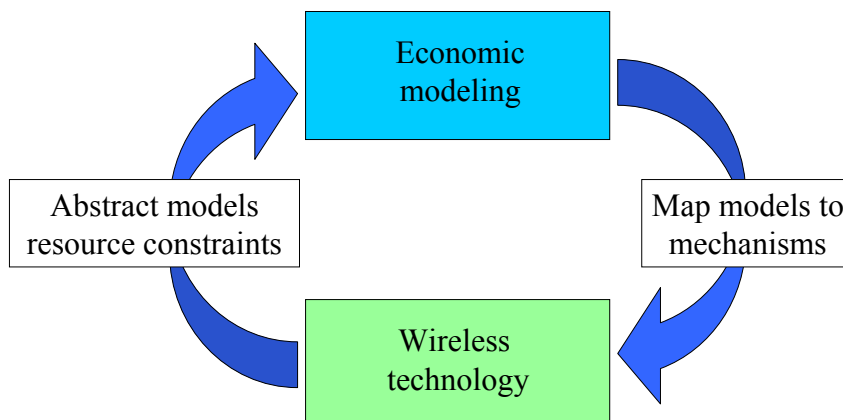


Resource Control in Wireless Networks

Vasilios A. Siris

Approach & goals



Roadmap

- Objective: **Efficient** resource control for **elastic traffic** in CDMA networks
- Overview of **contributions**
- **Wireless resource constraints** in uplink & downlink
- **Economic modeling**: Social welfare maximization
- **Application** issues & numerical investigations
- Related work & conclusions

Contributions

- Formulate and analyze framework for **efficient resource control** of **elastic traffic** in CDMA based on **social welfare maximization**
- Consider wireless **resource constraints** in both **uplink** and **downlink**
- Joint optimization over **signal quality** and **transmission rate**
- For **elastic traffic**, **user net utility optimization** can be **decomposed** into **two sub-problems**:
 - **Signal quality adaptation**: do at CDMA layer
 - **Rate control**: do at transport layer

Contributions (cont)

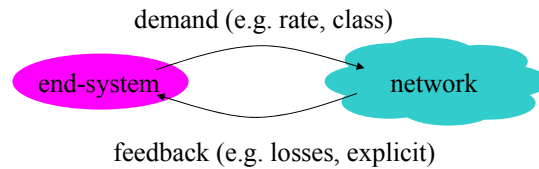
- Uniform framework for **seamless congestion control in wired/wireless networks**
 - Also account for mobile battery consumption
- Use of **ECN (Explicit Congestion Notification)** as **common signalling framework**
 - **Routers** marks packets based on congestion in **wired network**
 - **RNC (Radio Network Controller)** marks packets based on congestion in **wireless network**

Why economic modeling?

- Successfully applied to **fixed networks**
 - Kelly, Gibbens et al, Key et al, Low et al, Kunniyur et al, etc
 - Generalization of congestion control algorithms
 - Use of Explicit Congestion Notification (ECN)
- **Efficient** and **robust** resource utilization
- **Distributed** and **decentralized** solution
- Other work has also considered application of economic ideas to wireless networks
 - Utilities and “prices”

Congestion control and resource usage

- Closed-loop control loop

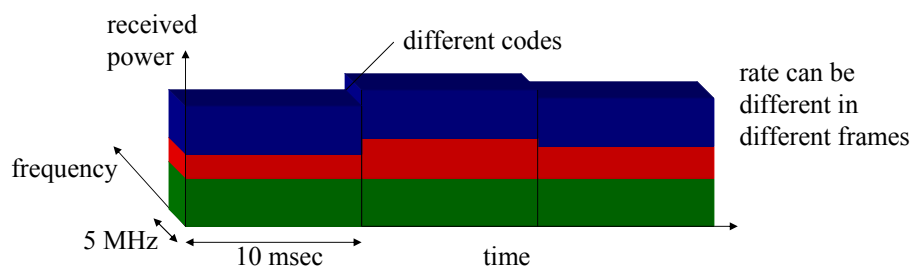


- Feedback depends on **level of congestion** and **resource usage**
- Shared resources in CDMA: **radio spectrum (uplink)** and **base station power (downlink)**
- End-system reaction to feedback modeled with **utility functions**

WCDMA technology

CDMA (Code Division Multiple Access)

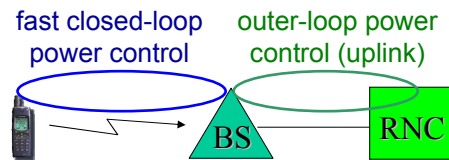
- Wideband CDMA (WCDMA) most widely adopted 3G air interface
 - Based on Direct Sequence CDMA (DS-SS)
- Signals from different mobiles separated based on **unique codes**
- **Transmission rate** can change between frames



Resource constraints in WCDMA

- **Shared resource** in WCDMA uplink: **radio spectrum**
 - WCDMA downlink: **base station power**
- QoS depends on **two parameters**
 - transmission rate
 - signal quality (signal-to-interference ratio, γ)

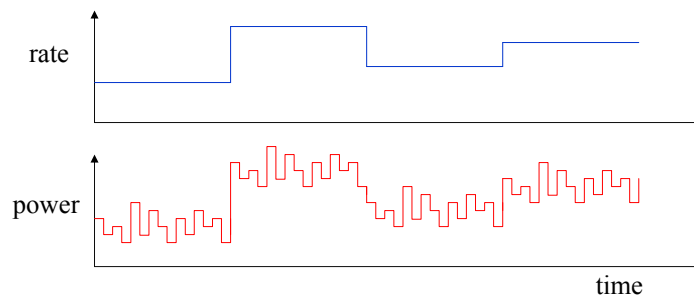
Power control in WCDMA



- **Fast closed-loop power control:** between MS and BS
 - Adjusts transmission power to achieve target **signal quality** (Signal-to-Interference Ratio, SIR)
 - Both uplink & downlink, frequency: 1500 Hz
- **Uplink outer-loop power control:** between BS and RNC
 - Adjusts target SIR to achieve given **frame error rate** (data: 10-20%, voice: 1%), frequency < 100 Hz
- **Increase power** when **interference increases**
- **Diverge** when **signal qualities are infeasible**
- Our approach affects only **outer-loop power control**

Relation to power control

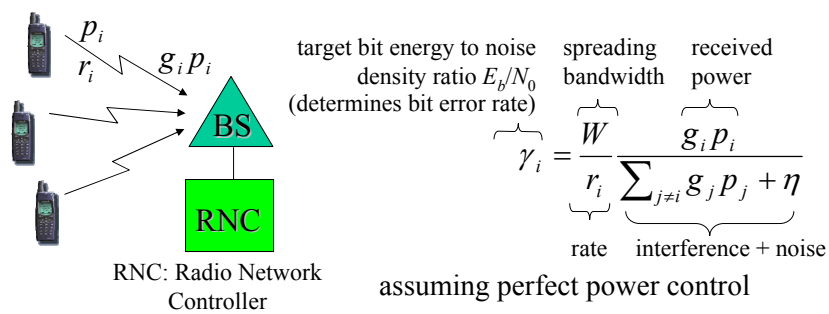
- WCDMA: rates fixed within single frame (10ms)
- **Fast closed-loop power control** (Mobile-BS) operates at 1500 Hz (0.67ms)



