When the Price Is Right: Enabling Time-Dependent Pricing of Broadband Data

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ABSTRACT

In an era of 108% annual growth in demand for mobile data and $10/GB overage fees, Internet Service Providers (ISPs) are experiencing severe congestion and in turn are hurting consumers with aggressive pricing measures. But smarter practices, such as time-dependent pricing (TDP), reward users for shifting their non-critical demand to off-peak hours and can potentially benefit both users and ISPs. Although dynamic TDP ideas have existed for many years, dynamic pricing for *mobile data* is only now gaining interest among ISPs. Yet TDP plans require not only systems engineering but also an understanding of economic incentives, user behavior and interface design. In particular, the HCI aspects of communicating price feedback signals from the network and the response of mobile data users need to be studied in the real world. But investigating these issues by deploying a virtual TDP data plan for real ISP customers is challenging and rarely explored. To this end, we carried out the first TDP trial for mobile data in the US with 10 families. We describe the insights gained from the trial, which can help the HCI community as well as ISPs, app developers and designers create tools that empower users to better control their usage and save on their monthly bills, while also alleviating network congestion.

Author Keywords

Broadband access pricing; Dynamic pricing; Time- and usage-based pricing; Mobile application interface; Economics

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

The growing popularity of smart mobile devices (*e.g.,* smart phones, tablets), bandwidth-hungry applications (*e.g.*, media streaming), cloud-based services (*e.g.,* file backup, file sharing), and media-rich web content is projected to result in an 18-fold increase in global mobile data traffic between 2011 and 2016 [5]. Faced with such a demand surge and the resulting network congestion, Internet Service Providers (ISPs) have turned to access pricing as a congestion management tool. In the US, most large ISPs (*e.g.,* AT&T, Verizon, T-Mobile) have eliminated their unlimited flat-rate data plans in favor of tiered plans with $10/GB usage-based pricing (UBP) for overages [19]. But UBP cannot alleviate peak congestion without a time-dependent pricing component to provide dynamic feedback on network congestion levels [19].

Thus, a natural next step to consider in this pricing evolution is Time-Dependent Pricing (TDP) of mobile data, which exploits consumers' time elasticity of demand more effectively. In fact, some Indian and African ISPs are already using dynamic tariffing for voice calls [25]. Following this trend, recent years have witnessed an increasing interest in dynamic congestion pricing for *mobile data* among networking researchers [12, 15]. However, introducing TDP requires not only good economic models and systems capability, but also an understanding of user behavior and effective client-side interfaces. While the user aspects of data caps and bandwidth speed have recently received attention within the community [1], relatively little has been done to understand how economic factors affect Internet user behavior. With the growing adoption of network-enabled devices and an evolving pricing paradigm, it is more important than ever for the human-computer interaction (HCI) community to explore the design aspects and user response to changes in access pricing schemes.

To this end, we developed a system to allow ISPs to offer time-dependent prices and client-side GUIs (graphical user interfaces) that let users monitor and respond to these prices. We conducted a field trial with AT&T iPad2 users from 10 households and surveyed them to study their reactions to TDP plans and features. To the best of our knowledge, this *TDP trial for mobile data traffic* is the first of its kind in the US [12].

Our main contributions are to: (1) present findings on user responses to TDP for mobile data from stakeholder surveys, focus group studies, and a field trial, demonstrating TDP's potential to empower consumer choice while addressing ISPs' network congestion; (2) introduce an engineering framework for experimenting with network provisioning and pricing by acting as a resale ISP with consumer-facing interfaces; and (3) highlight how economics and user behavior should be jointly considered as HCI addresses increasingly complex socio-technical ecosystems.

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We first provide some background on TDP plans and review several works related to visual tools for broadband access. We then give an overview of the challenges and design considerations for our TDP mobile app, followed by a discussion of our field trial and its findings. In particular, our work contributes to the HCI community by bringing into its purview an emerging direction in Internet access pricing and exploring the associated design choices.

PERSPECTIVES OF STAKEHOLDERS

The Internet ecosystem consists of multiple stakeholders, including ISPs, consumers, content providers, and regulators, who are all impacted by pricing policy changes. Over the last 2 years, we interacted with several of them to understand the problems that are driving these changes and the benefits that new plans like TDP can provide.

ISP Perspective

With wireless traffic growing at 108% annually [5], ISPs are finding it hard to manage congestion on their network. Even next-generation technology is not enough, as spectrum capacity may run out by 2013 [8]. Consequently, ISPs are now resorting to penalty measures that regulate demand, such as capping, throttling, and overage penalties.

However, such measures to curb demand may be not only ineffective, but even harmful to the Internet ecosystem. For example, usage-based pricing cannot alleviate peak congestion, as it does not provide any incentives for consumers to avoid using the network at peak hours [19]. Clark [6] pointed out that *"the fundamental problem with simple usage fees is that they impose usage costs on users regardless of whether the network is congested or not."* Similarly, a simple two-period pricing plan (*e.g.,* day time and night time charges) fails to exploit the inherent time elasticity of several mobile applications that cannot wait half a day (*e.g.,* preemptive file downloads).

In contrast, TDP provides consumers with dynamic feedback on the network congestion level by offering time-varying incentives to shift their demand to less congested hours. An Indian ISP told us that TDP could create a win-win for both providers and consumers with the company benefitting by moving traffic to off-peak periods and customers benefitting by delaying consumption to lower tariff periods. We also spoke to several US ISPs at the National Exchange Carrier Association (NECA) Expo 2011, where one executive informed us: *"Clearly, customers do not want any form of usage measurement or control under traditional definitions. I'd be very interested in seeing a pitch for time-dependent pricing"* (Delhi ISP, email communication, September 2011).

