Congestion Pricing for Resource Control in WCDMA

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- Resource usage in uplink and downlink
  - depends on rate & signal quality, and power
- Congestion pricing for elastic traffic
  - captures congestion in wireless & wired networks, and cost of battery power
- ECN marking at the RNC for conveying congestion of wireless resources
- Alternative application of congestion pricing
- Extensions:
  - hybrid code/time division multiplexing
  - rate-inelastic, quality-elastic traffic
  - power control based on congestion pricing

Notes

- Emphasize that what we call price/charge need not be the charge that appears in an end-users bill. We use models based on congestion pricing for resource control; prices are internal to the network signals

Motivation

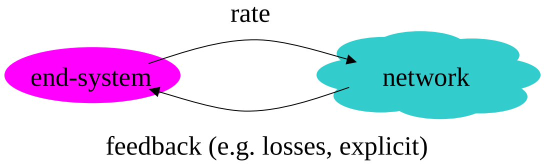
- Congestion pricing can be used for efficient and robust resource control in fixed networks
- ECN (Explicit Congestion Notification) used for signaling price/congestion information
- Simple network, intelligence at edges

➔ Limited ability to increase capacity in mobile wireless networks

➔ Apply/extend ideas to wireless networks, in particular CDMA

Congestion Control and Resource Usage

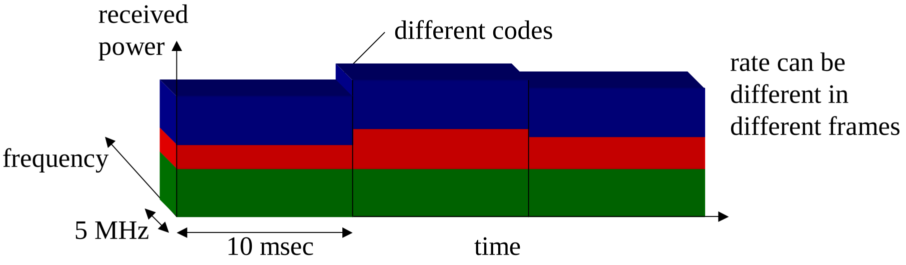
- Congestion control loop



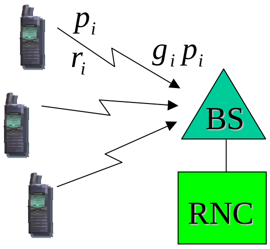
- Feedback depends on level of congestion and resource usage
- Shared resources in CDMA: radio spectrum and base station power
- Different resource constraints in uplink and downlink

CDMA (Code Division Multiple Access)

- Signals from different mobiles separated based on unique code
- Wideband CDMA (WCDMA) most widely adopted 3G air interface
- WCDMA is based on Direct Sequence CDMA (DS-CDMA)



Resource Usage in CDMA: Uplink



RNC: Radio Network Controller

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

assuming perfect power control

uplink is ***interference-limited***

resource constraint in uplink $\displaystyle \sum_i \frac{1}{\frac{W}{r_i \gamma_i} + 1} < 1$

resource usage in uplink $\displaystyle \frac{1}{\frac{W}{r_i \gamma_i} + 1}$

approximations for large # of mobile users

$$\sum_i r_i \gamma_i < W$$

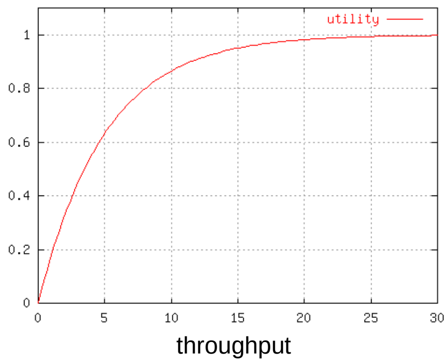
$$r_i \gamma_i$$

Notes

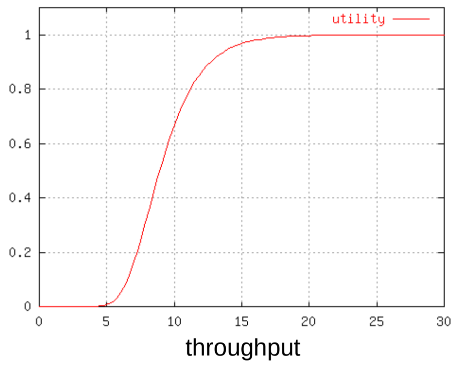
- Assumptions are perfect closed-loop power control, operating on faster timescale
- Previous model does not take into account power constraints at mobiles; can extend to take this into account ; Resource constraint will not have “1” on right hand side, but something less determined by mobile with smallest gain/power.
- Assumed single cell and base station. However, if there are K base stations and there is (perfect) soft handover, constraint becomes \sum r_i\gamma_i < K

