A LONGITUDINAL EVALUATION OF HTTP TRAFFIC

by

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Abstract

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In this thesis we analyze over five years of HTTP traffic observed at a small research institute and eight months of HTTP traffic from a small residential population to characterize the evolution of various facets of web operation. We leverage the longitudinal data to study various characteristics of the traffic, from client and server behavior to object and connection characteristics. In addition, we assess how the delivery of content is structured, including the use of browser caches, the efficacy of network-based proxy caches, and the use of content delivery networks.

Chapter 1

Introduction

The Hypertext Transfer Protocol [BLFBl$^+$94, FGM$^+$99] has been an influential protocol on the Internet over the past fifteen years. While the protocol has undergone some changes over that time period, its widespread implementation, simplicity, and flexibility have resulted in its usage not only as a platform for direct dissemination of information (for example, formatted with HTML [BLC93]), but also as a crucial building block for other applications such as BitTorrent [Coh03] and Youtube [you].

The flexibility exhibited by HTTP as both an information delivery system and as a component of more complex web-based applications has resulted in an ever-changing development and server landscape. Furthermore, the use of a myriad number of web browsers (each with potential behavior changes from version to version) has the ability to effect changes in HTTP traffic from the client side. Given this dynamic state, it behooves researchers to frequently re-appraise the state of HTTP traffic on the Internet in order to understand the new and different ways in which HTTP is being used.

To further this goal, we examine HTTP traffic logs collected from the border between the local enterprise and the Internet for two edge networks serving two distinct user populations. The first set consists of over five years of data from a small research institute, while the second set consists of eight months of data from a small residential community.

While our user populations are small, the longevity of our data allows us to glean insight from studying the ways in which usage of the web changes over time. Furthermore, having data from two distinct vantage points allows us to better evaluate those properties of web use that are intransient, versus those that are population-specific.

Our contribution serves to both inform the community's mental model on how HTTP is currently used in the wild and to remind the community that web behavior can and does sometimes change quickly. In addition, a multi-faceted view of web content delivery is useful in setting up realistic testbeds and simulations to accurately reflect the structure of today's web.

1.1 Areas of Study

In the following chapters, we explore several facets of web traffic. We begin by discussing related work in Chapter 2. In Chapter 3, we provide an overview of the general characteristics of our traces, including counts of HTTP requests, connections, HTTPS connections, and the number of server IPs and hostnames encountered.

In Chapter 4, we examine the basic properties of HTTP transactions. We show the volumes of the different types of HTTP requests, and then move on to examine HTTP object sizes. An understanding of HTTP transaction sizes is crucial for applications such as HTTP cache design, constructing models of web traffic, and provisioning web services. We also examine the effects of a design decision by a major webmail service.

In Chapter 5, we study properties of the TCP connections underlying HTTP traffic. Metrics such as connection duration have a direct bearing on the design of application-layer switches/load balancers and web server timeout configuration. Furthermore, studying the elapsed time from a connection's establishment until its first request is relevant to claim-and-hold attacks (and the timeouts used to prevent them) as discussed in [AQRA10]. In addition, we study connection parallelism. Connection parallelism is of interest to several audiences – increased levels of parallism in recent years means designers of network hardware and software may have to cope with more TCP connections than in the past. Also, web server administrators may have to accept an increase in the number of connections they might see from any given IP address. Finally, protocol designers should be interested in the congestion control effects of increased parallelization – an increased number of flows means a single loss will only trigger a reduction in TCP's congestion window for a portion of the true load imposed on the network path.

We move on to examine client behavior in Chapter 6, beginning by studying the most popular traffic destinations by top-level domain. We continue by exploring the content types downloaded by our users, which we believe will help inform the community's mental model on where to focus optimization efforts. For example, many web server benchmarks are performed against static content, however our study finds that over the past five years, the number of PHP objects accessed has surpassed the number of HTML objects, indicating a fundamental shift in the duty of standard web server. We move on to examine the distribution of web requests by object, which is central to the design and operation of web caches. We also take a more in-depth look at caching in particular, examining both the savings we encounter from browser-based caches already implemented, as well as the potential savings of a border proxy cache. As caching relieves both latency (enhancing the end-user experience) and saves bandwidth (and money), caching research is relevant to anyone responsible for the web access of a population of users.

In Chapter 7, we explore the structure of today's web. We start by discussing the relationship between IP addresses and hostnames, examining trends in both the usage of CDNs and shared web hosting. We continue by analyzing the usage of a popular CDN, and test its claim that it provides between 15-30% of bytes sent worldwide.

We summarize our findings in Chapter 8 and discuss future research directions in Chapter 9. This thesis is based in part on work published in [CAP10].

Chapter 2

Related Work

As the literature is filled with thousands of papers that empirically assess the web (as a small example, the 2011 WWW conference included 90 research papers), we will address some of the broader categories of web measurement.

2.1 General Internet Traffic Classification

Numerous studies have been performed to characterize the Internet's overall traffic patterns. Here, we discuss some of these works with respect to their characterization of HTTP traffic.

Near the dawn of web popularity in 1993 and 1994, Paxson discusses in [Pax94] that due to the exponential growth of HTTP (over a 500-fold increase from March 1992 to October 1993), HTTP would soon outpace the telnet in impact on the Internet. Still, HTTP was not at this point considered a "major" protocol on the Internet.

As early as April 1995 however, [Mah97] notes that HTTP had become the leading source of traffic on the NSFNET backbone. By 1997, HTTP consumed 55-70% of web traffic [TMW97]. However, by the year 2000, the amount of HTTP traffic as seen by one Internet exchange was holding at approximately 55% [MC00]. At this time, a number of new protocols had appeared, such Napster, RealAudio, and gaming traffic, eating into HTTP's dominance in terms of data volume.

In a study of P2P traffic classification, Karagianni et al. note that through 2003 and 2004, HTTP remains at slightly above 50% of traffic (by bytes), despite the growing influence of P2P traffic. By 2009 however, Feldmann et al. note in [MFPA] that HTTP traffic has increased back to nearly 60%. However, by this point HTTP is clearly used for much more than simply transferring hypertext and associated objects. For example, the authors note that 25% of all HTTP content type headers are video/flv – a popular content-type for video "streaming" sites such as Youtube [you]. A recent report [san11] finds HTTP website usage at approximately 18%, yet its separate characterization of Netflix traffic and Youtube traffic (25% and 10%, respectively) implies still more than 50% of bytes using the HTTP protocol.

Aside from the volume of HTTP traffic noted by the studies above, we observe that HTTP is now an essential part of many people's daily lives. Web-based email systems, web-based calendaring systems, online office suites, and online social networks running on HTTP have become critical components of the world's communication infrastructure.

2.2 HTTP Traffic Characterization

One of the first major efforts to characterize the usage of the World Wide Web (and therefore HTTP as well) was performed by Cunha, Bestavros, and Crovella in 1995 [CBC95]. While [CBC95] was performed using a widely deployed modified web browser as opposed to the packet logging used in our own study (and several others), the types of data collected in [CBC95] are similar to our own. The authors discuss the distribution of document sizes, the popular TLDs and file extensions accessed by their users, and the potentials impacts of caching.

One closely related work to our own is [HCJS03], in which the authors analyze TCP packet headers of port 80 traffic in order to make observations on trends in HTTP requests over time. The authors utilize three of their own traces, providing a small amount of data from 1999, 2001, and 2003. The authors also use results from Barford, Crovella, and others in previous papers to provide a look at the changes in HTTP traffic from 1995 to 2003. Unfortunately, the authors' lack of HTTP header data precluded any analysis of evolving content types or other such trends requiring packet data.

2.3 HTTP Modelling

As discussed above, HTTP has been a major component of overall IP traffic for over 15 years. Therefore, network operators and designers are obligated to account for the dynamics of HTTP traffic when designing networks. In order to do so however, one must have a model of how HTTP will in fact behave on a network.

One of the seminal works in this field is [AW96], where Arlitt and Williamson use logs obtained from six WWW servers in order to find invariants in web traffic. Across their six datasets, they find ten specific invariants which include: the success rate of lookups, the distribution of file types, the mean file transfer size, the proportion of distinct requests, the proportion of documents that are accessed only once, the file size distribution, the popularity of documents, file inter-reference times, the percentage of requests from remote sites, and the distribution of the sources of requests. While some of these items may still find a place in today's web (for example, the file size distributions may be similar across many sites today), others have been obsoleted due to changing web usage – for example, a website such as slashdot.org will have very few local accesses, whereas an institutional website such as case.edu will have a substantial amount of local accesses.

Another critical work in this field is [Den96], where Deng models HTTP traffic in light of it's ON/OFF pattern. In other words, when a user clicks on a web link, this typically produces a series of HTTP interactions where the desired page as well as all of its associated objects is downloaded (designated as "ON"), followed by a period during which the user is idle (or "OFF"). Deng attempts to model the distribution of three items:

the durations of "OFF" periods, the durations of "ON" periods, and finally, the inter-arrival times of requests during "ON" periods.

One year later, Mah [Mah97] further explored modelling HTTP traffic. In this work, Mah explores relationship between HTTP documents (an entire HTTP page with its associated objects) and HTTP files (individually requested items). Mah also explores the distributions of HTTP request and reply sizes. Like previous authors, Mah concludes that users rarely request many different documents from the same server in succession.

In an attempt to put these and the many other attempts to model aspects of HTTP traffic to good use, Barford and Crovella in [BC98] built a simulator of web traffic with an aim of allowing network and web server operators to load-test their websites with a reasonable approximation of real traffic. Furthermore, this model enabled researchers to create a realistic traffic workload for simulators and testbeds. The authors compare their similator, named "SURGE," to an already existing simulator known as "SPECweb96". The authors note that "SPECweb96" is designed to test a web server's ability to answer HTTP requests at a given rate, where as "SURGE" is designed to simulate the request patterns of a group of users of a given size. The authors note that in many cases, the SURGE workload required dramatically more CPU resources on the webserver than SPECweb96.

2.4 Characterization of Specific HTTP Traffic Types

Given the multitude of technologies that have developed "on top of" standard HTTP, it has become necessary to study the behavior of these technologies specifically in order to understand their effect on the Internet at large.

2.4.1 AJAX Traffic

One of the most significant technologies added to the web since its inception has been AJAX [Gar05]. Prior to AJAX, the vast majority of web traffic was caused either directly by a user's action (e.g., clickling a link to load a new page), or indirectly by the user's action (e.g., loading component objects for a given page). Furthermore, in order to update a page with new information, the entire page (or frame) had to be reloaded. AJAX and related technologies allow code running in the user's browser to make web requests for various purposes – for instance, to keep a list of emails or stock quotes current – and then update parts of a web page based upon data received.

In 2008, Schneider et al. [SAAF08] examined the impact of AJAX traffic at the network/HTTP level based upon traces from two large user populations. Some interesting conclusions drawn by these authors include: AJAX connections tend to last longer and span more requests than regular HTTP connections, often perform prefetching, and sometimes transfer far more bytes than their associated "regular" HTTP connections.

