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

![Congestion Control Loop Diagram]

- 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)

![CDMA Diagram]
Resource Usage in CDMA: Uplink

BS

RNC: Radio Network Controller

uplink is *interference-limited*

resource constraint in uplink

\[ \sum_i \frac{1}{r_i \gamma_i} < 1 \]

resource usage in uplink

\[ \frac{1}{r_i \gamma_i} + 1 \]

approximations for large # of mobile users

\[ \sum_i r_i \gamma_i < W \]

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 \( \sum r_i g_isigma_i < K \).
Utility for elastic traffic

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

![Utility vs. Throughput](image1)

- 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*

\[
\text{maximize} \quad U(r \cdot P_s(\gamma)) - \lambda \cdot r \cdot \gamma \\
\text{over} \quad r, \gamma
\]
Resource Usage in CDMA: Downlink

- Target bit energy to noise density ratio $E_b/N_0$ (determines bit error rate)
- Power-limited downlink

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

Downlink resource constraint
$$\sum_i p_i < \bar{p}$$

Congestion Pricing for Elastic Traffic: Downlink

- User optimization problem
  $$\text{maximize } U(r \cdot P_i(\gamma)) - \lambda \cdot p$$
  $$\text{over } r, \gamma$$

- Downlink: for given rate and quality, charge depends on path gain, hence mobile position
  $$\gamma_i = \frac{W g_i p_i}{r_i \theta_i g_i \sum_{j \neq i} p_j + \eta}$$

- 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

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

wireless network

BS

RNC
Extensions: adding congestion charge of fixed/wired network

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

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 \( E_b/N_0 (\gamma) \) 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 $\gamma$
- **Proposition:** Optimal $\gamma^*$ is independent of the price $\lambda$ and the utility, and depends only on $P_s(\gamma)$:

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

- Above allows decoupling of selection of $\gamma$ (target $E_b/N_0$) and of rate adaptation
  - selection of $\gamma^*$ done at CDMA layer
  - rate adaptation done at CDMA or transport layer

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$P_s$ 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*
  - $\gamma^*$ 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

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Power ctrl based on congestion pricing

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

\[
\text{maximize} \quad U(\gamma) - \lambda \cdot p \\
\text{over} \quad p
\]

- If $U(\gamma) = \text{wlog}(\gamma)$, objective is to keep charge $\lambda p$ 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 \textit{general utility}, can \textit{vary} \( w(t) \) \textit{slowly} to achieve
  \[
  w(t) = U(\gamma(t)) \gamma(t)
  \]

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

Contributions

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

\[ P_s \text{ for different modulation and FEC} \]
Algorithm for setting of $\gamma$ (target $Eb/N0$) 

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

\[
\text{WHILE TRUE}
\]
\[
\text{IF } \frac{Ps(k) - Ps(k - 1)}{\text{Step}} > F_{\text{high}} \quad \text{Ps(k)} \quad \text{Gamma}
\]
\[
\text{Gamma} + = \text{Step}
\]
\[
\text{IF } \frac{Ps(k) - Ps(k - 1)}{\text{Step}} < F_{\text{low}} \quad \text{Ps(k)} \quad \text{Gamma}
\]
\[
\text{Gamma} - = \text{Step}
\]

where

$Ps(k)$ : packet success rate at step $k$
$\Gamma$ : target $Eb/N0$
Step : target $Eb/N0$ update step
$F_{\text{high}}, F_{\text{low}}$ : parameters (e.g. 1.1, 0.9)

Algorithm for setting of $\gamma$ (target $Eb/N0$) - 2

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

\[
\text{WHILE TRUE}
\]
\[
D = \Gamma * \left(1 - \frac{Ps(k - 1)}{Ps(k)}\right)
\]
\[
\text{IF } D > F_{\text{high}} * \text{Step}
\]
\[
\text{Gamma} + = D - F_{\text{high}} * \text{Step}
\]
\[
\text{IF } D < F_{\text{low}} * \text{Step}
\]
\[
\text{Gamma} + = D - F_{\text{low}} * \text{Step}
\]

where

$Ps(k)$ : packet success rate at step $k$
$\Gamma$ : target $Eb/N0$
Step : target $Eb/N0$ update step
$F_{\text{high}}, F_{\text{low}}$ : parameters (e.g. 1.1, 0.9)
Power ctrl based on congestion pricing - 3

- Following two problems are equivalent:

\[
\begin{align*}
\text{maximize over } p & \quad \mathbf{w} \log(p) - \lambda \cdot p \\
\text{maximize over } p & \quad \mathbf{w} \log(p) - \lambda \cdot p
\end{align*}
\]

- Above due to

\[
\gamma_i = \frac{W}{r_i \theta \sigma_i \sum_{j \neq i} p_j + \eta}
\]