Utility for elastic traffic

- *Utility*: denotes the *value* a user get from specific *level of service*
- Elastic traffic: *level of service*=*average throughput*



no minimum rate



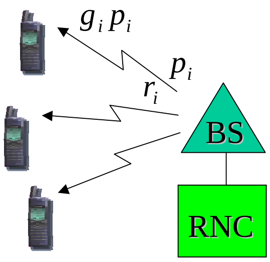
with minimum rate

Congestion Pricing for Elastic Traffic: Uplink

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

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

Resource Usage in CDMA: Downlink



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

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

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

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

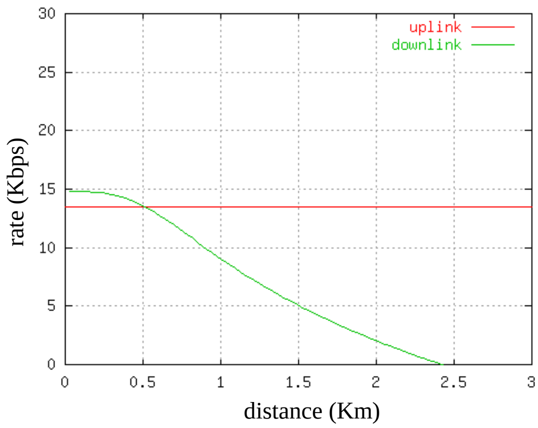
$$\gamma_i = \frac{W}{r_i} \frac{g_i p_i}{\theta_i g_i \sum_{j \neq i} p_j + \eta}$$

  - *not the case* for the *uplink*

Notes

- Note that in downlink, optimization again performed in terms of r,gamma; the latter becomes the target in fast power control, which operates on faster timescale.
- The alternative of doing power control based on congestion pricing is discussed later.
- In WCDMA rate can take only discrete values.

Congestion Pricing in Uplink and Downlink: concave utility



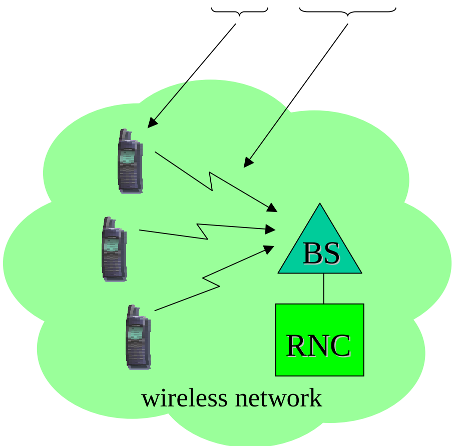
- Uplink: rate independent of mobile position
- Downlink: rate depends on mobile position => efficient use of base station power

Notes

- In downlink, having smaller rate for far away mobiles increases efficiency

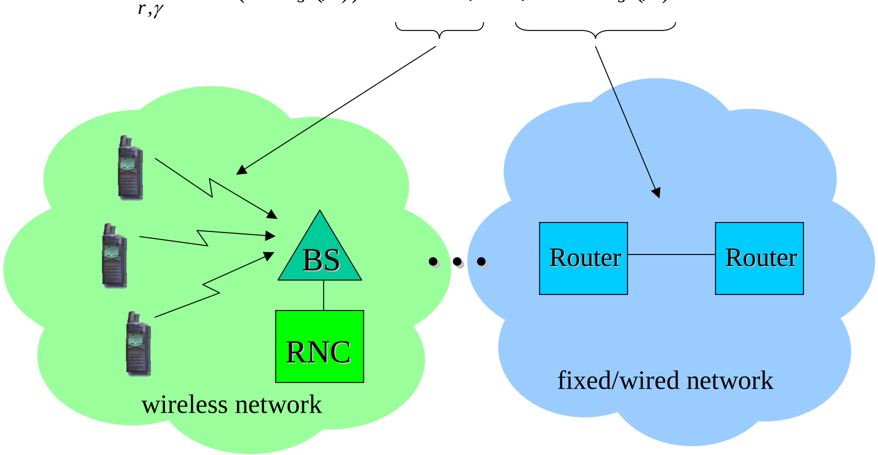
Extensions: adding cost of battery power

