Viability of Reverse Pricing in Cellular Networks: A New Outlook on Resource Management

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Joint work with Sang Yeob Jung, Joon Soo Kim, and Jun Ki Hong
Center for Flexible Radio: Practically Limitless User Spectrum (PLUS)

Licensed Spectrum

Open Access Spectrum

Licensed Flexible Service over Shared Spectrum:
user-deployed, low cost/complexity, ultra-dense cells

Pain "Sharing"

Protection

Cognitive Radio (conventional)

FR+

Server

MAC

DB

sparse sensing

0.4 GHz

6 GHz
Dynamic Spectrum Access via High-Resolution/Low-Complexity Spectrum Sensing

**High-Resolution Low-Complexity Sensing at Yonsei**
- Spectrum Res.: 50 kHz
- Time Res.: 200 ms
- Spatial Res.: 10 m x 10 m

**Sensing Map**
- Frequency: -125 dBm to >10 dBm

**Opportunity Map**
- High opportunity (1)
- Low opportunity (0)

**Sensing Map → Opportunity Map**
- 1단계: Spectrum Sensing Map
  - Receiver Mobility
  - Interference Prediction
- 2단계: DSA Opportunity Map

**Realtime DSA at Yonsei**
- FBMC-based
- Flexible Duplex

**Cloud DB/MAC at SNU**
- Cloud Sensing/OP Map DB
- Cloud MAC Interf. Mngmt.

**Cloud DB/MAC**
Part 1. Introduction
1. **Total traffic** volume increase: 3.04 times (47.66 → 145.05 MB/day).
2. Aggregate **walking and nomadic user traffic** proportion increase: 2.64 times (14.74 → 38.93%)
3. **Nomadic heavy user** traffic proportion increase: 2.83 times (10.35 → 29.29%)

## Visual Example of Our Experimental Data Collection

<table>
<thead>
<tr>
<th>Year</th>
<th>2012</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radio access technology</strong></td>
<td>WCDMA / LTE</td>
<td>WCDMA / LTE / LTE-A</td>
</tr>
<tr>
<td><strong>Number of participants</strong></td>
<td>82 (male: 61, female: 21)</td>
<td>70 (male: 54, female: 16)</td>
</tr>
<tr>
<td><strong>Experimental period</strong></td>
<td>avg. 1.28 weeks</td>
<td>avg. 1.13 weeks</td>
</tr>
<tr>
<td><strong>Measurement applications</strong></td>
<td>LifeMap</td>
<td>My Data Manager, Moves</td>
</tr>
<tr>
<td><strong>User speed</strong></td>
<td><em>Walking</em>: up to 10 km/h (avg. 2.58 km/h)</td>
<td><em>Nomadic</em>: above 10 km/h (avg. 31.9 km/h)</td>
</tr>
</tbody>
</table>

User Convexity: Convex-Shaped over Velocity

Def. **User convexity**: the traffic volume ratio of nomadic users to walking users

User convexity increase: 1.29 times (2.35 → 3.04)

Solution: Traffic Convexity Aware Cell Association

Road to 5G: “How to Match Supply to Demand?”

Pricing: Prof. Frank Kelly’s Seminal Work [Kelly98]

- **Effective tool** for design, operation, and management in cellular networks

Mismatch: “Theory” and “Practice”

- High spatiotemporal user demand uncertainty
  - Network demand: 10x in peak-hours vs. off-peak hours [Ha12]

“New congestion pricing framework”

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**Smart Data Pricing (SDP)** [Sen13]

- Broad set of ideas and principles beyond the traditional pricing (e.g., flat-rate or usage-based pricing)
  - **Edge devices** as a part of network management
  - Not just how much to charge, but also **when** and **how to charge**

SDP 1. Operator-driven Time-Dependent Pricing (Forward Pricing) [Ha12]

- Low prices in less-congested periods, shifting usage from peak to off-peak periods

CLAIM: Operator still has to face or predict demand uncertainty

Fig. 1. Spectrum usage efficiency over time
SDP 2. Reverse Pricing [Jung15]

- Common in travel industry (e.g., airlines and hotels) - priceline.com
- Concept: Data amount/rate purchased, rather than sold

