TUBE: TIME DEPENDENT PRICING FOR MOBILE DATA

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Joint work with:
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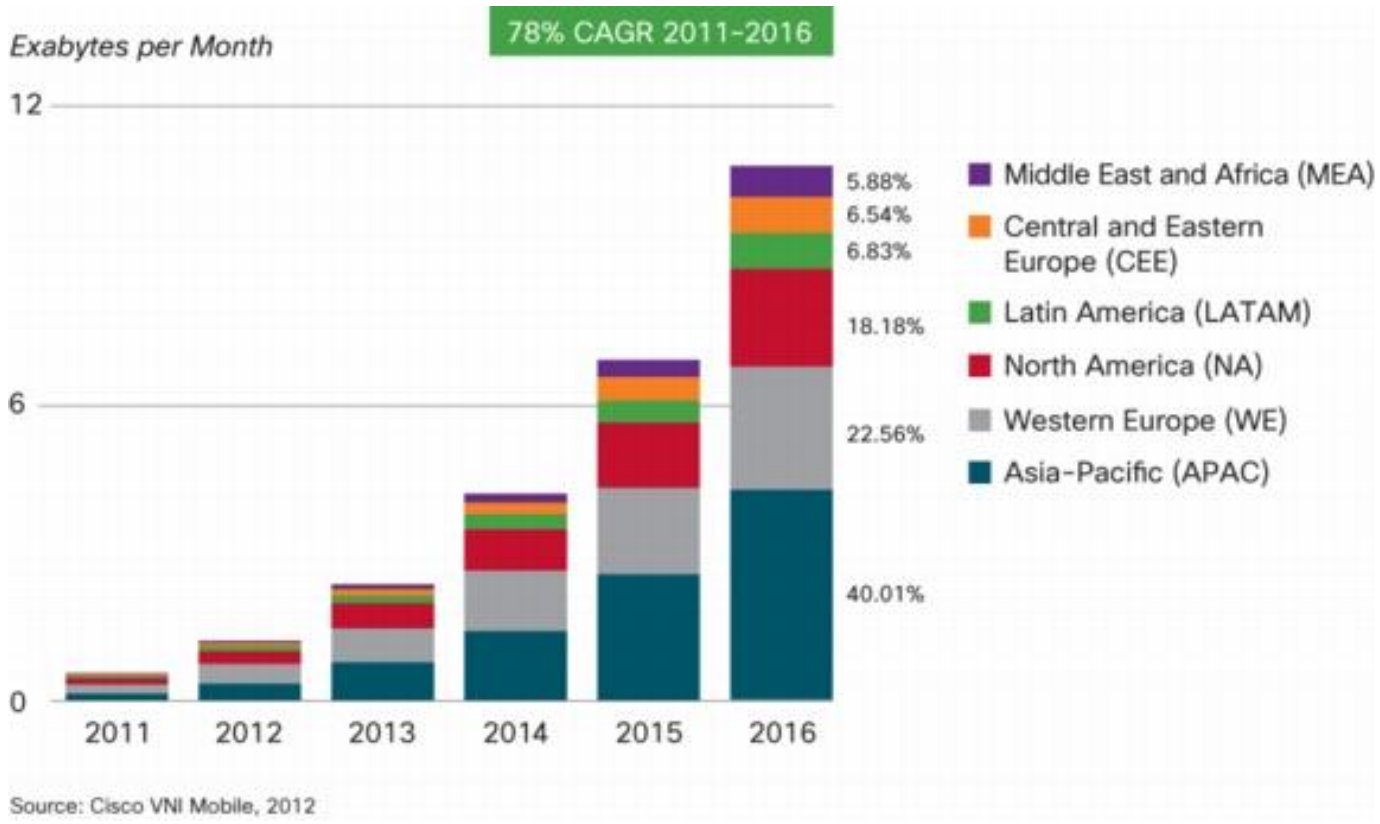
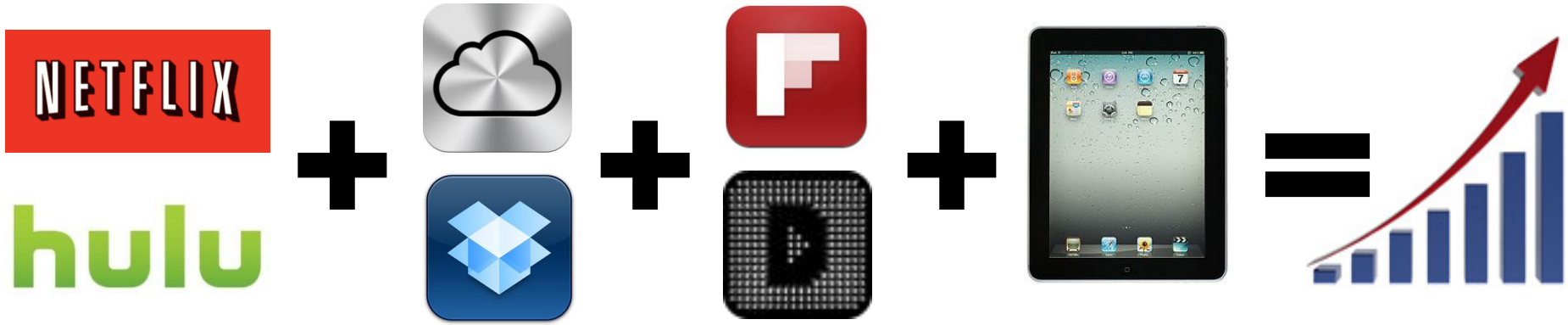
(Mobile) Data Explosion



Mobile data growing at 78% annually

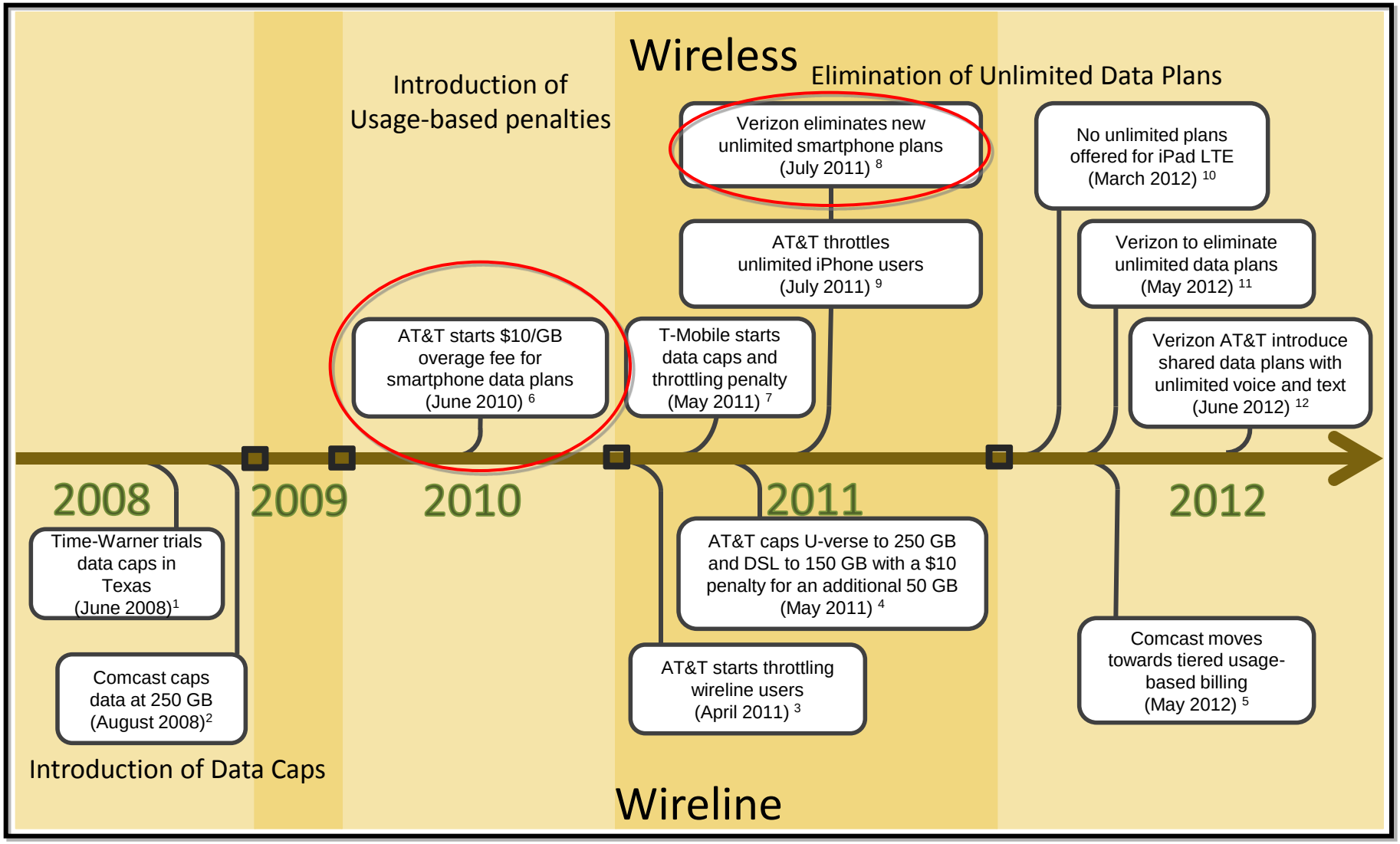
2.4 billion mobile users worldwide, 260 million US mobile data users by 2017

Driving Forces

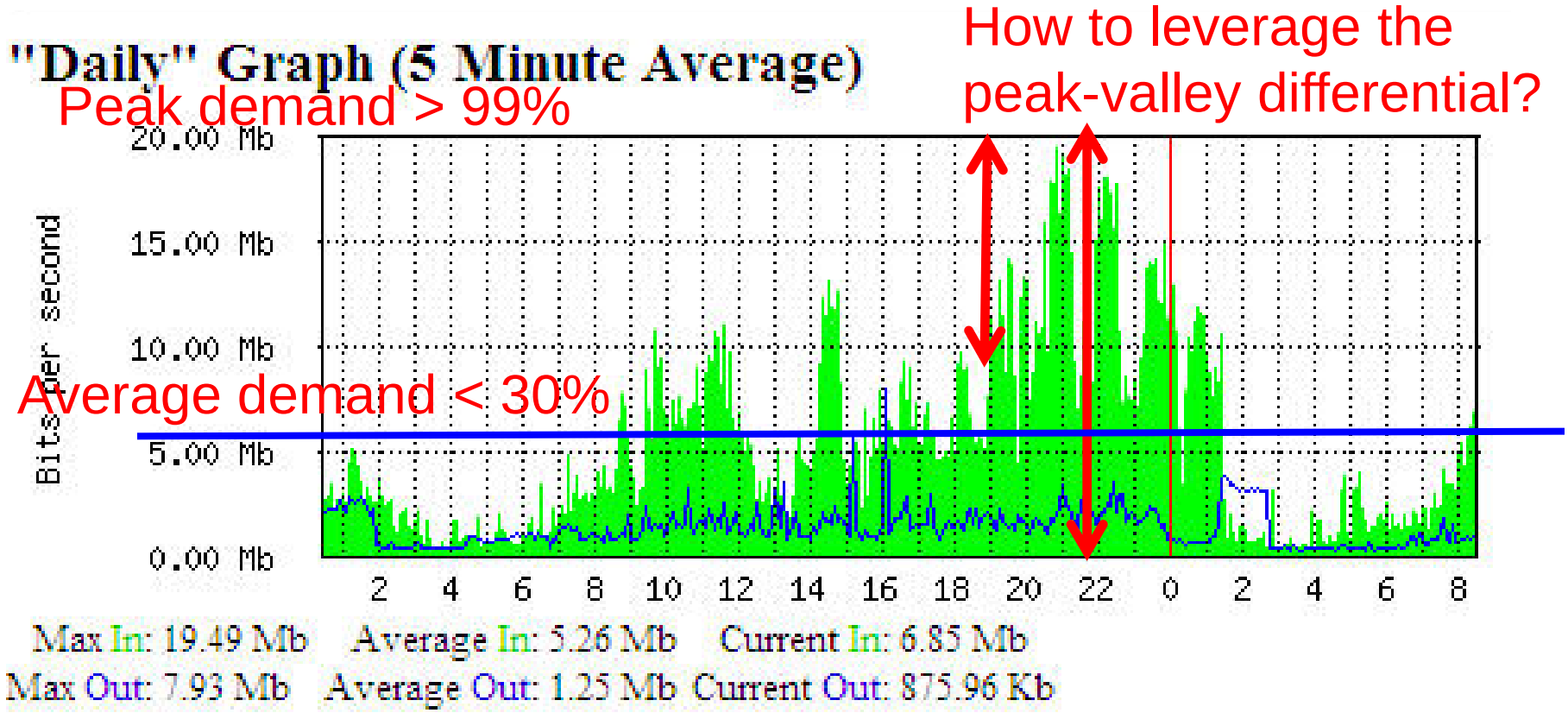


Mobile Video | Cloud Sync | Data-hungry Apps | High-res Devices | A Perfect Storm

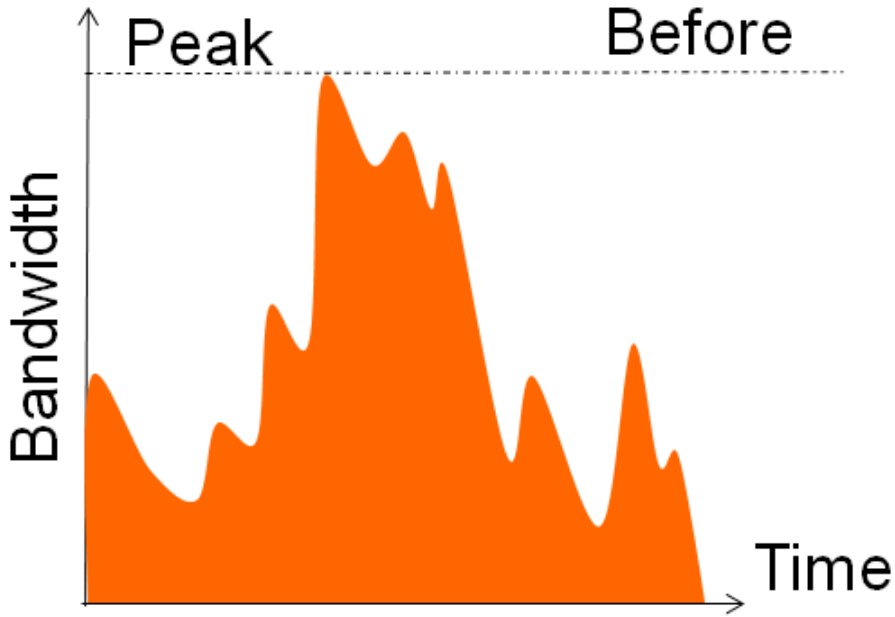
Industry Moves: US ISPs

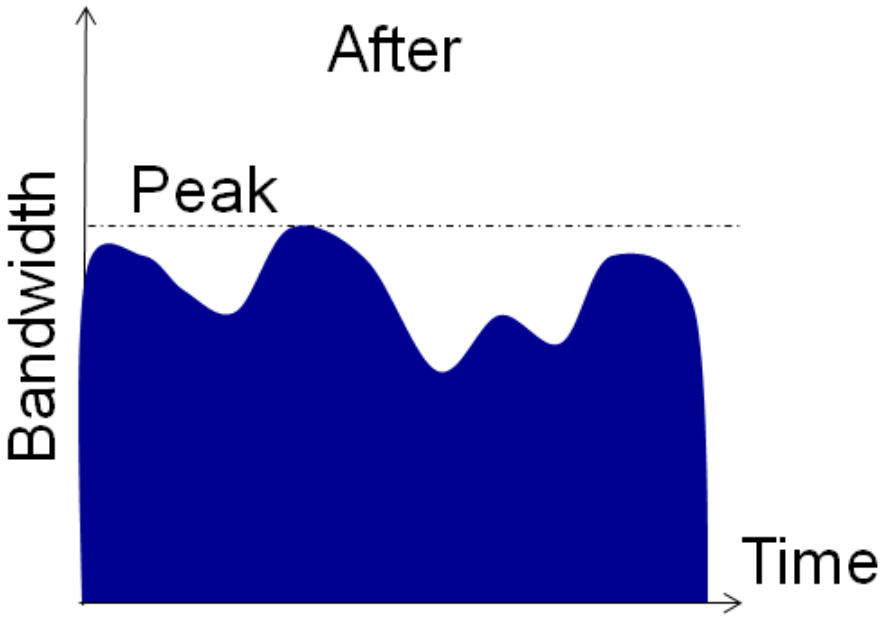


But Not Heavy All the Time



What do we ultimately want?





