Effects of Pricing on Internet User Behavior *

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The Internet Demand EXperiment (INDEX) conducts experiments to measure
demand for quality-differentiated Internet access as a function of bandwidth, traffic
volume, applications, and pricing structure. This paper presents an overview of re-
sults based on aggregated data from five pricing experiments. In these experiments,
pricing is based either on time, volume, a combination of both, or a flat-rate buy out
option. Quality of Service (QoS) is differentiated by varying bandwidth for incoming
and outgoing traffic. After describing the experimental design and characterizing
our subject pool using demographic data, we examine the change in service usage
by comparing the five experiments in terms of traffic generation, QoS selection, and
expenditure.

Keywords: Demand for quality-differentiated Internet access, experimental studies,
pricing of network services

1. Objectives

Different pricing structures can meet requirements of different user groups,
resulting in a higher overall value of the network. In this paper, we present an
analysis of aggregated data from the INDEX Project that supports these claims
and shows how different pricing schemes affect user behavior and utilization of
network resources.

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INDEX, the INternet Demand EXperiment, is a market trial for quality-differentiated Internet services. INDEX provides Internet access over ISDN lines to a group of users from the Berkeley campus community. The subjects select network services from a menu of quality-price offerings and pay for their usage. INDEX’ long-term objectives are to identify the key parameters for user perception of service quality, quantify the correlation between application type and service demand, and measure the economic value that individual users place on distinct activities and network resource levels. This information will help to define market segments for quality-differentiated network services that accommodate future demand and applications with different requirements.

In this article, we analyze five different pricing experiments. The first experiment, *Variable Symmetric Bandwidth*, gives users the choice between six different bandwidths at different prices. The data is used to estimate the price elasticity of demand for connection speed to the Internet. In the *Variable Asymmetric Bandwidth* experiment, in-bound and out-bound bandwidth can be chosen separately. Data from this experiment helps to determine whether users value bandwidth for incoming traffic more than for outgoing traffic, and also reveals differences in effective line utilization. In the *Byte Volume* experiment, users face per-byte charges. After the subjects have become acquainted with both time- and volume-based pricing, the *Combined Volume Bandwidth* experiment offers them the choice of being charged on the basis of minutes, bytes, or a combination of both. The experiment aims to elicit their preferences towards one of these charging principles. Finally, the *Flat Rate Buy Out* experiment features a time-based pricing structure with a flat rate buy out option to examine the total value which users place on access at different bandwidths.

The remainder of the article is organized as follows: We first briefly describe the experimental setup and technical environment in which INDEX operates (a detailed overview of the technology, setup and design of the entire INDEX Project can be found in [3]). The third section characterizes the subject population and provides design details of the experiments conducted. The fourth section deals with the analysis of the aggregated data. After presenting some measurement data on prices and expenditure, we compare the experiments in terms of the average number of bytes transmitted and the amount of time that our subjects spend on the Internet.
2. Experimental Setup

2.1. INDEX Access Network Provision

The INDEX access network provides IP service over dedicated, 128kbps ISDN lines between the subjects’ homes and the INDEX Project Network Operations Center. For this purpose, INDEX loans a pre-configured Cisco 762 ISDN router to each subject participating in the experiment and installs an ISDN phone line at their home. The 128kbps basic rate interface lines coming from the subjects’ homes are then multiplexed over ISDN primary rate lines at the Pacific Bell central office before they reach the INDEX Project Network. In contrast to common industry practice, the whole network is heavily overprovisioned to make sure that none of the subjects experience deteriorations of their selected quality level due to potential bottlenecks at the INDEX access network.

![INDEX Network Diagram](image-url)

At the INDEX network, all IP packets go through either a Cisco 7507 or 7513 Internet router. These routers forward all outbound traffic to a set of Billing Gateways (BGWs) specifically designed to meter usage and adjust the service quality of individual connections. All traffic on behalf of a given user is combined at the Billing Gateways, so that the quality for this bundle can then be controlled accordingly. The INDEX network is connected to the outside world through a Cisco 7200 router that is directly attached to the UC Berkeley 100 Mbps FDDI backbone.
2.2. User Interaction, Accounting and Billing

INDEX uses a locally developed system for metering individual subject usage. The user interacts with this system by means of the “Control Center”, a Java application running on the user’s computer. This is the central application enabling users to select different Qualities of Service and control their usage of network resources. Apart from functions for login and authentication, it consists of panels informing the user about the current experiment, the price schedule currently in effect and the possible choices. The subjects can choose a service quality by clicking on a button and change the Quality of Service even during an active session. The Control Center also provides usage feedback by displaying a summary of charges accumulated over the session, the day and the month.

