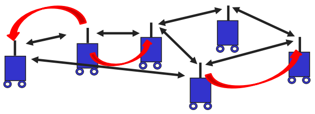
# EE360: Lecture 9 Outline
# Resource Allocation in Ad Hoc Nets

- 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?

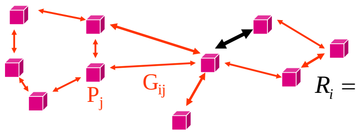
- QoS
  - Adapts to application needs, network/link conditions, energy/power constraints, …
- Routing
  - Adapts to topology changes, link changes, user demands, congestion, …
- Transmission scheme (power, rate, coding, …)
  - Adapts to channel, interference, application requirements, throughput/delay 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

# Power Control Adaptation



$$R_i = \frac{G_{ii}P_i}{\eta_i + \sum_{i \neq j} G_{ij}P_j}$$

- 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

# Power Control for Fixed Channels

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

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

- Write the set of constraints in matrix form

$$F_{ij} = \begin{cases} 0, & i = j \\ \dfrac{\gamma_i G_{ij}}{G_{ii}}, & i \neq j \end{cases} \qquad \mathrm{u} = \left[\frac{\gamma_1 \eta_1}{\mathrm{G}_{11}}, \ldots, \frac{\gamma_N \eta_N}{\mathrm{G}_{NN}}\right]^T$$

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**

$$\text{Centralized}: \quad P(k+1) = FP(k) + u$$

$$\text{Distributed}: \quad P_i(k+1) = \frac{\gamma_i}{R_i(k)} P_i(k)$$

## 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

$$R_i = \frac{G_{ii} P_i}{\eta_i + \sum_{i \neq j} G_{ij} P_j} \geq \gamma_i$$

**⇐ Original constraint**

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

**⇐ Multiply out and take expectations**

$$(I - \overline{F})\overline{P} + \overline{u} \geq 0$$

**⇐ Matrix form**

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

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**

$$\frac{E[G_{ii} P_i]}{E\left[ \eta_i + \sum_{j \neq i} G_{ij} P_j \right]} = \gamma_i$$

- **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**

$$\varepsilon_k = (\overline{F} - F(k)) P(k) + (\overline{u} - u(k))$$

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

**Under appropriate conditions on $\varepsilon_k$**

$$P(k) \to \overline{P}^*$$

## 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 $a_k \to 0$

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

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

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

- 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

$$E[G] = \begin{pmatrix} 1 & .0375 & .02 \\ .0375 & 1 & .04 \\ .02 & .04 & 1 \end{pmatrix} \qquad \gamma_i = 5 \quad \eta_i = 1 \quad \forall i$$

- Note that $\rho_F$=.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

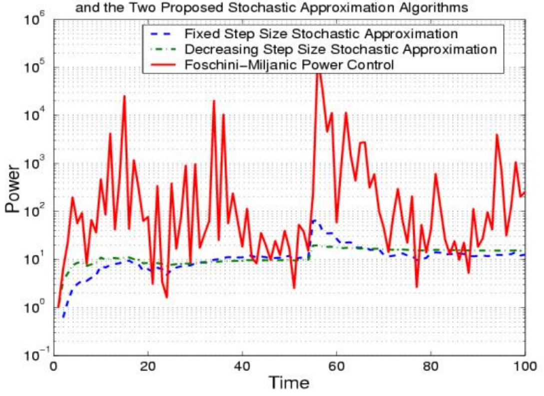
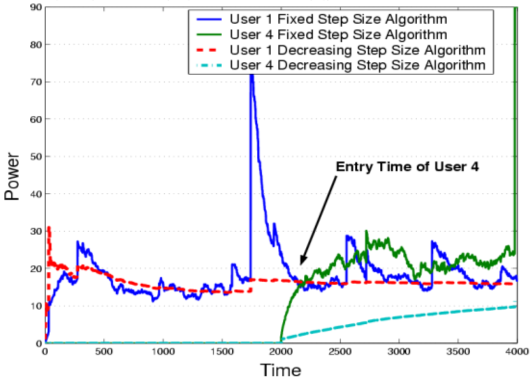


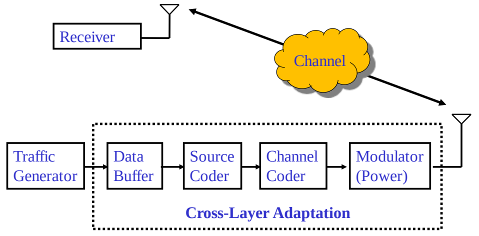
Fig. 3 Comparision of the Stand and Modified Stochastic Approximations Algorithms: Transmit Powers with an Admission Event at Time 2000



## 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


Receiver
Channel
Traffic Generator
Data Buffer
Source Coder
Channel Coder
Modulator (Power)
Cross-Layer 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

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

Interference term

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

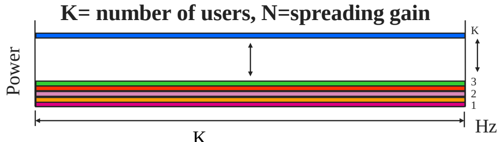
- The receiver $c_i$ takes different values for different structures (MMSE, de-correlator, etc.)

