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 (Halhe 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

Power Control Adaptation

- Each node generates independent data.
- Source-destination pairs are chosen at random.
- Topology is dynamic (link gain $G_{ij}$ time-varying)
- Different link SIRs based on channel gains $G_{ij}$
- Power control used to maintain a target $R_i$ value

Power Control for Fixed Channels

- Seminal work by Foschini/Miljanic [1993]
- Assume each node has an SIR constraint

$$R_i = \frac{G_i P_i}{\eta \sum_{j \neq i} G_{ij} P_j} \geq \gamma_i \quad (1 - F) P + u \geq 0, \quad P \geq 0$$

- Write the set of constraints in matrix form

$$F_y = \begin{cases} 0, & i = j \\ \gamma G_{ii}, & i \neq j \\ \gamma G_{i}, & \end{cases} u = \left[ \frac{\gamma_1 \eta_1}{G_{11}}, \ldots, \frac{\gamma_N \eta_N}{G_{NN}} \right]^T$$

Scaled Interferer Gain
Scaled Noise
Optimality and Stability

- Then if $r_F < 1$ 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
  \[ E[\log R_i] = \log \gamma_i \quad \Rightarrow \quad ER_i \geq \gamma_i \]
- How to define optimality if network is time-varying?

Can Consider A New SIR Constraint

\[ R_i = \frac{G_i P_i}{\eta_i + \sum_{j \neq i} G_j P_j} \geq \gamma_i \quad \Leftrightarrow \text{Original constraint} \]

\[ E \left[ F_i P - \gamma_i \left( \frac{\eta_i}{E[G_i]} + \sum_{j \neq i} F_j P_j \right) \right] \geq 0 \quad \Leftrightarrow \text{Multiply out and take expectations} \]

\[ (I - F)P + \bar{u} \geq 0 \quad \Leftrightarrow \text{Matrix form} \]

\[ F_{ij} = \begin{cases} 0, & i = j \\ \gamma_i E[G_i] & i \neq j \end{cases} \quad \sigma = \left[ \begin{array}{c} \gamma_i \eta_i/E[G_i] \\ \vdots \\ \gamma_i \eta_i/E[G_{iN}] \end{array} \right] \]

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

Robbins-Monro algorithm

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

Where $g_k$ is a noise term

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

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

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: \( a_k = \sum_{n=1}^{k} a_k \to \infty \quad \sum_{n=1}^{k} a_k^2 = \infty \)
- A fixed step size algorithm will not converge to the optimal power allocation
  \( P(k) \Rightarrow \tilde{P} \) where \( E[\|P^* - \tilde{P}\|^2] = O(a) \)
- 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
  \( E[G] = \begin{pmatrix} 1 & 0.375 & 0.02 \\ 0.02 & 1 & 0.04 \\ 0.04 & 0.02 & 1 \end{pmatrix} \)
- Note that \( p_f = 0.33 \) so we should expect this network to be fairly stable

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
  \[ S_i = \frac{1}{\sqrt{N}} [v_{i1}, \ldots, v_{iN}] \]
  \[ SIR_j(t) = \frac{(c_j^T S_j)^2 a_j(t) z_j(t)}{(c_j^T c_j) \sigma^2 + \sum_{i \neq j} (c_j^T S_i)^2 a_i(t) z_i(t)} \]
- The receiver \( c_j \) 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 \( K \to \infty \) and \( \frac{K}{N} \to \alpha \) 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 nonlinear dynamics for the system state
  \[ \pi(t) = \lim_{K, N \to \infty} \Pi_k(t) \text{ and } \pi(t+1) = \pi(t)P(\pi(t),g) \]
- Furthermore \( \pi = \pi P(\pi, g) \) has a unique fixed point
Wideband Optimal Control Problem

\[
\min_{\pi} \pi(g)r(g)^T
\]

subject to:
\[
\pi(g)P(g,\pi(g)) = \pi(g), \sum \pi(g) = 1, f(\pi) \leq \alpha
\]

- 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

![Graph showing Power vs. System Load vs. Deadline Constraint](image)

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

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 acknowledgments 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 acknowledgments
  - Explicit acknowledgments.
  - Echo acknowledgments.
  - 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 $\sum_{j<i} L_j \leq L_i$
- Adaptive ARQ: adaptive window size
  - Fixed Block Length (FBL) (block-based feedback, easy synchronization)
  - Variable Block Length (VBL) (real time feedback)

**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

**Delay/Throughput/Robustness across Multiple Layers**

- 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**

- Link state information
- Traffic flows
- Congestion-distortion optimized routing
- Congestion-distortion optimized scheduling
- Loss-resilient source coding and packetization
- Rate-distortion preamble

**Video streaming performance**

- Video streaming performance
  - 3-fold increase
  - 5 dB
Approaches to Cross-Layer Resource Allocation*

Network Optimization

- Dynamic Programming
- Network Utility Maximization
- Distributed Optimization
- Game Theory

State Space Reduction
- Wireless NUM
- Multiagent NUM
- Distributed Algorithms

Mechanisms Design
- Stackelberg Games
- Nash Equilibrium

*Much prior work is for wired/static networks

Network Utility Maximization

- Maximizes a network utility function

\[ \max \sum_{k} U_k(\tau_k) \]

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

Routing

Fixed link capacity

- 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

\[ \max \mathbb{E}[\sum U_k(\tau_k(G))] \]

s.t. \( \mathbb{E}[\tau(G)] \leq \mathbb{E}[R(S(G),G)] \)

\( \mathbb{E}[S(G)] \leq \mathcal{S} \)

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

Rate-Delay-Reliability

- Policy Results
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

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