But not all forms of TDP are effective. For example, dynamic real-time pricing is less popular with consumers because of the uncertainty in offered prices [24]. Thus, TDP plans need to be designed to provide some guarantees about the future prices, as in the electricity market's "day-ahead" pricing. With day-ahead TDP, users know the prices for the next twenty-four hours at any given time and can thus plan ahead of time. ISPs, on the other hand, can adjust their prices each day according to user behavior estimates.

Consumer Viewpoints

In using TDP, consumers can save on their monthly bills by using less bandwidth during peak and more in the off-peak (or discounted) hours. Several applications and services today (*e.g.,* large downloads, cloud synchronization, etc.) can be scheduled automatically in the discounted periods even without user intervention.

As a part of exploring user response to TDP, we conducted pre-trial surveys in India and the US. The India survey involved 546 respondents and was conducted in 5 metropolitan cities by a professional agency in accordance with our instructions and questionnaire. In the US, the pre-trial surveys were conducted both online and by the authors in person in Philadelphia and on the Princeton University campus, with a total of 155 respondents. In both surveys, we asked respondents how long they would be willing to delay using different types of apps for a given monetary incentive. More than 50% reported that they would wait up to 10 minutes to stream YouTube videos and 3-5 hours for file downloads. Given these initial data, we next set out to conduct a real trial to verify the efficacy of TDP plans.

Content Provider Considerations

Faced with increasing consumer worries about overage fees, content providers like Netflix are now allowing *"users to dial down the quality of streaming videos to avoid hitting bandwidth caps"* [18]. But with TDP, content providers can take advantage of discounted periods to forward and cache their content closer to the edge (*e.g.,* client device), thus improving their users' quality of experience.

Policy Developments

In the US, there is now a general acceptance of the fact that ISPs need to explore new pricing policies to *"match their prices to cost."* In 'New Rules for an Open Internet,' the Federal Communications Commission chairman J. Genachowski announced: *"The rules also recognize that broadband providers need meaningful flexibility to manage their networks to deal with congestion.... And we recognize the importance and value of business-model experimentation"* [10].

RELATED WORK

As early as 2006, researchers have recognized the effects of cost on mobile data usage and the need for mechanisms to track spending on mobile data [22]. With ISPs exploring new pricing policies that aim to limit their mobile users' bandwidth, these observations are becoming more relevant than ever. Many networking researchers have already proposed using dynamic price signals as feedback from the network to the consumer as a feasible future direction for pricing strategies [23, 25]. Such policies include TDP, in which users get rewarded for using less during the peak hours [12, 15]. However, realizing such data plans requires assumptions of rational behavior to be realized in practice, i.e., that people perceive the pricing signals and change their behavior. Results from the *Berkeley INDEX* project [7] in the 1990s for wired Internet suggest that users can view prices and select desired QoS levels (i.e., bandwidth speed). Similar systematic studies on the HCI aspects of *time-dependent pricing for mobile data* are needed today to address the issue of wireless network congestion– an area that has remained largely unexplored.

Recently, there have been calls to investigate HCI aspects of TDP in the context of ecological sustainability and energy consumption [21]. Even without economic incentives, careful UI design of energy monitors has been shown to effect changes in consumer behavior [9, 21]. These investigations have ranged from a large-scale media art installation visualizing energy consumption in an office building, to power strips that change color to show the energy used by individual electrical sockets [13, 14]. A recurring tradeoff in visualizing energy usage is the use of pictorial versus numerical usage amounts. For instance, the iPhone application *WattBot* allows users to monitor their home energy usage, with colors indicating usage amounts [20]. While the colors enabled users to quickly grasp their qualitative energy usage, users also wanted to track their evolving usage behavior by viewing their usage history [3]. In addition to the "manner" of presenting usage data, users expressed concern over the "convenience" of checking their usage. For instance, researchers testing a desktop widget that showed computer energy efficiency found that users appreciated the inconspicuous, easy-access nature of the widget [16]. We incorporate these design considerations in the client-side UI of our TDP application and evaluate its effectiveness through post-trial interviews.

In the context of broadband networks, only a few works have developed human-facing systems to manage network usage, though networking is widely viewed as an HCI concern [11]. The *Eden system* [26] modifies a home router to allow users an intuitive interface for managing their "home network experience." The focus of such home-networking tools has been on designing GUIs to help users understand the physical location of different devices in their home and perform membership management, access control, network monitoring, etc. Similarly, the *Homework* project [17] modifies the handling of protocols and services at the home router to monitor data usage, prioritize different devices, and monitor other users' data consumption (usually in the context of parental control) in order to reflect the interactive needs of the home. Other works have focused on understanding the impact of monitoring and sharing bandwidth speed in a *wired* home network [2]. Chetty et al. [4] carried out a field trial of *Home Watcher* to study the effect of viewing others' bandwidth usage on social dynamics in the household.

While these previous works have addressed network intervention (e.g., throttling, capping, parental control) and its related visualization tools, they were limited to either modifying the network stack within the OS [4] or deploying a custom-built access point [17]. In contrast, our work focuses on studying the impact of economic incentives (i.e., pricing) on user behavior, and hence requires us to interpose ourselves between the ISP (i.e., AT&T) and its real customers (i.e., participants) as a resale ISP. Moreover, we work in the *wireless network* environment and explore the role of TDP in creating a "win-win" across ISPs and users by alleviating congestion. Our GUIs were thus designed to be effective for *mobile devices* in terms of form-factor, presentation, and convenience. We also incorporated features like parental control and usage history; as in previous works, these were found to be desirable to users, even in the TDP paradigm.