- **Outer loop power control** (BS-RNC) adjusts target E_b/N_0 ($=\gamma$) to achieve specific frame or block error rate

Resource Usage in WCDMA Uplink

Resource usage in CDMA: Uplink



uplink is **interference-limited**

resource constraint in uplink

$$\sum_i \frac{1}{\frac{W}{r_i \gamma_i} + 1} < 1$$

resource usage in uplink

$$\frac{1}{\frac{W}{r_i \gamma_i} + 1}$$

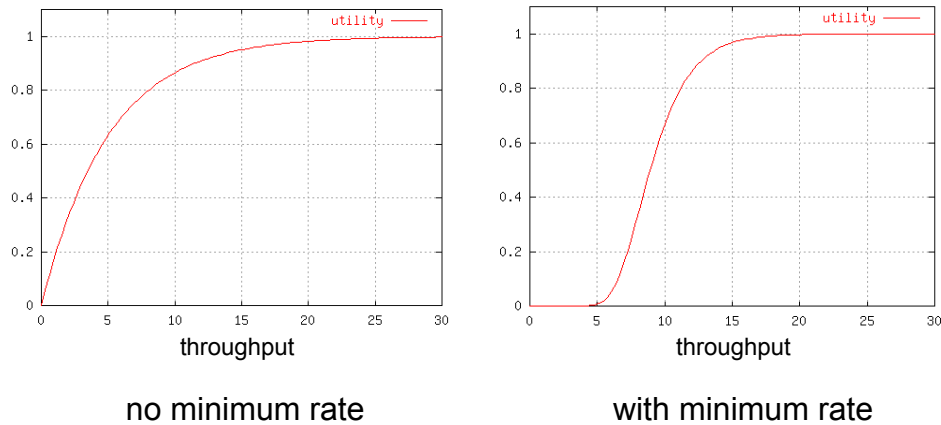
approximations for large # of mobile users

$$\sum_i r_i \gamma_i < W$$

$$r_i \gamma_i$$

Utility for elastic traffic

- **Utility**: user's *value* for specific *level of service*
- Elastic traffic: *level of service*=*average throughput*



Congestion pricing for elastic traffic: Uplink

- Utility for elastic traffic
 - average throughput: $r \cdot P_s(\gamma)$
 - utility: $U(r \cdot P_s(\gamma))$ pkt success rate
- Charges proportional to resource usage $r \cdot \gamma$
- User objective is to **maximize net utility**

$$\text{maximize over } r, \gamma \quad U(r \cdot P_s(\gamma)) - \lambda \cdot \overbrace{r}^{\text{price per unit resource}} \cdot \overbrace{\gamma}^{\text{resource usage}}$$

Social welfare maximization: Uplink

- **Social Welfare maximization** problem:

$$\begin{aligned} &\text{maximize} && \sum_{i=1}^N U_i(r_i P(\gamma_i)) \\ &\text{over} && \{\gamma_i \geq 0, i = 1, \dots, N\}, \{r_i \geq 0, i = 1, \dots, N\} \\ &\text{such that} && \sum_{i=1}^N r_i \gamma_i \leq W \end{aligned}$$

- Lagrangian for S.W. maximization problem:

$$L = \sum_i U_i(\gamma_i) + \lambda \left(W - \sum_i r_i \gamma_i \right)$$

↑
shadow price for constraint

Properties of the optimal solution

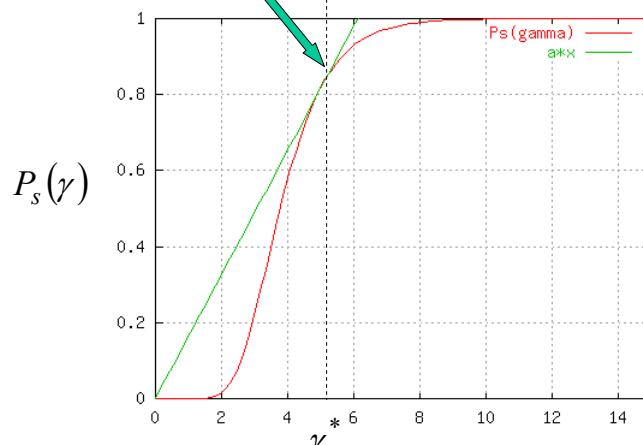
- Net utility maximization done over **two variables**: transmission rate r and signal quality γ
- **Proposition**: For elastic traffic, optimal γ^* is **independent** of **price** λ & **utility**, depends **only** on $P_s(\gamma)$

$$P_s(\gamma^*) = P_s'(\gamma^*) \cdot \gamma^*$$

- Above allows **decoupling** of selection of γ^* (target E_b/N_0) and of rate adaptation
 - selection of γ^* done at CDMA layer
 - rate adaptation done at higher layer (e.g. transport)

P_s for DPSK modulation, no FEC

$$P_s(\gamma^*) = P_s'(\gamma^*) \cdot \gamma^*$$



$$\begin{array}{ll} \gamma < \gamma^* & P_s(\gamma^*) < P_s'(\gamma^*) \cdot \gamma^* \\ \gamma > \gamma^* & P_s(\gamma^*) > P_s'(\gamma^*) \cdot \gamma^* \end{array}$$

Algorithm for setting of γ (target E_b/N_0)

- Performed by outer loop power control
- Based on convex / concave behavior of $P_s(\gamma)$

```

WHILE TRUE
  IF  $\frac{P_s(k) - P_s(k-1)}{\text{Step}} > F_{\text{high}} \frac{P_s(k)}{\text{Gamma}}$ 
    Gamma += Step
  IF  $\frac{P_s(k) - P_s(k-1)}{\text{Step}} < F_{\text{low}} \frac{P_s(k)}{\text{Gamma}}$ 
    Gamma -= Step
  
```

where

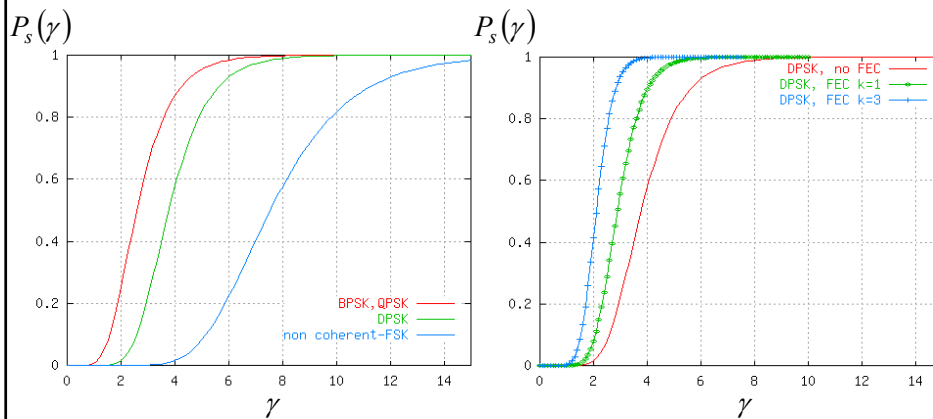
$P_s(k)$: packet success rate at step k

Gamma : target E_b/N_0

Step : target E_b/N_0 update step

$F_{\text{high}}, F_{\text{low}}$: parameters (e.g. 1.1, 0.9)

