Resource Control for Elastic Traffic in CDMA Networks

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ACM MobiCom 2002
Sep. 23-28, 2002, Atlanta, U.S.A.

Funded in part by BTexact (British Telecommunications), UK

Our approach

CDMA technology:
resource constraints,
user control variables that
affect resource usage

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Economic modeling:
utility functions,
congestion prices,
social welfare maximization

Framework for efficient
resource control in
CDMA networks

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)

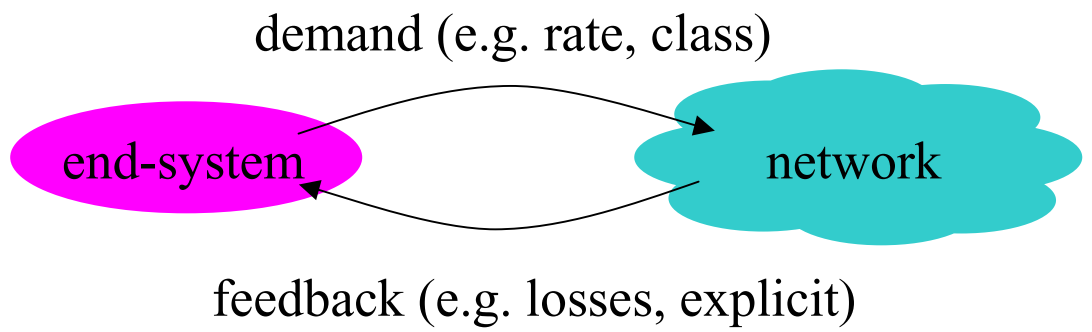
- Uniform framework for seamless congestion control in wired/wireless networks
  - Also account for mobile battery consumption
- Use of ECN (Explicit Congestion Notification) as common signalling framework
  - Routers marks packets based on congestion in wired network
  - RNC (Radio Network Controller)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

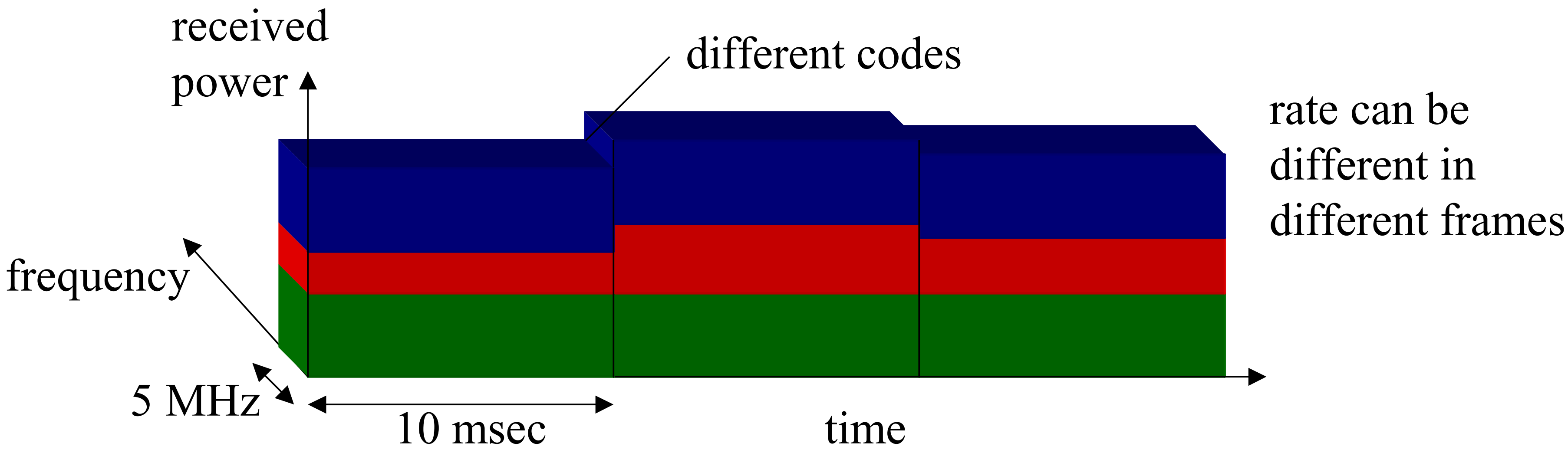
- Closed-loop control loop



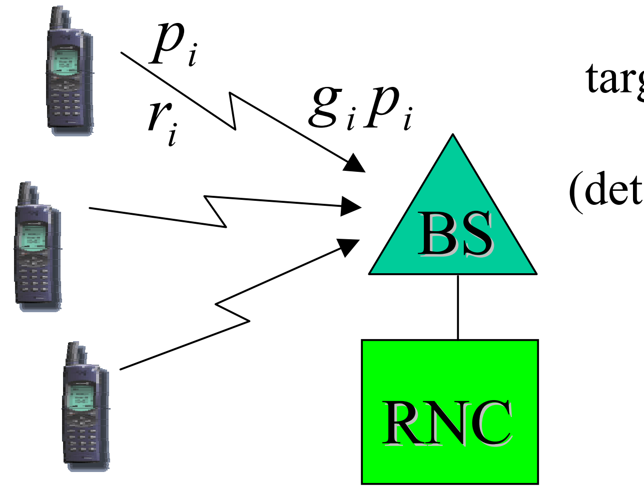
- Feedback depends on level of congestion and resource usage
- Shared resources in CDMA: radio spectrum (uplink) and base station power (downlink)
- End-system reaction to feedback modeled with utility functions

CDMA (Code Division Multiple Access)

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



Resource usage in CDMA: Uplink



RNC: Radio Network Controller

target bit energy to noise density ratio E_b/N_0 (determines bit error rate) — spreading bandwidth — received power