2.4.2 Internet Video Traffic

In [GALM07], the authors attempt to characterize the usage of Youtube at an educational institution. The authors conclude that while some traditional web strategies such as institution-level caches may be effective in coping with the amount of Youtube traffic, the sheer breadth of content available hurts the potential for caching this traffic. Also, the authors note that the size and long-running nature of Youtube transactions require substantial server capacity. A recent study [KKGZ11] of an online TV service called Hulu [hul] explores the possible benefits of caching and prefetching videos – finding that 50% hit rates can be achieved with caches sized in the tens of GB.

2.5 Caching

The dramatic increase of web traffic in the mid 90's necessitated some strategies by both end-user network and server operators in order to decrease traffic. The concept of caching is both simple and applicable several places in the path from a web content provider to an end user. One of the most simple forms of a cache is the browser cache – if a user has already downloaded a a particular object recently, there is no reason to re-fetch it if needed again. This scheme has been easily extended to the institutional case – if an object has already been recently downloaded by one user of an institution, there is no need for a subsequent request from another user at the same institution to re-fetch it from the origin site. Not only does such a scheme alleviate load on content provider servers and in access networks, but returning objects from a nearby cache also reduces the latency to retrieve such an object, thereby enhancing the user experience.

One of the first in-depth examinations of this concept of an institution-level cache was performed by Caceres et al in [CDF+98]. In this study, the authors examined not only the "hit rate", or percentage of requested data bytes that could be fulfilled by an institutional or ISP-level cache, but also the potential increase in consumed bandwidth when a client aborts a partial transfer of an HTTP document when the client's cache has already downloaded the entire document. Finally, the authors also propose using web proxy caches as connection caches, where TCP connections are maintained from the proxy to popular websites to avoid the latency of the TCP handshake.

Also in 1998, Barford et al. published [BBBC99] as re-examination of a prior work [CBC95] in order to specifically examine any changes in the cacheability of Internet content from 1995 to 1998. The authors find that the shared components of users' working sets had decreased over that time period, and that therefore institution-level caches had become somewhat less effective. In addition, the authors provide an analysis of the effectiveness of different cache-control algorithms.

In [Wan99], Wang discusses many of the early Internet caching schemes, including hierarchal caches, distributed caching, hybrid models, and the tradeoffs between them. Wang also discusses the performance measures of web caches, cache eviction policies, and HTTP protocol elements that can help guide caching behavior. Four years later, Podlipnig and Böszörmenyi more closely examined [PB03] the tradeoffs of possible cache replacement algorithms.

2.6 CDNs

Like caching, Content Distribution Networks (CDNs) were created to help manage the dramatic growth of web traffic. While most caching schemes were created to alleviate latency or traffic load at the level of the end user or access network, CDNs were created to alleviate the traffic load at the publishing (or origin) web server. Before the advent of CDNs, website operators faced with capacity issues had few options – typically, operators needed to pay for additional dedicated servers and/or bandwidth at either the operator's facility or a rented server farm. Also, wide geographic distribution of replicas of a website was both difficult and expensive. Therefore the CDN business model was developed, in which a CDN would buy many servers at geographically distributed locations and sell capacity to many website operators. With this new model, website operators needed only to operate a single server from which the CDN would fetch content, while client requests for the website would be routed to a nearby CDN server.

One early study of the effectiveness of this scheme is [STA01], in which Shaikh et al. examine some common practices of CDNs such as assuming a client is located near its recursive DNS resolver and preventing caching of DNS responses. The authors find that these assumptions are not always sound as some clients are not located near their recursive DNS resolver, and in some webpages performing a separate DNS query for each object can dramatically increase the latency to load a page.

In 2001, two studies [JCDK01] [KWZ01] were released which analyzed the performance of some of the major CDNs in use at the time. [JCDK01] emphasized measuring the effect of a CDN's server selection on end-user performance, finding that in most cases the CDN did not choose the optimal server (out of the entire set of CDN servers), but did consistently provide better performance than an origin-site download of an object. [KWZ01] discovered that once a reasonable CDN server had been obtained, it is rarely worth the latency cost of an additional DNS lookup to attempt to obtain a slightly better CDN server.

Later in 2002, Jung, Krishnamurthy, and Rabinovich explored the effects of flash crowds and Denial of Service (DOS) attacks on the Internet's infrastructure in [JKR02]. While a flash crowd consists of many legitimate users attempting to access a newly-popular resource, DOS attacks often consist of many computers requesting server resources in order to deny service to legitimate users. While these two events have a fundamentally different motivation, the authors analyze the high-demand pattern exhibited by both. The authors then continue by demonstrating some changes in CDN architecture that would have the potential to better handle (and distinguish between) both of these types of events.

Chapter 3

Datasets

For this work we used logs of web traffic taken at the border routers connecting two distinct populations to the Internet. In both cases, we used the Bro intrusion detection system [Pax99, bro] to reconstruct HTTP sessions from the observed traffic stream. These sessions are then logged using Bro's standard HTTP logging policy[1] (found in http.bro in the Bro package). The logs include timestamps, involved IP addresses, URLs, HTTP transaction types and sizes, hostnames and HTTP response codes.

3.1 ICSI

The International Computer Science Institute (ICSI) is a small, non-profit research institute located in Berkeley, California. Most ICSI employees are full-time computer science researchers, along with a supporting administrative staff. The ICSI dataset used runs from January 2006 through September 2011. Due to the size of the dataset we analyze only the eleventh through eighteenth days of each month for logistical reasons. We do not believe this biases our results. The original logs include all incoming and outgoing HTTP traffic. However, we winnowed to only the outgoing connections (i.e., ICSI clients) as we do not wish to bias our results by the particular characteristics of the few server instances at ICSI.

[1] Bro's standard HTTP logging policy has changed somewhat over the years as described in Section 3.1.

While the size of our user population is small - an average of 167 distinct client IP addresses each month with a standard deviation of 16 - the boon of this dataset is its duration. An overview of the dataset is shown in Figure 3.1.

In Figure 3.1, we show an overview of the ICSI dataset. We note an overall upward trend in requests, HTTP connections, and HTTPS connections – conforming to our mental model that web usage is still growing. We observe a large jump in connections at the end of 2007. Before December of 2007, the Bro system at ICSI used a configuration that caused multiple HTTP connections to be assigned the same identifier. Therefore from the beginning of 2006 to the end of 2007, we undercount connections by a significant factor (there is no way to retrieve the true number of connections during that period from the data we have). When we discuss connection-related facets of our dataset in Chapter 5, we consider only data from 2008 and beyond.

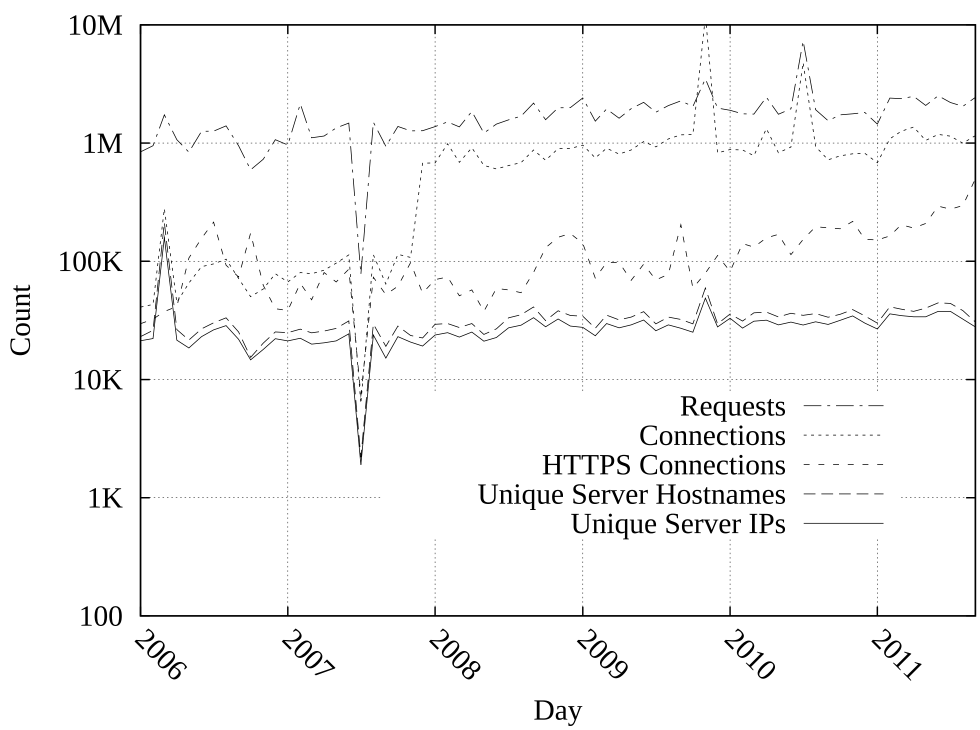


Figure 3.1: ICSI Dataset Summary

3.2 CCZ

The Case Connection Zone [ccz] is a research project that provides a neighborhood adjacent to Case Western Reserve University with high-speed broadband access. The current deployment reaches approximately 100 houses with gigabit Internet connectivity. The user population is a mix of both students and non-students. The data in this set runs from February through September of 2011. The hardware provided to CCZ users is known to perform Network Address Translation (NAT), therefore our view of client IP addresses more closely reflects the number of occupied housing units represented by CCZ as opposed to the number of users. Furthermore, our HTTP traffic logs provide no good way to approximate the number of users. The mean number of client IPs seen each month is 73 with a standard deviation of 8. While we see fewer client IPs originate from our CCZ vantage point, we see higher overall web activity than in our ICSI population. An overview of the dataset is shown in Figure 3.2.

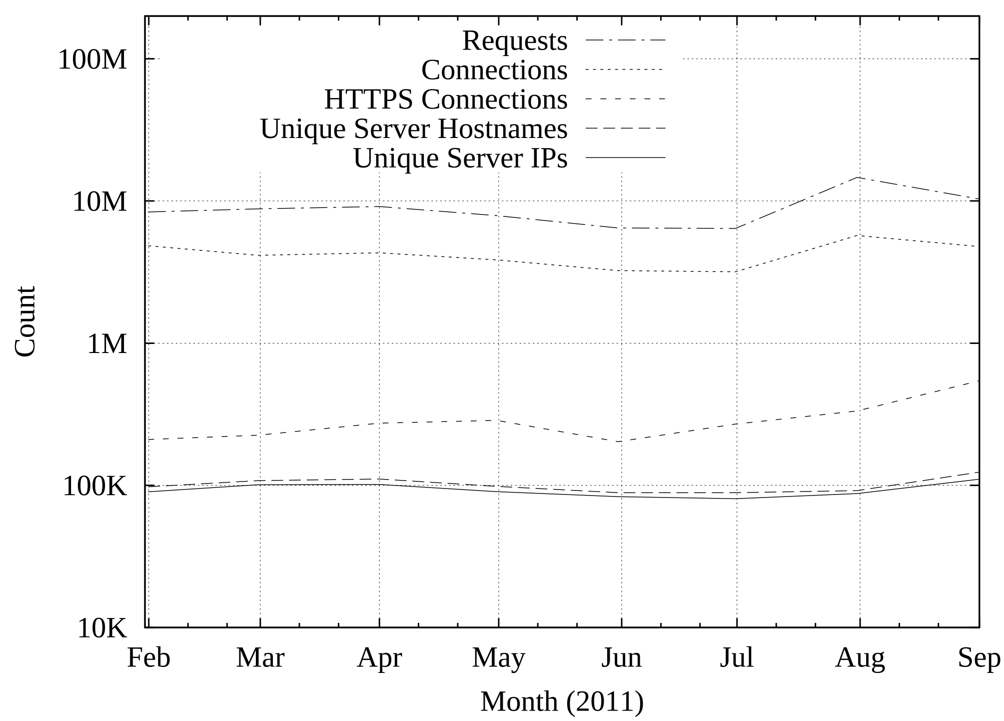


Figure 3.2: CCZ Dataset Summary

Chapter 4

HTTP Transactions

This chapter provides an overview of the basic properties of the HTTP transactions in our datasets, including the HTTP methods utilized by these transactions and several measures of the sizes of these transactions. Using these metrics, we are able to spot the both influence of newer web technologies such as AJAX [Gar05] and the evolution of underlying embedded web objects. Furthermore, we are able to realize the impact of design decisions made by the operators of large websites on the basic properties of the web traffic we see in general.