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



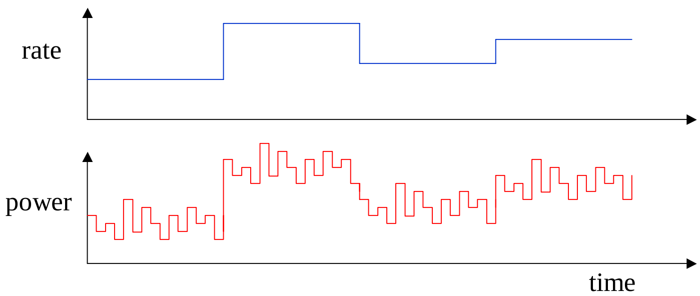
Extensions: adding congestion charge of fixed/wired network

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



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 (=γ) to achieve specific frame or block error rate

Properties of the optimal solution

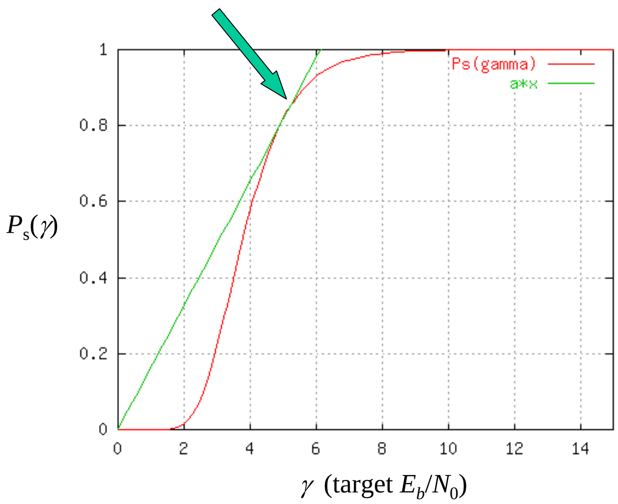
- Net utility optimization done over *two variables*: rate r and signal quality γ
- *Proposition*: Optimal γ^* is *independent* of the *price* λ and the *utility*, and depends *only* on $P_s(\gamma)$:

$$P_s(\gamma) = P'_s(\gamma)\gamma$$

- 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 CDMA or transport layer

P_s for DPSK modulation, no FEC

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

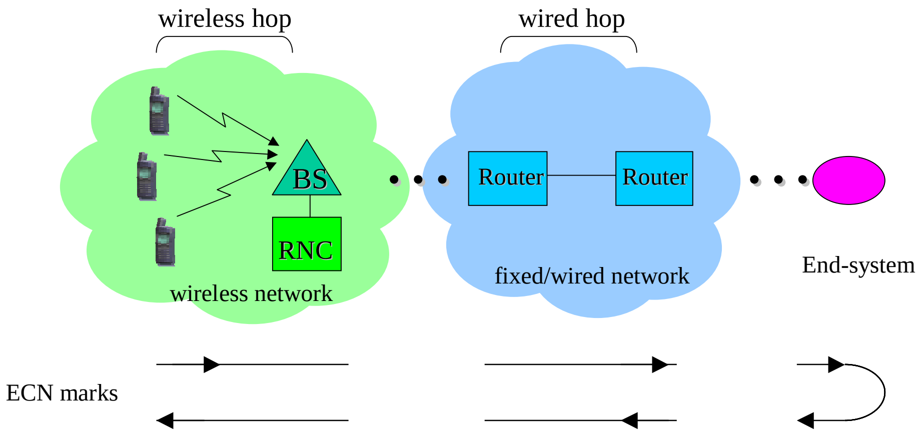


Notes

- Up to now fast closed-power control is not changed.
- What is changes is how target Eb/N0 is determined.

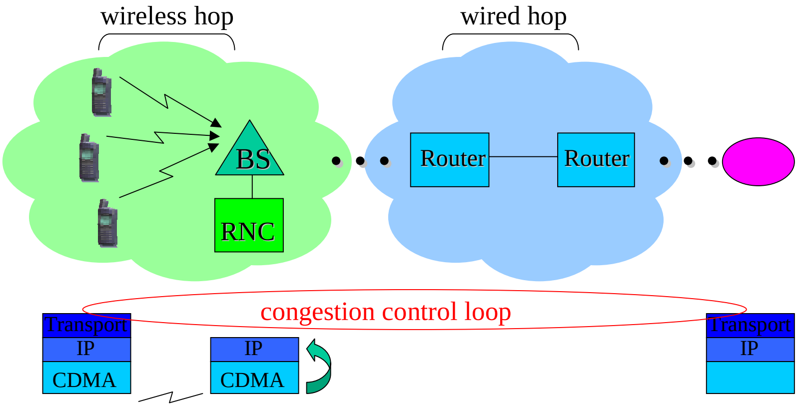
Seamless wired/wireless congestion control