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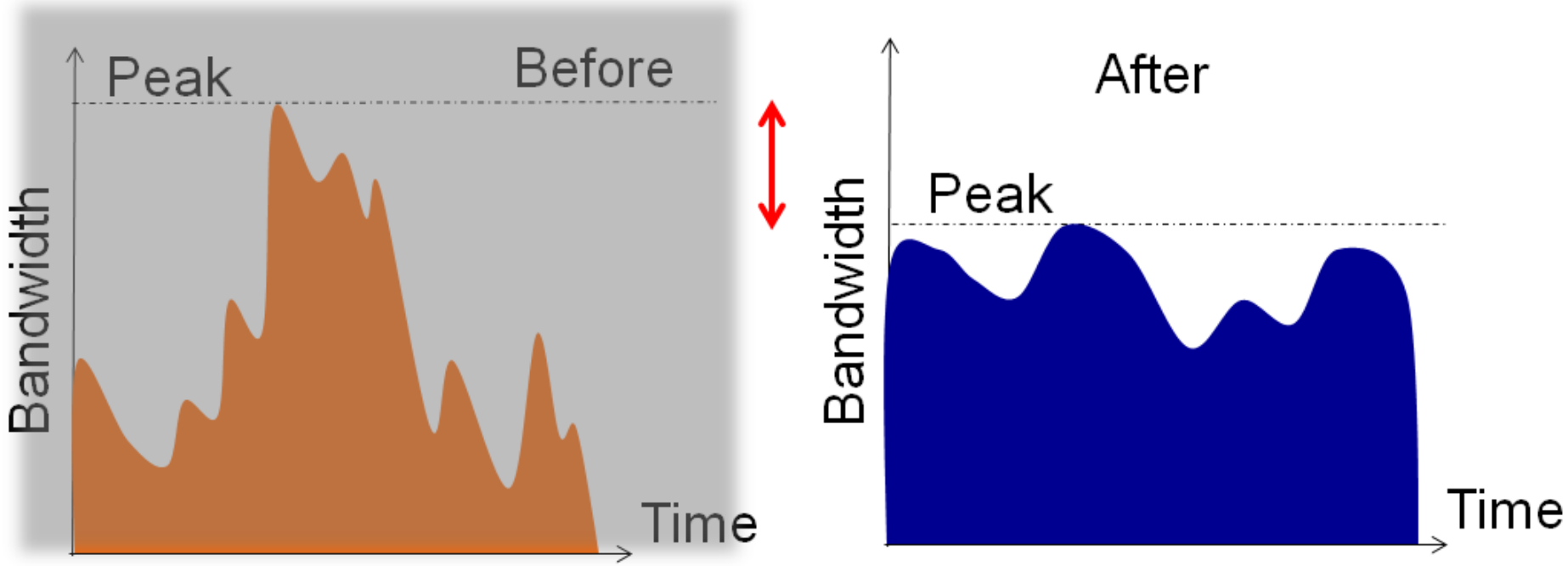
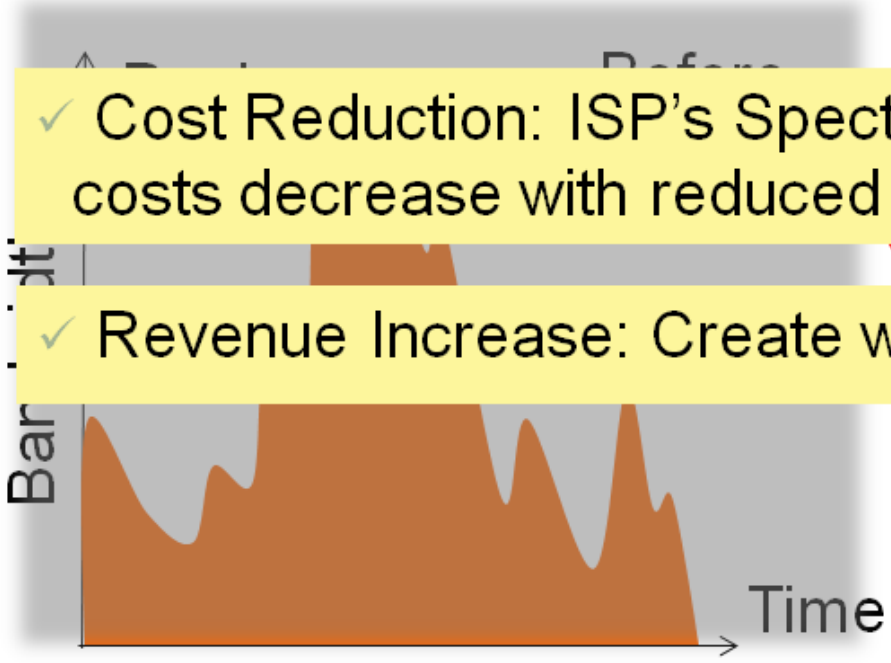
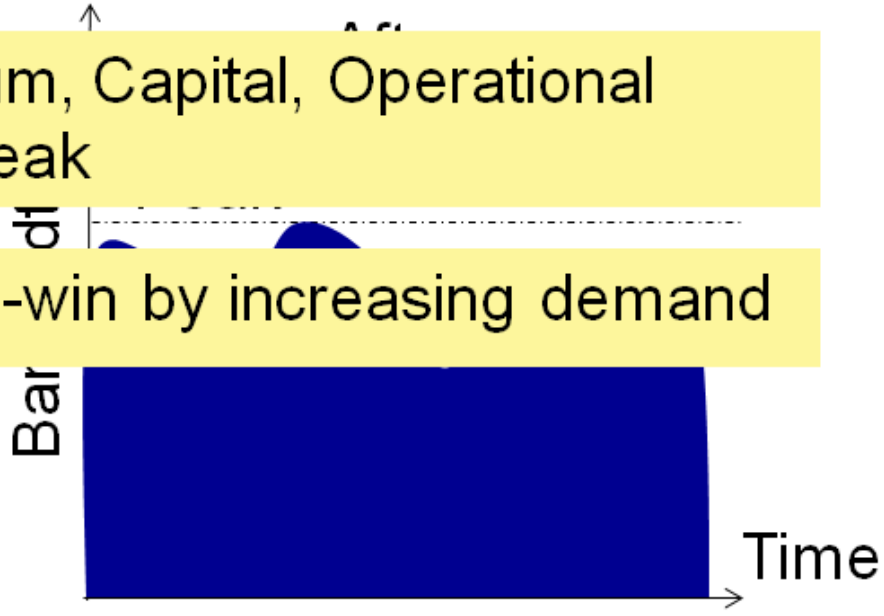


What do we ultimately want?

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

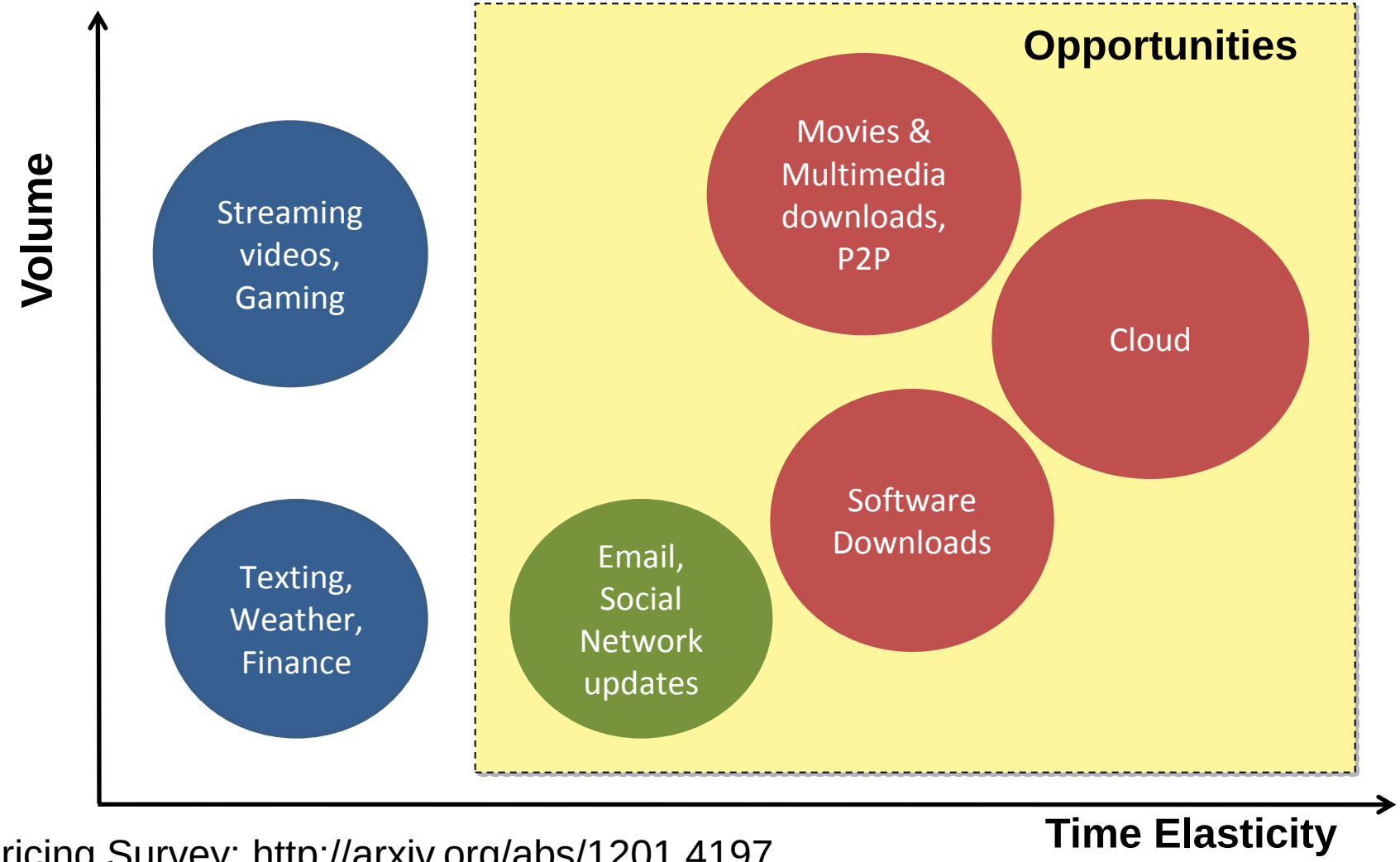


$50 for 5GB



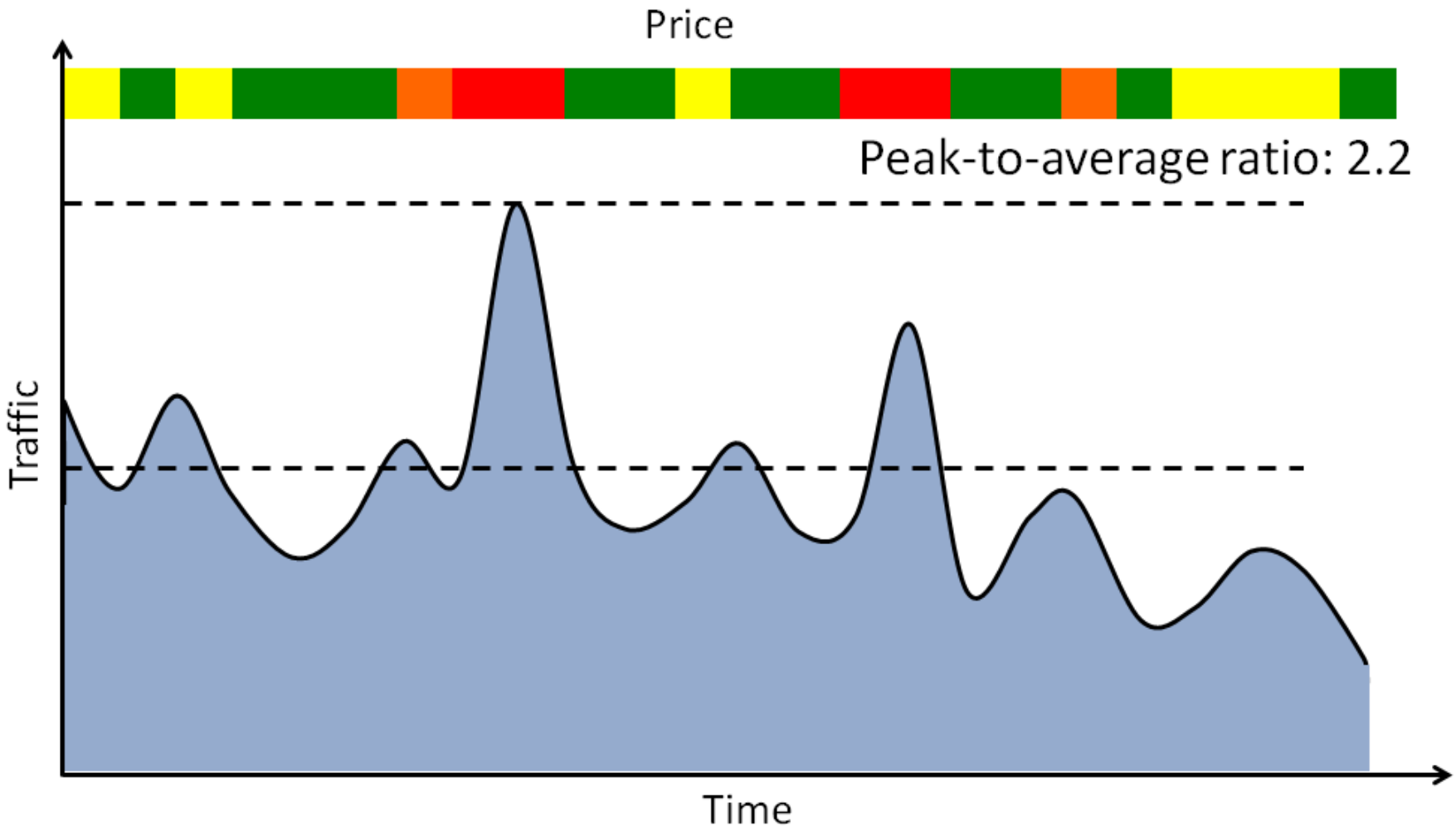
$60 for 10GB

Time Elasticity: Opportunities



Pricing Survey: http://arxiv.org/abs/1201.4197

Time-Dependent Pricing (TDP)