**User 1**

Resource recommendation rule: 10 GB + ? GB

Name user 1’s price: ? $/GB

Demand: 10 GB
Payment: 10 $

**User 2**

Resource recommendation rule: 5 GB + ? GB

Name user 2’s price: ? $/GB

Demand: 5 GB
Payment: 5 $

Available capacity: 20 GB
Price: 1 $/GB
Hidden bid-acceptance threshold: ? $/GB

Objective

**Q. How to design reverse pricing w/ forward pricing to achieve “triple-win” solutions?**

1. Resource utilization efficiency
2. Users’ total payoffs
3. Operator’s total revenue

**Realistic Issues - Incomplete Information**

1. *Demand uncertainty*: user demand expectation but not variance
2. *User heterogeneity*: willingness to pay, bidding profiles
Part 2. Teaser
Resource Utilization Efficiency

Fig. 2. Total user demand

$p^* = \{1.5616, 1.5628, 1.4471, 1.4754, 1.5370, 1.6212, 1.5817, 1.6746, 1.5973, 1.6871, 1.5600, 1.4823\}$
Users’ Total Payoffs

Fig. 3. Total user payoff
Viability of Reverse Pricing (3/7)

Operator’s Total Revenue

Fig. 4. Operator’s revenue
Viability of Reverse Pricing (4/7)

Q. Is proposed reverse pricing is **Real, Implementable**?

- We **Architected & Prototyped** a fully functional reverse pricing system via App. & Server
- Through experiment study, we will **confirm viability** of reverse pricing or compare theory and practice

![Trafficbid App and Server Diagram]

*Can download* to search “Trafficbid”

[http://ramoyonsei.angelworks.co.kr/ta_admin/index.php?/home](http://ramoyonsei.angelworks.co.kr/ta_admin/index.php?/home)
Viability of Reverse Pricing (5/7)

App. Prototype

<table>
<thead>
<tr>
<th>Calling plan</th>
<th>Time</th>
<th>Recommended data amount</th>
<th>Minimum participation price</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 GB</td>
<td>00:00 ~ 06:00</td>
<td>5 MB</td>
<td>0.1 $ / MB</td>
</tr>
<tr>
<td>55000 원</td>
<td>06:00 ~ 12:00</td>
<td>15 MB</td>
<td>0.2 $ / MB</td>
</tr>
<tr>
<td>Auto-mode</td>
<td>12:00 ~ 18:00</td>
<td>30 MB</td>
<td>0.4 $ / MB</td>
</tr>
<tr>
<td></td>
<td>18:00 ~ 24:00</td>
<td>60 MB</td>
<td>0.6 $ / MB</td>
</tr>
</tbody>
</table>

ex) 1기가에 1만원 사용시 1GB, 10000 입력

5000원

Change

Bid
### Results

<table>
<thead>
<tr>
<th>Number</th>
<th>Time</th>
<th>Winning bid</th>
<th>Success / Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00:00 ~ 06:00</td>
<td>0.2 $/ MB</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>06:00 ~ 12:00</td>
<td>0.3 $/ MB</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>12:00 ~ 18:00</td>
<td>0.4 $/ MB</td>
<td>O</td>
</tr>
<tr>
<td>4</td>
<td>18:00 ~ 24:00</td>
<td>0.7 $/ MB</td>
<td>O</td>
</tr>
</tbody>
</table>

### Data usage pattern

![Data usage pattern chart](chart.png)
Viability of Reverse Pricing (7/7)

**Server**

- Set minimum participation price, winning bid, user-specific recommended data amount
Part 3. System Model
Resource-Constrained & Time-Slotted Network

- A total amount of $Q$ limited resource (e.g., data amount, rate, bandwidth, etc)
- A single operator
- A set $\mathcal{I} = \{1, \cdots, I\}$ of users
- A set $\mathcal{H} = \{1, \cdots, H\}$ of time slots (e.g., peak, normal, off-peak demand slots)

Fig. 5. Resource-constrained & time-slotted network
User’s Payoff Function

- The payoff function for user $i$ at time slot $h$

$$u_i(\theta_i^h, s_i^h, p^h) = \theta_i^h \ln(1 + s_i^h) - p^h s_i^h$$

- Logarithmic utility function is commonly used to model the proportionally fair resource allocation [Basar02]
- $\theta_i^h$ is the maximum price per unit resource for user $i$, implying changing necessities of resource over time

Interaction Between Operator and Users

**Stage I.** Pricing based on demand predictions

**Stage II.** Use or report resources as a price taker

**Stage III.** Resource allocation rule & Hidden bid-acceptance threshold

**Stage IV.** Name your own price

Analysis: Backward Induction

Fig. 6. Timing of the game that characterizes the interaction between operator and users
Part 4. Analysis
Stage IV. Name Your Own Price (1/2)

Users’ Participation Decisions in Stage IV

• Operator publicly specify a minimum participation unit price $0 \leq p_{\text{min}}^h < p^h$ below which $x_i^h$ is not sold.