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



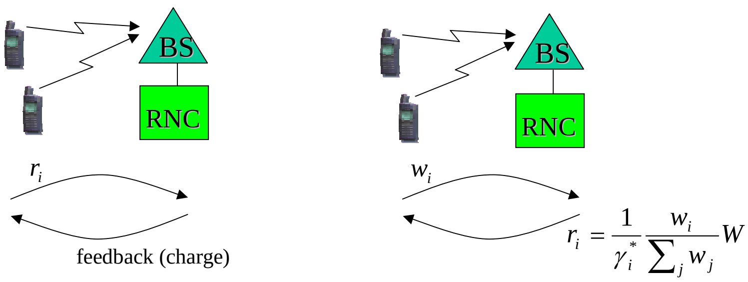
Seamless wired/wireless congestion ctrl (2)

- 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*



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

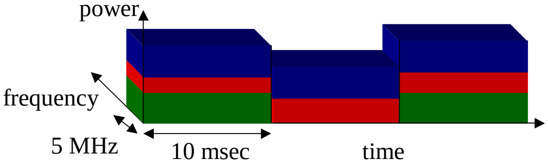
- Previous models included price (congestion) feedback and rate adaptation by mobile users



- 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 $1/\gamma^*$

Extensions

- Hybrid code division/time division multiplexing
  - quantify *resource usage*
  - utility depends not only on average throughput, but also on *continuity of transmission*



- Have assumed perfect power control operating at faster timescale compared to rate control
  - Rate-inelastic, quality-elastic traffic
  - Fast power control based on congestion pricing

Power ctrl based on congestion pricing

- Rate inelastic / signal quality elastic traffic:
  - fixed rate
  - utility: $U(\gamma)$
- User optimization problem (downlink)

$$\begin{array}{ll} \text{maximize} & U(\gamma) - \lambda \cdot p \\ \text{over} & p \end{array}$$

- If $U(\gamma)=w\log(\gamma)$, objective is to keep charge λp constant, equal to w (willingness to pay)

Power ctrl based on congestion pricing - 2

- Application to power control

$$\frac{d}{dt}p(t) = \kappa\left(w - \lambda \cdot p(t)\right)$$

- Assumed $U(\gamma)=w\log(\gamma)$. For *general utility*, can *vary* $w(t)$ *slowly* to achieve

$$w(t) = U'\left(\gamma(t)\right)\gamma(t)$$

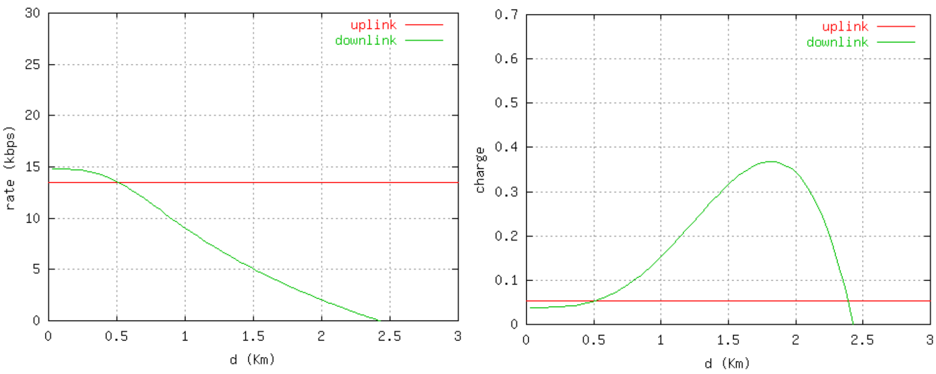
- Advantages:
  - traditional power control algorithms *converge only if feasible*
  - introduction of congestion pricing has added *robustness* and *efficiency*

Contributions

- Framework for *resource control* in CDMA: captures *congestion charge* in *wireless* & *wired* networks and *cost of battery power*
- Decoupling (mathematically proven) of *quality selection* and *rate adaptation*
- ECN marking at RNC based on congestion and resource usage for *seamless wireless/wired congestion control*
- Extensions:
  - hybrid code/time division scheduling
  - rate inelastic-quality elastic traffic
  - *power control based on congestion pricing*