In summary, our study not only offers a new prototype and insights from a field trial of time-dependent pricing of data, but also contributes to the literature on HCI in network usage by exploring the relationship between economic incentives and user behavior.

CHALLENGES

Exploring the impact of TDP plans for mobile data is especially challenging for several reasons: first, we need to create a "virtual" TDP data plan for 3G users of an ISP that offers them time-varying prices. This involves both a server-side (ISP) implementation for sending price information and a client-side app for user response. Second, it requires creating a communication infrastructure to become a resale ISP. Third, feedback from consumer focus groups must be incorporated in designing client-side GUIs to make them simple and intuitive.

Each of these issues and the solutions we adopted are discussed next. While we explain the basic principles involved in the computation of time-varying prices, the detailed economic models used and system implementation can be found in recent networking literature [12, 15]. The discussion in this paper will instead focus on the HCI aspects of the TDP trial and the qualitative insights that we obtained.

Creating Virtual TDP Data Plans

To conduct this day-ahead TDP trial, we worked with AT&T and recruited trial participants from the Princeton University campus. The primary participants were each given an iPad2 with a 2 GB data plan and our client-side app installed. The iPads were the only tablets owned by the participating families, and they were actively engaged with the iPads throughout the trial. To avoid distorting the results, the primary device users shared their devices among family members, as they would have done normally. Our trial setup in no way impeded the devices' mobility.

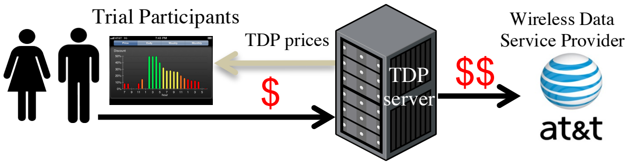


Figure 2: Money flow diagram for the TDP trial.

During the trial period, we paid participants' monthly bills from AT&T for the 2GB plan and overage fees, and instead offered them a TDP plan with time-varying price discounts on a baseline usage-based fee of $10/GB. The participants paid us monthly in accordance to this TDP plan. Thus, we effectively became a *resale ISP* of AT&T's connectivity for these participants, as illustrated in Figure 2. We could then create our own TDP data plan and vary the offered prices to observe the responses of our participants.

Trial Setup

Becoming a resale ISP requires extensive engineering and system integration. Since AT&T is the real 3G provider for these iPads, we created an APN (Access Point Name) setup between AT&T's mobile network core and our lab facilities to redirect the data traffic (uplink and downlink) from these selected devices to our DNS- and NAT-enabled servers before rerouting it back into the Internet. This setup is illustrated in Figure 3.

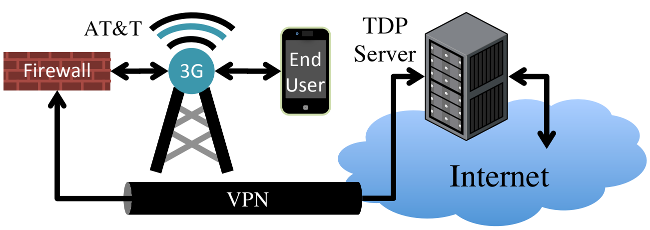


Figure 3: Schematic of the data flow in the trial setup.

Our server monitored participants' aggregate usage to adjust the future offered prices, which were announced 24 hours in advance (as in day-ahead TDP). In each hour, a price point for the 24^{th} next hour was calculated based on past usage under already offered prices, and sent to the client-side app. Thus, at any time a participant could launch our TDP app on their devices to see the prices for the next 24 hours and plan their usage accordingly.

Implementation Overview

Offering a TDP plan requires both ISP server-side and client-side modules. On the server side, using traffic history logs, we ran Matlab-based prediction algorithm to predict future demand as a function of the prices and calculate the future prices to offer. The ISP server-side modules were implemented on a Linux platform with an Intel Xeon 2.0 GHz CPU and 8 GB of RAM. We assigned a unique IP address to each device and created a *Netfilter* rule to measure its usage, which was stored in MySQL DB. The server supports JSON/HTTP and can exchange information with any device with browsing capability.

The client-side (iPad) module is the mobile application (TDP app) with which trial participants interact. Platform restrictions from Apple severely constrained many of the possible TDP functionalities, so we jailbroke the iPads to gain root access to the operating system. We were then able to monitor usage at the application level, block apps on users' request, place an indicator bar on the top icon tray of the home screen, etc. In the iOS platform, we hook several internal functions to track each application's usage and run a daemon process to dispatch requests and display TDP prices as well as to block apps if needed.

Focus Group Studies

Arguably, the most critical system component for TDP's success is the GUI of the client app. This app should be designed carefully to meet multiple functionality goals:
(a) *Data monitoring:* How should we visually communicate price and usage information to users for usage monitoring?
(b) *Consumer empowerment:* What kind of information will empower consumers to make usage decisions? What type of control knobs do consumers prefer to manage?
(c) *Automation:* Will users want to automate their usage decisions using an *autopilot* mode of operation?

During the design phase, we conducted focus group studies in the University campus with about 5 people in each to obtain feedback on our GUI designs. We also solicited opinions on whether the iPad application's form-factor was preferable for this trial. Additionally, we obtained inputs from leading industry experts of AT&T, MTA, NECA, Bell Labs, and Reliance Communications of India. Over a four-month period, we asked for new feedback with each new version of the UI design and prototype of the mobile app.