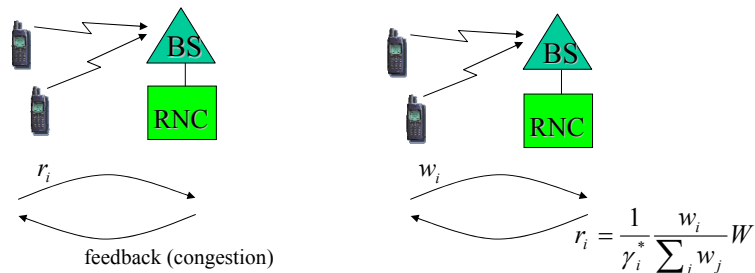
P_s for different modulation and FEC



- With FEC \Rightarrow lower γ
- $P_s(\gamma)$ typically higher than 80%

Rate allocation at the RNC based on users' willingness-to-pay

- Previous models included price (congestion) feedback and rate adaptation by mobile users

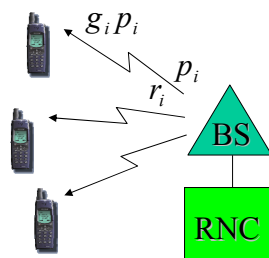


- Alternative is to do *rate allocation at the RNC*
 - γ^* selected as before
 - users *declare* a willingness-to-pay w
 - *rates allocated* proportional to w and $1/\gamma^*$

Motivated by Kelly'97

Resource Usage in WCDMA Downlink

Resource usage in CDMA: Downlink



target bit energy to noise
density ratio E_b/N_0
(determines bit error rate)

$$\gamma_i = \frac{\overbrace{W}^{\text{spreading bandwidth}}}{\underbrace{r_i}_{\text{rate}}} \frac{\overbrace{g_i p_i}^{\text{received power}}}{\underbrace{\theta_i g_i \sum_{j \neq i} p_j + \eta}_{\text{interference + noise}}}$$

downlink is **power-limited**

resource constraint
in downlink $\sum_i p_i < \bar{P}$

resource usage
in downlink p_i

Congestion pricing for elastic traffic: Downlink

- User optimization problem

$$\begin{array}{l} \text{maximize} \\ \text{over} \end{array} U(r \cdot P_s(\gamma)) - \lambda \cdot \overbrace{p}^{\substack{\text{price per} \\ \text{unit resource}}} \cdot \overbrace{p}^{\substack{\text{resource} \\ \text{usage}}} \\ r, \gamma$$

- Downlink: for given rate and quality, **charge** depends on **path gain**, hence **mobile position**

$$\gamma_i = \frac{W}{r_i} \frac{g_i p_i}{\theta_i g_i \sum_{j \neq i} p_j + \eta}$$

not the case for the uplink

Social Welfare maximization

- **Social Welfare maximization** problem:

$$\begin{array}{l} \text{maximize} \\ \text{over} \\ \text{such that} \end{array} \sum_{i=1}^N U_i(\gamma_i(p_1, \dots, p_N)) \\ \{p_1, \dots, p_N\} \\ \sum_{i=1}^N p_i \leq P$$

- a user's signal quality affected by powers (resource usage) of all other users
- resource constraint on total power

Social Welfare maximization (2)

- Lagrangian for S.W. maximization problem:

$$L = \sum_i U_i(\gamma_i(p_1, \dots, p_N)) + \mu \left(P - \sum_i p_i \right)$$

Social Welfare maximization (2)

- Lagrangian for S.W. maximization problem:

$$L = \sum_i U_i(\gamma_i(p_1, \dots, p_N)) + \mu \left(P - \sum_i p_i \right)$$

- First order conditions (for large # of mobiles)

$$U_i' \frac{W}{r_i} \frac{g_i}{I_i} - \underbrace{\sum_j U_j' \frac{W g_j p_j}{r_j} \frac{\theta_j g_j}{I_j^2}}_{\text{marginal congestion cost imposed by a user}} - \underbrace{\mu}_{\text{shadow price for power constraint}} = 0$$

marginal congestion cost imposed by a user shadow price for power constraint

Social Welfare maximization (3)

- To achieve S.W. maximization in a **distributed manner**, we can have users face price λ :

$$\lambda = \sum_j U_j' \underbrace{\frac{Wg_j p_j}{r_j}}_{\text{marginal congestion cost imposed by a user}} \underbrace{\frac{\theta_j g_j}{I_j^2}}_{\text{shadow price for power constraint}} + \mu$$

Social Welfare maximization (3)

- To achieve S.W. maximization in a **distributed manner**, we can have users face price λ :

$$\lambda = \sum_j U_j' \underbrace{\frac{Wg_j p_j}{r_j}}_{\text{marginal congestion cost imposed by a user}} \underbrace{\frac{\theta_j g_j}{I_j^2}}_{\text{shadow price for power constraint}} + \mu$$

- Individual **user optimization**

$$\text{maximize}_{p_i} U_i(\gamma_i) - \overbrace{\lambda p_i}^{\text{feedback}}$$

congestion
usage

Social welfare maximization: Downlink

- Lagrangian for S.W. maximization problem:

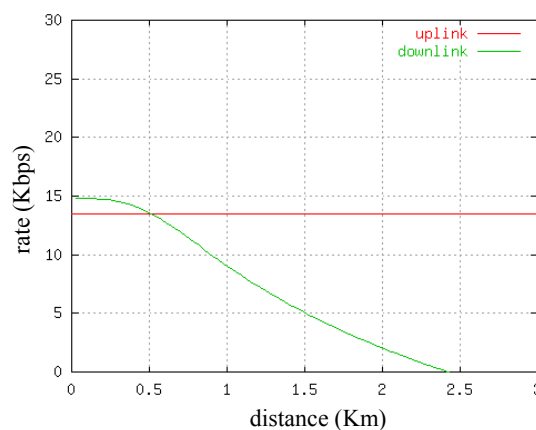
$$L = \sum_i U_i(r_i P_s(\gamma_i(p_1, \dots, p_N))) + \mu \left(\bar{p} - \sum_i p_i \right)$$

- First order conditions (for large # of mobiles)

$$U_i' P_s' \frac{W g_i}{I_i} - \underbrace{\sum_j U_j' P_s' \frac{W p_j \theta_j g_j^2}{I_j^2}}_{\text{marginal congestion}} - \underbrace{\mu}_{\text{shadow price for power constraint}} = 0$$

marginal congestion shadow price for
cost imposed by user power constraint

Congestion Pricing in Uplink and Downlink: concave utility

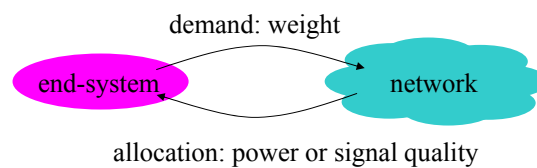


- Uplink: rate independent of mobile position
- Downlink: rate depends on mobile position => efficient use of base station power