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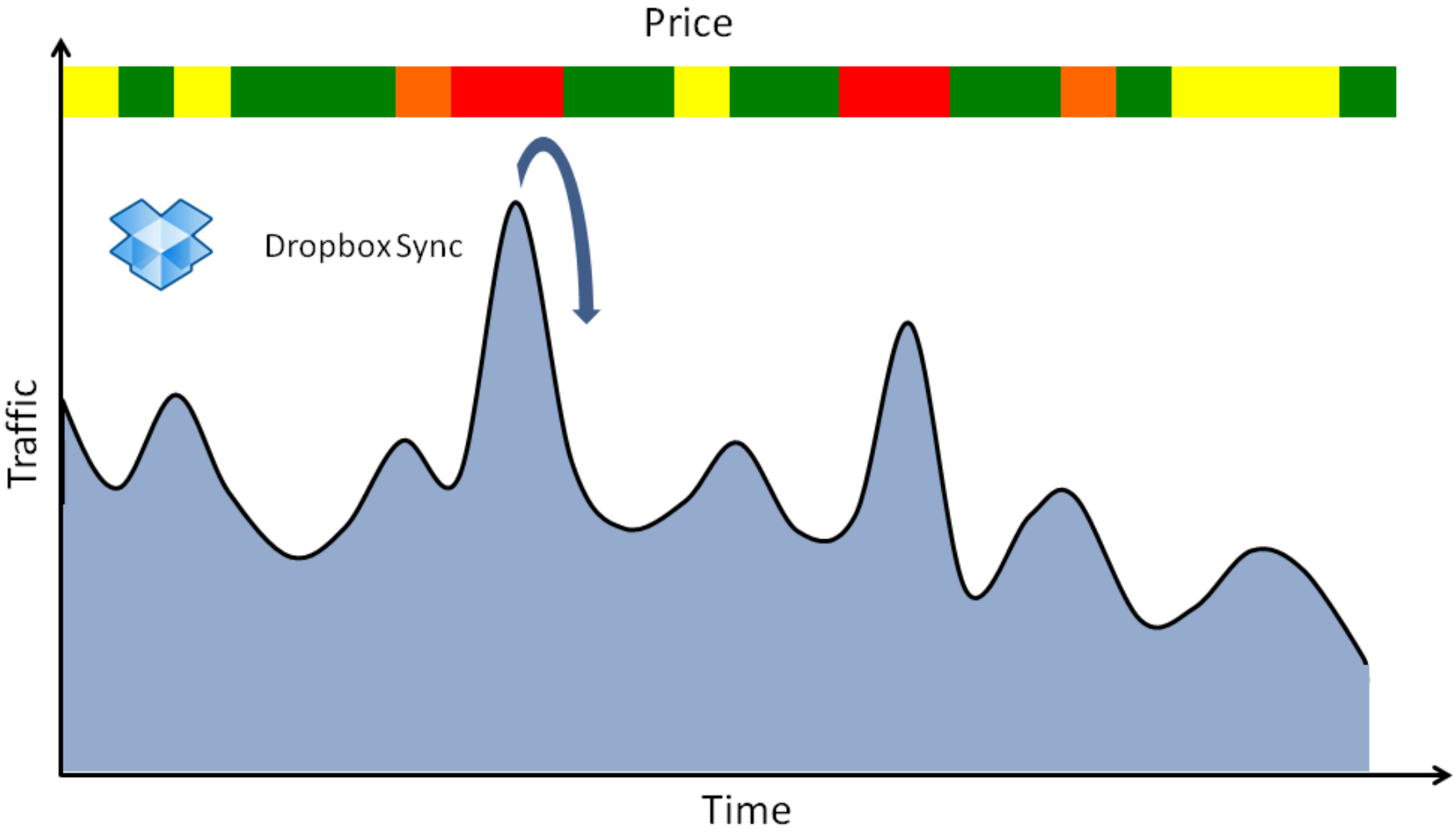

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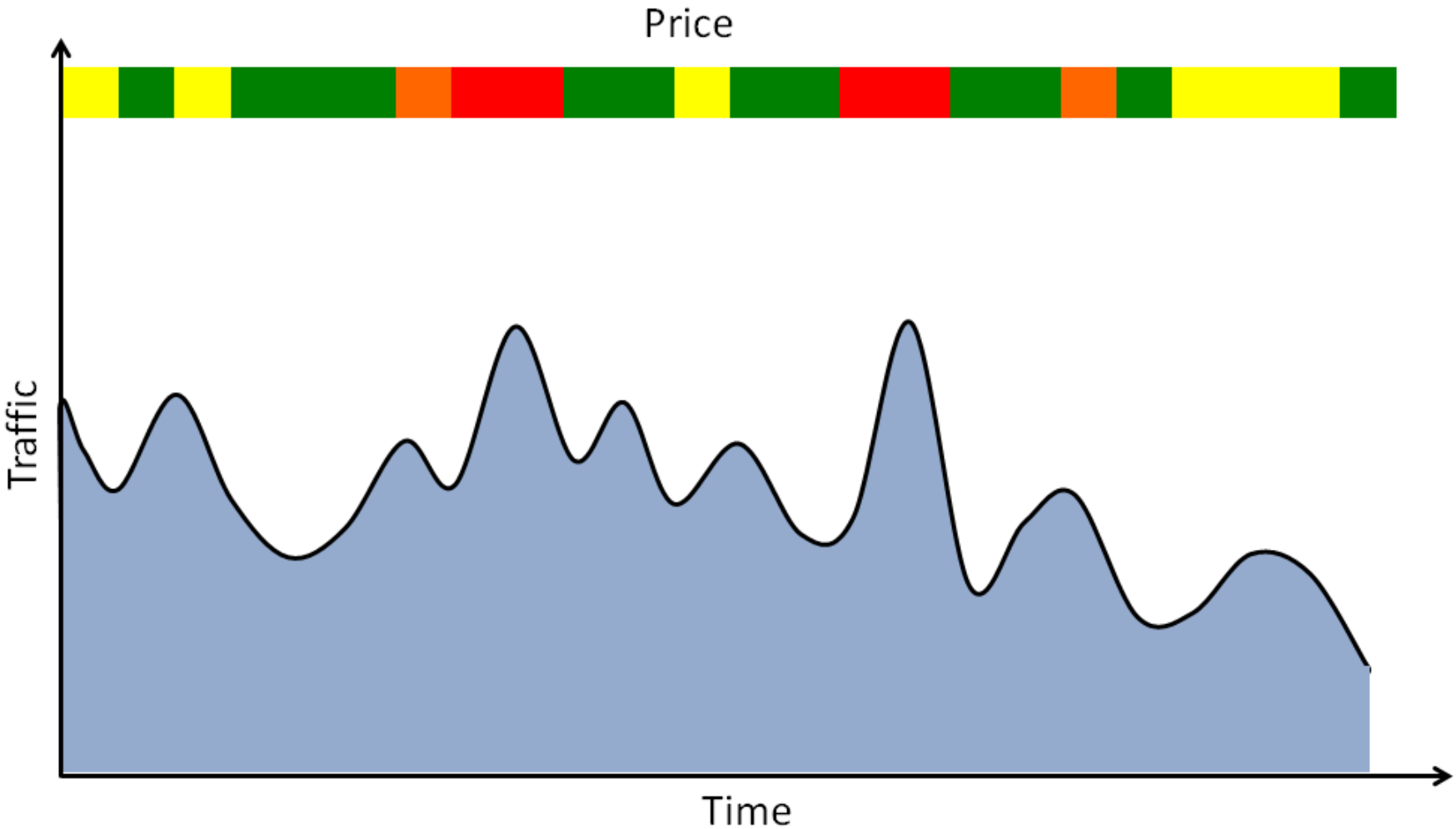

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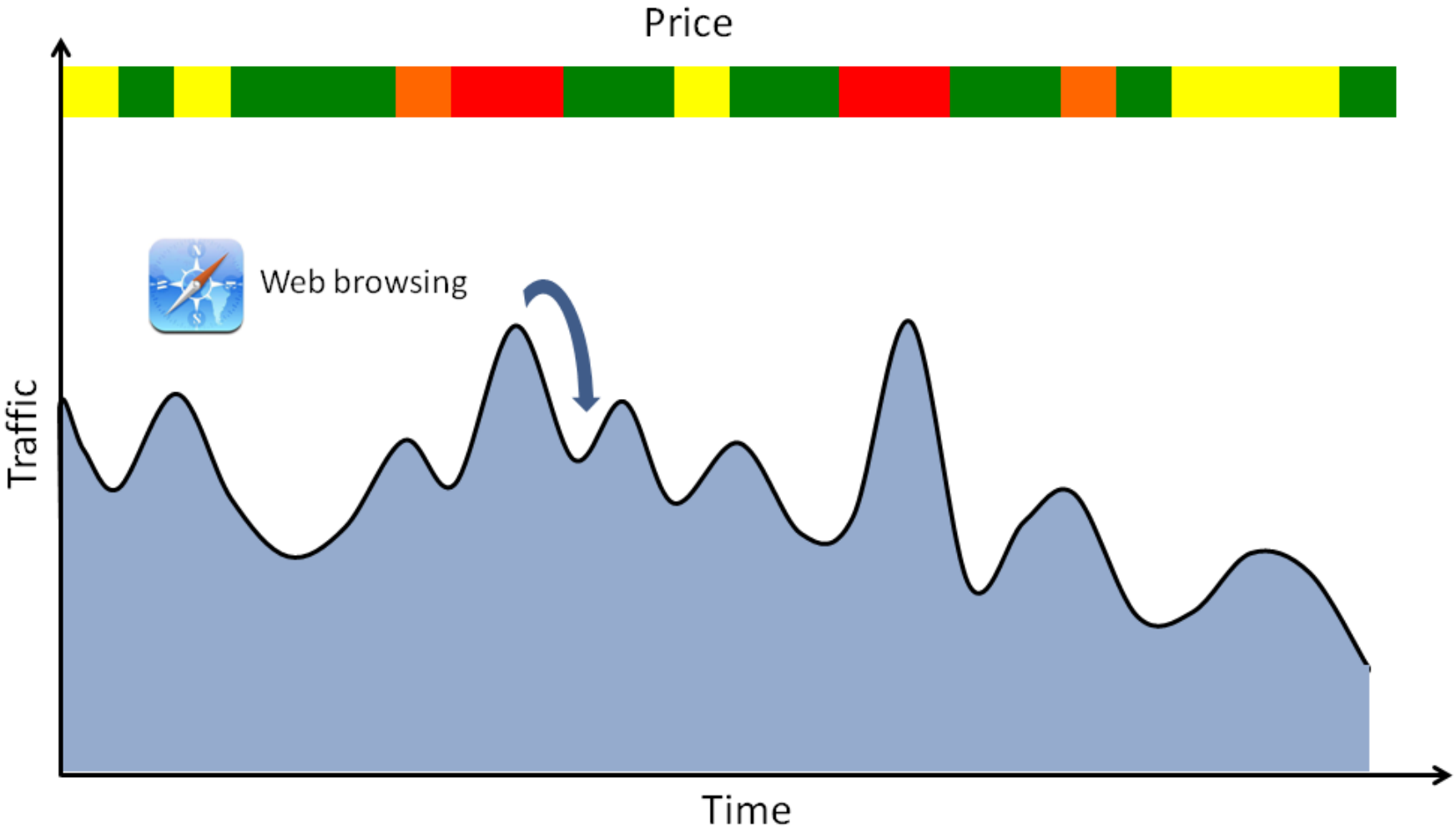

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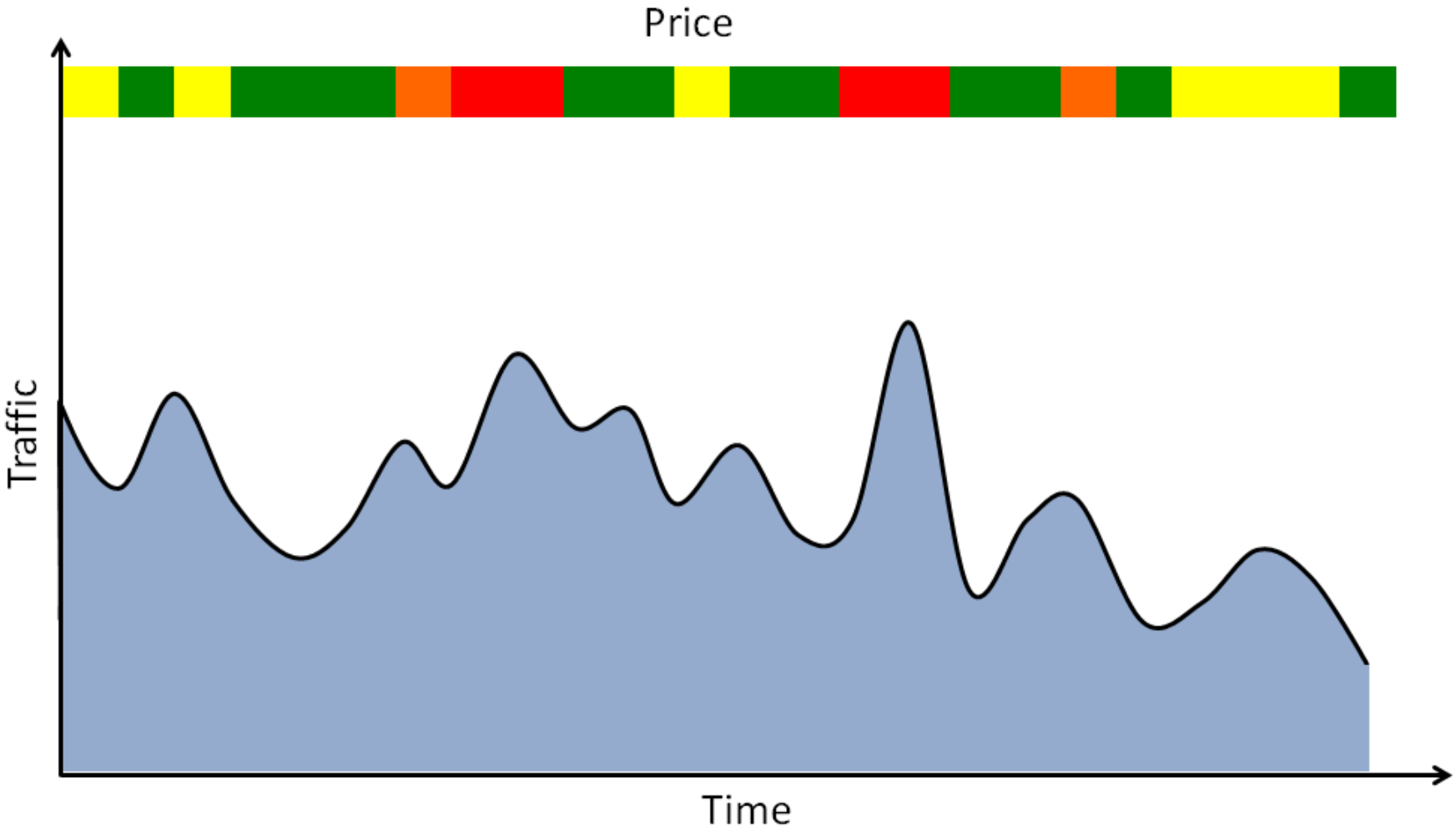

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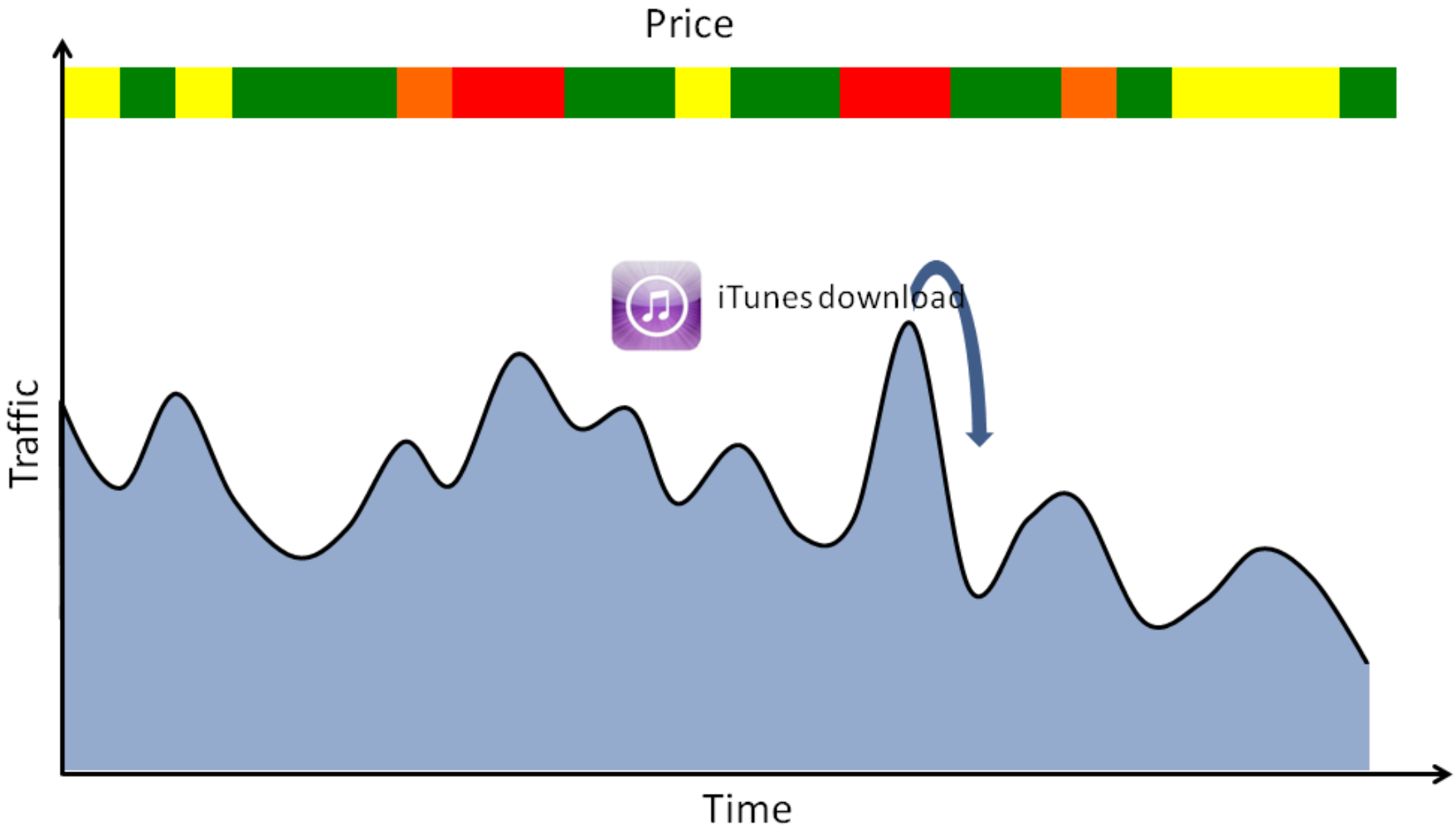