## 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

K= number of users, N=spreading gain



- Let $\mathrm{K,N}\to\infty$ and $\frac{\mathrm{K}}{\mathrm{N}}\to\alpha$ 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 <u>optimal control problem</u>

## 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 $\boldsymbol{P}(\Pi_K(t),\boldsymbol{g})$ as the single user transition matrix
- In the wideband limit we have deterministic non-linear dynamics for the system state

$$\pi(t) = \lim_{K,N\to\infty}\Pi_K(t) \quad \text{and} \quad \pi(t+1) = \pi(t)P\big(\pi(t),g\big)$$

- Furthermore $\pi = \pi P\big(\pi, g\big)$ has a unique fixed point

## Wideband Optimal Control Problem

$$\min_{g} \quad \pi(g) r(g)^T$$

subject to:

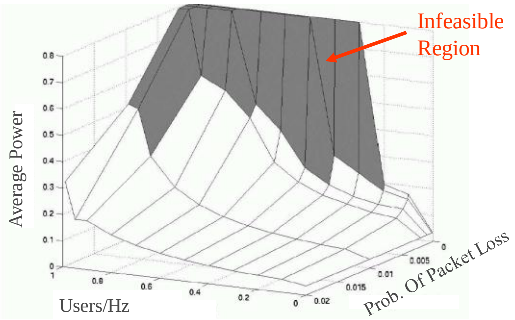
$$\pi(g)P\big(g,\pi(g)\big) = \pi(g), \sum \pi(g) = 1,\ f(\pi) \le \alpha$$

- **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

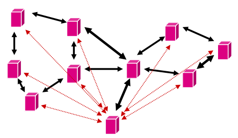
- **Assume deadline sensitive data (100ms)**
- **50 km/h Microcell (same channel as before)**
- **Minimize average transmission power subject to a deadline constraint**
- **Assume we have a matched filter receiver**
- **What happens as system load increases?**
  - **Let "number of users per Hz" vary 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

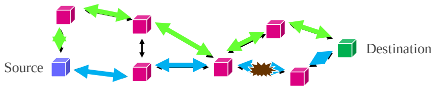
- Application Layer
  - Design optimization criterion
  - Data prioritization
  - Adaptive QoS
- Network Layer
  - Adaptive routing
- MAC Layer
  - Access control
  - MUD/interference cancellation/smart antennas
- Link Layer
  - Adaptive rate, coding, power, framing, etc.
  - Adaptive retransmission/hierarchical 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.

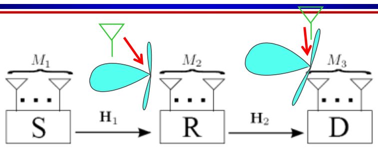
# Route dessemination

- Route computed at centralized node
  - Most efficient route computation.
  - Can't adapt to fast topology changes.
  - BW required to collect and desseminate 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.

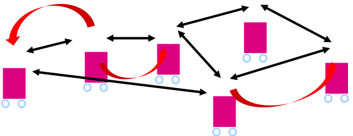
# MIMO in Ad-Hoc Networks



- 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*

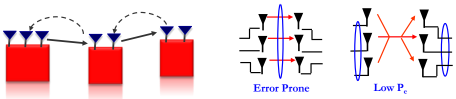
# How to use Feedback in Wireless Networks



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

Output feedback, CSI, Acknowledgements: Noisy/Compressed

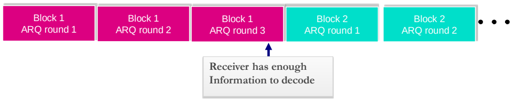
# Diversity-Multiplexing-Delay Tradeoffs for MIMO Multihop Networks with ARQ



- 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

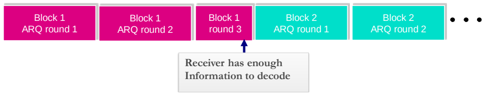
- **Fixed ARQ: fixed window size**
  - **Maximum allowed ARQ round for ith hop $L_i$ satisfies $\sum_{i=1}^{N} L_i \leq L$**
- **Adaptive ARQ: adaptive window size**
  - **Fixed Block Length (FBL) (block-based feedback, easy synchronization)**



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 | • • •

Receiver has enough Information to decode

  - **Variable Block Length (VBL) (real time feedback)**

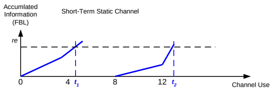


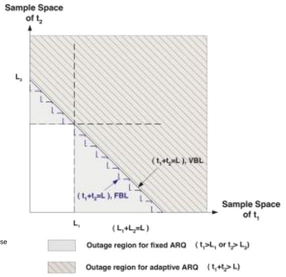
Block 1 ARQ round 1 | Block 1 ARQ round 2 | Block 1 round 3 | Block 2 ARQ round 1 | Block 2 ARQ round 2 | • • •