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

rate — interference + noise

assuming perfect power control

uplink is ***interference-limited***

resource constraint in uplink

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

resource usage in uplink

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

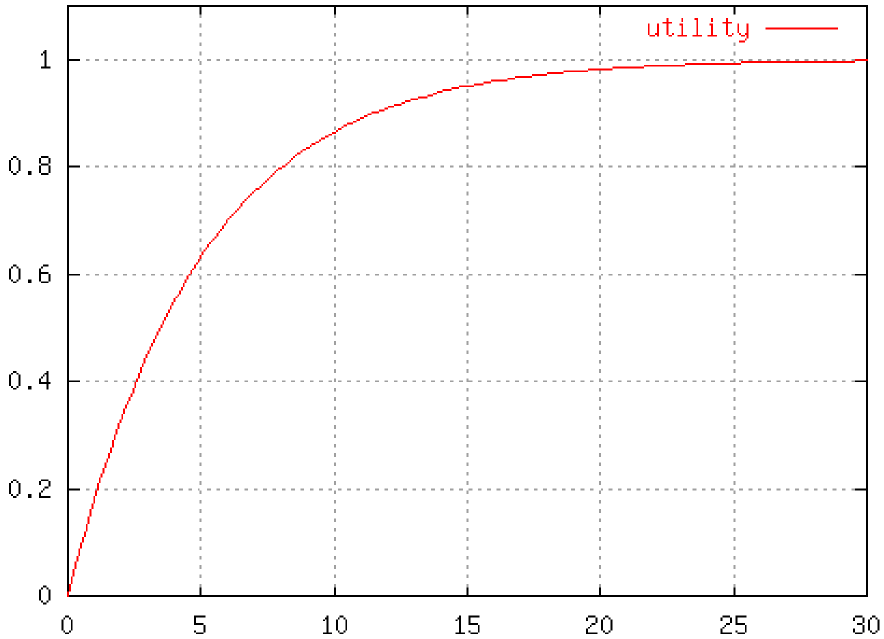
approximations for large # of mobile users

$$\sum_i r_i \gamma_i < W$$

$$r_i \gamma_i$$

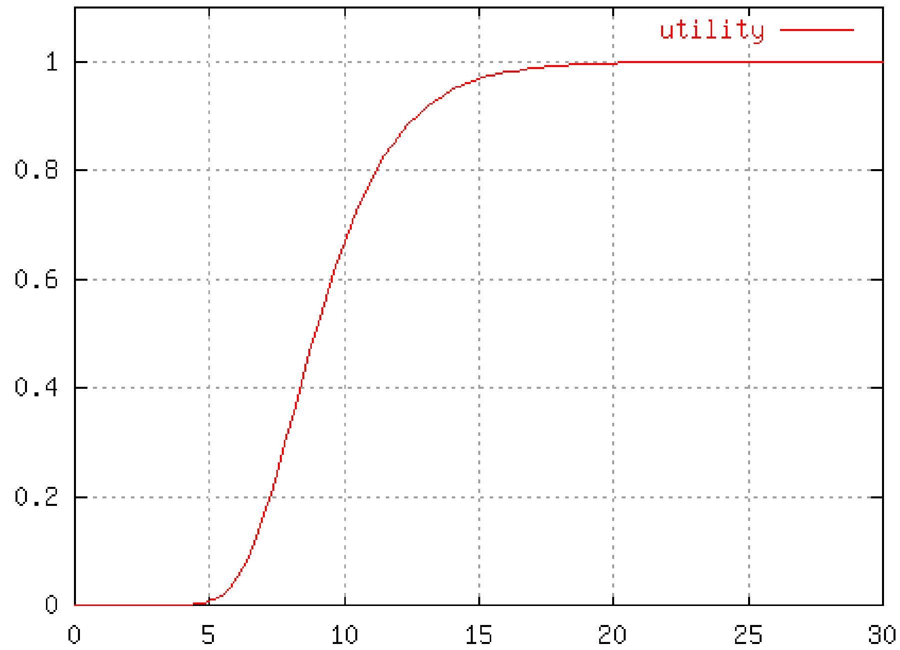
Utility for elastic traffic

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



throughput

no minimum rate



throughput

with minimum rate

Congestion pricing for elastic traffic: Uplink

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

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

$$\text{over} \quad r, \gamma$$

Social welfare maximization: Uplink

- Social Welfare maximization problem:

maximize $\sum_{i=1}^{N} U_i\left(r_i P(\gamma_i)\right)$

over $\{\gamma_i \geq 0, i = 1,\ldots N\}, \{r_i \geq 0, i = 1,\ldots N\}$

such that $\sum_{i=1}^{N} r_i \gamma_i \leq W$

- Lagrangian for S.W. maximization problem:

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

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 $P_s(\gamma)$

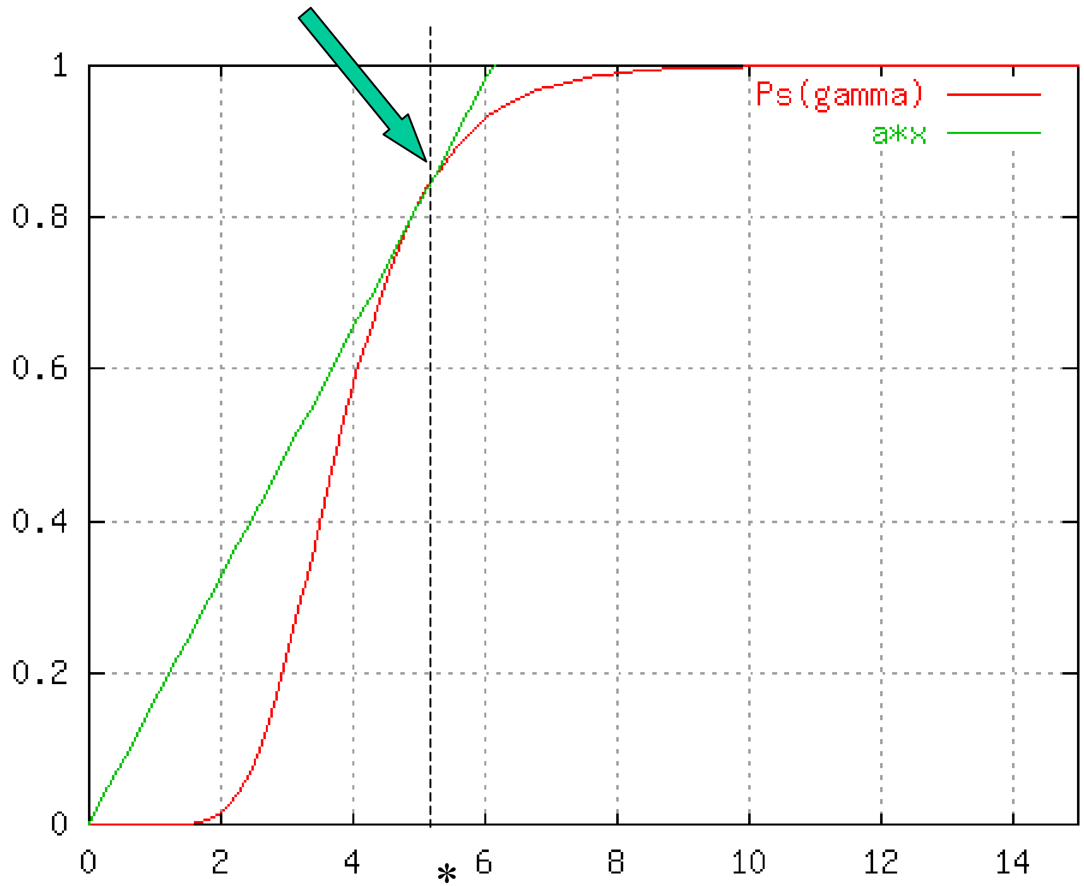
$$P_s(\gamma^*) = P_s'(\gamma^*) \cdot \gamma^*$$

- 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

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

$P_s(\gamma)$



γ^*

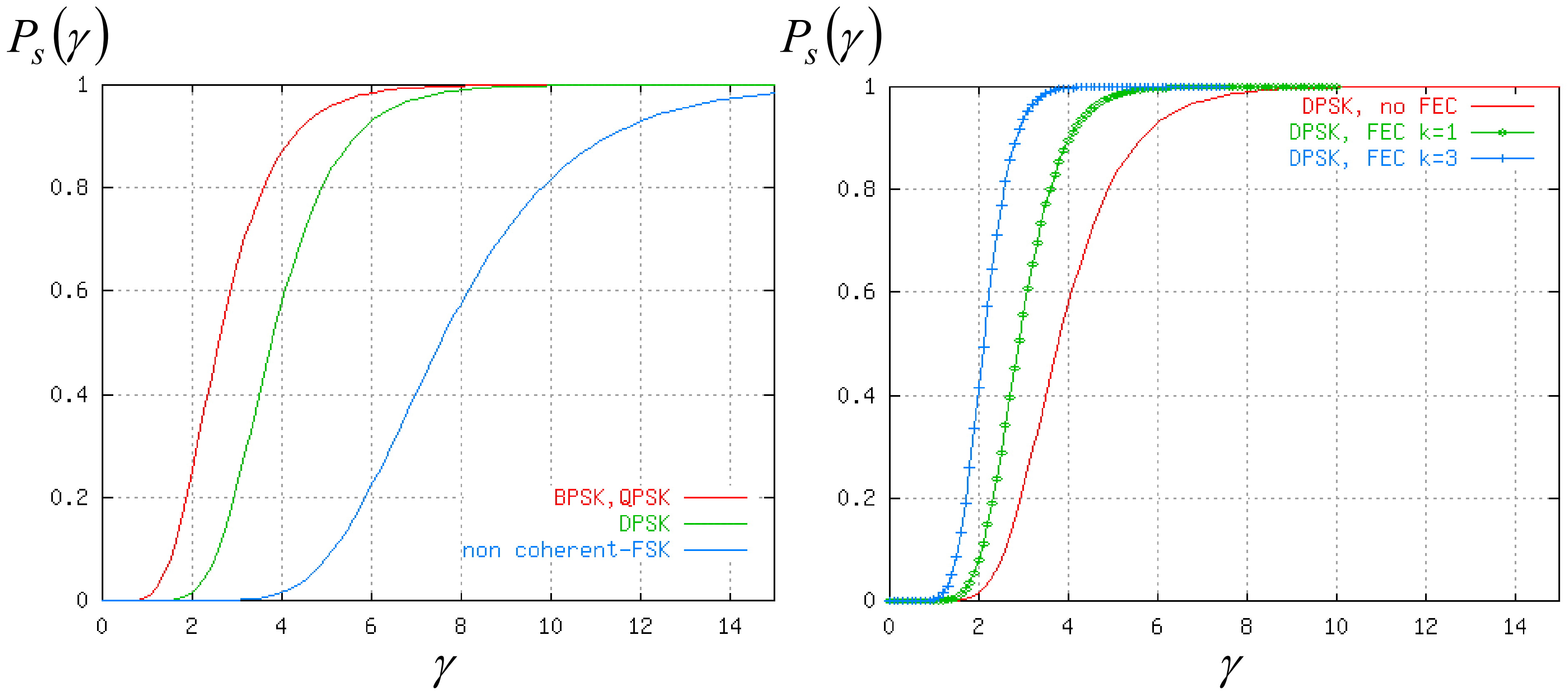
$\gamma < \gamma^*$

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

$\gamma > \gamma^*$

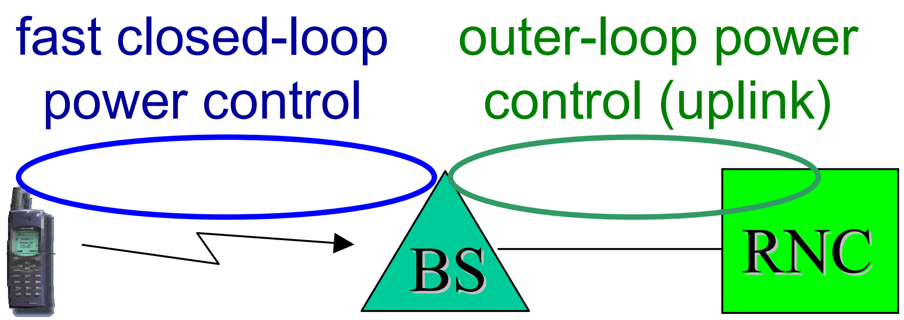
$P_s(\gamma^*) > P_s'(\gamma^*) \cdot \gamma^*$