Power control in WCDMA

- Fast closed-loop power control
 - Adjusts transmission power to achieve target signal-to-interference ratio (SIR)
 - Both uplink & downlink, frequency: 1500 Hz
- Outer-loop power control
 - Adjusts SIR to achieve given frame error rate
 - Frequency < 100 Hz

Application of model: two approaches



- Two approaches:
 - Allocation of power levels
 - Allocation of signal quality (signal-to-interference ratio)
- Users can adjust weight based on their utility

Application of model: two approaches

- Direct application to power control

$$p_i = \frac{w_i}{\sum w_j} \rho P$$

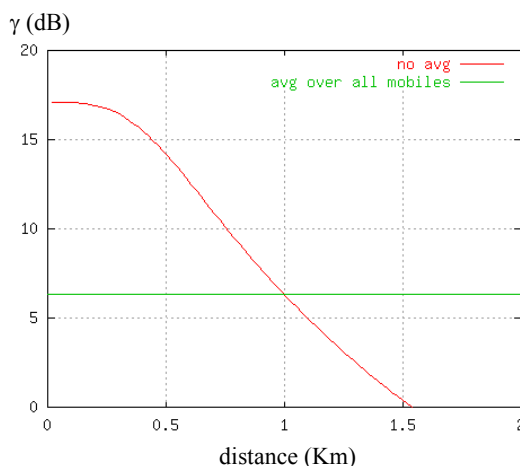
- affects fast closed-loop power control
- results in varying signal quality

- Estimate average power, then signal quality γ

$$\bar{p}_i = \frac{w_i}{\sum w_j} \rho P \quad \gamma_i = \frac{W}{r_i} \frac{1}{\bar{l}_i \bar{I}_i} \frac{w_i}{\sum w_j} \rho P$$

- affects outer-loop power control
- fast closed-loop power control remains same
- weights can be associated with different classes

Numerical results: dependence on position



- No averaging (red line)

$$\gamma_i = \frac{W}{r_i} \frac{1}{\bar{l}_i \bar{I}_i} \frac{w_i}{\sum w_j} \rho P$$

Quality **depends** on position

- Averaging over all mobiles (green)

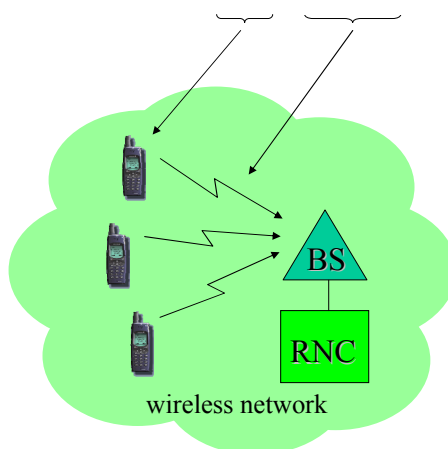
$$\gamma_i = \frac{W}{r_i} \frac{1}{\bar{l} \bar{I}} \frac{w_i}{\sum w_j} \rho P$$

Quality **independent** of position

Extensions:
Consideration of battery costs
Wireless/wired networks
Seamless congestion control using ECN

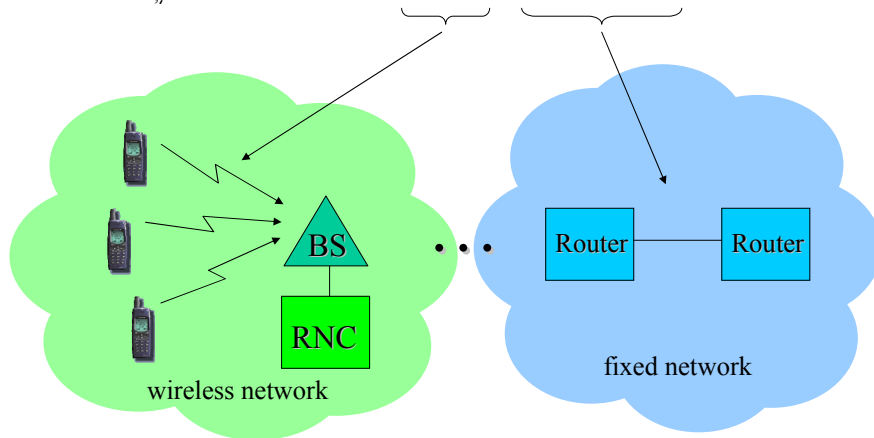
Extension: adding cost of battery power

$$\max_{r,\gamma} U(r \cdot P_s(\gamma)) - \underbrace{v \cdot p}_{\text{battery cost}} - \underbrace{\lambda \cdot r \cdot \gamma}_{\text{congestion cost}}$$



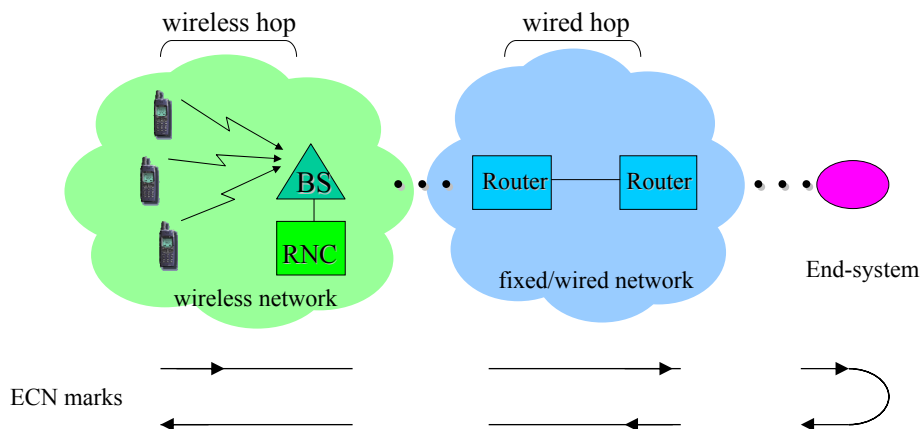
Extension: adding congestion charge of fixed network

$$\max_{r, \gamma} U(r \cdot P_s(\gamma)) - \lambda \cdot r \cdot \gamma - \mu \cdot r \cdot P_s(\gamma)$$



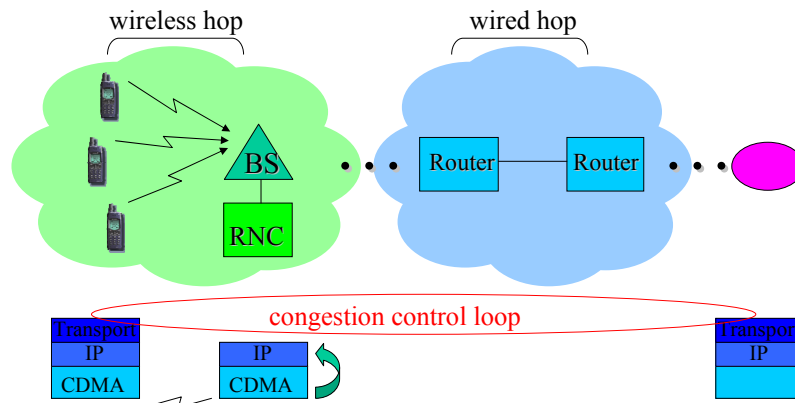
Seamless wired/wireless congestion control