![INDEX Project "Control Center"

Figure 2. INDEX User Interface ("Control Center")

The Control Center application communicates user choices and selected quality levels as control data to the “supervisor” process. This supervisor process informs the Billing Gateway to treat this user’s connections according to the selected quality level. The Billing Gateway in turn meters the traffic and reports back to the supervisor process. User traffic is recorded at a fairly detailed level for both billing purposes and subsequent off-line analysis.
2.3. Network QoS Emulation

After a subject has chosen a desired quality level, the QoS must be adjusted (i.e., degraded) accordingly. To achieve this, the INDEX Billing Gateways do not only measure network usage, but they also exercise a form of admission control to selectively degrade the performance of connections (e.g., all connections on behalf of a given subject). User quality choices map to entry points of an internal “emulated network” composed of different elements including leaky bucket, random router and packet delay or packet drop. This behavior can be altered quickly in response to subject choices or experimentally controlled processes.

3. Experimental Design

3.1. Subject Population

INDEX has recruited subjects affiliated with the University of California at Berkeley (students, faculty, staff). As of December 1999, there is data on the first 70+ subjects recruited for the project. The data used for this article covers the period from April 1998 to February 1999. All subjects go through the same sequence of experiments. Because not all of the subjects joined INDEX at the same time, some of them had not yet completed all experiments when the analysis for this paper was done. The number of users that we report below for the earlier experiments is therefore moderately higher than for the later experiments.

INDEX recruitment procedures aim to obtain a suitable variation in field of study, expected Internet usage, computer sophistication, travel distance to campus, and general demographic characteristics. Nevertheless, it is evident that the sample, like any other, remains biased. In order to compensate for this sampling bias, we undertook a detailed demographic survey of our subject pool. Many of its questions are taken from a representative, population-projectable study conducted by Nielsen Media Research [2]. Once the entire subject pool has been recruited, an extrapolation model will be calibrated in order to generalize findings from the INDEX Project’s demographic base to the general U.S. population.

The demographic data permits a general characterization of the current subject pool. As expected, the subjects have a high level of education: 40 % have a post-graduate degree, 17 % some post-graduate school experience and 20 % a bachelor’s degree. 19 % are currently in college or have some college experience. High School represents the highest level of schooling for only 4 % of the
subjects. Most INDEX subjects are also experienced Internet/computer users: 92% first used the Internet three or more years ago (compared to only 9% in the Nielsen survey), and 88% (Nielsen 49%) have been computer users for at least five years. These numbers, combined with other data on type and frequency of computer and Internet usage, suggest that the current INDEX subject population is more representative of tomorrow’s user generation than of the present general U.S. population. Apart from the significant sample-specific characteristics related to education and computer experience, the general demographic base of our subject pool spans a wide range of attribute values. The income distribution is remarkably widespread, as can be seen in Figure 3. Significant differences between INDEX data and Nielsen data can only be found in the income ranges from $20k to 29.9k, $30k to 39.9k and > $100k. The subjects’ age distribution ranges from 20 to 73 years with an average age of 35 and a median of 29 years.

3.2. Design Details

Non-experimental studies are forced to rely on cross-sectional variation in price and demand to infer the price elasticity. In contrast, INDEX varies prices during the experiments to measure the demand response for each individual. All experiments are preceded by a free trial week that provides reference data and
allows the subjects to become familiar with the pricing structure.

3.2.1. Variable Symmetric Bandwidth Pricing

The first experiment faced by all subjects, Variable Symmetric Bandwidth, allows users to choose between six different access link bandwidths (8 kbps, 16 kbps, 32 kbps, 64 kbps, 96 kbps, 128 kbps). It permits to examine the price elasticity of demand and addresses the question of whether individuals value high access link bandwidths sufficiently to pay higher prices. The bandwidth selection can be changed instantaneously, even during an active session. Subjects are charged a per-minute rate that depends on the selected connection speed. Prices increase with bandwidth. The first five weeks of this six-week long experiment feature weekly changes of the price schedule. During the last week of this experiment, prices change daily.