P_s for different modulation and FEC



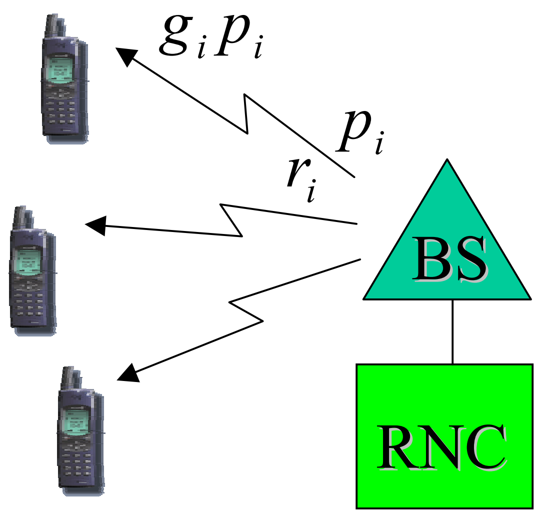
- With FEC => lower γ
- $P_s(\gamma)$ typically higher than 80%

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
- Our approach affects only outer-loop power control

Resource usage in CDMA: Downlink



$$\overbrace{\gamma_i}^{\text{target bit energy to noise density ratio } E_b/N_0 \text{ (determines bit error rate)}} = \frac{\overbrace{W}^{\text{spreading bandwidth}}}{\underbrace{r_i}_{\text{rate}}} \frac{\overbrace{g_i p_i}^{\text{received power}}}{\underbrace{\theta_i g_i \sum_{j \neq i} p_j + \eta}_{\text{interference + noise}}}$$

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

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

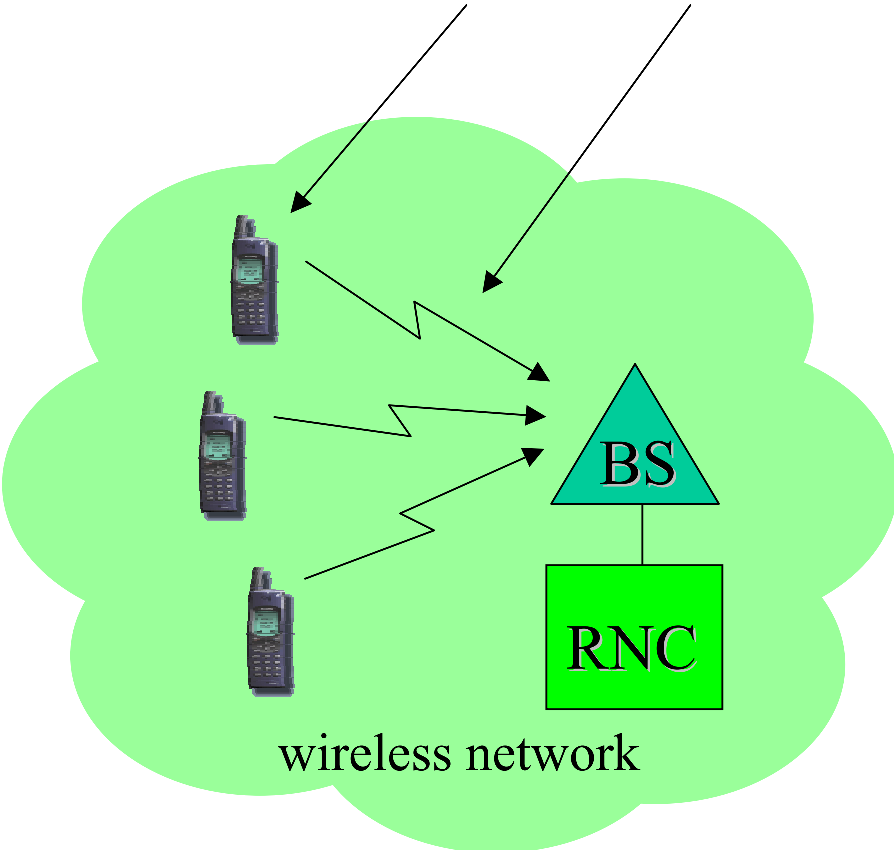
- Downlink: for given rate and quality, *charge* depends on *path gain*, hence *mobile position*