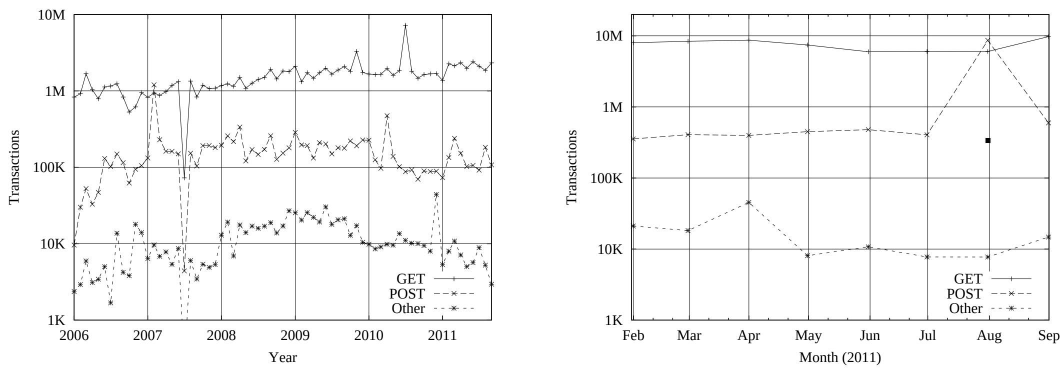
4.1 Transaction Types & Numbers

We begin by characterizing the frequency and types of HTTP transactions, grouping them into categories for `GET` requests, `POST` requests, and all other transaction types. In Figure 4.1, we observe the request types over time for both datasets. We can see that the ICSI data shows a clear growth in all request types over time (there appears to be a drop in `POST` requests starting in February of 2010 – this will be discussed in Section 4.2). Furthermore, we see a rise in both `POST` and other HTTP request types with respect to `GET` requests throughout 2006. Part of this is due to the rise of AJAX [Gar05] applications, which often utilize `POST` queries more heavily than traditional websites.

In the ICSI data we see a sustained rise in the raw number of web requests despite a relatively stable user population. While the CCZ might initially seem not to support this, we note that the CCZ user population was likely artificially low during the summer months of May, June, July, and August when many students would have left for summer break. In Figure 4.2(a), we show the ratio of the number of `POST` requests to `GET` requests at ICSI. The relative growth of `POST` requests through 2006 is evident, at which point `POST` requests stay between 8% and 15% of `GET` requests throughout 2007-2009, with some exceptions. Starting in 2010 however, `POST` requests tend to stay under 10% of the number of `GET` requests. The CCZ `POST`/`GET` ratio (not pictured) stays between 4% and 8% for the duration of the study.

In Figure 4.1(a), we see a massive drop in all categories in July of 2007 – the cause of which was a glitch in our measurement infrastructure, causing approximately 95% of our logs for that month to disappear. While any data loss has the potential to bias results, we feel this loss does not do so for four reasons. First, we cannot find any reason within the traffic itself for the measurement loss (e.g., high traffic volume). Second, when examining the metrics from that month that do not rely on the raw number of HTTP transactions, we see no significant irregularities; Figure 4.3 shows no irregularity during that month and Figure 4.2 shows only a slight dip in the `POST`/`GET` ratio during that month. Third, even the total absence of data from this month would not limit our ability to study long-term trends (such as in Figure 4.3), as we do not use that month in isolation to draw any conclusions. Finally, if this loss were going to affect our object size distribution graphs such as in Figure 4.5, we would expect to see some deviation in the median and average `GET` sizes in Figure 4.3.

In Figure 4.1(b), we see a spike in `POST` requests in the CCZ data in August – further investigation revealed a single client performing several `POST` requests per second to a single server for a sustained time period. The lone point on the graph represents the value of the `POST` request line when this server is removed from consideration, which shows that the remainder of the traffic behaves as expected based upon the previous and subsequent months. The cause of this traffic is discussed in Section 6.1.



(a) ICSI (b) CCZ

Figure 4.1: HTTP Transaction Types

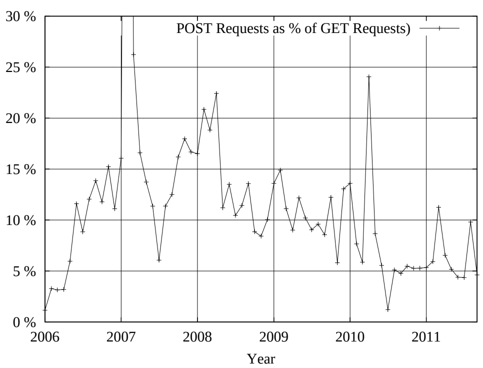
4.2 Transaction Sizes

One of the most important aspects of HTTP analysis is in the sizes of objects transferred as these sizes are all crucial in informing decisions on caching, pipelining, and client bandwidth usage (though perhaps, to some extent, these sizes may be a *result* of the latter). In [BBBC99], the authors note that the median transaction size tends to be a more stable metric than the mean – a behavior we do not see when we look at our month-to-month data. When we examine transaction sizes by year at ICSI we find a more stable median, between 615 and 940[1] bytes. In their study, the authors' user population consisted of 306 users making periodic use of a total of 29 workstations, somewhat smaller than our own. Unfortunately, the lack of month-to-month data in [BBBC99] inhibits further exploration of this discrepancy.

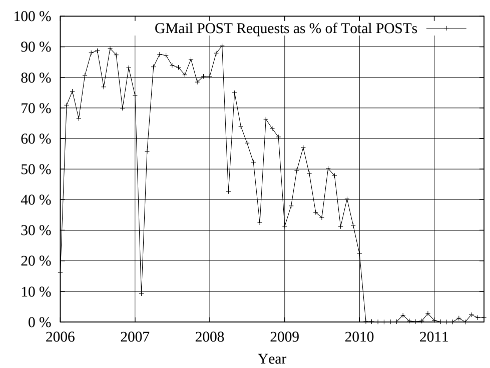
As we see in Figure 4.3(a), the median transaction size in our ICSI dataset is quite volatile. On the one hand, this wide variation and bursty behavior frustrates our ability to

[1] In 2010, we actually find a median of 1621 bytes due to a traffic spike in July 2010. In this month, approximately half of all HTTP requests were destined for a single host, with requests to this host having a median size of 2429 bytes. When we remove this spike from consideration, we observe a median of 940 bytes.

get a good grasp on exactly how the web is being used. On the other hand, it reminds us of the unpredictable nature of the network, and the users who use it. For example, the spike in median GET request sizes in March 2006 in Figure 4.3(a) has no simple explanation – we can find no single (or small group) of hostsnames, client or server IPS, or objects responsible for this behavior. On the other hand, the spike in the median POST request size in April of 2010 turns out to be a single user using an automated process to upload a massive amount of photos to a popular photo-sharing website, resulting in hundreds of thousands of large POST requests that month.



(a) POST Requests as % of GET Requests



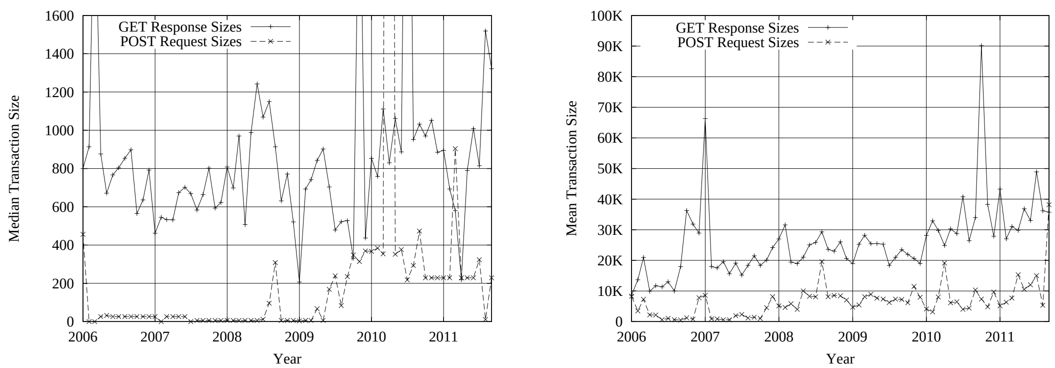
(b) Gmail POST Requests as % of All POST Requests

Figure 4.2: Raw Request Count Comparisons (ICSI)

Another characteristic of Figure 4.3(a) is the very low POST request size until mid-2009. The driving force behind these small POST requests turns out to be Google's popular mail service Gmail [gma]. We found that Gmail usage results in periodic POST requests of a small size – 52% of the POST requests to Gmail over the course of the entire ICSI dataset were precisely 6 bytes, and 83% were under 100 bytes. In January of 2006, we see a relatively high median POST request size. As we can see in Figures 4.1(a) and 4.2, in January of 2006 Gmail usage has not yet taken off. In February of 2006 however, Gmail and POST request usage increases dramatically – POST requests overall increase threefold, with over 70% going to Gmail. While non-Gmail POST requests rise naturally over the course of our dataset, Gmail POST requests remain dominant enough to keep the median

POST request size very small until mid-2009.

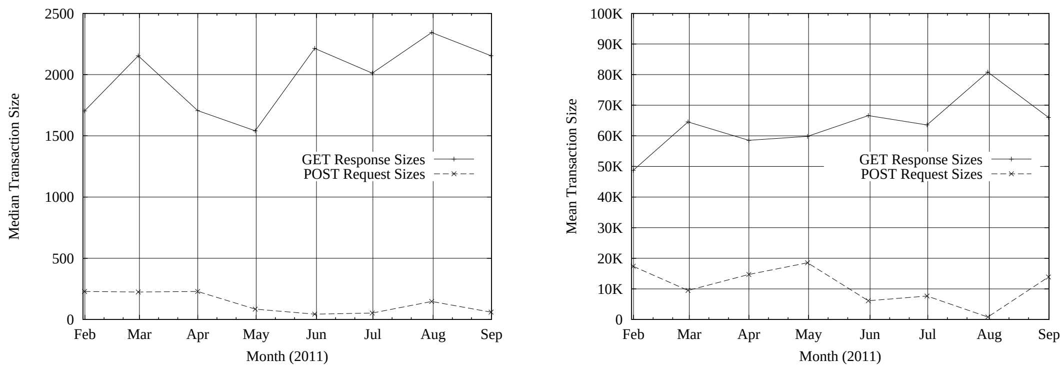
Starting in June of 2009, the median POST request size begins to increase above its historic low; we also see in Figure 4.1(a) that starting in February of 2010 the POST request volume appears to fall. With the exception of April 2010, the number of POST requests in 2010 stays below the levels seen in 2007-2009, and does not appear to increase back to 2007-2009 levels consistently through to the end of our measurement period. Also starting in February of 2010, we see an uptick in the number of HTTPS connections in Figure 3.1, a trend which continues through to the end of our collection period. This fall in the absolute POST request volume we can observe in Figure 4.1(a), as well as the uptick in HTTPS connections in Febuary of 2010 appears to exactly coincide with the date that Gmail simply turned HTTPS on for all Gmail users by default [gma10]. Therefore, we hypothesize that these POST requests did not disappear, but simply moved out of our view. Unfortunately, we are unable to verify this hypothesis with our in-network data collection as we have no view into HTTPS payloads.



