Pricing and Power Control for Joint Network-Centric and User-Centric Radio Resource Management

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OUTLINE

- Background & Motivation
- System Model: Utility, Pricing Mechanism, & Revenue
- Problem description
  - User-centric objective
  - Network-centric objective
- Numerical Results
- Approximate Solution
- Conclusions
Effective radio resource management is essential for the success of wireless communications.

Radio resource management can be classified into two categories:

- **User-centric**: Maximize the interest of each individual user.  
  * Distributed power control.  
  * Minimization of outage probability.

- **Network-centric**: Optimize collective objective for all users.  
  * Maximization of sum of rates (information capacity).  
  * Maximization of sum of throughputs.
The two categories are motivated by different interests and will generally lead to (sometimes very) different resource allocations.

- Examples of user interests:
  * Maximize individual throughput
  * Minimize individual transmit power while meeting some SIR target

- Example of network interest:
  * Maximize network revenue

What if network-centric and user-centric objectives are allowed to compete/compromise with each other?
• Pricing mediates between the user-centric and network-centric objectives.

• Pricing does not necessarily imply dollar pricing. It was a policing mechanism in previous power-control work.
**USER-CENTRIC METRIC: UTILITY**

**Definition 1** *Utility* models the level of satisfaction that a user achieves from consuming a good or using a service.

![Diagram](attachment:image_url)

(a) voice

(b) data

- Wireless data user cares about:
  - Throughput; hence transmission rate and frame success rate (FSR).
  - Battery life; hence transmit power.
WIRELESS DATA UTILITY

Definition 2 Utility of a wireless data user is the average amount of data received correctly at the base station per unit of average battery energy expended:

\[
U_i \equiv \frac{T_i}{p_i} = \frac{R_i f(\gamma_i)}{p_i} \text{ Bits Joule}. \quad (1)
\]

- \(p_i\): Transmitter power of user \(i\)
- \(T_i\): Throughput of user \(i\)
- \(\gamma_i\): SIR of user \(i\)
- \(R_i\): Transmission rate of user \(i\)
- \(f(\gamma_i)\): approximate frame-success rate.

- \(f(\gamma) \equiv [1 - 2\text{BER} (\gamma)]^M \approx [1 - \text{BER} (\gamma)]^M.\)
  
  \(M\): packet length measured in bits.
Users are charged according to their throughputs.

Revenue is defined as the aggregate payment from all the users:

\[
\text{Revenue} \equiv \sum_i \rho_i \equiv \sum_i \lambda T_i ,
\]  

(2)

where,

\[
\rho_i \equiv \lambda T_i = \text{Payment} \text{ made by user } i \text{ for achieving throughput } T_i ,
\]

\[
\lambda = \text{Unit price, charging rate, or pricing factor}
\]

( equivalent to dollar per unit throughput),

\[
T_i = \text{Throughput of user } i .
\]
USER-CENTRIC OPTIMIZATION

- Users’ satisfaction are reduced by their payments.

- They engage in a non-cooperative game resulting in distributed power control:

$$\max_{p_i \in S_i} U_{i_{net}} (p) , \quad \forall i ;$$

$$U_{i_{net}} \equiv U_i - \lambda T_i = \text{net utility}.\,$$

- This non-cooperative game has a unique Nash Equilibrium, at which no user can improve its net utility by unilaterally changing its power.

- For any $\lambda$, a round-robin iterative algorithm converges to the unique Nash eqm. given by $p^*(\lambda)$.

- User optimization is a machine generating $p^*(\lambda)$.
NETWORK-CENTRIC OPTIMIZATION

\[
\max_{\lambda \geq 0} \sum_i \lambda T_i (p^*(\lambda)) \quad \text{[Maximize Revenue (total payment)]},
\]

Let \( \rho(\lambda) \equiv \text{Revenue} \equiv \sum_i \lambda T_i (p^*(\lambda)) \).

- Through \( p^*(\lambda) \), the network knows its revenue \( \rho(\lambda) \) at each \( \lambda \).
- Network searches in one-dimension for the \( \lambda^* \) that maximizes \( \rho(\lambda) \).
\[
\rho(\lambda) \equiv \text{Revenue} \equiv \sum_i \lambda T_i(p^*(\lambda)).
\]

- Sensibility of our formulation:

1. \(\rho(\lambda) \geq 0\), because throughput \(T_i \geq 0\).
2. \(\rho(\lambda) = 0\) when \(\lambda = 0\).
3. \(\rho(\lambda) \to 0\) when \(\lambda \to \infty\):
   - Users cannot afford to transmit when price is too high.
   - Network cannot derive arbitrarily high revenue by greedily increasing \(\lambda\).

**Lemma 1** The revenue \(\rho(\lambda)\) has at least one maximum at some finite positive pricing factor \(\lambda^*\).
JOINT OPTIMIZATION

NETWORK

$$\max_{\lambda \geq 0} \sum_i \lambda T_i (p^*(\lambda))$$

\[ \lambda \]
\[ p^*(\lambda) \]

USERS

$$\max_{p_1} U_1 - \lambda T_1$$
$$\max_{p_2} U_2 - \lambda T_2$$
$$\ldots$$
$$\max_{p_N} U_N - \lambda T_N$$
**NUMERICAL EXPERIMENT**

Table 1: Main System Parameters Used in Numerical Simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Bandwidth $W$</td>
<td>1MHz</td>
</tr>
<tr>
<td>Transmission Rate $R$</td>
<td>10 kbps</td>
</tr>
<tr>
<td>Total Bits per packet $M$</td>
<td>96 bits/frame</td>
</tr>
<tr>
<td>Information Bits per packet $L$</td>
<td>80 bits/frame</td>
</tr>
<tr>
<td>AWGN Power at receiver $\sigma^2$</td>
<td>$5 \times 10^{-15}$ Watts</td>
</tr>
</tbody>
</table>
Path gains: \( h_1 > h_2 > h_3 > \ldots > h_9 \)

\( h = \text{const.} / d^4 \)
SENSIBILITY OF SOLUTION

(c) Individual payments and total revenue as functions of $\lambda$

(d) Allocation at max. revenue

Users with better channels are served better (higher throughputs and more utilities) as usual (e.g., as in water filling), but they pay proportionally more.
CONCLUSIONS

- User-centric and network-centric objectives are mediated via pricing.

- User-centric optimization:
  - Distributed power-control formulated as a non-cooperative game
  - Each user maximizes its net utility \((U_i - \lambda T_i)\)

- Network-centric optimization:
  - One-dimensional search for the revenue \((\sum_i \lambda T_i)\) maximizing unit price \(\lambda^*\)

- Numerically shown that revenue has a unique maximum.

- We develop a computationally simple and accurate approximation to \(\lambda^*\) (ask me off line if interested).

- Main Result: Users with better channels receive better services as usual (like in water filling), but they pay proportionally more.