• User $i$ decides whether to take part in the pricing process, i.e.,

$$\theta_i^h \ln(1 + x_i^h) - p_{\text{min}}^h x_i^h \geq \theta_i^h \ln(1 + s_i^h) - p^h x_i^h$$  \hspace{1cm} (1)

• From (1), define the set of potential users that would name strictly positive prices at time slot $h$, i.e.,

$$\mathcal{I}^+(p_{\text{min}}^h) = \left\{ i \in \mathcal{I} : p_{\text{min}}^h \leq \frac{\theta_i^h \ln ((1 + x_i^h)/(1 + s_i^h)) + p^h s_i^h}{x_i^h} \right\}$$  \hspace{1cm} (2)

Group 1: name own price!

Group 2: Do not name own price!
Users’ Bidding Strategies in Stage IV

• Hidden bid-acceptance threshold (price): $\tau^h \sim U[p_{min}^h, p^h]$

\begin{equation}
P1: \max_{p_{min}^h \leq b_i^h \leq p^h} u_i(\theta_i^h, x_i^h, b_i^h)P\left(b_i^h \geq \tau^h\right) + u_i(\theta_i^h, s_i^h, p^h)P\left(b_i^h < \tau^h\right), \forall i \in \mathcal{I}^+(p_{min}^h), \forall h \in \mathcal{H} \tag{3}
\end{equation}

**Proposition 1.** For each user $i \in \mathcal{I}$, the optimal solution for Problem $P1$ at each time slot $h \in \mathcal{H}$ is given by

\begin{equation}
b_i^{h*} = \begin{cases} 
\frac{1}{2x_i^h} \left[ \theta_i^h \ln \left( \frac{1+x_i^h}{1+s_i^h} \right) + s_i^h p^h + x_i^h p_{min}^h \right], & \forall i \in \mathcal{I}^+(p_{min}^h), \\
0, & \forall i \in \mathcal{I}\setminus\mathcal{I}^+(p_{min}^h). 
\end{cases} \tag{4}
\end{equation}
Stage III. Resource Recommendation Rule & Hidden Bid-Acceptance Threshold (1/4)

**Issue 1. Resource Allocation Rule**

- Q. What is *fairness criterion* among users for resource allocation?
  - Constraint 1. Demand \( \leq \) Capacity
  - Constraint 2. Revenue via reverse pricing \( \geq \) Revenue via forward pricing

![Diagram of resource allocation]
Stage III. Resource Recommendation Rule & Hidden Bid-Acceptance Threshold (1/4)

Issue 1. Resource Allocation Rule (Cont’d)

• Q. What is **fairness criterion** among users for resource allocation?

  ➡ A. Proportional residual resource recommendation rule

```
Operator

20 GB
1 $/GB

• ‘user payment ∝ residual resource’

User 1

10 GB + (2/3) × 5 GB

User 2

5 GB + (1/3) × 5 GB
```
Stage III. Resource Recommendation Rule & Hidden Bid-Acceptance Threshold (2/4)

Issue 2. Minimum Participation Unit Price

• Q. How to publicly specify a minimum participation unit price?
  ➡ A. At least the revenue earned by forward pricing

**Lemma 1.** The minimum participation unit price that the operator sets should satisfy the following condition

\[
p^h > p^h_{\text{min}} \geq \frac{p^h \sum_{i \in \mathcal{I}} s^h_i}{Q}, \quad \forall h \in \mathcal{H}.
\]

![Diagram showing resource allocation between Operator and Users](image)

Operator

- 20 GB
- 1 $/GB, 0.75 $/GB

User 1

- 10 GB + (2/3) × 5 GB

User 2

- 5 GB + (1/3) × 5 GB
 Issue 2. Minimum Participation Unit Price (Cont’d)

• Q. How to set minimum participation unit price for revenue maximization?

➡ A. As a strategic variable, taking the following tradeoff into account

![Graph showing bidding profiles under different minimum participation unit prices](image)

Fig. 7. The comparison of bidding profiles under different minimum participation unit prices
Issue 3. Hidden Bid-Acceptance Threshold

• Q. How to set hidden bid-acceptance threshold given a specific minimum participation unit price?