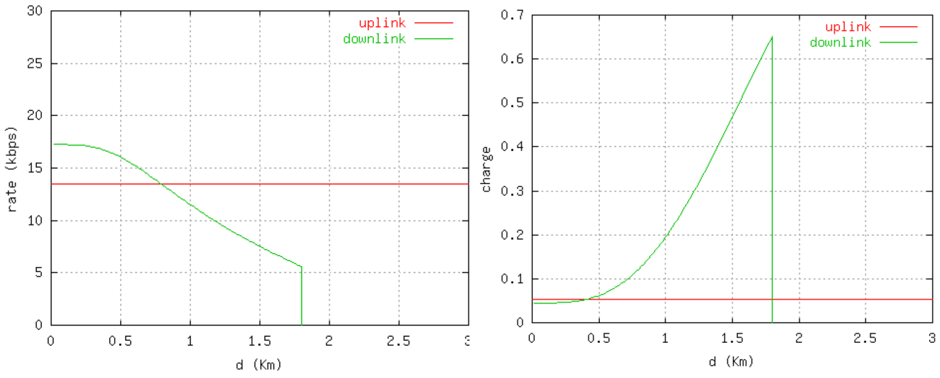
Additional slides

Congestion Pricing in Uplink and Downlink: concave utility



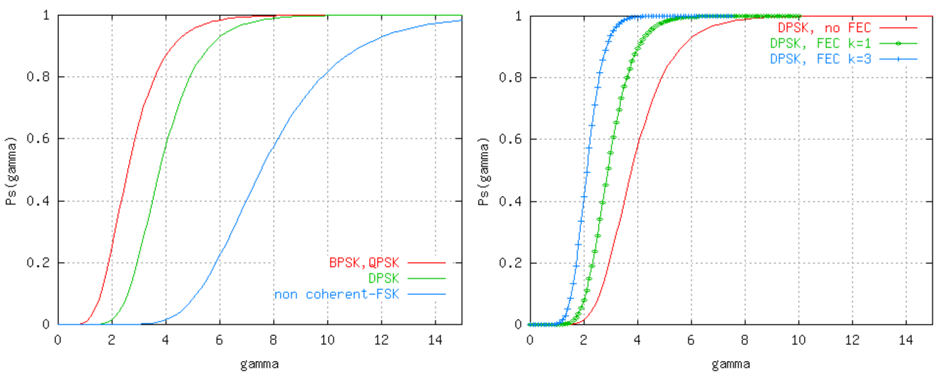
- Uplink: rate and charge independent of mobile position
- Downlink: rate and charge depend on mobile position

Congestion Pricing in Uplink and Downlink: sigmoid utility



- Downlink: at some distance rate and charge drops to zero

P_s for different modulation and FEC



Algorithm for setting of γ (target *Eb/N0*)

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

WHILE TRUE

$$\text{IF } \frac{\text{Ps(k) - Ps(k - 1)}}{\text{Step}} > \text{F\_high } \frac{\text{Ps(k)}}{\text{Gamma}}$$

Gamma += Step

$$\text{IF } \frac{\text{Ps(k) - Ps(k - 1)}}{\text{Step}} < \text{F\_low } \frac{\text{Ps(k)}}{\text{Gamma}}$$

Gamma −= Step

where
Ps(k) : packet success rate at step k
Gamma : target Eb/N0
Step : target Eb/N0 update step
F_high, F_low : parameters (e.g. 1.1,0.9)

Algorithm for setting of γ (target *Eb/N0*) - 2

- To achieve smoother convergence: make change of γ depend on $P_s(\gamma)/\gamma - P'_s(\gamma)$

```
WHILE TRUE
  D = Gamma * (1 - Ps(k - 1) / Ps(k))
  IF D > F_high * Step
    Gamma += D - F_high * Step
  IF D < F_low * Step
    Gamma += D - F_low * Step
```

where
Ps(k) : packet success rate at step k
Gamma : target Eb/N0
Step : target Eb/N0 update step
F_high, F_low : parameters (e.g. 1.1, 0.9)

Power ctrl based on congestion pricing - 3

- Following two problems are equivalent:

maximize $w\log(\gamma) - \lambda \cdot p$ over p	maximize $w\log(p) - \lambda \cdot p$ over p

- Above due to

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