The 8 kbps service is priced at zero cents per minute. The price for each bandwidth above 8 kbps is the sum of the price for the next lower bandwidth and an independent random price increment. The exact algorithm for generating price increments was designed to produce a vector of strictly increasing prices: $F(p_{incr}) = p_{min} + \gamma \cdot \alpha q^\theta$ with $p_{min} = 0.1$, $\alpha = 2.8$, $\theta = \frac{10}{3}$ where the factor $\gamma$ equals 0.6 for the increment from 8 kbps to 16 kbps, 0.7 for the increment from 16 to 32 kbps and 2.0 for all other increments. $q$ is a long-period uniform random deviate between 0 and 1 exclusive of the endpoint values. Setting $\theta$ at $\frac{10}{3}$ produces a distribution with most mass farther away from $p_{min}$ and a shorter right hand tail. This formula yields a distribution of prices from a minimum of 0.1 c/min for 16 kbps service to a theoretical maximum of 20.94 c/min for 128 kbps service with smoothness in the price intervals. It provides many low-priced alternatives for low-speed choices while still allowing exploration of the high-price range.

3.2.2. Variable Asymmetric Bandwidth Pricing

The Variable Asymmetric Bandwidth experiment differs from the first experiment in only one aspect: Subjects can choose different bandwidths for traffic from the Internet and to the Internet separately. This experiment is motivated by access technologies with different data rates for down-stream and up-stream traffic (e.g. ADSL and CATV). In addition, the experiment seeks to determine whether individuals value bandwidth for in-bound traffic differently than bandwidth for out-bound traffic.

The pricing structure is based on the algorithm of the Variable Symmetric
Bandwidth experiment. To ensure that a subject would have the same bill for the same exact service in the absence of behavioral changes, and to make the results from the two experiments directly comparable, $\gamma$ is conceptually cut in half. The resulting prices are then applied separately to bandwidth for in-bound and out-bound traffic, i.e. the price for a given service class (8 kbps, 16 kbps, 32 kbps, 64 kbps, 96 kbps, 128 kbps) amounts to half of the price in the first experiment.

3.2.3. Byte Volume

In the Byte Volume experiment, subjects face per-byte charges that change weekly during the six weeks of the experiment. This pricing structure reflects actual network usage. It also has attractive properties for congestion control on the basis that service degradation occurs due to network traffic. This pricing structure also constitutes a departure from traditional telephone-oriented, per-minute pricing to which individuals are accustomed. The experiment seeks to explore whether users understand the basis for such prices, and the price sensitivity of the amount of traffic generated by users.

The pricing structure is straightforward. Users have two options: Free 8 kbps service or 128 kbps service billed on a per-byte basis. Prices are varied during the experiment from 0.1 to 20 c/mbyte. This range is divided into three segments (low/medium/high). In order to make sure that a subject faces prices out of all three segments, two draws from a uniform distribution within each segment are performed. The resulting six prices are then permuted and presented to users in a random order to eliminate potential time-dependent effects and intertemporal substitution.

3.2.4. Combined Volume Bandwidth Pricing

The Volume Bandwidth experiment was designed to understand the preference structure of individuals in regard to their inclination towards time- or volume-based charges and whether their choices of appropriate self-selecting tariffs are economically rational. The price structure is based on different combinations of per-minute and per-byte charges. The subjects are offered the choice of being charged exclusively on the basis of either minutes or bytes, or a combination of both. Subjects are presented with a choice of six different bandwidths as in the Variable Symmetric Bandwidth experiment.

The underlying price schedules feature a constant volume price and variable
per-minute prices for capacity that increase with bandwidth in a linear fashion. As shown below, the full per-megabyte price is a random draw from three different prices \( p \in \{12 \text{ cents}, 8 \text{ cents}, 4 \text{ cents}\} \). The linear combination of the volume- and time-based charges is determined by five discrete values \( \alpha \in \{0, 0.25, 0.5, 0.75, 1\} \). The resulting price vectors are shown in Table 1. During the first 6 weeks of the 12-week long experiment, \( \alpha \) is fixed to let subjects become acquainted with the tariff structure. After that, subjects choose their \( \alpha \) (i.e. the weights of the per-minute/per-byte combination) at the beginning of each week. The chosen combination then stays in effect for the entire week and cannot be changed.

<table>
<thead>
<tr>
<th>Bandwidth (kbps)</th>
<th>( \alpha = 0 )</th>
<th>( \alpha = 0.25 )</th>
<th>( \alpha = 0.5 )</th>
<th>( \alpha = 0.75 )</th>
<th>( \alpha = 1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( c/\text{min} )</td>
<td>( c/\text{mb} )</td>
<td>( c/\text{min} )</td>
<td>( c/\text{mb} )</td>
<td>( c/\text{min} )</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>{12,8,4}</td>
<td>0.1</td>
<td>{9,6,3}</td>
<td>0.2</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
<td>{12,8,4}</td>
<td>0.2</td>
<td>{9,6,3}</td>
<td>0.4</td>
</tr>
<tr>
<td>64</td>
<td>0</td>
<td>{12,8,4}</td>
<td>0.4</td>
<td>{9,6,3}</td>
<td>0.8</td>
</tr>
<tr>
<td>96</td>
<td>0</td>
<td>{12,8,4}</td>
<td>0.6</td>
<td>{9,6,3}</td>
<td>1.2</td>
</tr>
<tr>
<td>128</td>
<td>0</td>
<td>{12,8,4}</td>
<td>0.8</td>
<td>{9,6,3}</td>
<td>1.6</td>
</tr>
</tbody>
</table>