These preliminary studies suggested that consumers like the idea of time-varying prices, as it empowers them to choose not only *how much* but also *when* to use their device so as to save some money. They indicated that: (i) it is preferable that TDP prices vary at an hourly granularity and not on the order of minutes (*e.g.,* real time), (ii) day-ahead prices are appealing as they allow advance planning, (iii) viewing superimposed usage and price history is useful in knowing when someone used how much data, and (iv) features that enable finer control of their usage are deemed useful.

We also gathered that users found it convenient to view the TDP price discounts in a color-coded form, *e.g.,* red (<10%), orange (10-19%), yellow (20-29%), green (>30%). We limited the discount offered to be at most 50% on the $10/GB baseline fee, in order to lower bound any revenue loss during the trial. The idea for color-coding TDP prices/ discounts, which was inspired by *traffic light* signaling in transportation networks, resonated well. The price discounts were also made available as numerical values as a secondary signal for color-blind users. The respondents desired a *parental control* feature to block certain apps at certain times of the day when prices were high, and wanted information on how much data *each application* consumes—information that is currently not easily available on iOS devices. This feedback, along with functionality goals, guided our TDP app's design.

DESIGN OF TDP APP

We next discuss the TDP app's UI features, grouped by their functionality goals.

Monitoring Features

1) *Indicator bar:* To conveniently indicate prices to our users, we provided an indicator bar on the top icon tray of the iPad's home screen, as shown in Figure 4. The indicator is color-coded and shows the percentage discount from the baseline price on offer. Users could thus monitor the prices at any time without needing to launch our TDP app.

Figure 4: Color-coded price discount indicator bar on the iPad home screen for easy reference.

2) *Price information:* On launching the TDP app, the main screen shows the user all the basic information in a split-screen mode, as seen in Figure 5. The user's current bill based on the TDP charges is displayed on top, followed by a scrollable list of color-coded percentage price discounts and usage information and a graphical view of the offered price discounts for the next 24 hours.

The scrollable list shows data on the past and future 24 hours, highlighting the current hour's information. Users can see their usage in past hours, alongside a color-coded view of prices at different times. By clicking on the color-coded price display button, users can view it either in $/GB or as a percentage discount from the $10/GB baseline.

The bottom half of the screen will by default provide users with an easily understandable bar graph view of the future TDP prices to help them in planning ahead. Using the navigation buttons at the bottom of the screen, users can instead view their usage history (by day, week, or month) or information on their top-5 bandwidth-consuming apps.

3) *Usage history:* As described above, users can monitor their usage from the app's main screen itself. To give them a better experience, we created a larger *landscape* view mode that shows up on tilting the iPad horizontally, as in Figure 6. Users can swipe through the superimposed price and usage history with their fingers. As before, the data can be viewed on a daily, weekly, or monthly granularity.

4) *Top-5 Apps:* From the pre-trial focus groups, we gathered that most people were unaware of their most bandwidth consuming apps. Hence, we provided this feature, shown in Figure 7(a), to help them know which app's usage they may want to reduce.

5) *High-usage notifications:* This feature was used to test users' responsiveness to pop-up notifications and usage-deferral recommendations at high-priced periods.

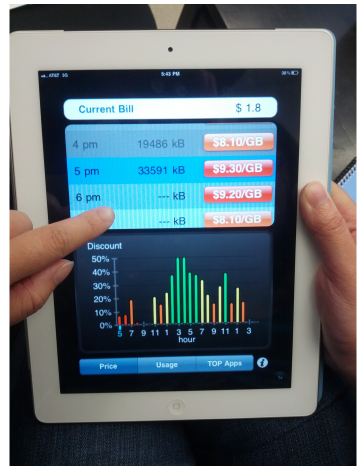


Figure 5: Vertical view of the main app with a split screen view showing the color-coded future prices and history below and a scrollable history list on top.

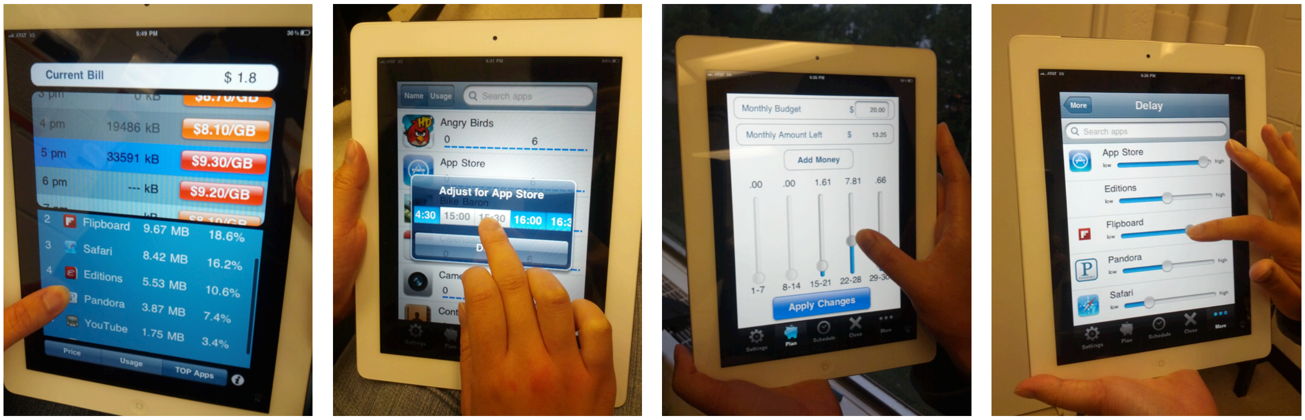
Figure 6: The landscape view shows the superimposed price and usage history by day, week, and month.

Consumer Empowerment Features

1) *Parental Control:* A user can select an app from the list of all installed apps, and then disable the hours in which (s)he does not want the app to run, as seen in Figure 7(b). This is especially useful in TDP to prevent children from streaming media-rich content in high price periods.