(a) Median (b) Mean

Figure 4.3: ICSI HTTP Transaction Sizes

While the data provided by our CCZ study does not have the same power to show longitudinal shifts, it does provide a nice contrast to the ICSI data. For example, the median and average GET response sizes are substantially larger than those of the ICSI population, even over the same time period. As we see in Figure 4.6, CCZ users persistently transfer bigger files than the ICSI users. While there are many possible explanations, one simple route is to examine the types of users in these groups. At ICSI, most users are full-time employees, and therefore most web browsing is likely to be as a result of job-related activities. The CCZ population, on the other hand, is a large group of residential users (many of whom are students) – far more likely to access media over the Internet. As expected, we found that the proportion of requests to Facebook, Youtube, and Netflix was much higher in the CCZ population than in the ICSI population.



(a) Median (b) Mean

Figure 4.4: CCZ HTTP Transaction Sizes

In Figure 4.5, we examine the changing sizes of web objects downloaded at ICSI over the years of our logging. In Figure 4.1(a), we show that the number of HTTP requests has increased over the years. Now, in Figure 4.5 we see that not only has the number changed, but the requests are getting bigger. For example, in 2006 the largest 1% of requests were above 93KB, but in 2011 the largest 1% are above 260KB. Likewise, in 2006 the largest 0.1% of requests were above 849KB, but in 2011 these are above 3.4MB. At the other end, we see that approximately 15-25% of all requests result in no content bytes being returned – these tend to be 304 (HTTP Not Modified) and 302 (HTTP Redirect), among others. However, we see no yearly trend to these responses with no content. We also recognize that the distribution of document sizes we see exhibits the heavy tail discussed in [CB97], [Mah97], and many other studies of web and network traffic in general.

Figure 4.6 shows the CCDF of `GET` sizes derived from the CCZ population, and we compare this to our 2011 result from ICSI. As mentioned before, CCZ object sizes tend

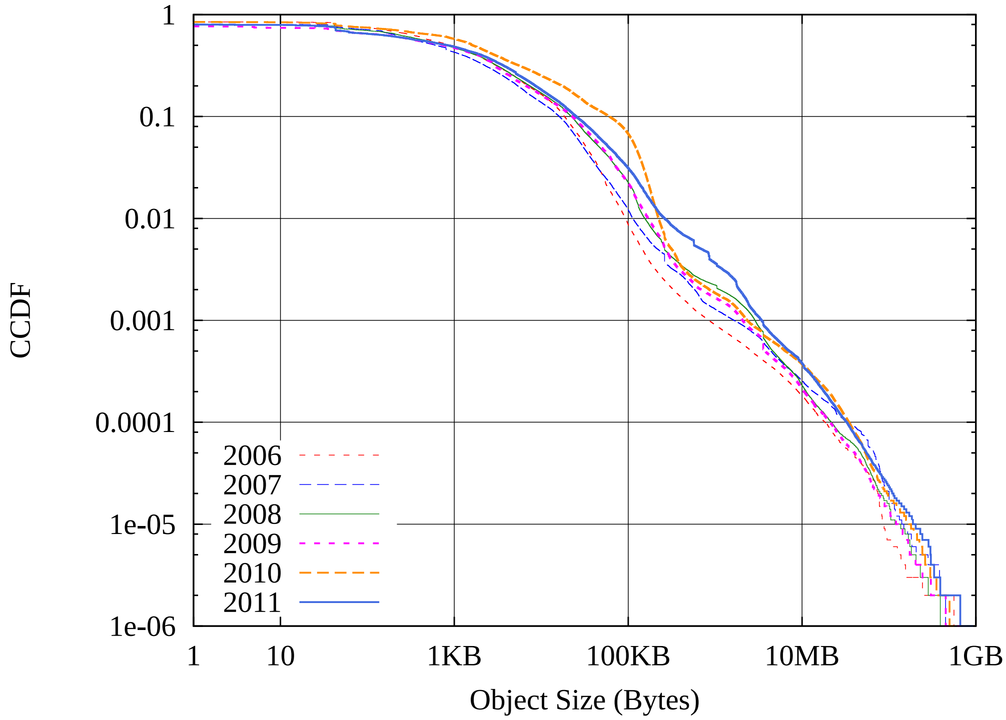


Figure 4.5: ICSI

to be larger than those from ICSI. This difference is most prominent around the 1% mark, where the top 1% of CCZ requests exceed 1MB, yet the top 1% of ICSI requests are only above 260KB. Both distributions taper off with just a few HTTP responses in the near-gigabyte range. In addition, it is clear that the shape of these two curves is quite similar. The persistent heavy tail exhibited was noted as a network invariant in [AW96], and both of our datasets reaffirm this.

In [HCJS03], the authors track changing metrics of HTTP requests across a variety of datasets just as we do here. In Table 4.1, we examine the median response sizes of their own University of North Carolina (UNC) traces, as well as from several other traces the authors of [HCJS03] use – originally from [Mah97], [CBC95], and [BBBC99]. For the UNC traces, there is a decrease in the median response size over the three traces. However, while ICSI shows a slight decrease from 2006 to 2011, there is no apparent trend. In addition, our ICSI and CCZ (2011) datasets have substantially different medians. The pair of traces from around 1999 also have much different median response sizes, therefore

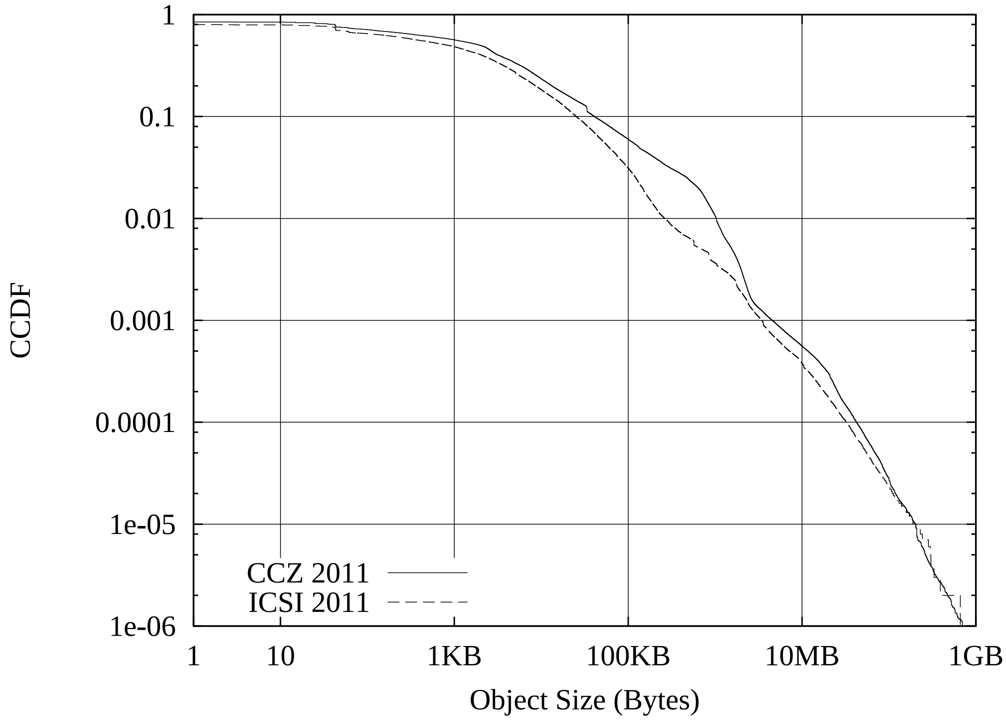


Figure 4.6: CCZ

Cunha (1994/1995)	Mah (1995)	Barford (1998)	UNC (1999)	UNC (2001)	UNC (2003)	ICSI (2006)	ICSI (2011)	CCZ (2011)
2,245	2,035	2,416	1,164	733	632	895	845	1,977

Table 4.1: Median Response Sizes (bytes)

it would appear that the specific values of the response-size distribution varies with the population and time. However, we must reiterate that despite the difference in precise values, the general shape of the distribution remains the same across all of the datasets discussed.

Chapter 5

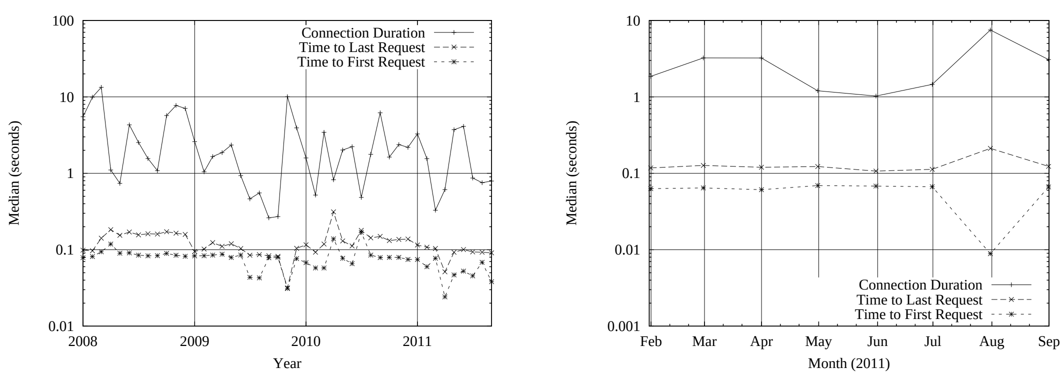
HTTP Connections

In this chapter, we discuss various properties of the TCP connections underlying our HTTP traffic. We start by examining some basic properties of the connections such as duration, time from connection establishment until the first and last HTTP request is sent, and number of requests per connection. We continue by discussing connection parallelism both at the client level and at the client/server pair level. In our ICSI dataset, we begin our examination of these properties starting in January of 2008 due to the logging issue described in Section 3.1.

5.1 HTTP vs. TCP

In Figure 5.1(a), we show the median connection duration and the median time from the establishment of a connection until the first and last request is sent. The ICSI and the CCZ data in Figure 5.1 are quite similar, with the median time to first request nearly always between 60 and 100ms. The time to last request is also consistent, typically between 100ms and 200ms. We show a much longer median duration than time to last request however, with median connection durations typically between 1 and 10 seconds. Given our knowledge of object sizes from Section 4.2, we find it unlikely that this gap is consumed entirely by the transfer of an object, indicating that there is substantial idle time at the end of many connections before closing. Unfortunately, our lack of object transfer duration information prevents us from directly testing this hypothesis.

