Rate Control in Wireless Networks

ECE 299.02
Spring 2007
Today’s Discussions

- Recall key MAC layer issues/ideas
  - Recall 802.11 → SS radios, PLCP, HT problems, RTS/CTS, CS
  - Recall D-Antennas → Spatial reuse, higher range, capture ...

- Introducing rate control
  - Motivation to exploit variations in channel conditions
  - Rate control ideas in literature, ARF in 802.11

- Receiver-based Rate Control
  - The Idea, Evaluation
  - Issues/Discussions
  - Opportunistic rate-control

- What lies ahead?
Recall Lecture 2

- RTS/CTS + Large CS Zone
  - Alleviates hidden terminals, but trades off spatial reuse
Recall Lecture 3

**Omni Communication**

Silenced Node

**Directional Communication**

**No** Simultaneous Communication

**Ok** Simultaneous Communication
Research Directions

- **Benefits from protecting data communication**
  - RTS/CTS and carrier sensing
  - MACA, MACAW, 802.11 ...

- **Benefits from spatial filtering**
  - Directional communication
  - Capture-awareness

- **Benefits from exploiting channel conditions**
  - Rate adaptation to extract higher performance
  - Power control is a dual problem
Some Basics

- Friss’ Equation
  \[
  P_R = \frac{P_T G_T G_R}{K r^\alpha}
  \]

- Shannon’s Equation
  \[
  C = B \times \log_2 (1 + \text{SINR})
  \]

- Bit-energy-to-noise ratio
  \[
  \frac{E_b}{N_0} = \text{SINR} \times \frac{B}{R}
  \]

Leads to BER

Varying with time and space

How do we choose the rate of modulation
# Estimate a value of SINR
# Then choose a corresponding rate that would transmit packets correctly (i.e., $E_b / N_0 > \text{thresh}$) most of the times
# Failure in some cases of fading $\rightarrow$ live with it
Adaptive Rate-Control

- Observe the current value of SINR
- Believe that current value is indicator of near-future value
- Choose corresponding rate of modulation
- Observe next value
- Control rate if channel conditions have changed
Is there a tradeoff?

Rate = 10
Is there a tradeoff?

What about length of routes due to smaller range?
Any other tradeoff?

Can anyone think of yet another IMPORTANT tradeoff

Hint: Related to the MAC Layer
Total interference

More nodes free to transmit packets (A, B, E)
Interference incident at receiver (D) increases
A Rate-Adaptive MAC Protocol for Multi-Hop Wireless Networks

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Background

- Current WLAN hardware supports multiple data rates
  - 802.11b - 1 to 11 Mbps
  - 802.11a - 6 to 54 Mbps

- The data rate is determined by the modulation scheme
Problem

Modulation schemes have different error characteristics

![Graph showing BER vs. SNR for different data rates (1 Mbps and 8 Mbps)]
Impact

Large-scale variation with distance (Path loss)

Path Loss

SNR (dB)

Distance (m)

Mean Throughput (Kbps)

Distance (m)

8 Mbps

1 Mbps
Impact

Small-scale variation with time (Fading)

[Diagram showing Rayleigh Fading with SNR (dB) on the y-axis and Time (ms) on the x-axis. The diagram includes markers for different modulation schemes such as QAM256 (8 Mbps), QAM64 (6 Mbps), QAM16 (4 Mbps), QPSK (2 Mbps), and BPSK (1 Mbps) at 2.4 GHz 2 m/s LOS.]
Question

Which modulation scheme to choose?
Answer → Rate Adaptation

- Dynamically choose the best modulation scheme for the channel conditions
Design Issues

- How frequently must rate adaptation occur?

- Signal can vary rapidly depending on:
  - carrier frequency
  - node speed
  - interference
  - etc.

- For conventional hardware at pedestrian speeds, rate adaptation is feasible on a *per-packet* basis

Coherence time of channel higher than transmission time
Adaptation → At Which Layer?

- Cellular networks
  - Adaptation at the *physical layer*

- Impractical for WLANs
  - RTS/CTS requires that the *rate be known in advance*

- For WLANs, rate adaptation best handled at MAC
Who should select the data rate?