2) *Budget adjustment:* Our TDP app provides users with fine-granular control over their weekly spending. As seen in Figure 7(c), using the sliders, users can adjust their weekly budget. Users also have the option to add more money.

3) *App-delay sensitivity settings:* Users can specify their delay sensitivities for each installed app using sliders positioned between "high" and "low" tolerance, as shown in Figure 7(d). This feature enables automated app scheduling to keep the user within a specified budget.



(a) (b) (c) (d)

Figure 7: View of (a) the top-5 bandwidth consuming apps in the bottom split-screen, (b) app-specific temporal blocking in parental control, (c) weekly budget adjustment screen, and (d) app-delay sensitivity settings screen.

Automation Features

Based on user-specified delay sensitivities and the available budget, we provided an autopilot mode of operation. In this mode, the TDP app computes a usage schedule for different apps to keep users within their specified daily budgets, based on the given prices for the next day and predicted usage. The autopilot mode can provide warnings or block apps until their scheduled period. The schedule screen allows users to see when each app has been scheduled.

TDP DEPLOYMENT

We tested the TDP system extensively between April and July 2011, and recruited 10 trial primary participants (the "primary participant" paid the monthly bills) in Princeton, New Jersey through word of mouth and email lists. For the duration of the trial, we provided each participant with a jailbroken iPad. To avoid bias, we did not give any monetary incentive for trial participation, aside from paying AT&T's $20 monthly bill for a 2 GB data plan and charging participants according to TDP. The demographic information of the primary participants and any secondary users who shared the device is given in Table 1. The trial was conducted from July 2011 to April 2012, during which we visited participants three to four times.

In the first phase of the trial, from July to September 2011, we handed out the iPads without the TDP app to let participants familiarize themselves with the device and to monitor their pre-TDP usage. In the second phase of the trial, from October to November 2011, we installed the TDP client app on participants' iPads and provided basic instructions. We also began offering TDP price discounts. From December 2011 to January 2012, we tested participants to see if they paid attention to the color or to the numerical discount value on the home screen price indicator. From February to March 2012, we kept offering TDP, visiting the participants again in April for a post-trial debriefing to get feedback on their user experience.

The interviews were all audio-recorded and transcribed, and three researchers coded the data. The excerpts presented here represent mutually agreed upon themes from the qualitative data. Where applicable, this data was compared to the observed quantitative usage patterns and pricing history to confirm the views expressed by the participants.

#	Primary Participant	Secondary User(s)
P1	Female, 40, Personal Assistant	None
P2	Male, 33, Grad Student	None
P3	Female, 34, Office Staff	Female, 3, Child
P4	Female, 50, Accounts Manager	Female, 26, Waitress Male, 23, Waiter Male, 18, Undergrad Female, 5, Child
P5	Female, 21, Student	None
P6	Female, 48, Admin. Assistant	Female, 22, Restaurant Cook
P7	Female, 35, Office Manager	Male, 41, Software Engineer
P8	Male, 31, Grad Student	None
P9	Female, 30, HR Manager	Male, 32, Theater Technician
P10	Female, 43, Office Support	Male, 43, Systems Technician Male, 14, Student Female, 8, Student

Table 1: Participants' demographic information.

FINDINGS

We first present the opinions expressed in our interviews with participants about smart devices and currently offered data plans. Next, we discuss their attitude towards TDP and the usefulness of various app features. We also asked about their preference for manual or automated control in scheduling apps. Lastly, we explored participants' opinions of TDP's potential impact on the Internet ecosystem.

Consumer Awareness

Opinions on Current Data Plans

When asked whether current data plans are reasonable, participants expressed concern over ISPs' shift from unlimited flat rate to tiered plans with $10/GB overages. One of them explained: *"To me, I think it's a fair price, but I know when my children uses it, if they use Netflix or something, then it gets to be too expensive."*(P10). This sentiment was also echoed by P4, who had to share the iPad with her children: *"I didn't really have to pay attention to that until this iPad came up because the data plan I have for the family phones is unlimited data for one price."*

Awareness about Data Usage

Though participants were concerned about emerging ISP pricing trends, about 80% of them reported before the trial that they had little sense of how much data they use per month or which apps are most bandwidth-intensive. Only a few showed some intuition: *"I would think any kind of video and music sites"* (P6), and *"I assume that anything that's running constantly or streaming, you know, like a movie is going to use more than just browsing the Internet I would think"* (P9). An interesting observation was that P9 was aware of the fact that she used more data on her iPad: *"I also know I've used the iPad a lot more liberally for things like that [TV shows] than I would on my iPhone."*

Attitude towards Time-Dependent Pricing

All our participants regarded the TDP data plan as viable – they would be willing to adopt it *"as long as the interface is simple to use"* (P2). But TDP's suitability for a particular person depends on the predictability of the offered prices. Even with day-ahead pricing, participant P3, a mother of a toddler, found herself less willing to wait if the hourly prices varied too much from day to day: *"I think it's definitely useful, but for families it really needs to be predictable."* However, others were more price-sensitive and even adapted their online activities based on the announced prices for the day: *"I think it is a nice option to have where I can get a discount per month depending on when I use it, and I can schedule my day that way"* (P10).

Elasticity of Demand

One of the key aims of the trial was to understand if users will delay certain types of applications, which is essential for TDP to successfully reduce ISPs' peak congestion.