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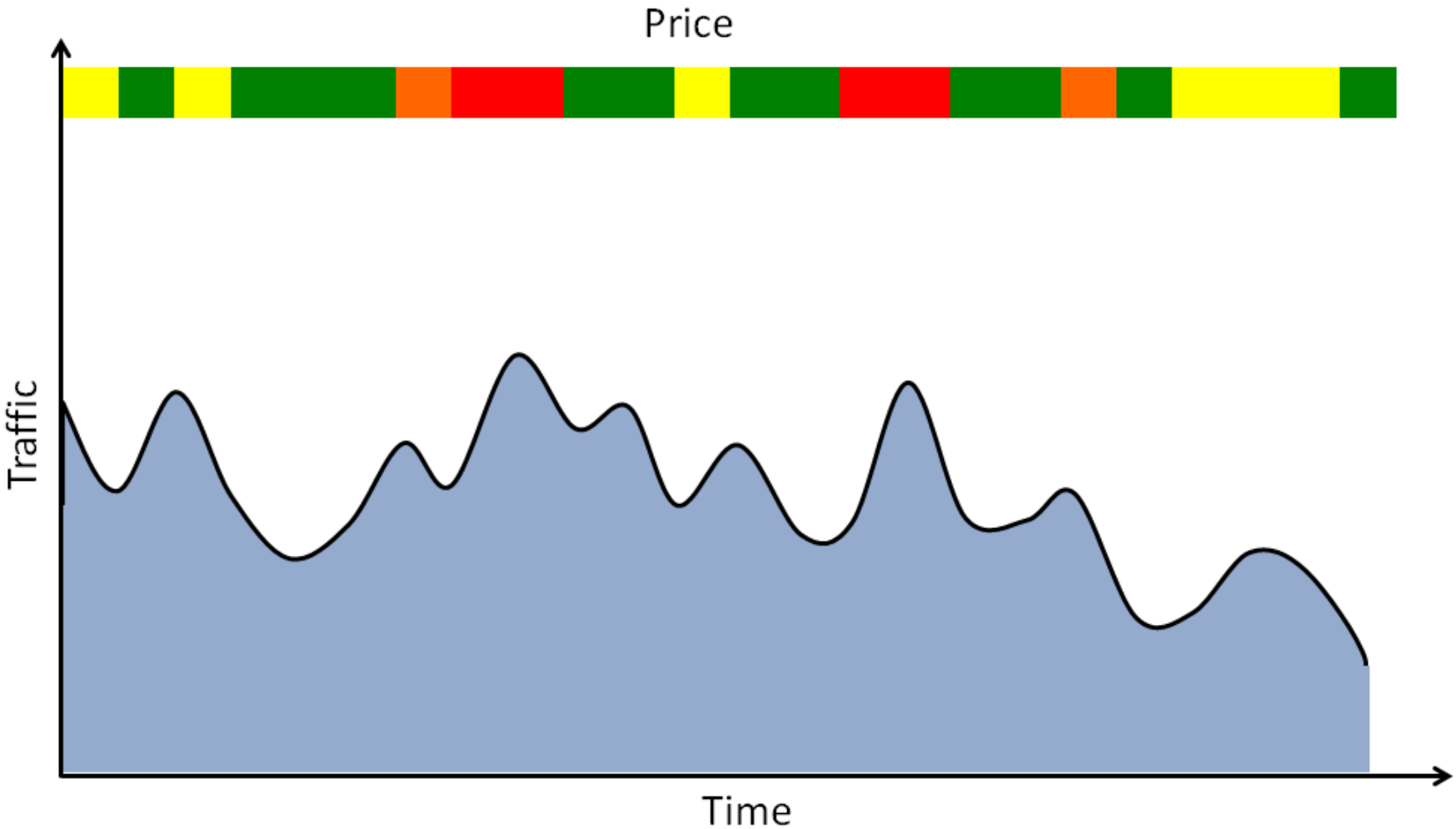

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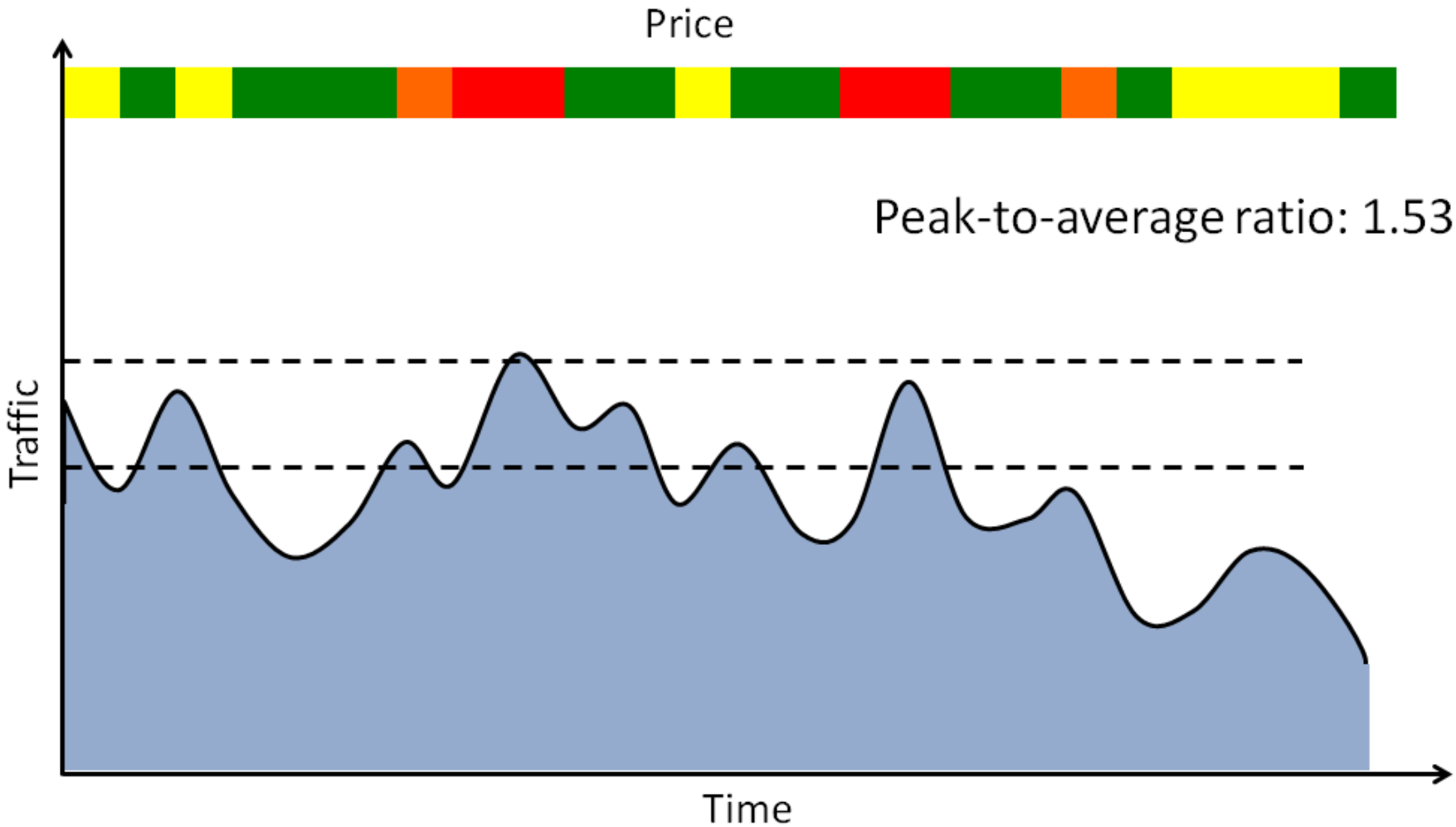

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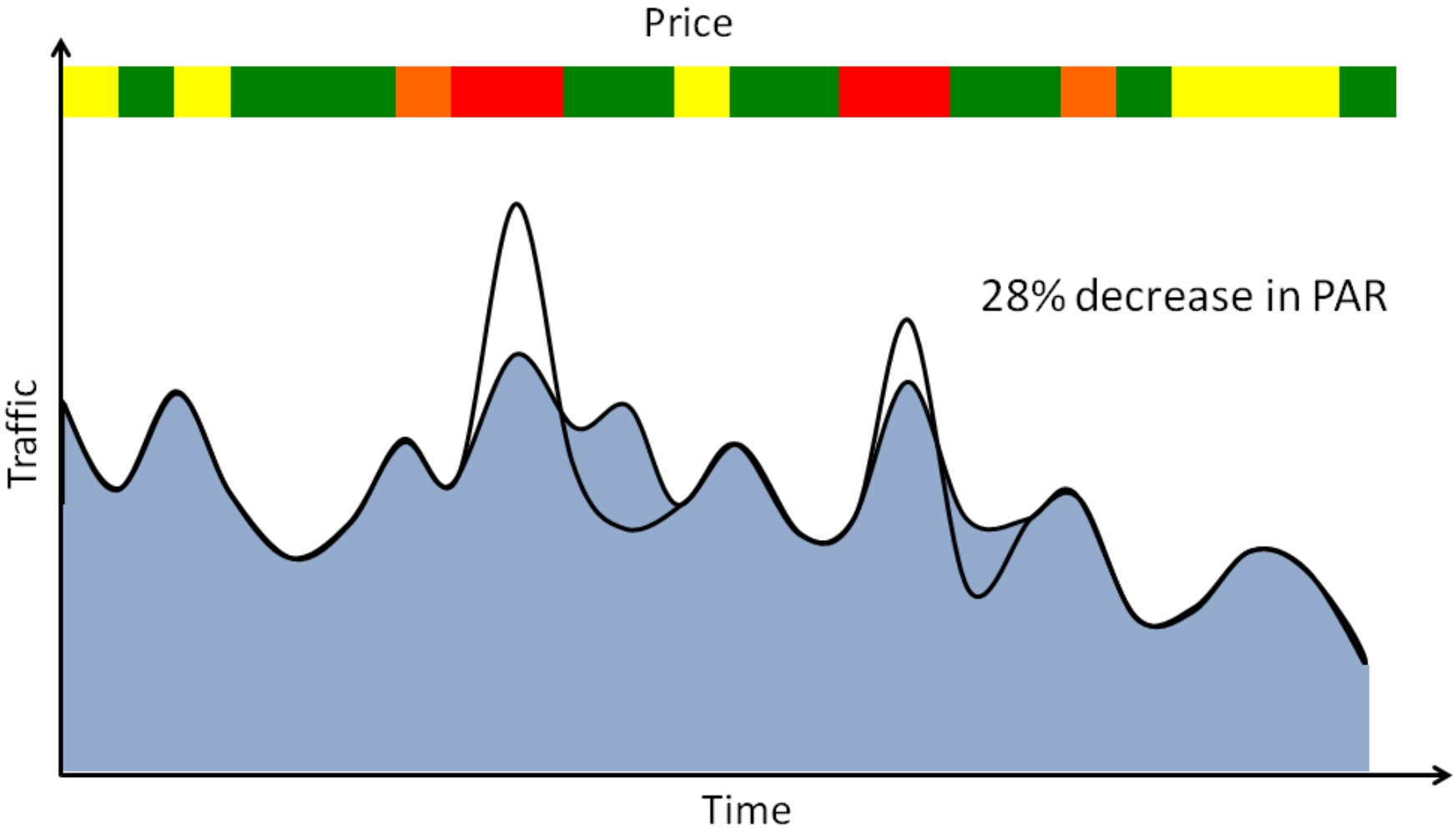