Receiver has enough Information to decode

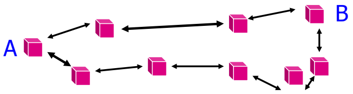
# Asymptotic DMDT Optimality

- **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**



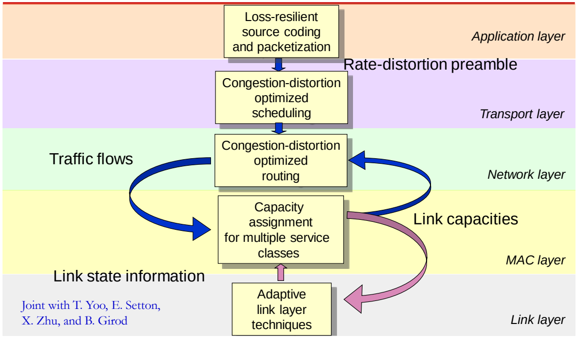


# Delay/Throughput/Robustness across Multiple Layers



- 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



Loss-resilient source coding and packetization

*Application layer*

Rate-distortion preamble

Congestion-distortion optimized scheduling

*Transport layer*

Traffic flows

Congestion-distortion optimized routing

*Network layer*

Capacity assignment for multiple service classes

Link capacities

*MAC layer*

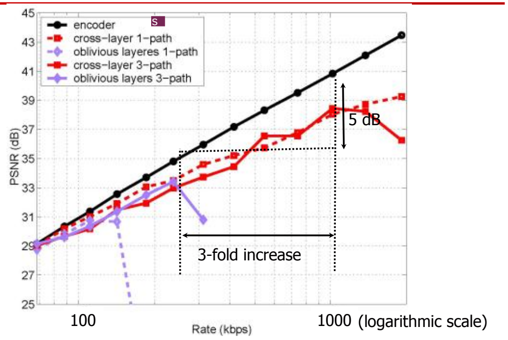
Link state information

Adaptive link layer techniques

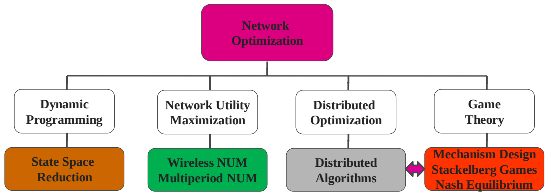
*Link layer*

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

# Video streaming performance



# Approaches to Cross-Layer Resource Allocation*



Network Optimization

Dynamic Programming

Network Utility Maximization

Distributed Optimization

Game Theory

State Space Reduction

Wireless NUM Multiperiod NUM

Distributed Algorithms

Mechanism Design Stackelberg Games Nash Equilibrium

*Much prior work is for wired/static networks

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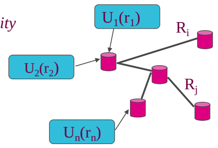
# Network Utility Maximization

- Maximizes a network utility function

$$\max \sum U_k(\overset{\textit{flow } k}{r_k}) \qquad s.t. \quad \underset{\textit{routing}}{A} r \le \underset{\textit{Fixed link capacity}}{R}$$

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



- Dynamics are only in the queues

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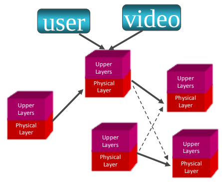
# Wireless NUM

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

$$\max \quad E[\sum U(r_m(G))]$$
$$\text{st}$$
$$E[r(G)] \le E[R(S(G),G)]$$
$$E[S(G)] \le \bar{S}$$



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# 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

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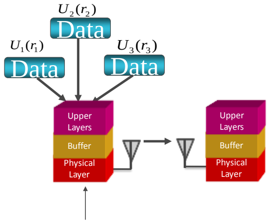
# Example: NUM and Adaptive Modulation

- 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

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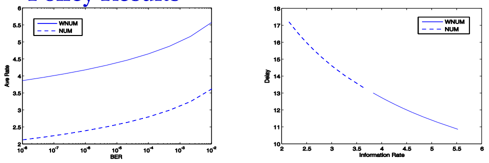
# Rate-Delay-Reliability

- Policy Results



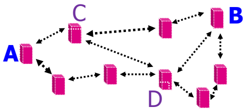
# Game theory

- 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

## FLoWS

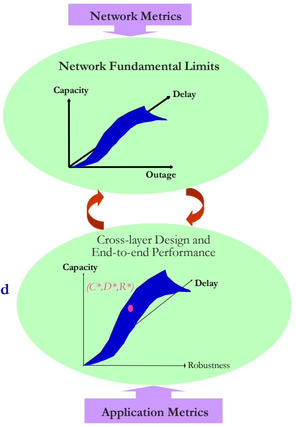
Fundamental Limits
of Wireless Systems

(DARPA Challenge Program)



**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