### 3.2.5. Flat Rate Buy Out

Featuring a time-based pricing structure with a flat rate buy out option, this experiment examines the total value which users place on unmetered access at different bandwidths. By obtaining this measure of user heterogeneity, the design of future Internet service plans should be helped greatly. The experiment offers the same bandwidth choices and per-minute pricing structure as in the Combined Volume Bandwidth experiment. However, at the beginning of each week of the 10 week long experiment, subjects are given the choice of buying out any of the bandwidths higher than 8 kbps in exchange for unlimited usage at that and all lower bandwidths for the duration of the week. The price for this flat rate buy out option increases linearly with the bandwidth that is being bought out. Once made, the buy-out decision is binding for that week and can not be changed until the following week. In contrast to most commercial flat-rate service plans, however, the subjects can also selectively use higher bandwidths by paying a
discounted per-minute charge.

The weekly buy-out price $\beta$ for 128 kbps forms the basis for all other buy-out options and is varied during the experiment from $1$ to $20$. As in the *Byte Volume* experiment, this price range is divided into three segments. Three draws with replacement from the low and high segments and four draws from the medium segment yield the 128 kbps buy-out prices for all ten weeks. The buy-out prices for 96, 64, 32 and 16 kbps are derived from the 128 kbps buy-out prices by multiplying them by 0.75, 0.5, 0.25 and 0.125, respectively. The resulting price sets for the individual weeks are then permuted and revealed to the subjects one at a time. Buying out a particular bandwidth also reduces the per-minute prices of all bandwidths higher than the one bought out. The resulting per-minute price vectors are summarized in Table 2.

<table>
<thead>
<tr>
<th>Bandwidth bought out</th>
<th>Flat Rate</th>
<th>Per-Minute Price (in cents)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(none)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16 kbps</td>
<td>0.125 $\cdot \beta$</td>
<td>0.4 0.8 1.6 2.4 3.2</td>
</tr>
<tr>
<td>32 kbps</td>
<td>0.25 $\cdot \beta$</td>
<td>0 0 0.4 1.2 2.0 2.8</td>
</tr>
<tr>
<td>64 kbps</td>
<td>0.5 $\cdot \beta$</td>
<td>0 0 0 0.8 1.6</td>
</tr>
<tr>
<td>96 kbps</td>
<td>0.75 $\cdot \beta$</td>
<td>0 0 0 0 0.8</td>
</tr>
<tr>
<td>128 kbps</td>
<td>$\beta$</td>
<td>0 0 0 0 0 0</td>
</tr>
</tbody>
</table>

4. **Analysis**

Regarding user acceptance of usage-based pricing, some interesting insights can be drawn from our subjects’ responses to some related questions from our stated preference survey. On a scale of 1 to 5, with 1 meaning “strongly disagree” and 5 meaning “strongly agree”, subjects could indicate how much they agreed or disagreed with the following statements: (1) “There are sufficient network resources right now so that Internet transmission quality is very good”; (2) “There will be sufficient network resources in the future so Internet transmission quality will be very good”; (3) “Available network resources should be distributed in such a way that the users who value them most should get the best quality, while users who value them less should get worse quality”; and (4) “Available network
resources should be distributed in such a way that the users who are willing to pay the most should get the best quality, while users willing to pay less should get worse quality”. The last two questions have been the subject of intense debate. Economists generally assume the terms “valuation” and “willingness to pay” to be identical; we split the issue into two separate questions to test whether this assumption would hold in this specific environment.