The time from the establishment of a connection until the first request is important when considering claim-and-hold denial of service attacks and the web server timeouts used to help mitigate them. In a claim-and-hold attack, an attacker makes a connection to a server to occupy a server resource (e.g. connection slot, memory) and then does nothing, attempting to hold that resource as long as the server will allow. In a study on claim-and-hold attacks [AQRA10], Al-Qudah et al. found that more than half of web servers studied did not enforce a limit on the time it takes a client to make a request as long as data is still being transferred. Further, over 93% of sites these authors studied allowed a `GET` request to last more than 30 seconds. As we show in Figure 5.1, most requests fully arrive in under 100ms from the establishment of a connection. Furthermore, we observe that while the last request in a connection often occurs 200-300ms into that connection, the connections themselves end on the order of seconds later, confirming that study's finding that web server timeouts are generally much longer than most clients require. In most months, we find that it takes at least 60ms for the first request to be made – indicating an area for optimization. Further illustrative of this room for improvement is the dip in time to first request in Figure 5.1(b), where non-browser HTTP activity at CCZ in August drives the median down. We discuss the source of this traffic in Section 6.1.

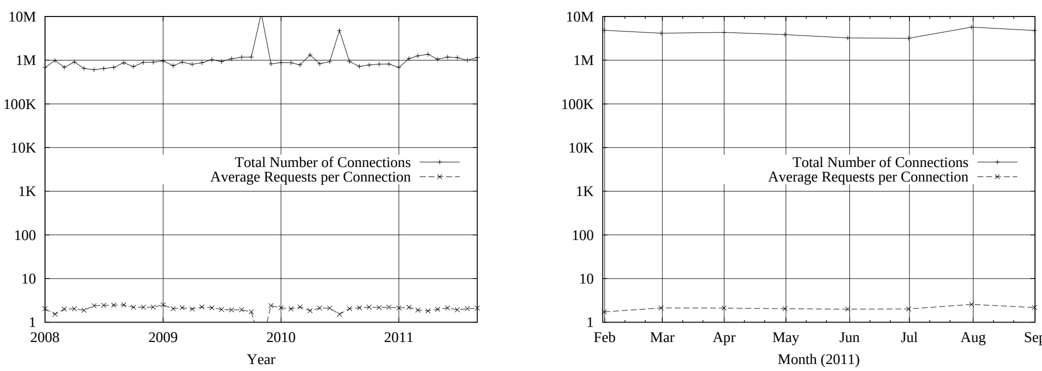


(a) ICSI

(b) CCZ

Figure 5.1: Median Connection Duration & Time to First Request

Next, we measure the relationship between HTTP requests in our datasets and the TCP connections that support them. In Figure 5.2, we show the average level of requests per connection has stayed reasonably consistent throughout our measurement period, as well as across datasets. This average of 2.1 requests per connection is driven low in no small part due to the fact that 60.7% of all connections in our ICSI dataset carried only a single request. Further, 21.3% of all connections in our ICSI dataset carried no requests at all – leaving only 18% of connections carrying two or more requests. We note that in one month – November 2009 at ICSI – the average drops below 1; in that month it seems some programmatic usage of HTTP greatly increased both the number of connections, and also the number of connections which had no requests at all. We find that a single client was responsible – eliminating it from consideration yields a connection count of 900K and an average of 2 requests per connection. In all other months, the mean number of requests per connection neither exceeded 2.5 nor fell below 1.5.



(a) ICSI (b) CCZ

Figure 5.2: Connections & Requests per Connection

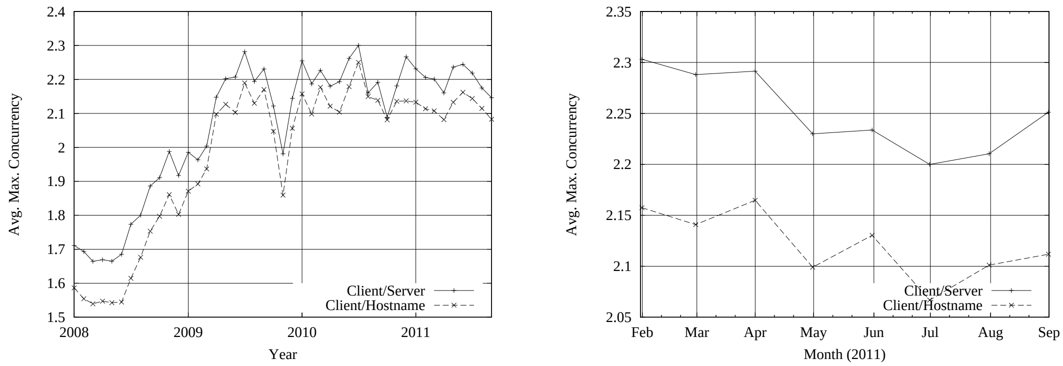
5.2 Parallelism

In this section, we investigate the use and evolution of parallel HTTP connections in both of our datasets. To measure parallelism we first calculate the maximum number of simultaneous connections opened between each (client IP, server IP) pair at any instant in time across each month of our datasets. We then plot the average of this value across all (client IP, server IP) pairs in Figure 5.3. We performed the same procedure for all (client hostname, server hostname) pairs using the HTTP Host header.

A striking feature of both our ICSI and CCZ datasets is the consistently higher level of client/server IP parallelism as opposed to client/server hostname parallelism. We conclude that web sites must be embedding objects that reside on different hostnames, yet are served by the same IP address. We also note that in 2008 and the first half of 2009 there is a 30% rise in the maximum parallelism levels exhibited, which we conclude is due to two major web browsers increasing their limits on the number of allowed simultaneous connections. In April of 2008, Firefox increased its default setting for the maximum number of simultaneous connections opened to a particular server from 2 to 6 [ffc]. In March of 2009, Internet Explorer followed suit and released a version increasing the maximum number of simultaneous connections from 2 to 6 as well [ie8]. We note that RFC 2616 dictates that clients should not open more than 2 simultaneous connections to any given server or proxy [FGM+99].

In order to further investigate, we further analyze two days worth of traffic – March 12, 2008 and March 12, 2010 (before and after the browser changes took place, respectively). On March 12, 2008, we note that of the 9003 client/server hostname pairs, 66% exhibit a maximum parallelism of 1, 28% exhibit a maximum parallelism of 2, and only 0.7% exhibit a maximum parallelism of 6. On March 12, 2010, 66% of connections lack any parallelism, 12% exhibit a parallelism of 2, and 9.4% exhibit a parallelism of 6. Finally, we note that our CCZ data from 2011 is highly similar to the ICSI data of 2010-2011, and that the CCZ dataset also exhibits similar modes in an analsyis of the client/server hostname pairs on March 12 of that dataset. This trend in the increase in parallelism from 2008 to 2010 was also observed in [Ihm11].

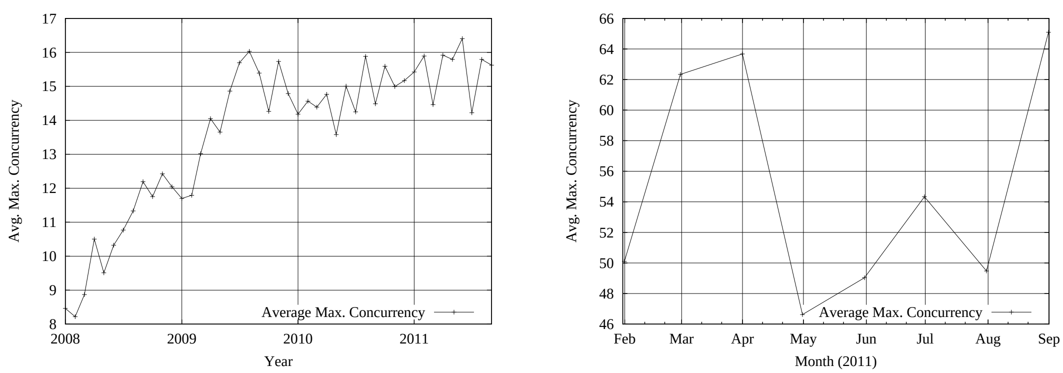
In Figure 5.4, we consider the parallelism across all connections made by a client irrespective of the destination. Again, we observe in the ICSI data the rise in parallelism



(a) ICSI (b) CCZ

Figure 5.3: Pairwise Average Maximum Parallelism

between 2008 and 2009 and relative stability during 2010 and 2011. When examining the CCZ data however, we show a dramatically higher level of parallelism than at ICSI. We manually checked this statistic for several individual days at both sites, and observed that the difference is consistent and not due to outliers. When examining the maximum number of simultaneous connections opened by each client during the month of September 2011, we found a mean of 15 connections with a median of 7 at ICSI and a mean of 65 connections with a median of 69 at CCZ. A similar measurement of parallelism was used in [Ihm11]; that author's numbers agree more closely with our ICSI data, however the dataset used in [Ihm11] was from a CDN, and therefore naturally only observes a subset of client behavior and hence would naturally be expected to be skewed to lower values.



(a) ICSI (b) CCZ

Figure 5.4: Average Maximum Parallelism by Client

Chapter 6

Client Behavior

Here we discuss the characteristics of web traffic which are driven by the users (and to an extent, the content creators) on the Internet. We will begin with an overview of some of the most popular Top Level Domains (TLDs) and file extensions. For all tables, we include an entry if it appeared in the Top-10 items in any year of the study such that we can assess trends. We continue by discussing the distributions of requests to both objects and hostnames on the Internet. Finally, we will discuss caching that is taking place on end-user machines by measuring HTTP 304 responses, as well as the potential for in-network proxy caches.