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

not the case for the uplink

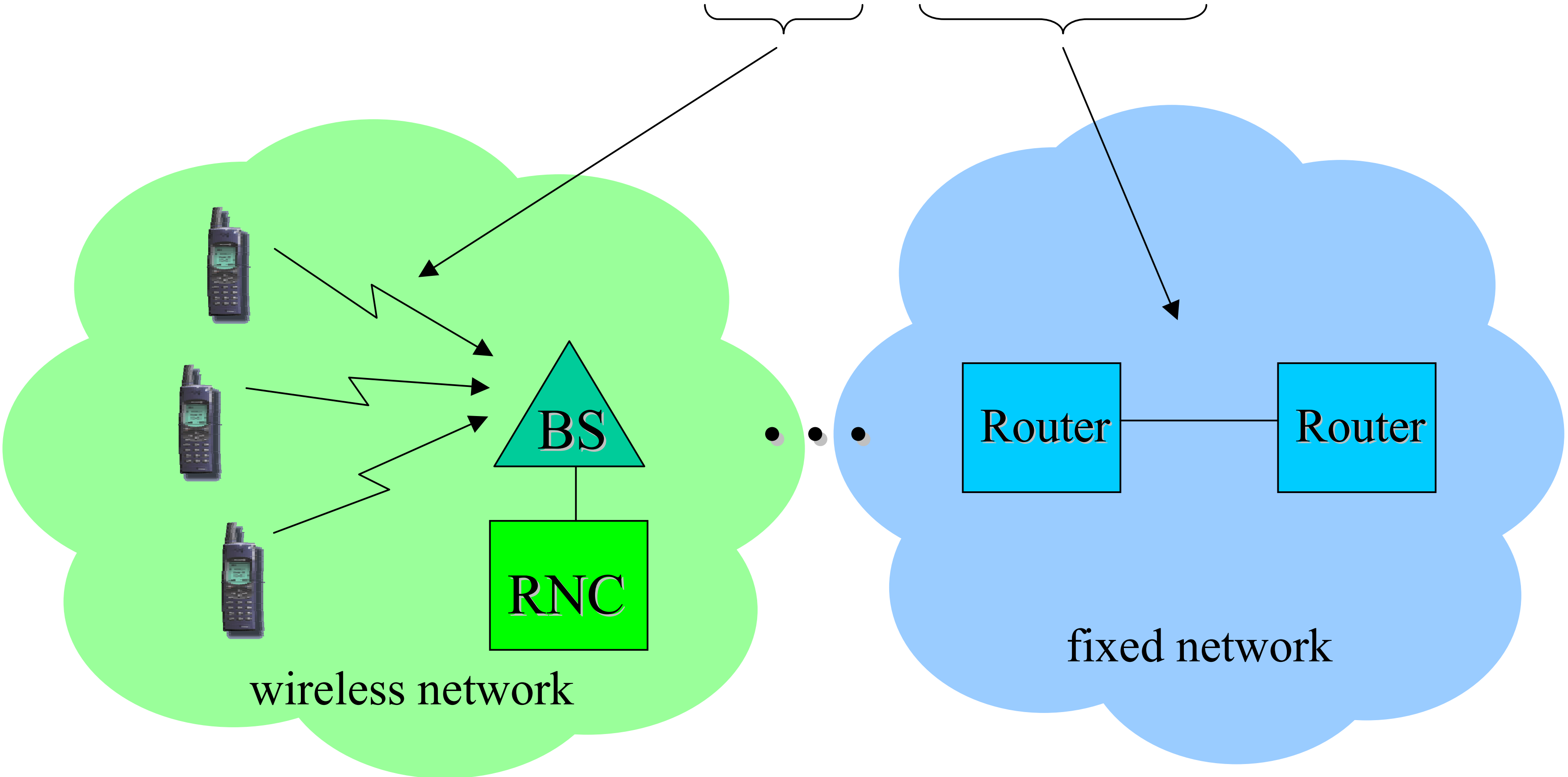
Extension: adding cost of battery power

$$\max_{r,\gamma} \; U\left(r \cdot P_s(\gamma)\right) - \underbrace{\nu \cdot p} - \underbrace{\lambda \cdot r \cdot \gamma}$$



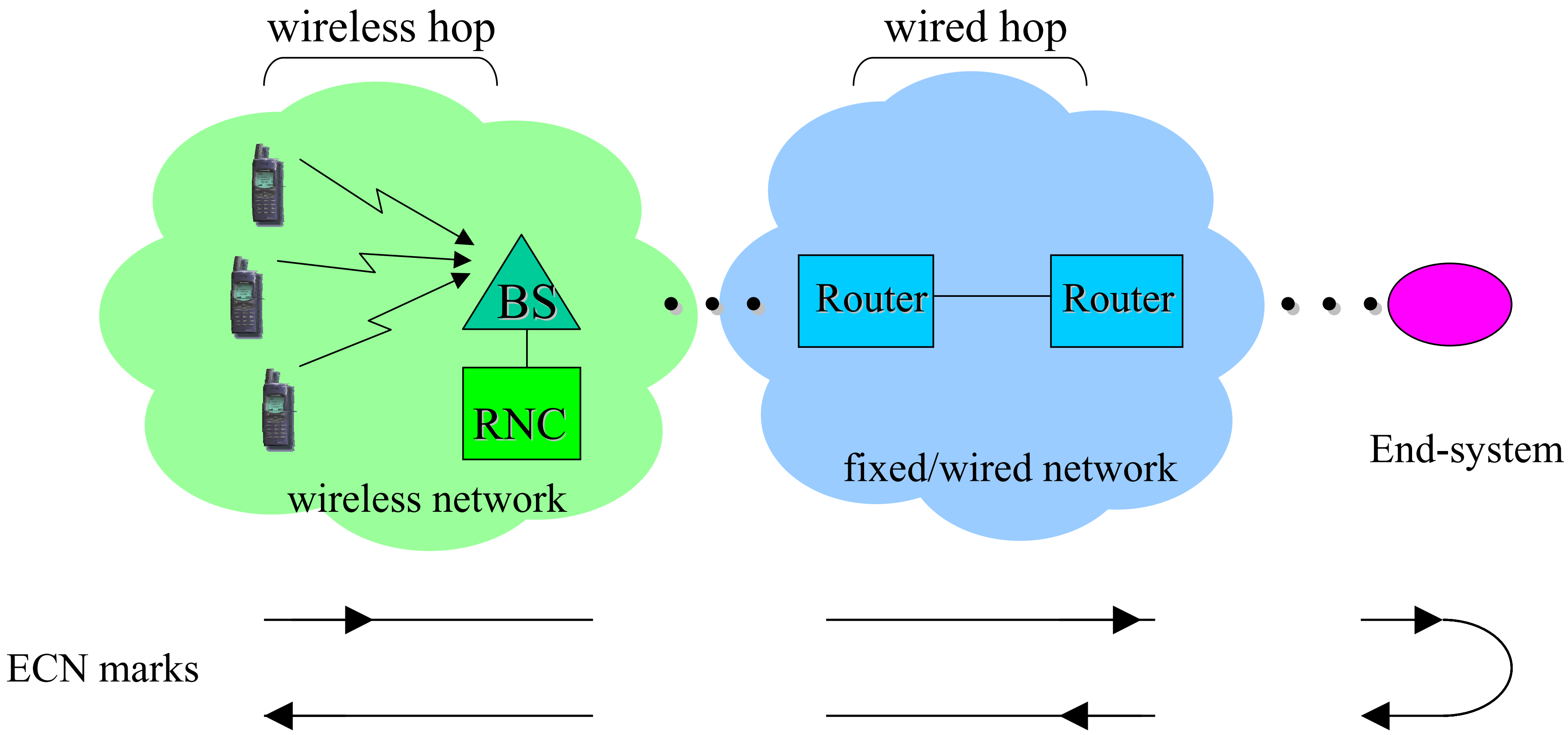
Extension: adding congestion charge of fixed network