As Figure 4 shows, almost all of our subjects agree that today’s Internet provides insufficient network performance, but in their opinion the situation will take a turn for the better in the future. As illustrated in the right graph of Figure 4, the answers to questions 3 and 4 are less definite. However, the majority of the subjects did express their willingness to accept changes in the way Internet resources are distributed. Looking at the deviations in the distribution of answers, we did indeed find differences. There seems to be a slightly more visible reluctance towards “valuation”-based network resource allocation when it is taken to its final consequence of being made financially accountable. Although more subjects seem to believe that user valuation can allocate resources better than a performance-dependent service charge, 41% still leaned towards approval of price-based resource allocation (response range 4 to 5), vs. 39% that to some extent disagreed (range 1 to 2). Because a survey can only collect data on stated preferences, these results can however be affected by strategic misrepresentation or justification bias. Therefore, the differences in the distribution of acceptance patterns do not seem significant enough to permit a more general conclusion.
What these answers show is that although our subjects have not yet experienced service-dependent prices when taking the survey, they are already cautiously inclined towards such a potential solution for today's Internet congestion problems. The revealed preference data presented in the next section will show the subjects' acceptance of usage-based pricing in greater detail.

4.1. Acceptance of Experiments

The subjects' response to the offered service prices is reflected in the average cost per megabyte and the average cost per minute they are willing to pay. The average cost per megabyte is defined as the ratio of total expenditure to the number of bytes transmitted at priced services. The average cost per minute is the ratio of total expenditure to the number of minutes connected to the Internet at priced services. It should be noted that the aggregated data presented here hides the large variation in prices faced by individual users and, consequently, the large variation in their demand.

Table 3
Cost per megabyte

<table>
<thead>
<tr>
<th>experiment</th>
<th>cost per mb</th>
<th>expenditure</th>
<th>bytes sent</th>
</tr>
</thead>
<tbody>
<tr>
<td>sym. bw.</td>
<td>18.1 c</td>
<td>170649 c</td>
<td>9431 mb</td>
</tr>
<tr>
<td>asym. bw.</td>
<td>18.8 c</td>
<td>131088 c</td>
<td>6979 mb</td>
</tr>
<tr>
<td>byte vol.</td>
<td>8.9 c</td>
<td>80610 c</td>
<td>9094 mb</td>
</tr>
<tr>
<td>vol. bw.</td>
<td>12.5 c</td>
<td>204933 c</td>
<td>16420 mb</td>
</tr>
<tr>
<td>flat rate bo.</td>
<td>7.2 c</td>
<td>147935 c</td>
<td>20515 mb</td>
</tr>
</tbody>
</table>

Table 4
Cost per minute

<table>
<thead>
<tr>
<th>experiment</th>
<th>cost per min</th>
<th>expenditure</th>
<th>connect time</th>
</tr>
</thead>
<tbody>
<tr>
<td>sym. bw.</td>
<td>1.1 c</td>
<td>170649 c</td>
<td>9211210 sec</td>
</tr>
<tr>
<td>asym. bw.</td>
<td>1.1 c</td>
<td>131088 c</td>
<td>7174222 sec</td>
</tr>
<tr>
<td>byte vol.</td>
<td>0.2 c</td>
<td>80610 c</td>
<td>26444546 sec</td>
</tr>
<tr>
<td>vol. bw.</td>
<td>0.4 c</td>
<td>204933 c</td>
<td>27768522 sec</td>
</tr>
<tr>
<td>flat rate bo.</td>
<td>0.2 c</td>
<td>147935 c</td>
<td>44996552 sec</td>
</tr>
</tbody>
</table>

As seen in Table 3 and Table 4, the average cost per minute of being online and the derived average cost per megabyte are nearly equal for the Variable Sym-
metric Bandwidth and the Variable Asymmetric Bandwidth experiments. There is a significant difference between the per-minute experiments and the per-byte experiment, because the average offered price in the Byte Volume experiment is lower. In the Combined Volume Bandwidth experiment, the cost per megabyte is relatively high, while the cost per minute is quite low. Being able to select their mix of per-byte and per-minute pricing allowed the subjects to adjust their weekly service plan to their individual usage profile. As will be explained in more detail in the next section, subjects apparently preferred the convenience of volume-based pricing. In comparison, the optimization process required by flat-rate pricing schemes is much rougher. As a consequence, flat-rate pricing schemes encourage usage because once the fixed charge has been paid, users do not have an incentive to further optimize marginal utility and marginal cost for every single activity they choose to engage in. The Flat Rate Buy Out experiment is an impressive testimony: Connect time and traffic increase dramatically, yet the costs per minute and per megabyte are the lowest of all experiments.

4.2. Demand Change under Usage-Based Pricing

4.2.1. Connection Utilization

The change in demand under usage-based pricing is an indication of preferred pricing schemes. The first change in user demand is visible in connection utilization, the percentage of purchased connection capacity that is actually used. Connection capacity is defined as the amount of bytes which could have been sent by a user fully utilizing all purchased bandwidths. Table 5 displays the connection capacity, the number of bytes actually sent, and the connection utilization for the free trial periods and the five experiments.