- Channel conditions are only known at the receiver
- Receiver’s hardware can provide useful information
  - SS, noise, interference, BER, multi-path characteristics

- The receiver is best positioned to select the data rate
Previous Work

- **PRNet**
  - Periodic broadcasts of link quality tables

- **Pursley and Wilkins**
  - RTS/CTS feedback for power adaptation
  - ACK/NACK feedback for rate adaptation

- **Lucent WaveLAN “Autorate Fallback” (ARF)**
  - Uses lost ACKs as link quality indicator
Pursley and Wilkins

- Caches per-node transmit and receive parameters
- RTS carries transmit parameters to receiver
- CTS may only carry power adjustment, not rate
- ACK/NACK may carry new parameters for subsequent packets
- May not work well for infrequent traffic

WHY?
Lucent WaveLAN “Autorate Fallback” (ARF)

- **Sender decreases rate after**
  - $N$ consecutive ACKS are lost

- **Sender increases rate after**
  - $Y$ consecutive ACKS are received or
  - $T$ secs have elapsed since last attempt

1 Mbps Effective Range

2 Mbps Effective Range
Performance of ARF

- Slow to adapt to channel conditions
- Choice of $N$, $Y$, $T$ may not be best for all situations
RBAR Approach

- Move the rate adaptation mechanism to the receiver
  - Better channel quality information = better rate selection

- Utilize the RTS/CTS exchange to:
  - Provide the receiver with a signal to sample (RTS)
  - Carry feedback (data rate) to the sender (CTS)
Receiver-Based Autorate (RBAR) Protocol

- RTS carries sender's estimate of best rate
- CTS carries receiver's selection of the best rate
- Nodes that hear RTS/CTS calculate reservation
- If rates differ, special subheader in DATA packet updates nodes that overheard RTS
Performance of RBAR

[Graph showing SNR (dB) over time for RBAR and ARF, with different modulation schemes indicated.]
Question to the class

- There are two types of fading
  - Short term fading
  - Long term fading

- Under which fading is RBAR better than ARF?
- Under which fading is RBAR comparable to ARF?
- Is there a case when RBAR is worse than ARF?
## Implementation into 802.11

<table>
<thead>
<tr>
<th>Frame Control</th>
<th>Duration</th>
<th>DA</th>
<th>SA</th>
<th>FCS</th>
<th>BSSID</th>
<th>Sequence Control</th>
<th>Body</th>
<th>FCS</th>
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- **Reservation Subheader (RSH)**

- **Encode data rate and packet length in *duration* field of frames**
  - Rate can be changed by receiver
  - Length can be used to select rate
  - Reservations are calculated using encoded rate and length

- **New DATA frame type with *Reservation Subheader (RSH)***
  - Reservation fields protected by additional frame check sequence
  - RSH is sent at same rate as RTS/CTS

- **New frame is only needed when receiver suggests rate change**
Ns-2 with mobile ad hoc networking extensions

- Rayleigh fading

Scenarios: single-hop, multi-hop

Protocols: RBAR and ARF

RBAR
- Channel quality prediction:
  - SNR sample of RTS
- Rate selection:
  - Threshold-based
- Sender estimated rate:
  - Static (1 Mbps)

Performance Analysis

<table>
<thead>
<tr>
<th>BER</th>
<th>SNR (dB)</th>
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<td>1E-5</td>
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Graph showing BER vs SNR with different modulation schemes and thresholds.
Performance Results

Single-Hop Network
Single-Hop Scenario

![Graph showing Mean Throughput (Kbps) vs Distance (m) for different modulation schemes: QAM256 (8Mbps), QAM64 (6Mbps), QAM16 (4Mbps), QPSK (2Mbps), and BPSK (1Mbps). The graph illustrates the decline in throughput as the distance between nodes A and B increases.]
Varying Node Speed

UDP Performance

- RBAR performs best
- Declining improvement with increase in speed
  - Adaptation schemes over fixed
  - RBAR over ARF
- Some higher fixed rates perform worse than lower fixed rates
Varying Node Speed
TCP Performance

- RBAR again performs best
- Overall lower throughput and sharper decline than with UDP
  - Caused by TCP’s sensitivity to packet loss
- More higher fixed rates perform worse than lower fixed rates
Infrequent Traffic
UDP Performance

- Similar results for shorter burst intervals
- Similar results for TCP (see tech report)
No Mobility
UDP Performance

- RSH overhead seen at high data rates
  - Can be reduced using some initial rate estimation algorithm
- Limitations of simple threshold-based rate selection seen
- Generally, still better than ARF
No Mobility
UDP Performance

- RBAR-P - RBAR using a simple initial rate estimation algorithm
  - Previous rate used as *estimated* rate in RTS
- Better high-rate performance
- Other initial rate estimation and rate selection algorithms are a topic of future work