⇒ A. Do not forgo potentially profitable trades via reverse pricing

**Proposition 2.** For any minimum participation unit price $p_{min}^h$ subject to (5), the hidden bid acceptance threshold is given by

$$\tau^h = p_{min}^h$$ (6)
Stage I and II. Forward Pricing and Users’ Desired Resources

Stage II. Users’ Desired Resources

\[
P_2: \max_{s_i^h} u_i(\theta_i^h, s_i^h, p_i^h) = \theta_i^h \ln(1 + s_i^h) - p_i^h s_i^h, \quad \forall i \in \mathcal{I}, \forall h \in \mathcal{H}
\]  

(7)

Stage I. Forward Pricing based on Demand Predictions

\[
P_3: \max_{P \geq 0} \sum_{h \in \mathcal{H}} \sum_{i \in \mathcal{I}} \mathbb{E}_{\theta_i^h} (\theta_i^h - p_i^h)
\]

s.t. \( \sum_{i \in \mathcal{I}} \left( \frac{\theta_i^h}{p_i^h} - 1 \right) \leq Q, \quad \forall h \in \mathcal{H}. \)

(8)

(9)

Proposition 3. Given \( Q > \frac{\sum_{i \in \mathcal{I}} \hat{\theta}_i^h + \epsilon_i^h}{\hat{\theta}_i^h - \epsilon_i^h} - I \), the optimal solution to Problem P3 is given by

\[
p_i^h^* = \frac{\sum_{i \in \mathcal{I}} \hat{\theta}_i^h + \epsilon_i^h}{Q + I}, \quad \forall h \in \mathcal{H}.
\]

(10)

Demand uncertainty stemming from time-varying willingness to pay.
Part 5. Numerical Results
Resource Utilization Efficiency

- Forward pricing: still fluctuating residual capacity due to intrinsic demand uncertainty
- Reverse pricing w/ forward pricing: no capacity left over resource scheduling horizon (only in this example)

$p^* =$ {1.5616, 1.5628, 1.4471, 1.4754, 1.5370, 1.6212, 1.5817, 1.6746, 1.5973, 1.6871, 1.5600, 1.4823}

Fig. 8. Toal user demand
Viability of Reverse Pricing (2/3)

**Users’ Total payoffs**

- The proposed pricing scheme always outperforms the forward pricing only
- Increased flexibility for pricing $\Rightarrow$ total user payoff $\uparrow$

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![Graph showing total user payoff over resource scheduling horizon](image-url)

**Fig. 9. Total user payoff**
Operator’s Total Revenue

- Perhaps surprisingly, operator can extract more revenue by reverse pricing
- Operator should re-examine the idea of involving users in pricing process

Fig. 10. Operator’s revenue
Operator’s Total Revenue

- At a particular time slot 1, $p_{\text{min}}^1$ should be chosen as 1.515, achieving maximum revenue gain (e.g., 28%)
- However, it is impossible to set it in reality due to some uncertainty of bidding profiles

Fig. 11. Operator’s revenue under $p_{\text{min}}^1$
Goal of Maximizing Operator's Revenue (2/3)

**Users’ Total Payoffs**

- Total user payoff is non-increasing over $p_{min}^1$
- This is due to the fact that users are induced to bid with higher prices as $p_{min}^1$ increases

![Graph showing total user payoff under varying $p_{min}^1$ values.](image)

Fig. 12. Total user payoff under $p_{min}^1$
Goal of Maximizing Operator's Revenue (2/3)

Resource Utilization Efficiency

- Resource utilization efficiency is non-increasing over $p_{\text{min}}^1$
- When $1.515 < p_{\text{min}}^1 < 1.519$, only some users name their own prices, decreasing resource utilization efficiency
- When $1.519 \leq p_{\text{min}}^1 \leq p^1^* = 1.5616$, no users name their own prices, degenerating forward pricing only case.

![Resource utilization efficiency graph](image)

Fig. 13. Resource utilization efficiency under $p_{\text{min}}^1$
Part 6. Conclusion
Q. How to design reverse pricing w/ forward pricing to achieve “triple-win” solutions?

1. Operator’s revenue - YES
2. Resource utilization efficiency - YES
3. Net utility summed over all users - YES

The idea of involving users in pricing decisions seems counterproductive. But, it may be the time to ‘re-examine’ this assumption.
Thank You

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