameters
  - Optimized performance, that
  - Meet constraints

- Channel sample driven policies
Example: NUM and Adaptive Modulation

- Policies
  - Information rate $r()$
  - Tx power $S()$
  - Tx Rate $R()$
  - Tx code rate

- Policy adapts to
  - Changing channel conditions ($G$)
  - Packet backlog
  - Historical power usage

Block codes used
Rate-Delay-Reliability

- Policy Results

![Graph 1: Average Rate vs. BER](image1.png)

![Graph 2: Delay vs. Information Rate](image2.png)
Game theory

- Coordinating user actions in a large ad-hoc network can be infeasible

- Distributed control difficult to derive and computationally complex

- Game theory provides a new paradigm
  - Users act to “win” game or reach an equilibrium
  - Users heterogeneous and non-cooperative
  - Local competition can yield optimal outcomes
  - Dynamics impact equilibrium and outcome
  - Adaptation via game theory
**Research Areas**
- Fundamental performance limits and tradeoffs
- Node cooperation and cognition
- Adaptive techniques
- Layering and Cross-layer design
- Network/application interface
- End-to-end performance optimization and guarantees
Summary

- The dynamic nature of ad-hoc networks indicate that adaptation techniques are necessary and powerful.
- Adaptation can transcend all layers of the protocol stack.
- Approaches to optimization include dynamic programming, utility maximization, and game theory.
- Network dynamics make centralized/distributed control challenging.
- Game theory provides a simple paradigm that can yield near-optimal solutions.