- Congestion control performed at *transport layer*
- Use ECN marking for congestion feedback
- RNC performs *marking* for *wireless hop*



Seamless wired/wireless congestion ctrl (2)

- RNC performs *marking* for *wireless hop*
 - RNC (IP layer) needs information from BS
 - marking depends on *congestion* and *resource usage*
 - no *shared buffer* in *uplink*

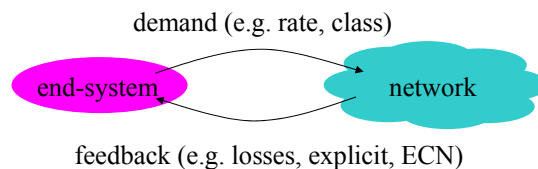


Key issues

- **Economic modeling** framework
 - utilities for modeling user/application preferences
 - efficiency = maximize aggregate utility
- **Resource usage (throughput) model**
 - EDCA: contention-based access
 - HCCA: controlled access (polling)
- Consider **elastic traffic**: can adapt rate based on network feedback

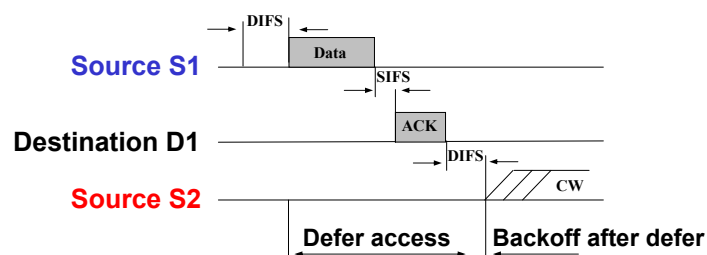
Congestion control and resource usage

- Elastic traffic: closed-loop control



- Feedback depends on **resource usage** and **level of congestion**
- End-system reaction to feedback
 - Control parameter influences demand (throughput)
 - Modeled with **utility functions**

DCF: Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)



- If **S1** senses channel idle for **DIFS** it sends data
 - Else waits for channel to be idle for DIFS and selects random backoff (**S2**)
- Backoff selected from interval $[0, CW-1]$
 - CW in $[CW_{min}, CW_{max}]$, **doubles** after collision

Extended Distributed Channel Access (EDCA)

- EDCA extension of DCF to allow differentiation based on
 - DIFS (AIFS in 802.11e)
 - CWmin
 - CWmax
 - Transmission Opportunity (TXOP)
- CWmin and TXOP appropriate for throughput differentiation

Model for contention-based access

- p-persistent model
 - Wireless station transmits with probability p , independent of previous attempts
 - Accurate when contention not high
- Relation with CWmin:
$$p = \frac{2}{CW_{\min} + 1}$$

Throughput for contention-based access

- Throughput for station i

$$x_i = \frac{E[X_i]}{E[T]}$$

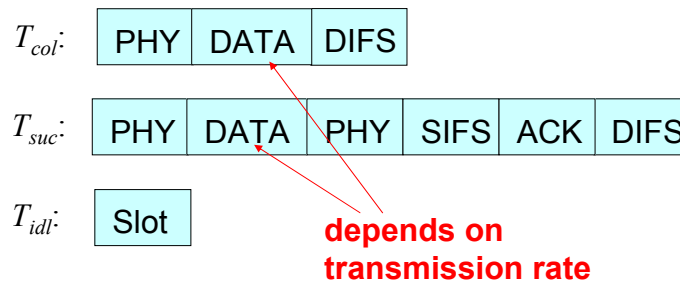
- $E[X_i]$ is average data transmitted by station i in one time interval (L : packet size)

$$E[X_i] = p_i \prod_{j \neq i} (1 - p_j) L$$

- $E[T]$ is average time interval (can be collision, successful transmission, or idle interval)

Average time interval $E[T]$

- Three types of intervals: T_{suc} , T_{col} , T_{idl}
- Basic CSMA/CA:



- Different for RTS/CTS

Throughput for contention-based access

- Throughput for station i: $x_i = \frac{E[X_i]}{E[T]}$
- Equal transmission rates ($P_{-i} = \sum_{j \neq i} p_j$)

$$= \frac{p_i(1-P_{-i})L}{\underbrace{\sum_k p_k(1-P_{-k})}_{\text{success prob}} T^{suc} + \underbrace{\left[P - \sum_k p_k(1-P_{-k})\right]}_{\text{collision prob}} T^{col} + \underbrace{1-P}_{\text{idle prob}}}$$

Throughput for contention-based access

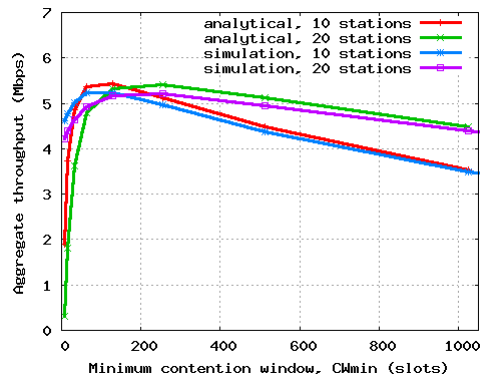
- Throughput for station i: $x_i = \frac{E[X_i]}{E[T]}$
- Equal transmission rates ($P_{-i} = \sum_{j \neq i} p_j$)

$$= \frac{p_i(1-P_{-i})L}{\sum_k p_k(1-P_{-k}) T^{suc} + \left[P - \sum_k p_k(1-P_{-k})\right] T^{col} + 1-P}$$

- Different transmission rates: For RTS/CTS, T^{col} does not depend on rate

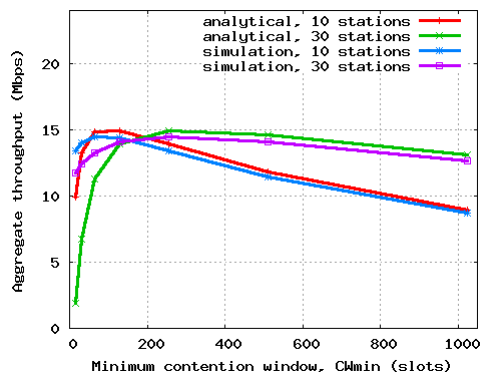
$$= \frac{p_i(1-P_{-i})L}{\sum_k p_k(1-P_{-k}) T_k^{suc} + \left[P - \sum_k p_k(1-P_{-k})\right] T^{col} + 1-P}$$

Simulation versus analysis: 802.11b



- ns-2 simulations, 802.11b, 10/20 flows, CSMA/CA
- Optimal CWmin same for both simulation & analysis

Simulation versus analysis: 802.11a



- ns-2 simulations, 802.11a 24 Mbps, 10/30 flows, CSMA/CA
- Optimal CWmin same for both simulation & analysis

