TUBE: TIME DEPENDENT PRICING FOR MOBILE DATA

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Joint work with:
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(Mobile) Data Explosion

Mobile data growing at 78% annually
2.4 billion mobile users worldwide, 260 million US mobile data users by 2017
Driving Forces

Mobile Video + Cloud Sync + Data-hungry Apps + High-res Devices = A Perfect Storm
Industry Moves: US ISPs

Wireless

- Verizon eliminates new unlimited smartphone plans (July 2011) 8
- AT&T throttles unlimited iPhone users (July 2011) 9
- T-Mobile starts data caps and throttling penalty (May 2011) 7

Wireline

- AT&T starts throttling wireline users (April 2011) 3
- AT&T caps U-verse to 250 GB and DSL to 150 GB with a $10 penalty for an additional 50 GB (May 2011) 4

Introduction of Data Caps

- Time-Warner trials data caps in Texas (June 2008) 1
- Comcast caps data at 250 GB (August 2008) 2

Introduction of Usage-based penalties

- AT&T starts $10/GB overage fee for smartphone data plans (June 2010) 6

Elimination of Unlimited Data Plans

- Verizon eliminates unlimited data plans (May 2012) 11
- No unlimited plans offered for iPad LTE (March 2012) 10
- Verizon AT&T introduce shared data plans with unlimited voice and text (June 2012) 12
- Comcast moves towards tiered usage-based billing (May 2012) 5
But Not Heavy All the Time

How to leverage the peak-valley differential?

Peak demand > 99%

Average demand < 30%
What do we ultimately want?
What do we ultimately want?
What do we ultimately want?

- Cost Reduction: ISP’s Spectrum, Capital, Operational costs decrease with reduced peak
- Revenue Increase: Create win-win by increasing demand

$50 for 5GB

$60 for 10GB
Time Elasticity: Opportunities

- Streaming videos, Gaming
- Texting, Weather, Finance
- Movies & Multimedia downloads, P2P
- Software Downloads
- Email, Social Network updates
- Cloud

Time-Dependent Pricing (TDP)

Peak-to-average ratio: 2.2
Time-Dependent Pricing (TDP)
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Peak-to-average ratio: 1.53
Time-Dependent Pricing (TDP)

28% decrease in PAR
Contributions

1. An architecture and a fully functional system for offering TDP for mobile data

1. User behavior models and optimized price computation

1. A realistic evaluation with real users
TDP Overview
TUBE Theory
Feedback Loop

Network Measurement → User Behavior Estimation → Price Calculation → Prices → User Interface

Usage
Waiting Functions

- Probabilistically estimate “willingness” to wait $W$

\[ W = \text{impatience} \]

Estimate parameters

\[ W_1, W_2, W_3 \]

discount

\[ w_\rho(d, \tau) = \frac{\bar{d}}{\lambda_\rho(\tau + 1)^\rho} \]

time waited
Minimizing Cost

\[
\Gamma_1 = \sum_{i=1}^{n} g \left( Y_i \left( 1 - \sum_{j \in i} \mu_j \sum_{k \neq i} w_j \left( d_k, |k-i|_n \right) \right) \right) \\
+ \sum_{k=1, k \neq i}^{n} Y_k \sum_{j \in k} \mu_j w_j \left( d_i, |i-k|_n \right) - C_i \right)
\]

\[
\Gamma_2 = \sum_{i=1}^{n} d_i \left( \sum_{k \neq i}^{n} Y_k \sum_{j \in k} \mu_j w_j \left( d_i, |i-k|_n \right) \right)
\]

Exceeding capacity

Offering discounts

minimize \( \Gamma_1 + \Gamma_2 \) variables \( d_i \)
Day-Ahead Pricing

- Guarantee prices one day in advance
- In each period, compute the price for the next day

\( n \) periods (one day)
Day-Ahead Pricing

- Guarantee prices one day in advance
- In each period, compute the price for the next day

Current time

\( n \) periods (one day)

To be computed
Day-Ahead Pricing

- Guarantee prices one day in advance
- In each period, compute the price for the next day

- Update waiting function parameters once a day
TUBE Architecture
Design Guidelines

1. Separating functionality
   ✷ Price computation on a central server
   ✷ Price display and scheduling the usage on the user devices

2. Scaling up the system
   ✷ User behavior estimation algorithm requires only aggregate, not individual usage data
   ✷ Formulate the price calculation as a convex optimization for computation scalability for many TDP periods

3. Protecting user privacy
   ✷ No Deep Packet Inspection (DPI) and no private data is exchanged.

4. Empowering user control
TUBE: TDP Architecture
TUBE Implementation
Server Side Design
Server Side Design

<table>
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<th>Number of TDP periods</th>
<th>Number of Periods</th>
<th>12</th>
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<td>15040</td>
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<tr>
<td>Price Calculation (sec)</td>
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<td>1.67</td>
<td>1.69</td>
<td>1.70</td>
<td>1.81</td>
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<th>Number of Application Type</th>
<th>Number of Periods</th>
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<th>4</th>
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<tr>
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<td></td>
<td></td>
<td>0.21</td>
<td>12.99</td>
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<td></td>
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<td>15.99</td>
<td>197.22</td>
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</table>
Client Side Design