<table>
<thead>
<tr>
<th>experiment</th>
<th>utilization</th>
<th>capacity</th>
<th>in-b byte</th>
<th>out-b byte</th>
</tr>
</thead>
<tbody>
<tr>
<td>free trial p.</td>
<td>1.8 %</td>
<td>6.6e+11</td>
<td>1.1e+10</td>
<td>1.3e+09</td>
</tr>
<tr>
<td>sym. bw.</td>
<td>7.5 %</td>
<td>1.3e+11</td>
<td>7.8e+09</td>
<td>1.7e+09</td>
</tr>
<tr>
<td>asym. bw.</td>
<td>9.6 %</td>
<td>7.3e+10</td>
<td>6.5e+09</td>
<td>5.0e+08</td>
</tr>
<tr>
<td>byte vol.</td>
<td>1.1 %</td>
<td>8.5e+11</td>
<td>8.0e+09</td>
<td>1.1e+09</td>
</tr>
<tr>
<td>vol. bw.</td>
<td>2.0 %</td>
<td>8.1e+11</td>
<td>1.4e+10</td>
<td>2.1e+09</td>
</tr>
<tr>
<td>flat rate bw.</td>
<td>1.9 %</td>
<td>1.1e+12</td>
<td>1.8e+10</td>
<td>2.8e+09</td>
</tr>
</tbody>
</table>
In the per-byte pricing experiments and the free trial weeks, there is no financial incentive for the subjects to disconnect or switch back to 8 kbps, so utilization is naturally lower than in the other experiments. As depicted in Table 5, the connection utilization differs considerably between time-based and traffic-based pricing experiments. The utilization for the per-minute pricing experiments is 4.2 to 5.3 times higher than for the free trial periods. Evidently, when subjects face per-minute prices, they economize by switching to the disconnect state or the free 8 kbps service after using the Internet.

Of particular interest is the difference between connection utilization in the Variable Symmetric Bandwidth experiment and the Variable Asymmetric Bandwidth experiment. Subjects took advantage of the offered flexibility to increase utilization in the Variable Asymmetric Bandwidth experiment. These results are encouraging – they show that our subjects understood and exploited the flexibility of advanced pricing schemes if these schemes are accompanied by the proper economic incentives. Considering the 7:1 ratio between total in-bound and out-bound traffic, the potential savings to be gained from lowering the out-bound bandwidth are obvious.

After the subjects had gone through the first three experiments and collected experience with both time- and volume-based pricing schemes, it turned out to be interesting to see how they behaved when given the choice of being billed either per minute or per byte. In the Combined Volume Bandwidth experiment, we saw a strong preference for byte volume pricing. 77% of all self-selected combination factors \( \alpha \) were set at 0.25 or 0, expressing a strong inclination towards byte volume pricing. Only 6% of all self-selected choices had a combination factor set at 1. The low connection utilization in this experiment also confirms this observation. We believe that the perceived convenience of “always on”-Internet service is responsible for this preference: Under byte volume pricing, there is no financial incentive to disconnect from the network, so users can stay online all the time (ready for incoming traffic like e-mail) while only paying for the bytes they actually transmit.

A similar reasoning also applies to the Flat Rate Buy Out experiment. There is a long history of consumer preference for flat rate tariffs in telecommunications. Every INDEX subject did at least once choose a flat-rate buy out option, and the vast majority (85%) did so in at least half of their buy-out decisions. As expected, compared to the weeks in which subjects opted for a measured rate, there is a significant increase in traffic during those bought out weeks. A low
utilization rate is a natural companion. However, it is important to note that this behavior was also accompanied by an evident appreciation of the offered flexibility to break out of the flat rate option: Of all the subjects that did not always buy out the full 128 kbps capacity, 83 % did at least once switch from their bandwidths covered by the flat rate to a higher measured-rate bandwidth (see [1] for a detailed analysis of this experiment).

![Figure 5. Left: Average daily connect time. Right: Average number of bytes transmitted](image)

### 4.2.2. Connect Time

The change in demand can also be seen by comparing the connect times for the free 8 kbps service and the services at higher bandwidths (16 kbps to 128 kbps). The left-hand side of Figure 5 illustrates the users' average daily connect time. Since the number of subjects is not the same in all experiments, the expenditures and connect time for different experiments cannot be compared directly. Therefore, we normalized the averages by dividing the measured values by the number of user-days. A user-day is defined as a day during which the user was actually using the service. Table 6 shows the number of users and user-days in each experiment.