Controlled access

- HCCA: polling-based mechanism
- Also case of downlink traffic
- Control variable: Transmission opportunity – TXOP o_i : time station i can transmit when it is given access to channel

$$x_i = \frac{R_i o_i}{\sum o_j}$$

R_i : transmission rate of station i

Maximizing aggregate utility

$$\begin{array}{ll} \text{maximize} & \sum_i U_i(x_i) \\ \text{over} & q_i \geq 0, i \in N \end{array}$$

- $x_i(\{q_i: i \in N\})$: throughput for station i
- q_i : control parameter (trans prob, TXOP)

Publications: WiOpt'06, WoWMoM'06 & Int'l patent submission (Mar'06)

Maximizing aggregate utility

$$\begin{aligned} & \text{maximize} && \sum_i U_i(x_i) \\ & \text{over} && q_i \geq 0, i \in N \end{aligned}$$

- $x_i(\{q_i; i \in N\})$: throughput for station i
- q_i : control parameter (trans prob, TXOP)
- Necessary conditions if U concave

$$\frac{\partial \sum_j U_j(x_j)}{\partial q_i} = \frac{\partial U_i(x_i)}{\partial q_i} + \underbrace{\sum_{j \neq i} \frac{\partial U_j(x_j)}{\partial q_i}}_{\text{congestion user } i \text{ creates to all other users}} = 0$$

Publications: WiOpt'06, WoWMoM'06 & Int'l patent submission (Mar'06)

Distributed optimization of transmission probability (same trans rates)

- User problem: Selection of transmission prob. p_i

$$\begin{aligned} & \text{maximize} && U_i(x_i) - \lambda p_i \\ & \text{over} && p_i \geq 0 \end{aligned}$$

- Global and user problems coincide if

$$\lambda = L \frac{(1-P)^2 T^{suc} + P(2-P)T^{col}}{E[T]^2} \sum U_j' p_j \quad P = \sum p_j$$

Distributed optimization of TXOP for HCCA

- User problem: Selection of TXOP o_i

$$\begin{array}{ll} \text{maximize} & U_i(x_i) - \lambda o_i \\ \text{over} & o_i \geq 0 \end{array}$$

- Global and user problems coincide if

$$\lambda = \frac{1}{\left(\sum o_j\right)^2} \sum U_j' R_j o_j$$

EDCA and HCCA coexistence

- Percentage of time allocated to EDCA: $\rho = \frac{T_{CP}}{T_{CP} + T_{CFP}}$

- Utility for EDCA user i: $U_i^{EDCA}(x_i^{EDCA}(\mathbf{p}, \rho))$

- Utility for HCCA user j: $U_j^{HCCA}(x_j^{HCCA}(\mathbf{o}, \rho))$

- Global efficiency problem:

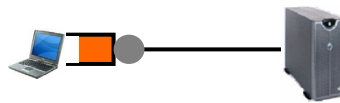
$$\begin{array}{ll} \text{maximize} & \sum_i U_i^{EDCA}(x_i^{EDCA}(\mathbf{p}, \rho)) + \sum_i U_i^{HCCA}(x_i^{HCCA}(\mathbf{o}, \rho)) \\ \text{over} & \mathbf{p} \geq 0, \mathbf{o} \geq 0, 0 \leq \rho \leq 1 \end{array}$$

Applications

- ECN (Explicit Congestion Notification)
 - ECN marks signal congestion level
 - ECN marks should reflect wireless channel contention
- TCP over EDCA with ECN marking
 - Optimal setting of CWmin
- Class-based service differentiation
 - Classes have different weights
 - Achieve throughput differentiation and efficient utilization

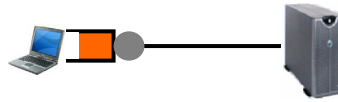
Wired link versus 802.11

- Wired link: **queue length** indication of congestion (e.g. RED)

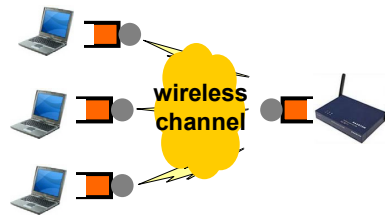


Wired link versus 802.11

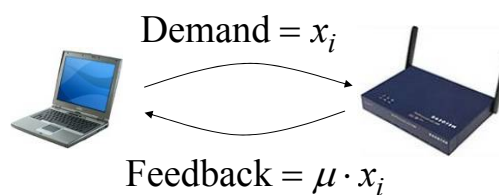
- Wired link: **queue length** indication of congestion (e.g. RED)



- Wireless 802.11: **each station has own queue**, contention property of **shared wireless channel**



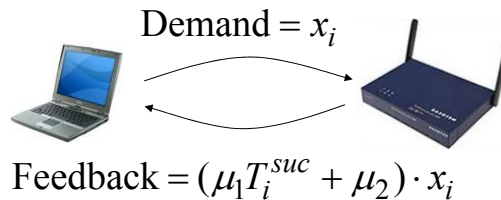
Distributed control of transmission probability (same trans rates)



- p_i (equivalently $CW_{\min,i}$) determines x_i
- Feedback depends on **resource usage** x_i and **level of congestion** μ
- Packets in **uplink and downlink** marked with prob. μ

$$\mu = \frac{(1-P)^2 T^{suc} + P(2-P)T^{col}}{(1-P)E[T]} \sum U_j' p_j \quad P = \sum p_j$$

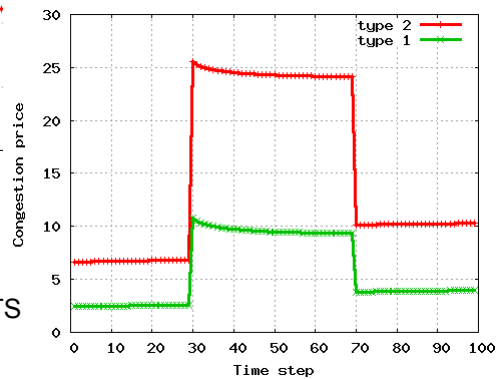
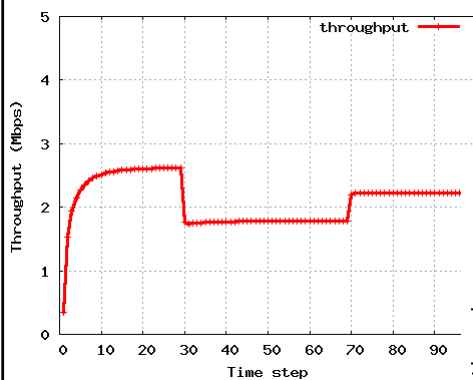
Distributed control of transmission probability (different trans rates)



- p_i (equivalently $CW_{\min,i}$) determines x_i
- Feedback depends on resource usage x_i (throughput), T_i^{suc} (depends on trans rate) and level of congestion μ_1, μ_2
- Different marking prob for stations with different trans rate