6.1 Top TLDs

In Table 6.1, we examine the most popular TLDs (e.g. .com, .net) at ICSI by the number of requests local users sent. As we see in the top two lines, the .com and .net TLDs dominate in every year, with .com responsible for 74%+ every year. Other TLDs that commonly appear near the top of the list include .org, .edu, and .de (perhaps in part due to ICSI's many collaborations with researchers in Germany). With the exception of .gov, every other TLD in our list corresponds to a country code TLD (ccTLD). Table 6.2 provides us with similar information from CCZ; we again see the popular .com, .net, .org, and .edu extensions,

TLD	2006		2007		2008		2009		2010		2011	
	TLD Rank	% Reqs.	TLD Rank	% Reqs.	TLD Rank	% Reqs.	TLD Rank	% Reqs.	TLD Rank	% Reqs.	TLD Rank	% Reqs.
com	1	74.1%	1	75.0%	1	79.2%	1	76.5%	1	81.3%	1	77.3%
net	2	10.7%	2	7.2%	2	7.6%	2	8.2%	2	8.7%	2	12.6%
org	3	4.6%	3	3.4%	3	3.0%	4	2.6%	3	2.6%	3	2.8%
edu	4	1.9%	4	1.4%	6	1.0%	6	1.2%	5	0.9%	5	0.8%
de	5	1.9%	5	0.8%	5	1.2%	5	1.8%	4	2.5%	4	2.4%
uk	6	1.3%	6	0.8%	7	0.8%	7	0.6%	7	0.4%	7	0.5%
es	7	0.7%	8	0.4%	4	1.3%	15	0.1%	11	0.1%	10	0.2%
gov	8	0.6%	7	0.6%	8	0.6%	11	0.4%	6	0.4%	6	0.5%
cz	9	0.5%	26	0.0%	38	0.0%	21	0.1%	41	0.0%	53	0.0%
ru	10	0.4%	21	0.1%	10	0.5%	27	0.1%	13	0.1%	40	0.0%
tr	24	0.1%	9	0.4%	15	0.2%	18	0.1%	28	0.0%	85	0.0%
tw	23	0.1%	10	0.3%	14	0.2%	34	0.0%	42	0.0%	39	0.0%
cn	14	0.2%	11	0.3%	9	0.5%	8	0.5%	9	0.3%	8	0.2%
jp	11	0.4%	12	0.2%	19	0.1%	3	4.0%	19	0.1%	25	0.0%
ro	65	0.0%	69	0.0%	11	0.4%	9	0.5%	29	0.0%	19	0.1%
fi	21	0.1%	17	0.1%	13	0.2%	10	0.4%	8	0.3%	23	0.0%
fm	35	0.0%	19	0.1%	18	0.1%	14	0.2%	10	0.2%	29	0.0%
it	27	0.0%	31	0.0%	26	0.0%	20	0.1%	37	0.0%	9	0.2%

Table 6.1: Requests to TLDs appearing in the Top-10 of any year at ICSI

however we also see a considerable amount of traffic to the .cz domain.

Over 99.9% of traffic to the .cz domain appears to have been generated by a BitCoin [Nak09] mining application. Bitcoin is a decentralized form of digital currency accepted as payment by some websites and people on the Internet. One can actually generate Bitcoins (the fundament unit of this currency) by performing cryptographic proof-of-work problems [JJK99]. Therefore, several communities have sprouted in which end-users pool computing resources in order to solve these proof-of-work problems and collectively share the Bitcoins that have been *mined*. It appears that the particular program interfacing with this network encountered an error causing a massive spike in requests; this is the same traffic responsible for the spike in `POST` requests in Figure 4.1(b).

We note that in the ICSI dataset, a TLD appearing in the Top 7 of any year (with one exception) never appears outside of the Top 8 in any other year. On the other hand, the TLDs that appear at rank 9 or 10 show wide variability from year to year, indicating a relatively small working set of Top-Level Domains. We also note that five out of the original six TLDs (.com, .net, .org, .edu, .gov, .mil) consistently appear at the top of our TLD rankings (only .mil is absent). In addition, we do not see any of the newer general-purpose TLDs such as .info, .name, or .me among our top TLDs at any point, indicating a slow adoption rate of the use of these new TLDs.

TLD	2011	
	TLD Rank	% Total Reqs.
com	1	63.4%
net	2	18.9%
cz	3	11.5%
org	4	1.6%
cn	5	0.8%
us	6	0.5%
edu	7	0.4%
tv	8	0.3%
uk	9	0.2%
kr	10	0.2%

Table 6.2: Top 10 TLDs at CCZ

6.2 Top File Extensions

In order to determine what types of content users commonly access, we recorded the most commonly requested file extensions. While we would rather examine the types of content users access by analyzing the HTTP Content-Type header or the HTTP payload content itself, our lack of complete HTTP header or payload data forces us to use the file extension as an approximation. Therefore, for this section we have excluded from consideration those URLs with no file extension. We show the top file extensions from ICSI in Table 6.3 and the CCZ extensions in Table 6.4. We see that the vast majority of objects requested are those usually found embedded in web pages (such as .jpg, .gif, .swf, .css, and .js), as opposed to those used for a primary web page (such as .html, .htm, and .php). In 1995 and 1999, two studies [CBC95] [AFJ99] also measured the top file types visited using client-based traces, and found similar results. However, in these studies there were only two dominant categories – images and HTML documents, the latter of which consisted of approximately 10% in both studies. In the 1995 study, dynamic content was explicitly measured and found to consist of 0.02% of requests. In our data, we note a much richer set of embedded object types (.css, .js, and .swf) in addition to images, and a favoring of dynamic content over static HTML pages. Only in 2006 of our ICSI dataset do we see HTML document requests in excess of 1.5%; in all other years of ICSI data, as well as in our CCZ dataset, we see that PHP requests exceed HTML requests, typically by 2-3 times. Within the image category,

Extension	2006		2007		2008		2009		2010		2011	
	Ext. Rank	% Reqs.	Ext. Rank	% Reqs.	Ext. Rank	% Reqs.	Ext. Rank	% Reqs.	Ext. Rank	% Reqs.	Ext. Rank	% Reqs.
gif	1	27.6%	1	20.4%	1	20.0%	1	17.9%	2	10.9%	2	12.5%
jpg	2	13.6%	2	10.6%	2	14.5%	2	13.8%	1	19.3%	1	15.7%
js	3	5.0%	3	5.0%	3	6.9%	3	7.8%	3	6.0%	3	7.5%
html	4	3.3%	10	1.2%	9	1.2%	10	1.4%	7	1.5%	8	1.4%
php	5	2.7%	4	4.5%	5	3.2%	6	3.1%	5	3.7%	5	4.8%
css	6	2.7%	7	2.3%	6	3.1%	5	3.2%	6	2.5%	6	3.5%
xml	7	2.0%	6	2.3%	7	2.1%	8	1.6%	9	1.1%	9	1.3%
png	8	1.6%	5	2.5%	4	3.8%	4	4.1%	4	4.7%	4	6.9%
swf	9	1.2%	9	1.2%	8	1.6%	9	1.4%	8	1.2%	10	1.2%
htm	10	1.0%	18	0.2%	18	0.2%	20	0.3%	23	0.1%	23	0.2%
smgif	19	0.2%	8	1.4%	287	0.0%	317	0.0%	79	0.0%		0.0%
aspx	13	0.8%	12	0.7%	10	0.9%	12	0.8%	10	0.7%	11	0.8%
fcgi	60	0.0%	83	0.0%	52	0.0%	7	1.8%	109	0.0%	79	0.0%
json	836	0.0%	133	0.0%	48	0.0%	21	0.3%	12	0.6%	7	1.7%

Table 6.3: Requests to extensions appearing in the Top 10 of any year at ICSI

Extension	2011	
	Rank	% Total Requests
jpg	1	22.2%
php	2	7.5%
gif	3	6.9%
png	4	5.3%
js	5	5.0%
css	6	1.8%
swf	7	1.3%
html	8	1.1%
xml	9	0.9%
json	10	0.7%

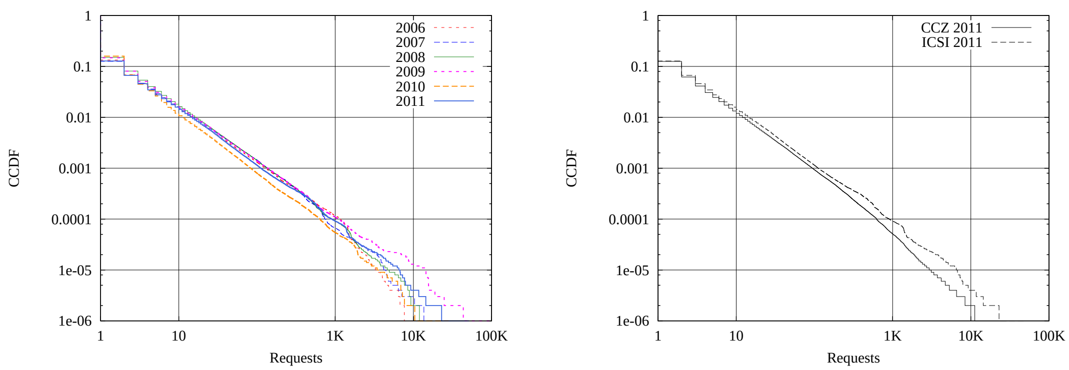
Table 6.4: Top 10 File Extensions at CCZ

we see in the ICSI data that there has been a shift away from the .gif image format with the .jpg format as the most used by in 2010 and 2011. We find .jpg is also the most-accessed image format by CCZ users, outnumbering .gif accesses by a 3:1 margin. Finally, the .png format grows in popularity from 1.6% at ICSI in 2006 to 6.9% of requests at ICSI in 2011; we also see the .png format popular at CCZ as well with 5.3% of requests.

6.3 Request Distribution by Object

In this section, we study the distribution of accesses to unique objects – which has direct relevance to the implementation of caching systems. When referring to an object, we mean a URL plus any parameters; as the content returned by a website typically varies with the parameters supplied, we consider these outputs to be distinct objects. In Figure 6.1, we show the number of times each object was accessed within a calendar year. In every year, 84-87% of objects were accessed only once. We also note the striking similarity in the shape of the distribution among all of the years of ICSI data and between the ICSI and CCZ datasets. In fact, the shape of our distributions match up well to those described in [BBBC99], [AFJ99], and [BCF$^+$99] – suggesting an invariant.

To assess the disparity between popular objects and unpopular objects, we study the data from ICSI in 2011, where we found that the most popular 1% of objects accounted for approximately 41% of the total `GET` requests and 20% of the total `GET` bytes received. Storing every version of all of these 86,084 most popular objects would require under 40GB of hard disk space, a modest amount of storage for today's servers. Moreover, the top 0.1% of objects account for 11% of all `GET` bytes received; storing every version of these would require just over 14GB of space, within the main memory capacity of many modern servers.



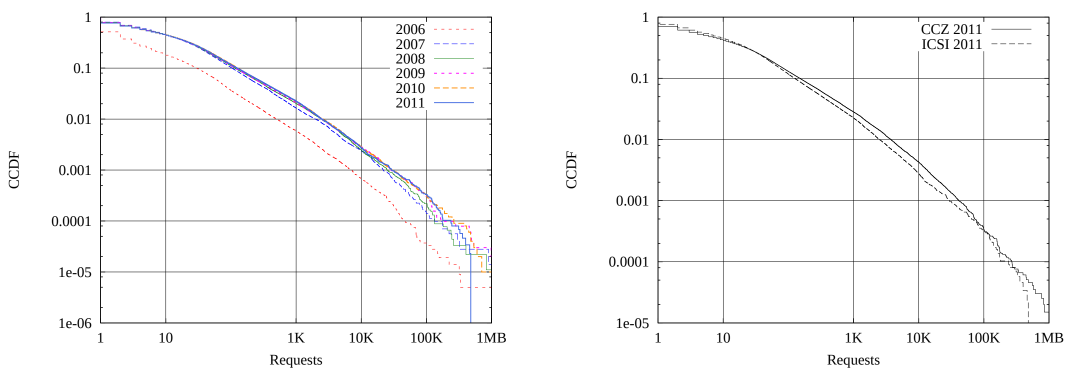
(a) ICSI (b) CCZ

Figure 6.1: Requests Per Object

6.4 Request Distribution by Hostname

In Figure 6.2, we examine the popularity of websites themselves by measuring the number of requests sent with a particular HTTP Host header. The distribution of accesses to unique hostnames can inform decisions on DNS cache size and the design of web appliances. At the hostname level we see less one-time referencing than at the object level, yet it is still present – in 2006 at ICSI we see 49% of hostnames visited only once, and in all other

ICSI years and at CCZ we see from 19-24% of hostnames visited once. Also confirming the results shown in [AFJ99], we find that the disparity between popular and unpopular hostnames is even higher than for objects – the most popular 1% of hostnames visited by ICSI users in 2011 were responsible for nearly 74% of the total requests. Furthermore, the number of hostnames visited is smaller than the number of objects – while in 2011 ICSI users accessed over 8.6M unique objects, they accessed only 87K unique hostnames, indicating that only a modest amount of memory would be occupied for a DNS cache at an institution the size of ICSI. Of course, this 87K hostnames figure reflects only hostnames accessed via the HTTP protocol – obviously undercounting the likely total requirements for an institutional DNS cache.