<table>
<thead>
<tr>
<th>experiment</th>
<th>free t.p.</th>
<th>sym.bw.</th>
<th>asym.bw.</th>
<th>byte v.</th>
<th>v.bw.</th>
<th>flat bo.</th>
</tr>
</thead>
<tbody>
<tr>
<td># of users</td>
<td>71</td>
<td>72</td>
<td>66</td>
<td>59</td>
<td>51</td>
<td>40</td>
</tr>
<tr>
<td># of user-days</td>
<td>1002</td>
<td>2271</td>
<td>1799</td>
<td>1523</td>
<td>2605</td>
<td>1801</td>
</tr>
</tbody>
</table>

Table 6
Number of user-days
As expected, in the free trial periods, subjects stay connected longer at higher bandwidths than in all other experiments, except one notable exception: The flat rate experiment, during which average daily connect time at bandwidths above 8 kbps was even longer. When subjects face per-byte pricing, the change in behavior is only minor, although the relative proportions of traffic types change considerably: There is a scant decrease in connect time at bandwidths above 8 kbps and a significant increase of connect time at 8 kbps. Under per-minute pricing, however, user behavior is dramatically different. For both time-based experiments, the time spent online at 8 kbps approximately equals the connect time for services at higher bandwidths in the free trial period. In other words, the ratio of paid vs. unpaid connect time has effectively been reversed. Since the Volume Bandwidth experiment features a combined pricing structure, one would anticipate the disparities in connect time under time- and volume-based charges to roughly cancel out in this experiment. We in fact found connect times at and above 8 kbps to approximately balance each other in this experiment. As a general observation, it is also interesting to note that the total connect time per user-day does not vary more than about 9% across all the different experiments.

Although the overall time that users set aside for Internet usage on a given day varied only within these relatively tight bounds, the variations in connect time over different access speeds and the change in connection utilization demonstrate that subjects adapt their usage pattern to the different pricing structures. In the per-minute pricing experiments, they increase utilization and reduce priced connect time by switching back and forth from the free 8 kbps service to the priced services.

4.2.3. Traffic Generation

The impact of usage-based pricing on user behavior can also be observed when looking at the average number of bytes transmitted per user-day (see section 4.2.2). The right-hand side of Figure 5 shows the average number of bytes sent per experiment and per service class (8 kbps vs. all other bandwidths).

In the free service experiment, on average 12 mbyte are transmitted at high bandwidth services, versus 6 mbyte in the per-byte pricing experiment. Also, under per-byte pricing, the number of bytes sent at 8 kbps increased. Comparing the Variable Symmetric Bandwidth and the Variable Asymmetric Bandwidth experiment, we can point out a notable property of user behavior. We see that the subjects consumed about the same total amount of bytes per day in both exper-
iments. The average expenditure per day for the two experiments is also almost identical. But a look at the distribution of expenditures reveals an interesting change (Figure 6): Subjects spent 50% less money per user-day on out-bound traffic than in the Variable Symmetric Bandwidth experiment. Moreover, as we can also see in Figure 6, they also spent the money saved this way on in-bound traffic.

![Bar chart showing average expenditure](image)

**Figure 6.** Average expenditure

When the subjects could influence the way their money was allocated, they spent significantly more money on in-bound than on out-bound traffic. The expenses for out-bound traffic accounted for less than 35% of total expenses. When the subjects paid for the exact amount of traffic that they generated in the *Byte Volume* experiment, that percentage came even further down to about one tenth of total expenditures.

Although both connect time and amount of transferred bytes soared in the *Flat Rate Buy Out Experiment*, the expenditure pattern is virtually the same as in the *Variable Symmetric Bandwidth* experiment. At this granularity level, the data does however hide information about the variation among users, which we will explore in the next section.
4.3. User Segmentation

Whenever the marginal cost of network resource utilization is zero (like under a flat-rate pricing scheme), light users effectively subsidize heavy users that are not made financially accountable for their consumption of resources. The extent of this cross-subsidy depends on the variation in demand among users. In this section, we show that this variation in demand is indeed large and that consequently, the majority of Internet users should benefit from usage-based pricing. To demonstrate that a fair pricing mechanism needs to have a usage-based component, we examine user expenditure under usage-based pricing schemes (byte volume- and time-based pricing) and an imputed flat-rate pricing scheme.