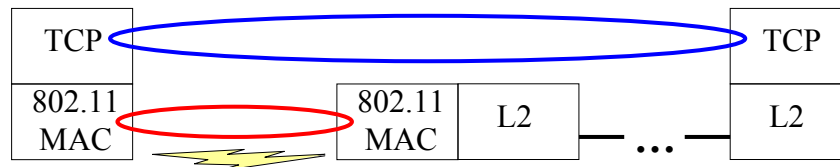
$$\mu_1 = \frac{(1-P)}{E[T]} \sum U_j' p_j \quad \mu_2 = \frac{P(2-P)T^{col}}{(1-P)E[T]} \sum U_j' p_j$$

Throughput and price as function of time



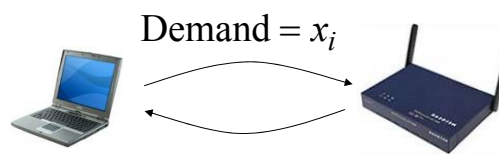
- model only transient behavior, not MAC details
- $R_1=11$ Mbps, $R_2=2$ Mbps, RTS/CTS
- time 0: $N_1=N_2=5$, time 30: $N_2=30$, time 70: $N_2=10$

TCP over EDCA with ECN



- Use ECN (Explicit Congestion Notification) to convey congestion information from both wireless/wired links
- Setting of 802.11 MAC parameters (CWmin)
 - Cross-layer interaction between TCP and MAC layer

TCP over EDCA with ECN



Feedback = $(\mu_1 T_i^{suc} + \mu_2) \cdot x_i$ (rate of ECN marks)

$$\mu_1 = \frac{(1-P)}{E[T]} \sum U_j' p_j \quad \mu_2 = \frac{P(2-P)T^{col}}{(1-P)E[T]} \sum U_j' p_j$$

- Implicit utility for TCP: $U_{TCP}(x) = -\frac{2}{RTT^2 x}$
 - models TCP's macroscopic behavior

TCP over EDCA with ECN (cont)

- Same transmission rates and round trip (RTT)

$$P = \frac{\sqrt{T^{col}} - 1}{T^{col} - 1}$$

- Optimal transmission probability independent of utility
- Optimal CWmin (N: # of users)

$$p = \frac{P}{N} \quad CW_{\min} = \frac{2}{p} - 1$$

TCP over EDCA with ECN (cont)

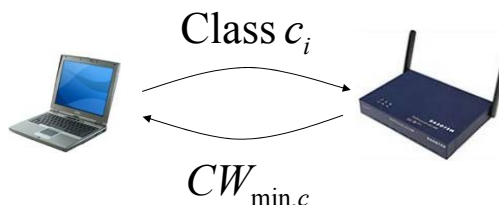
- Different transmission rates

$$p_i = \sqrt{\frac{(1-P)E[T]}{(1-P)^2 T_i^{suc} + P(2-P)T^{col}}} \frac{1}{\sum \frac{1}{p_j}}$$

- Optimal CWmin

$$CW_{\min,i} = \frac{2}{p_i} - 1$$

Class-based differentiation



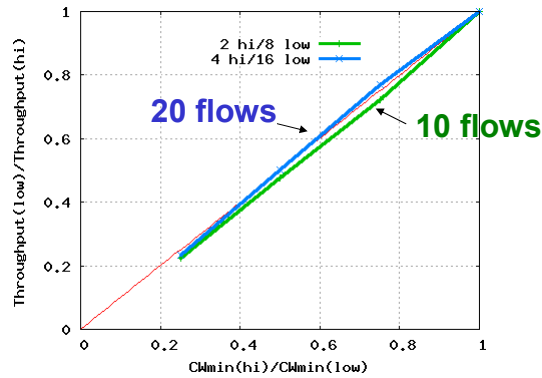
- User i selects class c_i , e.g. during association
- Each class has a weight w_c
- Access Point (AP) computes optimal $CW_{\min,c}$
- Closer to 802.11e's communication model
 - CW_{\min} broadcasted by AP

Optimal CW_{\min} : same transmission rate

- Input
 - N_c : # of users of class c (from associations or recent activity)
 - w_c : weight of class c (declared during association or authentication)
- AP computes
 - Aggregate transmission probability: $P = \frac{\sqrt{T^{col}} - 1}{T^{col} - 1}$
 - $CW_{\min,c}$ for each class c (802.11e then broadcasts this in beacon frames)

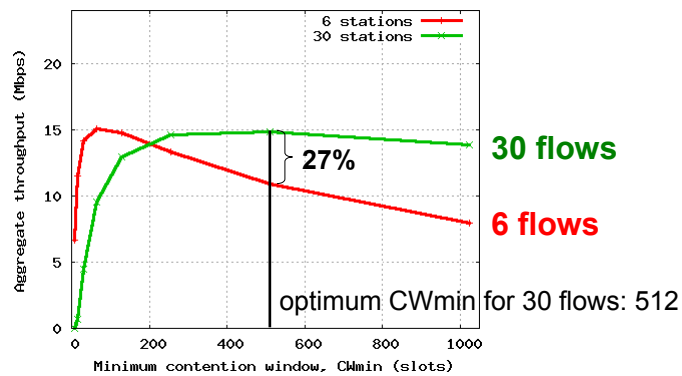
$$p_c = \frac{w_c}{\sum_c N_c w_c} P \quad CW_{\min,c} = \frac{2}{p_c} - 1 \quad (\text{rounded to power of 2})$$

Throughput differentiation based on CWmin



- ns-2 simulations, two classes (hi and low)
- Throughput ratio inversely proportional to CWmin ratio

Gains with selection of optimum CWmin



- Analysis, 24 Mbps, 1/3 hi and 2/3 low, $w_{\text{hi}}=2$, $w_{\text{low}}=1$
- 27% throughput reduction if optimum CWmin for 30 flows (512) used for 6 flows

Optimum CWmin: different trans rates

- Input

- N_c : # of users of class c
- w_c : weight of class c
- $c(i)$: class of user i
- R_i : transmission rate of user i (wireless cards can provide this information)

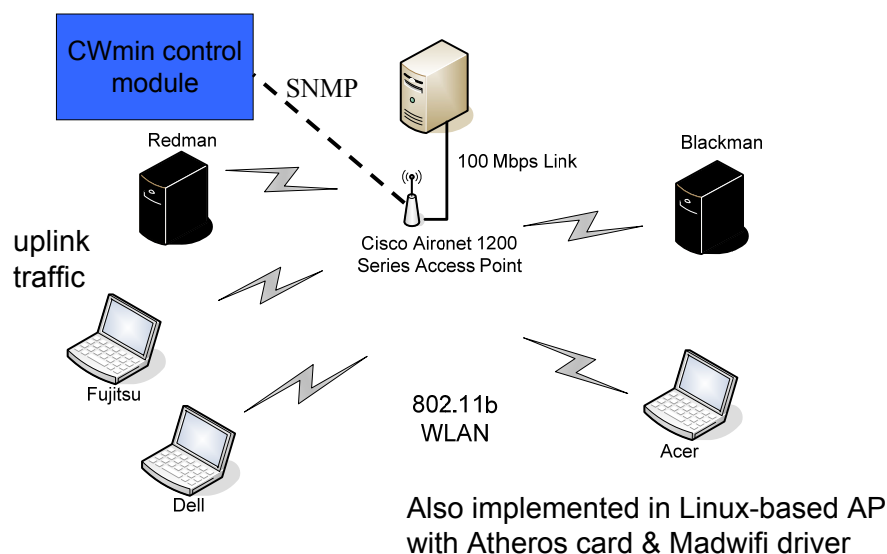
- AP computes

- Transmission probability:

$$p_i = \frac{w_{c(i)}}{\sum N_j w_j} \frac{(1-P)E[T]}{(1-P)^2 T_i^{suc} + P(2-P)T^{col}} \quad \sum_i p_i = P$$