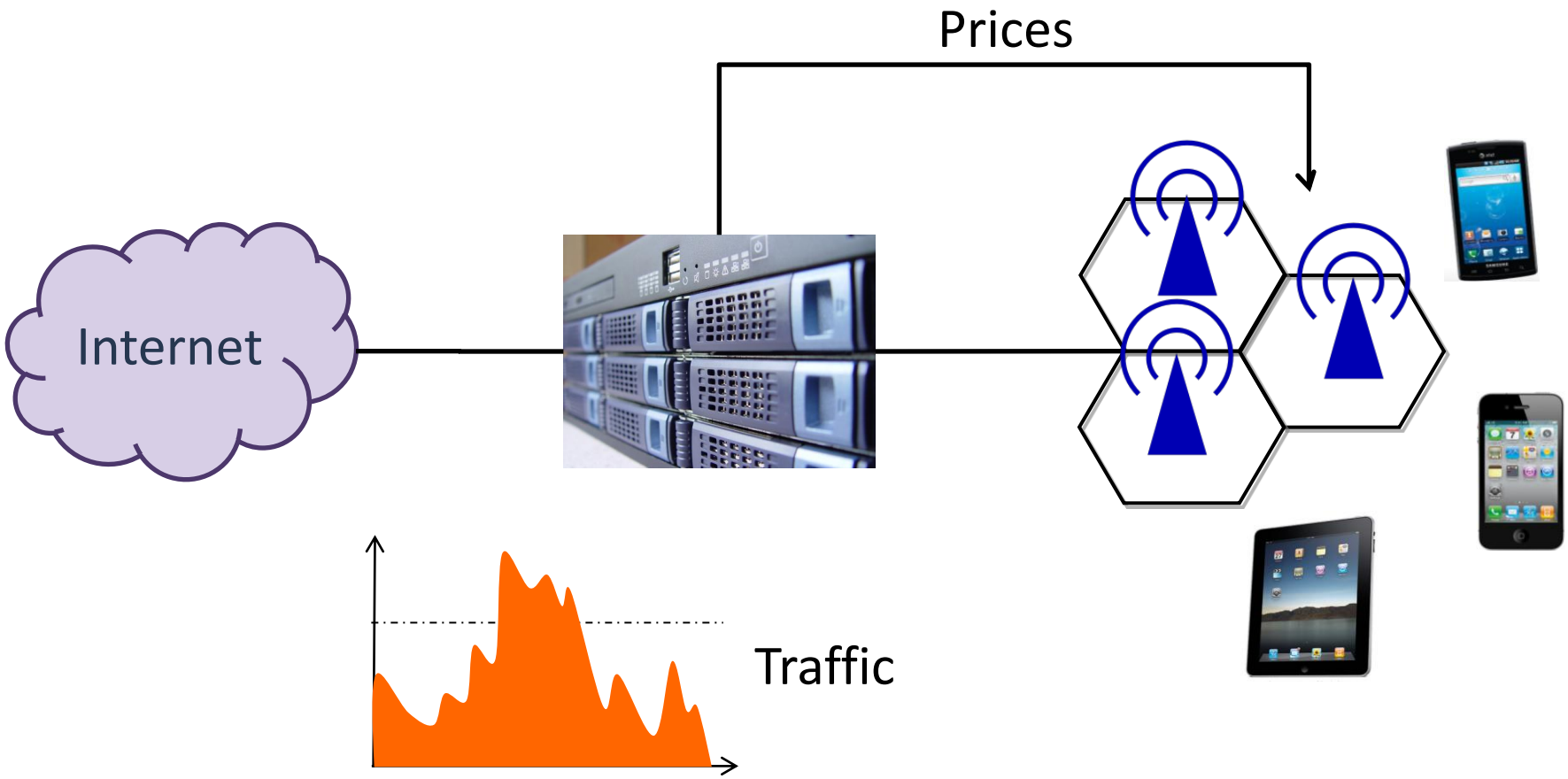
Contributions

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

1. **User behavior models and optimized price computation**

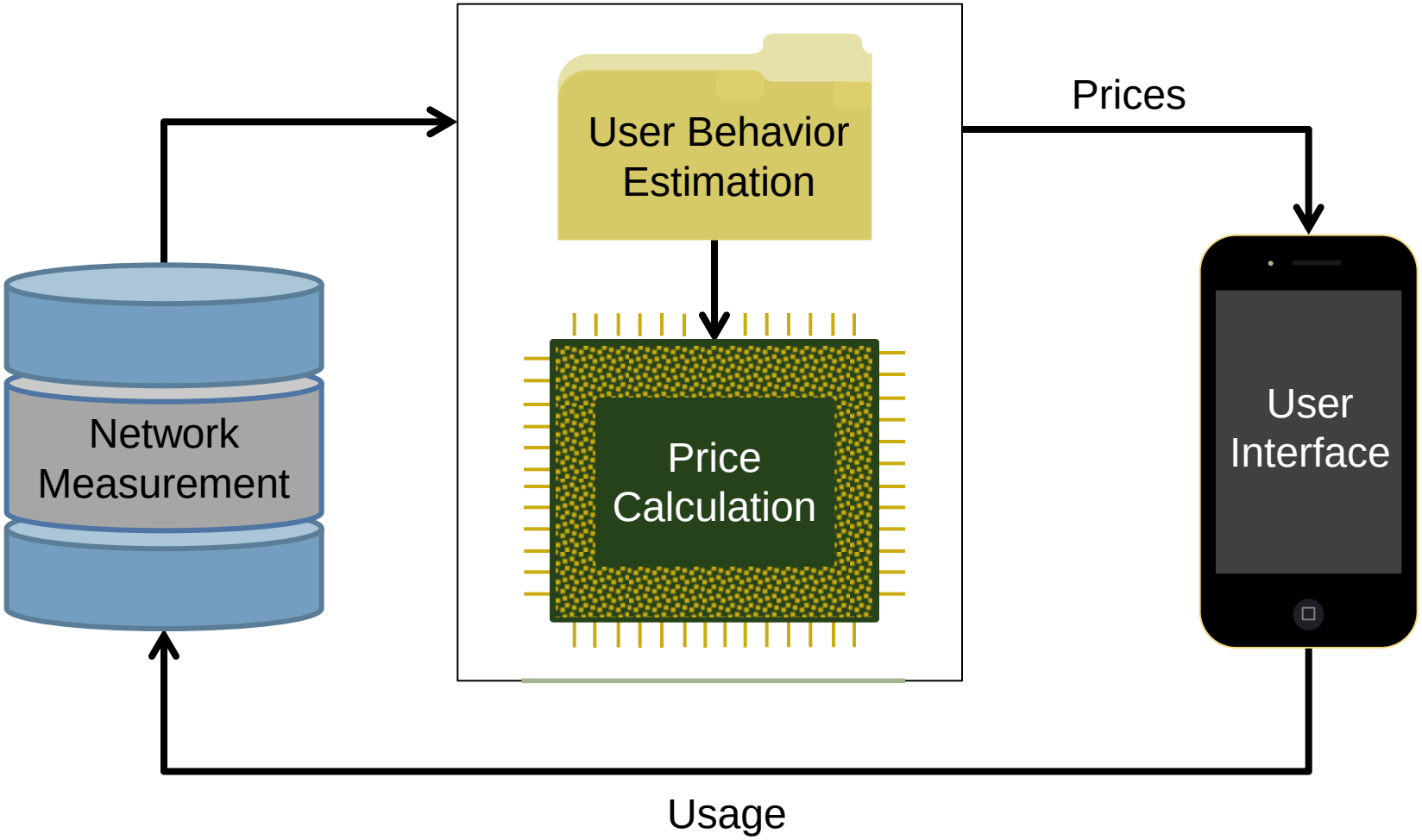
1. **A realistic evaluation with real users**

TDP Overview



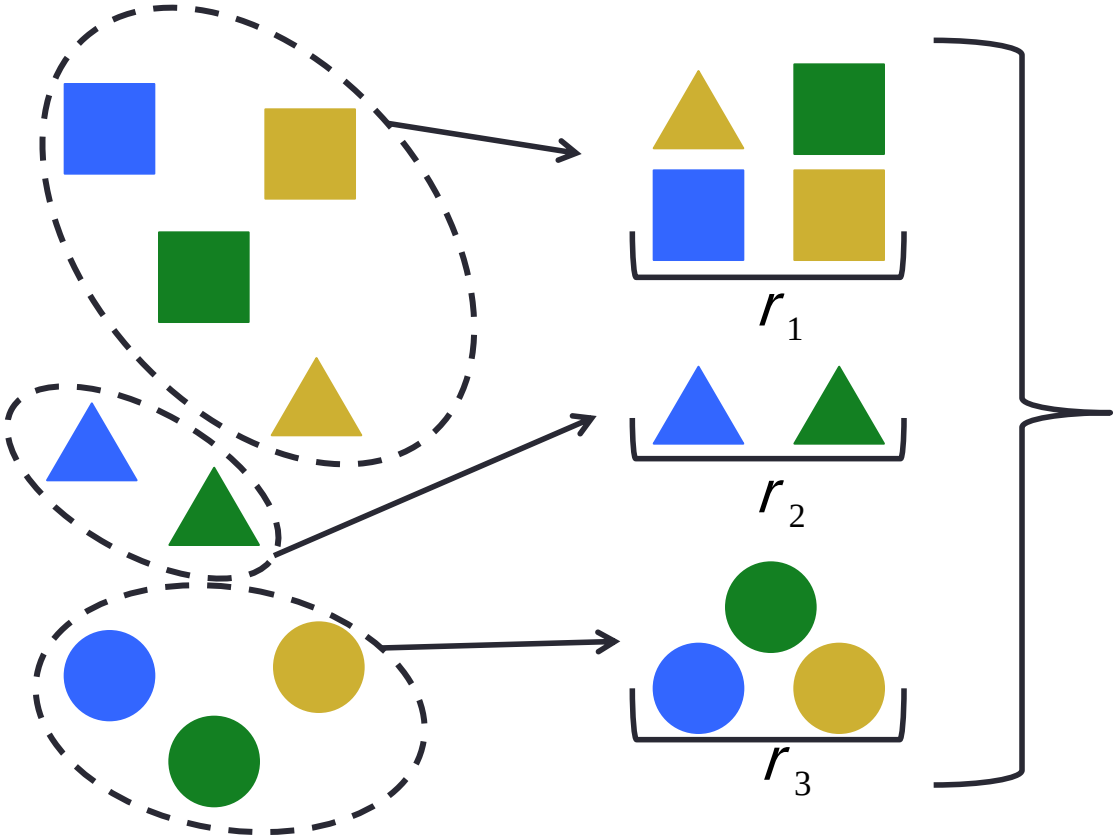
TUBE Theory

Feedback Loop



Waiting Functions

- Probabilistically estimate "willingness" to wait w



r = impatience

Estimate parameters

$$m_1 w_{r_1} + m_2 w_{r_2} + m_3 w_{r_3}$$

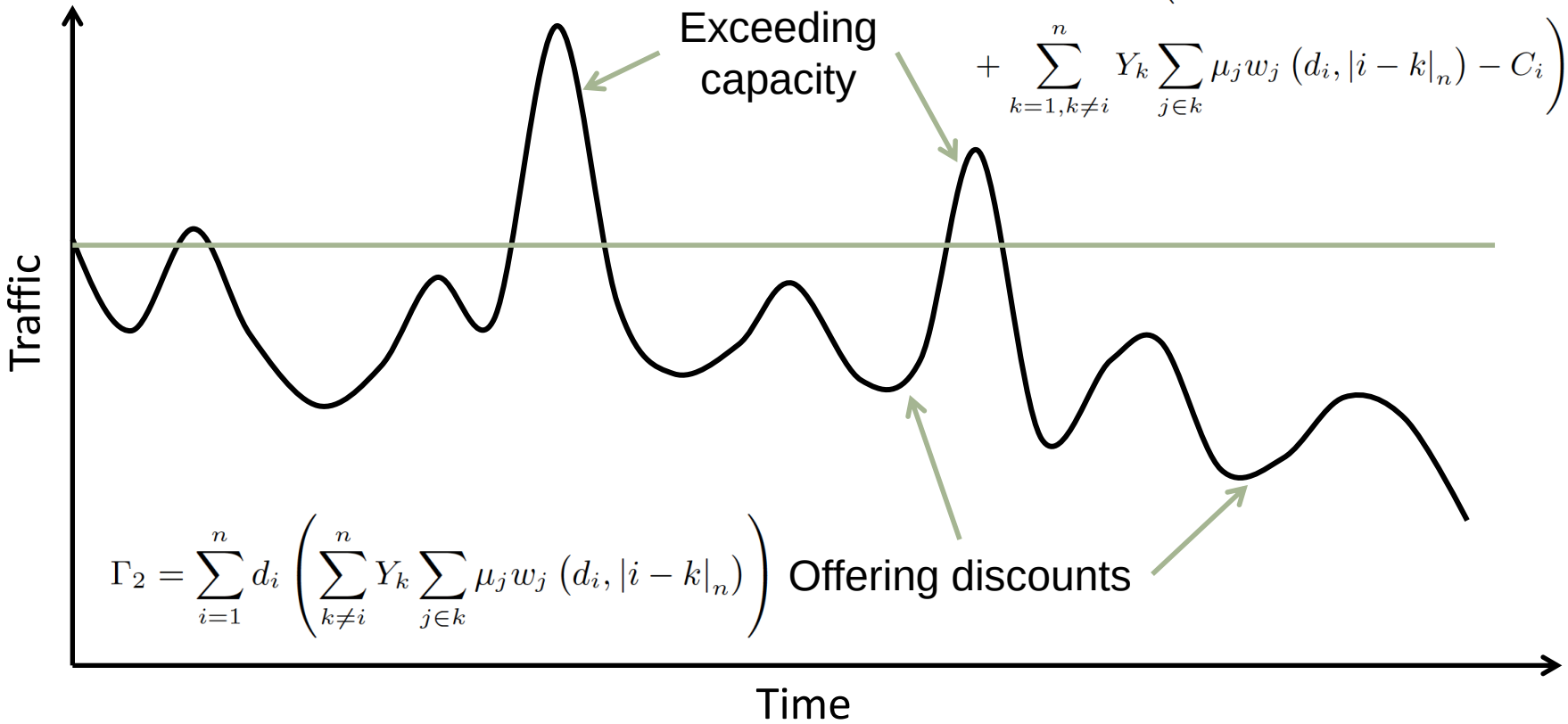
discount

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

time waited

Minimizing Cost

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

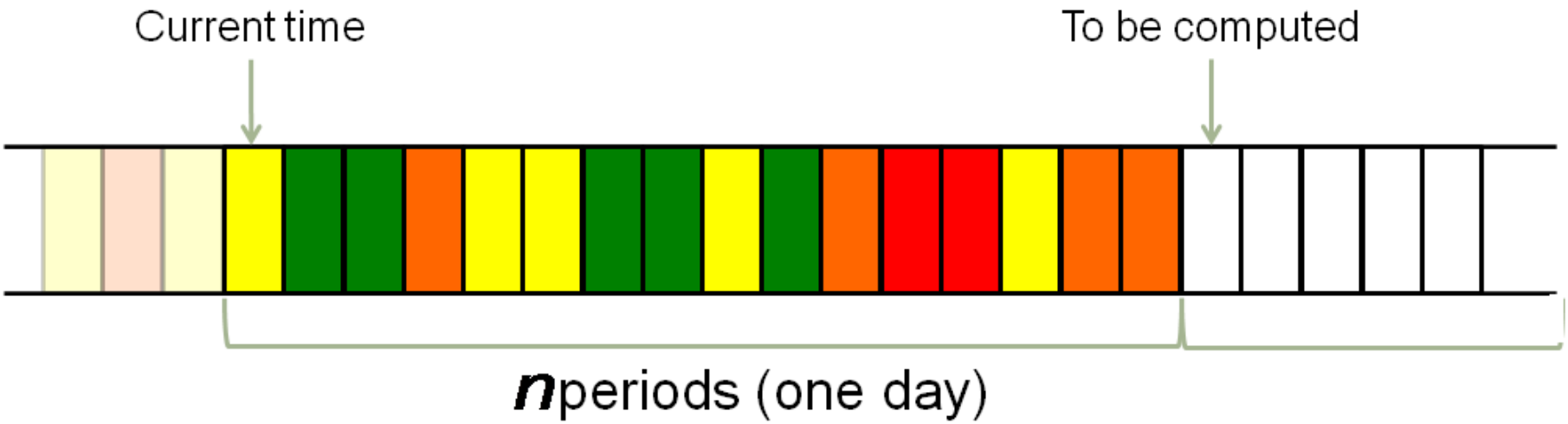


$$\Gamma_2 = \sum_{i=1}^{n} d_i \left(\sum_{k \neq i}^{n} Y_k \sum_{j \in k} \mu_j w_j \left(d_i, |i-k|_n \right) \right)$$

minimize $G_1 + G_2$ variables d_i

Day-Ahead Pricing

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



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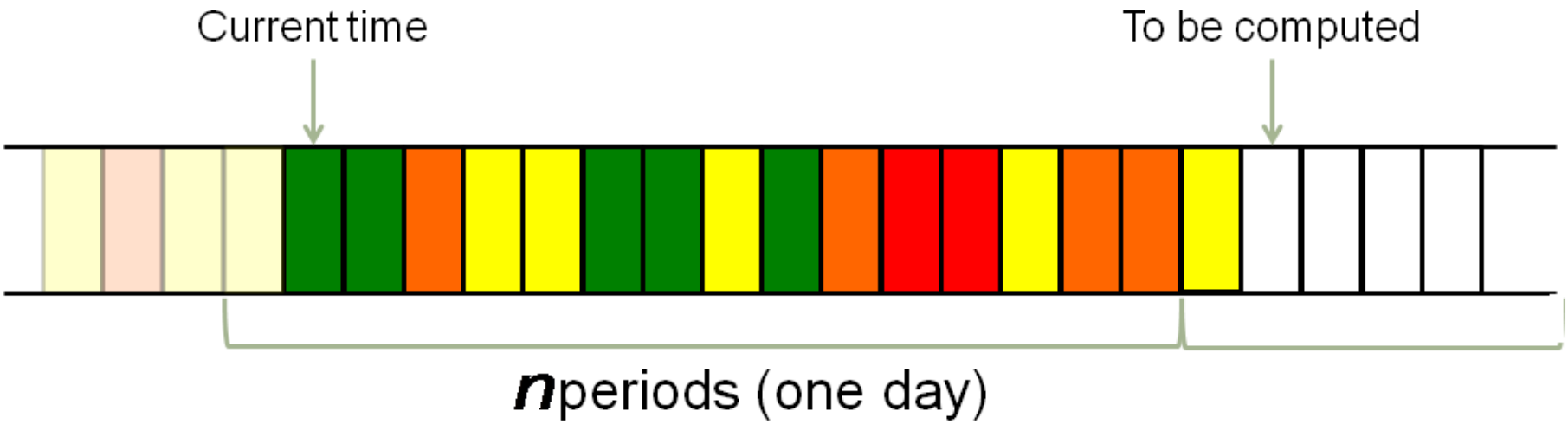

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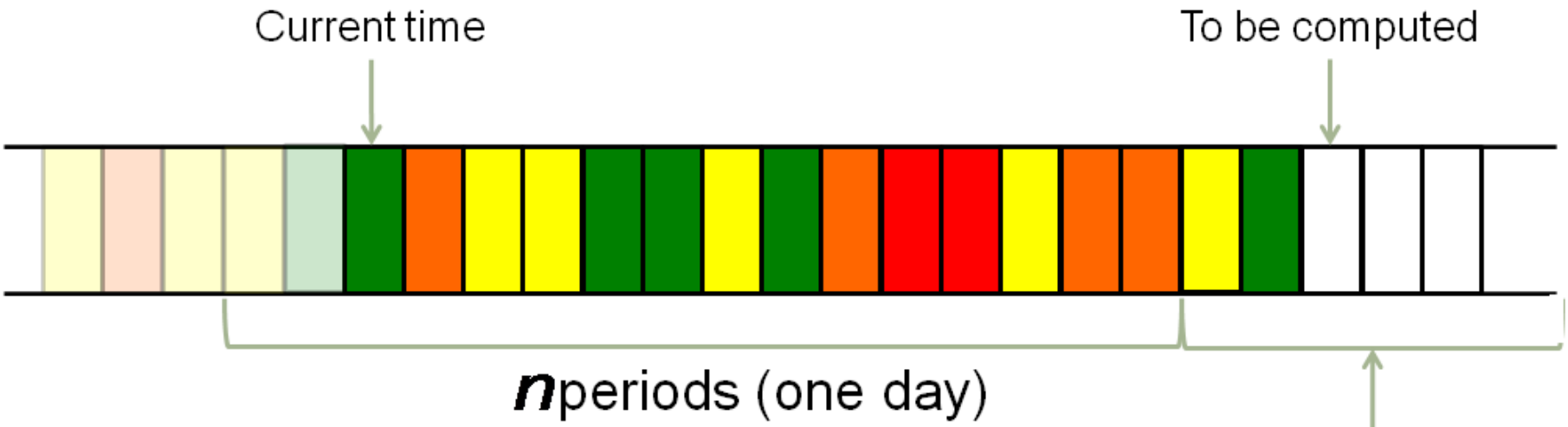