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



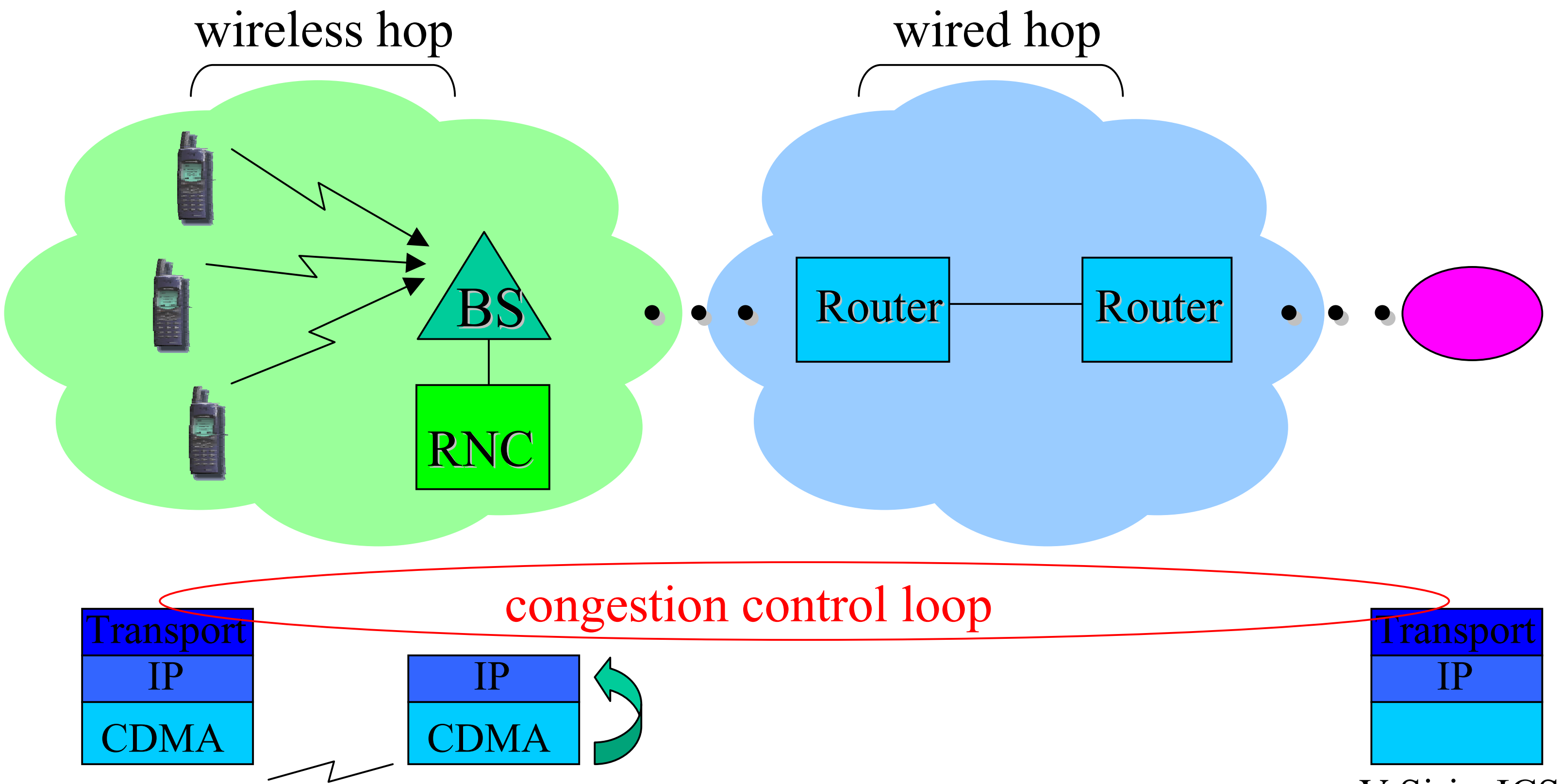
Seamless wired/wireless congestion control