Graphical User Interface

- Settings Display
- Top 5 Apps Display
- Usage Display
- Price Display
- Price Status bar Display
- Current Bill Display
- Popup Display

Daemon

- Price Dispatcher
- Budget Manager
- Usage Collector

Price DB

Usage DB

- Pull
- Local

Autopilot Algorithm

- Budget
- App PPI
- Scheduler

Enforcer

- Notifier
- Task Manager
- Allow/Block

Delegation

- Manual
- Autopilot

<table>
<thead>
<tr>
<th>Type</th>
<th>Status bar</th>
<th>App usage</th>
<th>Daemon Support</th>
<th>LOC</th>
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<tr>
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<td>No</td>
<td>No</td>
<td>Partial</td>
<td>25K</td>
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<td>Android</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>5.4K</td>
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<tr>
<td>Windows</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>5.3K</td>
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TUBE Princeton Trial
Princeton Trial: Money Flow

- 50 AT&T participants: 27 iPhones, 23 iPads
- Faculty, staff, and students
- 14 Academic Departments & Divisions
Princeton Trial: Data Flow

User's iPhone, iPad

BSC

3G Core Network

MCS

VLR

HLR

AuC

SGSN

GGSN

AT&T's mobile network

AT&T's mobile network

DNS

NAT

TUBE Servers

Gateway

PSTN

AT&T Firewall

VPN

Data Flow

Internet
TUBE App: Information Screens

(a) Price display.  (b) Usage history.  (c) Top five apps.
TUBE App: Scheduling Screens

(d) Delay indices.
(e) Budget.
(f) Scheduling.
Princeton Trial Results
Two main goals of the trial

1. How do people respond to pricing changes and GUI design?

1. Can the end to end TDP system work in the real world and can our architecture scale up?
Usage Statistics

- How much bandwidth participants use? – ‘Heavy tailed’
- Which applications use the most bandwidth – Streaming and surfing
UI Effectiveness

Do users respond more to the numerical values of TDP prices or to the color of the price indicator bar on the home screen?

✓ Users paid more attention to indicator color than the numerical discount values
**UI Effectiveness**

✔ Users paid more attention to *indicator color* than the numerical discount values

<table>
<thead>
<tr>
<th>Type</th>
<th>Periods</th>
<th>First Stage</th>
<th>Second Stage</th>
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<td></td>
<td></td>
<td>Color</td>
<td>Discount</td>
</tr>
<tr>
<td>1</td>
<td>2, 8, 14, 20</td>
<td>Orange</td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td>3, 6, ..., 24</td>
<td>Orange</td>
<td>10%</td>
</tr>
<tr>
<td>3</td>
<td>5, 11, 17, 23</td>
<td>Orange</td>
<td>10%</td>
</tr>
</tbody>
</table>

Period types 1 and 3

Period types 2 and 1
Optimized TDP Impact

Does the peak usage decrease with time-dependent pricing? And does this decrease come at the expense of an overall decrease in usage?

- Optimized TDP reduces the peak-to-average ratio
- Overall usage significantly increases with TDP
Optimized TDP Impact

Does the peak usage decrease with time-dependent pricing? And does this decrease come at the expense of an overall decrease in usage?

» Optimized TDP reduces the peak-to-average ratio
» Overall usage significantly increases with TDP

PAR reduces by 30%

Overall usage increases by 130%
Trial Limitations and Extensions

Limitations:
1. Single bottleneck
2. Mobility
3. Control group
4. Time granularity

Extensions:
1. Location/congestion dependent pricing
2. Commercial operator trials
Summary

1. A fully functional system for offering TDP for mobile data

2. People are sensitive to time-dependent prices and indeed shift their Internet usage to off-peak periods

3. The pilot trial motivates future study on TDP for different markets and demographics
Thank you!

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✓ DataMi: http://www.datami.com
✓ DataWiz: http://www.datawizapp.com
Backup Slides
TDP Performance

![Graph showing TDP Performance with different TDP configurations and network capacity comparison over a period of hours.]

Legend:
- **Blue line**: With Static TDP
- **Green dashed line**: With Optimized TDP
- **Red dotted line**: Network Capacity
Price Sensitivity

Do users wait to use mobile data in return for a monetary discount?

» Average usage **decrease** in high-price periods relative to the changes in low-price periods
Notification Effectiveness

Do notifications impact usage?

» 80-90% of users decrease or did not increase their usage after the 1st notification

» For all subsequent notifications, about 60-80% of the active users decrease their usage, while the others remained price-insensitivity
Impact on Ecosystem

Does the application usage distribution change due to TDP?

- People are motivated to use more bandwidth during low-price periods, “valley filling”.

![Bar chart showing application usage distribution before and with TDP](chart.png)