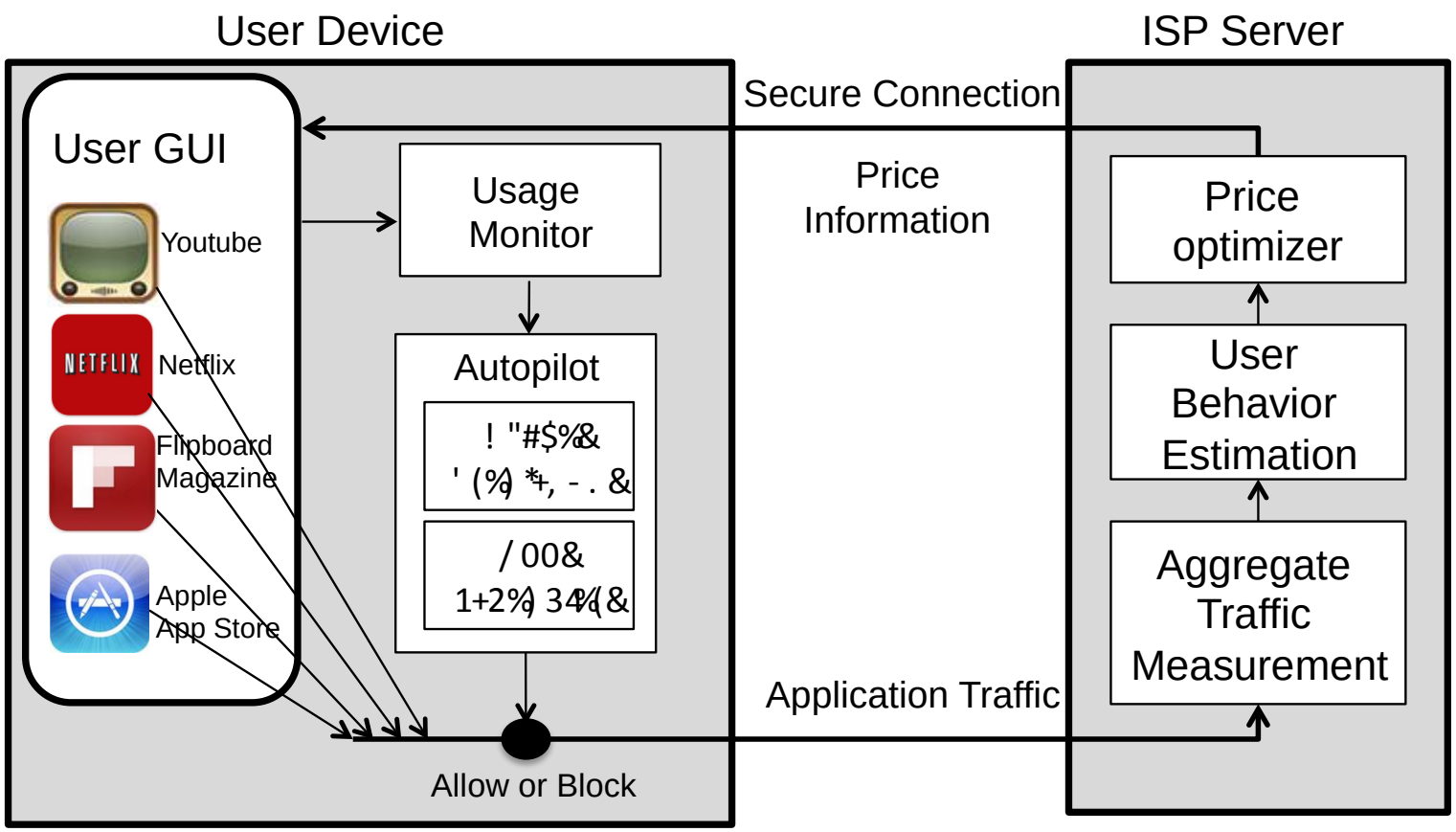
- Update waiting function parameters once a day

TUBE Architecture

Design Guidelines

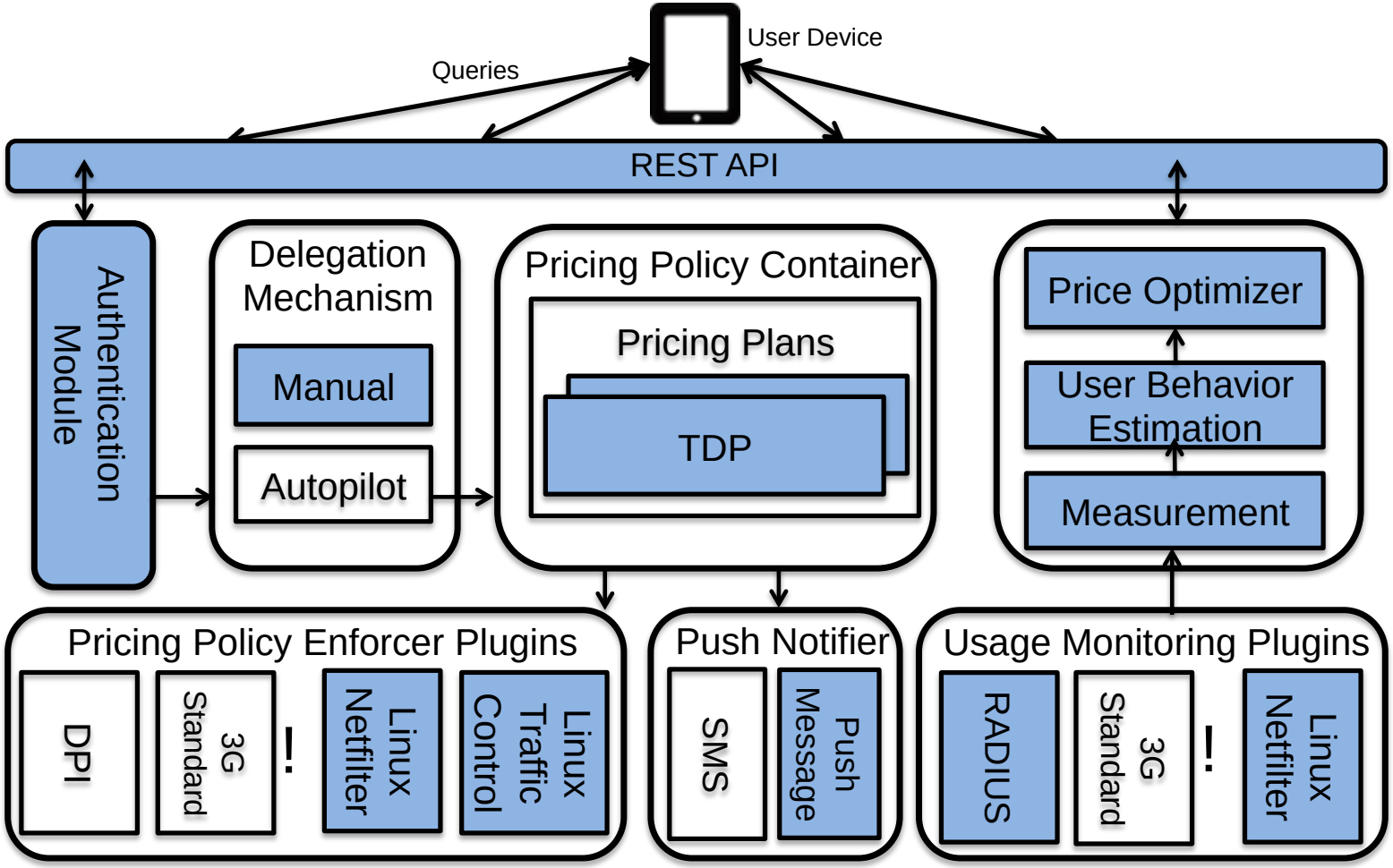
1. **Separating functionality**
   - Price computation on a central server
   - Price display and scheduling the usage on the user devices
2. **Scaling up the system**
   - User behavior estimation algorithm requires only aggregate, not individual usage data
   - Formulate the price calculation as a 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

Number of TDP periods

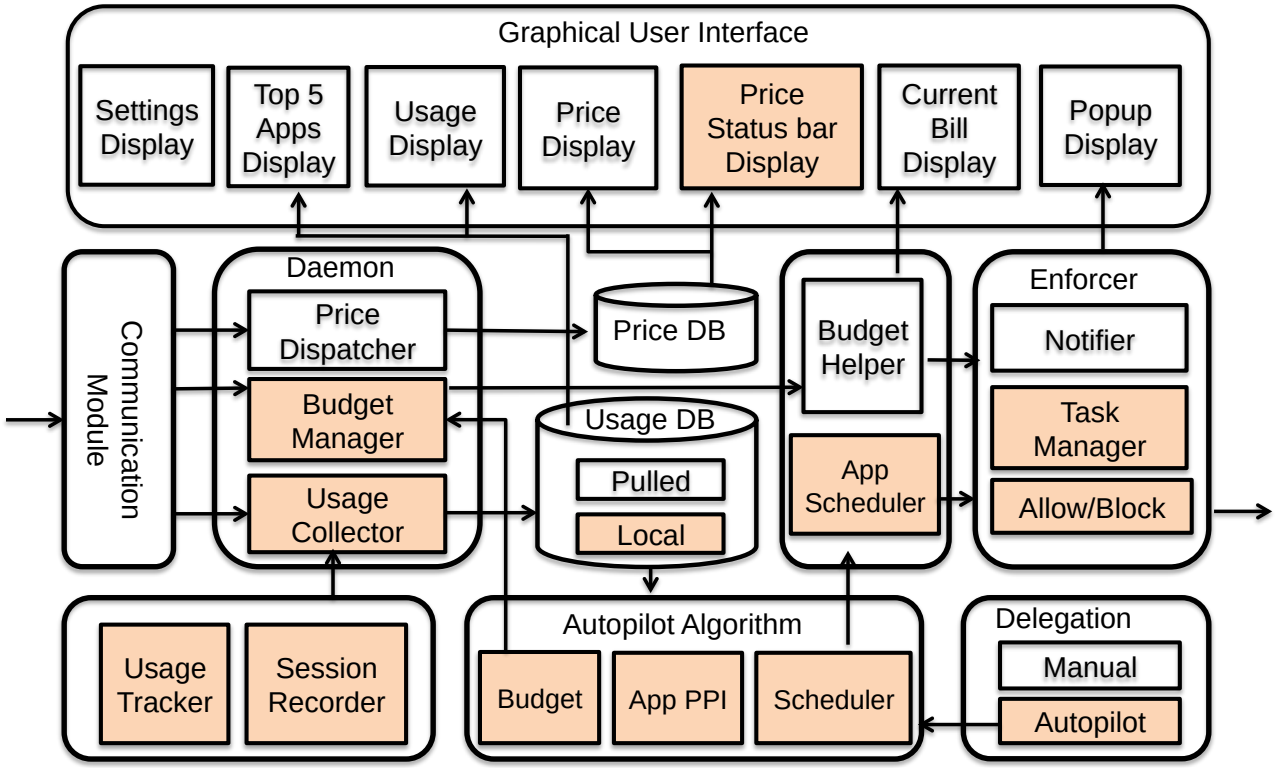
Number of Periods	12	24	48	96	144
Behavior Estimation (sec)	12.76	200.0	959.6	1967	15040
Price Calculation (sec)	1.67	1.69	1.70	1.81	1.84

Number of TDP periods x Number of application types

	Number of Application Type		
Number of Periods	2	4	8
12	0.21	12.99	21.52
24	3.33	47.08	75.47
48	15.99	197.22	215.42

(mins)

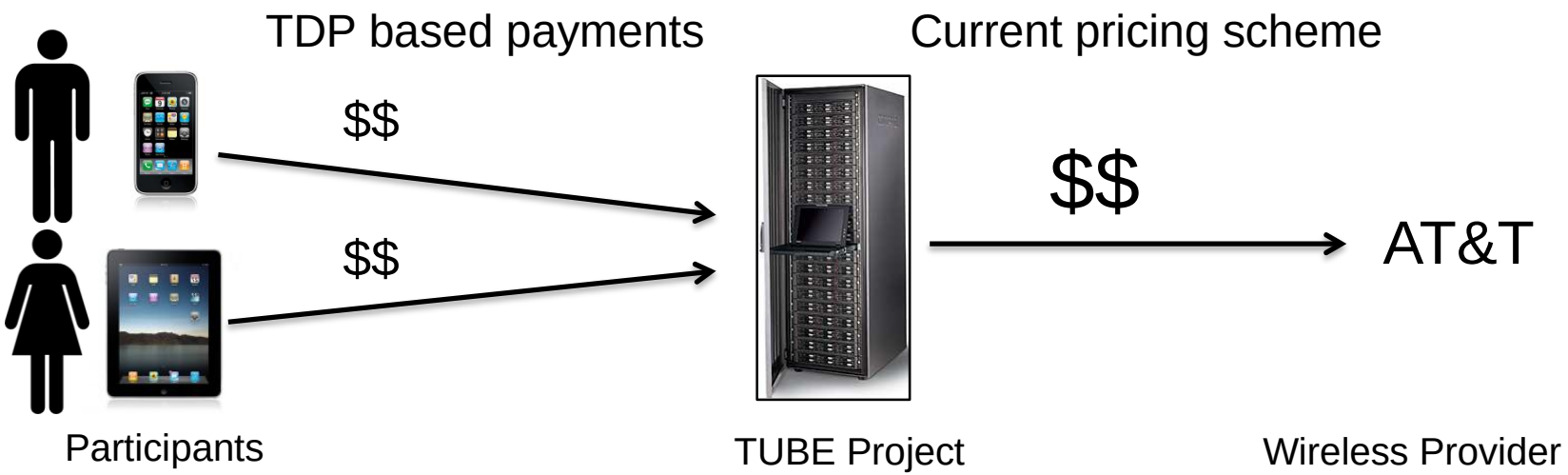
Client Side Design



Type	Status bar	App usage	Daemon Support	LOC
iPhone	No	No	Partial	25K
Android	Yes	Yes	Yes	5.4K
Windows	Yes	Yes	Yes	5.3K