- 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*



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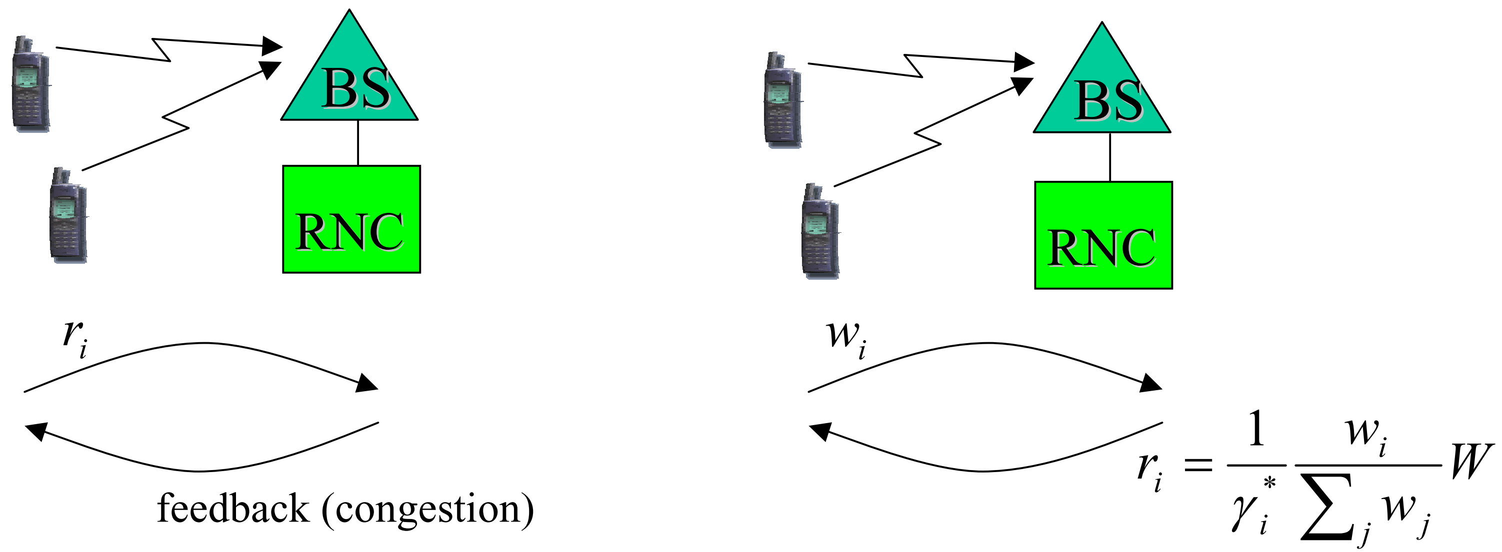
Rate allocation at the RNC based on users' willingness-to-pay

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



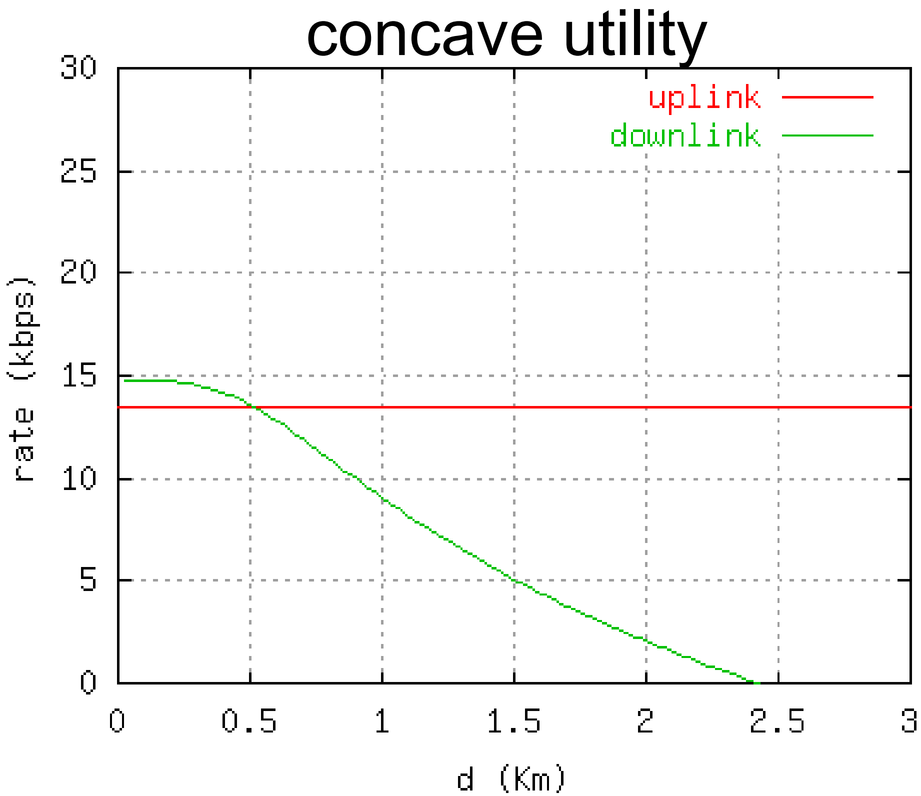
- Alternative is to do *rate allocation at the RNC*
  - γ^* selected as before
  - users *declare* a willingness-to-pay w
  - *rates allocated* proportional to w and $1/\gamma^*$