In general, we found that participants were willing to delay non-critical, high-bandwidth consuming apps most of the time, but not critical activities. For example, when asked if they would time shift their demand to a discounted period, participant P9 replied: *"If I'm surfing the web, I'm doing it now, I am not waiting, but for my movie usage it's kind of specific, so yeah."* Similarly, participant P1 described: *"If I'm trying to look up directions [GPS], it probably couldn't wait. But if I were trying to research on buying something and the discounts weren't good, I could wait a couple of hours to do it later."* When asked about the kind of apps they were willing to wait for, most participants reported that they deferred the use of social networks and streaming services: *"Social networking, emailing, or Skyping, I would definitely wait for that"* (P6).

These insights are particularly valuable given that in the aggregate usage data shown to us by partner ISPs, the congestion level could vary by a factor of 2 within a few minutes and by a factor of 10 within hours. Hence, TDP can effectively exploit the differing degrees of demand elasticity among applications to temporally flatten out the aggregate demand curve by offering economic incentives.

Cost Savings

The participants also reported that our TDP app helped them to be more conscious in avoiding unnecessary usage at high price periods: *"Yes, and [I] was less likely to goof off and waste more time and data"* (P5). In fact, many tried to save money by limiting usage to discounted periods: *"I made a conscious effort to look for the discounts"* (P10).

Moreover, they did not feel that the TDP plan required them to significantly modify their behavior: *"I go to my bank account everyday, so I would think that this would just become a natural thing"* (P6).

Sales-Day Effect in Discounted Hours

An interesting phenomenon we observed during the trial is that the high discount offers induced a 'sales-day' effect among several participants; that is, they started using more than they otherwise would have. When asked about this, participant P9 told us: *"[laughs] Kind of! But that also goes towards my personality of if it's on sale I must buy it!"* In fact, relative to participants' pre-TDP usage, we observed a 130% overall increase in usage with TDP, possibly due to such a sales-day effect. This result benefits ISPs: with TDP, they can offer discounts to shift traffic from peak to off-peak periods, as well as increase demand in off-peak hours. The result is mutually beneficial, as ISPs benefit from "valley filling" and users gain by consuming more at the discounted rates in off-peak times.

Effectiveness of TDP App GUIs

We now discuss our participants' response to the TDP app itself and which display features they found appealing. Participants unanimously agreed on 3 key aspects: (a) usefulness of indicator bar on the iPad's home screen, (b) color-coding the price discounts, and (c) usage history.

Response to Price Displays

Participant P4 explained that she kept an eye on the indicator bar and looked at the day-ahead price chart to tailor her usage to the "green" (high discount) periods: *"I paid attention to the little color icon that you guys have up on the top, and I tried to tell everyone not to use it unless it was in green… I do look at the chart and see at what point the discounts might come in."* The effectiveness of color-coding the price bars was evident in several responses: *"I would see if it's a good color for me"* (P7). Only a few said that they paid attention to the discounts themselves and not just the colors: *"I do look at the percentage. I will go to the app and just see where it's gonna be over the next few hours"* (P10). We analyzed the usage in periods in which we intentionally varied the discounts by 1% to switch the color from yellow to green, and observed a statistically significant increase in demand in the 'green' period.

Response to Usage Information

Participants also use the usage history displays to track their usage over time. A mother of 3 explained how it empowered her to monitor and control her children's usage when she was at work: *"I can go back and see when they were using it!"* (P4). She also gave an anecdote on having used this feature to check whether people at an iPad repair shop had used her data plan while fixing her broken screen.

One user (P3) suggested that just like the home screen's price indicator bar, she would like a usage indicator showing the remaining data quota or monthly budget. Our results thus imply that platforms like iOS should consider allowing developers to add icons to the top task bar of the home screen in order to improve user convenience.

Response to Notifications

In one phase of the trial we provided pop-up notifications to remind participants every 10 minutes if they used a lot of data in high-price periods. While many participants opined that this was not an inconvenience, *e.g.*, *"As a bill-payer I would think it is very useful"* (P4), others though that *"the pop-ups were a bit annoying. I think it would be nice if the warning messages appear on the top of the screen"* (P2).

In general, participants preferred notifications of low prices in future hours to reminder notifications during high-price periods, as the former provided immediate guidance on when to use data: *"I think it's a great idea, when the iPad would say 'If you wait for half an hour, you can have 25% discount'. I thought it was incredibly useful for my decision"* (P6). Some participants also suggested adding prediction based pop-ups, such as *"[i]f you watched this movie, you would be over your usage quota"* (P9).

Empowering Consumer Choices

Top-5 Apps Usage Information

To educate our participants about their per-app usage, we provided them with the usage consumed by each of their top-5 bandwidth consuming apps. One of them noted *"usually it's always the same type of thing – the Internet, YouTube, Facebook, those type of things"* (P4). This awareness also got her to pay more attention to other usage patterns: *"If I connect to my email and work and I have a thousand emails in my mailbox and it downloads all that stuff… that's a big consumer as well."* The usefulness of this information is perhaps best highlighted in a suggestion from participant P6: *"Absolutely. I mean it would be nice if there were an indicator on the app icon themselves."*

Parental Control

A major concern of many in the pre-trial survey was their ability to not only monitor but also control the usage of secondary users. For example, in referring to her kids, participant P6 told us: *"I don't think they realize how long they've been on there."* Regarding the parental control feature we introduced in TDP, one participant asserted: *"I think there's a lot of parents that would use it"* (P4). This finding corroborates the results of earlier works [2, 4, 17] that implemented parental control in home networks.

Decision Making in TDP

In the automated mode of operation, the TDP app can schedule usage based on predicted behavior, usage history and future prices. Although we believed that such a mode would be useful, our participants preferred to manually control their usage: *"I like to control my device manually,"* participant P2 informed us. Some showed reluctance to delegate control to the device: *"It's really annoying to be put in the autopilot mode. I would not want a computer to tell me what to use and when to use it"* (P3).