To show the variation in resource consumption, we first calculate the cumulative expenditure for the Variable Symmetric Bandwidth experiment. After aggregating and normalizing the expenditure data on a per-user basis, we rank users by their traffic volume, processing heaviest users first. The resulting upper curve in Figure 7 plots the cumulative expenditure versus cumulative traffic, starting from the heaviest users close to the graph's origin and proceeding to the lightest users on the far right. Each dot represents one subject. We now compare this actual distribution of expenditures with the distribution of an imputed flat-rate tariff. We impute a flat-rate expenditure to each user by dividing the total actual revenues by the number of users participating in this experiment. The lower curve in Figure 7 represents the resulting flat-rate tariff.

A comparison of those two curves shows that 18 of the 22 heaviest users (31% of the subject population) had higher actual expenditures than they would have had under flat-rate pricing. As illustrated in Figure 7, these 18 users accounted for over 10 gbytes of actual traffic and over 60% of total expenditures. But there are also 4 of the remaining 50 low-usage subjects that did not generate that much traffic but paid more than the imputed flat-rate tariff. In total, 69% of all subjects are better off in the Variable Symmetric Bandwidth pricing experiment.

We also made an equivalent investigation for the Byte Volume experiment. We used the same procedure as in the Variable Symmetric Bandwidth experiment to obtain the curves shown in Figure 8. The results of this investigation are even more convincing. The 13 heaviest users out of all 59 subjects (22% of the subject population) that had completed the experiment had to pay a higher
charge compared to the imputed flat-rate pricing. All remaining 46 subjects (78%) were better off under Byte Volume pricing. The distribution is even more skewed than in the Variable Symmetric Bandwidth experiment – the 13 heaviest users in the Byte Volume experiment account for more than 6 gbytes of traffic and more than 70% of total expenditures.

Another advantage of usage-based pricing can be illustrated by looking at the cumulative distribution of traffic and the effect of usage-based pricing on traffic generation. Figure 9 shows the cumulative distribution for the free trial periods, the time-based Variable Bandwidth experiments and the Byte Volume experiment. The x-axis represents the number of subjects (in percent) that participated in a particular experiment. We again ranked users by their traffic volume, sorting the heaviest Internet users out first. The y-axis represents the cumulative percentage of bytes transmitted during an experiment.

All four curves illustrate that the amount of bytes generated by all users is not equally distributed, even under usage-based pricing: In all experiments, priced or unpriced, 30% of the subjects are responsible for over 70% of all traffic. Furthermore, Figure 9 shows that time-based pricing reduces the number of bytes generated by the high-volume users significantly. Most interesting, however, is the slope of the Free Trial Period curve. Starting out with byte counts well above the priced experiments, this curve crosses all other curves on its way to the right.
side of the graph. This nicely demonstrates the disciplining effects of usage-based pricing: The consumption of the heaviest users is forced down, leading to a more balanced overall distribution.
5. Conclusion

This paper presented an overview of results from the INternet Demand Experiment (INDEX). We illustrated the change in individual demand for Internet access under different usage-based pricing structures. In particular, we compared connection utilization, bytes transmitted, and connect time for five experiments: Variable Symmetric Bandwidth, Variable Asymmetric Bandwidth, Byte Volume, Combined Volume Bandwidth, and the Flat Rate Buy Out experiment.

We have shown that demand is very sensitive towards different pricing structures. While the overall time that our subjects set aside for Internet usage varied only within relatively tight bounds, we were able to demonstrate that the subjects understood and exploited the flexibility of advanced pricing schemes for their own advantage. Our subjects were able to increase connection utilization in the Variable Asymmetric Bandwidth experiment although it required some knowledge about in-bound and out-bound traffic. In the per-minute pricing experiments, they significantly reduced the time they were connected to the Internet at priced bandwidths compared to the Byte Volume experiment, which also had the lowest connection utilization. While most subjects have an evident preference for flat-rate pricing, the vast majority also appreciates and makes use of tariff options that permit quick reactions to changing demand – as witnessed by the widespread temporary use of higher bandwidths that were not covered by a flat-rate tariff.

Our findings also confirm the existence of large variations in user demand. The disparity between heavy and light Internet users is likely to widen as Internet penetration increases. Under such circumstances, equitable pricing mechanisms are crucial for avoiding large inefficiencies and cross-subsidies. We demonstrated that usage-based pricing fulfills these requirements. It is a fair way to charge people and leads to efficient use of network resources. Under a flat-rate tariff that is set to recover the same revenue as usage-based fees, 69% of our subjects would have to subsidize the traffic generated by the remaining 31%. Those 69% are better off under usage-based pricing. We conclude that these services increase the overall value of the network if they are available to both light and heavy users on an on-demand basis.

Other analyses of INDEX data seek to estimate individual user preferences. This real-world data can support network provisioning decisions on the way towards an Integrated Services Internet that will provide a universal platform for ever more users and services.
References