(a) ICSI (b) CCZ

Figure 6.2: Requests Per Hostname

6.5 Caching

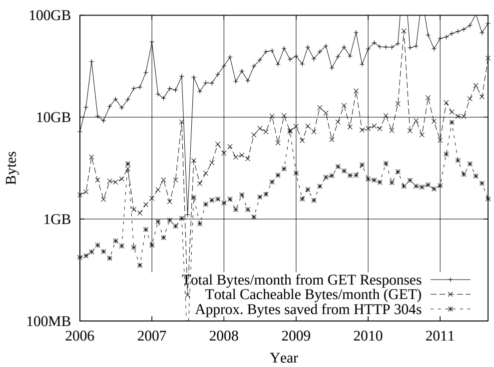
Next we discuss both the level of client-side caching we are able to directly observe, as well as the overall potential for an in-network proxy cache. In Figure 6.3(a), we examine three metrics pertinent to caching: the number of `GET` bytes received, the number of `GET` bytes that we consider to have been cacheable, and the `GET` bytes that were saved using `304 Not Modified` responses. The first line in this graph is the number of `GET` bytes received, and we can see the growth in network usage by bytes over time.

The second line of Figure 6.3(a) shows those bytes whose transfer we believe could have been avoided with an institution-level cache. We define a transferred object as cacheable if it has been previously retrieved that month and if the size has not changed. In other words, if two accesses in a row to the same URL with the same parameters yields two objects of a different size, none of those bytes are counted as cacheable. If however, the second access returns an object of the same size as the first object, then we count all of the bytes of the second object as cacheable. While this is less precise than verifying whether or not subsequent lookups to the same object yield the same content, this approximation is necessary as our logs do not contain any object content or representation thereof (such as a hash).

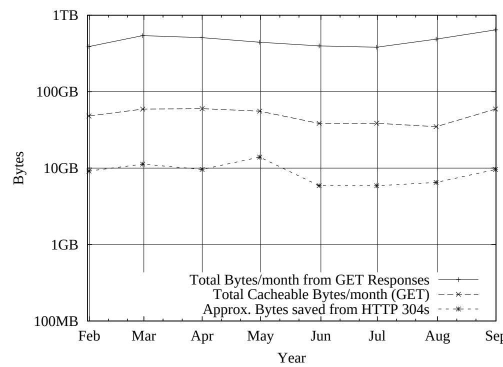
In order to assess the efficacy of this technique, we utilized 5.75 days of full-payload packet traces from January 2010 and formed tuples of URLs and sizes (u, s) accessed in the traces. For each (u, s) we record the number of different MD5 hashes over the full content of the object observed and find that 1.4% of the 846K (u, s) pairs have multiple MD5 hashes. Furthermore, this constitutes 6.7% of the bytes fetched over the course of the trace. Therefore, our assumption that an object that changes will also result in the size of the object changing is largely correct (i.e., over 93% of the cases in our calibration experiment).

The last line in Figure 6.3(a) is an estimate of a lower bound on the number of bytes saved using HTTP 304s. Every time we encounter a 304 response, we reference a list of all objects accessed that same day – if the object has already been accessed that day, then we record the most recent size associated with that object as having been saved. If that object was not otherwise accessed that day, we do not record any savings. Therefore, while our cacheability line measures an upper bound on the performance of an institution-level cache, our 304 savings is quite likely a lower bound. We also note that in two occasions the savings from 304 requests exceeds the total cacheable bytes recorded that month – this is possible as we measure only those bytes actually transferred that might have been saved by a cache, without including those bytes already saved by 304s.

As we can see in Figure 6.3(a), the raw number of bytes transferred has increased steadily over the course of the study. The number of potentially cacheable bytes has increased at a similar rate. The savings in transferred bytes due to 304 responses appears to have also kept pace, falling somewhat towards the end of our measurement period. Notable also is the distance between the cacheable bytes and 304 savings lines throughout much of the study – we see that an institution-level cache has much more potential for performance than we see from the browser-level caching utilizing HTTP 304 requests. Figure 6.3(b) shows us similar data for CCZ. The traffic volumes are less volatile within CCZ, but we find a similar pattern in the differences between the lines across the ICSI and CCZ datasets. We note that at both vantage points, a shared proxy cache would not need more than 100GB of storage – well within the capabilities of a modern server.



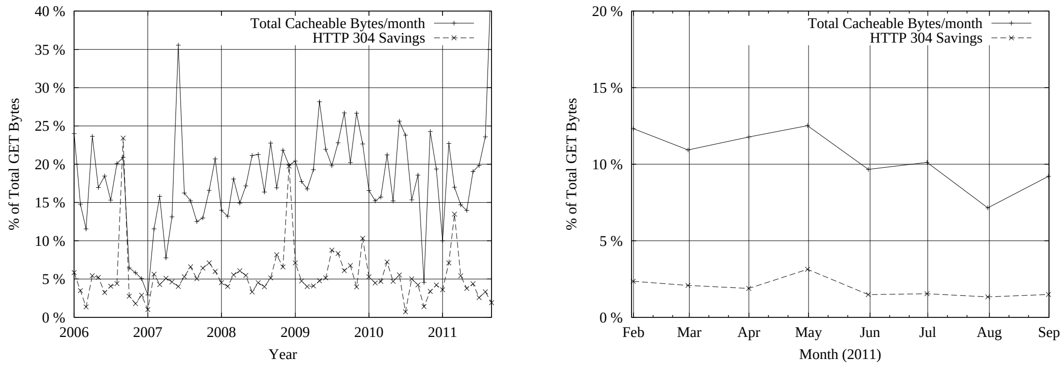
(a) ICSI



(b) CCZ

Figure 6.3: Caching

In Figure 6.4, we re-plot the data from Figure 6.3 as a fraction of the total amount of data retrieved. At ICSI, we classify between 15-25% of traffic as being cacheable in most months. Furthermore, we find that were it not for the usage for HTTP 304s, monthly traffic volume would increase by approximately 5%. We find that CCZ users have less caching potential – between 7.5-12.5% – and derive less benefit from HTTP 304s – 2-3% of bytes. The amount of cacheable content we observe in both datasets is less than the 30-50% found in some older studies [BBBC99] [CDF^{+}98], but similar to the amount a recent study [Ihm11] found to be possible for an HTTP object-level cache.



(a) ICSI (b) CCZ

Figure 6.4: Caching Ratios

Chapter 7

Server Structure

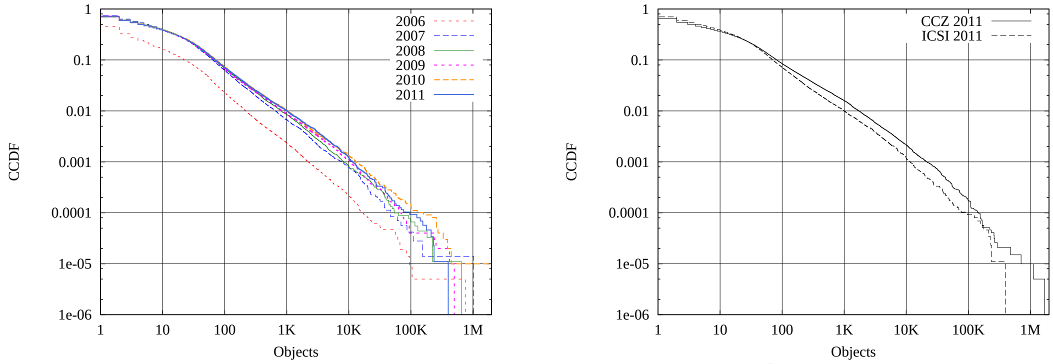
In this chapter, we study the relationships between websites (such as www.cnn.com) and the physical servers that send content on the websites' behalf by examining their hostnames and IP addresses, respectively. We begin by observing the distribution of the number of objects served by each website. We then look at the extent to which replication and CDN-like technologies are used to distribute the load of a website to many physical servers, as well as the extent to which the servers themselves are shared by multiple websites. Finally, we pick a single CDN (Akamai [DMP$^+$02]) and measure the level of traffic received from this CDN.

7.1 Object Concentration

Figure 7.1 shows the distribution of the number of distinct objects[1] requested from each website hostname. At ICSI, in all years except 2006, we find that roughly 30% of websites serve only a single object to our entire user population. Approximately 72% of websites serve 10 or fewer objects, and roughly 1% serve 1,000 or more objects, with some websites serving hundreds of thousands of distinct objects. We were able to find no discernable

[1] It is important to note that we consider any distinct set of (URL, client-supplied parameters) to be a distinct object, as one would expect the output of a page to vary with the parameters given.

year-to-year trend. The number of objects enumerated on each website as seen by the CCZ users remains quite close to the distribution observed at ICSI until reaching the 0.0001% most object-laden sites, where CCZ users accessed in excess of 1M distinct objects.



(a) ICSI (b) CCZ

Figure 7.1: Objects Per Hostname

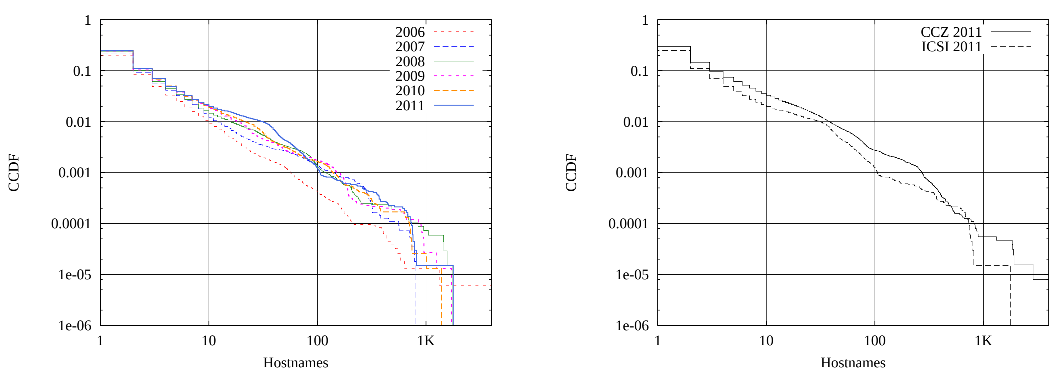
7.2 IP/Hostname Topology

The number of hostnames observed for a particular IP address illustrates the extent to which a specific IP address is shared. This sharing can be as simple as a web hosting provider placing multiple customer websites on a single server, or as complex as the dynamic shifting of customer content to underutilized edge servers in a content delivery network. As there is no standard for discovering the hostnames on a server (aside from a single hostname discovered via a reverse DNS lookup [Lot87]), our examination is only of those hostnames that our clients query directly. Our results on the concentration of hostnames to a particular IP address should therefore be considered a lower-bound.