Participants were uncertain whether such scheduling would interfere with their desire to use the device: *"[T]hat might not be the way you want it scheduled"* (P4). For non-critical apps and activities, however, participants were more willing to use automated scheduling*: "If you could put it in a queue and let the system figure out when the cheapest time to do it is"* (P7). Additionally, participant P8 pointed out that an autopilot mode of operation would likely be adopted only *"if it is sufficiently intelligent to figure out the importance of each application usage."* Thus, in order to realize TDP automation, HCI researchers should pay close attention to the tension between users' willingness to automate non-critical downloads and their desire to be in control of their usage decisions at any time.

Impact on the Internet Ecosystem

Empowering users with the knowledge of how much each app consumes and letting them decide when to use more data can have implications for the Internet ecosystem. Hence, we asked the participants whether they think that such plans can hurt application development. While 20% were ambivalent, the rest felt that introducing TDP would not be harmful. The viewpoints expressed regarding the app development process can be grouped into three categories:

Developer indifference: TDP will not hurt applications because their developers do not consider consumer concerns: *"I think developers are going to put out there whatever they want, and that's not their problem"* (P7).

Competitiveness: Another user thought that TDP will foster better competition: *"It's going to get developers to try and figure out how we can get more using less bandwidth"* (P6).

Responsibility: The issue of developers' obligation to create network-friendly apps was also raised: *"I don't think it will* *discourage innovation. App developers should care about the bandwidth consumption of their apps"* (P2).

Application Developer Perspective

To learn the other side of the story, we reached out to app developers with an online survey and asked whether apps are created with bandwidth consumption in mind. The opinions we received were divided. For example, one iOS developer with 4 years of experience and 12 apps told us "*No, most app developers do what must be done. Only experienced app developers will look for ways to reduce bandwidth usage"* (D1). Developer D2 with 5 years of experience echoed this view: *"User experience and interface seem to be the main need in the App Store."* But another iOS developer with 2 years of experience and 3 apps opined that apps do consider data usage: *"Bandwidth overhead is very important to the user and should thus be important to the developer too"* (D3). However, he added that the *"previous version of Facebook app was - because of all UIWebViews - very slow on mobile connections. Reducing the bandwith by using native UI interfaces gave a huge speed bump."* When asked whether TDP plans will hurt app development, developer D1 felt that developers *will adapt* to new plans, while D3 felt that it won't have any effect: *"I don't think that developers will change their design just because of changes in data plans."*

The developers also provided examples of apps that can actually benefit from TDP: *"applications that can cache websites and newsfeeds to read later"* (D3), *"Dropbox or any file sharing and backup app"* (D2), and apps like YouTube that can choose *"different resolutions depending on network availability"* (D1). But, developer D3 opined: *"The Internet's greatest advantages above all other media is, that it's always up-to-date. It is the fastest media and adding such plans will cut off this advantage. The users want to be up-to-date."*

DISCUSSIONS

A major concern today for the Internet's sustainability is the explosive growth in demand for data and its cost implications for consumers. This work investigates time-dependent pricing (TDP) as a direction for alleviating network congestion. The findings in this study are not only useful to HCI designers and researchers for understanding consumers' response to TDP, but also for the community to lead in the design and HCI aspects related to changing pricing practices worldwide. To this end, we develop a fully functional system to conduct the first TDP trial for mobile data in the US. We discuss the feasibility and benefits of TDP next, followed by the insights emerging from this trial.

Feasibility and Benefits of TDP

Our investigations showed that consumers today are very concerned about the increasing cost of data plans, but are not fully aware of their monthly usage. We also found that users are keen to save on their Internet bills; given the right economic incentives, many are willing to wait for some form of a *feedback signal* from the network on the congestion levels and change their behavior for non-critical applications. This is therefore a promising direction in the evolution of Internet pricing, and follows similar trends in other markets like electricity and transport networks [23]. ISPs also benefit from TDP. From our trial's usage logs, we calculated that the maximum peak-to-average ratio of data demand decreased by 30% while the total traffic increased by up to 130% with TDP, mostly due to the filling up of discounted valley periods from the sales-day effect. Thus, TDP can lead to a "flatter" demand profile with lower peaks and better utilization in off-peak hours.

UI Design Considerations

Our trial participants viewed the client-side TDP app as not only an enabler of usage deferral decisions, but also a tool helping them *self-educate, monitor,* and *control* their usage and spending. One participant summarized this by saying: *"To me, this application educates you"* (P4). TDP thus helps users to be more responsible with their usage while offering them rewards to avoid network congestion.

We found that our TDP trial participants liked UI information displays, such as the color-coded price discounts, the indicator bar on the home screen, usage history, and usage deferral recommendations. The trial also revealed interesting insights on the user control aspects of TDP, which feed into the findings from earlier works [2, 4, 17]. First, our participants viewed parental control at the *granularity of apps* as being useful in managing their usage in a TDP regime. Second, they showed a desire to control their usage *manually* instead of delegating control to an autopilot mode. When coupled with the desire for parental control, we see that users want to take charge of their consumption behaviors, for themselves and their families, in ways that require transparency and flexibility.

HCI and Network Economics

As HCI tackles increasingly complex socio-technical ecosystems, e.g., mobile Internet, cloud computing, smart grids, etc., incorporating economic analysis as a part of user behavior studies is becoming important. This work on investigating users' behavior in different pricing regimes is an initial building block in this area of HCI research.