Why useful?
Performance Results

Multi-Hop Network
Multi-Hop Network
UDP Performance

Similar results for TCP
Multi-Hop Network
Sensitivity to RSH Loss

- Aggregate throughput is unaffected by RSH loss
- High loss probability results in only slight change in fairness
Multi-Hop Network
Sensitivity to RSH Loss

- Similar results
- Slightly more unfairness (vs. ARF) for no loss
  - (overall fairness problem due to MAC backoff by node A)
RBAR Summary

- Modulation schemes have different error characteristics

- Significant performance improvement may be achieved by MAC-level adaptive modulation

- Receiver-based schemes may perform best
  - Proposed Receiver-Based Auto-Rate (RBAR) protocol
  - Implementation into 802.11

- Future work
  - RBAR without use of RTS/CTS
  - RBAR based on the size of packets
  - Routing protocols for networks with variable rate links
Other proposals in rate-control

Quick survey/discussion
Opportunistic Auto-Rate (OAR)

- In multihop networks, there is intrinsic diversity
  - One among many possible transmissions take place
  - Decision made based on channel contention
  - Exploiting this diversity can offer benefits

- RBAR does not exploit this diversity
  - It optimizes per-link throughput

- OAR identified possibility of exploiting channel diversity
  - Identify transmitters with better channel quality
  - Let these transmitters transmit more packets
OAR Idea

Basic Idea
- If bad channel, wait for better channel quality
- If good channel, transmit as much as possible
Why is OAR any better?

- 802.11 alternates between transmitters A and C
  - Why is that bad

Is this diagram correct?
Why is OAR any better?

- Bad channel reduces SINR $\rightarrow$ increases transmit time
  - Fewer packets can be delivered

A

\[\text{Data} \quad \text{Data} \quad \text{Data}\]

B

\[\text{Data} \quad \text{Data} \quad \text{Data}\]
OAR Protocol Steps

- Transmitter estimates current channel
  - Can use estimation algorithms
  - Can use RBAR, etc.

- If channel better than base rate (2 Mbps)
  - Transmit proportionally more packets
  - E.g., if channel can support 11 Mbps, transmit (11/2 ~ 5) pkts

- OAR upholds temporal fairness
  - Each node gets same duration to transmit
  - Sacrifices throughput fairness → the network gains!!
OAR thoughts

- OAR does not offer benefits when

- OAR may not be suitable for applications like

- With TCP how can OAR get affected?
OAR thoughts

- OAR does not offer benefits when
  - Neighboring nodes do not experience diverse channel conditions
  - Coherence time is shorter than N packets

- OAR may not be suitable for applications like
  - Voice traffic, video traffic ... why ??

- With TCP how can OAR get affected ?
  - Back-to-back packets can increase TCP performance
  - However, bottleneck bandwidth can get congested quick
  - Also, variance of RTT can increase
Exploiting Diversity in Rate Adaptation

Yet another idea exploits multiple user diversity
- Among many intermediate nodes, who has best channel
- Use that node as forwarding node
- Forwarding node can change with time
  - Due to channel fluctuations at different time and space
The Protocol Overview

• MAD using Packet Concatenation (PAC)

**Diagram:**
- **Sender:** GRTS
  - **User 1:** CTS 1
    - **User 2:** CTS 2
      - **User k:** ... CTS k
    - **Data:** SF DATA 0 DATA 1 DATA 2
      - **ACK:** ACK 0~2

Since at least one intermediate node is likely to have good channel condition, transmitter can transmit at a high data rate or concatenate multiple packets:

- Choosing subset of neighbor-group is important
- Coherence time of channel must be greater than packet chain
- Group needs to really have independent channel gain
  - Correlated channel gains can lead to performance hit.
Summary

Rate control can be useful
- When adapted to channel fluctuations (RBAR)
- When opportunistically selecting transmitters (OAR)
- When utilizing node diversity

Benefits maximal when
- Channel conditions vary widely in time and space

Correlation in fluctuation can offset benefits
- OAR and Diversity-based MAC may show negligible gain

Several more research possibilities with rate control
What lies ahead?

- **Routing based on rate-control**
  - Choosing routes that contain high-rate links
  - ETX metric proposed from MIT accommodates link character
  - Opportunistic routing from MIT again - takes neighbor diversity into account (best paper Sigcomm 2005)
  - Fertile area for a project ...

- **Dual of rate-control is power control**
  - One might be better than the other
  - Decision often depends on the scenario → open problem

- **Directional antennas for DD link for data/ack**
  - Rate control can be introduced → Not been studied yet

... many many more
Questions?