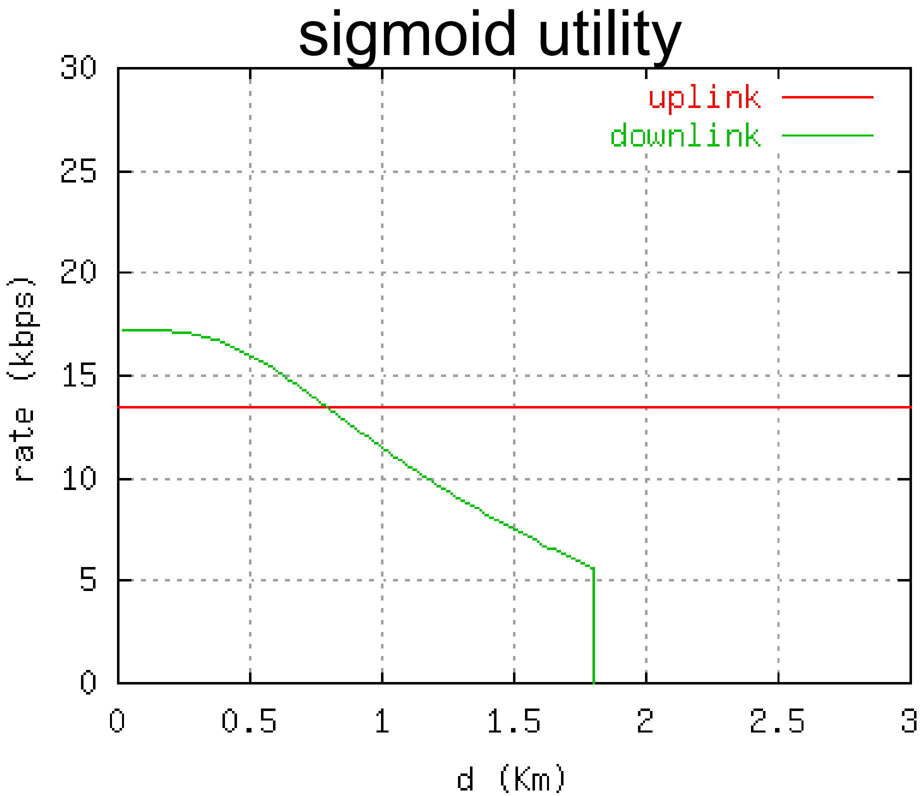
Motivated by Kelly'97

Numerical investigations

- Qualitative rather than quantitative
- Dependence of rate and power allocation on
  - mobile distance from base station
  - utility (concave, sigmoid)
  - load

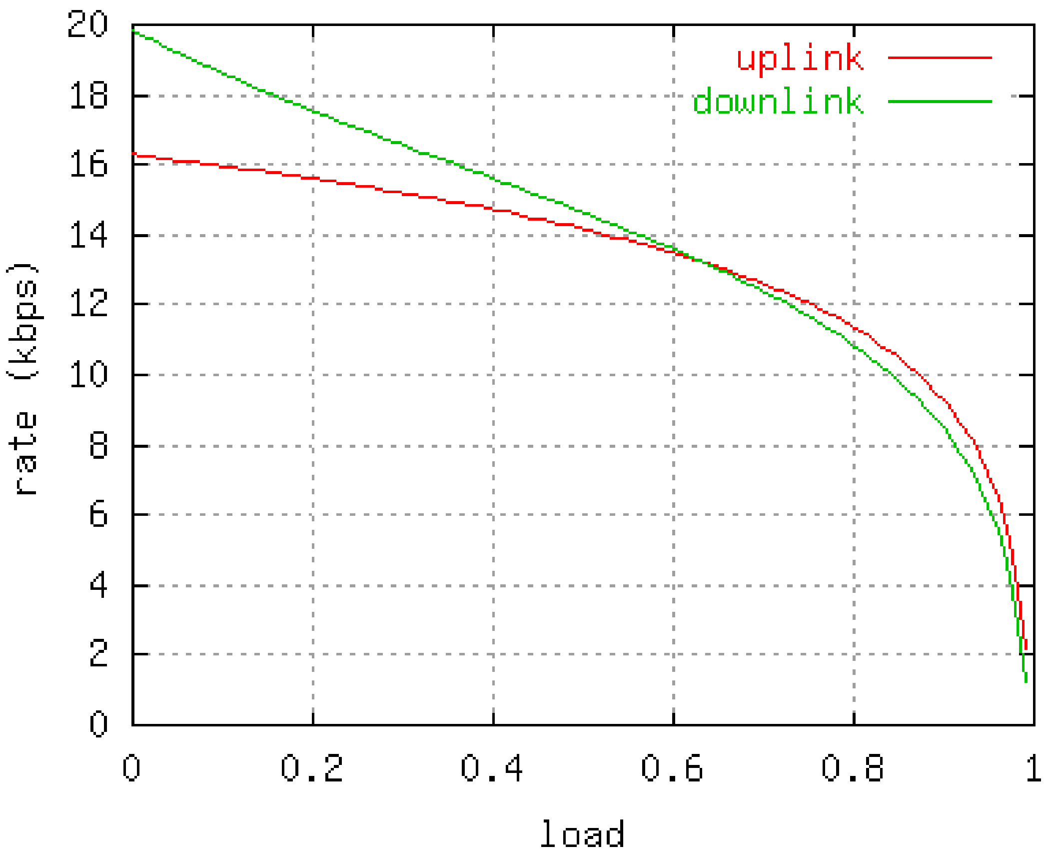
Rate allocation & distance





- Uplink: rate independent of mobile position
- Downlink: rate depends on mobile position
- Sigmoid utility, downlink: rate drops to zero at some distance

Rate allocation and load



- Uplink & Downlink: rate drops with load

Related work

- Mandayam, Goodman, et al. IEEE Personal Comm.'00, IEEE Trans. Comm.'02
  - Utility equal to transferred bits per unit power
  - Pareto improvements with introduction of prices
- Song & Mandayam, IEEE JSAC'01
  - Utility function of transmission rate
  - Constraints on maximum error rate
  - Maximize sum of utilities
  - Centralized solution
- Xiao, Shroff & Chong, Infocom'01
  - Utility-based power control
  - Utility function of signal quality
- Others: Nandagopal et al., Campbell et al., etc

Differences with our work

- Formulate and analyze framework for efficient resource control of elastic traffic in CDMA networks
  - Based on social welfare maximization
- Consider wireless resource constraints in both uplink and downlink
- Joint control of signal quality and transmission rate
  - For elastic traffic, user net utility maximization can be decomposed into two sub-problems
- Uniform framework for seamless congestion control in wired/wireless networks & account for mobile battery consumption
- ECN (Explicit Congestion Notification) as common signalling framework

Other and ongoing work

- Different forms of utility & multiple wireless hops
- Hybrid code and time division multiplexing
- Cell coverage (“cell breathing”)
  - Limited power at mobile hosts
- Seamless congestion control in wireless/wired
  - Marking algorithms, IP at RNC ?
- Interaction & modification of existing mechanisms
  - Service differentiation
- Resource control in WLANs based on 802.11

Joint project with BTexact (British Telecom), UK & Athens Univ. of Economics and Business (AUEB)

www.ics.forth.gr/netlab/wireless.html