Our work also introduces a framework for realistic experimentation with the HCI aspects of network economics. By interposing between ISPs and their customers, we act as a *resale ISP* with user-facing apps and ISP-side economic analysis.

CONCLUSIONS

TDP can benefit consumers, ISPs, and other stakeholders in the Internet ecosystem by providing price incentives for congestion alleviation. However, the success of such plans depends on the HCI aspects of helping users understand and respond to economic incentives. We thus developed a fully functional prototype for offering TDP and carried out a trial with real customers. Our results indicate that smarter pricing practices and intuitive interface designs can help users modify their data usage behavior. This work brings together ideas from the HCI, economics, and networking communities as an initial building block for research in this rapidly evolving area of Internet access pricing.

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REFERENCES

1. Chetty, M., Banks, R., Brush, A.J., Donner, J. and Grinter, R. "You're capped!" Understanding the effects of bandwidth caps on broadband use in the home. In *Proc. CHI 2012*, ACM Press (2012): 3021 – 3030.
2. Chetty, M., Haslem, D., Baird, A., Ofoha, U., Sumner, B. and Grinter, R. Why is my Internet slow?: Making network speeds visible. In *Proc. CHI 2011*, ACM Press (2011): 1889 – 1898.
3. Chetty, M., Tran, D. and Grinter, R. Getting to green: Understanding resource consumption in the home. In *Proc. UbiComp 2008*, ACM Press (2008): 242 – 251.
4. Chetty, M., Banks, R., Harper, R., Regan, T., Sellen, A., Gkantsidis, C., Karagiannis, T. and Key, P. Who's hogging the bandwidth?: The consequences of revealing the invisible in the home. In *Proc. CHI 2010,* ACM Press (2010): pp. 659 – 668.
5. Cisco, Visual Networking Index 2011 – 2016. http://www.tinyurl.com/VNI2012.
6. Clark, D. D. Internet cost allocation and pricing. In *Internet Economics*, eds. L. W. McKnight and J. P. Bailey. MIT Press, Cambridge, MA, USA, 1997.
7. Edell, R. J., *Internet Demand Experiment: Technology and Market Trial.* PhD Thesis, UC Berkeley, 2001.
8. Electronista Staff. Verizon preps LTE femtocells, says it hits limits in 2013. *Electronista* (2012), 5 March 2012.
9. Froelich, J., Findlater, L. and Landay, J. The design of eco-feedback technology. In *Proc. CHI 2010*, ACM Press (2010): 1999 – 2008.
10. Genachowski, J. New Rules for an Open Internet. FCC (2010).
11. Grinter, R.E., Edwards, K. W. and Newman, M. W. The work to make a home network work. In *Proc. ECSCW*, Springer (2005): pp. 469 – 488.
12. Ha, S., Sen, S., Joe-Wong, C., Im, Y., and Chiang, M. TUBE: Time-dependent pricing for mobile data. In *Proc. SIGCOMM*, ACM Press (2012): 247 – 258.
13. Heller, F. and Borchers, J. PowerSocket: Towards on-outlet power consumption visualization. In *Ext. Abstracts CHI 2011*, ACM Press (2011): 1981 – 1986.
14. Holmes, T. Eco-visualization: Combining art and technology to reduce energy consumption. In *Proc. C&C 2007*, ACM Press (2007): 153 – 162.
15. Jiang, L., Parekh, S. and Walrand, J. Time-dependent network pricing and bandwidth trading. In *Proc. NOMS Workshops 2008*, IEEE (2008): 193 – 200.
16. Kim, T., Hong, H. and Magerko, B. Design requirements for ambient display that support sustainable lifestyle. In *Proc. DIS 2010*, ACM Press (2010): 103 – 112.
17. Mortier, R., Rodden, T., Tolmie, P., Lodge, T., Spencer, R., Crabtree, A., Koliousis, A. and Sventek, J. Homework: Putting interaction into the infrastructure. In *Proc. UIST*, ACM Press (2012): pp. 197– 206.
18. Newman, J. Got bandwidth caps? Netflix has you covered. *Technologizer* (2011), 23 June 2011.
19. Odlyzko, A., St. Arnaud, B., Stallman, E. and Weinberg, M. Know Your Limits: Considering the Role of Data Caps and Usage Based Billing in Internet Access Service. Public Knowledge White Paper (2012).
20. Petersen, D., Steele, J. and Wilkinson, J. WattBot: A residential electricity monitoring and feedback system. In *Ext. Abstracts CHI*, ACM Press (2009): 2847 – 2852.
21. Pierce, J. and Paulos, E. Beyond energy monitors: Interaction, energy, and emerging energy systems. In *Proc. CHI 2012*, ACM Press (2012): 665 – 674.
22. Roto, V., Geisler, R., Kaikkonen, A., Popescu, A. and Vartiainen, E. Data traffic costs and mobile browsing user experience. In *Proc. Workshop on Empowering the Mobile Web*, in conjunction with WWW 2006.
23. Sen, S., Joe-Wong, C., Ha, S., and Chiang, M. Incentivizing time-shifting of data: A survey of time-dependent pricing for Internet access. *IEEE Communications Magazine 50*, 11 (2012), 91 – 99.
24. Shih, J., Katz, R. and Joseph, A. D. Pricing experiments for a computer-telephony-service usage allocation. In *Proc. GLOBECOM,* IEEE (2001), pp. 2450 – 2454.
25. Standage, T. The mother of invention. *The Economist*, Special report (2009), 24 September 2009.
26. Yang, J., Edwards, W. K. and Haslem, D. Eden: Supporting home network management through interactive visual tools. In *Proc. UIST*, ACM Press (2010): pp. 109 – 118.