- $CW_{min,i}$ for user i : $CW_{min,i} = \frac{2}{p_i} - 1$ (rounded to power of 2)

802.11e test-bed implementation

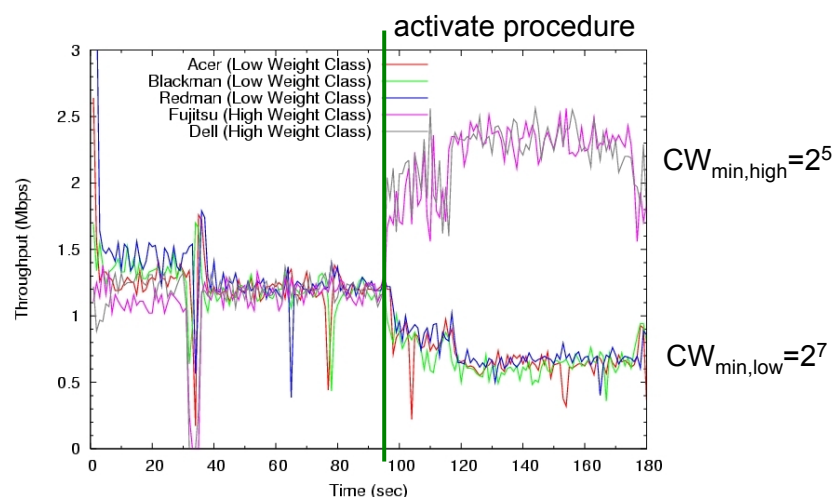


Equipment

- Cisco 1200 Series Access Point
 - IOS Version 12.3(4)JA
 - SNMP CISCO IEEE 802.11 QoS MIB
 - WMM enabled on wireless interface
- D-Link DWL-G650 Atheros based Wireless Cards
 - Atheros 5211 chipset
 - Used by Linux Boxes (Kernel 2.6.15-1.1831_FC4)
- D-Link DWL-AG660 Wireless Cards
 - Atheros 5212 chipset
 - Used by Window XP (SP2) Nodes (needed to hack .inf file)

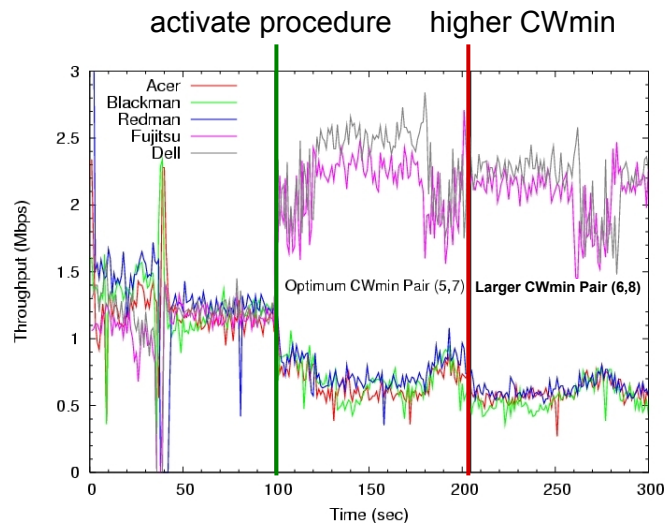


Service differentiation: optimal CWmin



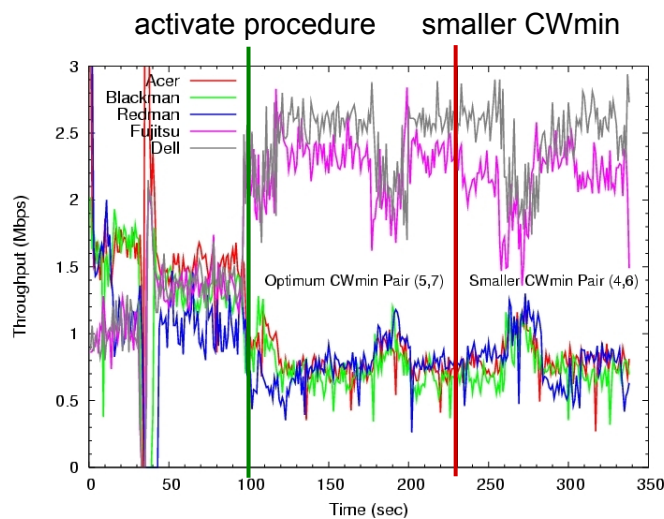
- 5 wireless stations, 2 classes, weights: $w_{high}=4$, $w_{low}=1$

Service differentiation: optimal & higher CWmin



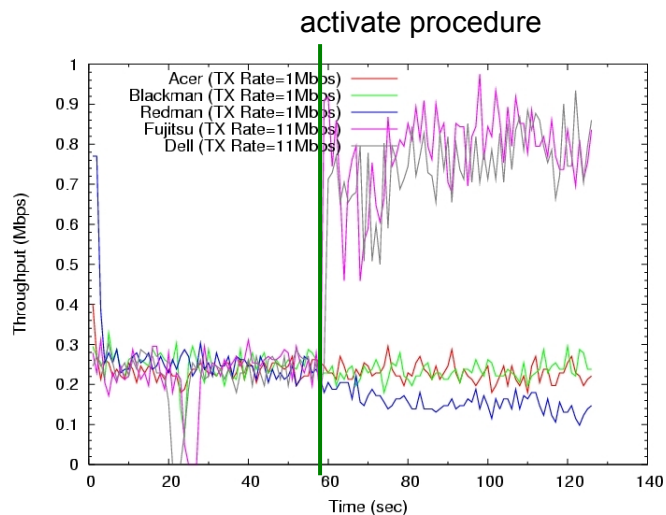
- 5 wireless stations, 2 classes, weights: $w_{\text{high}}=4$, $w_{\text{low}}=1$
- Higher CWmin leads to smaller throughput

Service differentiation: optimal & smaller CWmin



- 5 wireless stations, 2 classes, weights: $w_{\text{high}}=4$, $w_{\text{low}}=1$
- Smaller CWmin does not lead to higher throughput

Multi-rate experiment



- 3 stations with rate 1 Mbps, 2 with 11 Mbps
- all stations have same weight

Conclusion

- Models for **efficient resource control** in **Wireless LANs** and **mobile networks**
 - Influence of **control parameters** on **resource usage** and **congestion level**
 - Depend on **medium access procedures**
- **Cross-layer interaction**
 - TCP and MAC
 - rate/signal quality/power control in CDMA
- How to **set MAC parameters** to achieve **efficiency** and **throughput differentiation**
- **Real implementation**