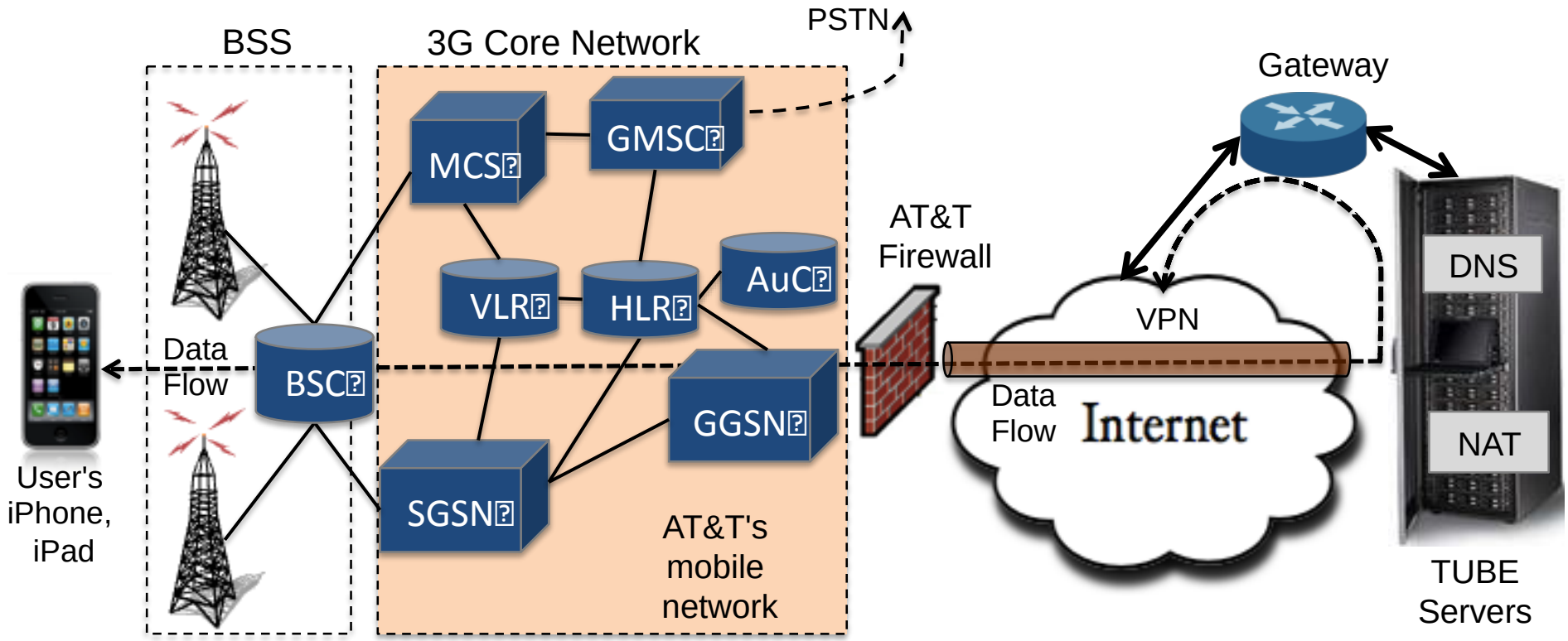
TUBE Princeton Trial

Princeton Trial: Money Flow

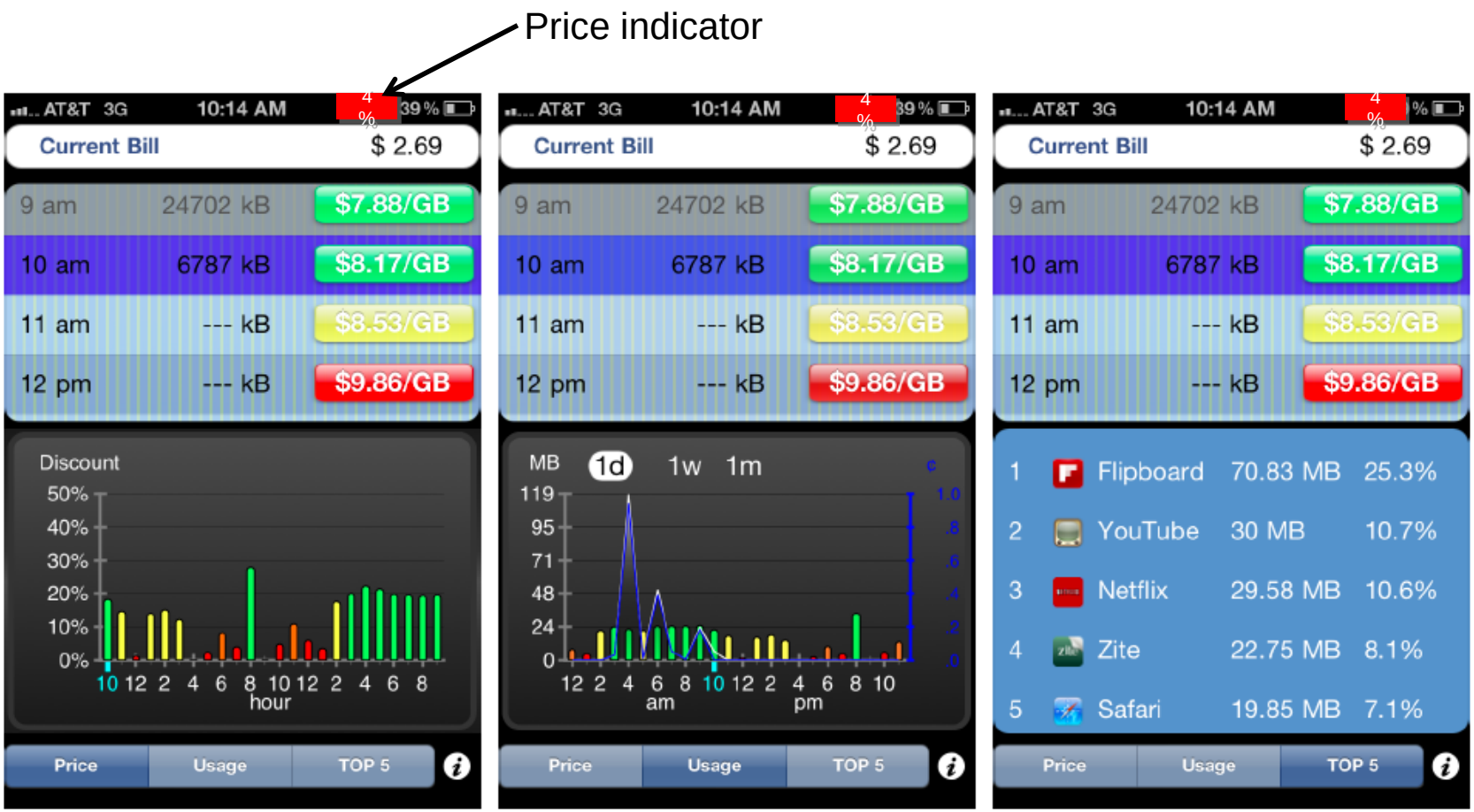


- 50 AT&T participants: 27 iPhones, 23 iPads
- Faculty, staff, and students
- 14 Academic Departments & Divisions

Princeton Trial: Data Flow

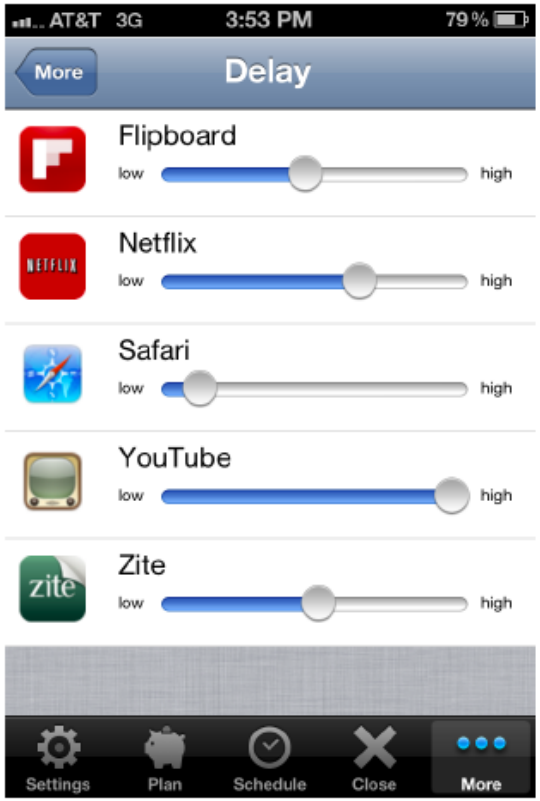


TUBE App: Information Screens

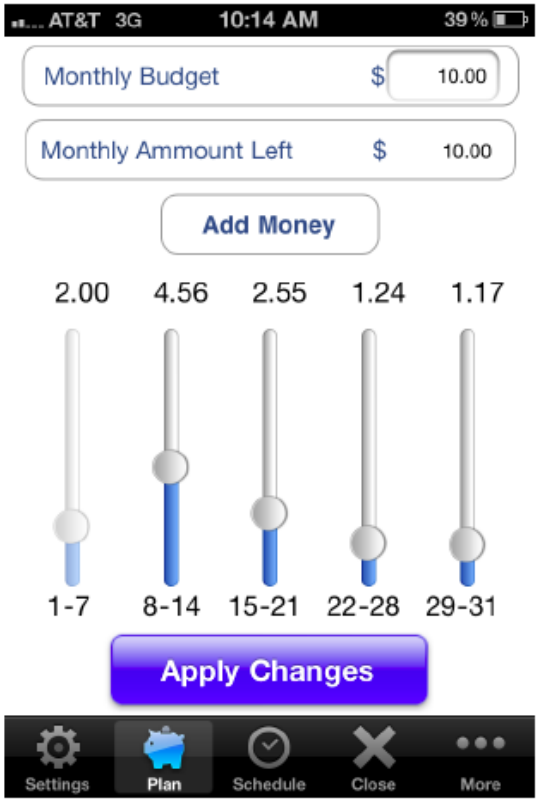


(a) Price display. (b) Usage history. (c) Top five apps.

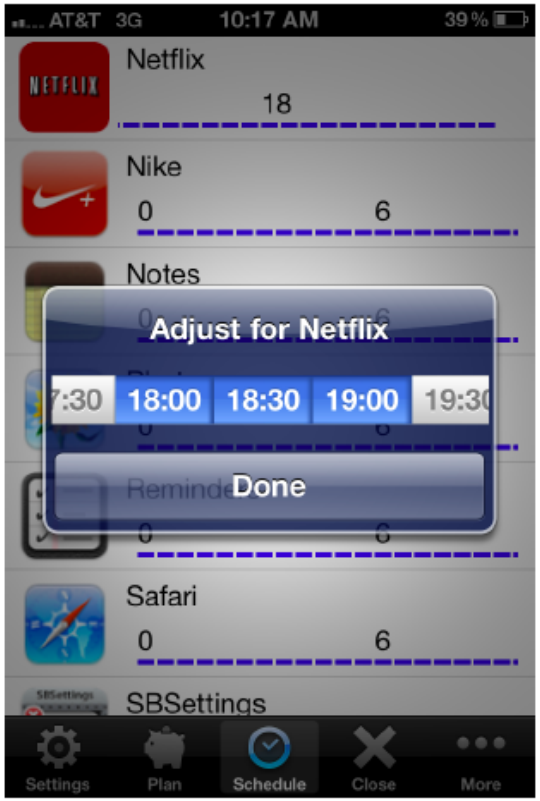
TUBE App: Scheduling Screens



(d) Delay indices.



(e) Budget.



(f) Scheduling.

Princeton Trial Results

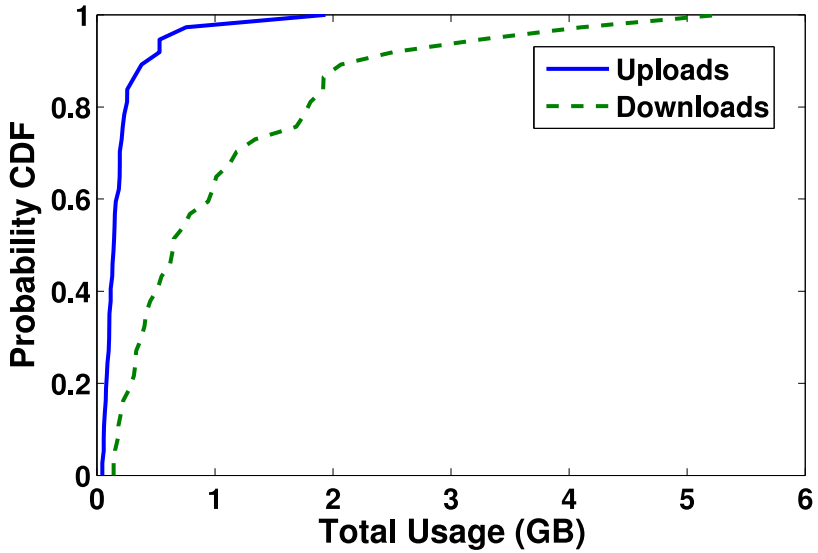
Two main goals of the trial

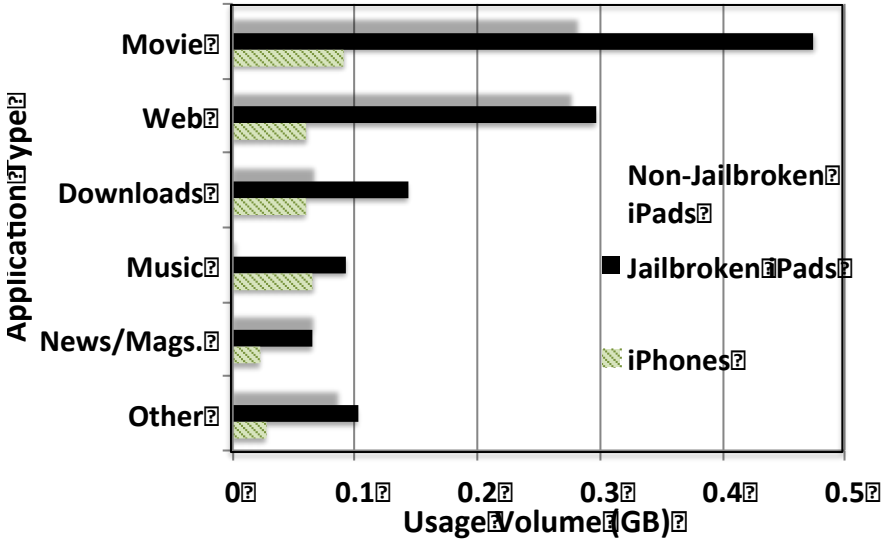
1. **How do people respond to pricing changes and GUI design?**

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

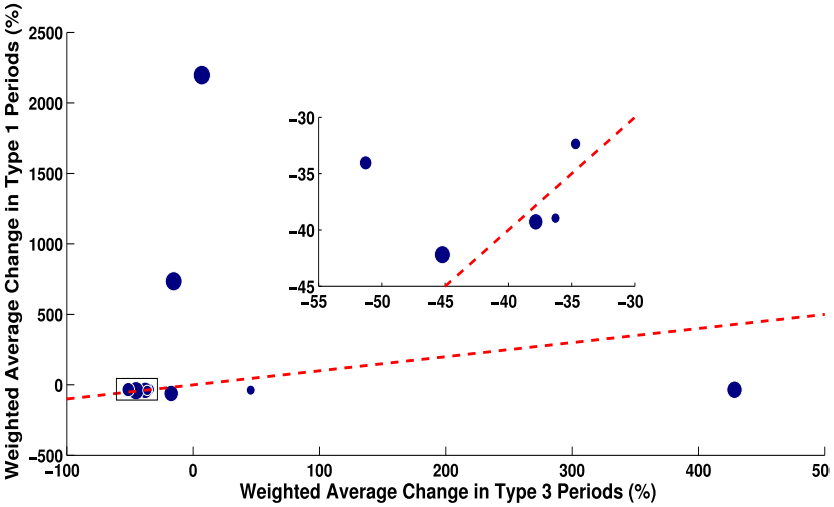
Do users respond more to the numerical values of TDP prices or to the color of the price indicator bar on the home screen?