Characterizing the inverse relationship by counting the number of IP addresses observed for a specific hostname allows us to start to gain an understanding as to how websites are utilizing more advanced platforms for content delivery than the traditional model in which each website lives on a single server. In recent years, content delivery networks such as Akamai [DMP+02] have revolutionized web scalability by offering a system in which users of a client's website are automatically redirected to one of thousands of possible servers to retrieve that website's content. Similarly, services such as Amazon EC2 [ec2] (better known as a *cloud*) provide a flexible set of distribued virtual machines for use by clients – enabling both websites and custom applications to run in a distributed fashion.

As shown in Figure 7.2(a), at ICSI in 2006, approximately 80% of server IPs visited appeared to serve only one hostname. In 2011, 75% of server IPs visited served a single hostname – not a substantial increase in shared servers. At the 1% mark however, there is a trend towards an increased density of hostnames per IP – from 10 to roughly 30 across our observation period; however when examining the most highly shared IP addresses, we find no significant change over time. In other words, while the number of IPs that serve multiple hostnames shows little change, many of these shared IP addresses are serving more hostnames than in the past.

In the CCZ dataset in 2011 we find that about 70% of server IPs visited are linked with a single hostname as shown in Figure 7.2(b). The top 1% of IPs with the most hostnames show approximately 35 hosts per IP address. At the 0.1% mark, we see the biggest difference between our two datasets – ICSI users leverage at least 103 hostnames on these highly-loaded IP addresses, while CCZ users utilize at least 262.

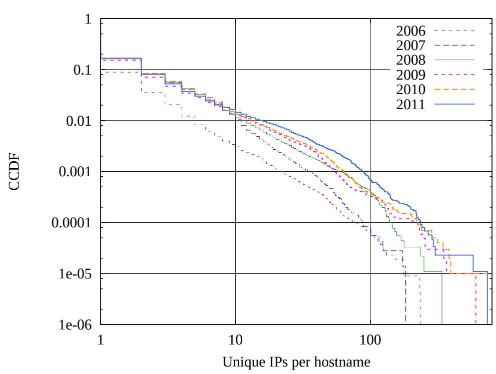


(a) ICSI (b) CCZ

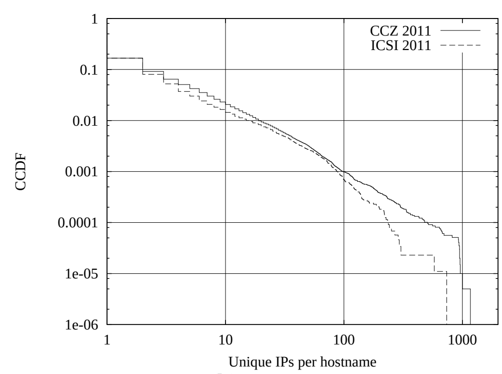
Figure 7.2: Hosts per IP

Figure 7.3(a) illustrates that the majority of websites visited from ICSI are not distributed over multiple IP addresses. 83% of hostnamess we encounter use a single IP address. Another 8% appear to be running on a pair of IP addresses, while another 5% run on 3-4 IP addresses; the remaining 4% of hostnames are observed on 5 or more IP addresses. The data from 2006 indicate a lower number of IP addresses per hostname than in subsequent years, however when considering the 99% least-distributed hostnames, there is no strong year-over-year trend. When we examine the higher levels of dispersion of a hostname, it seems that the most-distributed hostnames are becoming even more distributed – for example, in 2006 the 0.01% most distributed hosts were seen on at least 74 IP addresses, whereas in 2011 the top 0.01% most distributed hosts were seen on about 237 or more IPs. In absolute terms, ICSI users saw 61 hostnames represented by 100 or more IP addresses each in 2011.

In Figure 7.3(b), we note similar behavior between the CCZ and ICSI (2011) datasets. At the 0.01% level, the CCZ users see at least 479 IP addresses used by a given hostname, compared to ICSI's 237.



(a) ICSI



(b) CCZ

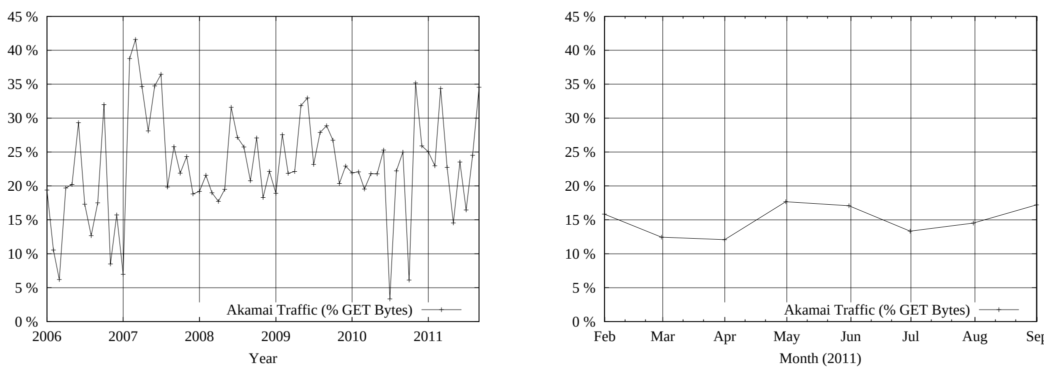
Figure 7.3: IPs per Host

7.3 Content Delivery Networks

Content delivery networks (CDN's) are typically comprised of a large number of computer servers (or clusters thereof) distributed widely in both geography and network location. One prevalent CDN, Akamai [DMP+02], has placed thousands of servers in the datacenters of Internet service providers around the world in an effort to maintain a presence in the edge of the Internet. Akamai's customers pay for their content to be served by Akamai, and allow Akamai to control the DNS names used for these customer websites. When Akamai receives a DNS request for a customer's domain name, it replies with the address of one of these Akamai edge servers that has the desired content, the capacity to handle the request, and has an acceptable network latency to the client. By this scheme, Akamai's customers have access to immense aggregate network capacity to serve clients, and the diverse set of edge servers means that the set of clients will likely see a lower round-trip time (and therefore better performance) than if requests were served by machine(s) at a single location.

Akamai claims to deliver between 15-30% of the world's Internet traffic at any given time, according to a report published on their website [aka11]. In order to test this claim, we utilize logs of DNS queries made at both of our measurement sites. When we encounter a DNS lookup that returns a CNAME in a manually compiled list [Tri09] of CNAMEs used by Akamai, we flag that IP address as an Akamai edge server. For example, when resolving the host *ak.buy.com* (known at the time of writing to be an Akamai customer), we see in the DNS response a CNAME for *a1554.b.akamai.net*. This *akamai.net* domain suffix is one of several manually gathered by performing DNS lookups on known Akamai customers.

Figure 7.4(a) illustrates the percentage of bytes received from known Akamai edge servers in `GET` requests from the total bytes received in `GET` requests that month at ICSI. We stress that this is a lower bound on traffic received from Akamai – there may be traffic from Akamai that did not exhibit a DNS redirection to a CNAME in our list, and would therefore be misclassified as non-Akamai traffic. Even so, it appears that Akamai's claim that it send 15-30% of bytes sent worldwide is reasonable. In the ICSI data, we find that after 2006, measured Akamai traffic almost never falls below 15%. While we see two sharp dips in Akamai traffic in 2010, these dips are the result of spikes in non-Akamai traffic driving down Akamai's measured proportion of traffic, not from a reduction in raw bytes from Akamai (not pictured). Furthermore, the portion of Akamai traffic is often about 20%, and occasionally rises above 25%. For our CCZ user population in Figure 7.4(b), we do not observe Akamai traffic exceed 17.6%. However, Akamai traffic never dips below 12%. While we do not continually observe the 15% claimed by Akamai, the results of our lower-bound analysis seem reasonably consistent with Akamai's claims.



(a) ICSI (b) CCZ

Figure 7.4: Akamai Traffic (% GET Bytes)

Chapter 8

Summary

In this study we examined over five years of web activity from one vantage point and eight months from another in order to assess web use via several metrics. We both compare our results with existing work in the field and provide a much higher resolution view of changes over time than previous studies. We studied evolving/dynamic properties of the web and highlighted a number of trends.

In Chapters 3 and 4, we observed an increase in nearly all raw counts such as number of requests, number of bytes, etc. In Chapter 3, we showed that HTTPS connections increased in number in 2010-2011. We observed that average transaction sizes have tended to increase over the course of our study in Section 4.2, while finding no discernible pattern in median transaction sizes. Our study of connection parallelism in Section 5.2 was able to track the increases in parallelism made by changed in popular web browsers in 2008. In Section 6.2, we studied popular object types and observed a trend towards dynamic content and newer image formats.

We also found many properties that exhibited little change over the course of the study. First, we noted that the shape of the distribution of object sizes stayed the same over all years and at both vantage points. Second, we observed that the average number of requests per connection stayed around 2 for most months at both vantage points. Third, the original Internet TLDs remain the most popular, .com and .net in particular. Fourth, images remain the commonly requested type of file. Finally, the shapes of the distributions of both object and hostname popularity remain static.

We also examined the structure of the web, finding that top websites are distributing content from a wider set of sources than in years past. We investigated the claims of a major CDN, finding its claims of traffic volume realistic. While we have not examined every aspect of web use, we believe that our contribution will assist in grounding the community's mental models and experiments in long-term empirical observation.

Chapter 9

Future Work

There are many avenues related to the research in this thesis that remain unexplored. Moreover, given the differences among the possible vantage points for studies such as this one, there is always the potential for the same experiments to yield different results for different user populations. Indeed, the vantage points used in this study did not yield the same results. Aside from the expansion of this study to additional vantage points, we discuss several possible directions that merit further investigation.

Primary/Secondary Object Classification: Some other works such as [HCJS03] perform separate analysis on primary objects (i.e., the page a user actually visits) vs secondary or embedded objects. While our limited header data and lack of full content complicate differentiating the two, if we were able to infer this difference from our data we would be able to provide a more meaningful analysis of the most popular websites. In addition, this would allow us to analyze the use of generic web objects referenced from many websites (such as advertisements or analytic software).

Distinction between automatic and user-generated requests: Users on today's web are not the only drivers of traffic. The proliferation of AJAX applications, as well as the usage of HTTP as a transport for other applications using technologies such as SOAP [BEK^{+}00] has caused much web traffic to be application-driven. We would like to explore the differences between this application-driven and user-driven traffic.

Page Load Times: If we were able to enumerate the primary and embedded objects of complete web pages, we could measure the loading time required for the pages of different websites. This would allow us to evaluate the impact of certain design decisions such as using multiple subdomains to serve embedded objects.

Analysis of multiple CDNs: Akamai is not the only major CDN in the world. Limelight is well known to be the primary CDN for Netflix, while Google operates its own CDN for services such as Gmail and Youtube. Studying these CDNs as well would yield a better view of the world's largest traffic sources.

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