- ✓ Users paid more attention to indicator color than the numerical discount values

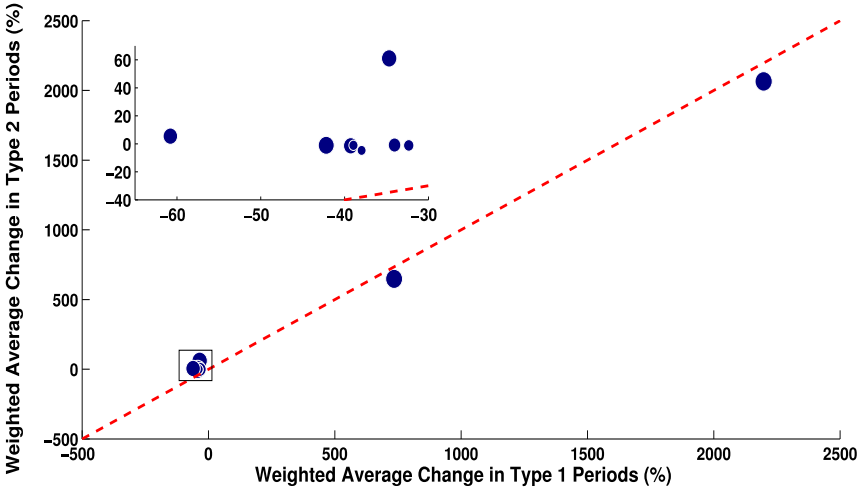
UI Effectiveness

- ✓ Users paid more attention to indicator color than the numerical discount values

Type	Periods	First Stage		Second Stage	
		Color	Discount	Color	Discount
1	2, 8, 14, 20	Orange	10%	Orange	28%
2	3, 6, …, 24	Orange	10%	Green	30%
3	5, 11, 17, 23	Orange	10%	Orange	9%



Period types 1 and 3

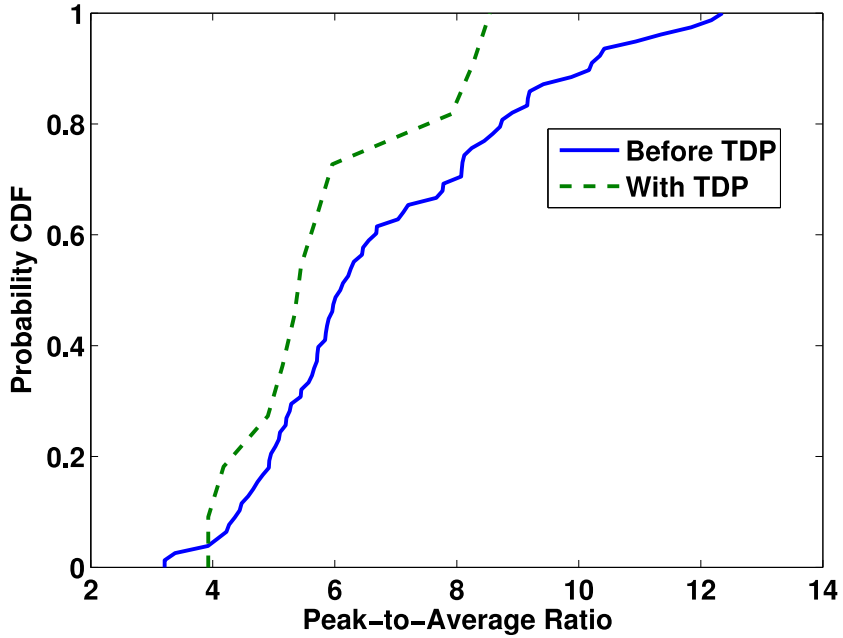


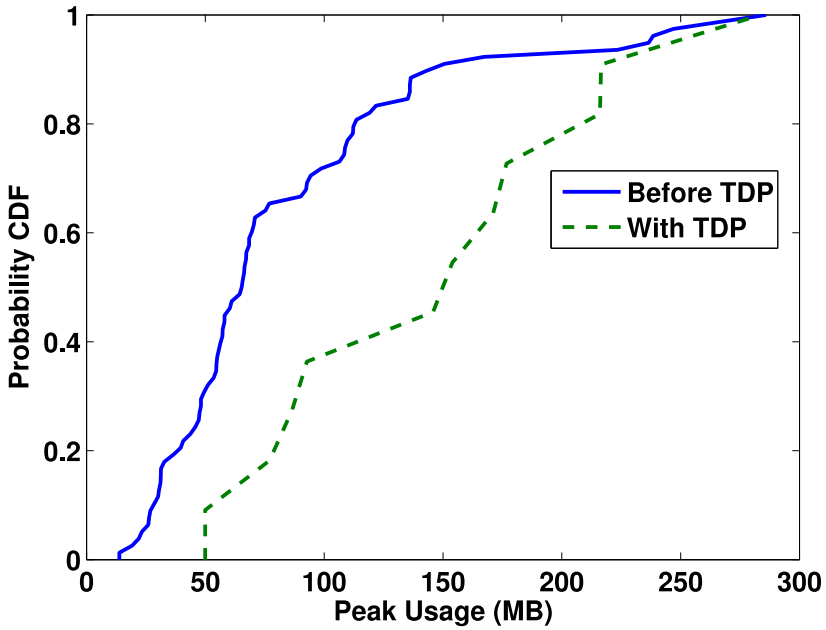
Period types 2 and 1

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





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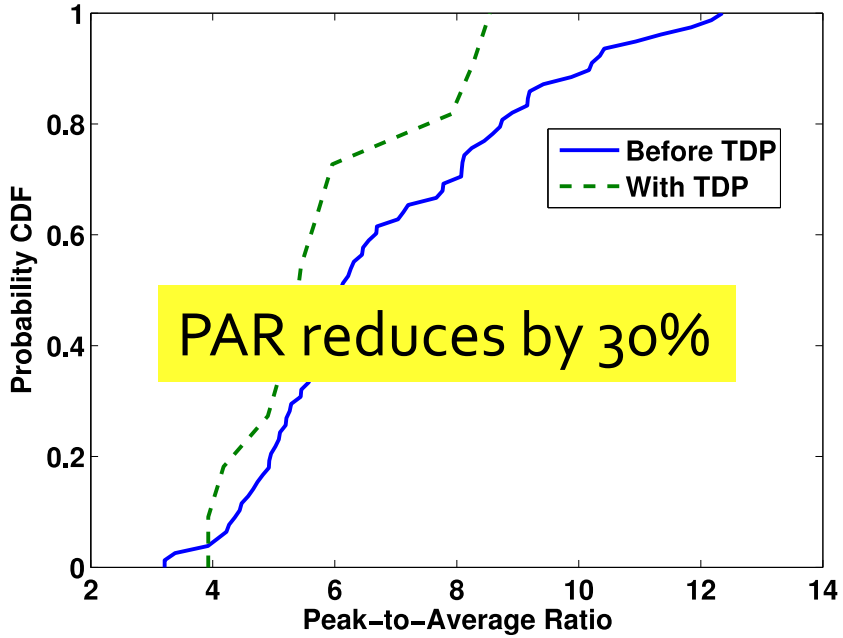

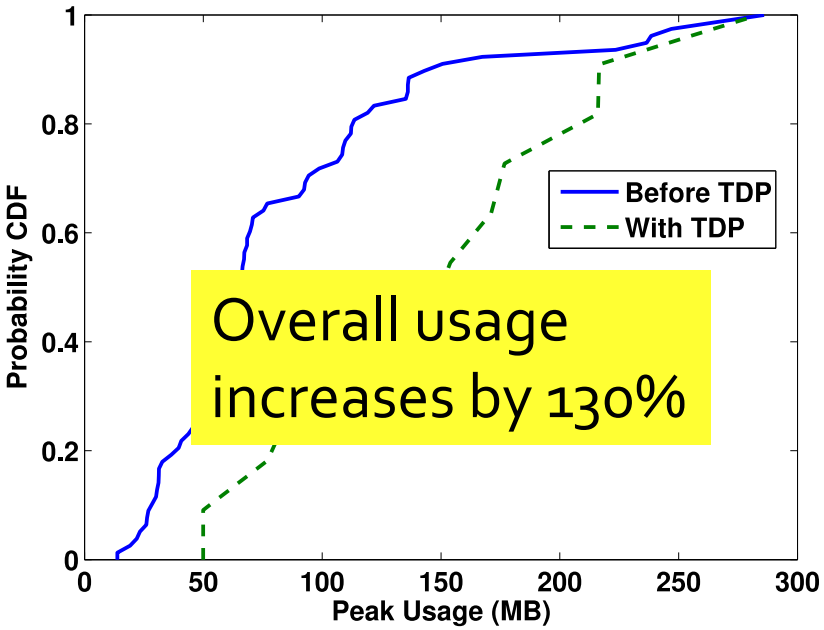

Trial Limitations and Extensions

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**

TUBE

Thank you!

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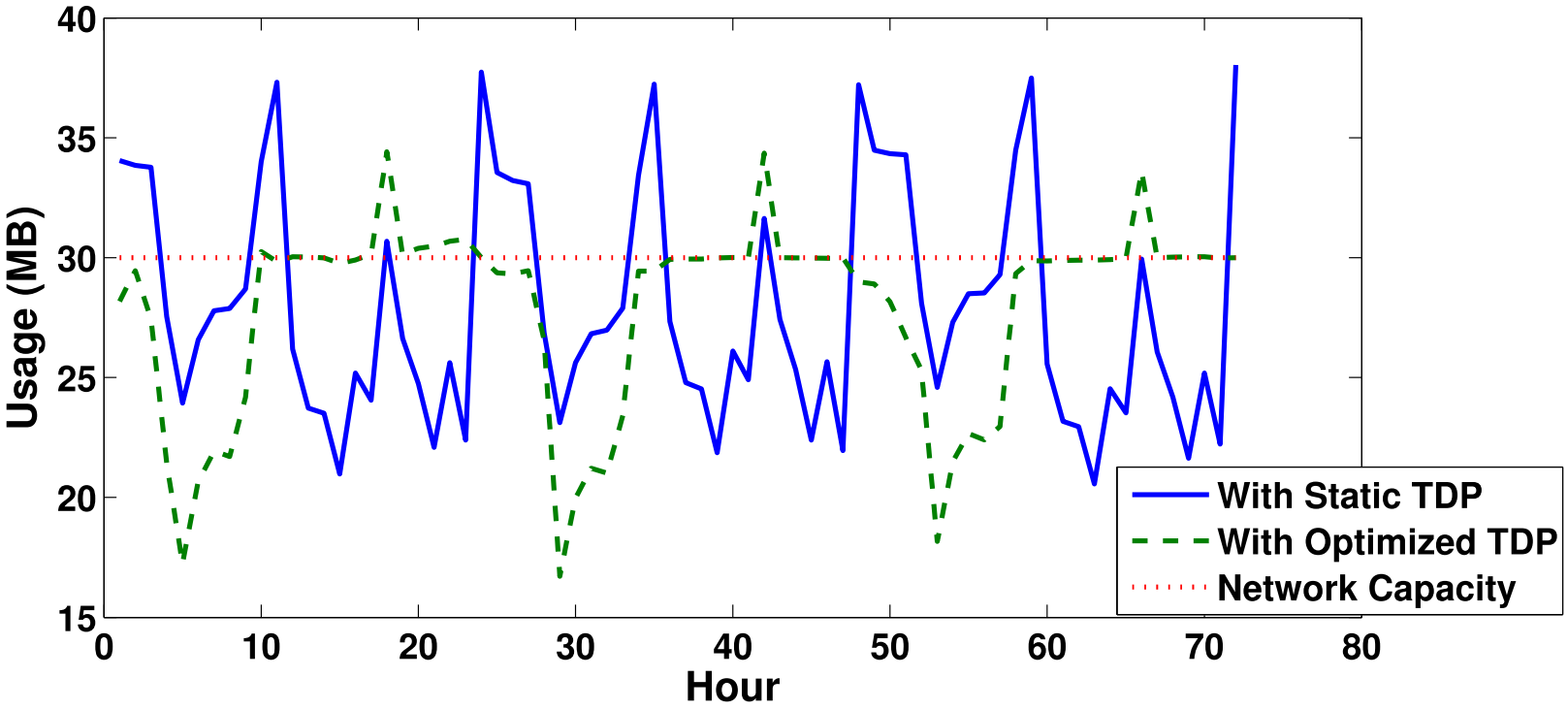
- ✓ **DataMi**: http://www.datami.com
- ✓ **DataWiz**: http://www.datawizapp.com
- ✓ **SDP Forum**: http://scenic.princeton.edu/SDP2012

Backup Slides

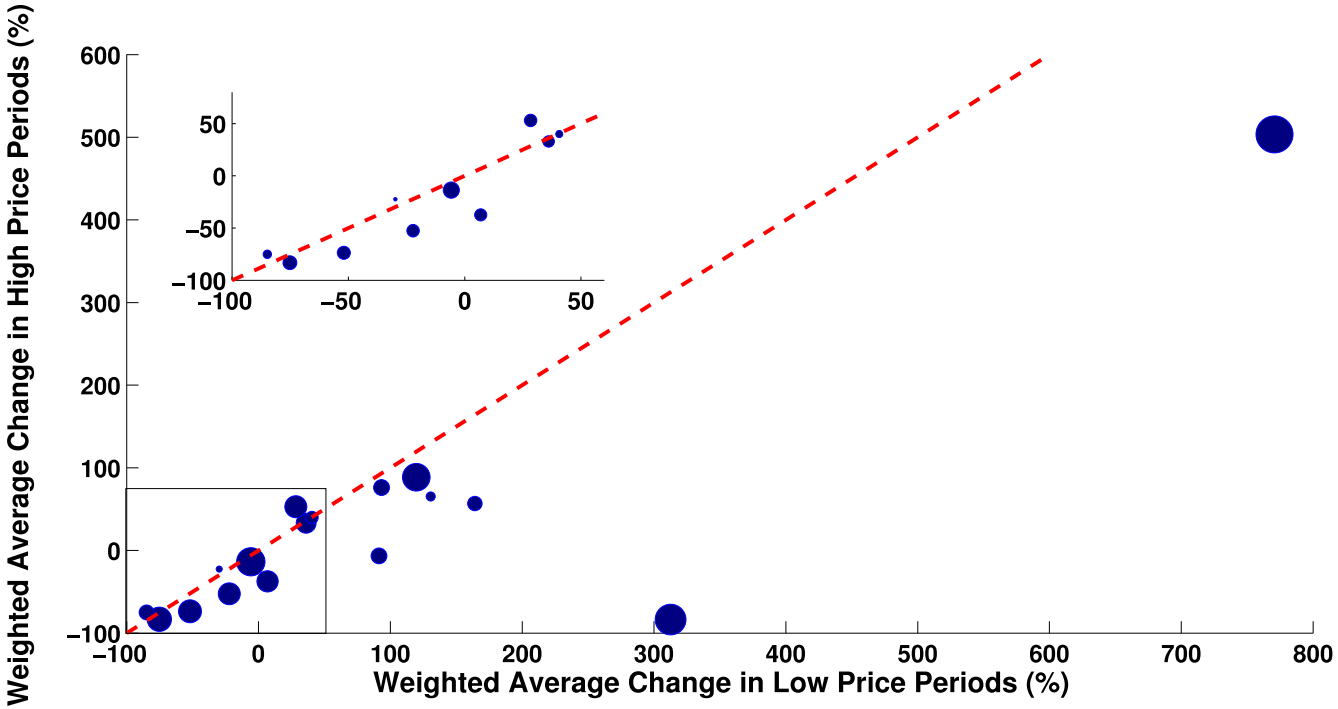
TDP Performance



Price Sensitivity

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

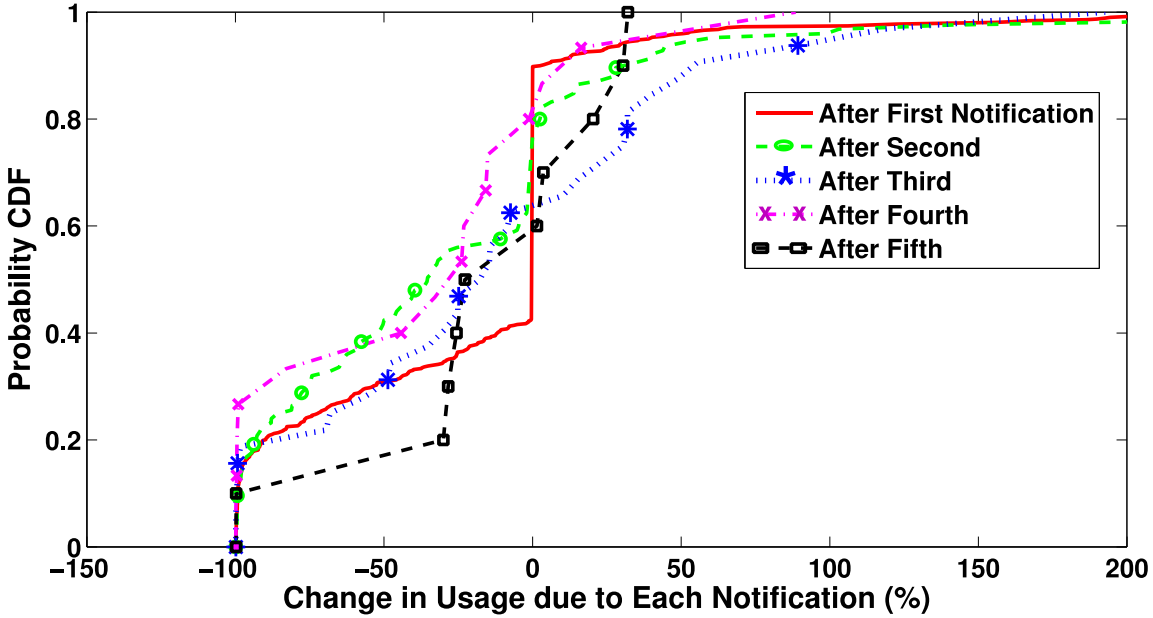
» Average usage decrease in high-price periods relative to the changes in low-price periods



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".